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PORTUGAL
and
UNITED STATES

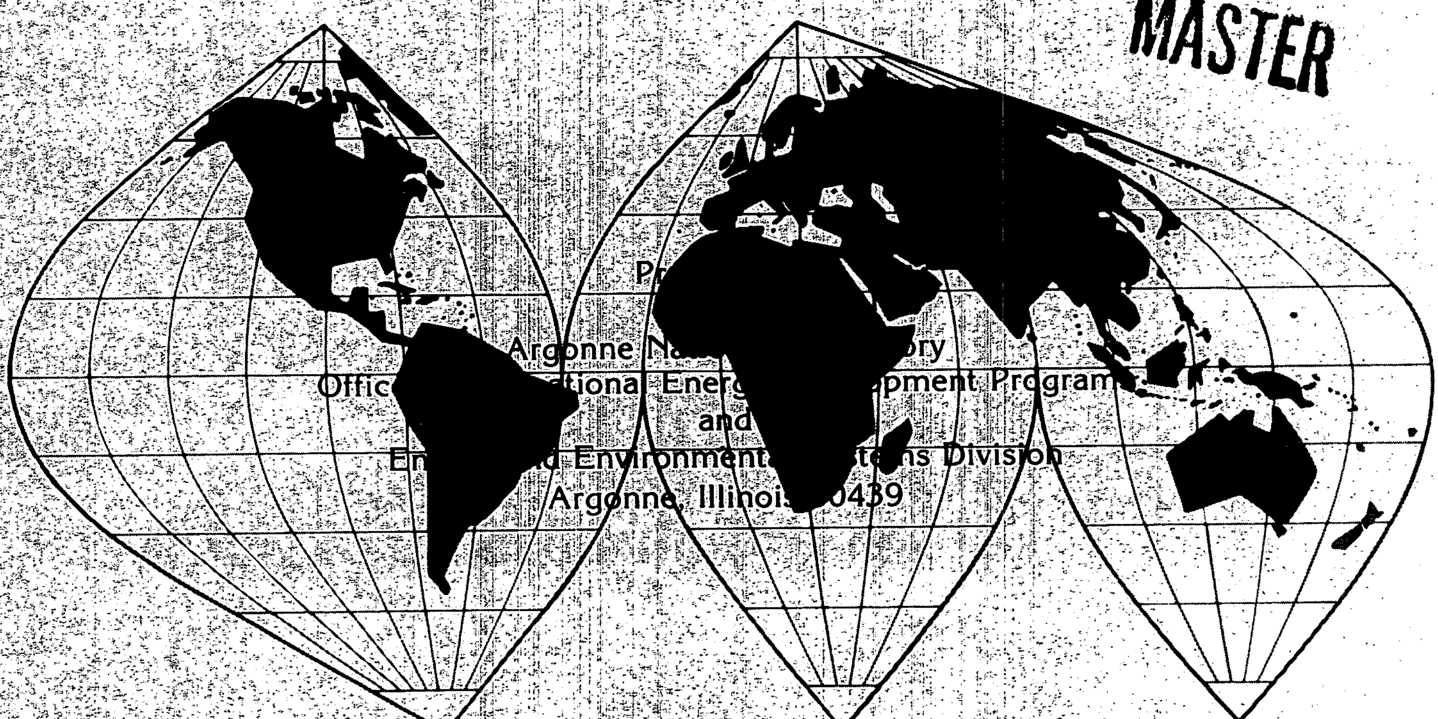
COOPERATIVE ENERGY ASSESSMENT

Directorate General of Energy
Ministry of Industry and Energy
Government of Portugal

U.S. Department of Energy
Assistant Secretary for International Affairs
Office of Country Energy Assessments

REFERENCE REPORTS
Part 1 of 3 Parts

September 1981



Prepared by
Argonne National Laboratory
Office of International Energy Development Programs
and
Energy and Environmental Systems Division
Argonne, Illinois 60439

DISCLAIMER

PORTUGAL
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COOPERATIVE ENERGY ASSESSMENT

Directorate General of Energy
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U.S. Department of Energy
Assistant Secretary for International Affairs
Washington, D.C. 20585

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REFERENCE REPORTS
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FOREWORD

During fiscal years 1980 and 1981, the United States in cooperation with the Government of Portugal conducted a comprehensive assessment of Portugal's energy resources, needs, and uses and developed several alternative energy strategies for meeting projected energy requirements. The process began when, in June 1979, U.S. Ambassador Richard J. Bloomfield extended an invitation to the Government of Portugal to participate in a joint Portugal/U.S. Cooperative Energy Assessment. The assessment officially commenced on June 19, 1979, when Portugal (in a letter from Eng. Alvaro Barreto, then Minister of Industry, Government of Portugal, to the U.S. Embassy in Lisbon) accepted Ambassador Bloomfield's invitation, which led to the commencement of actual assessment activities in November 1979. The final draft report was presented by Ambassador Bloomfield to Minister of Industry and Energy, Bayão Horta and approved by the Government of Portugal in July 1981. This assessment was a collaborative effort by a team of U.S. and Portuguese experts in energy resources and technologies, development economics, and energy systems planning and analysis. The U.S. Department of Energy managed the United States' component of the assessment with the overall policy guidance of the U.S. Department of State and with primary technical management by Argonne National Laboratory.

This part of Volume III of the Portugal/United States Cooperative Energy Asssessment report was prepared by the United States Geological Survey. The Geological Survey, a bureau of the United States Department of the Interior, prepared this report on behalf of the Government of Portugal and the United States Department of Energy.

Additional copies of the report can be obtained from the National Technical Information Service (U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161) under the terms of its current price schedule.

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This assessment was conducted jointly by Portuguese and United States technical experts on the basis of information available from a number of sources both in Portugal and the United States. The assessment, its assumptions and its observations do not necessarily reflect the official policy of either government. Neither the Government of Portugal or the Government of the United States, the U.S. Department of Energy, nor any of their contractors, subcontractors, or their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any contained information.

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UNITED STATES
DEPARTMENT OF THE INTERIOR
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PROJECT REPORT
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ENERGY RESOURCES OF PORTUGAL

REPORT PREPARED ON BEHALF OF THE GOVERNMENT OF PORTUGAL AND
THE UNITED STATES DEPARTMENT OF ENERGY

1981

ENERGY RESOURCES OF PORTUGAL

By

UNITED STATES GEOLOGICAL SURVEY

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SUMMARY

Energy for the future is of great concern to all nations, regardless of the state of their industrial development, or their endowment with resources of conventional fuels. In most developing countries, this concern is accentuated by inadequate knowledge of indigenous resources; shortage of experienced personnel; shortage of funds for exploration, evaluation, and development of new supplies; and high costs of importing needed fuels from abroad. To solve the problems of meeting future demands for energy, governmental energy policies should be based on comprehensive assessments of the discovered and potential energy resources, and on an understanding of the factors involved in the development and utilization of those resources.

Development of new sources or major increase in production of known sources of energy is a many-faceted, highly complex, and expensive undertaking. Of necessity, it should start with adequate knowledge of the resource base available for exploration. In other words, an accurate assessment of the quantity and quality of identified resources of each energy commodity is needed, plus an evaluation of probable but unproven reserves, and an estimate, based on the best available data and expertise, of the undiscovered resources.

The U. S. Department of Energy, in cooperation with the U. S. Department of State and the U. S. Geological Survey, Department of the Interior, is assisting selected developing nations in the identification of their domestic sources of energy. For each of the selected countries, the first phase of the investigation is the compilation and evaluation of the information at hand concerning energy resources, and to project data for future supply and demand for energy. Such preliminary phase I evaluations of information available in the United States were made for Portugal.

The second phase of the project involved in-country visits by U. S. Geological Survey (USGS) teams of energy specialists to evaluate each of the significant nonrenewable energy sources, including geothermal and nuclear energy. This investigation was carried out in close collaboration with Portuguese counterparts; the findings of the USGS team are presented herein.

In this report, statistical data on production and consumption and supporting information were obtained from U. S. Bureau of Mines records supplemented by additional data obtained in Portugal. Geologic descriptions and analysis of known areas and of areas having possible future potential have been prepared by the U.S. Geological Survey.

Approximately 80 percent of Portugal's land area contains outcropping crystalline rocks of Precambrian and Paleozoic ages and intrusive and extrusive crystalline rocks of other ages; about 20 percent of the land area consists of sedimentary rocks ranging from Cambrian to Pleistocene. Only about 30 percent of Portugal has been mapped geologically at a scale of 1:50,000.

Portugal lacks sufficient indigenous supplies of organic fuels to meet its energy demands, and so must import large quantities of petroleum and coal. Approximately 80 percent of Portugal's electric energy is produced by hydroelectric stations; thermal stations produce the other 20 percent.

Portugal has produced no crude oil, natural gas, or condensate; no resources or reserves in these categories are listed for Portugal in the 1976 World Energy Conference report. Exploratory wells have been drilled offshore to test for oil and gas along the western and southern coasts of Portugal; all wells were abandoned as commercially unsuccessful, but some were reported to have had oil shows. Until the last year or so (1980), no significant onshore petroleum exploration had been done in Portugal since 1963.

Production of coal in Portugal has declined steadily to the present annual yield of about 200,000 metric tons. On the basis of estimates in only three coal fields, resources of coal of all ranks in Portugal total at least 76 million (10^6) metric tons. Only one mine, the Pejao, in the northern part of the country, produced coal in 1979, and 90 percent of that production was used for electric power generation at one thermal plant.

Uranium is mined near Viseu and Guarda in the northern part of Portugal; the Nisa mine in east-central Portugal will begin producing uranium ore in 1985 after installation of a processing plant. Portugal produced 95 metric tons of uranium oxide (U_3O_8) from ore stocks in each year from 1972 through 1974; production is assumed to have continued at the same rate since then. The uranium deposits are listed as vein, contact, and other (presumably shale) in the 1976 World Energy Conference report. At the time that this energy resource assessment was being conducted by the USGS, a comprehensive study of the uranium resources of Portugal had just been completed by a team of consultants to the International Uranium Resources Evaluation Project (IUREP) under the auspices of the Organization for Economic Cooperation and Development, Nuclear Energy Agency and the International Atomic Energy Agency (OECD NEA/IAEA). In order to avoid needless duplication of effort, an assessment of the uranium resources of Portugal was not made by the USGS; rather, Portugal was to obtain the assessment directly from OECD NEA/IAEA.

Geothermal energy has not been developed in mainland Portugal; however, hot springs that may have geothermal energy potential are known in the Minho district in the northwest. Geothermal energy resources exist in the Azores and a program of evaluation and exploration with technical assistance from the USGS is presently in progress there.

Exploration of known mineral resource areas, rather than exploration for new mineral districts, appears to be the mining industry's policy in Portugal. Mining, which constitutes a very small part of the Portuguese economy (less than one percent of both the GNP and the employment), is directed mainly to building stone and construction materials, 51 percent; iron and other metallic ores including uranium, 32 percent; nonmetallic ores, 11 percent; and coal, 6 percent. The mining industry significantly influences the local and regional economies, but only slightly influences the national economy.

Authors of the reports included herewith as a part of this assessment individually recommend additional investigations, exploration, and evaluations that should be made for each energy resource. Portugal's best prospect for near-future development of additional energy resources appears to be in the hydroelectric sector. The geomorphology of mountainous terrane traversed by rivers with relatively open valleys permits building of dams near desired localities. Development for production of indigenous energy resources, even in limited amounts, may alleviate some of the drain on the Portuguese economy caused by importing expensive energy.

In any analysis of supplies of minerals available for present or possible future exploration, it is very important to understand the meaning of the terms used. Much confusion and misunderstanding can result from undefined or loosely used terminology, and statistical tables can be misinterpreted if the basis for quantification is not clearly set forth.

The U.S. Geological Survey and U.S. Bureau of Mines (U.S. Geological Survey Circular 831, 1980) have addressed this problem, and have arrived at the following definitions, which are in standard use in their publications, and are adhered to in this report.

Resource: A concentration of naturally occurring solid, liquid, or gaseous materials in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.

Identified Resources: Resources whose location, grade, quality, and quantity are known or estimated from specific geologic evidence. Identified resources include economic, marginally economic, and subeconomic components. To reflect varying degrees of geologic certainty, these economic divisions can be subdivided into measured, indicated, and inferred.

Undiscovered Resources: Resources, the existence of which are only postulated, comprising deposits that are separate from identified resources. Undiscovered resources may be postulated in deposits of such grade and physical location as to render them economic, marginally economic, or subeconomic.

Reserves: That part of the reserve base which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials.

REFERENCES CITED

U.S. Bureau of Mines and U.S. Geological Survey, 1980, Principles of the mineral resource classification system of the U.S. Bureau of Mines and U.S. Geological Survey: U.S. Geological Survey Circular 831.

CHAPTER A

PETROLEUM POTENTIAL OF PORTUGAL

By

Mahlon Ball, Robert Carter, and Gary Younse
U.S. Geological Survey

INTRODUCTION

Mainland Portugal (fig. 1) encompasses 89,211 km^2 and had a population of 9,694,000 in 1976 (World Bank Atlas, 1978). The country's indigenous energy resources are not sufficient; therefore, the nation must import large quantities of petroleum and coal. No hydrocarbon resources or reserves were listed for Portugal in the World Energy Conference (1977) report. Portugal consumes approximately 150,000 bbls of oil per day (McCaslin, 1978), which is the lowest per capita consumption rate in Western Europe (Erricker, 1976). Oil products, however, accounted for 84 percent of gross energy consumption and 17 percent of total imports in 1978.

In 1977, Iraq and Saudi Arabia supplied the bulk of petroleum imports to Portugal (table 1). Generation of electricity, which has been primarily provided by hydropower, now must be further supplemented by crude-oil power, owing to drops in hydropower and in coal production, which decreased from 250,056 tons in 1972 to 228,480 tons in 1974 (Erricker, 1976).

Under the terms of the International Energy Development Program, the Portuguese and United States Governments agreed in April 1979 to undertake a long-term assessment of Portugal's energy resources. An evaluation of Portugal's petroleum potential was planned along with surveys of coal, uranium, geothermal energy sources, energy-related minerals, hydropower, biomass, and solar resources.

This report is the result of a month of data analysis in Portugal by M. Ball, a petroleum geophysicist, and R. Carter, a petroleum geologist, and a literature search in October 1979 by G. Younse. Considerable information was available from Portuguese Government agencies, including oil company and government reports dealing with such items as well summaries, logs, and seismic, gravity, magnetic, temperature, and geochemical data to make an initial assessment of the petroleum prospects. Nevertheless, this report does not represent an in-depth treatment of the subject of Portugal's petroleum potential. Instead, the report is a summary, produced in a short period of time, based on the detailed research of government, industrial, and academic scientists for an area that has a considerable exploration history.

The report reviews Portugal's petroleum position with respect to the history of exploration, regional geology, petroleum geology, and the out-

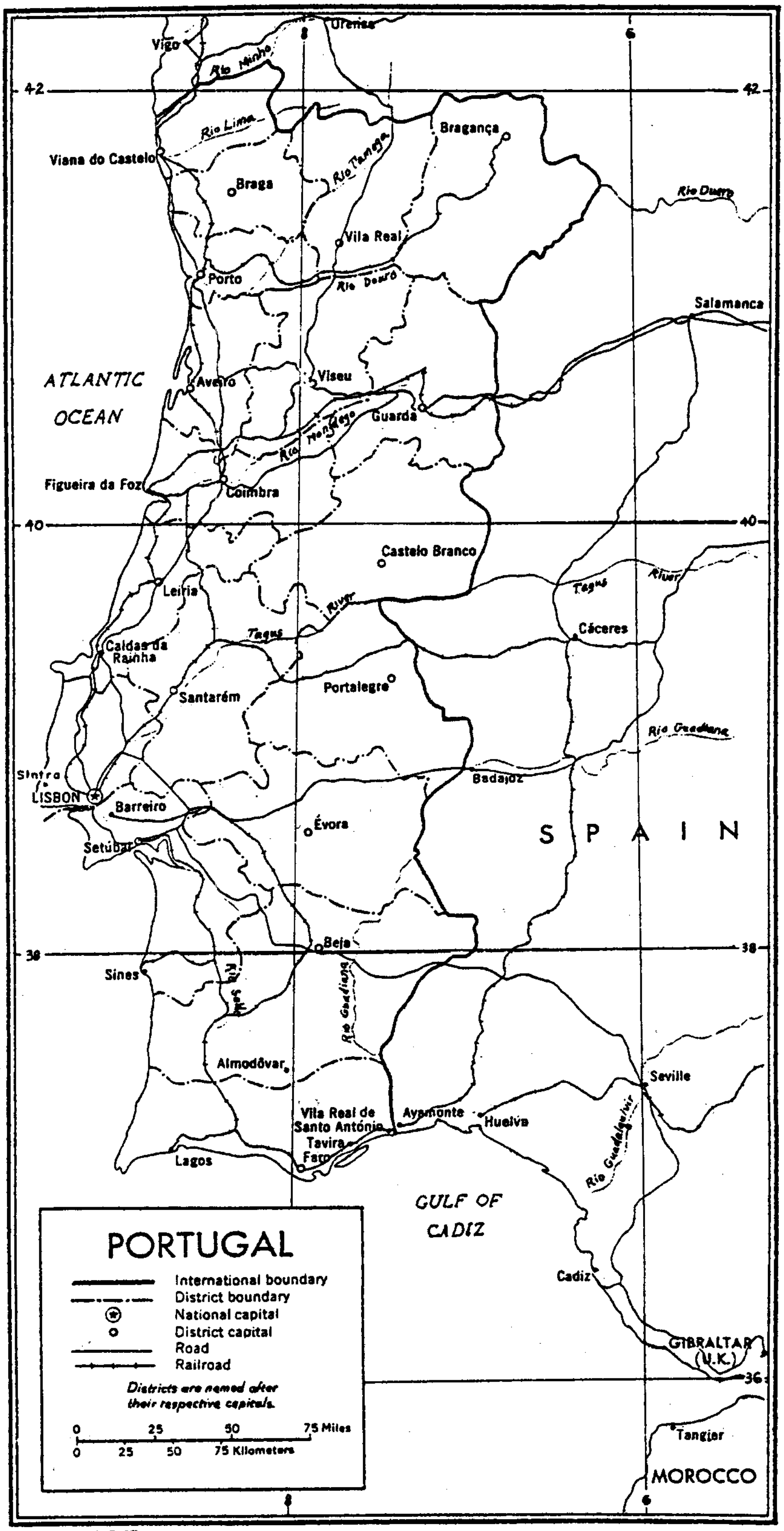

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Figure 1. Index map of Portugal.

Table 1. Portugal's petroleum imports, 1976-1977 (Financial Times, London, 1978)

COUNTRY	MARKET SHARE IN PERCENTAGE	
	1976	1977
IRAQ	29.0	38.7
SAUDI ARABIA	27.7	28.8
USSR	18.0	15.9
IRAN	19.4	11.4
OMAN	0.0	5.2
OTHER	5.9	0.0

look following the latest phase of exploratory drilling. Because of unsuccessful exploration efforts to date, we conclude that it is unrealistic to hope that future exploration efforts will solve Portugal's energy problems. Despite the fact that the cadre of workers involved are most capable and competent, the level of the government's effort in analyzing existing data and developing information that could interest oil companies in another cycle of petroleum exploration is inadequate. The effort is small in terms of the amounts of data to be examined. It is small in terms of the great capital investment made in the drilling and in acquiring the existing geophysical measurements. Finally, it is especially small relative to the cost of imported oil. As industry activity at present is nearly nil, government must fill the gap. Expansion of this effort seems to be justified.

The Portuguese Ministry of Industry and Technology, the Petroleum Company of Portugal (Petrogal), the Geological Survey, and related agencies of the host government were most cooperative and helpful. Jorge Barreto de Faria, Director of the Bureau of Oil Prospection and Exploration; Luis A. C. Cardoso da Silva, Deputy General Director; Joao Marcelino Marques, head of the Geological and Geophysical Department; and Manuela Costa, Geophysicist, were especially accommodating. Many of the statements in this report are based on discussions of the petroleum geology of Portugal with Senhor Marques and Senhora Costa.

PETROLEUM EXPLORATION HISTORY

Petroleum exploration was initiated in Portugal with the working of asphalt deposits north of Lisbon in 1844 (Owen, 1975). The deposits were developed and have resulted in limited production of asphalt (Tiratsoo, 1976). Drilling for petroleum began when the Anglo Portuguese Oil Company drilled 13 shallow wells onshore between 1939 and 1947 (table 2). Beginning in 1947, the Companhia dos Petroleos de Portugal, with Mobil Exploration Portugal Inc., and Compagnie des Petroles France-Afrique, drilled 69 onshore wells by 1963. Most of the wells were limited to shallow depths; only 10 wells were drilled below 2,000 m, and only one of these reached basement. Despite oil shows in several wells, no commercial oil production was achieved, and onshore drilling ceased in 1963. Offshore concessions were then offered by the Portuguese Government. Exploration offshore began in 1973 and by June 30, 1979, 22 wells had been drilled off the west and south coasts (table 3; fig. 2). Some wells had reported oil shows, but none proved to be commercial. Following the disappointing results of the offshore drilling program, the government offered onshore blocks for lease during 1978. By late 1979, only four offshore and seven onshore concessions were in force (fig. 3).

REGIONAL GEOLOGY

Portugal contains three major geotectonic elements: 1) the Hercynian basement, 2) Mesozoic to Cenozoic epicontinental basins, and 3) an inland Tertiary basin (Schott and Stoppel, 1976; Carvalho, 1977, fig. 4). The Hercynian basement is a western part of the Iberian Meseta and is further subdivided into northern and southern blocks. The northern block consists of Upper Precambrian to Middle Devonian metasedimentary and metavolcanic rocks. Unconformably overlying these metamorphic rocks are Upper Carboniferous and Lower Permian continental facies. Both rock units are intruded by upper Paleozoic granite and locally are intensely folded. The southern block consists of spilite-quartz-keratophyre volcanic and flysch deposits which range in age from Late Devonian to Middle Pennsylvanian (Schott and Stoppel, 1976; Carvalho, 1977).

The Lusitanian and Algarve epicontinental basins are Mesozoic to Cenozoic in age and are located on the western and southern fringes, respectively, of the Iberian Meseta. These basins are characterized by sequences of sedimentary rocks, as much as 5 km thick, which have been accumulating since Triassic time. The inland Tejo Basin, an eastward extension of the elongated Lusitanian Basin, contains predominantly Tertiary sedimentary rocks (Schott and Stoppel, 1976).

The Iberian Meseta first took shape during Precambrian time with the initiation of geosynclinal sedimentation that extended into the Late Devonian. Coeval with sedimentation were distension tectonics and, locally, rhyolitic or spilitic volcanism. The main period of folding, the Hercynian orogeny, began during the Middle Devonian and is thought by some to have been caused by a northeastward-plunging subduction zone to the southwest of the Iberian Meseta (Bard and others, 1973). Lefort (1979) postulated that a northward-dipping subduction zone existed to the northeast of the Iberian Meseta in the Bay of Biscay area during the Middle Devonian. This northward subduction ceased during Late Devonian time and culminated in the collision of the Spanish Plate (Iberian Meseta) and the Amorican Plate (France). Subduction to the south of the Iberian Meseta is inferred to have continued

Table 2. Onshore wells drilled in Portugal 1939-1963.
[Taken from Gabinete Para A Pesquisa E Exploracao De Petroleo, unpub. data, 1979]

ANOS (YEAR)	Nº DE SONDAGENS / METROS FURADOS (NUMBER OF WELLS / DEPTH IN METERS)					TOTAL	
	500m.	500/1000m	1000/2000m	2000/3000m	3000/4000m	SONDAGENS (WELLS)	METROS (METERS)
1939/1947	12	——	1	——	——	13	3356m.
A.P.O.C.	2192m	——	1164m.	——	——		
1947/1955	24	4	6	1	——	35	19963m.
C.P.P.	6300m.	2995m.	8328m.	2340m.			
1955/1959	3	1	6	4	3	17	30854m.
C.P.P.+M.E.P.I	1430m.	693m	9048m.	9159m.	10524m.		
1960/1961	10	1	1	——	——	12	2696m.
C.P.P.	710m.	623m.	1363m.	——	——		
1962/1963	——	——	3	2	——	5	9886m.
C.P.P+COPEFA	——	——	4395	5491m.	——		
TOTAL	49	6	17	7	3	82	
	10632m.	4311m.	24298m.	16990m.	10524m.		66755m.

A.P.O.C. = ANGLO PORTUGUESE OIL COMPANY
C.P.P. = COMPANHIA DOS PETRÓLEOS DE PORTUGAL
M.E.P.I = MOBIL EXPLORATION PORTUGAL INC.
C.O.P.E.F.A. = COMPAGNIE DES PÉTROLES FRANCE-AFRIQUE

Table 3. Offshore wells drilled 1973-1979. [Taken from Gabinete Para A Pesquisa E Exploracao De Petroleo, unpub. data, 1979]*

CONCESSIONARIOS (CONCESSIONS)	AREAS DE CONCESSAO (CONCESSION AREA)		SISMICA (SEISMIC) Km	SONDAGENS WELLS	
	N.º (No.)	Km²		N.º (No.)	FURADOS(M) (DEPTH M)
SHELL PROSPEX/ /SACOR	4-5-6-13 14-16-17 19-20	6733	9464	9	22778
SUN/AMERADA/PHILLIPS	11-12	1660	1382	2	5811
ESSO	9-10-15	2239	1907	2	5080
CHEVRON/GEOSUL/PETRO GARBE					
Areas to 200-meter depth	31-32	1423	783	1	2249
Areas between 200 and 1000-meter depths	203-204-205	2691	2226	1	2637
TEXACO					
Areas to 200-meter depth	1-2-3-24-25	3238	2576	6*	12165
Areas between 200 and 1000-meter depths	213-214-215	2318	1548	—	—
CHALLENGER/EREX					
Areas to 200-meter depth	33	670	445	1	3083
Areas between 200 and 1000-meter depths	201-202	1737	1039	—	—
TOTAL	30	22709	21336	22	53803

* Includes three wells abandoned for mechanical reasons in concession 2.

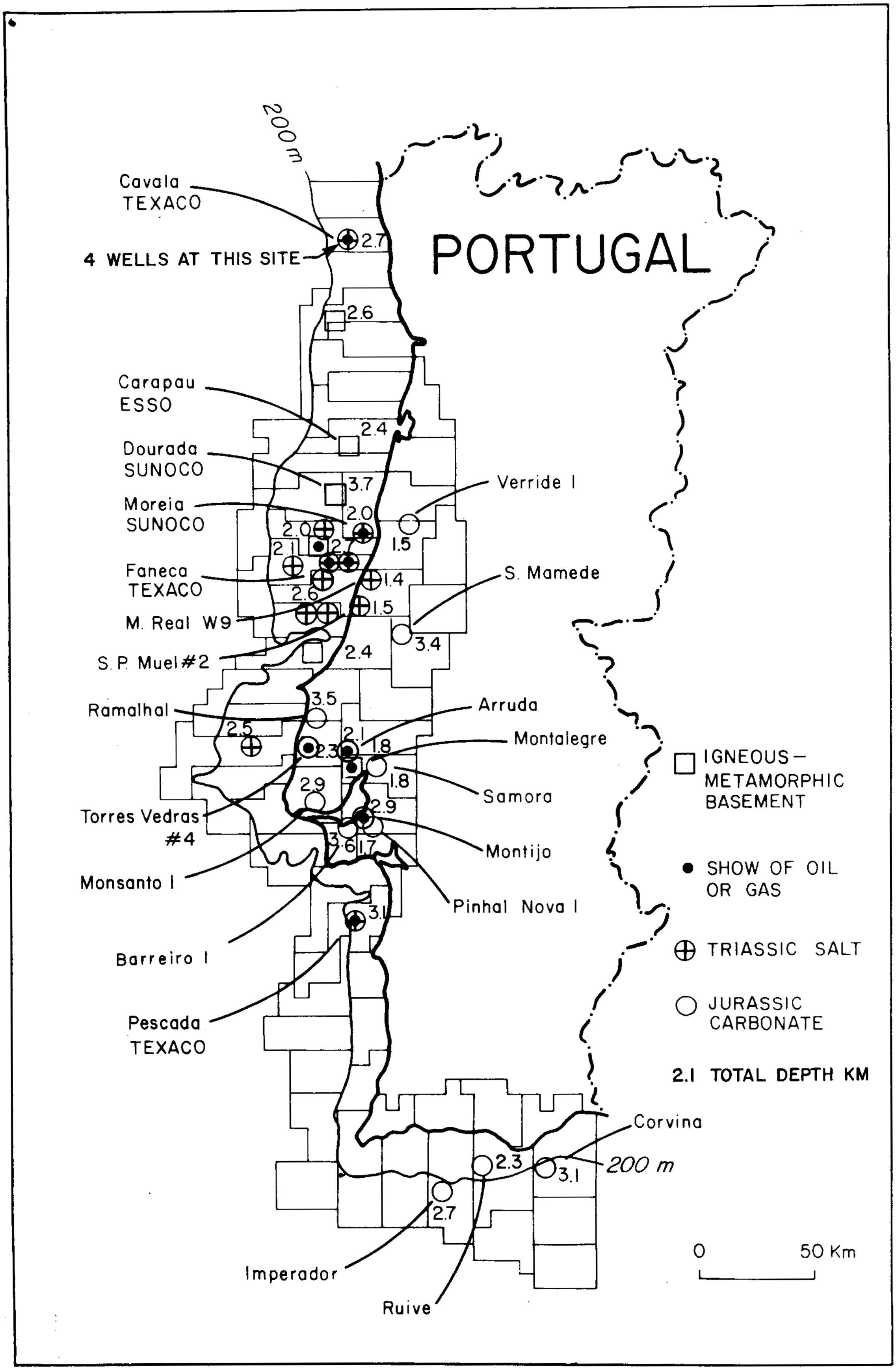


Figure 2. Location of deep exploratory wells and rock penetrations, Portugal. Symbols indicate nature of rocks at total depth and presence of oil or gas shows. Total depths to the nearest 0.1 km are posted adjacent to the wells (Gabinete Para A Pesquisa E Exploracao De Petroleo, unpub. data, 1979).

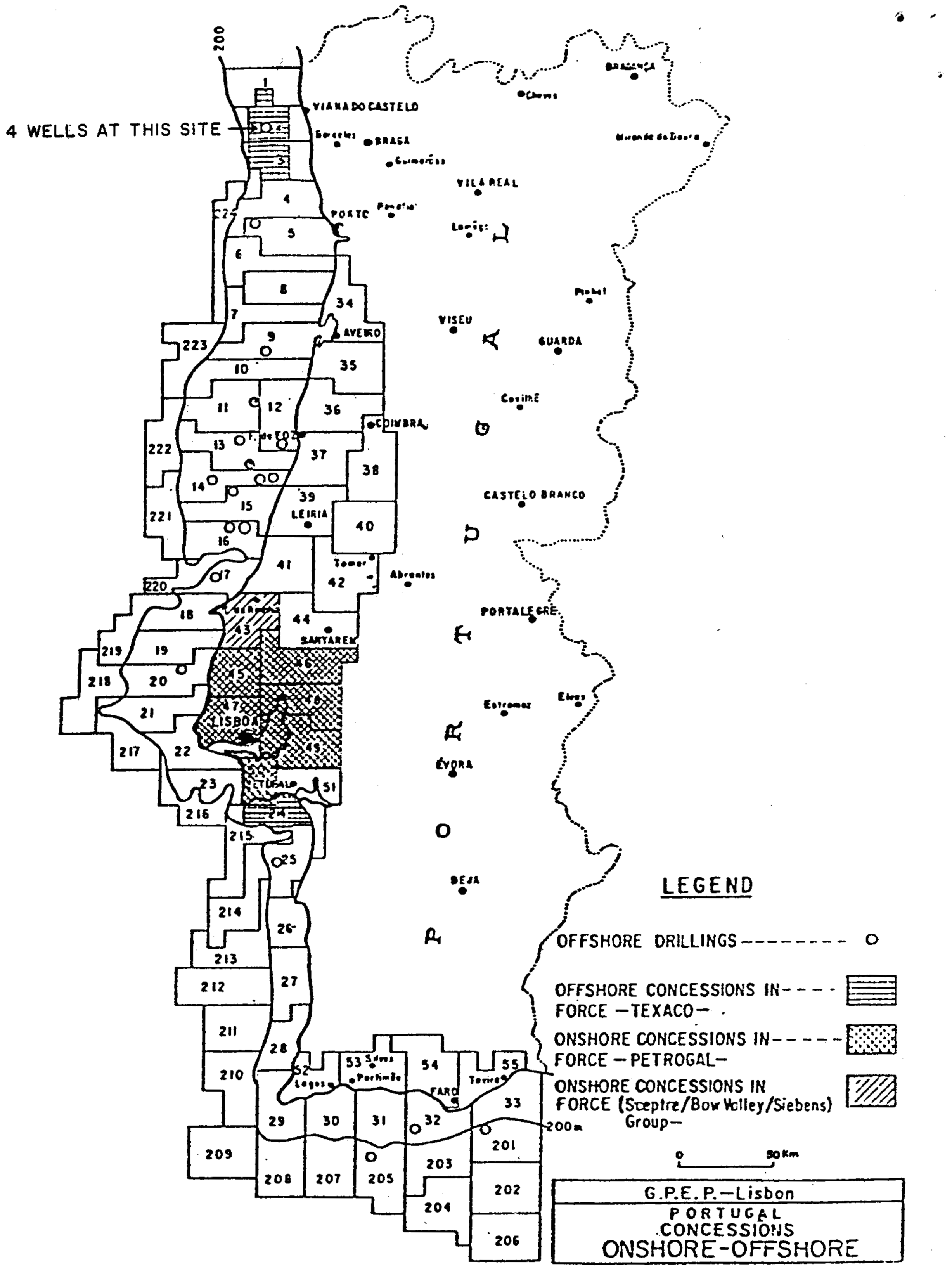


Figure 3. Oil exploration concessions in force, Portugal, 1979 (Gabinete Para A Pesquisa E Exploracao De Petroleo, unpub. data, 1979).

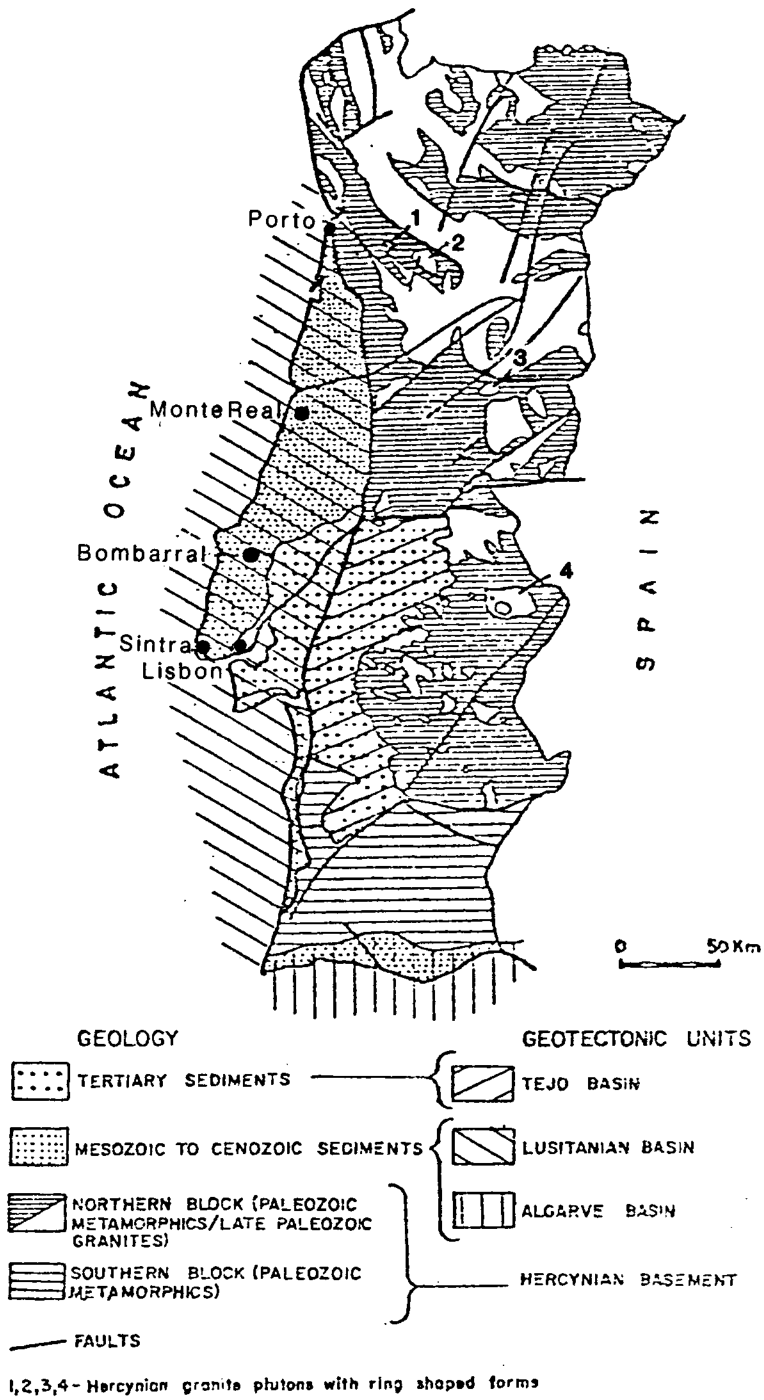


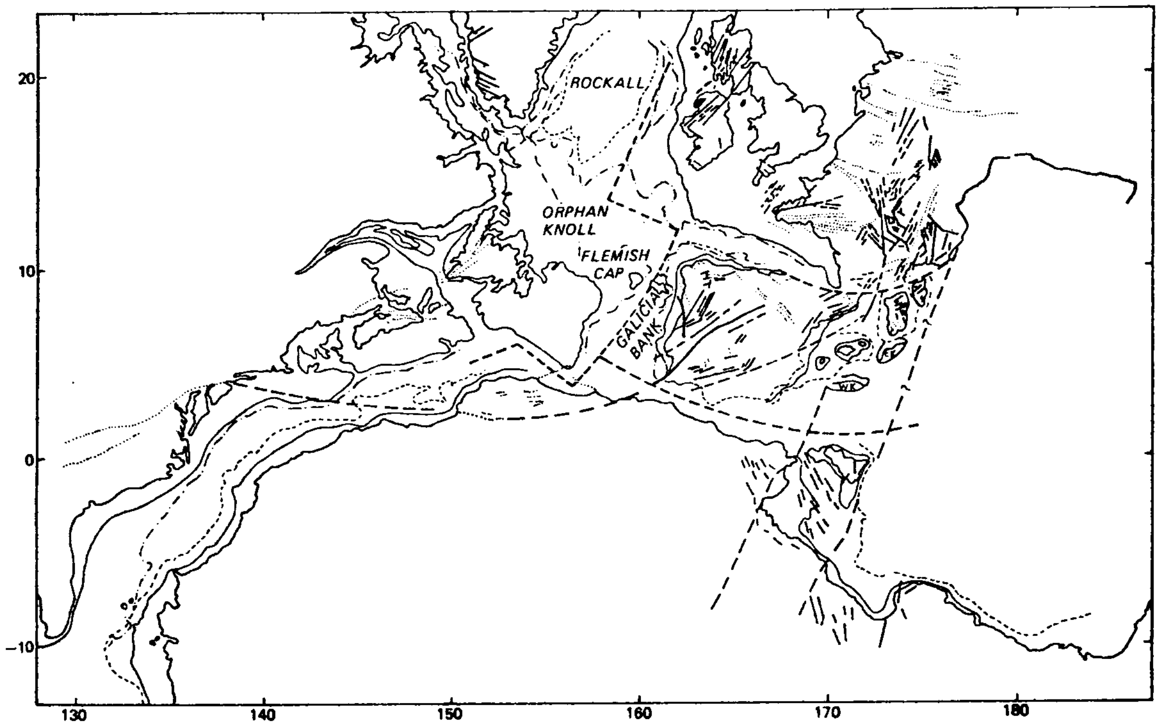
Figure 4. Geology and geotectonic units of Portugal (Carvalho, 1977).

until the Middle Pennsylvanian. Granitic intrusions, continued crustal shortening, and transcurrent sinistral faulting accompanied the folding. Peneplanation and isostatic readjustment of the Iberian Meseta continued into Mesozoic time, following the cessation of subduction to the south (Bard and others, 1973).

Analysis of the pattern of magnetic anomalies in the North Atlantic pioneered by Pitman and Talwani (1972), clearly shows that Europe and North America remained attached (fig. 5) as they moved away from Africa in earliest Jurassic time (Keen, 1979). During this time the south boundary of the peninsula, including Portugal's south coast, was the locus of a major left-lateral strike-slip fault. In the Early Cretaceous, the peninsula separated from the Grand Banks of Canada and Europe began drifting away from North America. Continued continental spreading in Late Cretaceous and Cenozoic time was complicated by the Alpine collision of Africa and Europe.

Sibuet and others (1979) discussed extensively the role of continental spreading in the evolution of the western Iberian continental margin and the formation of basins in this region. They postulated that true spreading in the North Atlantic Basin began in the late Early Cretaceous (latest Aptian) with a regeneration of basement tectonics accompanying the opening between Iberia and the Grand Banks. Uchupi and others (1976) ascribed the formation of the Bay of Biscay to counter-clockwise rotation of the Iberian Peninsula during early North Atlantic spreading as Iberia moved with North America left laterally relative to the African continent. When Europe and North America separated, the European block with Iberia attached moved away from North America more rapidly than Africa and the relative direction of motion between Iberia and Africa changed to right lateral (Uchupi and others, 1976). This relationship has been confirmed by first-motion studies (Banghar and Sykes, 1969; Krause and Watkins, 1970).

Jansa and Wade (1974) presented a detailed reconstruction of the European, African, and North American plates, based on magnetic anomaly patterns and on Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) drilling and geologic data from Canadian-Atlantic basins and juxtaposed northwestern African and southwestern European basins. They characterized the Mesozoic stratigraphy for this entire region as consisting of Upper Triassic and Lower Jurassic red beds and salt deposited in grabens and half-grabens that formed under the influence of extensional tectonism related to the inception of seafloor spreading. Deposits of this type are the oldest found in the Lusitanian and Algarve Basins of Portugal (Schott and Stoppel, 1976). The present configuration of these epicontinental basins must reflect distension movements related to the opening of the North Atlantic during Late Jurassic to Early Cretaceous time, and left-lateral strike-slip motion which acted in the Tethys or ancient Mediterranean to the south. Jurassic deposits became increasingly more open marine; some organic-rich potential source rocks were deposited in restricted, structurally controlled lows early in the period, followed by 2- and 3-km thick accumulations of deep-water carbonate deposits, shale, and shallow platform carbonate deposits in the Middle and Late Jurassic. Loading by the thick Jurassic carbonate deposits, initiated salt movement in Late



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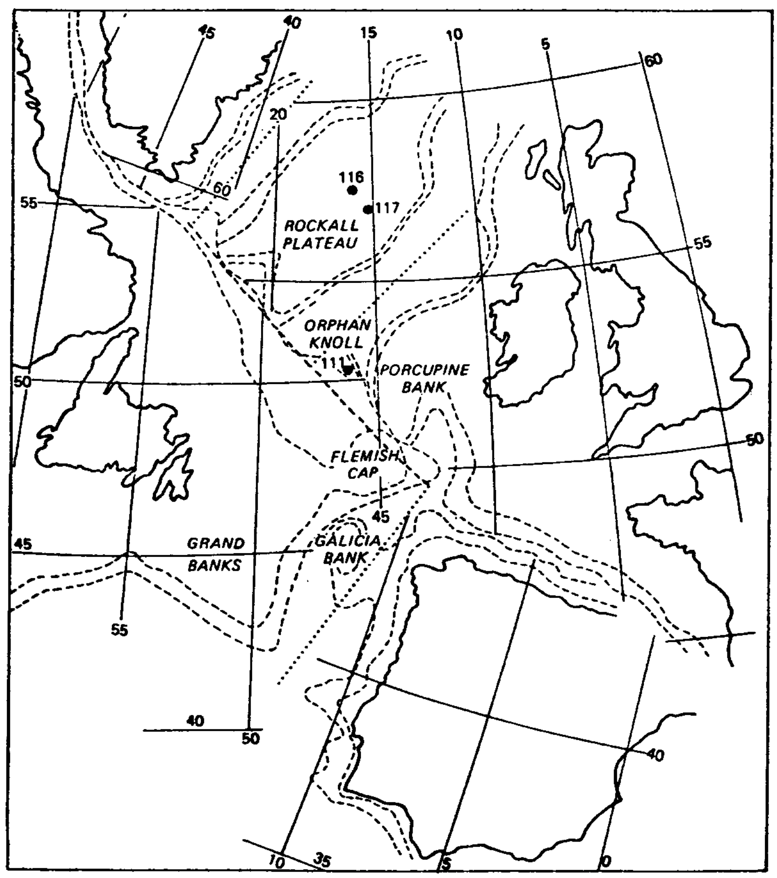

B

Figure 5. Examples of: A) a relatively "tight-fit reconstruction" (Late Hercynian, from Le Pichon and others, 1977), and B) a relatively "loosefit reconstruction " (Late Jurassic, from Laughton and others, 1975)--of the plates defining the western and eastern paleoboundaries of the North Atlantic Ocean (Sibuet, and others, 1979).

Jurassic time. Upper Jurassic sections thicken markedly in areas of salt withdrawal on the basin axis. A regional regression resulted in an unconformity that truncates some Jurassic strata and deposition of a predominantly terrigenous clastic older Cretaceous section. Horsts and grabens that compose the individual basins affected types and patterns of sedimentation. The thickest deposits of clastic rocks tended to be in structural lows, whereas some highs were loci of thinner neritic limestones (Montadert and others, 1974).

Worldwide Late Cretaceous transgression resulted in deposition of carbonate rock and shale. Regionally, the Cenozoic deposits are a regressive assemblage of terrigenous clastic sand and shale thickening locally in continental basins caused by the Alpine orogeny. In Portugal, eastward expansion of the Lusitanian Basin led to formation of the Tejo Basin (fig. 4) during Tertiary time.

An interesting aspect of Jansa and Wade's (1974) comparison of Grand Banks and Iberian stratigraphy is the similarity of the Paleozoic stratigraphic sections that underlie the Mesozoic and Cenozoic rocks. These Paleozoic deposits consist of thick sequences of terrigenous clastic material of Devonian and younger age. These rocks are thought to have been eroded off highs that formed during the late Paleozoic Variscan (Hercynian-Amorican) orogeny. The rocks are metamorphosed to varying degrees. In Portugal, they are considered by most geoscientists to be part of the basement beneath prospective hydrocarbon targets. This is not true of the rocks in North America (Amoco and Imperial Ltd., 1974). The Carboniferous flysch deposits of southwest Portugal appear to contain some organic-rich zones which, in hand specimens, do not appear to be metamorphosed.

All aspects of analogy between the Grand Banks and the Iberian offshore are made vitally important by Chevron's recent discovery, Hibernia P-15 (Clock, 1979), located on the northeast corner of the Grand Banks (fig. 6). Ben Smith, Manager of Chevron Standard of Canada, states that the field's setting is on the southwest margin of the Northeast Newfoundland Basin (Smith, 1980). This basin narrows toward the south and continues across the eastern margin of the Grand Banks as the Jeanne d'Arc Basin. The basin opens toward the north into the Labrador Basin. This region is geologically more like the North Sea than the Nova Scotian and the U.S. Atlantic Basins; that is, source beds are oil prone.

PETROLEUM GEOLOGY

Approximately 50 percent of Portugal's combined onshore and continental shelf area is surfaced by crystalline rocks of Precambrian and Paleozoic ages and intrusive and extrusive crystalline rocks of various ages. The remaining 50 percent of the area consists of sedimentary rocks that are largely confined to coastal strips and offshore areas, according to Carta Geologica de Portugal (Portugal, Servicos Geologicos, 1972) and Carta Geologica de Plataforma Continental (Instituto Hydrographico, Service de Formento Mineiro e Servicos Geologicos Portugal, 1978). The Lusitanian, Algarve, and Tejo Basins in particular,

Figure 6. Location of Chevron Standard Ltd. Hibernia P-15 well off eastern Canada (Clock, 1979).

and the continental slope and rise in general, hold promise for hydrocarbon potential.

Lusitanian Basin

The north-trending Lusitanian Basin is bordered on the east by the Iberian Meseta, and its axis coincides approximately with Portugal's Atlantic coastline on the Carta Tectonica de Portugal (Ribeiro, Conde, and Monteiro, 1972). The western margin of the basin as defined by geophysical data is a basement ridge under the continental platform edge at the 200-m depth contour.

Sedimentary rocks in the Lusitanian Basin range from Triassic to Quaternary in age, and are at least 3,668 m thick (Sunoco Dourada offshore well, fig. 2). Triassic deposits, including evaporite, dolomite, marl, and quartz sandstone, constitute the oldest sedimentary rocks known in the basin. Lower and Middle Jurassic rocks consist of marine limestone, dolomite, and marl. Upper Jurassic rocks consist of 1,200 m of limestone, marl, and sandstone. The uppermost Jurassic, Cretaceous, and Paleogene rocks consist of nonmarine fluvial to limnic sandstone and conglomerate interbedded with marine limestone. Oligocene to Miocene sandy and clayey sedimentary rocks also are present locally. Pliocene rocks consist of marine sandstone, of which some is arkosic; also present are diatomite and shale, with lignite beds from the nonmarine to limnic upper Pliocene sequences. Salt stocks of Miocene age form diapiric structures and are responsible for the redeposition of some gypsum blocks in the Neogene section (Schott and Stoppel, 1976).

Most onshore oil shows have been found in rocks of Jurassic age. Prospective reservoirs are in sandstone and bituminous limestones of the Upper Jurassic Cabacos Formation, much of which contains bitumen in joints and coral fragments. Where such limestone is characterized by reefal or a subreefal facies, or even where fractured, prospective reservoirs might be expected. Brecciated limestone beds on the flanks of diapirs are possible reservoirs. Other possible reservoirs are the detrital beds of the Upper Jurassic Abadia Formation. Porosities as high as 35 percent have been reported from the Lower Cretaceous Torres Vedras sandstone beds.

Possible source rocks are the bituminous shales of Early Jurassic age and the previously mentioned bituminous limestone of the Upper Jurassic Cabacos Formation. Maximum temperatures, as measured by wireline logs in several wells, onshore and offshore, were above or higher than 100°C at depths of more than 3,000 m. Such temperatures are adequate for hydrocarbon generation in sedimentary rocks of Jurassic age, according to Hood and others (1975). Hydrocarbon trap seals are present as evaporites, argillaceous limestones, and shales, but not necessarily in optimum positions; they are often interspersed between the source beds and the reservoir beds.

Fault zones associated with major submarine canyons impinging on the western Portuguese shelf partition the Lusitanian Basin into sub-basins. The Nazare Canyon fault zone in the north and the Sao Vicente Canyon fault zone in the south appear to continue onshore into Hercynian strike-slip faults in the crystalline Meseta (fig. 7).

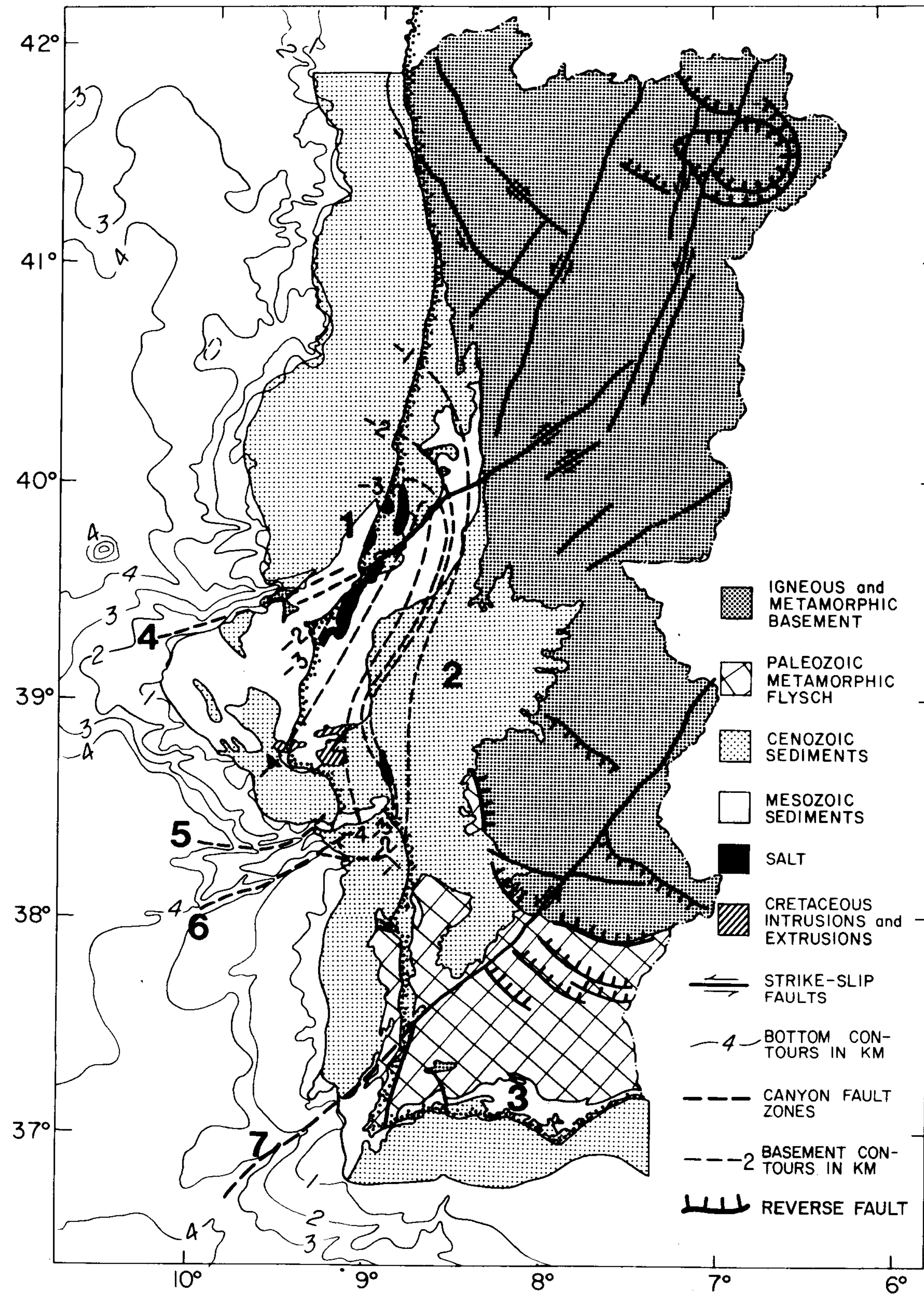

Figure 7. Tectonic-geologic map of Portugal. The large numbers, 1-7, indicate the following: 1. Mesozoic-Cenozoic Lusitanian Basin; 2. Cenozoic Tejo Basin; 3. Mesozoic-Cenozoic Algarve Basin; 4. Nazare Canyon; 5. Lisbon Canyon; 6. Setubal Canyon; and 7. Sao Vincenti Canyon (Portugal, Servicos Geologicos, 1972, and Instituto Hydrographico, Service de Formento Mineiro e Servicos Geologicos Portugal, 1978).

Second-order shears in the left-lateral regimen dating from the latest Triassic to the earliest Jurassic until at least the Aptian appear to offer the best possibilities for causing reactivation of the NE-SW Hercynian lineaments of the Iberian Meseta. These shears include NE- oriented, right-lateral strike-slip faults and normal faults (Moody, 1973; Wilcox and others, 1973). Eastward continuations of the Lisbon Canyon fault zone and the Setubal Canyon fault zone (fig. 7) are not clear cut. However, the south margin of the Serra da Arrabida with its north-dipping Mesozoic strata must mark the Setabul Canyon fault with down-to-the-south displacement. A similar down-to-the-south displacement striking a little north of east seems likely on a fault on the north shore of the Tejo River along the Lisbon waterfront. This complex fault zone contains east and northeast components and may project northeastward toward the major onshore salient of the Lusitanian Basin, i.e., the Cenozoic Tejo Basin. Normal displacements noted on these faults do not rule out the possibility of strike-slip displacements.

North of the Nazare Canyon fault trend, an almost complete section of Triassic to Cenozoic sedimentary rocks is present: the Cenozoic strata crop out on the shelf and shore (fig. 4). Sixteen offshore and three deep onshore test wells were drilled in this sub-basin north of the Nazare Canyon. Eleven holes bottomed in the Triassic (fig. 2); four holes penetrated basement, including the deepest Lusitanian Basin test, the Sunoco Dourado. These holes were located on structurally high areas above salt domes and basement fault-bounded blocks. One hole terminated in the Lower Jurassic. Five of the wells had shows of oil and gas.

The area between the Nazare and Setubal Canyon fault zones is referred to as the Lisbon sub-basin; Mesozoic rocks crop out onshore and on the shelf of this area. The complicated structure consists of folds and faults. Surface dips exceeding 5° are common. A profusion of dikes and flows and the Cretaceous granitic batholith at Sintra add to the complexity. Breached salt ridges border the seaward side of the basin axis. Twelve deep tests, two of which were offshore, have been drilled in the sub-basin (fig. 2). One test bottomed in the Triassic, nine in the Lower Jurassic, and two went to basement.

Only one well has been drilled in the Lusitanian Basin south of the Setubal Canyon fault zone. The stratigraphic section described from the Texaco Pescada Well (fig. 2) in concession 25 is: 34 m of Upper Triassic silty shale with slight indications of gas in the basal part; 375 m of Upper Triassic and Lower Jurassic shale and dolomite with halite and anhydrite; 53 m of Lower Jurassic dolomite; 518 m of Middle Jurassic argillaceous limestone; 1,215 m of Upper Jurassic limestone; 355 m of Lower Cretaceous shale and sandstone with interbedded limestone; and 164 m of upper Miocene sandstone, shale, and silty shale.

Delineation of salt basins and estimation of sediment thicknesses and depths to crystalline basement rocks have been made by gravity and magnetic measurements (Faria, 1975). More than 30,000 km of gravity and magnetic profiles at 2- to 5-km line spacing were obtained to achieve a network for mapping these parameters. Oil companies and Government agencies cooperated to map the seafloor geology. Common Depth Point (C.D.P.) reflection seismic data amounting to 13,000 km were collected in areas deemed propitious on the basis of the gravity and magnetic results. These seismic data were collected by contractors and oil companies. Efforts were made to achieve good quality control; however, problems caused by reverberation of energy off the hard seafloor exposed over much of the shelf are apparent in the Government's copies of the obtained records. Dips tend to be clearly discernible, but correlation of events over appreciable distances is difficult, in some cases almost impossible. The large quantities of velocity data available from well surveys and stacking analyses could be used in reprocessing some of the more critical seismic lines.

Rock samples recovered from wells and outcrops both onshore and offshore have been the basis for stratigraphic studies of sedimentary facies and environments of deposition. A major effort was made to identify potential source materials and to determine the maturation of these source substances. Synthesis of facies analysis and source studies led to the conclusion that although limited amounts of hydrocarbon source materials were present in structural depressions, low thermal gradients coupled with shallow burial depths prevented maturation of much of the organic-rich matter and thus inhibited hydrocarbon-producing potential. Middle Jurassic argillaceous limestones that are not subject to formation of fractures or leaching are thought by some oil company scientists to have created a seal between Lower Jurassic source materials and the porous terrigenous clastic rocks of the Lower Cretaceous that constitute the region's most promising reservoir beds.

Reconstruction of the exploration effort onshore in the Lusitanian Basin is hindered by the fact that the most recent drilling took place more than 15 years ago. Early efforts concentrated on sites of surface seeps and shows, but much information from the early wells has been lost. Another drawback is that rugged terrain interferes with geophysical measurements over much of the onshore area. Detailed mapping projects are being carried on by Portuguese scientists of the national oil company. Good-quality seismic data are being obtained on the flat plains of inland basins containing Cenozoic sedimentary fill. Current prospects include seismically defined salt and basement structures similar to the structural features tested offshore.

Among the most valuable data obtained in the onshore drilling are the velocity surveys from the deeper onshore test wells such as Ramalhal 1 and Barreiro 1, between Lisbon and Setabul (fig. 2). Results of a 1957 well survey at Ramalhal are shown in figure 8. This well, spudded in Upper Jurassic shale, penetrated a predominantly shale and chalk section in the upper 2 km and massive Jurassic carbonate rocks in the basal 1.5 km. Velocities range from 2.7 to 3.8 km/sec in the upper section and from 5.7 to 7 km/sec in the lower part. It seems that high clay content and extremely low porosities prevail for these very dense rocks. Some difficulty in obtaining good deep reflections in the Lusitanian Basin is evident and must stem from the drastic impedance contrast at the boundary between dense massive Jurassic

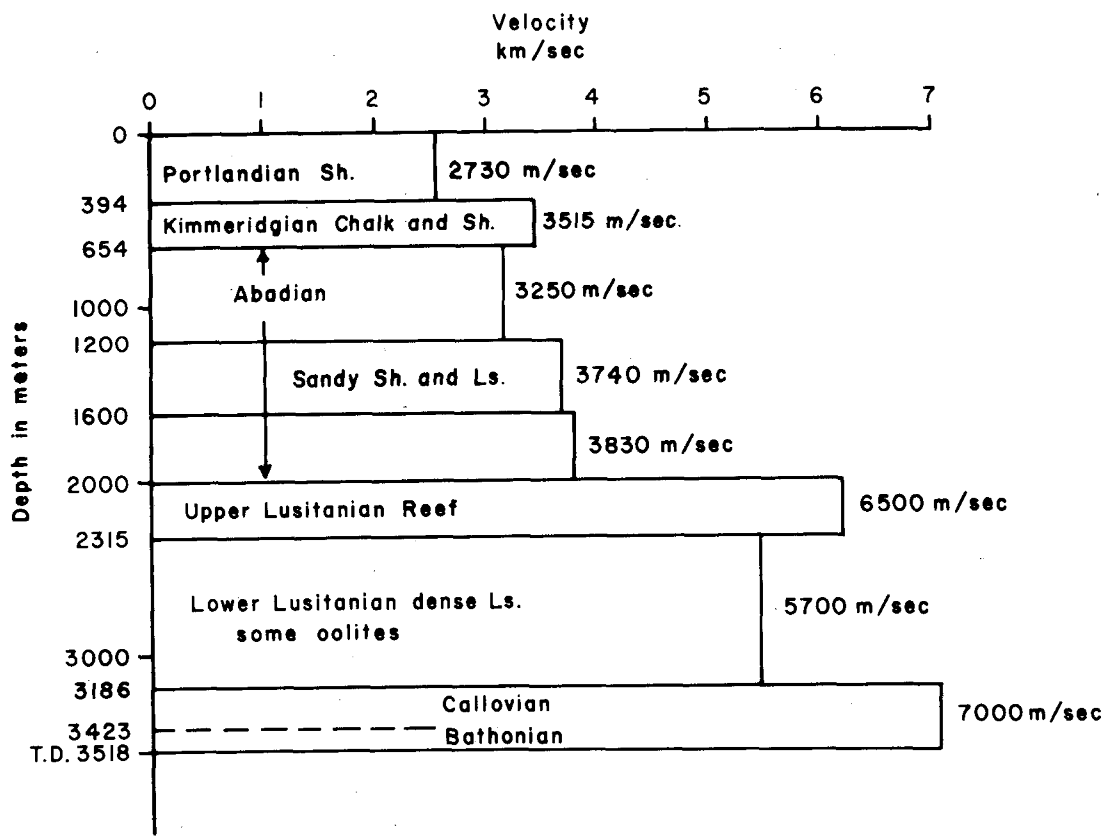

Figure 8. Well-velocity survey, Ramalhal 1 well, Portugal (Cabinete Para A Pesquisa E Exploracao De Petroleo, unpub. data, 1979).

carbonate rocks and overlying chalk, sand, and shale. A survey at Barreiro 1 in 1957 revealed similar velocities in the Jurassic carbonate rocks at a maximum interval velocity of 6.5 km/sec. The shallow section consists of 800 m of Neogene sandstone having a velocity of 1.945 ± 0.025 km/sec and 300 m of Cretaceous and Upper Jurassic sandstone having a velocity of 3.70 ± 0.02 km/sec. The Ramalhal 1 had the highest bottom-hole temperature known from the Lusitanian Basin, 106°C at 3500 m depth. The bottom-hole temperature at Barreiro 1 was 105°C at 3600 m depth. The velocity and temperature values from these onshore wells are comparable with those measured in offshore wells.

Tejo Basin

If the Cenozoic sediments of the Tejo Basin prove to be similar to deposits in Spain's Cadiz basin, they may contain traps for hydrocarbons. Some Paleozoic flysch deposits on the south and east margins of the basin do not appear to be unduly metamorphosed and thus could serve as possible hydrocarbon source rocks, the overlying Cenozoic sedimentary rocks serving as possible reservoir rocks. Test wells near the western edge of the basin have bottomed in Jurassic carbonate rock and Triassic salt, although no wells have been drilled to basement rocks in the Tejo Basin.

Algarve Basin

The Algarve Basin of southern Portugal has very limited onshore extent (fig. 4). The basin continues seaward beneath a narrow shelf into the subbottom of the Gulf of Cadiz. Toward the east the basin opens into the Guadalquivir Basin of southern Spain. The complex structural history of this basin includes major strike-slip fault displacements during the early Mesozoic and a concentration of compressional tectonic features resulting from the Cenozoic Alpine collision of Europe and Africa. The structural styles revealed in geophysical surveys of the area and confirmed by three deep tests are, however, remarkably similar to those of the Lusitanian Basin. Coverage of seismic, gravity, and magnetic surveys on the Algarve Shelf is comparable in scale to those of the Lusitanian Basin offshore area. The seismic data are of relatively high quality. Correlations of events can be made with confidence and have been upheld by drilling results. Basement features consist of tilted fault blocks bounded by down-to-the-basin normal faults. Evaporite deposits are concentrated in structurally low areas.

Trap configuration results from draping of sediments over basement blocks, diapirism, and east-trending folds that may have been caused by compression at the European-African plate boundary. Stratigraphy, velocities, and thermal gradients (2.3°C/100 m) are similar to those in the Lusitanian Basin. Recent exploration efforts were abandoned after three dry holes were drilled (fig. 2). These test wells were located on the largest mapped structural features, but encountered inadequate source materials. Organic matter recovered from these holes was not sufficiently mature for hydrocarbon generation. Some interest has been rekindled in the Algarve Basin as a result of successful drilling in the adjacent shelf of Spain. Apparently, Miocene gas traps are a source of commercial accumulations in several new wells drilled in that area. The producing trend projects into Portuguese waters on the upper slope of the Algarve Basin margin.

Continental Slope and Rise

Montadert and others (1974) present seismic profiles across the outer shelf, slope, and rise off northwest Portugal (reproduced here as figs. 9, 10, and 11). These lines reveal seaward extension of block-faulted basement that has overlying sediments thick enough to require as much as 3 seconds of travel time for seismic waves in structurally controlled low areas east of Galicia Banks and west of Vigo seamount. Montadert and his co-workers tentatively identified some carbonate buildups on structural highs and attributed the thickened sections in structural lows to deposition of Cretaceous sedimentary rocks. Recently, a substantial amount of information has been published (Groupe Galice, 1979; Sibuet and others, 1979) as a result of drilling and site surveys at hole 398 (fig. 12) of the International Project for Ocean Drilling (IPOD). Seaward extensions of the Lusitanian Basin beneath the slope and rise are inferred on the basis of identification of diapiric structures thought to have cores of Triassic and Liassic evaporite deposits. The drill site was located on the south flank of a basement high, Vigo Seamount. Although the section is relatively thin, 1743 m were penetrated and 936.6 m of core recovered. The hole bottomed in Hauterivian pelagic sediments with some varved sapropels. Lower Cretaceous black shale containing 1 to 1.5 percent organic carbon derived from plant material was penetrated. Analysis of these carbon-rich sedimentary beds indicate that they would be hydrocarbon source rocks, but thermal maturation of these beds in hole 398 was insufficient to generate hydrocarbons.

Results from drilling in the Grand Banks area of eastern Canada have been much more positive than those from the Iberian offshore. Production tests for the Hibernia P-15 have been 20,000 bbl/day (Ocean Oil Weekly Rept., 1980). The Hibernia structure is a large fault anticline; the basinward limb of the anticline reflects the regional dip, whereas the landward limb is a roll-over into a large growth fault. The structure is approximately 24 km from north to south and 12 km from east to west. There are two producing wells on the structure 6 km apart. Smith (1980) showed a schematic section that implied that the structure formed as a result of growth faulting triggered by salt flowage from an old basement offset where thick salt had been deposited. Production occurs in the Mesozoic stratigraphic section between 2400-4200 m. Net pay thickness is 75 m in 8 zones. Ultimate reserves have been estimated at 0.5-3 x 10^9 bbl. Smith (1980) stated that the 0.5 figure is very conservative. It appears that the Grand Banks exploration effort, which had resulted in 40 dry holes, may now be redeemed by the discovery.

RECOMMENDATIONS

Lusitanian and Algarve Basins

The concept of a single Lusitanian Basin limited to the western Iberian continental shelf and its adjacent shore seems inappropriate in light of the

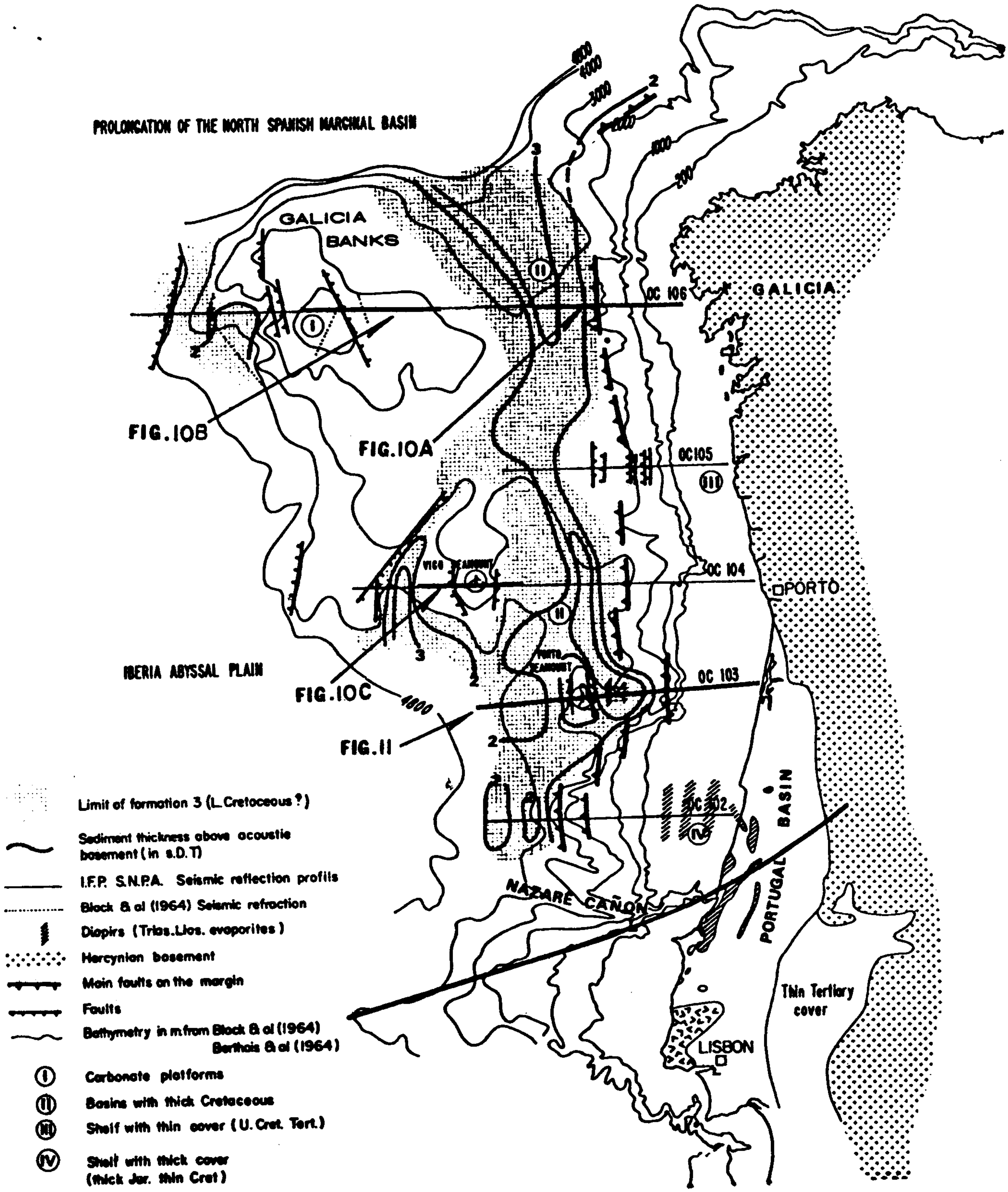

Figure 9. Continental margin of Portugal from Lisbon to Galicia (Montadert and others, 1974).

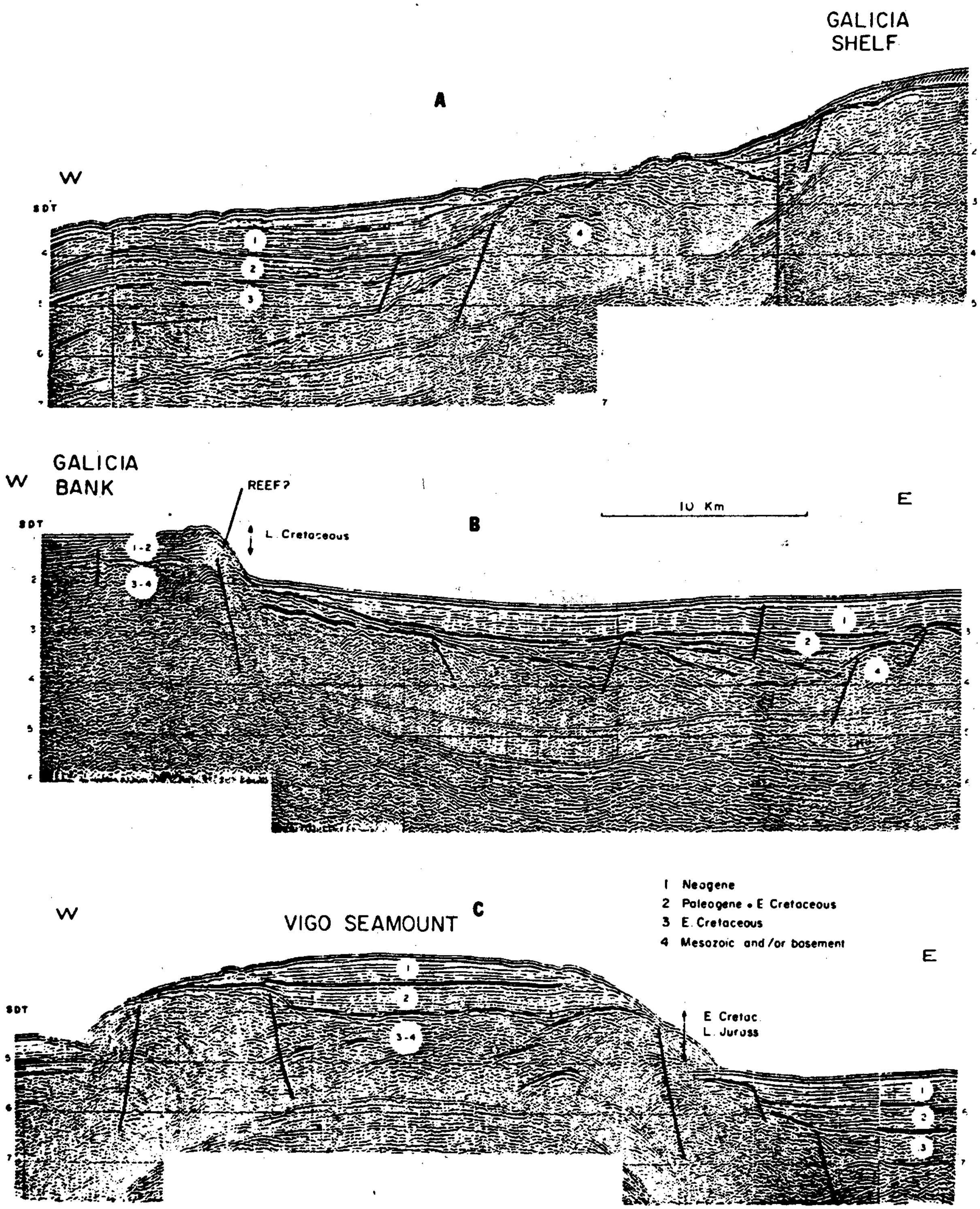

Figure 10. Seismic profiles crossing the Galicia Bank and Vigo Seamount (Montadert and others, 1974).

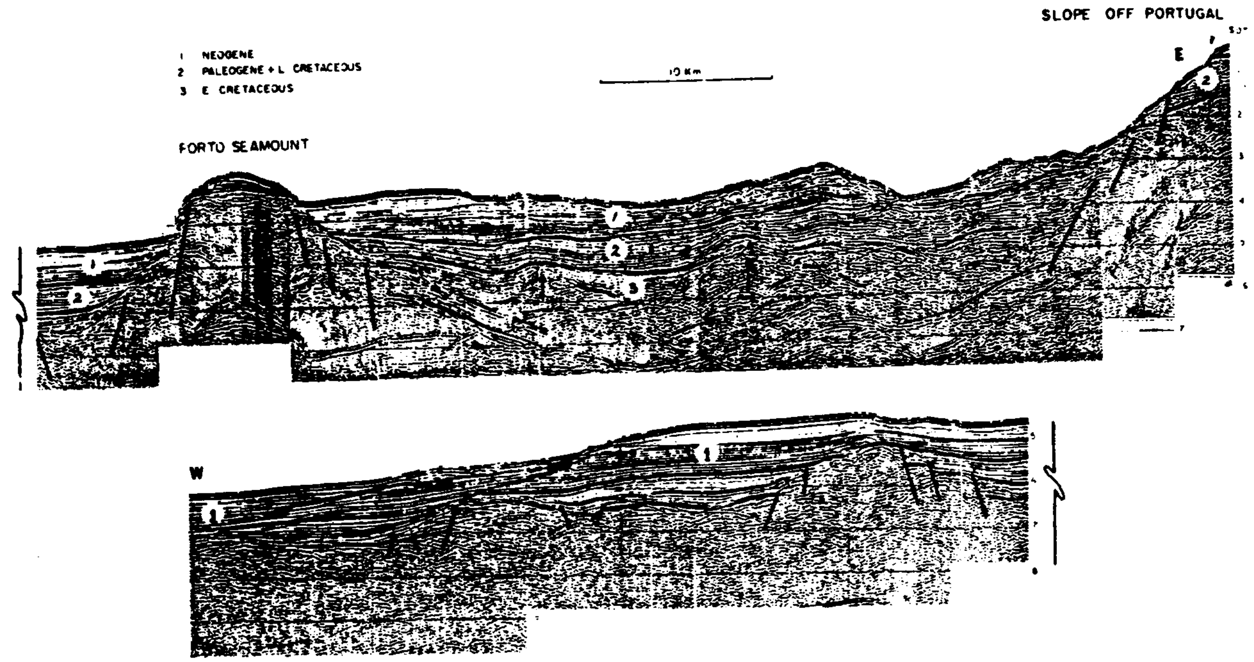

Figure 11. Seismic profile crossing Porto Seamount (Montadert and others, 1974).

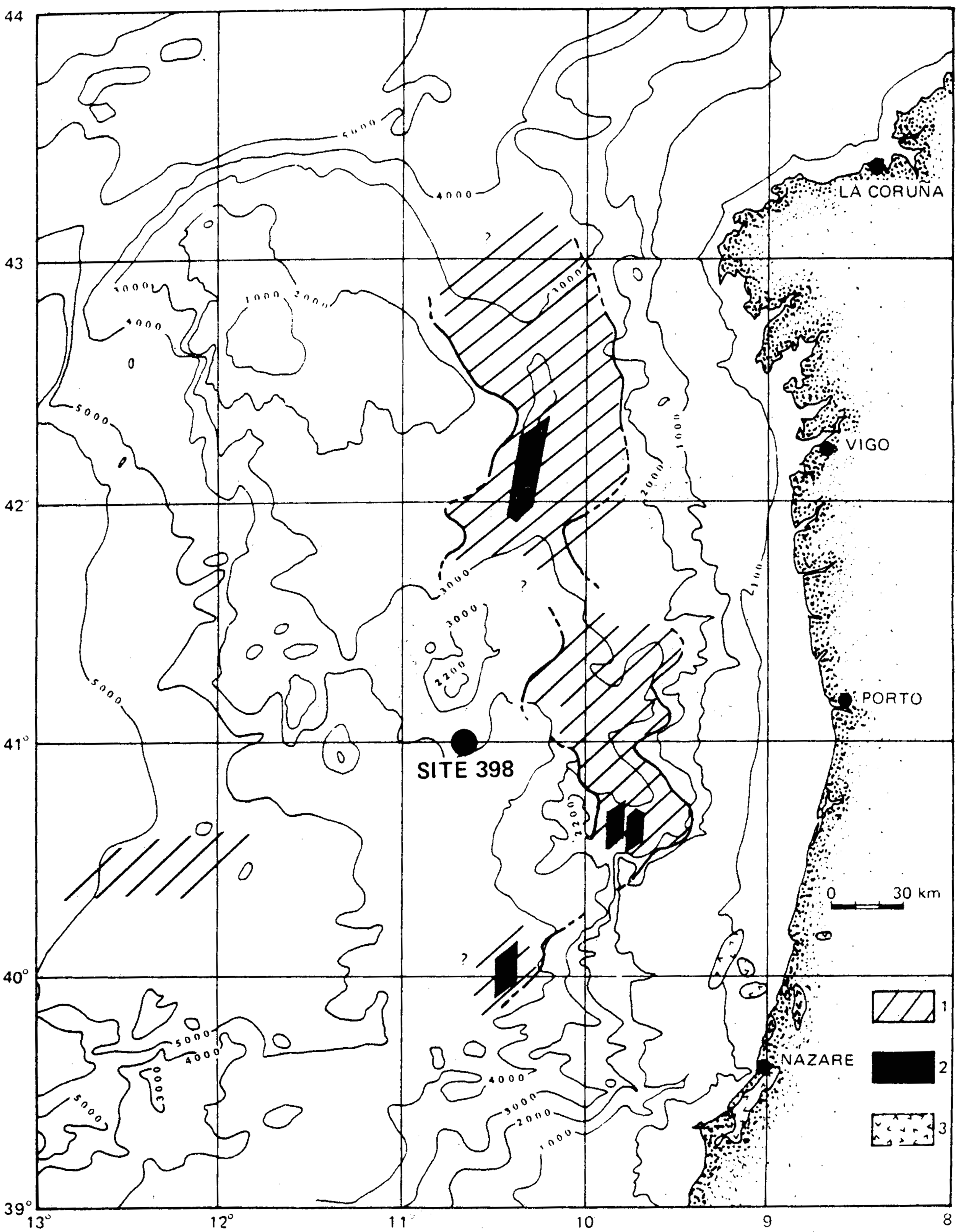

Figure 12. Seaward prolongation of the Lusitanian Basin. Patterns indicate the following: 1. probable basin extensions; 2. areas of diapirs beyond the shelf; and 3. diapirs onshore and on the shelf (Rehault and Mauffret, 1979).

new geophysical and drilling information. It is now apparent that the basin extends beneath the slope and rise and contains a large number of structurally controlled sub-basins. Salt and terrigenous clastic deposits thicken into the structurally low areas. The concentration of diapiric structures on the west flank of the basin axis onshore in Portugal is suggestive of displacement of the salt mass toward the west and out of the deepest part of the basin which is also a half-graben whose eastern margin is formed by a major down-to-the-west fault.

Insufficient amount of mature source materials seems to be a major factor limiting the hydrocarbon potential of Portugal. Every effort should be made to follow development of the Hibernia P-15 field on the Grand Banks as this may provide new clues in searching for adequate source rocks. Analyses of the Paleozoic flysch deposits on the south flank of the Meseta should be made to determine their potential as source rocks. Favorable findings in this regard would broaden the area of possible hydrocarbon potential.

Identification of future prospects in the Lusitanian and Algarve Basins will depend on the ability of the Portuguese scientists to build on the already considerable body of knowledge resulting from their own and industry's efforts. This task involves the incorporation of new drilling information in reassessing geophysical interpretations. Good regional studies are already available. Analyses of gravity, magnetic, and seismic data have led to a sound understanding of tectonic history. Regional stratigraphic studies are complete. What now must be done is to show the implications of these studies regarding character of potential reservoirs, seals, and source rocks.

This job consists of compiling and synthesizing all pertinent data for each structural prospect. The current program for completion of well summaries by the Gabinete para a Pesquisa e Exploracao de Petroleo (G.P.E.P.) is a good start in this direction. Each prospect's dossier should include: 1) A regional structure map, with cross sections, showing the prospect setting; 2) gravity and magnetic maps, with estimated depth to basement and discussions of structural significance of anomalies; 3) local structure contour maps on basement, top of massive Jurassic carbonate rocks, top of Lower Cretaceous, and on the Neogene-Paleogene boundary; 4) interpreted dip and strike seismic lines over the structural feature and through wells on structure, if wells are available; 5) cross sections showing correlation of seismic events and interval velocities with stratigraphic and lithologic units; 6) narratives based on the above data describing the origin and time of origin of trapping configuration, potential reservoir and seal rocks, quality of source material and degree of maturation. Once prospect files are complete and the prospects are graded, oil companies may be attracted to form agreements that could lead to renewal of lease concessions and further drilling.

The Miocene gas play on the Spanish shelf east of Portugal's Algarve Basin presents a special opportunity to explore for resources of natural gas for Portugal. Accurate compilation of structural types and volumes, reservoir porosity and permeability and production rates, together with amounts of proven reserves, should permit decisions to be made regarding whether exploration is justified in Portuguese waters and what future resources and production rates might be expected. The G.P.E.P. is currently gathering all available information on this subject.

Tejo Basin

The possible interaction of the Cenozoic sediments with underlying upper Paleozoic flysch deposits on the south and east margins of the Tejo Basin should be investigated. Paleozoic rocks should be sampled and assayed for amount and maturation level of organic carbon. If the flysch deposits are found to contain mature source materials, the extent of these source beds should be determined, and trapping configurations in proximity to source rocks should be tested.

Continental Slope and Rise

The analogy between the Grand Banks and Iberian offshore and the present production tests of the Hibernia P-15, emphasize the need to scrutinize existing seismic, gravity, and magnetic data and the acquisition of additional geophysical coverage on the slope and rise, in order to identify areas of thick sediment where possible source materials may have reached maturation.

CONCLUSIONS

We conclude that it would be unreasonable to suppose that future exploration successes will solve Portugal's energy needs of approximately 50×10^6 bbl of oil per year. To produce this amount yearly would require reserves of about 500×10^6 bbl. Although there are untested structures in the Portuguese offshore capable of trapping hydrocarbons in quantities of this order of magnitude, past experience in the drilling of 22 dry offshore tests has indicated that some combination of inadequate reservoirs, seals, or source beds has inhibited accumulations of commercial quantities of oil.

However, in view of current petroleum prices, even limited domestic production could constitute an important plus for the economy, and the presence of oil shows in outcrop and in many dry holes is encouraging. Drilling and geophysical data acquired to date have cost tens of millions of dollars. Based on a consumption of 150,000 bbl/day and the 1979 price of approximantly $20/bbl, foreign oil required yearly by Portugal costs conservatively one billion dollars. Existing investment and the cost of foreign oil emphasize the need for government acquisition of additional data, and especially the analysis of existing data. The G.P.E.P. has more than 25,000 km of reflection seismic data available for interpretation. One experienced interpreter can analyze 2,000 km in a year, yet only three interpreters are available for this work. When the wealth of magnetic, gravity, and well data available in addition to the seismic profiles and the G.P.E.P. staff of eight professionals is considered, we must conclude that the effort should be intensified and expanded.

REFERENCES CITED

Amoco Canada Petroleum Co. Ltd. and Imperial Oil Ltd. Exploration Staffs, 1974, Regional geology of Grand Banks: American Association of Petroleum Geologists Bulletin, v. 58, p. 1109-1123.

Banghar, A. R., and Sykes, L. R., 1969, Focal mechanisms of earthquakes, in The Indian Ocean and adjacent regions: Journal of Geophysical Research, v. 74, p. 632-649.

Bard, J. P., Capdevila, R., Matte, P., and Ribeiro, A., 1973, Geotectonic model for the Iberian Variscan orogen: Nature, Physical Sciences, Ed., v. 241, p. 50-52.

Carvalho, D., 1977, Lineament patterns and hypogenic mineralization in Portugal: Portugal Estudos, Notas e Trabalhos do S.F.M., v. 23, fasc. 3-4, p. 91-108.

Clock, G., 1979, Area off eastern Canada shows brighter prospects: Oil and Gas Journal, Dec. 17, p. 14-23.

Erricker, D., 1976, Portugal, in European Offshore Oil and Gas Yearbook: Kogan Page Limited, London, p. 91.

Faria, J. B., 1975, Pesquisa de petroleo em Portugal: Portugal Ministerio da Industria e Technologia, Internal Report, p. 1-11.

Financial Times, London, 1978, Portugal puts its faith in oil: European Energy Report no. 9, June 6, 1978.

Groupe Galice, 1979, The continental margin off Galicia and Portugal: Acoustical Stratigraphy and Structural Evolution, in Sibuet, J. C. and others, 1979, Initial Reports of the Deep Sea Drilling Reports, v. 47, pt. 2, Washington (U. S. Government Printing Office, p. 622-633.

Hood, A., Gutjahr, C. C. M., and Heacock, R. L., 1975, Organic metamorphism and the generation of petroleum: American Association of Petroleum Geologists Bulletin, v. 59, p. 986-996.

Instituto Hydrographico, Service de Formento Mineiro e Servicos Geologicos Portugal, 1978, Carta Geologica da Platforma Continental: Instituto Hydrographico, Service de Formento Mineiro e Servicos Geologicos Portugal, escala 1:1,000,000.

Jansa, L. F., and Wade, J. A., 1974, Geology of the Continental Margin off Nova Scotia and Newfoundland: Geological Survey of Canada, Paper 74-30, p. 51-105.

Keen, C. E., 1979, Mesozoic and Cenozoic Plate Tectonics off Eastern Canada: American Geophysical Union Transactions, v. 60, p. 746.

Krause, D. C., and Watkins, N. D., 1970, North Atlantic crustal genesis in the vicinity of the Azores: Royal Astronomical Society, Geophysical Journal, v. 19, p. 261-283.

Laughton, A. S., Roberts, D. G., and Graves, R., 1975, Bathymetry of the northeast Atlantic; Mid-Atlantic Ridge to southwest Europe: Deep-Sea Research, v. 22, p. 791-810.

Lefort, J. P., 1979, Iberian Amorican Arc and Hercynian Orogeny in western Europe: Geology, v. 7, p. 348-388.

Le Pichon, X., Sibuet, J. C., and Francheteau, J., 1977, The fit of continents around the North Alantic Ocean: Tectonophysics, v. 38, p. 169-209.

McCaslin, J. C., 1978, Portugal, in International Petroleum Encyclopedia: Petroleum Publishing Co., Tulsa, Oklahoma, U.S.A., p. 139.

Montadert, L., Winnock, E., Deltiel, J. R., and Grau, G., 1974, Continental margins of Galicia-Portugal and Bay of Biscay, in The geology of continental margins, Burk, C. A., and Drake, C. L., eds.: Springer-Verlag, New York, p. 323-342.

Moody, J. D., 1973, Petroleum exploration aspects of wrench-fault tectonics: American Association of Petroleum Geologists Bulletin, v. 57, p. 449-476.

Ocean Oil Weekly Report, 1980, Canada's Hibernia P-15 discovery moving cautiously toward development: Ocean Oil Weekly Report, v. 14, no. 16, p. 1.

Owen, E. W., 1975, Trek of the oil finders; a history of exploration for petroleum: American Association of Petroleum Geologists Memoir, no. 6, p. 1550.

Pitman, W. C., III, and Talwani, M., 1972, Sea-floor spreading in the North Atlantic: Geological Society of American Bulletin, v. 83, p. 619-646.

Portugal, Servicos Geologicos, 1972, Carta geologica de Portugal: Portugal, Servicos Geologicos, 2 sheets, scale 1:500,000.

Rehault, J. P., and Mauffret, A., 1979, Relationships between tectonics and sedimentation around the northwestern Iberian margin, in Initial Reports of the Deep Sea Drilling Project, v. 47, pt. 2: Washington (U.S. Government Printing Office), p. 663-682.

Ribeiro, A., Conde, L., and Monteiro, J., 1972, Carta tectonica de Portugal: Portugal, Servicos Geologicos, scale 1:1,000,000.

Schott, W., and Stoppel, D., 1976, Portugal, in International map of natural gas fields of Europe: Germany, Bundesanstalt fur Geowissenshaften und Rohstoffe, p. 107-110.

Sibuet, J. C. and others, 1979, Initial Reports of the Deep Sea Drilling Project, v. 47, pt. 2: Washington (U.S. Government Printing Office), 787 p.

Smith, B., 1980, The Hibernia Oil Field, Newfoundland Section Meeting, Geological Association of Canada, St. John's, Newfoundland, Canada.

Tiratsoo, E. N., 1976, Oil fields of the world: Scientific Press Limited, Beaconsville, England, p. 93.

Uchupi, A., Emery, K. O., Bowin, C. O., and Phillips, J. D., 1976, Continental margin off western Africa; Senegal to Portugal: American Association of Petroleum Geologists Bulletin, v. 60, p. 809-878.

Wilcox, R. E., Harding, T. P., and Seely, D. R., 1973, Basin wrench tectonics: American Association of Petroleum Geologists Bulletin, v. 57, p. 96.

World Bank Atlas, 1978, Population table: World Bank, Washington, D.C., P. 8.

World Energy Conference, 1977, Survey of energy resources, 1976: Copyright 1977 by the World Energy Conference, London (selling agent: R & R Clark, LTD, Edinburgh).

CHAPTER B

COAL IN PORTUGAL

By

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INTRODUCTION

The estimated original and remaining coal resources of Portugal are small. Coal has been reported in at least 16 areas (see fig. 1) and has been produced from 9 mines or mining areas. One mine is presently in operation; mines have produced coal since 1894 and have depleted the reserves about 40 percent. Individual summary records are not available for coal tonnages mined, lost in mining, and remaining as reserves or resources for Portugal, but based on estimates at only three fields, potential resources of coal of all ranks total at least 76,000,000 metric tons(t).

Most coal in Portugal has been classified as anthracite or lignite. Lack of as-received coal analyses hinders verification of these classifications. Apparently the coal of the Pejao and San Pedro da Cova coal fields ranges from semi-anthracite to anthracite. The brown coal or lignite of the Cabo Mondego and other localities may have been misclassified; there are no available as-received analyses, but apparently this coal is actually subbituminous in rank.

Most coal beds in Portugal are steeply dipping and are of Carboniferous (Pennsylvanian) and Permian or Mesozoic (Jurassic and Cretaceous) age. Generally the coal beds and associated strata are enfolded between older sedimentary rocks of Paleozoic age or are in fault contact with crystalline and/or metacrystalline rocks of Precambrian age.

The coal basins generally are narrow elongate synclines having steeply inclined flanks; therefore, the coal resources are restricted in outcrop and are difficult to mine economically by methods that are normally applicable. Furthermore, the coal beds are apparently lenticular, and unless supported by much drill data, correlations and reserve and resource estimates are generally difficult to make. The thickness of individual semi-anthracite and anthracite beds varies considerably laterally, probably due to postdepositional compression during folding and faulting and associated metamorphism.

Coal mining in structural settings similar to those of Portugal's coal fields cannot be accomplished by means of the conventional methods used for mining of most flat lying to nearly flat lying coal beds. Extraction is difficult and mechanized mining methods generally cannot be used. Additionally, the lack of large known or proven reserves hinders securing necessary finances for normal coal mining and extraction methods. In Portugal the structural setting of Portugese coal fields and the lack of funds has resulted in labor-intensive mining and higher-than-normal costs. The quality of the coal deposits is generally poor, and the energy return per unit of coal produced is low; therefore, the cost of the energy utilized is high.

Acknowledgments

The information reported here was drawn mainly from interviews with members of the Ministry of Industry and Technology of Portugal. Contacts and appointments were made by Jose C. Netto, Chief Executive for the Portugal Department of Energy, with the several members of the Directorate of Geology and Mines. Information contributed by the Director General of Mines and Geologic Services, Carlos Goncalves, and used here was invaluable, as were his kindness and courtesy. Details of the geology of most of the coal mining areas were ably supplied by Dr. Lopes da Silva Freire (specialist in coal); J. M. Santos Oliveria (geochemistry and analytical techniques) of the Servico De Fomento Minero, Porto, ably served as an assistant and translator in interviews with Dr. Freire.

DESCRIPTIONS OF DEPOSITS

The Porto coal district

The first mined, and currently the only coal producing areas in Portugal are two Upper Pennsylvanian coal fields lying in a complexly deformed synclinal depression in the Porto coal district southeast of the city of Porto in northern Portugal. The fields lie in a narrow belt of complexly folded and faulted Stephanian coal-bearing rocks that are bounded on the west and southwest by Precambrian rocks and on the northeast and east by older Paleozoic rocks. As shown on figure 1, the two fields are the San Pedro da Cova and the Pejao.

San Pedro da Cova coal field

The San Pedro da Cova or northern field of the Porto district produced anthracite or semianthracite from a mine of the same name until 1977 and has provided about 30 percent of Portugal's output of coal. Currently it is inoperative and there are no apparent plans for reopening it. Resources in 1977 were estimated at less than 10,000,000 t. Records show that the mine produced more than 9,000,000 t between 1894 and 1972 from two coal beds each about 1 m thick. A large amount of drilling on the north side of the northwestern part of the coal field has proved that coal exists to a depth of 110 m. South of that area, cross sections based on other drill holes indicate as many as 10 beds locally ranging in thickness from 1 to 2 m. Mine workings in the central part of the coal field penetrated three to six coal beds ranging from 25 cm to more than 1 m in thickness; four of the six beds locally are more than 1 m thick. The south-central part of the field received only local exploration but further to the south, drill data shows as many as 10 coal beds locally ranging in thickness from 50 cm to 4 m; at one locality a coal bed is 7 m thick but includes a 1 m parting. Also further southward, drill data indicate at least seven coal beds ranging in thickness from 2 to 7 m.

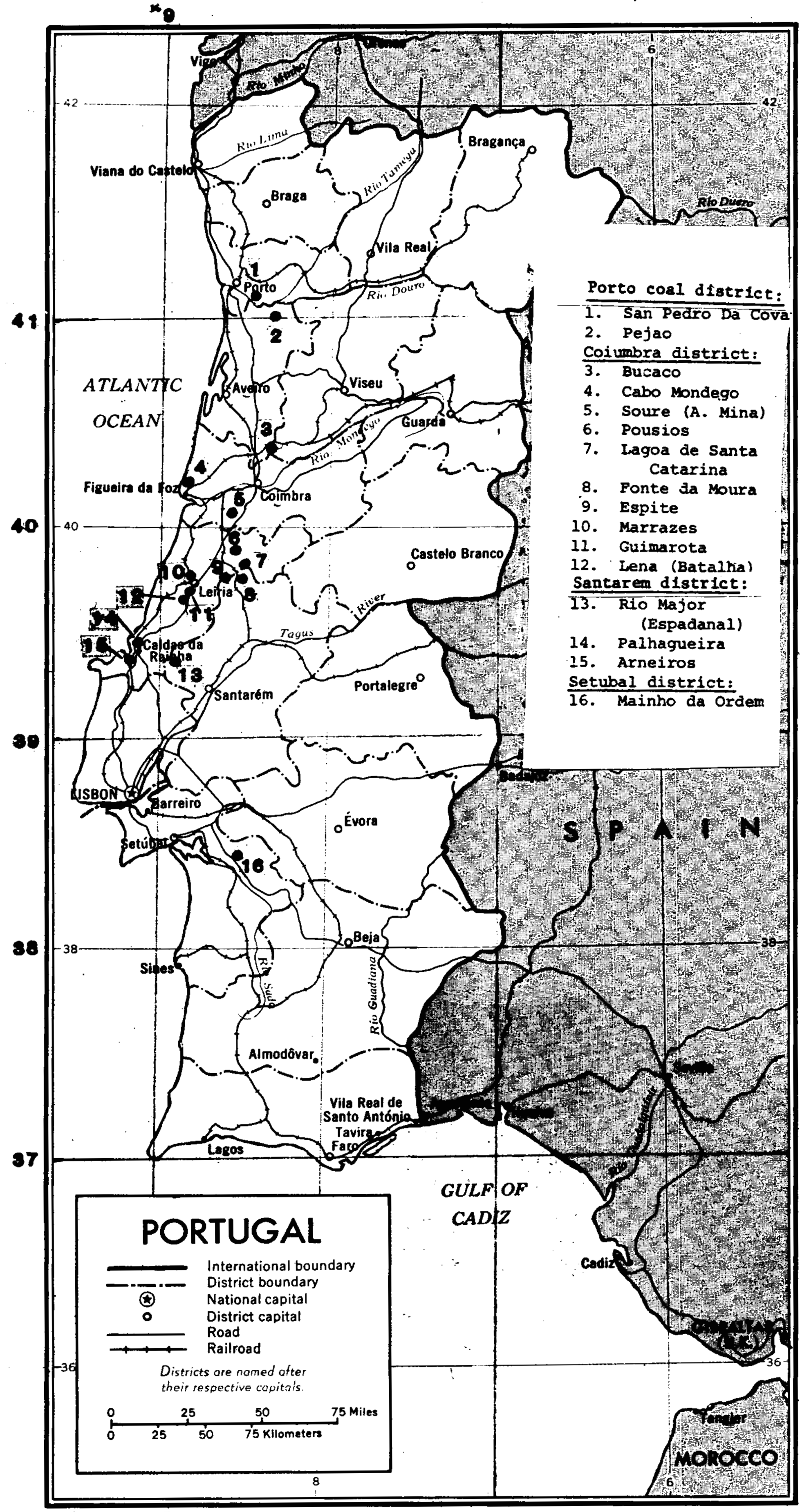

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Figure 1. Coal deposits of Portugal.

The data suggest that these beds may be in a synclinal fold and that the upper three beds are duplicated.

This drill information apparently has not been used for correlating the coal beds or for estimating the resources or reserves of the area. The drill data do however appear to indicate a potential for further coal production in the San Pedro da Cova area. To determine this may necessitate more closely spaced drill holes; the existing data appear to warrant this.

Pejao coal field

The Pejao coal field, to the south and southeast of the San Pedro da Cova field, is a continuation of the Douro Basin. The field contains the same type and quality of coal--medium quality anthracite or semianthracite. The coal is in two or three beds that average 1 m or more in thickness. From 1918 to 1979 the Pejao coal field produced more than 11,000,000 t. In 1977, officials of the operating company estimated about 25,000,000 t of original proven reserves. Since 1979 the estimate has risen more than 3,000,000 t. Currently remaining reserves are believed to be about 17,000,000 t. The average maximum depth of the estimated reserves is 40 m. The reserves were delineated by drilling, and the tonnage was estimated using a specific gravity of 1.5 for the coal. Data were not made available as to percentage of coal mined versus the coal lost in mining. Current production of the Pejao field averages 740 t/d. About 90 percent, or 660 t/d, provides the energy for an electric generating power plant composed of three generators of 50 MWh each; one generator is for reserve. Each generator uses 900 to 1,000 t/d of coal, but the coal is beneficiated with fuel oil to generate the power. Ten percent, or 74 of the 740 t produced in the Pejao field is used to make hydraulic lime. If production continues at the present rate, the reserves of the Pejao field will be exhausted in 15 to 18 years.

The results of an ongoing exploration program will determine the degree of modernization of a new plant, the planned production, and probably a new set of cost figures. The present cost of mining is about 1,200 escudos/ton ($24.00 U.S.). The actual cost F.O.B. mine including some interest and benefication costs is 1,512 escudos/ton ($30.00 U.S.). Coal in this mine has been removed for 2.5 km southeast along the strike of the beds and downdip to 400 m below the surface (210 m below sea level). The thickness of beds ranges from 0.5 to 12 m. Ash content of the coal ranges from 18 to 40 percent.

Coal has been extracted to 85 m below sea level (320 m below the surface) as far as 3 km east of Paraduces. Drilling found coal of good quality to depths of 300 m in three beds ranging in thickness from 3 to 5 m or a total of 11 m. In addition, the drilling delineated a syncline and proved duplication of two of these coal beds on the limbs. Plans have been made for a drilling program to prove additional reserves below those presently mined. Also, plans are being made to sink a shaft from the lowest producing level, the 6th, to an undeveloped 11th level (600

m) to produce from the additional proven reserves. This shaft will enable mining to proceed to a depth of 810 m. The proposed shaft will be about 300 m east of the Douro River near the currently operative material supply shaft.

The Coiumbra coal district

The Bucaco coal field

The Bucaco coal field of the Coiumbra district is mined out and abandoned. This small coal field is located in an isolated depression of Permian rocks 23 km north of the city of Coimbra, 30 km southeast of Aviero (fig 1.), and about 3 km southeast of Anadia. The field produced some coal believed to be of subbituminous rank. Records of production and resource estimates are not available.

The Cabo Mondego coal field

This coal field is located in a basin of Jurassic rocks on the coast of Portugal (fig. 1). These Upper Jurassic rocks, part of which are known to be coal-bearing, extend about 17 km east (eastern area) of the Cabo Mondego mine (mine area) and about 2 km west to the coast and on westward under the sea (offshore area).

The coal crops out on land for about 5 km and under the sea an unknown distance. Dip of the coal beds ranges from 30° to 45° and the average thickness is about 1.20 m. The coal has been reported as brown coal but has the appearance of high ash subbituminous coal. This Cabo Mondego coal field reportedly was mined in the 18th century. In 1937, the coal was essentially mined out to a depth of 297 m in the general area of the mine. Later drilling proved additional resources down to a depth of 700 m. A total of 22 drill holes penetrated coal beds ranging in thickness from 10 to 75 cm.

The total estimated remaining resources are about 11,000,000 t of medium-quality high-ash and high-sulfur subbituminous coal as indicated by the following tables:

Cabo Mondego coal field coal resources to depth of 700 m

Area	Depth (m)	Resources (metric tons)
	Measured	
Mine area	0 - 300	Depleted
Mine area	300 - 700	249,200
Eastern area	0 - 700	5,465,000
Offshore area	0 - 700	437,200
	Total measured	6,151,400

	Indicated	
Mine area	300 - 700	874,400
Eastern area	0 - 700	3,122,800
Offshore area	0 - 700	874,400
	Total indicated	4,871,600
	Total remaining resources	11,023,000

(Remaining resources onshore 9,711,400 t)
(Remaining resources offshore 1,311,600 t)

Analytical data

	Range (percent)
Moisture	6-12
Volatile material	23-35
Ash	22-33
Fixed carbon	26-38
Sulfur content	4-7

Calorific value: 3200 to 4080 c. (Btu 5760 to 7344)

The Soure coal field

The Soure coal field, sometimes called A. Mina, is located 20 km southwest of Coimbra (fig. 1) and 2.3 km northeast of Soure. Mining has been discontinued, and there are no available reports giving the details of the coal, the geology, production, or resources. The coal is in rocks of Pliocene age and is, therefore, most probably of lignite rank.

The Leiria coal district

The Leiria district contains several coal fields that occupy folds comprising a synclinorium. On the northwest, south, and eastern flanks of the synclinorium, rocks of Triassic, Jurassic, and Cretaceous age are overlain unconformably by rocks of Tertiary age. The eastern flank of the synclinorium in places is in fault contact with rocks of Mesozoic and Paleozoic age. Known coal-bearing areas are chiefly on the north, west, and south limbs of the synclinorium. The district extends from near Pombal, site of the Pousios coal field, southward to the Lena coal field near Batalha. The area between includes the coal fields of Lagoa de Santa Catarina, Fonte da Moura, Espite, Marrazes and Guimarota.

The Pousios coal field

The Pousios coal field (fig. 1) contained a small amount of coal in rocks of Late Jurassic age. The coal, now depleted, was mined at three different places within an area of about 4.5 km^2 southeast of Pombal and Pousios. These coal beds were exploited on the northern flank of a downwarp area measuring about 30 km from north to south and 25 km from east to west. The dip of the coal beds is relatively gentle, ranging from 5° to 10°, and the thickness of individual beds ranges from 60 to 80 cm with some evidence indicating a possible thickening of the beds toward the center of the depression. The coal beds have been reported to emit a petroliferous odor, a fact this author could not confirm.

An occurrence of lignite in undifferentiated rocks of Pliocene and Pleistocene age is known 7 km southwest of Pombal and 2.5 km east of Carnide. Lack of exploration and development of the deposit indicates that it probably is of little importance.

The Lagoa de Santa Catarina coal field

The Lagoa de Santa Catarina coal field (fig. 1) is a very small deposit in an outlier of rocks of Cretaceous age. The area is about 2.5 km west of the Rio Nabao and 2.5 km west of Alvaizere some 10 to 12 km southeast of Pousios. There are no available records of production or resources for this field.

The Fonte da Moura coal field

The Fonte de Moura coal field (fig. 1) lies within rocks tentatively assigned to an Early Cretaceous age. The three major coal beds attain thicknesses as much as as 2 m; locally there are six thin coal beds. No analyses are available, but the coal is believed to be subbituminous. Resource estimates are not known for this coal field. A short unpublished report by Dr. Jose Freire (1935) of the Servico De Fomento Minero indicates that the thicker coal beds contain sufficient resources for economic development and therefore justify more exploration.

The Espite coal field

Exploration of the Espite coal field (fig. 1) has been widespread in the area from 1 to 6 km north and northwest of Espite. The location and distribution of the 12 shafts and openings would indicate that the coal underlies a fairly large area; however, no records indicate the thickness of coal nor depths to the beds. The coal occurs in rocks of Late Jurassic age. Analyses are not available to determine the rank of the coal, and resource estimates have not been made.

The Marrazes coal field

A very small mine 0.25 km northeast of Marrazes marks the site of this coal field about 2.5 km north of Leiria (fig. 1). The coal bed is in rocks of Pliocene age. Although there are no available analyses the coal is considered to be lignite. Resource estimates are not available.

The Guimarota coal field

The Guimarota coal field is in rocks of Jurassic age situated 1.5 km south-southwest of Leiria (fig. 1). The coal is considered to be lignite and was used for a lime kiln in the vicinity of the mine. The mine was abandoned in 1963. No records of analyses, production, resources estimates, or coal bed thickness are available. The mine was reopened in 1973, but only to obtain vertebrate fossils. These fossils are chiefly lizards of Jurassic age.

The Lena coal field

The Lena coal field is also known as Batalha (fig. 1). Five mine or prospect locations 1.5-3 km southeast of Batalha outline an area of about 30 km^2 where strata of Late Jurassic age contain coal that may have potential for development. At one mine the coal was reported to be about 1 m thick and dipping steeply near vertical and faulted. Some 10-15 km south of this area, coal has been found, and possibly mined, also in rocks of Jurassic age, in an apparent southerly extension of those which crop out along the west limb of the faulted anticline. The recumbent syncline to the west does not appear to be complexly faulted or folded and may be considered a potential coal producing area that should be explored in more detail. Locally, Upper Jurassic rocks appear to be overlain unconformably by Lower Cretaceous rocks, suggesting the possibility that a much larger area of Upper Jurassic coal-bearing rocks is present northeast of the Lena mine area.

The Santarem district

The Rio Major (Espadanal) coal field

Only one coal field, the Rio Major has been reported in the Santarem district. Small areas of lignite near Palhagueira and Arneiros about 25 km west of Rio Major field have been assigned to the Lisbon District, but more likely also belong in the Santarem District (fig. 1). North-striking rocks of Jurassic age separate the lignite-bearing Pliocene rocks at Rio Major field from the others near Palhagueira and Arneiros. Coal is present at six different localities near Palhagueira and Areniros, but no records are available for the quality or quantity of lignite in these areas. The Rio Major, also known as the Espadanal, coal field lies within a small, ovate syncline about 3,400 m long in a northwest direction and a maximum width of 1,000 m. This total area of about 300 ha has been explored by 42 drill holes. Maximum depth to the lowest of the coal beds is 125 to 135 m. The coal beds are classified as lignite, and although of irregular thickness, average between 9 and 10 m thick. The area contains three continuous lignite beds intercolated with diatomite; in places, a fourth, discontinuous bed has been found.

An average analysis for the lignite shows:

	Percent
Moisture	12.8
Ash	38.7
Volatile material	26.8
Fixed carbon	19.2
Sulfur	2.5

Mines in the Rio Major field operated in the years 1916 through 1927 as small pits and underground workings. The lignite was used by the railroad by blending it with higher quality coal. The lignite was also used in making fertilizer during World Wars I and II. Resources have been variously calculated at 38,000,000 t, 27,000,000 t and 23,000,000 t. However, the resource figure of 23,000,000 t of lignite and 25,000,000 t of diatomite computed by engineer Carlos Goncalves of the Portugese Directorate of Geology and Mines in 1979 appear to be the most reliable estimates.

The Setubal district

Coal has been reported at one locality in this district. This deposit called Mainho da Ordem lies on the north limb of the Sado syncline about 17 km northeast of Alacer do Sol. The coal-bearing rocks appear in the bottom plate of an overthrust and are reported to be Westphalian (Pennsylvanian) in age. Coal analyses and resource estimates are not available. This mine reportedly was operated in early historic time and is now mined out.

COAL RESOURCES

The remaining coal resources of Portugal presently are as follows:

Coal field	Measured reserve	Indicated potential resources	Total remaining resources
Pejao	17,000,000	25,000,000	42,000,000
Cabo Mondego	6,000,000	5,000,000	11,000,000
Rio Major	23,000,000		23,000,000
Total coal and lignite resources	46,000,000	30,000,000	76,000,000

The coal fields of the Porto District, presently the only coal producing district in Portugal, are considered to have remaining coal reserves of approximately 17,000,000 t, all of which are in the Pejao field. Further exploration is planned and when carried out probably will add approximately 25,000,000 t of potential resources. At the present rate of production of about 300,000 t per year and assuming 50 percent extraction, this could give a life of about 70 years to the mines.

The coal field of Cabo Mondego is estimated to have 6,000,000 t of measured reserves and 5,000,000 t of indicated potential resources. The measured resources alone would be sufficient to give a mine life of 20 years for 1,000 t daily production.

The lignite field at Rio Major has 23,000,000 t of proven lignite which, under present economic conditons, should seriously be considered as a potential energy source by industry.

CONCLUSIONS AND RECOMMENDATIONS

The coal resources of Portugal are small, in part because of the small area of coal-bearing rocks and in part because of the lack of resource information on the known coal deposits. Increased energy demand in Portugal and the deterioriating world-energy supply suggest the need to reappraise and reassess these coal resources. Coal, which in the past was considered uneconomical to produce, might now be a viable economic resource because of increase in demand and price.

The Duro coal basin of the Porto district has a southwest boundary fault where northwest-trending, potentially coal-bearing rocks of Late Pennsylvanian age in a narrow belt about 10 km long are in contact with Precambrian to the southwest. If the fault is a southwest-dipping thrust or high-angle reverse, it is possible that Precambrian rocks have overridden the upper part of the Pennsylvanian and thus obscure coal-bearing rocks below. Careful field examination along with geophysical work may reveal some areas where the possibilities of finding more coal should be tested by drilling through the thrust plates. Another narrow strip of potentially coal-bearing rocks of Pennsylvanian age extends for almost 60 km through the proven San Pedro da Cova and Pejao coal fields, and onward to the southeast. Detailed geologic mapping and measurement of stratigraphic sections, augmented by geophysical surveys may indicate that part of this potentially coal-bearing Pennsylvanian section also underlies the overthrust plate. Further to the southeast along this general trend three additional areas of Pennsylvanian rocks also warrant additional geologic scrutiny and/or detailed mapping.

The coal in Jurassic rocks of the Cabo Mondego coal field has been drilled at 22 locations. Neither the spacing nor locations of these drill holes were available for this report. Coal has reportedly been found ranging in thickness from 10 to 75 cm. Evidently these holes were drilled in the general area of mining; further drilling is not recommended unless it is done with intent to reopen the mines. However, other nearby areas also contain coal-bearing rocks of Late Jurassic age, and detailed mapping of surface geology augmented by geophysical surveys might point the way to a drill program of some value in these areas. Although the areas are disturbed by faulting, the unravelling of detailed stratigraphy may prove fruitful in locating additional coal resources.

The Leiria coal district, as has been previously indicated, contains several coal fields or coal occurrences from Jurassic through Pliocene in age. Most of these deposits, those Jurassic in age, are located on the limbs of a large syncline and have been either mined out or, as in the case of (Batalha) Lena, are considered to be of little value. However, a deep drill hole (T.D. 1494m) located about 16 km northeast of Leiria near the Espite coal field indicates correlations between coal beds there and the other coal fields in the district. Such a correlation could point to new areas for exploration in the basin between Leiria and the area just east of the Rio Nabao and in the rocks of Jurassic age some 10-25 km southeast of Leiria.

CHAPTER C

GEOTHERMAL RESOURCES IN PORTUGAL AND THE AZORES

By

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SUMMARY

Portugal

The potential for geothermal energy in mainland Portugal is confined to direct use of low-enthalpy (that is, low-temperature) fluids. Chemical geothermometry of thermal spring waters indicates that most reservoir temperatures are less than 100° C. The highest estimated reservoir temperatures (144° average) for thermal waters emitted at Chaves are unreliable because of the exceptionally high CO_2-content of the waters.

Thermal springs are located in northern Portugal, in the western coastal plain, and in southwestern Portugal. Those in the north are primarily along major faults, which, along with the springs themselves, are primary exploration targets. Thermal waters are apparently produced by deep circulation along these faults, particularly in areas of granitic basement. In western and southwestern Portugal, springs may be emitted along minor faults or fractures. The springs in northern Portugal are hottest and come from reservoirs having the highest calculated reservoir temperatures.

Solution equilibrium calculations suggest that precipitation of solids is unlikely to pose problems for utilization of the waters. Corrosion, on the other hand, may be a problem unless the waters are permitted to oxidize during or prior to use.

Development costs will be primarily drilling costs. Hot waters may be present at shallow depth along fault zones (less than 1 km), but hot rock reservoirs may be at much greater depths (2-3 km). Drill tests will be necessary to predict the total flow rate possible at individual sites and, therefore, the rate of beneficial heat production.

The Azores

The potential for electrical generation from geothermal energy is excellent in the Azores. Geothermal systems are likely to exist beneath major silicic calderas, beneath clusters of young silicic domes, and along basaltic fissure systems. Silicic calderas or silicic dome complexes are present on San Miguel, Terceira, Fayal, Graciosa, Flores, and Corvo. Basaltic fissure systems exist on San Miguel, San Jorge, Fayal, and Pico. Pico Volcano, on Pico Island, may also have an underlying hydrothermal system, which is not manifest at the surface.

Geothermal potential is greatest on Terceira, San Miguel, and Flores, which together account for 93 percent of the assessed electrical-generation capacity of approximately 2000 MW (for a 30-year period).

Current exploration and drilling are in the Ribeira Grande region on the north flank of Aqua de Pau Volcano, San Miguel. Results of previous drilling suggested that 200°-250° C fluids were confined to a thin aquifer approximately 600 m deep in which waters are migrating downslope from a heat source near Fogo caldera. Total estimated potential of the Ribeira Grande field, if thermal fluids are so confined to such a thin aquifer, may be roughly 10-30 MW (for a 30-year period, if no heat is resupplied). Problems encountered during the initial phases of drilling suggest that even this total potential electricity may not be recoverable owing to low aquifer permeability or scaling (self sealing). More recent drilling indicates that other possible productive areas are connected to basaltic fissure systems at depths of 500-700 m. If geological, geophysical, and geochemical investigations can be completed as scheduled, production of energy from geothermal sources in the region may be possible in December 1983 (H. A. Correia, 1980, written commun.).

The cost of drilling for geothermal power increases rapidly with depth of drilling. Typical costs in the United States range from roughly $300/meter (1978 dollars) for geothermal wells 600 m deep to $700/meter for wells 2500 m deep. In view of the great cost of deep drilling, some possible geothermal resource areas identified in this report may be economically unattractive. These areas include especially, basaltic fissure systems (3.8 percent of total energy available), which are likely to have temperatures greater than 150° C only below 2-2.5 km. Conversely, the greatest and least expensive potential may be at Furnas Caldera on San Miguel, where extensive thermal springs suggest a shallow hydrothermal system. Geothermal energy production may, however, be incompatible with current aesthetic, recreational, and medicinal spa uses for the area.

Exploration and development costs will primarily reflect drilling costs and their dependence upon depth to the resource. Costs of geological and geophysical surveys and shallow-temperature drilling for each geothermal resource area will remain roughly constant at about $400,000-$600,000 (1977 U.S. dollars). Drilling costs for Ribeira Grande deep wells have increased from approximately $600/m (1976/77 dollars) to $825/m (1979 dollars), twice that of drilling costs in the U.S. (H. A. Correia, 1980, written commun.).

INTRODUCTION

The terminology and methods of this geothermal-resource assessment of Portugal and the Azores largely follow that of U.S. Geological Survey Circular 790, "Assessment of Geothermal Resources of the United States - 1978" (Muffler, 1979). Because current geothermal-energy technology requires ground water to transfer the heat from the hot-rock reservoir to the surface, I have included in my estimates of the available resource the energy which is contained in identified or inferred hydrothermal reservoirs. I am thus excluding the energy contained in magma (Smith and Shaw, 1975) because the technology for its extraction does not exist and is not likely to exist in the foreseeable future (Peck, 1975). My estimates of the available resource in Portugal are confined to that which is contained in hydrothermal systems inferred to exist beneath thermal springs.

For the Azores I have estimated the thermal energy present in all areas which, on the basis of geological criteria, appear likely to have higher than normal subsurface temperatures. I have assumed, in order to calculate the recoverable part of this energy, that hydrothermal systems exist in each of these areas, though in many, no thermal springs or fumaroles are present. (For many reasons, a hydrothermal system may not be manifest at the surface.) If a hydrothermal system does not exist in any of these areas, the thermal energy will not be recoverable by means of current technology in the current economic situation, although future technology may permit economical recovery of thermal energy from hot dry or impermeable rock (Smith, 1978; Cummings and others, 1979). Included in the resource estimate for the Azores, then, are probable economic resources (hydrothermal reservoirs) and sub-economic resources (hot dry or impermeable reservoirs), which may be economic in the future. I have distinguished in the tables those possible resource areas that have thermal springs or fumaroles, which suggest the existence of a hydrothermal system.

The nature of hydrothermal systems is briefly summarized in Portuguese by Aires-Barros (1978). The systems fall into two categories--vapor-dominated and liquid-dominated. Vapor-dominated systems, of which Lardarello, Italy, and The Geysers, California, are the most outstanding examples, produce almost entirely useable steam, but they are extremely uncommon; none have been identified in Portugal or the Azores. Liquid-dominated systems emit steam, useful for electrical generation, and hot water. The temperature and pressure of the system and the powerplant design dictate the relative proportions of these two components that will be produced and thus the efficiency and cost of power generation.

Direct use of geothermal fluids for electrical generation is currently limited to reservoirs of 150° C or greater. Binary generating systems, in which thermal fluids transfer their heat to another fluid of lower boiling temperature which in turn drives the turbines, can make use, at somewhat greater expense, of fluids as cool as 130° C. Following Brook and others, 1979, I present in this paper estimates of the amount of electricity that can be produced only by systems at temperatures above 150° C or greater. I assumed that cooler waters would be put to non-electrical uses, such as those summarized in figure 1. An estimate of the beneficial heat production of such waters is given.

Procedure for estimating resources

Following Brook and others (1979), I estimate for known and inferred hydrothermal systems: (1) the accessible resource base, that is, the quantity of thermal energy stored in the reservoir at technologically and economically accessible depths (assumed to be 3 km or less, corresponding to the depth of the deepest geothermal wells currently in production);

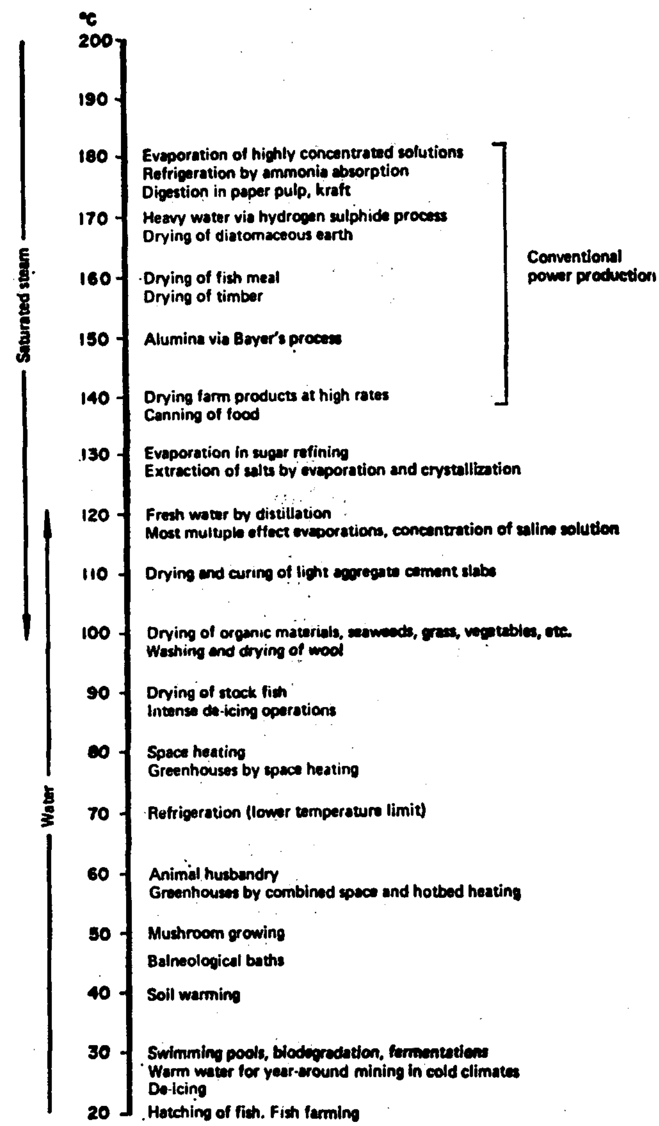

Figure 1. Direct-use temperatures of geothermal fluids. (From Lindal, 1973).

(2) the resource, that fraction of the stored energy that can be recovered at the wellhead; and (3) the amount of electricity that could be produced from the resources. The procedures for arriving at each of these estimates are described by Brook and others (1979).

For each hydrothermal system, the reservoir volume (area times thickness) and the reservoir temperature must be estimated. The thermal energy within the reservoir can them be calculated:

$$q_r = c \times a \times d \times (t - t_{ref})$$

where:

q_r = reservoir thermal energy in joules (J)

c = volumetric specific heat of rock plus water (2.7 $J/cm^3/°C$)

a = reservoir area

d = reservoir thickness

t = reservoir temperature

t_{ref} = reference temperature (15° C, mean annual surface temperature)

Nathenson (1975) has evaluated the factors that control the recovery of thermal energy from the reservoir. For an ideal reservoir having 20 percent effective and total porosity, 50 percent of the thermal energy can be recovered as the hot water is withdrawn and new cold water moves into and through the reservoir. Nathenson and Muffler (1975) and Brook and others (1979) assumed that non-ideal behavior in real reservoirs would reduce the recovery factor by an additional 50 percent to 0.25. I use the same recovery factor. the reservoir thermal energy, then, is multiplied by this recovery factor (0.25) to yield the thermal energy available at the wellhead.

In practice, the recovery factor can be as low as 0. That is, should there be inadequate fluid to carry the heat to the wells, inadequate permeability to permit the fluids to escape, or significant precipitation of solids from the fluids, thus hindering recovery, it may be impossible (with current technology) to recover the reservoir thermal energy. It is generally not possible to evaluate the recovery factor without drilling into the reservoir.

To generate electricity, thermal energy available at the wellhead must first be converted to mechanical energy which performs the work of driving the turbines. Energy is lost in the form of waste heat during the conversion. The amount of work that can be obtained (the "available work") depends upon the initial and final temperatures of the working fluid, the fluid enthalpy and entropy, and the depth of the reservoir.

The ratio of available work to reservoir thermal energy has been theoretically evaluated by Brook and others, and the solutions are summarized in figure 2 (reproduced from Brook and others, 1979, p. 26). Figure 2 shows that the amount of available work is strongly dependent upon the temperature of the reservoir but is only slightly dependent upon its depth.

The amount of electricty that can be produced is also reduced by mechanical and other losses during real power generation. This conversion efficiency is dependent upon the particular generation system used and the temperature of the fluids. Nathenson (1975) has calculated "utilization factors", the ratio of electricity that can be produced to available work, and these have been graphicaly summarized by Brook and others (1979, figure 6, p. 26). For the present calculations, I follow Brook and others in assigning a constant utilization factor of 0.4.

To facilitate comparisons, electrical energy is reported in megawatts of electricity obtainable during a 30-year period. The last stages of the calculations are then summarized:

$$\frac{\begin{matrix}\text{Wellhead}\\ \text{available}\\ \text{work}\end{matrix} \quad \text{X} \quad \begin{matrix}\text{Utilization}\\ \text{factor}\\ = 0.4\end{matrix} \quad \text{X} \quad \begin{matrix}\text{conversion}\\ \text{factor}\\ 1\ \text{J/sec} =\\ .001\ \text{MWe}\end{matrix}}{30\ \text{years}} = \begin{matrix}\text{MW}_e\\ \text{electrical}\\ \text{energy for}\\ 30\ \text{years}\end{matrix}$$

This calculation yields an estimate of the rate at which electrical energy could be produced for 30 years before the heat initially present in the reservoir is dissipated. The actual production rate can be greater or less for shorter or longer periods, respectively. Resupply of heat from deeper sources may increase the lifetime of the reservoir, but resupply cannot be predicted.

Following Brook and others, for reservoirs predicted to be cooler than 150° C, I have calculated the amount of beneficial heat available, rather than an electrical-generation capacity. The fraction of the thermal energy at the wellhead that can be beneficially recovered is assumed to be 24 percent (Brook and others, 1979).

To evaluate the potential of low-enthalpy fluids one should know the rate and temperature at which fluids could be withdrawn. Unfortunately, the flow rate cannot be predicted without drilling. Minimum values for both flow rate and temperature are those of the surface springs in each area. These data were available to me for only those springs reported by Aires-Barros (1978). For comparison, I have converted these data into kilowatts (1 kilowatt = 1 joule/second).

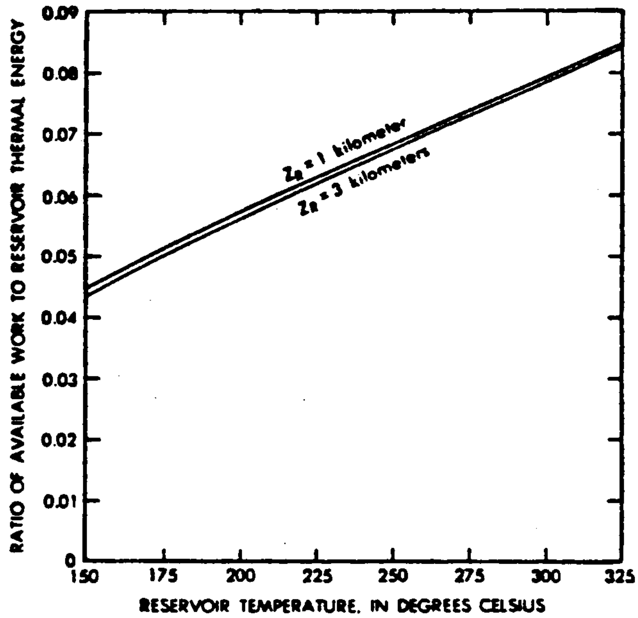

Figure 2. Ratio of available work to thermal energy in the reservoir for hot-water systems, plotted as a function of reservoir temperature and depth to the middle of the reservoir (Z_R). A recovery factor of 0.25 was used to calculate the available work. (Figure 5 of Brook and others, 1979, p. 26.)

Procedure for estimating the volume and temperature of reservoirs

To calculate a resource estimate it is necessary to estimate the volume of the reservoir (its subsurface area times its vertical extent) and its temperature.

Volume

Electromagnetic, gravity, passive seismic, and borehole heat-flow surveys and/or deep drill holes may provide enough information to assess the volume of a reservoir accurately. However, these data are expensive to acquire and are not generally available. Consequently, the area and vertical thickness of reservoirs usually must be estimated on the basis of geological criteria.

In general, estimating the presumed subsurface reservoir area, by correlation with an area on the surface (such as the area over which thermal springs are emitted or the area enclosed by a caldera wall), is easier than estimating the depth and vertical thickness of a reservoir. I have assumed, following Brook and others (1979), that unless evidence indicated otherwise, the bottom of all reservoirs is at a depth of 3 km, even though in many circumstances, temperatures probably would increase or remain constant below that depth. The deepest geothermal production wells currently in use are approximately 3 km deep, and deeper drilling is exceedingly expensive. Moreover, rock porosity decreases as depth increases, so hydrothermal reservoirs cannot continue downward indefinitely.

The depth to the top of a reservoir cannot usually be determined from geochemical or geological information. For possible geothermal resource areas in the Azores, I have specified criteria that bear upon the depth at which high temperatures will be found, such as the presence of thermal areas and post-caldera silicic volcanism, and have assigned depths upon that basis. The uncertainty is great.

In mainland Portugal, where the only indication of a thermal reservoir may be an isolated spring, I have generally used the standard mean values assumed by Brook and others (1979), that is, area = 2 km^2 and thickness = 1.5 km, to arrive at a volume estimate of 3.3 km^3.

Reservoir volume estimates are a major source of uncertainty in the geothermal resource assessment. Additional geological and geophysical data will help refine these estimates.

Temperature

Reservoir temperatures can be estimated by applying chemical geothermometers to thermal waters. The use of geothermometers has been discussed in detail by Brook and others (1979), Fournier (1977), and White (1970).

Geothermometers cannot yield valid temperature estimates unless the following assumptions are met:

1. Reactions take place between rock and water within the reservoir. The reactions are temperature dependent, and equilibruim is attained in the reservoir.

2. The supply of all constituents required by the reactions is sufficient.

3. The water does not reequilibrate with surrounding rocks after it leaves the reservoir.

4. Thermal water and cold ground water do not mix.

The last of these assumptions is commonly violated. Truesdell and Fournier (1977) have devised methods that permit, under favorable circumstances, estimation of reservoir temperatures for mixed thermal waters. Unfortunately, these mixing models cannot be applied to Portugal's thermal springs because analyses of the cold ground-water component are not available.

Geothermometers commonly yeild incorrect results if the thermal water is acidic (fostering rock-water reaction near the surface), or if the water is rich in CO_2 or HCO_3^- (Brook and others, 1979; Paces, 1975). Special methods of sample collection, storage, and analysis are also required to assure accurate results (Thompson, 1975). Many of Portugal's thermal waters were collected and analyzed 50 or more years ago, and the sampling and analytical procedures are poorly known. In general, temperatures calculated by different geothermometers that disagree by more than 20° C should be considered suspect.

Temperatures reported herein were calculated by use of the silica geothermometer of Fournier and Rowe (1966) and the Na-Ca-K geothermometer of Fournier and Truesdell (1973). The methods outlined by these authors were used to select approximate constants and reactions. In addition, Mg corrections have been applied to Na-Ca-K temperatures, following the methods of Fournier and Potter (1979). Problems encountered with the application of gothermometers are discussed in the appropriate sections below.

Prediction of scaling and corrosion problems

The expense of using geothermal fluids may be significantly increased if the fluids are either corrosive or rich in dissolved components that precipitate and clog the recovery, circulation, or power-generation equipment. To the extent that the fluid compositon and temperature can be predicted, the likelihood that either of these problems will be encountered can also be predicted. This can be done by calculating whether specific solid components are saturated in the solution, that is, whether ($G_{fm} > 0$). These complex calculations were performed by a computer program SOLMNEQ--SOLUTION-MINERAL EQUILIBRIUM COMPUTATIONS

(Kharaka and Barnes, 1973); this program calculates the equilibrium distribution of 162 dissovled species and their state of reaction with 158 solid phases. The reliability of the calculations is dependent upon the accuracy and completeness of the analysis and, in particular, the accuracy of the pH determination. Changes in the oxygen fugacity can also produce important changes in the calculated stable mineral assemblage.

Precipitation of minerals as described below may cause corrosion and scaling problems.

(1) Carbonate minerals:

Aragonite, calcite, siderite: At concentrations above saturation level, but less than 2-5 times saturation level, carbonate minerals precipitate slowly and may provide protection against corrosion. When the solutions are highly supersaturated, carbonate minerals may form rapidly and adhere to metal surfaces ("scaling"). Scaling may be severe when the concentration exceeds 15-20 times saturation level (Barnes, 1965).

Dolomite: In Mg^{2+}- and HCO_3^--rich waters, dolomite and magnesian calcite will precipitate more rapidly than calcite. In HCO_3^--poor waters dolomite forms less rapidly (Feth and Barnes, 1979).

(2) Iron oxides and hydroxides: Precipitation of iron oxides and hydroxides is common. However, these minerals do not generally adhere to metal surfaces, and the accumulated precipitates can usually be flushed out of the system as often as is necessary.

(3) Troilite (FeS): Severe corrosion can be expected in areas of troilite precipitation, because of the formation of strong acids in the vicinity of the troilite.

(4) Silica minerals (quartz, chalcedony, cristobalite, amorphous silica): The kinetics of growth of silica polymorphs from thermal waters is poorly known. However it is unlikely that scaling or clogging problems will develop at concentrations less than 10 times saturation level (I. Barnes, 1979, oral commun.).

The effect of oxygen on the stability of several of the above discussed minerals is critical. At high oxygen fugacity, deposition of $Fe(OH)_2$ is favored over deposition of troilite or siderite. Predicted corrosion due to troilite or scaling due to siderite may be prevented therefore, if geothermal fluids are allowed to oxidize.

GEOLOGICAL SETTING OF GEOTHERMAL RESOURCES OF MAINLAND PORTUGAL

The following information is compiled from varous published and unpublished sources. Much of the unpublished geochemical work has been performed by Dr. Fernando Moitinho de Almeida of the Servicos Geologicos de Portugal (SGP). The tectonic interpretation is the work of Dr. Antonio Ribeiro, also of the SGP.

Table 1 lists thermal springs of Portugal that have emission temperatures greater than 27° C (compiled from Moitinho de Almeida and Moura (1970)). Because mineral springs are valued for drinking water and medicinal baths, exploration for and examination of mineral springs has be extensive. It is unlikely that additional thermal springs will be discovered in Portugal.

Thermal springs are in three different physiographic regions of Portugal: the northern hilly to mountainous region, the western Mesozoic to Cenozoic sedimentary basin, and the southwest Algarve (Southern Portugal).

Because heat flow and other valuable geophysical data (such as electrical resistivity measurements) are unavailalble for most of Portugal, thermal springs are the only reliable and estimable clue to the existence of geothermal resources.

Thermal springs in northern Portugal

Thermal springs are most common in the northern hilly and mountainous region. The warmest springs, and the hottest calculated reservoir temperatures, are also in this area. Bedrock consists of Precambrian and lower Paleozoic metasedimentary and metavolcanic rocks, intruded by Hercynian syn- to post-tectonic mafic to silicic plutonic rocks. No Tertiary plutonism or volcanism has been recognized in this area.

Major strike-slip and normal faults trend northwest across northern Portugal, and one of these is the southern boundary of this northern physiographic province. In the north, elevated terraces indicate approximately 400 m of Quaternary uplift. In the south, no Quaternary uplift has taken place. Apparently, rapid Quaternary uplift has resulted in a steeper geothermal gradient in the north.

Figure 3, shows that many thermal springs occur along or near major falts that cut granitic rocks, in which offset is difficult to recognize. This correlation suggests that thermal waters are heated during deep circulation on faults. Fractures in granitic rocks apparently are more conducive to deep circulation than fractures in metamorphic rocks.

The importance of faults in controlling the distribution of springs on a local scale is apparent in the discussion of thermal springs of exploration targets in Portugal, even in areas where thermal springs do not exist. In addition, the size and shape of hydrothermal reservoirs may be dominantly fault controlled.

The compositions of selected thermal waters from northern Portugal are reported in table 2. Calculated Na-Ca-K temperatures are around 100° C where β may equal 1/3 or 4/3 (see Fournier and Truesdell, 1973), and where silica solubility may be controlled by chalcedony rather than quartz. I have followed the procedures described by Fournier and Truesdell (1973) to define β and have used the chalcedony silica geothermometer for

Table 1. Thermal springs of Portugal.

[Data reported in this table are reproduced from Moitinho de Almeida and Moura, 1970, and Aires-Barros, 1978. Reservoir temperatures have been recalculated as discussed in the text.]

(No. fig. 3)	Thermal spring	Location	Orifice temperature	Composition	Total dissolved solids (mg/l)	Flow rate (l/min)	Average reservoir temperature[a]	Corrosion or Scaling problems?[b]	Comments
1	Moncao	42°5'N, 8°30'W	49.5°C	Na, HCO_3	200-1,000 mg/l				
2	Chaves	41°45'N, 7°30'W	73.5°C	Na, HCO_3	1000-10,000	83.3	144° C	Scaling possible	Reservoir temp. probably too high
3	Geres	41°40'N, 8°10'W	48.5°C	Na, HCO_3, F	200-1,000	23.6	67-94° C		
4	Taipas	41°25'N, 8°25'W	32°C	Na, HCO_3, S	200-1,000; 100-200				
5	Vizela	41°20'N, 8°20'W	62°C	Na, HCO_3, S	200-1,000	16.0	117° C	Scaling or corrosion possible	
6	Carlao	41°20'N, 7°25'W	34°C	Na, HCO_3, S	200-1,000				
7	San Laurenco	41°15'N, 7°20'W	36°C	Na, S	?				
8	Canavezes	41°10'N, 8°10'W	35.3°C	Na, HCO_3, S	200-1,000				
9	Moledo	41°10'N, 7°50'W	39°C	Na, S	200-1,000	175	67-76° C	Corrosion possible	
10	Aregos	41°5'N, 8°W	61°C	Na, HCO_3, S	200-1,000	720	87° C	Scaling or corrosion possible	
11	San Jorge	40°55'N, 8°30'W	30°C	Na, HCO_3, S	200-1,000				
12	Banhos do Areola	40°55'N, 7°20'W	37.5°C	Na, S	?				
13	Longroiva	40°55'N, 7°15W	30°C	Na, S	?				
14	Carvalhal	40°50'N, 7°55'W	32°C	Na, HCO_3, S	200-1,000				
15	Banhos de Caveca	40°50'N, 7°40'W	29°C	Na, HCO_3, S	200-1,000				
16	San Pedro do Sul	40°45'N, 8°10'W	69°C	Na, HCO_3, S	200-1,000	583.3	86° C	Scaling or corrosion possible	
17	Alcafache	40°35'N, 7°50'W	51.5°C	Na, HCO_3, S	200-1,000	83	90° C	Corrosion possible	
18	San Gemil	40°30'N, 7°55'W	51°C	Na, S	200-1,000		50, 91° C	Corrosion possible	Poor agreement of geothermometers
19	Felgueiras	40°25'N, 7°50'W	35°C	Na, HCO_3, S	200-1,000				
20	Luso	40°20'N, 8°25'W	27.5°C	Na	<100				
21	Monteigas	40°20'N, 7°35'W	46°C	Na, S	100-200	360	61, 91; 100, 131° C	Corrosion possible	Poor agreement of geothermometers Best estimate less than 100° C.
22	Unhais de Serra	40°15'N, 7°40 W	30.2°C	Na, S	200-1,000				
23	Bicanho	40°5'N, 8°45'W	28 C°	Cl, Na	200-1,000				
24	Azenha	40°5'N, 8°45'W	28.8°C	Cl, Na	200-1,000				
25	Monfortinho	40°N, 6°50'W	28.2°C	Na	<100				
26	Fervenca	39°35'N, 8°55'W	28°C	Cl, Na	1,000-10,000				
27	Piedade	39°35'N, 9°W	28°C	Cl, Na	1,000-10,000				
28	Salir do Porto	39°30'N, 9°10'W	29°C	Cl, Na	1,000-10,000				
29	Arrabidos	39°20'N, 9°10'W	29.2°C	S	?				
30	San Mamede de Rolica	39°15'N, 9°10'W	33°C	S	?				
31	Cucos	39°5'N, 9°15'W	41°C	Cl, Na	1,000-10,000				
32	Estoril	38°40'N, 9°25'W	35.5°C	Cl, Na	1,000-10,000				
33	Banhos da Poca	38°40'N, 9°25'W	28°C	Cl, Na	1,000-10,000				
34	Alcacarias do Duque	38°40'N, 9°5'W	30.8°C	Cl, Na	200-1,000				
35	Malhada Quente	37°20'N, 8°30'W	28°C	Na, HCO_3	200-1,000				
36	Monchique	37°15'N, 8°30'W	32°C	Na, HCO_3, S	200-1,000				
37	Alferce	37°20'N, 8°25'W	27°C	Cl, Na	200-1,000				

[a]Reservoir temperatures are reported only for those samples to which a Mg correction has been applied.

[b]Nearly all spring waters will precipitate iron oxides or hydroxides, requiring periodic flushing of lines. Corrosion and some scaling problems can be avoided by permitting waters to oxidize. See text.

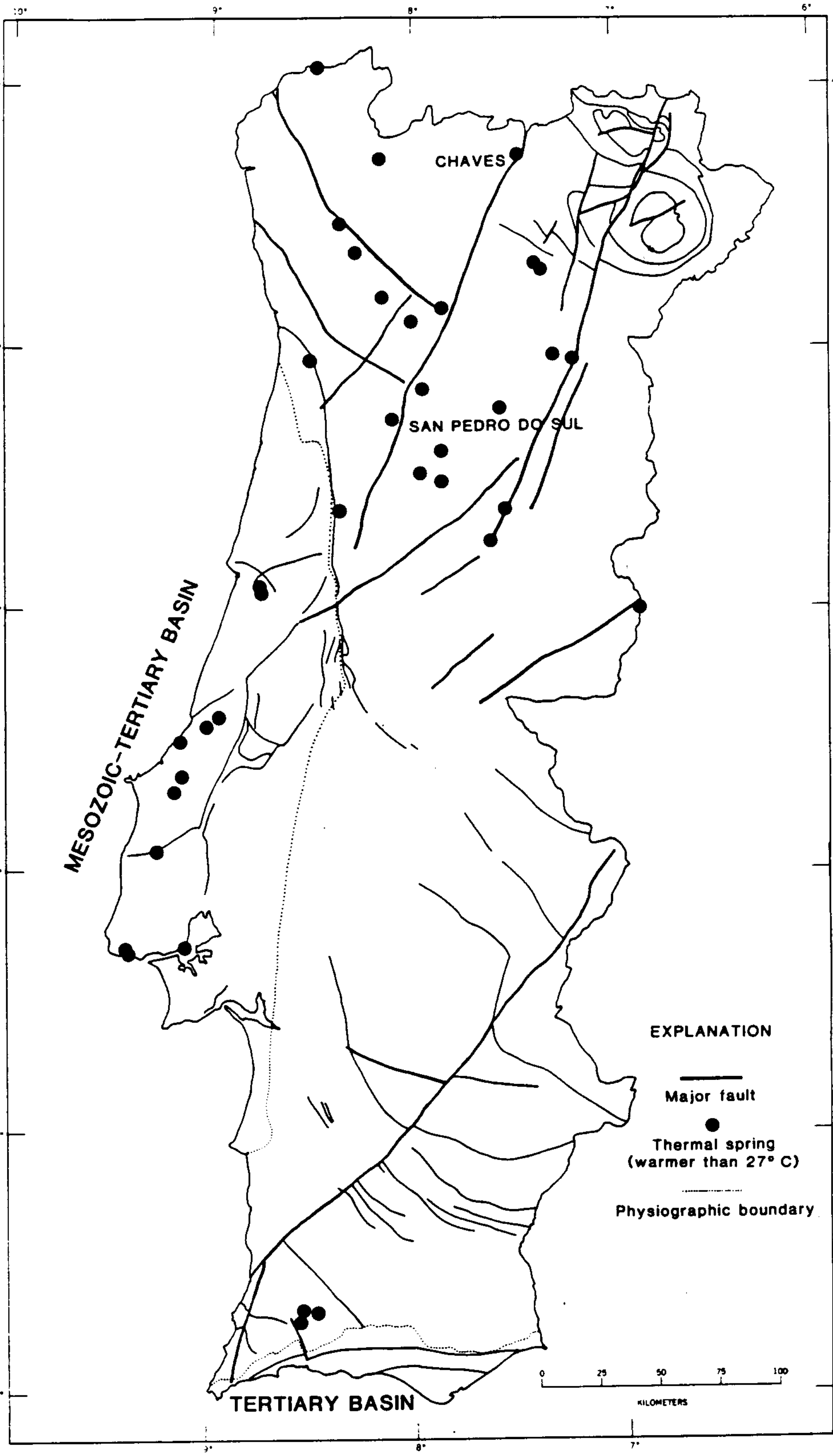

Figure 3. Map of Portugal showing thermal springs warmer than 27°C (from Moitinho de Almeida and Moura, 1970), major faults, and sedimentary basins (from Ribeiro and others, 1972).

Table 2. Compositions of thermal waters in northern Portugal.

[Table modified from tables by Aires Barros (1978), who used data from Almeida and Almeida (1970, 1975)]

	Chaves					Manteigas		Aregos
	Spring 1	Spring at Grande Hotel	San Pedro do Sul	San Gemil	Aleafache	Spring Nascente 1	Nascente 2	Ribeiro
T°C	72,8	45,0	67,5	49,5	50,9	40,1	45,3	61,0
pH	6,93	6,72	8,65	8,12	8,38	9,12	9,32	8,7
flow (l/min)	83,3	—	583,3	—	83	360		720
SiO_2 (mg/l)	99,6	68,0	69,6	73,5	63,6	41,0	48,3	61,45
Na^+ (mg/l)	623,8	604,7	90,3	120,3	105,0	45,8	52,5	90,95
K^+ (mg/l)	65,4	—	3,2	3,8	3,4	1,55	1,69	3,11
Ca^{2+} (mg/l)	27,3	25,2	3,6	1,6	4,5	1,17	0,92	3,97
Mg^{2+} (mg/l)	3,90	4,60	0,88	2,2	0,31	0,11	0,02	0,76
Fe^{2+} (mg/l)	0,90	0,08	0,80	0,08	0,10	0,04	0,04	1,03
Li^+ (mg/l)	3,50	—	0,16	—	0,37	0,13	0,15	0,08
Cl^- (mg/l)	47,9	52,5	27,70	56,1	37,0	7,1	7,8	30,20
F^- (mg/l)	7,8	7,9	2,20	17,5	14,5	9,3	10,7	1,80
SH^- (mg/l)	—	—	5,11	3,7	1,37	0,4	1,2	6,29
SO_4^{2-} (mg/l)	30,9	26,3	24,97	4,2	1,6	12,5	15,8	26,80
HCO_3^- (mg/l)	1 744,6	1 549,4	—	176,3	187,9	50,6	43,9	—
CO_3^{2-} (mg/l)	—	—	77,55	—	—	8,4	14,4	79,30
NO_3^- (mg/l)	0,5	5,0	0,31	—	—	—	—	0,62

	Gerês						Moledo			Vizela		
	Bica	Forte	Telha	Mendes	Contra-Forte	Águas Novas	Lameira 28	Lameira 30	Rio	Médico	Rio	Mourisco
T°C	42,5	46,5	25,3	37,3	48,1	43,4	37,0	39,0	39,1	31,4	47,5	31,6
pH	8,65	8,46	6,93	—	—	—	—	—	—	8,75	8,70	8,80
Flow (l/min)	23,6	—	—	—	—	—	(1)	(1)	(1)	—	—	15,97
SiO_2 (mg/l)	86,75	83,82	42,63	75,20	79,70	78,97	42,00	40,85	49,56	73,97	78,35	66,50
Na^+ (mg/l)	67,25	68,46	28,91	68,39	71,70	69,35	75,90	75,13	76,20	92,63	96,70	93,81
K^+ (mg/l)	2,21	2,26	1,68	2,53	2,90	2,80	1,77	2,18	2,41	4,09	5,97	4,25
Ca^{2+} (mg/l)	3,84	2,63	2,81	4,70	4,86	4,81	4,35	4,31	4,64	3,50	4,81	2,86
Mg^{2+} (mg/l)	0,34	0,09	0,48	0,38	0,43	0,50	0,49	0,45	0,40	0,48	1,00	0,22
Fe^{2+} (mg/l)	—	—	—	0,20	0,21	0,14	0,52	0,56	0,42	1,14	1,08	2,44
Li^+ (mg/l)	0,30	0,33	0,18	0,22	0,28	0,24	0,15	0,15	0,16	0,22	0,24	0,24
Cl^- (mg/l)	12,90	22,12	12,51	13,35	14,39	14,34	21,26	20,76	20,52	31,24	31,95	27,82
F^- (mg/l)	12,10	7,60	2,08	10,30	11,50	10,60	2,12	2,07	2,20	0,11	0,12	0,20
SH^- (mg/l)	—	—	—	—	—	—	3,03	4,93	5,37	9,76	10,47	10,69
SO_4^{2-} (mg/l)	9,88	10,10	14,40	11,66	9,76	10,59	21,01	20,08	26,16	15,34	16,62	11,20
HCO_3^- (mg/l)	119,48	118,14	48,61	—	—	66,21	—	—	—	—	—	—
CO_3^{2-} (mg/l)	—	—	—	64,75	68,58	—	70,58	70,21	68,15	86,80	94,70	92,31
NO_3^- (mg/l)	—	—	—	1,84	1,53	1,53	0,73	0,61	0,17	3,10	3,10	0,24

*The flow of the springs in Moledo were calculated as 175 l/min., which at present is considered sufficiently large.

samples yielding Na-CA-K temperatures (including the Mg correction) lower than 100° C. The results are reported in table 3. The estimated reservoir temperatures reported in table 3 are cooler than those of Aires-Barros (1978) because I have used: (1) the Mg-correction; (2) β=4/3 for several samples; and (3) the chalcedony rather than the quartz geothermometer for several samples.

With the exception of the temperature calculated for Chaves, the calculated temperatures are all less than the minimum temperature required for electrical generation, even with a binary system. Most temperatures are less than 100° C. The exceptionally high temperature calculated for the waters at Chaves is within the range feasible for electrical generation by a binary system, but for reasons discussed in the following section, this estimate is possibly too high.

Results of solid-phase equilibrium calculations for some of the analyses in table 2 are reported in table 4; the results indicate that scaling is not likely to be a serious probem in any of the waters (with the possible exception of Chaves, where siderite may form), but that formation of iron oxides and hydroxides may require periodic flushing of equipment. Corrosion could be a minor problem for some waters, and it may be relatively severe at San Gemil and Manteigas, where the waters are supersaturated with troilite, but understurated with carbonate minerals.

Chaves

The hottest thermal springs in Portugal, emitted at 75° C, are at Chaves (fig. 3). Thermal waters are emitted by ten or more natural artesian springs and several shallow (2-5 m) wells from an area that covers approximately 225,000 m^2.

Chaves lies along one of Portugal's major north-northeast trending faults. This fault extends 190 km within Portugal and continues to the north into Spain. Thermal springs at Moledo (70 km south of Chaves, Carvalhal (105 km south), and San Pedro do Sul (120 km south), as well as numerous cold CO_2-rich springs, occur on or near the same fault.

Individual springs in the Chaves region (fig. 4) appear to be controlled by small faults or joints parallel to the regional north-northeast trend. This control is illustrated, for instance, by the soils; and isotherms contoured from water temperatures in shallow wells. Quartz-filled veins locally follow the same trend.

The waters emitted at Chaves are exceptionally rich in HCO_3^- and, compared to other Portuguese spring waters, are high in Na+ and Ca^{2+}. Isotopic studies are currently in progress to evaluate the sources of the carbonate, but the scarcity of calcareous rocks in the country rock suggests that the CO_2 may have its source in the mantle. The Cl^- content is approximately the same at Chaves No. 1 spring (T=73° C, Cl^- = 47.9mg/l) and the Grande Hotel well (T=45° C, Cl^- = 52.5 mg/l), suggesting that temperature contrasts are due to conductive cooling of the thermal water

Table 3. Calculated temperatures (°C) for some thermal springs whose analyses are reported in table 2.

[Best values are underlined. All calculations include Mg correction]

Spring name	Silica geothermometer TQz_c	Silica geothermometer TChal	Na-Ca-K geothermometer $T_b = 1/3$	Na-Ca-K geothermometer $T_b = 4/3$	Reliable best average 1/
Chaves	137	109	151	152	2/ 144
San Pedro do Sul	118	88	79	83	86
San Gemil	121	91	50	50	
Alcafache	114	83	128	97	90
Manteigas I	94	61	125	91	
Manteigas II	100	69	131	102	
Aregos Ribeiro	112	81	89	92	87
Geres Bica	129	100	118	81	91
Geres Forte	128	98	129	90	94
Geres Telha	95	62	92	70	66
Geres Mendes	122	92	122	81	87
Geres Contraforte	125	96	121	85	91
Geres Aguas Novas	124	95	114	84	90
Moledo Lameira 28	95	62	106	72	67
Moledo Rio	102	70	119	81	76
Vizela Medico	121	91	113	109	117
Vizela Rio	124	95	96	93	

1/ Temperature estimates are considered reliable if they agree to within 20°C.

2/ For reasons discussed in text, this estimate is possibly too high.

Table 4. Results of SOLMNEQ calculations for selected thermal water analyses in table 2.

[Selected stable solid phases are reported. Values reported are Q/K (activity product divided by the temperature dependent reaction constant), which indicates the multiple supersaturation of the solid.]

	ARAGONITE	CALCITE	DOLOMITE	SIDERITE	HEMATITE	GOETHITE	TROILITE	QUARTZ	CHALCEDONY	CRISTOBALITE A
Chaves	1.5	1.7	1.8	24	-	-	-	3.9	2.0	1.3
S. Pedro Do Sul	1.7	1.9	3.9	1.4	10^{6}	10^{3}	10^{36}	2.3	1.2	-
S. Gemil	-	-	-	-	10^{3}	54	10^{35}	5.1	2.3	1.5
Alcafache	1.1	1.3	-	-	10^{4}	10^{2}	10^{35}	4.0	1.8	1.2
Manteigas I	-	-	-	-	10^{4}	10^{2}	10^{34}	2.6	1.1	-
Manteigas II	-	-	-	-	10^{4}	10^{2}	10^{34}	2.0	-	
Aregos	2.1	2.4	4.6	2.8	10^{6}	10^{3}	10^{36}	2.4	1.2	-
Geres Bica	-	1.0	-	-	-	-	-	6.6	2.8	1.8
Vizela Rio	2.0	2.3	4.2	6.8	10.6	10.3	10^{37}	4.9	2.1	1.4

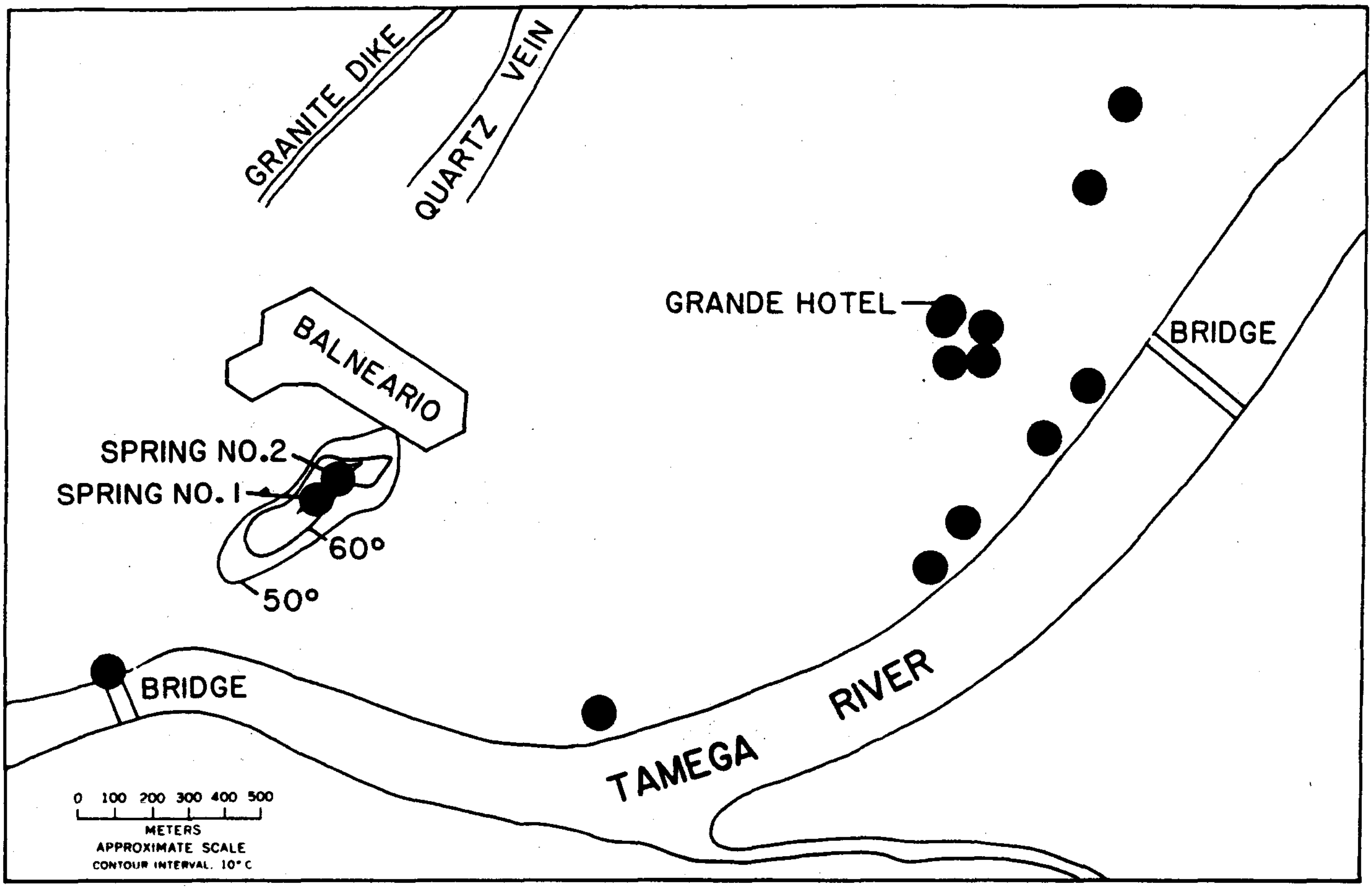

Figure 4. Detail of region of thermal springs in Chaves, compiled from Lima (1892) and unpublished information provided by Moitinho de Almeida (written communication, 1979). Isotherms show maximum water temperatures encountered in shallow wells (less than 5 meters deep) in the vicinity of springs 1 and 2. Several of the springs shown have become inactive since being reported by Lima (1892).

rather than mixing of hot and cold water (Fournier, 1977). The relatively high Cl^- content indicates that the hydrothermal reservoir is liquid dominated rather than vapor dominated (White, 1970).

Equilibium calculations indicate that carbonate and silica minerals are at saturation levels in the thermal waters. Dolomite, aragonite, and calcite are less than two times the saturation level. The concentration of siderite, however, is 24 times the saturation level, and rapid crystallization can be expected unless the water is allowed to oxidize, thus favoring formation of $Fe(OH)_2$ rather than siderite. Troilite is not at the saturation level, and corrosion problems are not anticiapted.

For Chaves No. 1 spring silica and Na-Ca-K geothermometers yeild temperatures of 137° C. (T_{qz}, conductive cooling) and 151° C. β = 1/3, adjusted for a Mg correction of -54° C), respectively. The Na-Ca-K temperatures may be too high if calcite was deposited after the water left the reservoir. The silica geothermometer may also give high results, because the highly carbonated waters may dissolve silicate minerals in the country rock more rapidly than quartz or chalcedony can precipitate (Brook and others, 1979).

No geophysical data are available to aid in defining the depth and dimensions of the geothermal reservoir. Because faults are regionally and locally important in controlling the location of thermal springs. The thermal waters probably are circulating deep within brecciated fault zones. The surface expression of the faults is the only evidence of the dimensions of this subsurface breccia zone. Clearly, several different interpretations are possible, and lead to widely different estimates of the reservoir volume and geothermal resource:

(1) AREA OF SPRING EMISSIONS=SUBSURFACE AREA OF RESERVOIR: This yields the smallest estimate of the area of the reservoir, 2.25 X 10^5 m^2. Because no information is available upon which to base a thickness estimate for the reservoir, I assume the same value used by Brook and others (1979), 1.5 km. Thus the reservoir volume is estimated to be 3.4 X 10^8 m^3.

(2) SUBSURFACE AREA OF RESERVOIR=WIDTH OF FAULT ZONE X SUBSURFACE LENGTH OF THE RESERVOIR (several estimates possible): The width in the Chaves region may be defined by the distance between the western and central fault segments (650 m) or western and eastern segments (3,000 m). Length may be defined by: The length of the area of spring emissions (750 m), the length of granitic outcrop along the fault zone (approximately 6,000 m), or any length less than or equal to the entire length of the fault system (190 km in Portugal). The last interpretation is equivalent to assuming that thermal springs at Chaves, Moledo, Carvalhal, and San Pedro do Sul are expressions of a single continuous reservoir. The various width and length assumptions yield the following calculated reservoir volumes:

WIDTH	LENGTH	THICKNESS	VOLUME
650 m	750 m	1500 m	7.3 X 10^8 m^3
	6000 m	1500 m	59 X 10^8 m^3
	190,000 m	1500 m	1900 X 10^8 m^3
3000 m	750 m	1500 m	34 X 10^8 m^3
	6000 m	1500 m	270 X 10^8 m^3

Based upon these volume estimates and the temperature estimate reported above, resources estimates for Chaves are reported in table 5.

Thermal waters at Chaves are currently used for medicinal spas. If reservoir temperatures predicted by geothermometers are as high as indicated (137-151° C), then thermal waters could be used for electricity generation by binary systems. If temperatures are not as high as predicted, thermal waters could be used for space heating and other direct uses suggested in figure 1, and "waste" waters could still be used for medicinal baths. (Currently, the water is circulated through cooling loops before it is used in the spas.)

Pumping thermal waters from depth would most likely result in cessation of artesian flow at the surface. Consequently, it would be necessary to pump thermal waters to the surface for any use.

Thermal springs in western Portugal

Thermal springs in western Portugal are emitted at lower temperatures than most of those in northern Portugal (Maximum 41° C), and apparently escape from cooler reservoirs. They are chemically distinct from those in the north; most are chloride-rich waters. Like those in the north, many thermal springs issue along faults.

The western coastal plain and offshore shelf of Portugal is a Mesozoic to Cenozoic sedimentary basin, in which sediments reach a maximum thickness of more than 4,000 m (Ribeiro and others, 1972). This basin and the geologically similar Algarve basin along the southern coast of Portugal and Spain have been the focus of petroleum exploration in Portugal. Temperature measurments in 17 drill holes in the western basin and 2 holes in the southern basin provide the only estimates of thermal gradient in Portugal. These results have been compiled by Moitinho de Almeida written commun., 1980). Too few determinations have been made for anyone to recognize significant heat-flow anomalies, but the average temperature, 50° C at 1,500 m depth (range: 33 to 66° C at 1,500 m depth), corresponds approximately to a gradient of 30° C/km, roughly the global average.

No geological evidence suggests that significant local heat-flow anomalies exist in the western basin. Thermal springs are apparently produced, as in northern Portugal, primarily by deep circulation of ground water along faults.

Table 5. Summary of estimated beneficial-heat production capacity of Portuguese thermal waters.

[See text for description of estimation methods]

Thermal spring	Volume estimate (km^3)	Temperature estimate (°C)	Available beneficial heat ($x10^{18}$ J)	Surface flow rate (l/min)	Surface emission temperature (°C)	Spring beneficial heat (kW)
Chaves	0.73-27	144	0.015-0.564	83.3	74	103
Geres	3.3	90	0.040	23.6	49	19
Vizela	3.3	117	0.055	16.0	62	17
Moledo	3.3	75	0.032	175	39	114
Aregos	3.3	87	0.038	720	61	732
San Pedro do Sul	3.3	86	0.038	583.3	69	670
Alcafache	3.3	90	0.040	83	52	72
San Gemil	3.3	70	0.029	-	57	-
Manteigas	3.3	75	0.032	360	46	276
Other springs						
N. Portugal (13)	42.9	80	0.452	-	-	-
W. Portugal (12)	39.6	60	0.289	-	-	-
S. Portugal (3)	9.9	45	0.048	-	-	-

Total available beneficial heat 1.108-1.657 x 10^{18} J

Chemical analyses of thermal waters in western Portugal are not available to me at the time of this writing. Moitinho de Almeida written commun., 1980) has calculated geothermometric temperatures for most of the springs, and his results for several are listed in table 6. These data have not been corrected for Mg^{2+} or HCO_3^-. Note that of these results, only the estimates of 57° and 61° C (T_{chal}, and $T_{Na-Ca-K}$, respectively) for Alcacarias do Duque agree within 20° C, the range expected for reliable estimates. Discrepancies may be due to the lack of Mg and CO_2 corrections, to poor sample handling and/or analysis, and/or failure to meet one of the basic assumptions of geothermometers discussed above. All of the reservoir temperatures of western Portugal are likely to be less than 100° C, and most may be about 60° C, but these estimates should be considered speculative until the original analyses can be reexamined and/or until new samples can be obtained.

Thermal springs in southern Portugal

In southern Portugal, thermal springs occur only within the vicinity of a single post-Hercynian syenite intrusion in the Monchique hills. The maximum emission temperature of these springs is only 32.1° C.

Although it has not experienced late Tertiary or Holocene volcanism, southern Portugal is adjacent to a slowly converging tectonic plate boundary. The rate of convergence increases eastward, and southern Spain has experienced Quaternary volcanism. Higher than normal heat flow is not, however, manifest in the two deep temperatures determined in petroleum exploration wells drilled offshore in the Mesozoic-Cenozoic Algarve sedimentary basin. Both yielded 50° C at a depth of 1,500 m, equal to the average of the 17 deep temperature measurements in western Portugal, corresponding to a normal geothermal gradient of approximately 30° C/km.

Ribeiro (written commun., 1979) has found evidence that southern Portugal has undergone approximately 200 m of Quaternary uplift, possibly contributing to a slightly higher than normal geothermal gradient. Analyses of thermal waters in southern Portugal are not currently available to me. Moitinho de Almeida (written commun.,1980) has performed geothermometric calculations for several springs, yielding, as for springs in western Portugal, highly discrepant and therefore unreliable results (table 7).

Table 6. Calculated temperatures (in ^{o}C) for selected thermal springs in western Portugal. (from Moitinho de Almeida, written commun., 1980)

[Mg and CO_2 corrections have not been applied; best values are underlined]

Spring name	Silica geothermometer		Na-Ca-K geothermometer		Reliable best average
	TQz_c	TChal	T_{β} 1/3	T_{β} 4/3	
Luso	55	15	163	49	
	31	-12	184	61	
Bicanho	42	0	83	29	
			148	79	
Fervenca	69	32	165	119	
Piedade	57	18	109	69	
Salir do Porto	39	-3	105	58	
Cucos	74	37	100	75	
	60	21	91	68	
	58	19	92	69	
	62	23	83	59	
	49	9	87	53	
	61	22	126	97	
Estoril	84	49	138	111	
	90	56			
	79	44	119	98	
	86	51	119	97	
Alcacarias do Duque	90	57	144	61	59
Banhos do Poca	74	37	131	99	

Table 7. Calculated reservoir temperatures in (°C) for thermal springs in southern Portugal, from Moitinho de Almeida, (written commun., 1980)

[Mg and CO_2 corrections have not been applied; best values]

Spring name	Silica T_{Qz_c}	T_{Chal}	Na-Ca-K T_β 1/3	T_β 4/3
Monchique:				
Sao Joao	56	17	109	87
San Joao	58	19	192	151
Pancade	64	25	177	125
Chagas	72	35	162	130
Alferce	91	58		
Malhada Quente	72	34		

Reservoir temperatures are most certainly less than 100° C and are probably in the range 30° to 60° C, suggested by T_{chal}.

GEOLOGICAL SETTING OF GEOTHERMAL RESOURCES OF THE AZORES

The Azores consist of nine volcanic islands. Seven (Santa Maria, San Miguel, Terceira, San Jorge, Pico, Fayal, and Graciosa) are east of the Mid-Atlantic Ridge (MAR) and trend west-northwest. The remaining two (Flores and Corvo) are west of the MAR and are aligned north-south. The archipelago extends 460 km from east to west.

The Azores occur in a structurally complex setting. The seven islands east of the MAR trend at a low angle across the East Azores Fracture Zone (EAFZ), a seismically active zone which connects to the Alpide Tectonic zone, a major tectonic element that extends through the Mediterranean and across Asia into Indonesia. The EAFZ does not continue directly across the MAR but is offset in a right-lateral sense before continuing to the west as a seismically inactive zone (the WAFZ--West Azores Fracture Zone). Near the Azores, the MAR also abruptly changes trend, and it widens by several times through the Azorean platform (Krause and Watkins, 1970).

Several hypotheses have been proposed recently to explain the existence and setting of the Azores. White and others (1976) suggested that the Azores were the trace of a mantle hot spot. Machado and others (1972) proposed that the MAR is cut by several west-northwest oriented transcurrent faults on the Azorean platform, and that each volcanically active island is underlain by a separate translated segment of the MAR. Krause and Watkins (1970) proposed that as a result of unequal spreading rates north and south of a formerly continuous (E and W)AFZ, the MAR split into a triple junction, separating the American, African and Eurasian plates. The "Terceira Rift" (Machado, 1955), then, is a spreading ridge, created out of a "leaky transform fault." In support of their theory, Krause and Watkins (1970) noted that Bangher and Sykes (1969) had identified the "Terceira Rift" as a tensional axis.

Of the nine Azorean islands, all but possibly Santa Maria have experienced Quaternary basaltic or silicic volcanism. Five of the islands (San Miguel, Terceira, San Jorge, Pico, and Fayal) have erupted since the islands were first settled in the 1400's (Machado, 1967). All of the islands except Santa Maria and Corvo have thermal springs and/or fumaroles.

Historic activity is summarized in table 8, compiled primarily from Machado (1967). Historic eruptions have included basaltic eruptions, primarily from fissure vents, and violently explosive silicic tephra eruptions from vents within major calderas. Because active volcanoes are a primary exploration target, it should be kept in mind that future eruptions, particularly explosive silicic tephra eruptions, pose serious hazards to people and facilities in the vicinity of active volcanoes. These hazards have not been evaluated, nor is the activity of the Azorean volcanoes currently monitored adequately to predict an eruption.

Evaluation of the geothermal resources of the Azores

The following features found in the Azores indicate possible geothermal resources:

(1) Thermal springs or fumaroles: Direct evidence of the existence of hydrothermal fluids.

(2) Young (less than 100,000 years old) silicic eruption deposits, either pyroclatic deposits associated with calderas or silicic flows and domes within or outside of a caldera: Silicic magmas are believed to form shallow magma chambers likely to be associated with active hydrothermal systems. Calderas and silicic domes may be surface expressions of these shallow magma chambers. Caldera structures may control hydrothermal circulation (for example, Yellowstone Caldera, Wyoming, USA; Eaton and others, 1975).

(3) Active central volcanoes, for example, Pico: Vents having a long history of eruptive activity may indicate an underlying magma chamber and hydrothermal system.

(4) Active fissure vent systems: Periodic emplacement of basaltic magma along fissures may produce a sheetlike local heat source rather than shallow magma chambers.

In general, regions of basaltic deposits are considered to have less geothermal potential, because basalts, owing to their low viscosity, ascend rapidly from great depth to the surface and do not form shallow magma chambers. Many Azorean basalts contain ultramafic nodules, believed to have been incor-

Table 8. Historic activity of volcanoes in the Azores. [Information compiled primarily from Machado (1967)]

Volcano	Historic eruptions and type	Dominant composition	Structural elements	Fumarolic activity	Comments
Fayal	1672 Basaltic; W flank; 0.36 km^3 1957-58 (Capelinhos)-basaltic; W flank; 0.08 km^3; small explosion in Fayal summit crater-1958	Basaltic w/trachytic cover	Summit caldera (2 km) w/ nestled cinder cone. Rift on W flank	Briefly in caldera after 1958 explosion. Also on cooling deposits of Capelinhos at least through 1967	E side of island cut by WNW-ESE-trending graben faults
Pico	1562 E flank 1718 Linear fissure NW flank & separate SE flank 1720 SE flank 1963 Submarine eruption of NW flank?	Basalts (little or no differentiates)	Summit crater (0.5 km) on stratocone; nestled cone within. Adventive cones along radial fissures	60°C fumaroles in summit region	Lack of trachyte is unusual
San Jorge	1580 Fissure eruptions (fissures parallel to elongation of island). Both produced 1808 small "glowing clouds". 2 widely separated parallel fissures were active in 1806 eruption 1964 Submarine	Basalts + minor andesites, rare trachytes on eastern part of island	Linear fissure vents, parallel to WNW-ESE trend	None at present	Eruptive activity has migrated from E to W
Submarine volcano SW of Terceira	1800 1902	?	Aligned w/San Jorge fissures, perhaps en echelon	?	
Graciosa	None	Trachytic older cone; also basalts-trachytes	Old central volcano w/ apical graben (NW-SE). Younger caldera (1.5 km x 0.8 km) SE end of island NW plain-young basalts	95°C fumaroles in cave in summit crater	Seismic attenuation(?) studies suggest existence of active chamber
Santa Barbara (Terceira)	1761 Basalt; multiple vents; E flank 1867 Submarine eruptions along WNW-ESE trending fissure W of caldera	Older lavas "andesitic" & trachytic; young pumice trachytic + cinder cones and young basalt flows	Summit caldera (complex) w/adventive lava domes and cinder cones	None reported	
Guilherme Moniz (Terceira)	None	Dominantly trachytic w/younger basalts	Complex caldera (3 km) w/a large dome on north rim	Active solfatara NE of crater area	Caldera is unusual in that it doesn't appear to have formed through a silicic tephra eruption & collapse
Submarine (Don João de Castro Bank)	1720 Eruption preceded by 2 months of felt earthquakes	?	Cone is ~ 1500 m above seafloor, reaching to within 15 m of sealevel	?	
Sete Cidades (San Miguel)	1444? Major pumice eruption, possibly related to caldera lake formation. Possibly lava flow extrusion also	Older cone, olivine andesites, alkaline trachyties. Younger lavas, basalts & trachytic pyroclasts	Summit caldera (5 km) smaller craters follow ring fracture zone within caldera. Rows of cinder cones trend WNW-ESE on SE slope	None reported but may exist below lake	
Submarine (adventive to Sete Cidades)	1638 1682 Generated pumice 1811 Poss. 1713	?	Vents are aligned NW-SE, nearly parallel to regional trend	?	
Agua de Pau (San Miguel)	1563 Major pumice eruption, prob. accompanied by caldera collapse; followed by lava emission from adventive vent on NW flank 1564 1652 Basic, effusive	Trachytic pumices, w/ syenitic inclusions. Andesite & basaltic flows in old cone and young adventive cones	Caldera (3 km)	Activity in summit caldera occurred for a few years after 1563 eruption. Active fumaroles are also present on N flank	Site of geothermal drilling (N flank) yielding >200°C waters. Large prehistoric eruption (Fogo A) 4600 yrs. b.p. erupted 0.6-0.7 km^3 magma
Furnas (San Miguel)	1630 Pumice eruption	Older lavas-"andesites" and basalts, some trachytes. Younger-trachytes and andesites	Caldera (6 km), immediately adjacent to older "extinct" caldera of Povoacão volcano (also 6 km)	Major solfatara inside caldera, especially on east side, also south side to the coast. T_{max} = 100°C	No young basalts are known on the volcano
Submarine (Monaco Bank)	1907 1911	?	2 separate vents?	?	

porated while the magma was in the mantle. These nodules indicate rapid ascent from the mantle and are inconsistent with residence in shallow magma chambers. On some volcanic islands, such as Hawaii, shallow basaltic chambers do exist, generally producing large subsidence calderas. Such calderas have not been recognized in the Azores.

The features described above that indicate possible geothermal resources in the Azores are evaluated in more detail below.

(1) Fumaroles and hot springs occur in the Azores within calderas or the vents of active central volcanoes (that is, Pico Volcano), on the flanks of active volcanoes (for example, the Ribeira Grande area on the flank of Agua de Pau), and along the seashore. The resources associated with thermal areas within calderas and craters can be estimated on the basis of this association. The methods for evaluating these resources are discussed below. Thermal springs on the flanks of cones, unless associated with silicic domes or flows, generally provide little indication of the volume of their associated hydrothermal reservoirs. Some, such as those at Ribeira Grande (San Miguel) may be the result of flow of hot fluids laterally from a heat source not located directly below the thermal area. To assume that the hydrothermal reservoir for such springs extends to 3 km depth may be in error. (See discussion of Ribeira Grande, below). Thermal springs emitted at sea level are not considered as resources. These are produced by lateral flow of thermal waters at the top of the saltwater lens beneath the island. The source of the heated water is difficult to evaluate, and because of mixing of thermal and marine waters, reservoir temperatures cannot be reliably predicted.

(2) The volume of potential hydrothermal reservoirs associated with silicic magmas is evaluated in the following manner: (A) For calderas, the subsurface area of the reservoir is assumed to be equivalent to the surface dimension of the structural wall of the caldera, which is at the base of the steep caldera wall. The top of the reservoir is assumed to be 2 km deep if there are no thermal manifestations within the caldera or on the upper flanks of the volcano. If a caldera has an extensive history of post-collapse intracaldera silicic dome eruptions or thermal manifestations, the depth to the top of the reservoir is assumed to be 1.5 km. If numerous intracaldera silicic domes as well as thermal manifestations are present, the the depth is assumed to be 1 km. Where thermal manifestations are extensive within such a caldera, the depth is assumed to be 500 m. (B) For clusters of silicic domes or flows, the subsurface area of the reservoir is assumed to correspond to the surface area encompassing all eruptive vents. The top of the reservoir is assumed to be 2 km deep if there are no nearby manifestations, or 1.5 km if they are nearby. Individual silicic domes or flows are not considered as resources.

(3) The only active major central volcano in the Azores is Pico. It appears to be dominantly or exclusively basaltic, and hence may not be associated with a shallow magma chamber. I assume, in the absence of indications otherwise, that the volume of Pico's reservoir is the standard value of 3.3 km^3 (Brook and others, 1979). This should be considered a speculative resource estimate.

(4) The geothermal resource potential of basaltic fissure systems has been derived by calculating the volume of rock heated by basaltic dikes of specified thickness (2 m) and initial temperature (1,200° C), assuming conductive cooling only and magma resupply at the same site every 200 years. Conductive cooling calaculations were performed following Jaeger (1968), equation 9, using a constant thermal diffusivity coefficient of 0.01 cm^2/sec. The heat added by crystallization of the magma and the heat lost by vaporization of water in the country rock were not considered. I assumed that the dike is emplaced into a region having an initial geothermal gradient of 33° C/km. The calculations thus yield first approximations to the spatial migration of isotherms through the country rock with time.

The volume of the hot reservoir depends significantly upon the choice of dike thickness; the rate of magma resupply; the length of time that eruptions have been recurring at the assumed rate; and the length of the fissure system.

The dike thickness chosen (2 m) was the average of three measured dikes in the walls and on the flank of Caldeira on Fayal. Any change in the actual dimension of the dike will change the distance of a given isotherm from the center of the fissure by a factor of half the thickness of the dike of meters.

Only for San Miguel is the geological history known sufficiently to evaluate the rate of eruption for the basaltic fissure system active during the past 5,000 years. Here, according to studies of Booth, Croasdale, and Walker (1978), at least 30 eruptions have taken place in 4,500 years within the central "waist" area, of which 20 were on the same fissure or an en echelon branch of the same fissure. This history indicates an average basaltic eruption frequency of once every 150 years for the entire central region and once every 230 years for the main fissure. For the calculations, I have assumed an average resupply rate of every 200 years. Figure 5 illustrates how the temperature at a given distance from the center of the dike will vary with time as resupply rate changes.

To estimate the length of time that fissure systems on other islands have been active, I have assumed that: (A) the frequency of eruptions is everywhere the same as that at the fissure system on San Miguel; and (B) the length of time that a fissure has been active is proportional to the spatial density of vents along that fissure. The lifetime of any fissure can then be estimated by comparison to San Miguel, where 76 vents were formed along 17.9 km of fissure during a 4,500-year period.

The lengths of fissure systems can be determined readily from published maps. Offshore extensions of fissures are not considered. Evidence for the lateral continuity of point vents on fissures is provided by the 1957-58 eruption of Capelinhos volcano, at the northwest end of an 8.3-km-long fissure system on Fayal. Each of the two main vents at Capelinhos formed along the main west-northwest fissure trend, but only a few hundred meters apart (Forjaz and Weston, 1967). In May 1958, when eruption volume increased significantly at the Capelinhos vent, steam explosions took

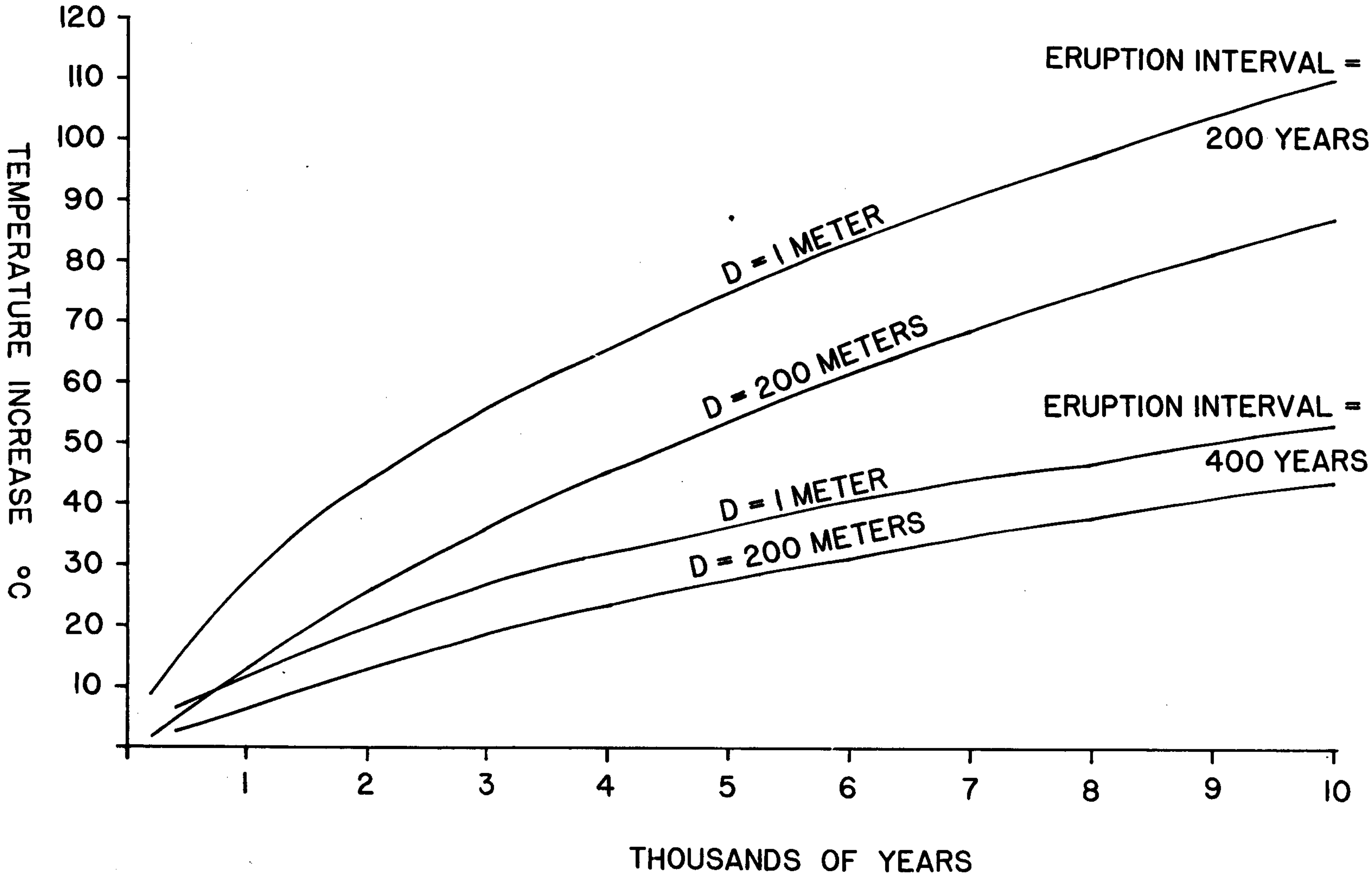

Figure 5. Temperatures in the country rock 1- and 200-m from the center of a periodically replenished basalt dike (with initial temperature = 1200°C and width = 2m) as a function of time for resupply intervals of 200 and 400 years.

place on the floor of the caldera 11 km east-southeast along the trend of the same fissure. Fumaroles remained active at the site of these explosions for several months, terminating the day that the Capelinhos eruption ceased (Machado and others, 1962).

San Miguel

Exploration for geothermal resources has started on San Miguel, the largest and most populated Azorean island. Exploration has been mainly in the Ribeira Grande region, on the north flank of the Agua de Pau volcano. This exploration program is discussed in detail below. At the time of my investigation, November 1979, drilling of the third deep hole (PV-1) was in progress, but the ability of the field to produce had not yet been proven.

Geothermal potential on San Miguel is excellent and is associated with three silicic calderas (Sete Cidades, Fogo on Agua de Pau Volcano, and Furnas) and with basaltic fissure systems in the central "waist" of the island (fig. 6). Povoacao Caldera, east of Furnas, appears to be much older than the three other calderas and lacks thermal manifestations (Machado, 1967). I assume that high temperatures are at too great a depth beneath Povoacao to be a viable resource. Furnas and Sete Cidades have experienced numerous silicic eruptions since their major caldera-forming eruptions, as indicated by silicic domes within each. Fogo Caldera, in contrast, may have formed only 4,500 years ago in a major tephra and pyroclastic flow eruption (Walker and Croasdale, 1971) and has only a single intracaldera silicic dome.

Thermal manifestations occur on the north flank of Agua de Pau in the Ribeira Grande region (discussed below), within Furnas Caldera, south of Furnas Caldera in the vicinity of Ribeira Quente, and at sea level along the west coast of the island on the flank of Sete Cidades.

Fumaroles and hot springs are emitted over a 1.8-km^2 area on the floor of Furnas Caldera. Temperatures of these spectacular springs, fumaroles, and boiling pots are as high as 100° C and are the basis for a locally important tourism industry in Furnas. This use may be incompatible with extensive geothermal exploitation within the caldera, as experience in New Zealand has shown that natural geysers and hot springs may cease to exist when geothermal fluids are extracted (Axtmann, 1975).

Chemical geothermometry for the Furnas area is unreliable. In particular, Mg corrections to the Na-Ca-K geothermometer are large (many greater than 100° C), and waters are generally saturated with amorphous silica, casting doubt upon temperatures predicted by the silica geothermometer. I have assumed, for resource assessment, that the reservoir temperature is 200° C. This temperature will be used to assess all possible resource areas in the Azores for which another temperature is not indicated by available data.

Chemical and temperature data for thermal springs near Sete Cidades Caldera along the west coast of the island are unavailable.

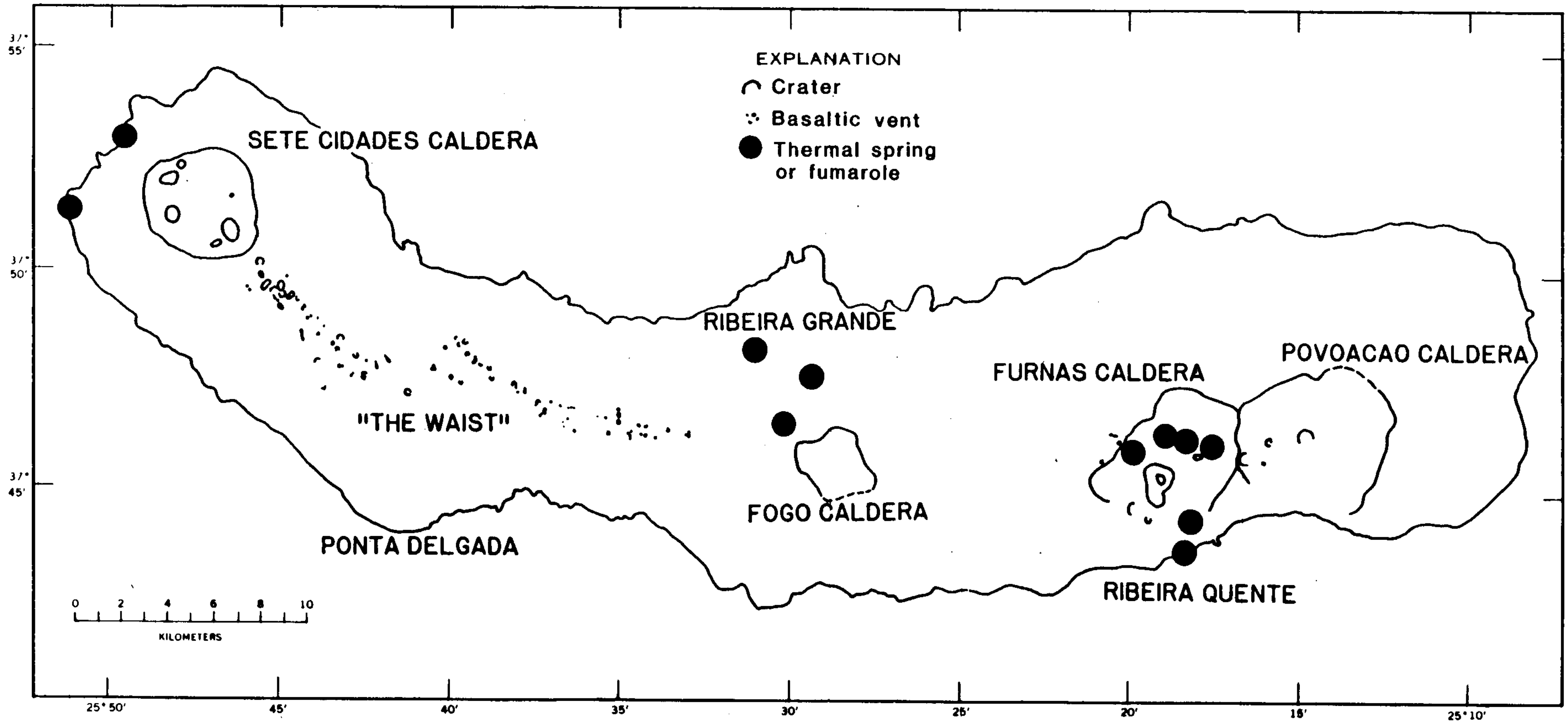

Figure 6. Map of the island of San Miguel, showing the four major silicic calderas and geologically recently active vents within them, basaltic vents in "the waist" area of the island, and thermal springs and fumaroles (large dots). Compiled from information in Zbyszewski and others, 1958.

Although thermal springs and fumaroles of the Ribeira Quente region are considered in table 9 to be separate from those of Furnas Caldera, the structure of this area is poorly known, and the two areas may have a common heat source and continuity at depth. Reservoir volume is poorly defined, especially because the heat source may be upslope from the area of thermal manifestations. The hot aquifer may be confined to a particular permeable horizon in which fluids flow laterally, and rocks above and below may be cooler. The assumption that the reservoir extends to a depth of 3 km may yield overestimates of the reservoir volume. This problem is discussed below in connection with the Ribeira Grande field.

Like data on other thermal areas on San Miguel, analytical data for the Ribeira Quente springs are inadequate to permit estimating the subsurface reservoir temperature.

Current Exploration at Ribeira Grande

Financial interest in geothermal energy began on San Miguel in 1973, when Dalhousie University (Canada), in the process of drilling a deep hole for petrological research on the north side of Agua de Pau, found hot water. Subsequent accounts of this hole have lost sight of the fact that the initial intent was to study the petrologic evolution of an oceanic island through deep drilling. Geothermal manifestations were not sought or desired (as they might be accompanied by hydrothermal alteration), and ultimately they led to premature termination of the drilling by a blowout (the violent and sometimes dangerous eruption of stream from the drill hole).

The following results of the Dalhousie drill hole are important to geothermal energy exploration on San Miguel:

(1) The hole found hot water (hotter than 200° C, possibly as hot as 252° C).

(2) The hot water apparently flowed from an aquifer at a depth of approximately 550 m. This conclusion was suggested by temperature logging and was corroborated by subsequent isotope geothermometer studies of calcite in the recovered core (discussed below). Core recovery in the 981 m hole was greater than 95 percent.

(3) The aquifer appears to be pyroclastic deposits confined between impermeable lava flows.

(4) Within the upper 550 m, the temperature increased rapidly but irregularly as the drill penetrated more and less permeable horizons. Below the most profilic aquifer (at 550 m), temperatures increased slowly, less than 10° C/km. Muecke and others (1974) concluded that the volcanic heat source is not directly beneath the drill site. Instead, the heat is probably transferred laterally by flow of the hot water downhill through the aquifer at depths of 550 to 650 m.

Table 9. Estimates of geothermal resources in the Azores.

NAME OF AREA, COMMENTS	RESERVOIR VOLUME (km^3)	RESERVOIR TEMPERATURE (^oC)	RESERVOIR THERMAL ENERGY ($10^{18}J$)	WELLHEAD THERMAL ENERGY ($10^{18}J$)	WELLHEAD AVAILABLE WORK ($10^{18}J$)	ELECTRICAL ENERGY (MW_e for 30 years)	TYPICAL U.S. DRILLING COSTS (1978 dollars/meter)
SAN MIGUEL							
*Sete Cidades Caldera; Many intracaldera silicic domes and cones. Depth assumed to be 1.5 km to top of reservoir.	18.9	200	9.44	2.36	0.53	226.	490
Carvao--Queimado fissure system (2 gaps); Active 4500 years. Minimum depth to 150° isotherm=2.4 km	2.1	157	0.81	0.20	0.037	15.6	680
*Fogo Caldera (Agua de Pau Volcano); One intracaldera silicic dome. Depth assumed to be 1.5 km to top of reservoir.	4.5	200	2.25	0.56	0.13	53.8	490
*Ribeira Grande (Best estimate, see text). Assumes reservoir covers 8 km^2 and is 700 m deep and 150 m thick.	1.2	200	0.60	0.15	0.034	14.3	320
*Furnas Caldera; Many intracaldera domes and extensive hydrothermal activity. Top of reservoir assumed to be at 500 m depth under area of fumaroles (4×10^6 m^2), 1 km over remaining area.	33.6	200	16.8	4.20	0.95	401.	280-390
*Ribeira Quente; Hydrothermal area. Depth assumed to be 1.5 km to top of reservoir.	3.0	200	1.50	0.38	0.085	35.8	490
Total for San Miguel				7.85		746.5	
TERCEIRA							
Caldeira de Santa Barbara; Contains several intra-caldera silicic domes and many more on flanks. Depth assumed to be 1.5 km to top of reservoir.	3.0	200	1.51	0.38	0.085	36.0	490
Silicic vents, NW flank of Santa Barbara. Top of reservoir assumed to be at 1.5 km depth.	7.5	200	3.75	0.94	0.21	89.6	490

(*) Indicates systems having hydrothermal manifestations at the surface.

Table 9. Estimates of geothermal resources in the Azores--continued

NAME OF AREA, COMMENTS	RESERVOIR VOLUME (km^3)	RESERVOIR TEMPERATURE (^oC)	RESERVOIR THERMAL ENERGY ($10^{18}J$)	WELLHEAD THERMAL ENERGY ($10^{18}J$)	WELLHEAD AVAILABLE WORK ($10^{18}J$)	ELECTRICAL ENERGY (MW_e for 30 years)	TYPICAL U.S. DRILLING COSTS (1978 dollars/meter)
TERCEIRA (continued)							
Silicic vents, E flank of Santa Barbara. Top of reservoir assumed to be at 1.5 km depth.	6.0	200	3.00	0.75	0.17	71.7	490
* Pico Alto; Silicic vents filling older silicic caldera? Fumarole area near margin. Depth to top of reservoir assumed to be 1.5 km.	29.4	200	14.7	3.67	0.83	351	490
* Caldeira de Guilherme Moniz; Fumarole area outside margin. Lacks intracaldera silicic domes. Depth assumed to be 1.5 km to top of reservoir.	10.5	200	5.24	1.31	0.30	125	490
Caldeira de Cinco Picos; Older caldera without thermal areas or intracaldera domes. Depth to top of reservoir assumed to be 2.0 km.	13.1	200	6.53	1.63	0.37	156	590
Total for Terceira				8.67		829.3	
FAYAL							
Caldeira; No thermal areas. Intermediate lavas within caldera. Depth assumed to be 1.5 km to top of reservoir.	1.2	200	0.59	0.15	0.033	14.1	490
Capelinhos--Cabeco dos Trinta fissure system; Assumed to be active 4500 years. Minimum depth to 150^o isotherm=2.4 km.	0.9	157	0.35	0.09	0.016	6.8	680
Total for Fayal				0.24		20.9	
SAN JORGE							
Pico Maria Isabel--Pico da Calheta fissure system; Assumed to be active 6000 years. Minimum depth to 150^o isotherm=2.0 km.	4.4	161	1.75	0.44	0.082	34.6	594

(*) Indicates systems having hydrothermal manifestations at the surface.

Table 9. Estimates of geothermal resources in the Azores--continued

NAME OF AREA, COMMENTS	RESERVOIR VOLUME (km^3)	RESERVOIR TEMPERATURE (^oC)	RESERVOIR THERMAL ENERGY ($10^{18}J$)	WELLHEAD THERMAL ENERGY ($10^{18}J$)	WELLHEAD AVAILABLE WORK ($10^{18}J$)	ELECTRICAL ENERGY (MW_e for 30 years)	TYPICAL U.S. DRILLING COSTS (1978 dollars/meter)
PICO							
*Pico Volcano; Fumaroles present in summit crater. Assume standard volume with top of reservoir 1.5 km below sealevel (2.5 km below surface).	3.3	200	1.66	0.42	0.094	39.8	700
Cabeco do Piquinho--Cabeco dos Trinta fissure system; Assumed to be active 4300 years. Minimum depth to 150° isotherm=2.5 km	2.5	156	0.94	0.24	0.043	18.2	700
Total for Pico				0.65		58.0	
GRACIOSA							
*Caldeira; Fumaroles and basic cones within caldera. Depth assumed to be 1.5 km to top of reservoir.	0.6	200	0.28	0.07	0.016	6.7	490
FLORES							
Pico do Sete Pes; Buried silicic caldera? Depth assumed to be 2 km to top of reservoir.	14.1	200	7.04	1.76	0.40	168	590
Pico da Se; Silicic dome complex. Depth assumed to be 2.0 km to top of reservoir.	4.8	200	2.40	0.60	0.14	57.3	590
*Ribeira da Cruz; Silicic dome complex with thermal spring. Top of reservoir assumed to be at 1.5 km depth.	3.3	200	1.65	0.41	0.093	39.4	490
Total for Flores				2.77		264.7	
CORVO							
Caldeirao; Summit caldera, lacks intracaldera domes or thermal areas. Depth assumed to be 2.0 km to top of reservoir.	1.1	200	0.57	0.14	0.032	13.5	590

(*) Indicates systems having hydrothermal manifestations at the surface.

Table 9. Estimates of geothermal resources in the Azores--continued

NAME OF AREA, COMMENTS	RESERVOIR VOLUME (km^3)	RESERVOIR TEMPERATURE (^oC)	RESERVOIR THERMAL ENERGY ($10^{18}J$)	WELLHEAD THERMAL ENERGY ($10^{18}J$)	WELLHEAD AVAILABLE WORK ($10^{18}J$)	ELECTRICAL ENERGY (MW_e for 30 years)	TYPICAL U.S. DRILLING COSTS (1978 dollars/meter)
TOTAL FOR AZORES (22 Identified Possible Geothermal Resource Areas)			83.36	20.83	4.68	1974.2	
San Miguel				7.85		746.5 (37.8%)	
Terceira				8.67		829.3 (42.0%)	
Fayal				0.24		20.9 (1.1%)	
San Jorge				0.44		34.6 (1.8%)	
Pico				0.65		58.0 (2.9%)	
Graciosa				0.07		6.7 (0.3%)	
Flores				2.77		264.7 (13.4%)	
Corvo				0.14		13.5 (0.7%)	

In 1976, the Regional Government of the Azores awarded a $1.4 million contract to GEONOMICS, a California firm, to organize a geothermal exploration program at Agua de Pau and to perform a battery of geochemical and geophysical studies. GEONOMICS held responsibility for planning and guiding the geothermal program through the completion of four deep exploratory drill holes.

GEONOMICS provided the following data: (1) Electrical resistivity maps 1/ and soundings of the Agua de Pau region; (2) A seismic noise (microseismic) survey; (3) A geochemical survey of thermal and nonthermal waters, primarily from Agua de Pau and Furnas; and (4) A shallow temperature survey. In addition, they provided reports on environmental and socio-economic impacts of geothermal development.

This work produced mixed results: (1) The electrical resistivity study disclosed four anomalously low resistivity regions, one of which (Area A, fig. 7) enclosed the Dalhousie drill hole. Area B, near Logoa, west of Fogo Caldera, is on the edge of the study area and was not completely defined. Areas C, near Villa Franca do Campo (southeast of the caldera) and D, northeast of the caldera, are near the shoreline, where intrusion of seawater into the ground water could produce the observed slight anomalies. GEONOMICS therefore cited areas A and B as exploration targets.

(2) GEONOMICS performed a seismic noise survey in the study area, using an eight-station array. The seismic noise was, however, overwhelmed by noise from the nearby seashore.

(3) GEONOMICS subcontracted the hydrochemical investigation to GEOTHERM-EX, Inc. Analyses of water and gas collected by GEOTHERM-EX were performed by LFE Environmental Analysis Laboratories, Richmond, California. GEOTHERM-EX concluded from their work that chemical geothermometry of springs and fumaroles on Agua de Pau is not reliable. The hottest springs and fumaroles emit acid sulphate waters, which, owing to their reactivity, generally do not reflect equilibrium conditions in the thermal reservoir. Local cold waters also have high concentrations of SiO_2 (65 to 130 mg/l) which implies that amorphous silica is dissolving readily from volcanic ash and casts suspicion on SiO_2-geothermometers. The best estimate of subsurface water temperature at Agua de Pau was obtained by applying mixing calculations to 38° C spring water at Caldeira Velha.

1/ GEONOMICS, INC., 1977, Agua de Pau Massif geothermal project, San Miguel, Azores, Portugal (in three parts: Electrical resistivity survey, Hydrochemical survey, Temperature gradient survey) On file at Azores Institute of Geosciences.

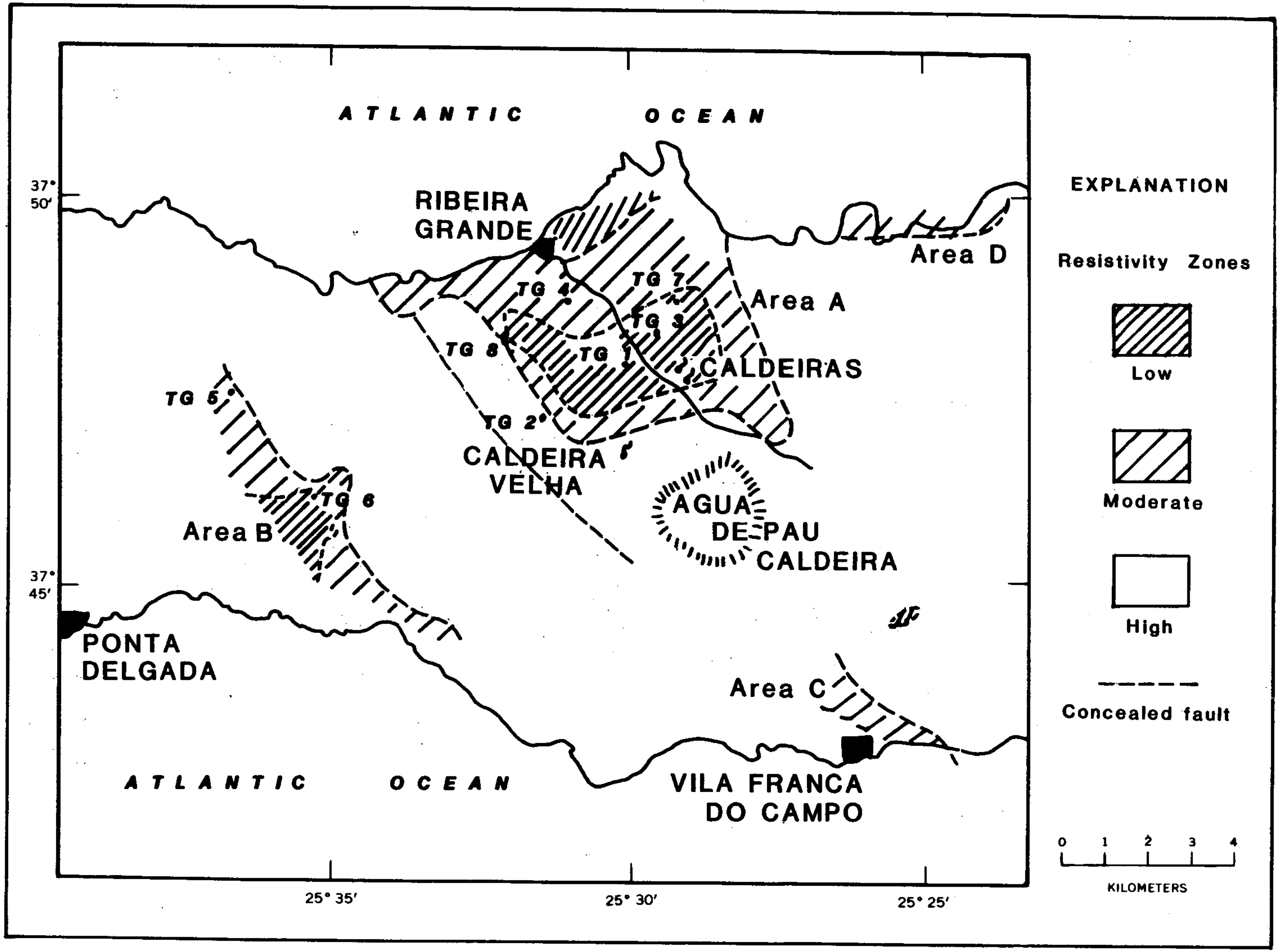

Figure 7. Sketch map of the Ribeira Grande region on the north flank of Agua-de-Pau volcano, from Aires-Barros (1979). The Agua-de-Pau Caldeira is also called the Fogo Caldera. Shown are low-resistivity regions identified by GEONOMICS (1977) and the sites of shallow temperature-gradient holes (TG 1-8). TG-4 is the site of the Dalhousie drill hole. RG-1 was drilled within the lowest resistivity zone near TG-3; RG-2 was drilled outside the zone near TG-7.

This yielded a rough and unreliable estimate of 200° C.

(4) Before the conclusion of the GEONOMICS involvement, five shallow temperature-gradient holes were drilled, and one more was planned. Subsequently, the LGT drilled one more, which suffered a blowout. In each hole, a low gradient was measured in the upper 100-150 m (due apparently to influx of meteoric water), and a higher gradient was found to the hole bottom (150-220 lcm). Holes drilled within the region of very low electrical resistivity of Area A showed higher maximum gradients (0.92° C/m and 0.81° C/m) than that of the hole drilled outside it (0.44° C/m). GEONOMICS concluded that:

(a) Measured gradients within the main anomaly suggest the possibility of a geothermal reservoir at a depth of approximately 0.5 km.

(b) Temperatures within the reservoir may be 200°-250° C.

(c) If this gradient exists over the area of the anomaly, the existence of sufficient permeability in production holes will be the decisive factor regarding the economic attractiveness of each deep drill hole.

Before deep drilling began, GEONOMICS filed for bankruptcy, and their participation in the San Miguel project ended. The following decisions were then made: (1) the LGT would take over the scientific direction of the program; (2) a French firm, EURAFREP, would provide technical assistance with drilling (not with site selection or interpretation); and (3) a Portuguese firm, ACAVACO, would do the drilling. Deep drilling then began; some drilling results are described below.

Hole RG-1.--RG-1, the first deep hole, was drilled June to August 1978. It was located within resistivity anomaly A and reached a depth of 1,229 m; the maximum temperature was approximately 250° C at 500-650 m depth. The hole initially produced 90,000 kg of fluid per hour, consisting of about 20 percent steam.

Unfortunately, fluid production began to decrease soon after drilling was completed. By October 1978, production had ceased entirely. This discouraging cessation of fluid production indicated one of the following conditions downhole: (1) The accessible reservoir is small and the steam had entirely escaped or (2) The hole had become clogged, possibly by precipitation of minerals from the thermal solutions. The second problem, known as scaling, can preclude development of an otherwise attractive reservoir.

In August 1979, RG-1 was mechanically cleaned after discovery that the hole was plugged at 326 m. Steam flow then resumed, though at a lower rate than that achieved immediately after drilling. The hole has been closed since cleaning to await further testing.

An important additional result of RG-1 is the temperature profile obtained. Temperatures increased to 230° C at 420 m and 248° C at 645 m, and then decreased to 213° C at the bottom of the hole. This temperature profile is consistent with the existence of a hot-water aquifer at 550-650 m depth, enclosed within colder, less permeable horizons.

Hole RG-2.--Hole RG-2 is about 400 m from RG-1 and is about 350 m outside the boundary of the low-resistivity zone identified by GEONOMICS. It is near the site of TG-7, a shallow temperature-gradient hole that had suffered a blowout during drilling.

RG-2 was a nearly dry hole. It reached a maximum temperature of about 220° C at approximately 600 m depth but never produced significant fluid flow, probably because temperatures dropped significantly during a long cooling period when a "fishing job" was performed on the well. Temperature recovery has not yet been sufficient to estimate production capacity (H. A. Correia, written commun., 1980).

Phase 2 of the drilling program.--Following the results of RG-1 and RG-2, General Electro-Magnetic Prospecting (GEMP) of Santa Rosa, California, was hired to perform magnetotelluric prospecting within the Ribeira Grande region. Their results, obtained during March to May, 1979, indicated the presence of several conductive regions within and outside the region of low resistivity defined by GEONOMICS. These regions are now considered the primary drilling targets.

Hole PV-1.--The site for the drill-hole PV-1 is approximately 100 m south of the Pico Vermelho cinder cone, well inside the zone of low resistivity identified by GEONOMICS and on a conductive zone identified by GEMP. Furthermore, it is only 10-20 m from an apparently major fault, which displaces the flank of Pico Vermelho, and along which the thermal springs at Caldeira Velho are emitted. The Dalhousie drill hole is near the extension of the same fault. Steam reportedly was emitted near the site of PV-1 20 to 30 years ago, but there is no longer any thermal activity.

Drilling began at PV-1 September 1979. Problems with gas production have delayed progress, so that at the time of my visit the hole had reached only 349 m, where a temperature of 216° C was found. Later reports (H. A. Correia, written commun., 1980) indicate that production capacity from the well will justify the installation of a 3MW geothermal power plant. Possibly, adequate permeability and porosity exists in the vicinity of the major fault along which PV-1 is located.

Regardless of the success or failure of PV-1, the LGT has contracted to drill a fourth hole. Present plans are to drill at a site west of the previous holes near Santa Barbara. This site (SB-1) was chosen on a magnetotelluric anomaly confirmed by dipole-dipole and is located within the broad resistivity low defined by GEONOMICS.

Assessment of the potential of the Riberia Grande field

GEONOMICS proposed that the Ribeira Grande field had a 200-400-MW_e generation capacity. The uncertainty in their estimate resulted from uncertainty in the reservoir temperature (200° or 250° C). Although the methods GEONOMICS followed in arriving at this estimate were not detailed in their reports (see footnote, p. 37), they apparently resemble those used by Brook and others (1979) and in this assessment.

GEONOMICS apparently assumed that the thermal reservoir beneath Ribeira Grande was delimited by the areas of the major electrical-resistivity low (8 km^2), and extended from a depth of 350 m (suggested by linear extrapolation of heat-flow gradients measured in shallow drill holes less than 220 m deep) to the cutoff depth of 3 km. Several lines of evidence suggest another model for the vertical dimensions of the reservoir, yielding a much smaller volume:

(1) Temperatures in RG-1 and RG-2 passed through maxima in the 550 to 650-m depth range. Temperatures in the Dalhousie hole increased rapidly to this depth, and then remained nearly constant at greater depth.

(2) In the Dalhousie hole, fluid flow was greatest at about 550 m depth, coinciding with the bottom of the steep thermal gradient. Abrupt temperature discontinuities within the hole suggest that little vertical mixing takes place between waters in different porous horizons separated by impermeable basalt flows (Muecke and others, 1974).

(3) Lawrence and Maxwell (1978) found that calcite in veins and vugs of the core recovered from the Dalhousie hole had equilibrated with hot waters only at 600-700 m depth.

(4) No geophysical or geological evidence, such as intermediate to silicic domes or flows, suggests that a shallow magmatic heat source is present beneath the Ribeira Grande region.

These four lines of evidence are consistent with the presence of a thin aquifer (100-150 m thick) at a depth of roughly 500-700 m that carries hot water downslope from a heat source near Fogo Caldera. If this hypothesis is correct, then the reservoir volume is roughly 1.2 km^3, rather than 21.2 km^3 as calaulated by assuming continuity from 350 m to 3 km, and the corresponding estimated electrical generation potential is only 10-30 MW_e (for a 30-year period). Whether this potential can ever be realized will depend upon obtaining adequate fluid flow from the reservoir.

Terceira

Geothermal potential of Terceira is excellent, as indicated by the abundance of silicic calderas and trachytic dome complexes. Terceira has three large calderas and possibly a fourth, now covered by silicic lava domes. The largest of these, Cinco Picos (fig. 8) is nearly obliterated by younger deposits, and recent basaltic eruptions have taken place within its interior, suggesting that silicic magma is no longer present beneath the caldera. Thermal resources beneath Cinco Picos are assumed to be deep.

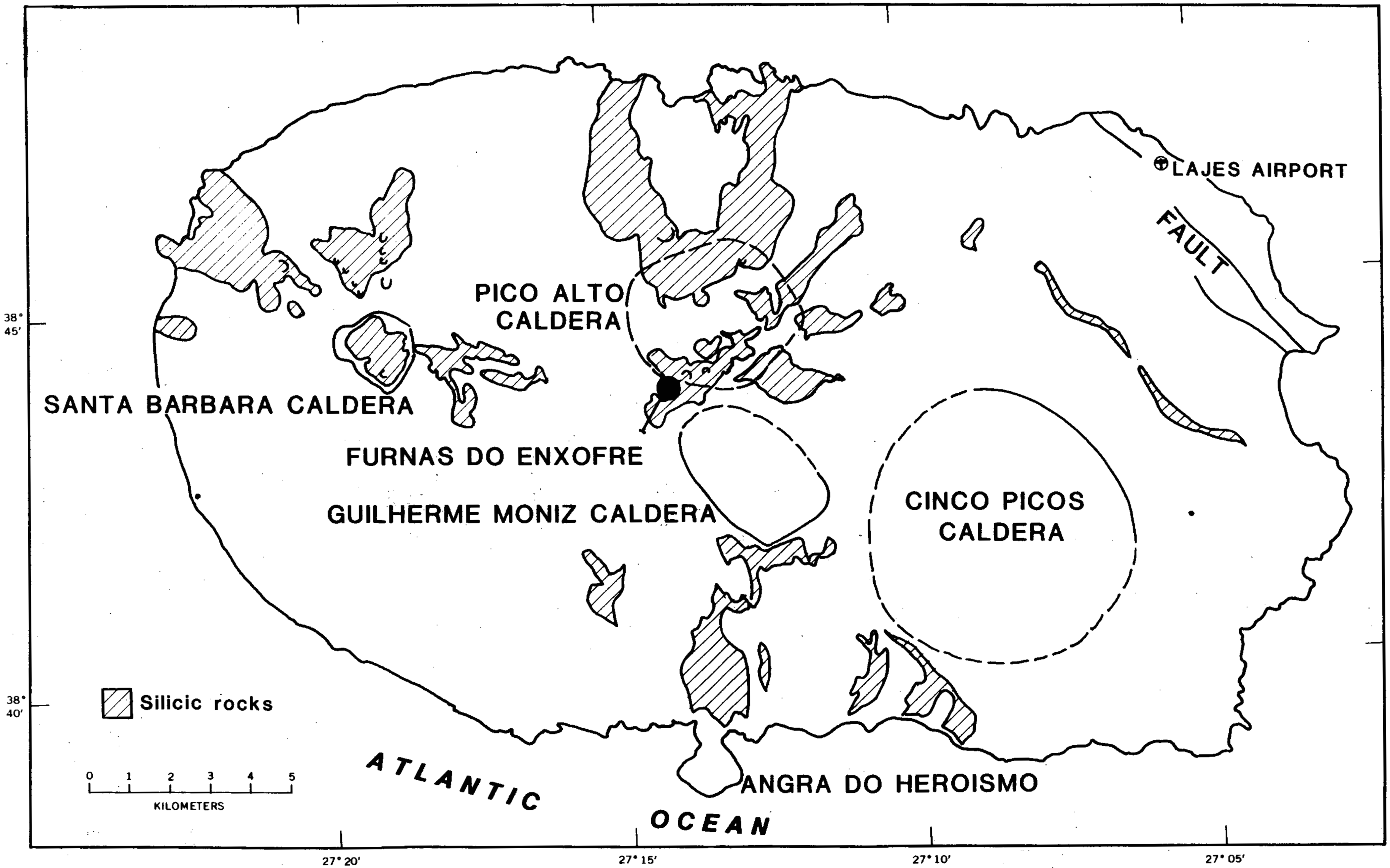

Figure 8. Map of the island of Terceira showing identified and inferred silicic calderas, large silicic flows and domes, major faults near Lajes Airbase, and the fumaroles at Furnas do Enxofre (large dot). Compiled from information provided in Self, 1971, and Zbyszewski and others (1970).

Guilherme Moniz Caldera is also partly obscured. Although the volcano is itself composed dominantly of trachytic lavas, Machado (1967) suggested that the caldera may not have formed by a silicic paroxysmal eruption. Basalt has been erupted through the caldera floor.

Santa Barbara Caldera is young and well defined and has several intracaldera silicic domes and adventive silicic dome and flow clusters.

Silicic domes on the central plateau north of Guilherme Moniz Caldera may fill another caldera. Self (1971) suggested that this caldera, termed Pico Alto, may have been the source of the Lajes Ignimbrite, a silicic ash-flow tuff that blanketed most or all of Terceira roughly 5,000-10,000 years ago.

Fumaroles are emitted over a 20,000 m^2 area at Furnas do Enxofre, near the center of the island. The sulfurous fumaroles, having temperatures as high as 98° C, are near the margin of Guilherme Moniz Caldera and its intersection with the ring of silicic domes that may mark the structural margin of the concealed Pico Alto Caldera. The heat source for these fumaroles may be associated with the substructure of either Pico Alto Caldera or Guilherme Moniz Caldera.

Carbonated thermal springs are emitted in the vicinity of Serreta, near a silicic dome that is adventive to Santa Barbara Caldera. Temperature and compositional data for these springs are not available.

Although thermal manifestations have not been identified in their vicinity, major northwest-trending faults adjacent to Lajes Airport may permit deep circulation of ground water, thus possibly providing hot waters for local direct use. Because it is unlikely that temperatures high enough to permit electrical generation would be found at shallow depth along these faults, I have not included this with the possible resources in table 9. Drilling will be necessary to test whether a hot-water source could be tapped in this vicinity.

San Jorge

San Jorge has been dominated throughout its history by basaltic fissure eruptions. This eruption history is reflected in the elongate shape of the island (fig. 9), which parallels the centrally located, historically active eruptive fissure. Silicic rocks (andesites and trachytes) are rare, but occur at the east and west ends of the island (Forjaz and Fernandes, 1970: Machado, 1967). Mineral springs occur in several places on the island, but whether or not they are warm has not been reported.

The central eruptive fissure extends approximately 27 km, locally splitting into two parallel branches 400 m apart. Along the fissures are 97 small and large vents. As discussed above, I have assumed that the 200-year eruption recurrence interval calculated for the fissures on San Miguel characterizes eruptions on other islands. This suggests,

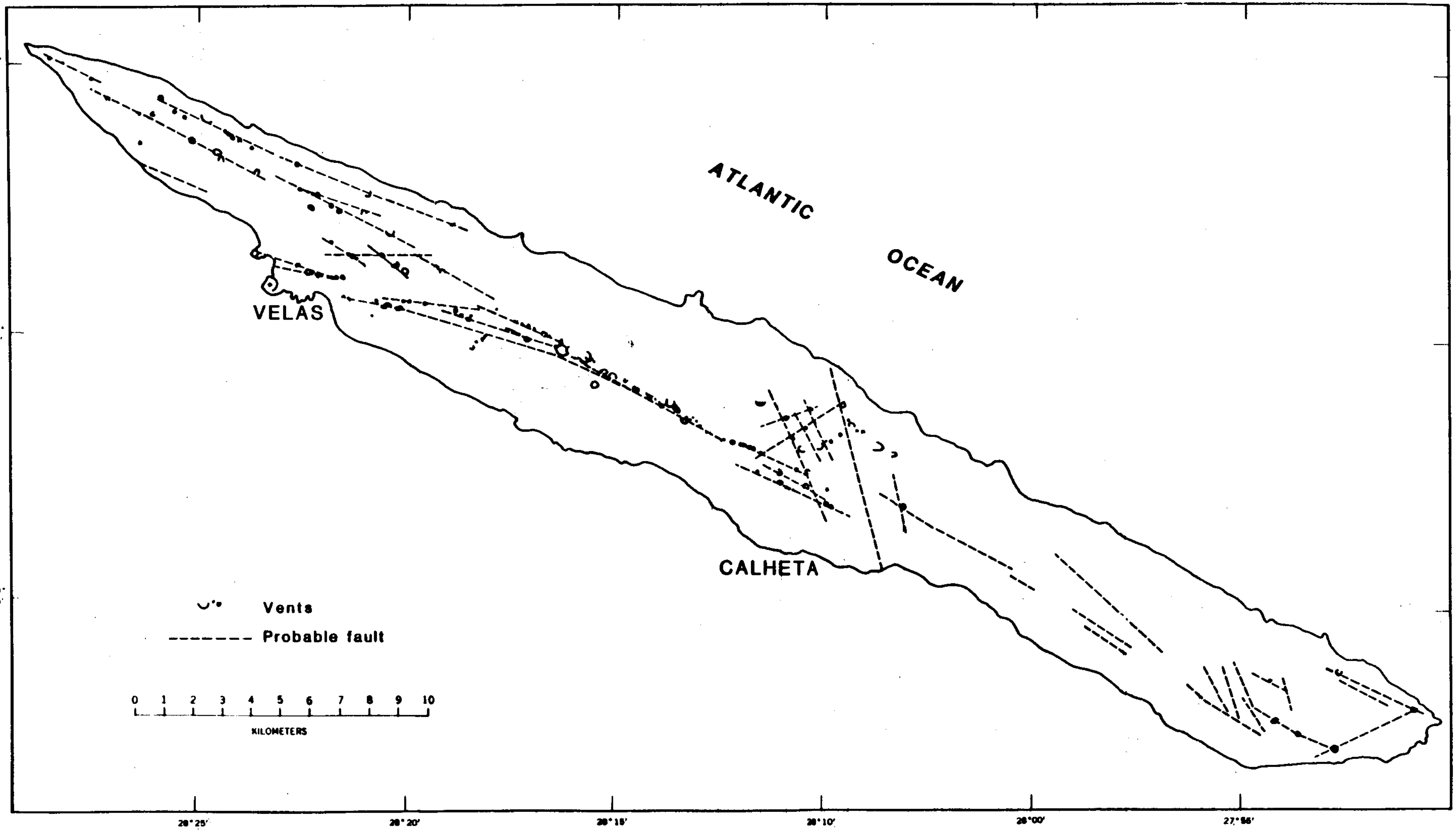

Figure 9. Map of the island of San Jorge, showing basaltic vents identified by Forjaz and Fernandes (1970).

when compared to the spatial density of vents along fissures on San Miguel, a period of roughly 6,000 years of activity for the San Jorge fissure.

Figure 10 shows the distribution of the 150° C isotherm in the country rock surrounding a dike after 6,000 years of conductive cooling, assuming magma resupply every 200 years. This diagram indicates that although temperatures in excess of 150° C can be generated, they will probably be found below 2 km depth. The geothermal potential for San Jorge, therefore, is not as promising as for the islands that have silicic calderas.

Corvos

The smallest and least populated island, Corvo (fig. 11), is dominated by a central caldera, apparently generated by a Quaternary silicic tephra eruption. The island has no known thermal springs or fumaroles, and has not experienced historic eruptions.

In view of the absence of thermal activity on the island, and the lack of post-caldera silicic domes, geothermal heat is unlikely to be present at depths beneath the caldera shallow enough to justify the expense of exploration and development for the small local demand.

Flores

Flores (fig. 12) has not erupted in historic time. However, thermal springs do exist at the southwest tip of the island along the seashore (Agua Quente do Lajedo, temperature greater than 50° C) and at 265 m altitude on the east flank of the island (Nascente do Poio do Moreno, temperature=27.2° C; Zbyszewski and others, 1968). The latter spring is within a cluster of silicic domes, and its geothermal potential will be evaluated as part of that association. The southwest springs, because they are emitted at sea level, are not considered as resources.

Silicic rocks (andesites and trachytes) are abundant and form two separate clusters of vents on the east and northeast flank of the island. Both clusters are considered possible geothermal resource areas. The center of the island is a high plain covered by recent basaltic cinder cones, maars, and craters (fig. 12). The young basaltic cones may have buried an older caldera complex, and the trachytic domes may be adventive to that caldera complex.

Although numerous roughly north-trending dikes are exposed along the north and south coasts of the island, no recent fissure vents likely to have geothermal potential have been found.

Unfortunately, complete analyses of thermal springs are not available, and thus, geothermometry is precluded.

Geothermal potential of Flores appears to be excellent, in particular for the vicinity of the silicic domes on the east flank of the island.

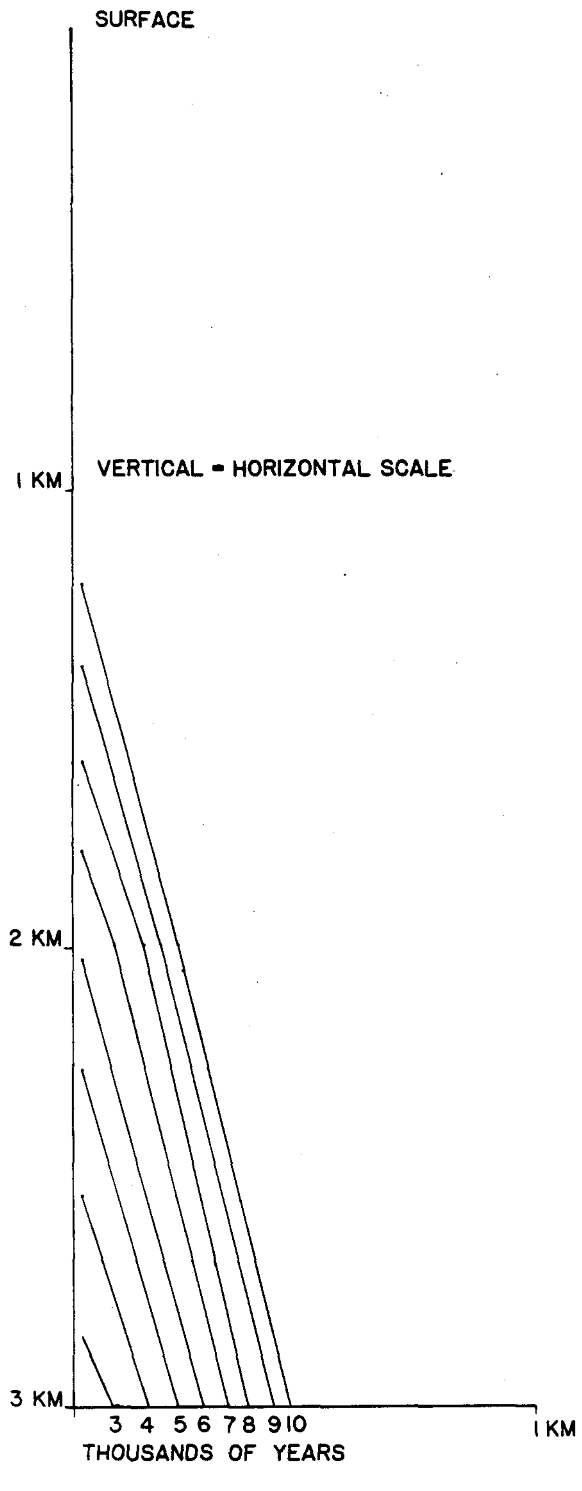

Figure 10. Cross section showing the distribution of the 150°C isotherm on one side of a dike (2 m wide) resupplied with basalt magma every 200 years as a function of the duration of activity along that fissure. Calculation assumes an initial thermal gradient of 33°C/km, initial temperature of the basalt = 1200°C, and conductive cooling. Procedure and other assumptions are discussed in text.

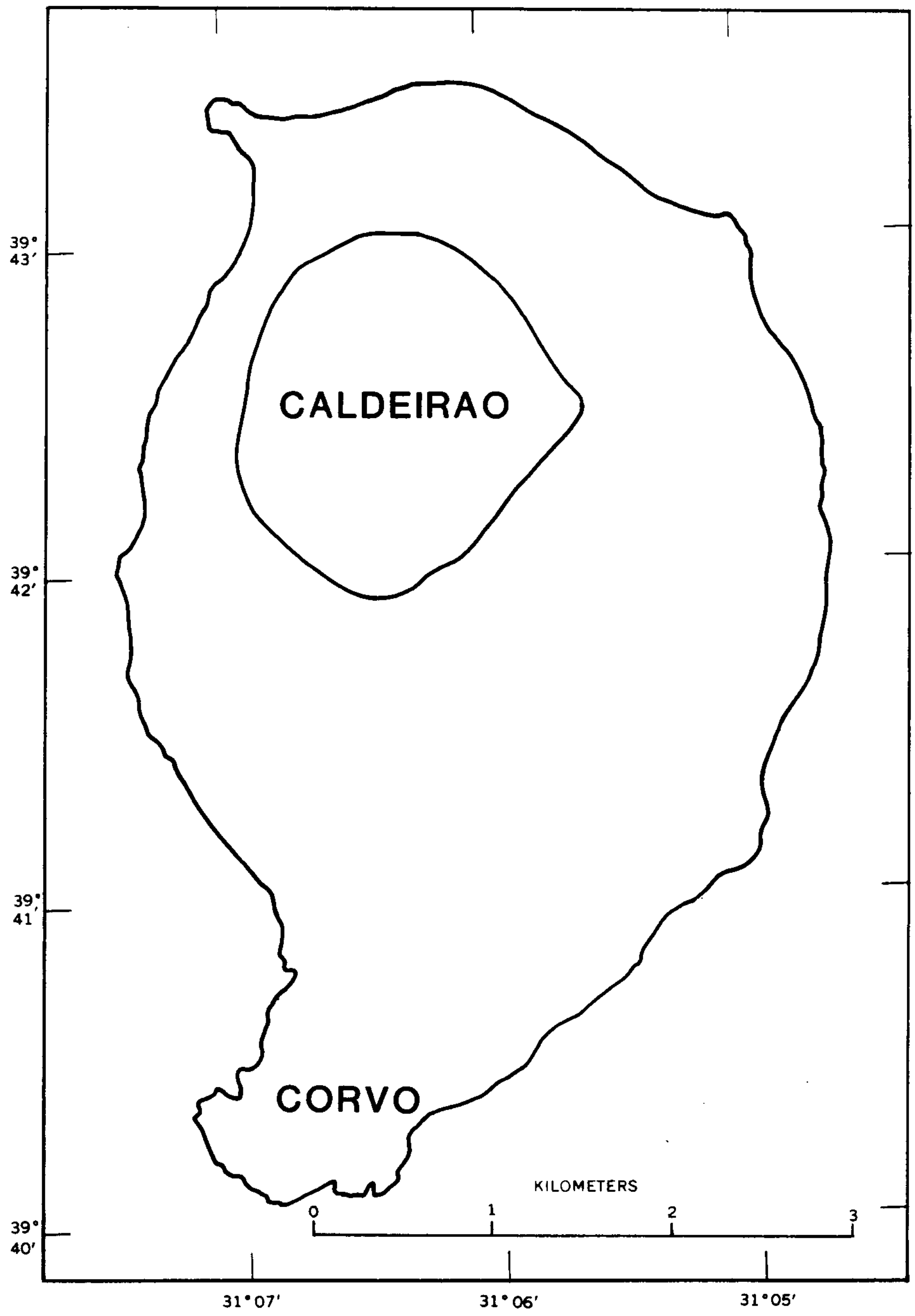

Figure 11. Map of the island of Corvo, showing location of silicic caldera. Compiled from information provided by Zbyszewski and others (1967).

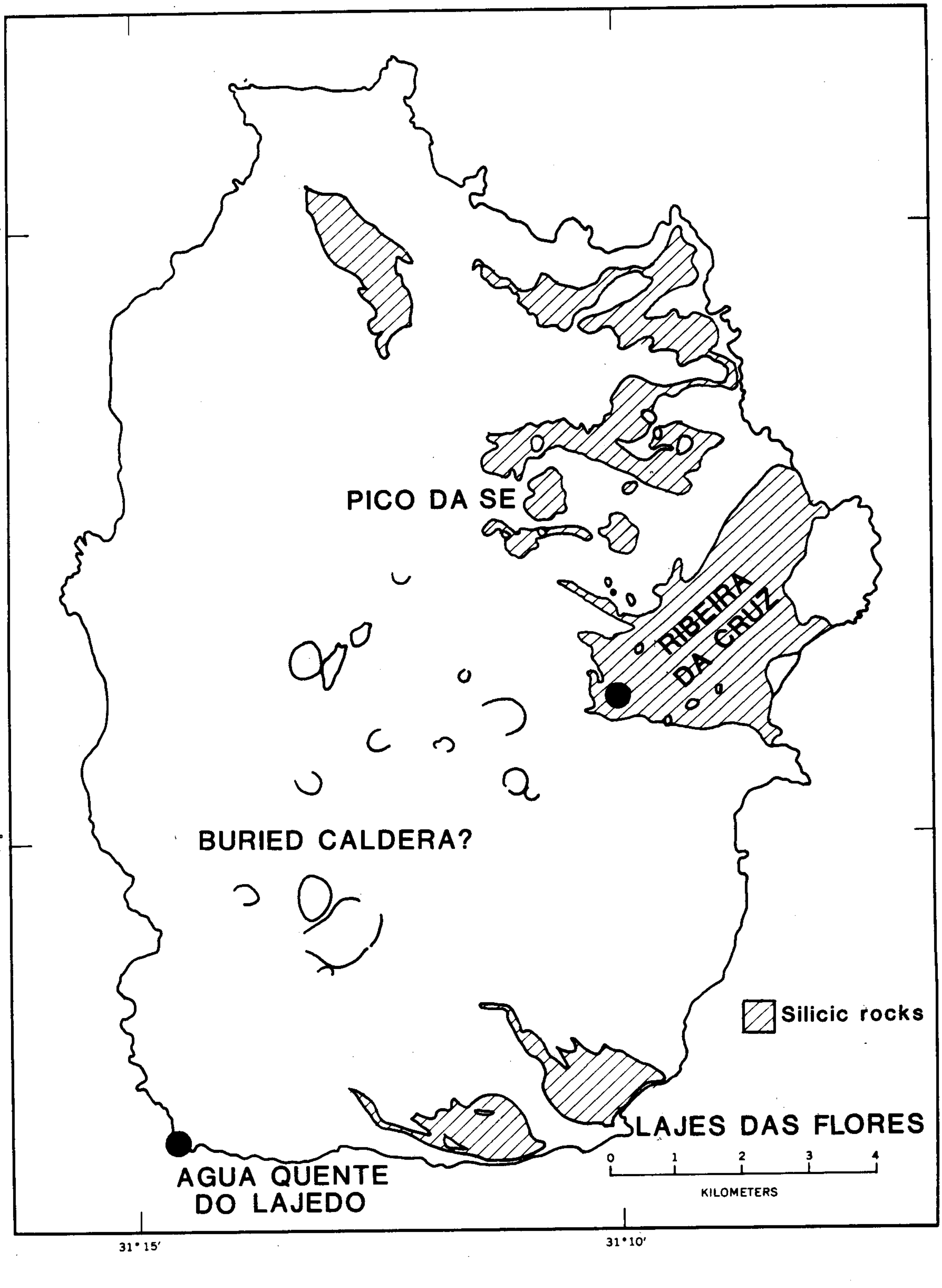

Figure 12. Map of the island of Flores, showing the distribution of silicic rocks and vents in the vicinity of Pico da Se and Ribeira da Cruz, thermal springs (large dots), and geologically recent basaltic vents on the high central plateau of the island which have possibly covered an older silicic caldera. Compiled from Zbyszewski and others (1968).

Graciosa

Graciosa has had no historic eruptions, but it has boiling-temperature fumaroles in the bottom of its silicic caldera, a submarine fumarole just off its northwest coast, and thermal springs at Termas do Carapacho on the southeast coast (temperature=42° C; Zbyszewski and others, 1971).

Geothermal potential is greatest in the vicinity of the silicic caldera, which dominates the southeast corner of the island (fig. 13). This relatively small (structural area= 3.8×10^5 m^2) caldera apparently formed through trachytic tephra eruptions and has had andesitic activity within and on its flanks since its formation.

Several parallel fissures along which basaltic cones are scattered occur in the northwest part of the island, but none appear to have been active long enough to be likely to have created a significant thermal reservoir in the surrounding country rock.

Silica geothermometry applied to the spring water at Termas do Carapacho yields 158° C by the quartz conductive curve. The problems encountered on San Miguel may apply to Graciosa as well, however, and the silica content of cold ground water may exceed that of this thermal spring. This reservoir temperature estimate is therefore uncertain. No other analytical data are available.

Although Graciosa has good geothermal potential, the island's energy needs are low. However, water is needed on Graciosa and could be provided by condensation of geothermal steam. The cost of establishing steam-condensing facilities in the caldera may be relatively small, if adequate steam flow could be obtained from shallow drill holes in the crater.

Fayal

The most recent volcanic eruption in the Azores was in 1957-58 at Capelinhos, at the western tip of Fayal (fig. 14). Capelinhos erupted 0.08 km^3 of basaltic lava in a 13-month period (Machado and others, 1962).

Capelinhos is at the western end of a basaltic fissure that extends 8.3 km on land, nearly reaching the island's central silicic caldera. Eruptive activity at Capelinhos during 1958 was accompanied by hydrothermal activity within the central caldera, suggesting that a structural connection may exist at depth between the fissure and the caldera. The spatial density of vents along the fissure is low, suggesting an active period of only about 3,000 years. Temperatures greater than 150° C are thus likely only at depths greater than about 2.5 km (fig. 10).

The caldera itself is another possible geothermal resource area. It may have formed in the relatively recent geological past, as a large volume of silicic tephra deposits, apparently erupted from the caldera, is very near the surface on the eastern half of Fayal. Lavas of intermediate composition have erupted within the caldera, but, except for a brief

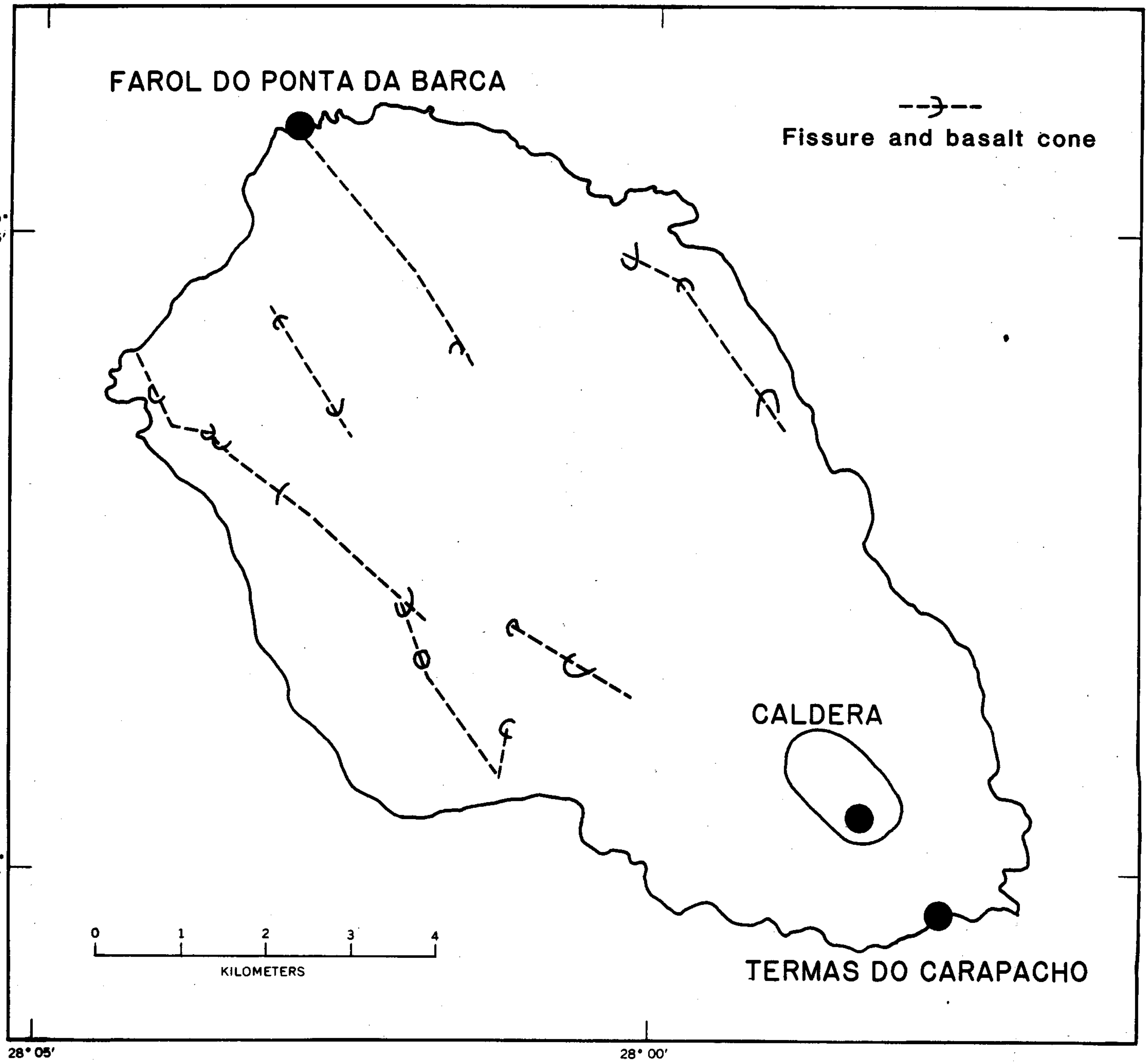

Figure 13. Map of the island of Graciosa, showing the silicic caldera, thermal springs, and fumaroles within the caldera. Compiled from Zbyszewski and others (1971).

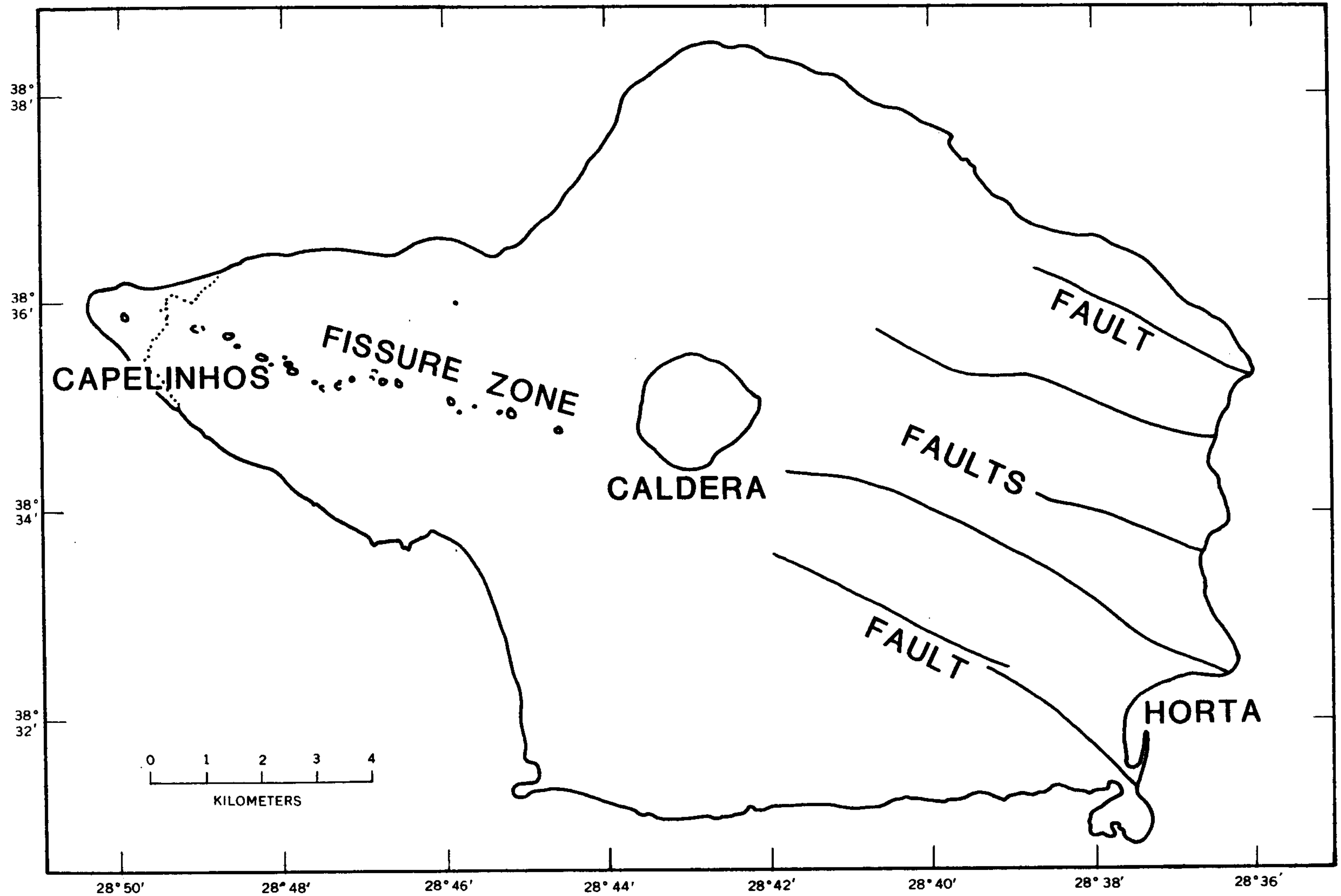

Figure 14. Map of the island of Fayal, showing major normal faults, the central silicic caldera, the basaltic fissure zone and Capelinhos, which erupted in 1957-58, creating the land area west of the fine dotted line. Compiled from Zbyszewski and others (1959).

period during the Capelinhos eruption, there have been no historic thermal manifestations within the caldera.

A few isolated trachytic domes crop out on the flanks of the caldera, and others may have been buried. These are not considered as possible resource areas.

Warm springs are emitted on the southwest coast at Varadouro. The temperature and composition of these springs have not been published.

Several major west-northwest trending faults offset the east flank of the island. Although thermal manifestations have not been recognized along these faults, deep groundwater circulation along the faults possibly could produce hot waters that could be tapped by shallow wells. Because temperatures sufficient to generate electricity are unlikely for these waters, these have not been tabulated with other resource potential in table 9. Because of the great depth at which high temperatures are likely to occur on Fayal, the potential for electrical generation is not promising.

Pico

Pico, the mountain for which the island is named, is the only high stratovolcano in the Azores. It appears to be unusual among stratovolcanoes in that its visible deposits are exclusively basaltic. Intermediate or silicic lavas, normally associated with such peaks, have not been recognized at Pico. To have constructed such a mountain, a central vent must have remained active for a comparatively long interval; hence, Pico Volcano may have geothermal potential. Fumaroles are present in the summit crater region. Unfortunately, there are no indications to aid in evaluating the reservoir volume; hence, for Pico, I have used the standard volume and depth of Brook and others (1973); the volume is 3.3 km^3 and the top of the reservoir is 1.5 km below sea level (which is roughly 2.5 km below the average surface).

The eastern side of the island (fig. 15) is dominated by basaltic cinder cones and a major fissure vent system from which the 1562-1564 lavas were erupted. The spatial density of vents on this system is 4.0 vents/km, suggesting 4,300 years of eruptive activity.

Except for fumaroles in the summit crater of Pico, thermal activity has not been reported on Pico island.

Because of the great depth at which high temperatures are likely to be found beneath Pico island, geothermal development on Pico is likely to be relatively expensive. For this reason, the potential for geothermal energy on Pico is less than that for some of the other islands.

Santa Maria

Santa Maria is the oldest and most eroded of the Azorean islands. Non-volcanic sedimentary basement rocks exposed on the island have been dated by means of fossils as middle Miocene and have been dated radiometrically

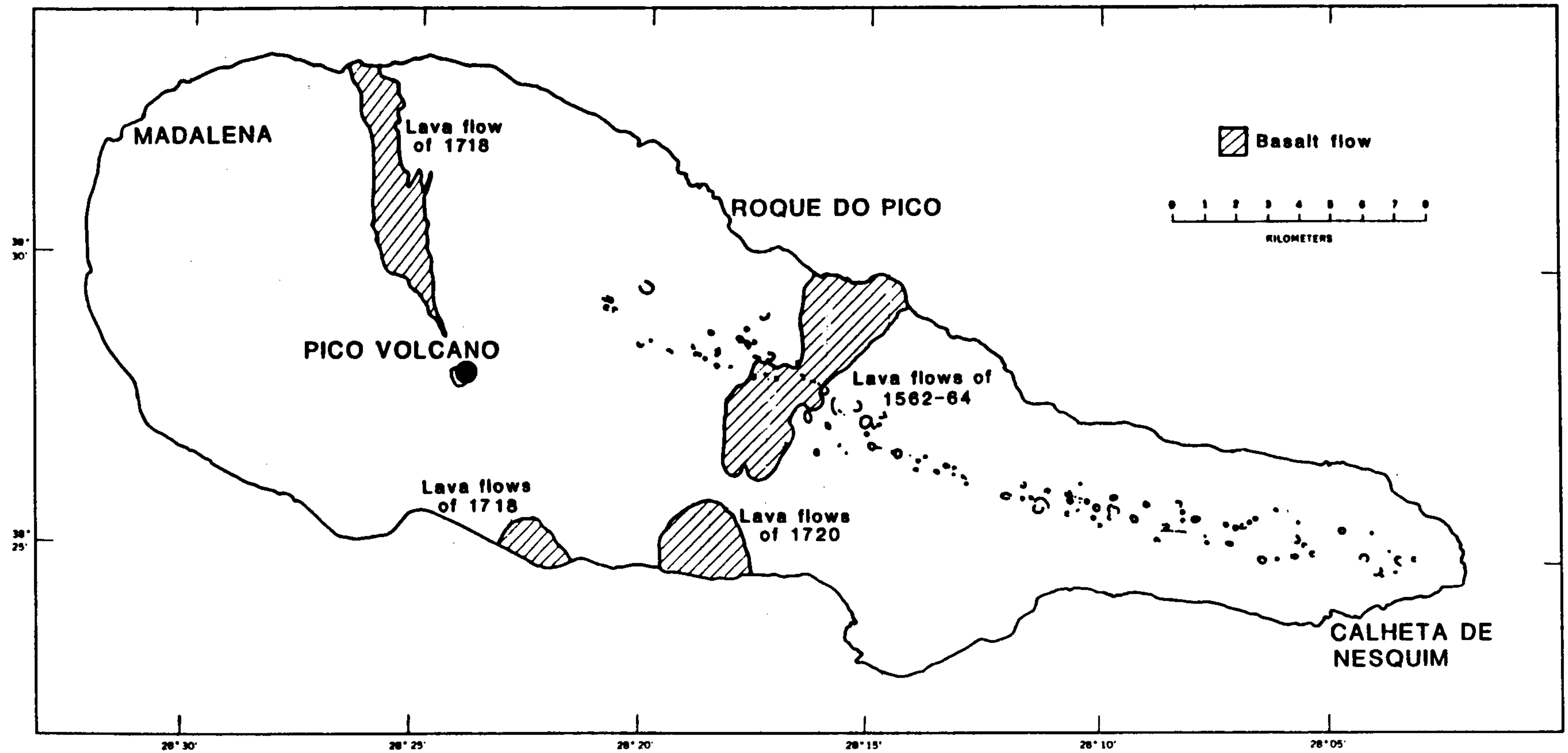

Figure 15. Map of the island of Pico, showing Pico volcano and basaltic flows and vents along fissures on the east side of the island. Compiled from Zbyszewski and others (1962), and Machado (1967).

as older than 4.2 m.y. (Abdel-Monem and others, 1968). These are the only old nonvolcanic basement rocks exposed in the Azores. No historic or geologically recent eruptions have taken place, and no thermal manifestations are present. Volcanic bedrock consists primarily of basalt and basaltic andesite (Zbyszewski and others, 1960).

Possible geothermal resource areas have not been identified on Santa Maria.

GEOTHERMAL EXPLORATION COSTS

The cost for geothermal exploration is divisible into two parts: first, the cost of geological and geophysical studies designed to pinpoint deep drilling sites; and second, the cost of deep drilling. The former is roughly the same for all exploration sites. The cost of drilling, however, increases dramatically as the depth of drilling increases.

The cost of the battery of geological, geophysical, and shallow-temperature surveys required to explore a possible geothermal resource area will probably be between U.S. $400,000 and $600,000 (1976-77), as judged by the Azorean experience at Ribeira Grande (table 10, first phase). The costs of individual studies in this phase are itemized in table 11, from R. O. Fournier (unpub. data, 1979). To develop low-enthalpy resources in Portugal, it will not be necessary to perform all the studies listed, and hence, exploration costs will be insignificant in comparison to drilling costs. Many of the geological and geochemical studies, are, in fact, already complete, and SGP has the capacity to perform electrical resistivity surveys at low cost.

Costs of deep drilling are difficult to estimate because problems generally cannot be predicted but are common and costly. Figure 16 shows the 1978 cost of 19 deep geothermal wells drilled to various depths in the western United States (data from Chappell and others, 1979). This figure clearly shows that the cost rises greatly as drilling depth increases. For a line fit to the data points (R=correlation coefficient=0.63), the predicted cost increases from $283 (1978) per meter for a 500-m hole to $802 (1978) per meter for a 3,000-m hole. Costs may be significantly higher when problems are encountered, such as happened at holes RG-2 and PV-1 on San Miguel.

Table 10. Summary of geothermal exploration and drilling costs for the Ribeira Grande field during 1976-1977. (Cost is shown in 1976-77 U.S. dollars)

	COST
FIRST PHASE	
Geological/geophysical exploration	$232,500
7 shallow (200 m) temperature-gradient holes	232,500
SECOND PHASE	
Deep-drilling site preparations	77,500
Purchase of drilling materials	957,500
Drilling supervision, technical training	92,500
Deep drilling of first hole (± 600 m)	420,000
Purchase of safety equipment	337,500
Support staff and equipment	65,000
TOTAL	2,415,000

Table 11. Approximate costs of geothermal exploration techniques (from R. O. Fournier, unpub. data, 1979). (Costs are U.S. dollars 1978-79.)

EXPLORATION EFFORT	COST
Geologic investigation--salary, office, field expenses per geologist per month	$ 3,500-4,000
Geochemetrical investigation--geochemist plus assistant plus vehicle per month and cost of analyses in commercial lab	12,000-18,000
Electrical surveys--per specific site	12,000-30,000
Gravity survey--per specific site	12,000-14,000
Passive seismic survey--per specific site	25,000-50,000
Airborn magnetic survey--per kilometer flown	7-9
Shallow temperature-gradient wells	20,000-50,000
Deep wells	See text

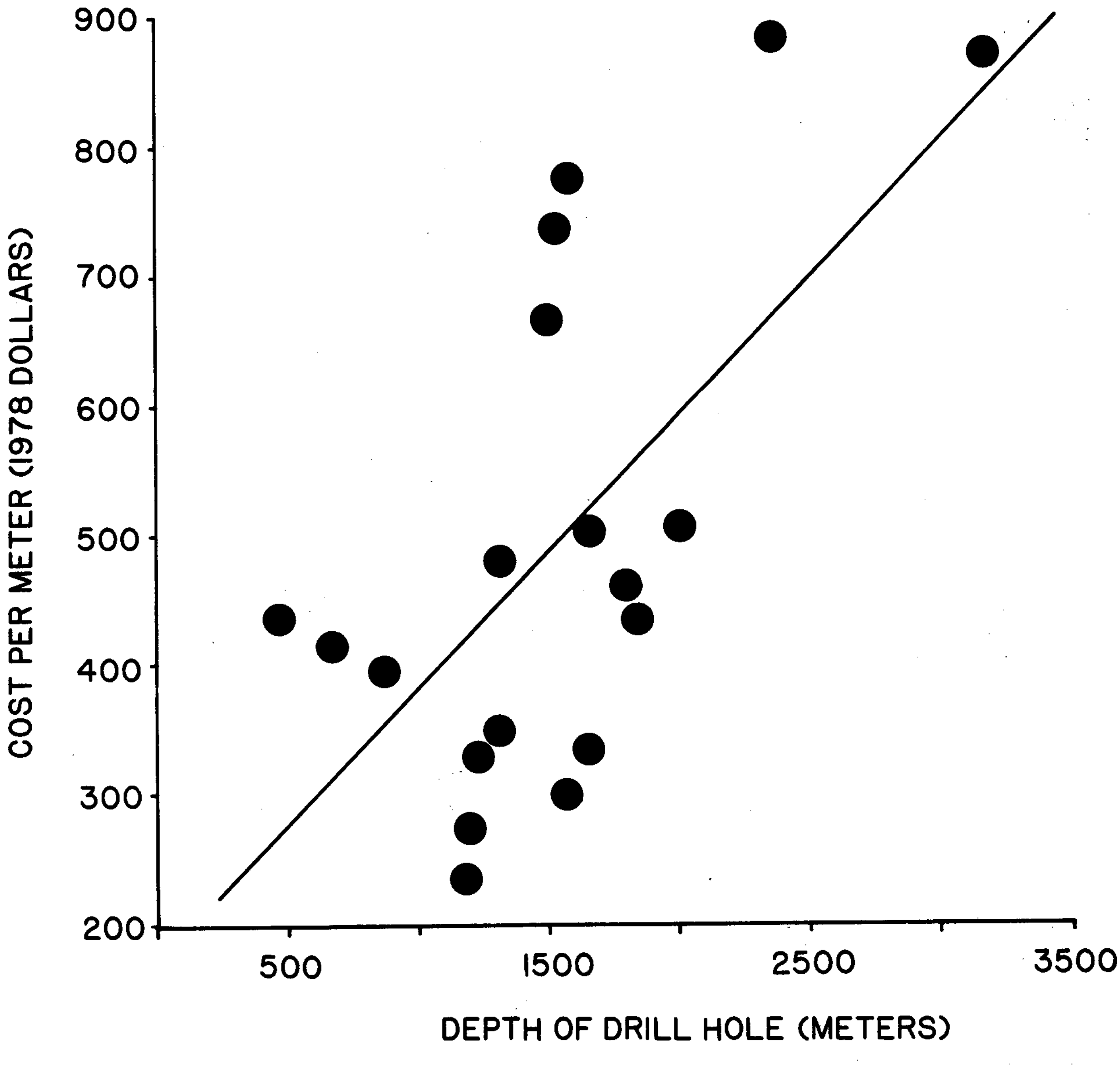

Figure 16. Graph illustrating the cost of drilling geothermal wells in the United States as a function of the depth of the well (from data of Chappell and others, 1979). The line shown is the least-squares fit to the data and has a correlation coefficient of 0.629. A semi-logarithmic fit yielded a correlation coefficient of 0.563.

Because the cost of mobilization is a major cost of drilling (see Chappell and others, 1979, for a breakdown in drilling costs), drilling costs in the Azores can be expected to be higher than those in the United States. To aid in evaluating the economic feasibility of different possible resources areas in the Azores, U.S. typical drilling costs for wells reaching the inferred depth of the top of the geothermal reservoir are reported in table 9.

The cost of drilling shallow small-bore wells (less than 100-300 m deep) is likely to be $50,000 or less per well. Such wells may suffice for the recovery of low-enthalpy waters from fault zones in Portugal or the Azores.

Table 12 shows typical costs for the production of electricity by geothermal fluids (R. O. Fournier, unpub. data, 1979). Geothermal fluids

Table 12. Comparison of predicted costs of electricity production by various methods for the period 1977-1980. (From R. O. Fournier, Unpub. data, 1979).

FUEL	COST mills/kWh	COST mills/10^6 joules
Geothermal		
Dry steam	22.5 - 24	6 - 7
Hot water above 200° C	25 - 30	7 - 8
Hot water below 200° C	36 - 50	10 - 15
Binary system	40 - 48	11 - 13
Oil	43 - 44	11.9 - 12.2
Coal	35 - 36	9.7 - 10.0
Nuclear	32 - 34	8.9 - 9.4

in the Azores are likely to be hot water, rather than dry steam. The actual costs depend upon the temperature and depth of the fluids, their content of dissolved solids and noncondensible gases, and the powerplant design. Overall costs may be increased for environmental protection or decreased if "waste" fluids are put to other uses, such as space heating, mineral recovery, or freshwater production.

CONCLUSIONS AND RECOMMENDATIONS

Portugal

Geochemical studies of thermal waters and detailed studies of the geology of thermal areas are well underway or completed in Portugal, providing an excellent base for further work. The next step toward development of low-enthalpy water resources is to perform geophysical studies to define the subsurface dimensions and depth of hydrothermal reservoirs. The SGP is able to perform electrical resistivity studies, so major expenses will not be encountered in this stage of exploration.

The greatest potential for hot-water production is for springs in the north. the choice of exploration targets must, however, be guided by anticipated needs and uses, inasmuch as the hot fluids cannot be transported far.

For some thermal springs in Portugal, waters can be put to immediate use at the temperature and rate at which they flow from the ground.

The Azores

The LGT has started to acquire equipment to launch a major geothermal exploration and development program in the Azores. They suffer, however, from a shortage of personnel, both scientific and technical, needed to put the program into operation. For many years to come, the Azoreans will need to rely upon expertise from outside sources through cooperative aid programs or contracts.

From the beginning of the geothermal program on San Miguel, a major problem has been that geophysical studies were initiated without a proper geological foundation. Mapping by Zbyszewski and others (1958) provides only a general picture of the age and structural relations. The scale of the mapping (1:50,000) is too large to show separate lithologies or the numerous small faults that cut the northern part of the Agua de Pau massif.

Detailed geological studies, including mapping, stratigraphy, and radiometric dating, are essential for any future geothermal exploration in the Azores. Geological studies should begin before geophysical studies or drilling, as they may help guide the selection (and certinaly the location) of subsequent geophysical studies, and they will provide information that will eliminate some of the ambiguity inherent in the interpretation of geophysical data. Geological studies can improve the results of all subsequent exploration, and may reduce its cost.

Immediate action needs to be taken to guide future development in the Ribeira Grande field on San Miquel. In addition to areal geological studies, returned core and cuttings from the deep wells should be examined, and efforts should be made to sample and analyze any fluids recovered from the wells. Some earlier geophysical results may be reinterpreted in light of the new information. Technical assistance is needed immediately to begin the work.

As described in this report, geothermal potential of the Azores is excellent. Potential and need are greatest on San Miguel and Terceira, where geothermal energy conceivably could fill all electrical power requirements by the year 2000. Additional geothermal exploration should be directed toward these two islands, and in particular, toward the areas where thermal manifestations are most evident: that is, the Ribeira

Quente, Furnas, and Fogo regions on San Miguel and the Pico Alto-Guilherme Moniz area on Terceira. Exploration should begin with detailed geological studies, which can then be used to plan future geophysical and geochemical exploration.

REFERENCES CITED

Adel-Monem, A., Fernandez, L. A., and Boon, G. A., 1968, Pliocene-Pleistocene minimum K-Ar ages of the older eruptive centres, Eastern Azores (abstract): American Geophysical Union Transactions, v. 49, p. 363.

Aires-Barros, L., 1978, Approveitamentos geotermicos consideracoes gerais a exploracao das altas e das baixas entalpias no territorio Portugues (in Portuguese): Boletim de Minas, v. 15, p. 1-13.

Almeida, A. de, and Almeida, J.D. de, 1970, Inventario hidrologico de Portugal, 2nd vol.-Tras-os-Montes e Alto Douro: Instituto de Hidrologia de Lisboa.

-----1975, Inventario hidrologico de Portugal, 3rd vol.-Beira Alta: Instituto de Hidrologia de Lisboa.

Axtmann, R. C., 1975, Environmental impact of a geothermal power plant: Science, v. 187, p. 795-803.

Bangher, A. R., and Sykes, L. R., 1969, Focal mechanisms of earthquakes in the Indian Ocean and adjacent regions: Journal of Geophysical Research, v. 74, p. 632-649.

Barnes, Ivan, 1965, Geochemistry of Birch Creek, Inigo County, California, a travertine depositing creek in an arid climate: Geochimica et Cosmochimica Acta, v. 29, no. 2, p. 85-112.

Booth, B., Croasdale, R., and Walker, G. P. L., 1978, A quantitive study of five thousand years of volcanism on Sao Miguel, Azores: Philosophical Transactions of the Royal Society of London, Ser. A., v. 228, p. 271-319.

Brook, C. A., Mariner, R. H., Mabey, D. R., Swanson, J. R., Guffanti, Marianne, and Muffler, L. J. P., 1979, Hydrothermal convection systems with reservoir temperatures $\geq$ 90° C, in Muffler, L. J. P., ed., Assessment of geothermal resources of the United States--1978: U.S. Geological Survey Circular 790, p. 18-85.

Chappell, R. N., Prestwich, S. J., Miller, L. G., and Ross, H. P., 1979, Geothermal well drilling estimated based in past well costs: Geothermal Resources Council Transactions, v. 3, p. 99-102.

Cummings, R. G., Morris, G. E., Tester, J. W., and Bivins, R. L., 1979, Mining Earth's heat; Hot dry rock geothermal energy: Technical Review, February, 1979, p. 59-78.

Eaton, G. P., Christiansen, R. L., Iyer, H. M., Pitt, A. M., Mabey, D. R., Blank, J. R., Jr., Sietz, I., and Gettings, M. E., 1975, Magma beneath Yellowstone National Park: Science, v. 188, p. 787-796.

Feth, J. H., and Barnes, Ivan, 1979, Spring-deposited travertine in eleven western States: U.S. Geological Survey Water-Resources Investigations Report, 79-35.

Forjaz, V. H., and Fernandez, N. Santa Maria, 1970, Carta geologica de Portugal--Ilha de San Jorge (Azores): Servicos Geologicos de Portugal, Lisbon.

Forjaz, V.H., and Weston, F. S., 1967, Volcanic activity in the Azores. Report for 1959-1964: Bulletin Volcanologique, v. 31, p. 261-266.

Fournier, R. O., 1977, Chemical geothermometers and mixing models for geothermal systems: Geothermics, v. 5, p. 41-50.

Fournier, R. O., and Potter, R. W., 1979, Magnesium correction to the Na-K-Ca chemical geothermometer: Geochimica et Cosmochimica Acta, v. 43, p. 1543-1550.

Fournier, R. O., and Rowe, J. J., 1966, Estimation of underground temperatures from the silica content of water from hot springs and wet-stream wells: American Journal of Science, v. 264, p. 685-697.

Fournier, R. O., and Truesdell, A. H., 1973, An empirical Na-K-Ca geothermometer for natural waters: Geochimica et Cosmochimica Acta, v. 37, p. 1255-1275.

Jaeger, J. C., 1968, Cooling and solidification of igneous rocks, in Hess, H. H., and Poldervaart, A., eds. The Poldervaart treatise on rocks of basaltic composition, v. 2: Interscience, New York, p. 503-536.

Kharaka, Y. K., and Barnes, Ivan, 1973, SOLMNEQ: Solution-mineral equilibrium computation: U.S. Department of Commerce National Technical Information Service PB-215 899, 81 p.

Krause, D. C., and Watkins, N. D., 1970, North Atlantic crustal genesis in the vicinity of the Azores: Geophysical Journal of the Royal Astronomical Society, v. 19, p. 261-283.

Lawrence, J. R., and Maxwell, S., 1978, Geothermal exploration in the Azores: $^{18}O/^{16}O$ in calcites from volcanic rocks: Journal of Volcanology and Geothermal Research, v. 4, p. 219-224.

Lima, J. M. R., 1892, Reconhecimento geo-hidrologico de Chaves (in Portuguese): Lisbon.

Lindal, B., 1973, Industrial and other applications of geothermal energy, in Armstead, H. C. H., Geothermal energy; Review of research and development: Paris, UNESCO, p. 135-148.

Machado, F., 1955, The fracture pattern of the Azorean volcanoes: Bulletin Volcanologique, v. 11, p. 119-125.

_____, 1967, Active volcanoes of the Azores, in Catalogue of the active volcanoes of the world, part 21. p. 9-52.

Machado, F., Parsons, W. H., Richards, A. F., and Mulford, J. W., 1962, Capelinhos eruption of Fayal Volcano, Azores, 1957-1958: Journal of Geophysical Research, v. 67, p. 3519-3530.

Machado, F., Quintino, J., and Monteiro, J. H., 1972, Geology of the Azores and the Mid-Atlantic Rift: International Geological Congress, 24th, Proc., Sect. 3, p. 134-142.

Moitinho de Almeida, F., and Moura, J. E. da Costa, 1970, Carta das nascentes minerais de Portugal (in Portuguese): Servicos Geologiques de Portugal, Lisbon.

Muecke, C. K., Ade-Hall, J. M., Aumento, F., MacDonald, A., Reynolds, P. H., Hyndman, R. D., Quintino, J., Opdyke, N., and Lowrie, W., 1974, Deep drilling in an active geothermal area in The Azores: Nature, v. 252, p. 281-285.

Muffler, L. J. P., ed., 1979, Assessment of geothermal resources of the United States-1978: U.S. Geological Survey Circular 790, 163 p.

Nathenson, Manuel, 1975, Physical factors determining the fraction of stored energy recoverable from hydrothermal convection systems and conduction-dominated areas, in White, D. E., and Williams, D. L., ed., Assessment of geothermal resources of the United States--1975: U.S. Geological Survey Circular 726, p. 104-121.

Paces, T., 1975, A systematic deviation from Na-K-Ca geothermometer below 75° C and above 10^{-4} atm. PCO_2: Geochimica et Cosmochimica Acta, v. 39, p. 541-544.

Peck, D. L., 1975, Recoverability of geothermal energy directly from molten igneous systems, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U.S. Geological Survey Circular 726, p. 122-124.

Ribeiro, A. Conde, L., and Monteiro, J., 1972, Carta tectonica de Portugal (in Portuguese): Servicos Geologicos de Portugal, Lisbon.

Self, S., 1971, The Lajes ignimbrite, Iilha Terceira, Azores: Comunicacoes Servicos Geologicos de Portugal, v. 55, p. 165-184.

Smith, M. C., 1978, Heat extraction from hot, dry, crustal rock: Pure and Applied Geophysics, v. 117, p. 290-296.

Smith, R. L., and Shaw, H. R., 1975, Igneous-related geothermal systems, in White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States--1975: U.S. Geological Survey Circular 726, p. 58-83.

Thompson, J. M., 1975, Selecting and collecting water samples from thermal springs for chemical analysis; A method for field personnel: U.S. Geological Survey Open-File Report 75-68, 12 p.

Truesdell, A. H., and Fournier, R. O., 1977, Procedure for estimating the temperature of a hot water component in a mixed water using a plot of dissolved silica vs. enthalpy: U.S. Geological Survey Journal of Research, v. 5, p. 49-52.

Walker, G. P. L., and Croasdale, R., 1971, Two Plinian-type eruptions in the Azores: Journal of the Geological Society of London, v. 127, p. 17-55.

White, D. E., 1970, Geochemistry applied to the discovery, evaluation, and exploitation of geothermal energy resources, in United Nations symposium on development and utilization of geothermal resources, Pisa, 1970, v. 1, pt. 2: Geothermics, Special Issue 2, p. 58-80.

_____, 1973, Characteristics of geothermal resources, in Kruger, P. and Otte, C., eds., Geothermal energy: Stanford, California, Stanford University Press, p. 69-94.

White, D. E., and Williams, D. L., eds., 1975, Assessment of geothermal resources of the United States--1975: U.S. Geological Survey Circular 726, 155 p.

White, W. M., Schilling, J. G., and Hart, S. R., 1976, Evidence for the Azores mantle plume from strontium isotope geochemistry of the Central North Atlantic: Nature, v. 263, p. 659-663.

Zbyszewski, G., Candido de Medeiros, A., da Veiga Ferreira, O., Rodrigues, L., and Rodigies, A., 1971, Carta Geologica de Portugal--Ilha Graciosa (Azores): Servicos Geologicos de Portugal, Lisbon.

Zbyszewski, G., da Veiga Ferriera, O., Rodrigues, L., and de Oliveira, J., 1958, Carta Geologica de Portugal--Ilha de Santa Maria (Azores): Servicos Geologicos de Portugal, Lisbon, scale 1:50,000.

Zbyszewski, G., Moitinho de Almeida, F., da Veiga Ferreira, O. Rodrigues, L., Rodrigues, A., 1959, Carta geologica de Postugal--Faial (Azores): Servicos Geologicos de Portugal, Lisbon.

Zbyszewski, G., da Veiga Ferreira, O., Rodrigues, L., and Rodrigues, A., 1960, Carta Geologica de Portugal--Ilha de Santa Maria (Azores): Servicos Geologicos de Portugal, Lisbon.

Zbyszewsli, G., Robeiro Ferreira, C., de Veiga Ferreira, O., Rodrigues L., and Rodrigues, A., 1962, Carta geologica de Portugal--Ihla do Pico (Azores):

_____, 1967, Carta geologica de Portugal--Ilha do Corvo (Azores): Servicos Geologicos de Portugal, Lisbon.

_____, 1968, Carta geologica de Portugal--Ilha das Flores (Azores): Servicos Geologicos de Portugal, Lisbon.

_____, 1970, Carta geologica de Portugal--Ilha Terceira (Azores): Servicos Geologicos de Portugal, Lisbon.

CHAPTER D

ASSESSMENT OF ENERGY RELATED MINERALS/COMMODITIES IN PORTUGAL

By

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INTRODUCTION

Despite the bleak preliminary assessment of Portugal's energy-related mineral resources (M. J. Bergin, U.S. Geological Survey, 1979, written commun.), Portugal has many of the mineral resources required to develop and transmit hydro- and thermally generated electric power in the future. A systematic, detailed exploration program under the Director-General of Mines and Geological Services and supported by the private sector has identified and developed large reserves of iron, copper, zinc, tungsten, and tin, although these minerals have been produced at a relatively low level (Macieira, 1977; Carneiro, 1978). Elimination of the metallurgical separation problems of the complex iron-copper-lead-zinc ores and the phosphor-bearing iron ores can considerably increase the production of these base metals.

The principal energy-related minerals or commodities produced in Portugal are cement, clay, iron, copper, tin, tungsten, lead, and zinc. Raw materials used in making cement, concrete, and brick, that is, limestone, clay, sand and gravel, are very abundant in the west-central part of Portugal.

NONMETALLIC COMMODITIES

Cement

Portugal is presently producing more than 3.4 million metric tons of cement per year from several plants located near Lisboa. In 1975, Portugal produced 5,200,000 t of noncrystalline limestone and marl for cement and hydraulic lime (Macieira, 1977). The amount of concrete used in energy-related industries and for hydroelectric installations (dams) is greater than that of any other energy-related raw material.

By calcining limestone, shale, granodiorite, or clay, sand or silt, gypsum, and iron oxides together at about 1,400°C, a complex alumino-silicate called cement is produced. These raw materials are abundant in Portugal.

Limestone and marble

Widespread deposits of limestone in Portugal contain billions of metric tons of material suitable for the manufacture of cement (Manuppella, 1969; Macieira, 1977). Many sites of limestone and marble quarries are shown on the geologic map of Portugal (Teixeira, 1972); some of the important sites are shown on figure 1 (localities 5,7,8,9, and 10). According to Macieira (1977), the annual production of limestone is greater than 11.8 million tons. Historically, marble has been used as building stone and to produce lime; annual production of marble is greater than 280,000 t. Much of the present marble production is shipped to Italy for resale.

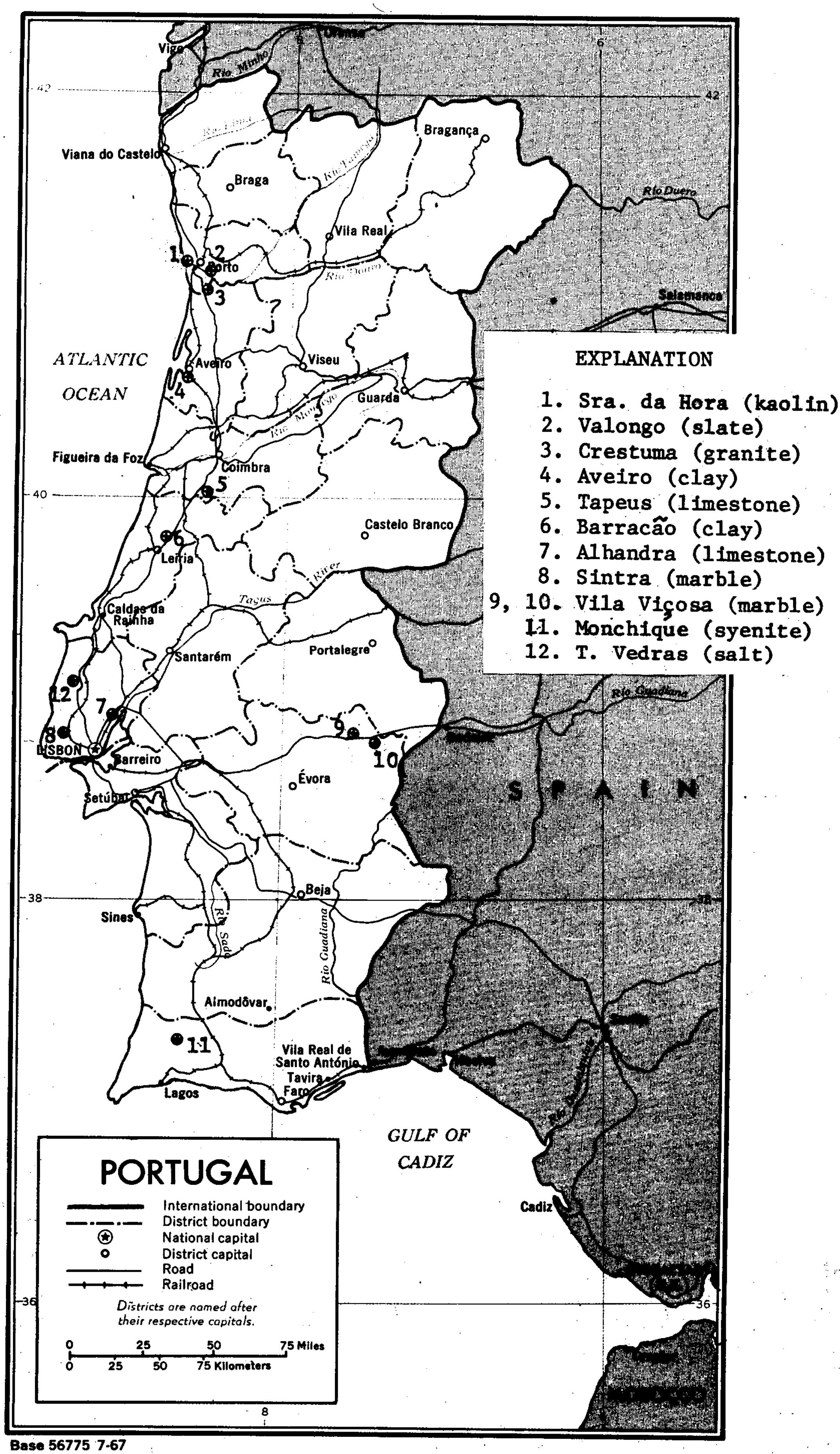

Figure 1. Localities of nonmetallic resources of Portugal.

Dolomite

Extensive deposits of dolomite that are suitable for certain cements, ceramics, and agricultural lime occur east and southeast of Lisboa, near Setubal (Manuppella, 1969). These deposits are estimated in millions of metric tons.

Clay

Known deposits contain millions of metric tons of clay for various uses. Present production of kaolin mostly from Sra. da Hora (fig. 1, loc. 1) is more than 60,000 t/yr, and that of clay used for refractory purposes is about 90,000 t/yr. Common clay used for roofing tiles and hollow bricks is produced in the Aveiro and Barracao regions (fig. 1, loc. 4 and 6). Barracao production is more than 4.7 million tons.

Salt

The high potential for mining large deposits of salt in Portugal is well known (Carneiro, 1971). Two deposits, salt domes, near T. Vedras (fig. 1., loc. 12) have an estimated cumulative reserve of several million tons. Production of rock salt in 1975 was about 293,000 t.

Sand and gravel

Supplies of these two materials are abundant. Present annual production of sand is more than 5.5 million tons. Gravel production is about 230,000 t/yr.

Other materials

Slate is produced mainly for roofing material (fig. 1, loc. 2); yearly production is about 44,000 t. Granite and diorite are mainly quarried for paving stone and building stone (fig. 1, loc. 3). Their annual production is greater than 4.2 million tons and 7 million tons respectively. Syenite is produced at Monchique (fig. 1, loc. 11).

METALLIC COMMODITIES

Iron

Almost every energy-related activity uses large amounts of iron and steel. Small amounts of manganese, chromium, molybdenum, titanium, tin, tungsten, nickel, tantalum, and vanadium are used for the production of iron and steel. Portugal has promising potential for ores of iron and many of these subordinate commodities. At the Lisboa plant more than 300,000 t of pig iron is produced annually. One of the main deterrents to increased production is the presence of phosphorus in the large reserves of iron ore at Moncorvo.

Moncorvo deposits

Near the city of Torre de Moncorvo, 13 miles from the Spanish border, are large low-grade sources for the production of pelleted iron ore, according to Skillings (1968) (fig. 2, loc. 1). Tests have been made to recover concentrate from the fine-grained itabirite-type crude ores by desliming and selective flotation.

The iron-ore deposits crop out along a ridge of hills called Serra de Reboredo at an altitude of about 900 m. The earliest excavations were made by the Romans and Arabs. The first geologic work was done in the 1920's. Ferrominas, E. P., was set up to develop these deposits. A new blast furnace of the Siderurgia Nacional has been proposed for the reduction of these ores, starting in 1981 (Moncorvo-Ferrominas, 1977). The Moncorvo iron formation consists of a series of pre-Ordovician schist and graywacke overlain by Ordovician schist and quartzite. The ore is mainly hematite, and lesser amounts of martite and specularite. Lazulite, apatite, and secondary phosphates account for the phosphorus content of the crude ore. The main ore contains 42 percent Fe, 30 percent SiO_2, and about 0.5 percent P_2O_2. Concentrates will contain about 64 percent Fe and about 2 percent P_2O_5. The five deposits at Moncorvo (Mua Hill, Carvalhosa, Pedrada, Cotovia, and Apriscos) contain an estimated 550-600 million tons of resources (table 1). These deposits contain about 270 million tons of measured and indicated reserves (proved and probable). The grade is 39.8 percent Fe and 0.51 percent P. Mua Hill, which has reserves totalling 126 million tons, will be the first deposit exploited. Drilling of Pedrada, the extension of the open pit, has revealed 200 million tons of reserves. With Mua ore body on the east end, the deposits extend westward for 8.5 - 10 km. Mua's ore is about 120 m thick and more than 900 m wide, forming an asymmetrical east-trending synform. The upper part (90 percent of the ore) has a grade of 44.6 percent Fe. Grade of the lower part is 44 percent. The north side dips steeply at 55°, whereas the south side dips no more than 15°.

Marao deposits

These deposits are contained in an area about 2.5 km long and 0.5 km wide, located approximately 97 km east of Porto (fig. 2, loc. 3). The deposits are contained in a marine sedimentary series of Early Ordovician age, mainly quartzite, metamorphosed by contact with a granitic intrusive rock (Zitzmann, 1970).

The minerals are mainly magnetite, grunerite, thuringite, and lepidomelane. Mineral concentrates are 65 percent Fe, 5.5 percent SiO_2, 0.16 percent S, and 0.13 percent P from ore containing 35-45 percent Fe, 25-34 percent SiO_2, and 0.45 percent P. Although the deposits were mined by the Romans, extensive exploration and development took place between 1949 and 1968. During that time about half a million tons of ore were mined. The total reserves are estimated to be about 10 million tons (table 1).

Tin and tungsten

Portugal was the first tin producer in Western Europe, and has large reserves of tungsten ores (Carneiro, 1971). Half of Portugal has potential for exploration of these metals. Sondermayer (1975) indicated an annual metal production of 555 t tin, and 1748 t tungsten.

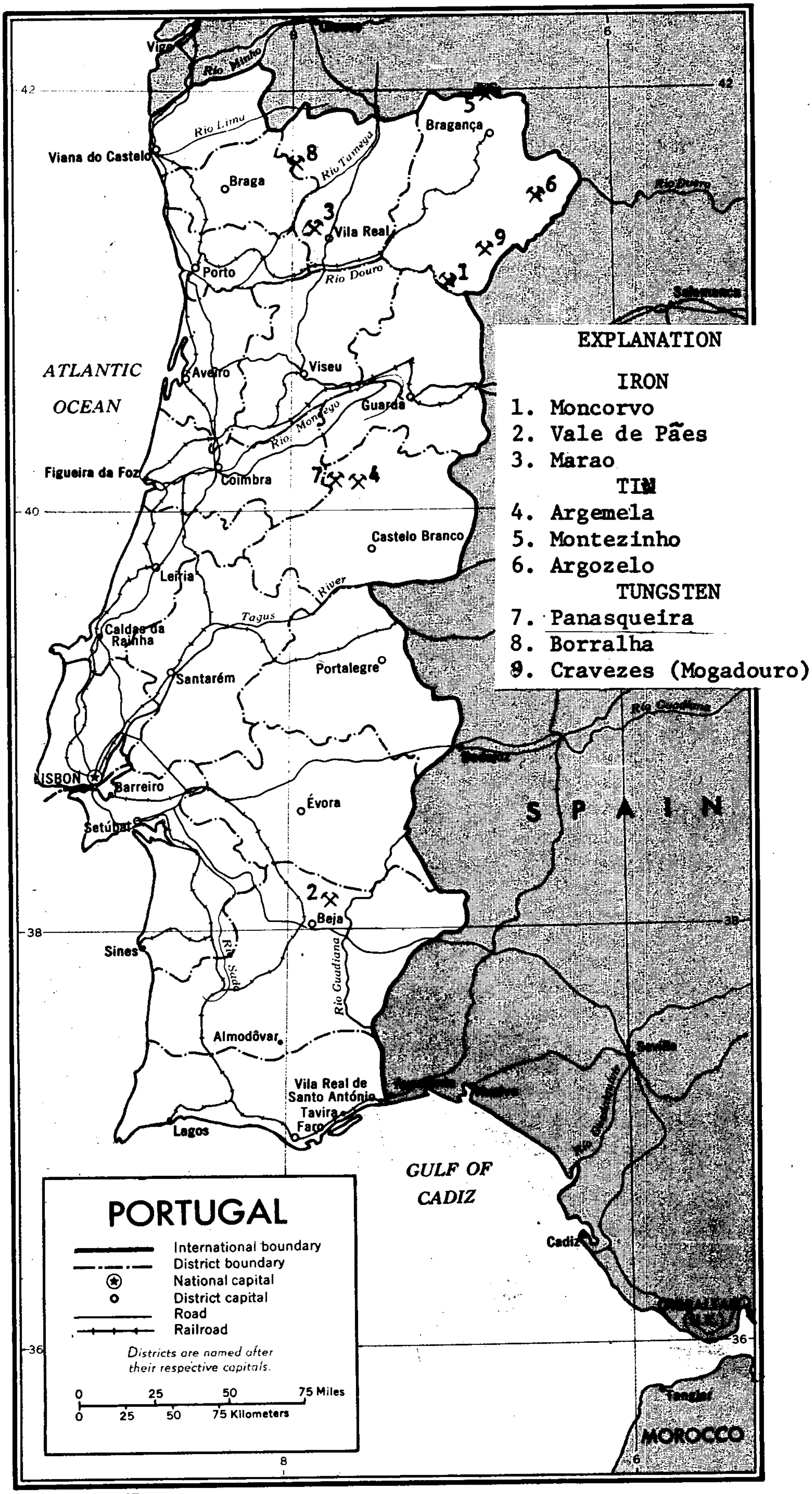

Figure 2. Iron, tin, and tungsten deposits in Portugal.

Table 1. Characteristics of ore at mines or deposits in Portugal.
[L1, Level 1; NA, Not Available]

Map loc.	Mine or deposit	Proved reserves (million tons)	Proved recoverable reserves (million tons)	Resources (million tons)	Mining method	Production (million tons per year)	Minerals and grade
	Iron						
1.	Moncorvo	550	270	NA	open-pit, slices 10 m height	4.3	hematite, martite
2.	Vale de Paes	NA	NA	8.5		NA	magnetite, 42% Fe; 19% SiO_2
3.	Marao	10	NA	NA	room & pillar	20000 t	magnetite 35-45% Fe; 25-34% SiO_2
	Tin						
4.	Argemela	40 above L1	80 below L1	NA	open cast	1.0 (present) 4.0 (projected)	cassiterite
5.	Montezinho	120 t Sn	NA	8000 t Sn	underground stoping	40 t conc 70% Sn	vein type 1.26 kg/t Sn
6.	Argozelo	680 t Sn	NA	1600 t Sn	underground stoping	70 t conc	vein type 1.36 kg/t Sn
	Tungsten						
7.	Panasqueira	NA	NA	NA	cut & fill stoping	Ca. 160 tx 74% W/month 64 t Sn/month	Av. grade 1.6 kg/t W wolframite; chalcopyrite
8.	Borralha	NA	NA	NA	underground stoping	NA	scheelite and wolframite
9.	Cravezes (Mogadouro)	NA	NA	5 plus			scheelite
	Copper						
10.	Aljustrel	95	41	200	cut & fill, sublevel stoping	1.20 (present) 2.65 (projected)	0.53-1.51% Cu; chalcopyrite
11.	Miguel Vacas	1.128 1.5% Cu 1 0.6% Cu	2.0 1.42% Cu	3 - 4	open cast, acid leaching & cementation	90000 t 180000 t	1.5% Cu
12.	Borralha	(14000 t 13-16% Cu)	NA	NA	underground stoping	270 t conc 16% Cu	
13.	Sao Domingos	30	20	NA	open pit; room & pillar		recover Cu by leaching
14.	Neves Corvo	50	NA	100?			1.5% Cu; 0.5-8% Zn
15.	Salgadinho	NA	NA	10 plus			0.2-7% Cu; some Au & Ag
16.	Tinoca - Azeiteiros	0.5 2.2% Cu	NA	1			
	Lead - Zinc						
10.	Aljustrel	(see copper)					2.98-3.20 Zn; 1.0-1.3% Pb
14.	Neves Corvo	(see copper)					1-10% Zn
17.	Preguica	1.0 10% Zn & Pb	NA	NA			10% Pb & Zn
18.	Algares-Balsa	14.7 Algares 14.5 Balsa	NA NA	NA NA	open cast and under-ground		2.54% Zn; 0.5% Pb
	Manganese						
19.	Cercal	6	3.5	8	open cast	25000-35000 t	veins 5 km long and 10 m thick 43% Fe; 8% Mn; 14% SiO_2

Panasqueira deposits

The Panasqueira deposits (fig. 2, loc. 7) in Beira Baixa Province became an important source of tungsten when that metal became important to the production of high-speed steel. Mining began after 1894 and reached a peak during World War I (Beralt Tin and Wolfram Ltd., 1977). When the wolframite market decreased, the mine produced cassiterite, as the tin market was relatively stable. The Beralt Tin and Wolfram Portugal became innovators by the introduction of table flotation to recover copper sulfides. Recently the company has constructed a 1.2 km decline with a conveyor to carry both men and ore (Mining Magazine, 1979). This decline opened up a lower level in the anastomosing, discontinuous flat-lying tungsten veins. The orebody is in a pre-Ordovician shale-graywacke formation that borders the Fundao granite batholith. The Hercynian orogeny deformed and fractured the rocks. Mineralized quartz veins are found in the metamorphosed shale beds that now comprise phyllites. The old mine workings contain a granite cupola that contracted, fractured the surrounding rock, and provided space for the mineral bearing veins. These subhorizontal veins are about 30 cm thick and dip about 4° to 8° southeast (Conde and others, 1971).

The main ore minerals are wolframite, chalcopyrite, and cassiterite. Some sphalerite (marmatite), arsenopyrite, pyrite, and marcasite occur with the main minerals. The ore bodies are in echelon circular lenses about 50 m in diameter. The main ore zone is 70-80 m thick, and extends about 2,000 m downdip. Longwall mining has been used, but new equipment has required a return to room-and pillar mining. Pillars are 15 m by 15 m. Sweeping of the stope floors is required as wolframite is heavy and friable.

Recently, production of ore has been about 435,000 t/yr (Conde, and others, 1971). Magnetic separation provides a tin and copper concentrate from which much of the copper is recovered on tables and by flotation. Present production is about 160 t/mo of wolframite and 64 t/mo of tin (table 1).

Borralha deposits

Minas de Borralha (fig. 2, loc. 8) spans about 70 years of mining. The ore bodies are in mica schist which was intruded by granite and metamorphosed to greenschist facies. The schist is highly faulted and contains many small drag folds. Subvertical veins, dipping 60° to 80° S., commonly intersect and pinch out (Conde and others, 1971).

The main ore minerals are wolframite, cassiterite, and scheelite, with smaller amounts of pyrite, chalcopyrite, molybdenite, and columbium-tantalite. These minerals are contained in subvertical and subhorizontal veins about 30 to 100 cm wide. The mine is developed on three levels at 60 m, 110 m, and 160 m. The government is presently exploring a massive sulfide deposit containing chalcopyrite and minor amounts of uranium minerals.

Argemela deposits

The mineralized area at Argemela is in the east-central part of Portugal, about 75 km east of Coimbra (fig. 2, loc 4). This area is estimated to contain

40 million metric tons of ore at a grade of 0.5-0.6 kg/t of tin metal. Two areas of higher grade mineral are contained within the general area and are estimated at 6 million metric tons at a grade of 0.8 kg/t of tin metal (table 1).

Open-cast mining, at a stripping ratio of 2:1, will be followed by heavy media preconcentration and gravity cleanup having an overall recovery of 75 percent metal. Two production schedules have been proposed:

I. Mining the higher grade areas at a full-production rate of one million t/yr of ore for a reserve life of 8 years.

II. Mining the general mineralized area at a rate of 4 million t/yr of ore.

Copper

Aljustrel deposits

The gossans of the massive sulfide deposits at Aljustrel (fig. 3, loc. 10) were mined by the Romans for their gold and silver content, and a bronze tablet on mining law was prepared here by the Romans in 200 A.D. The surface deposits were also exploited by the Arabs for copper. More recently, pyrite has been mined for sulfur for the production of sulphuric acid and the manufacture of fertilizers.

The very successful recent exploration near Aljustrel has led to the discovery of five new ore bodies of massive sulfides, which, in connection with the previously known ore bodies, have cumulative resources of about 200 million tons (table 1). The deposits are located in the keels of sharply folded synclines or on the flanks of anticlines, within a complex of volcanic rocks (Carvalho and others, 1971). The lithologic sequence, progressively from the southwest, comprises volcanic rocks, an altered zone, and a volcanic-sedimentary complex of siliceous graphitic schists, all overlying a volcanic sequence of siliceous pyroclastic rocks. The lower tuff unit contains some massive felsite and fragmental rocks. Air-fall tuffs are common.

The ores contain massive pyrite, chalcopyrite, sphalerite (marmatite), and galena. As is shown below for three individual mines, the sulfides range in average grade from 0.53 to 1.51 percent Cu, 2.98 to 3.2 percent Zn, 1.0 to 1.3 percent Pb, and 45.0 to 47.5 percent S. The ores also contain about 35 g/t Ag and traces of cobalt and gold.

Mine	S	Cu	Zn	Pb
Moinho	47.1	1.15	3.20	1.30
Feitais*	45.0	0.53	3.00	1.30
Gaviao	47.5	1.51	2.98	1.00

*The Feitais ore body contains low-iron sphalerite, and some cobalt, cadmium, and tin as cassiterite and stannite. The contents of other metals are: tin, 1.5 kg/t; cobalt, 300 g/t; and aluminum, 100 g/t.

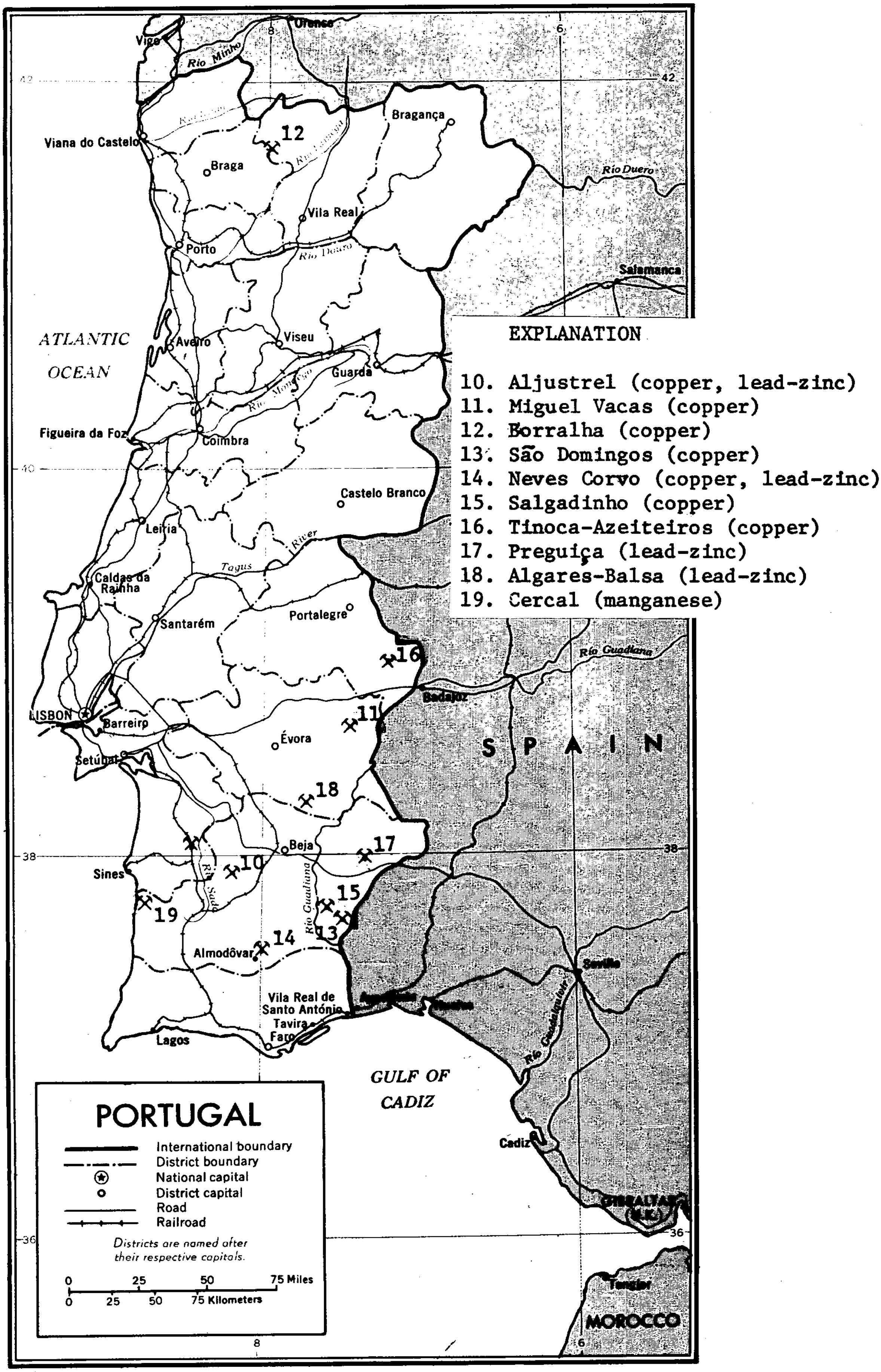

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Figure 3. Copper, lead-zinc, and manganese deposits of Portugal.

Present plans indicate an initial production of 1.2 million t/yr of crude ore. Production is projected to increase to 2.65 million t/yr (table 1). Present treatment by acid leaching and cementation recovers some of the copper. Future treatment by flotation and flash-smelting will recover iron, sulfur as acid, copper, zinc, and lead, as well as the silver and gold.

Miguel Vacas deposits

The mineralized area at the Miguel Vacas copper mine, about 150 km east of Lisboa (fig. 3, loc. 2) contains 1.1 million metric tons of oxide at a grade of 0.60 percent copper metal (table 1). The probable reserves of copper sulfide deposits is about 2 million metric tons of ore at a grade 1.42 percent copper metal.

Open-cast mining of the oxide ore, at a stripping ratio of 1.13:1, will be followed by acid leaching and cementation to obtain a copper cement. For this area two production schedules have been considered:

I. 90,000 t/yr (about 637 tons of copper metal) at an estimated reserve life of 12 years.

II. 180,000 t/yr (about 1265 tons of copper metal) at an estimated reserve life of 24 years.

Zinc and lead

The zinc belt in southern Portugal is an elongated area trending northwest. Goinhas (in press) states that these zinc-bearing strata have a strike length of 80 km and comprise chloritic and sericitic schist, quartz veins, tuff, and limestone of Silurian age, metavolcanic chloritic schist, and intercalated limestone of Ordovician age, dolomite of Early Cambrian age, and black schist and quartzite of Precambrian age.

The Hercynian orogeny developed a zone of structural complexity which has complicated mapping and exploration. Overturned folding and overthrust faulting appear to be common. The main ore resources are zinc-lead stratabound deposits in the Cambrian dolomite and small lenticular iron deposits in the volcanic sequence (Goinhas, 1972).

Algares-Balsa deposits

The Portel mining area which contains the Algares-Balsa deposits (fig. 3, loc. 18) is halfway between Evora and Beja and is situated within a large overturned anticline (Goinhas, in press). This structural feature has been refolded into a complex anticlinorium. The regional structure is cut by a lengthy northeast-trending fault containing a doloritic dike. Faulting in the Portel area appears to control the mineral deposition.

Minerals of the complex sulfide ore bodies are disseminated along microfractures within certain zones of the Cambrian dolomite, generally near the volcanic rocks. The Algares ore body contains pyrite, magnetite, pyrrhotite, barite, galena, sphalerite, and chalcopyrite. The ore minerals are concentrated in the anticlinal crests and controlled by faulting as well as by folding. Drilling has disclosed 5 - 7 million tons for two disseminated lenses of ore in dolomite, and 6.5 million tons of massive pyrite ore in mafic volcanic rocks. The average grade is 0.5 percent Pb, 4 percent Zn for the disseminated deposits, and 18 percent S, 26 percent Fe, and 0.25 percent Cu for the massive sulfide deposit.

The Balsa ore body consists of lead and zinc sulfides associated with pyrite in dolomite. The mineral-bearing microfractures average 10 m in width and consistently follow the contact with the overlying volcanic rocks. The Balsa deposit contains about 4.5 - 6 million tons of disseminated lead and zinc in silicified dolomite. Its grade ranges from 0.6 to 0.75 percent Pb, and 2.35 to 2.75 percent Zn. The deposit contains 30 to 35 g/t of silver. As 90 percent of the known reserves are between the surface and 100 m depth, the mining will be by open pit (table 1).

Manganese

The earliest production of manganese in Portugal was probably by the Romans from the oxidized zone of the iron and manganese carbonate deposits that occur in the broad northwest-trending zone of primary sulfide minerals that constitute the lead zinc belt.

Cercal deposits

Manganese minerals of ore grade are contained in veins as much as 5 km long and 18 - 22 m thick in the Cercal mining area (fig. 3, loc. 19). The host rock for these veins is a complex metavolcanic and sedimentary sequence of Devonian age. These rocks comprise felsic tuff, phyllite, graywacke, quartzite, and jasparoid, and are intruded by diabase sills.

Minerals in the primary zone comprise iron and manganese carbonate, with minor amounts of the sulfides of lead, zinc, copper and iron along with substantial amounts of recoverable barite. The oxidized zone contains mainly manganese and iron as lepidocrocite, pyrolusite, geothite, hematite, and psilomelane, and amorphous manganese oxide. The average content of the ore is 43 percent Fe, 8 percent Mn, 0.04-0.2 percent P, and 0.2 percent S. The proven reserves are estimated at about 6 million tons of Mn (table 1).

REFERENCES

Beralt Tin and Wolfram Ltd., 1977, A short history to commemorate the 50th anniversary of the company. Charter Consolidated Report, London, 20 p.

Brink, A. H., Petrology and ore geology of the Vila Real-Sabrosa-Vila Pouca de Aguiar Region, Northern Portugal. Amsterdam Universiteit Geologisch Instituut, Mededeling No. 255, 20 figs., 114 p.

Carneiro, F. S., 1971, Potencialidades Minerais da Metropole, Arquivos de Servicos Geologicos Portugal, Direccao Geral de Minas e Servicos Geologicos, No. 2, Lisboa.

__________, 1978, Caracterizacao economica da industria extractiva. Realidades e fantasias. Ordem dos Engenheiros, Congresso 78, tema 3, comm. 26, Porto, 9 tables, 11 figs., 10 p.

Carvalho, A. M. G. and Martins, O. R. 1971, Rochas e minerais nao metalicos de Portugal. Livro-Guia da Excursao No. 8, I Congresso Hispano-Luso-Americano de Geologia Economica, Servicos Geologicos de Portugal Direccao - Geral de Minas e Servicos Geologicos, Lisboa, 66 p.

Carvalho, A. M. G., 1970, Sobre a existencia de bentonite em Portugal. Estudos, Notas e Trabalhos do Servico de Fomento Mineiro, v. XIX, fascs. 3-4, Porto, p. 299-307.

Carvalho, Delfim, Goinhas, J. A. C. and Schermerhorn, L. J. G. 1971, Principais Jazigos Minerais do Sul de Portugal. Livro-Guia da Excursao No. 4, I Congresso Hispano-Luso-American de Geologia Economica, Servicos Geologicos de Portugal, Direccao Geral de Minas e Servicos Geologicos, Lisboa, 94 p.

Conde, L. N., Pereira, V., Riberiro, A., and Thadeu, E. D., 1971, Jazigos Hipogenicos de Estanho e Volframio. Livro-Guia de Excursao No. 7, Congresso Hispano-Luso-Americano de Geologia Economica, Servicos Geologicos de Portugal, Direccao Geral de Minas e Servicos Geologicos, Lisboa, 81 p.

Goinhas, J. A. C., 1972, Mining industry in Portugal-an outline. University of Arizona, Deptartment of Geological Engineering informal report, 18 p.

__________, in press, The southern Portugal zinc belt. Servicos Geologicos de Portugal, Lisboa, 9 p.

Macieira, F. A. C. G., 1977, Producoes, Exportacoes e Importacoes de Substancias Minerais de Portugal (Continente e Ilhas Adjacentes) EM 1975. Boletim de Minas, v. 14, no. 1, Servicos Geologicos de Portugal, Direccao Geral de Minas e Servicos Geologicos, Lisboa, 14 p.

Manuppella, G., 1969, Contribuicao para o conhecimento das rochas dolomiticas de Regiao de Setubal. Estudos, Notas e Trabalhos do Servico de Fomento Mineiro, v. XVIII, fasc. 3-4, Porto, 3 tables, 4 figures., p. 323-339.

Mining Magazine, Panasqueira develops for the future, August 1979, p. 96-103.

Moncorvo-Ferrominas, E. P., 1977, Moncorvco Iron Ore Project, informal report, Lisboa, 15 p.

Skillings, D. N., Jr., 1968, Moncorvo Property in Portugal. Skillings' Mining Review, v. 57, no. 9, p. 1 and 4.

Sluijk, D., Geology and tin-tungsten deposits of the Regoufe area, Northern Portugal. Amsterdam Universiteit Geologisch Instituut, Mededeling No. 286, 7 plates, 123 p.

Soen, O. I., The geology, petrology and ore deposits of the Viseu Region, Northern Portugal. Amsterdam Universiteit Geologisch Instituut, Mededeling No. 247, 8 plates, 179 p.

Sondermayer, R. V., 1975, The Mineral Industry of Portugal. U. S. Bureau of Mines Minerals Yearbook, p. 817-828.

Teixeira, C., 1972, Carta Geologica de Portugal na escala 1:500,000. Servicos Geologicos de Portugal, Lisboa.

Zitzmann, A. (ed.), 1970, The Iron Ore Deposits of Europe and adjacent Areas. Survey of World Iron Ore Resources, United Nations Sec-Gen Report, v. II, New York, p. 144, table 1.

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