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Joint Peru/United States Report on Peru/United States Cooperative Energy Assessment

MASTER

Volume 2 of 4 Vols.
Annex 1

August 1979

MASTER

U.S. Department of Energy
Assistant Secretary for International Affairs

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ENERGY RESOURCES OF PERU

By the U. S. Geological Survey

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

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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PROJECT REPORT
Peru Investigations
(IR)PE-6

ENERGY RESOURCES OF PERU

Prepared by the U.S. Geological Survey on behalf of the Government of Peru and the U.S. Department of Energy.

1979

ENERGY RESOURCES OF PERU

BY THE U.S. GEOLOGICAL SURVEY

INTRODUCTION

Purpose

Energy resources for the future are of great concern to all nations, regardless of the state of their industrial development, and regardless of how well they are presently endowed with known supplies of conventional fuels. In most developing countries, these concerns are exacerbated by inadequate knowledge of domestic resources; shortages of expertise, and funding for exploration, evaluation, and development of new supplies; high costs of importing needed fuels from abroad; and other factors. To arrive at the best available long-range solutions to meet future demands for energy, governmental energy policies need to be based on comprehensive assessment of the discovered and the potential energy resources, and on an understanding of the factors involved in the development and use of those resources.

Development of new sources or major enlargement of known sources of energy is a many faceted, highly complex, and expensive undertaking. Of necessity it should start from an adequate grasp 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. Department of the Interior, is investigating the possibilities for assisting developing nations to identify their alternative domestic sources of energy. For the Department of the Interior, the first phase of the investigation for each of the selected countries was to compile and evaluate the information at hand concerning energy resources, along with projections of supply and demand for energy. Preliminary evaluations of information available in the United States have been made for several countries, one of which is Peru. (See figs. 1 and 2).

The second phase of the project has involved in-country visits by U.S. Geological Survey (USGS) teams of energy specialists and evaluation of each of the significant nonrenewable energy sources, including geothermal and nuclear energy. This investigation was carried out in close collaboration with Peruvian counterparts and presents the findings of the USGS as the results of these in-country studies.

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Figure 1. Index map of Peru.

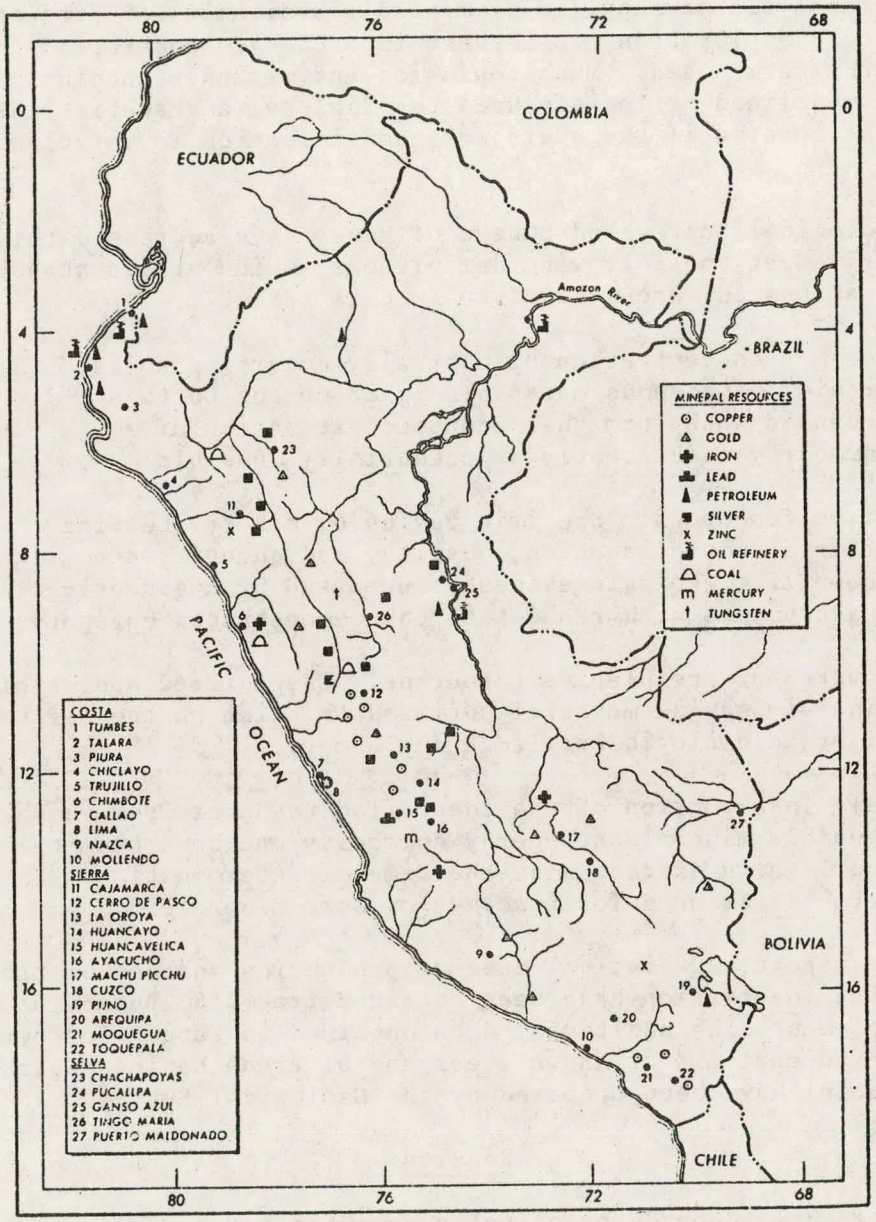


Figure 2. Major Peruvian mineral resources

Reference: Weil, and others, (1972, p. 290)

Methods

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 Geological Survey and Bureau of Mines 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 that economic extraction of a commodity is currently or potentially feasible.

Identified resources: Specific bodies of mineral-bearing material whose location, quality, and quantity are known from geologic evidence supported by engineering measurements with respect to the demonstrated category.

Undiscovered or speculative resources: Unspecified bodies of mineral-bearing material surmised to exist on the basis of broad geologic knowledge and theory.

Reserve: That portion of the identified resource from which a usable mineral and energy commodity can be economically and legally extracted at the time of determination. The term ore is used for reserves of some minerals.

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

Results

Peru presently depends principally on petroleum and hydropower for its energy requirements. These meet present requirements, but improvement in living standards for its people and industrialization will demand greatly increased supplies of energy.

Petroleum is the principal source of energy. With the completion and operation of the pipeline from northeast Peru across the Andes, Peru has very recently become self-sufficient in petroleum. New oil and gas

fields must be found, however, to replace dwindling supplies from older fields, and to provide any surplus for export. The geologic setting of known oilfields is reviewed and figures for estimated reserves are cited. In general, Peru is believed to have large additional potential for oil and gas, particularly in the jungle east of the Andes, but exploration for and development of new oilfields will be difficult, expensive, and time-consuming.

Eleven separate coal fields are known in Peru; complex structure and high ash content of much of the coal has precluded other than minimal utilization of the coal to date. Some of the coal is of coking quality. Geology of the more promising coal fields is reviewed, but reserves for the future are uncertain because of lack of relevant and adequate data. Coal potential for electric power and for coke needs to be carefully investigated, in order to utilize this significant though not large energy resource.

Various reconnaissance investigations between 1933 and 1972 have been made for uranium. These were almost entirely confined to the more easily accessible parts of western Peru. Although some areas of low-level radioactivity were detected, no deposits of possible economic potential were identified. An appraisal of the general geology of Peru suggests that unexplored eastern Peru may present a more favorable geologic environment for the occurrence of nuclear minerals than does western Peru.

Potential for geothermal energy, especially in southern Peru, is believed to be present and could be large. No serious investigations of this potential seem to have been made. Field investigations should be started as soon as possible, followed by drilling.

The report also includes a section on water needs and a section on energy-related minerals needed in connection with development of new supplies of energy from non-renewable sources.

STATUS OF ENERGY SUPPLY

Population

The population of Peru is currently about 16,000,000, up from about 13,600,000 in 1973. Of the total, 46 percent is American Indian, 43 percent is mixed, and 11 percent is Caucasian. Population density averages about 12 per km^2. Just over half the population lives in the 10 departments that front on the Pacific Ocean.

The large cities of the country are growing at an average rate of 5.5 percent per year. Lima, the national capital, and its port city, Callao, together have more than 3,700,000 people. Lima is growing at the rate of 4.55 percent a year, a rate that will bring it to 12,000,000 inhabitants by the year 2000. A considerable part of the growth of urban population has come by migration of rural people from the mountains (Organization of American States, p. 68), who have settled in makeshift shanty towns on the outskirts of the cities, especially Lima. These settlements always seem to grow faster than city services can be extended to them, and they therefore exist without electricity, water, and garbage collection, or at best, have a minimum of such services.

Production and consumption

As a developing country in the early stages of industrialization with an income of $760 per capita, Peru's energy demand is relatively low. Peru ranks in 44th place worldwide in consumption of energy, which in coal-equivalent terms is estimated to be 800 kilograms per capita, compared with 3,300 kilograms for France and 9,700 kilograms for the United States. On the basis of 1974 income, in Peru, 1.03 kilograms of coal-equivalent energy was required to produce $1.00 of GNP (gross national product), compared with 1.79 kilograms for the United States. In 1976, primary energy consumption reached 84,000 teracalories (1 Tcal = 10^{12} calories); the energy was derived from resources as shown in table 1. Since 1965, energy consumption has been increasing at a rate of 5.2 percent per year.

Relative to the country's present stage of development, the availability of energy from domestic and imported sources is considered adequate. Peru's demand for energy is, however, expected to increase as her standard of living improves. It needs to be emphasized that a large part of Peru's potential demand is not being satisfied. There are many small villages and rural communities throughout the country that do not enjoy the social and economic benefits of electrification. About 30 percent of the population is supplied with electricity.

Table 1. Primary energy consumption in Peru and dependence on primary energy imports.

Primary energy consumption in Peru

TYPE OF ENERGY	YEAR						
	1965		1970		1976		
	Tcal	% of total	Tcal	% of total	Tcal	% of total	Annual Increment (%)
HYDROPOWER	2868	5.8	4107	6.6	6158	7.3	7.2
NATURAL GAS	5056	10.2	4598	7.3	5332	6.4	0.5
OIL	30049	60.9	40782	65.2	57285	68.2	6.0
COAL	224	0.5	373	0.6	402	0.5	5.5
WOOD	7538	15.3	8798	14.1	10190	12.1	2.8
BAGASSE	3611	7.3	3851	6.2	4601	5.5	2.2
TOTAL	49344	100.0	62509	100.0	83968	100.0	5.2

Dependence on primary energy imports

YEAR	TOTAL CONSUMPTION (Tcal)	IMPORTS (Tcal)	SHARE OF IMPORTS IN CONSUMPTION (%)
1965	49344	1649	3.3
1970	62509	7881	12.6
1975	82868	23650	28.5
1976	83968	23166	27.6

The growth of Peru's economy has not been plagued by critical energy shortages. Large mining projects located far from established power centers have independent energy supply facilities as an integral part of the investment. Given the importance and energy demands of mining in Peru, this explains why a large part (37 percent) of total installed electrical capacity is controlled by independent generators.

The development of Peru's energy system has required great amounts of capital. In 1976, the $334 million 1/ investment in energy amounted to 2.4 percent of the GNP of $13.7 billion. On the other hand, energy development in 1976 represented 30 percent of total public investments. Currently, the energy sector employs 19,000 workers, or 0.3 percent of the economically active population.

For its energy requirements Peru depends primarily on petroleum, wood, abundant hydroelectric sources, natural gas, and to a small extent on bagasse. In 1976, Peru imported 28 percent of its energy needs. Peru is considered to be well-endowed with hydroelectric resources. In 1976, the latest year for which data are available, about 7 percent of all energy consumed in the country and about 74 percent of all electric energy generation was dependent on water power. Peru formerly produced and exported crude petroleum, but because of rising domestic demand, crude exports were discontinued in 1963. With the completion of the Trans-Andean pipeline in 1977, Peru expects to have once again a surplus of petroleum for export. The use of coal as an energy source is insignificant. Limited amounts of metallurgical coal are imported for the small steel plant at Chimbote. Nuclear sources and the non-conventional sources of solar, wind, geothermal power are not currently exploited.

Resources being exploited

Peru has taken good advantage of its hydroelectric potential. As shown in table 2, Peru's total installed electrical power capacity officially reported for 1976 was 2,473 megawatts, of which hydroelectric sources accounted for 57 percent and thermal electric sources 43 percent.

The growth of electrical capacity has generally kept in step with Peru's economic growth. The growth in hydroelectric sources has been more pronounced relative to thermal sources and its rate has fluctuated between 28 percent increase in 1965 to 9 percent increase in 1974. In 1976 in the large Lima area, demand increased 7.3 percent over the previous year. Construction of installed capacity has advanced such that there has not generally been an "energy gap" relative to demand. In 1974, mining activities in Peru accounted for 27.5 percent of total electrical demand, while other industry accounted for 27.3 percent of the total electrical demand.

1/ Conversion was at the average 1976 rate of sales (S) 55.8=US$1.00.

Table 2. Total installed electrical capacity

YEAR	ELECTRICAL ENERGY GENERATION gigawatt hours (GWh)			INSTALLED CAPACITY megawatts (MW)		
	Hydro	Thermal	Total	Hydro	Thermal	Total
1965	2,868	1,338	4,006	693	604	1,297
1970	3,821	1,708	5,529	923	754	1,677
1975	5,470	2,016	7,486	1,397	962	2,357
1976	5,731	2,036	7,767	1,397	1,076	2,473
Annual Increment %	7.3	3.6	6.2	6.7	4.7	5.9

Source:

Energy Sector in Peru, Actual Situation and Perspectives, by Hermann Montalvan, Director, Energy Planning Office, Ministry of Energy and Mines, Lima, Peru, November 1977, P. 6, 8, 12 -- Working paper presented at United Nations meeting on Energy Planning in Developing countries organized by the U.N. Center for Natural Resources, Energy, and Transporation.

In December 1976, Peru completed construction of an 856-kilometer oil pipeline, with a capacity of 200,000 barrels per day, across the Andean range, to connect the jungle fields in northeastern Peru to the Pacific port of Bayovar. The first crude from the jungle arrived at Bayovar in May 1977. The pipeline fill of 36-inch line is 3 million barrels of oil. A 250-kilometer spur pipeline having capacity of 80,000 barrels per day was completed in 1978 to connect the Shiviyacu field to the Trans-Andean pipeline.

With the use of this new oil pipeline system, Peru is expected to increase crude oil output to 170,000 barrels per day by late 1978. Peru would thus achieve self-sufficiency in crude oil and be able to resume exports. Peru's refinery capacity was increased to 198,200 barrels per day with the completion of the expansion of La Pampilla refinery in 1977.

Natural gas plays a smaller part in Peru's total energy situation, supplying 6.4 percent of total energy needs. Output of natural gas during the past decade has been flat. After a peak of 77.1 billion cubic feet in 1969, output declined steadily until 1974 when it moved upward to 69.8 billion cubic feet. In 1975, the last year for which official data is available, output declined again by 7 percent to 64.9 billion cubic feet utilized as follows:

	(in billion ft^3)
Released to the atmosphere--	24.8
Used as combustible---------	19.9
Used as lift gas----------	13.8
Returned to the deposit-----	3.1
Liquefied gas----------	1.9
For fertilizer----------	1.4
Total----------	64.9

Prior to 1975, fertilizer plants were not built to use natural gas inputs. Natural gas in 1975 was produced in two areas: the northwest coast produced 36.8 billion cubic feet (57 percent) and the nearby Continental Shelf produced 28.1 billion cubic feet (43 percent). Natural-gas liquids produced in 1975 totaled 613,000 barrels and included propane, butane, and hexane. Bottled gas is used in Peru for domestic purposes.

SUMMARY OF PERU'S HYDROCARBON POTENTIAL, ESTIMATED RESERVES, AND PROJECTED PRODUCTION RATES

by

Robert E. Mattick and Keith A. Yenne

Abstract

Peru has recently become self sufficient in hydrocarbon production and wishes to increase that production in order to maintain this self-sufficiency. In the 1975-76 period, however, a combination of negative exploration results in the Amazon basins and shortcomings in the Peruvian formula for foreign participation in petroleum development led to an exodus of most foreign companies. This, coupled with Peru's lack of available capital for extensive exploratory ventures, has caused exploration for new fields to all but cease. As a result, future production rates are expected to peak in about 1981 and, thereafter, to decline rapidly. The Peruvian government, therefore, is trying to attract foreign oil companies into exploratory ventures on more favorable terms and has recently opened up vast areas for service contracts. These include about 25 million offshore acres on the Pacific continental shelf and 1,175 million acres in the Amazon region.

From discussions with officials of Petroleos del Peru and foreign oil companies operating in Peru, the authors estimate that the total of Peru's measured, indicated, and inferred reserves of oil are about 1,095 million bbl. If new exploratory ventures to locate undiscovered oil deposits are not initiated, we expect Peru's oil production to peak at about 81.9 million bbl/yr in 1981, level off at about 70 million bbl/yr in the middle 1980's, and then rapidly decline to about 10 to 15 million bbl/yr in the year 2000. We believe that our predicted decline in production, at least through the early to middle 1980's, is irreversible because of the time lag that normally exists between exploration and production phases.

On the other hand, initiation of exploratory ventures in the next 10 years could significantly reverse the predicted low production rates for the late 1980's. The authors estimate, that in addition to the 1,095 million bbl of "identified" reserves, Peru has undiscovered recoverable oil resources of 2,060 million bbl. We include in this undiscovered category only those amounts of oil which might exist chiefly in structural traps of the Amazon region (1,490 million bbl) and in traps on the Continental Shelf and in onshore coastal basins (570 million bbl), that is, undiscovered resources which might be discovered in the next 10 years as a result of standard seismic exploratory methods. Assuming that 1,030

million bbl can be moved into the measured-reserve category by the 1990's, production in Peru could reach 116 million bbl/yr in the year 2000.

Depending upon advances in deep-water production technology and Peru's success in new exploration, our long-range predictions for oil production could be greatly exceeded. The reason for this is that our projections do not include estimates of undiscovered oil resources that might exist in deep waters beyond the Continental Shelf and in stratigraphic traps in the Amazon region. These oil reserves could be substantial--especially those probably associated with stratigraphic traps in the Amazon region. At the present time, however, the authors do not believe that these resources can be brought on-line much before the year 2,000. The search for stratigraphic traps in the Amazon basins must follow extensive accumulation of more subsurface information from drilling and must be aided by seismic stratigraphic studies.

Introduction

Peru, with an area of about 1,300,000 square km and a population of nearly 16 million, has recently become self sufficient in hydrocarbons. Like other developing nations, Peru wishes to increase her hydrocarbon production in order to maintain this self sufficiency and, as industrialization expands, to develop exportable surpluses. This report presents an overview of Peruvian geology, reviews the history of development of hydrocarbons in Peru, and considers future prospects for hydrocarbon production. The sections concerning Peruvian geology and the history of hydrocarbon development were written by Robert Garrison, Craig Glenn, and Gary Younse, and much of this information represents a distillation of a rapid survey of publications available in the United States.

Although available published information provides adequate descriptions of the basic stratigraphy, structure, geologic history, and petroleum geology of Peru, relatively few publications deal with more specialized topics such as analyses of depositional systems and tectonic development. Selected key references are included, and we thank Robert C. Morris of Northern Illinois University and Alfred C. Fischer of Princeton University for helpful discussions and directions to the appropriate literature.

The estimates of hydrocarbon reserves and projected future production rates presented in this report were made by Keith Yenne and Robert Mattick of the USGS. We spent approximately 4 weeks in Peru discussing present and future hydrocarbon production rates with Peruvian government officials, geologists, geophysicists, and engineers of Petroleos del Peru (PetroPeru), and with scientists of foreign oil companies (Occidental and Belco) presently working in Peru. We thank the personnel of PetroPeru, Occidental, and Belco for their many enlightening discussions, their explanations of Peruvian geology, and their help in making seismic records, drilling results, and

production figures available. The long-range production predictions contained herein, however, represent judgments (scientific, but in some cases value judgments, such as those pertaining to the time frame in which future exploration will occur) made solely by Mattick and Yenne.

The authors' objective in writing this paper is to present an overview of Peru's hydrocarbon production potential and, therefore, we have not attempted to analyze the various stratigraphic and structural elements that relate to the occurrence of petroleum accumulations in the basins of Peru. In particular we have presented no discussion of the characteristics of the various plays that have been identified in the Oriente basins nor of details of the past exploration in them. Such an analysis would require a much more in-depth study than undertaken to date and would involve such little known factors as depth to basement, possibilities for stratigraphic traps, fault traps, etc.

Regional geology

Geologic history

Peru lies at the convergent boundary between the Nazca and South American tectonic plates. Consequences of the collision between these plates include the down-bowing of the Peru-Chile trench west of Peru and the andesitic volcanism of the Andes. In late Paleozoic time, the region encompassing Peru apparently was a passive margin, and two thick sequences of Paleozoic shelf sediments were deposited in the Amazon area east of the present Andean volcanic area (fig. 3). The initiation of Late Triassic or Early Jurassic plate underthrusting was marked by the accumulation of volcanic-arc deposits in the area now known as the Western Cordillera. This volcanic arc formed at or west of the present coast of South America. Igneous activity has since migrated eastward, culminating in a major Pliocene-Pleistocene volcanic episode (fig. 3). Cenozoic volcanism has been episodic. This periodicity may be due to differential spreading rates at the East Pacific Rise. Crustal dilation, being the result of igneous intrusion below the volcanic cordillera, has produced eastward compression of the Paleozoic and Mesozoic sedimentary rocks that form an easterly belt of fold and thrust mountains. Significant events that evolved during the convergence of the plate boundaries were: (1) The formation of the hydrocarbon-bearing basins of the coastal belt (fig. 4) between the trench and the arc in Late Cretaceous-early Tertiary time, and (2) deposition of the oil-bearing fluvial-deltaic sandstones in the Amazon basins east of the arc during Cretaceous time.

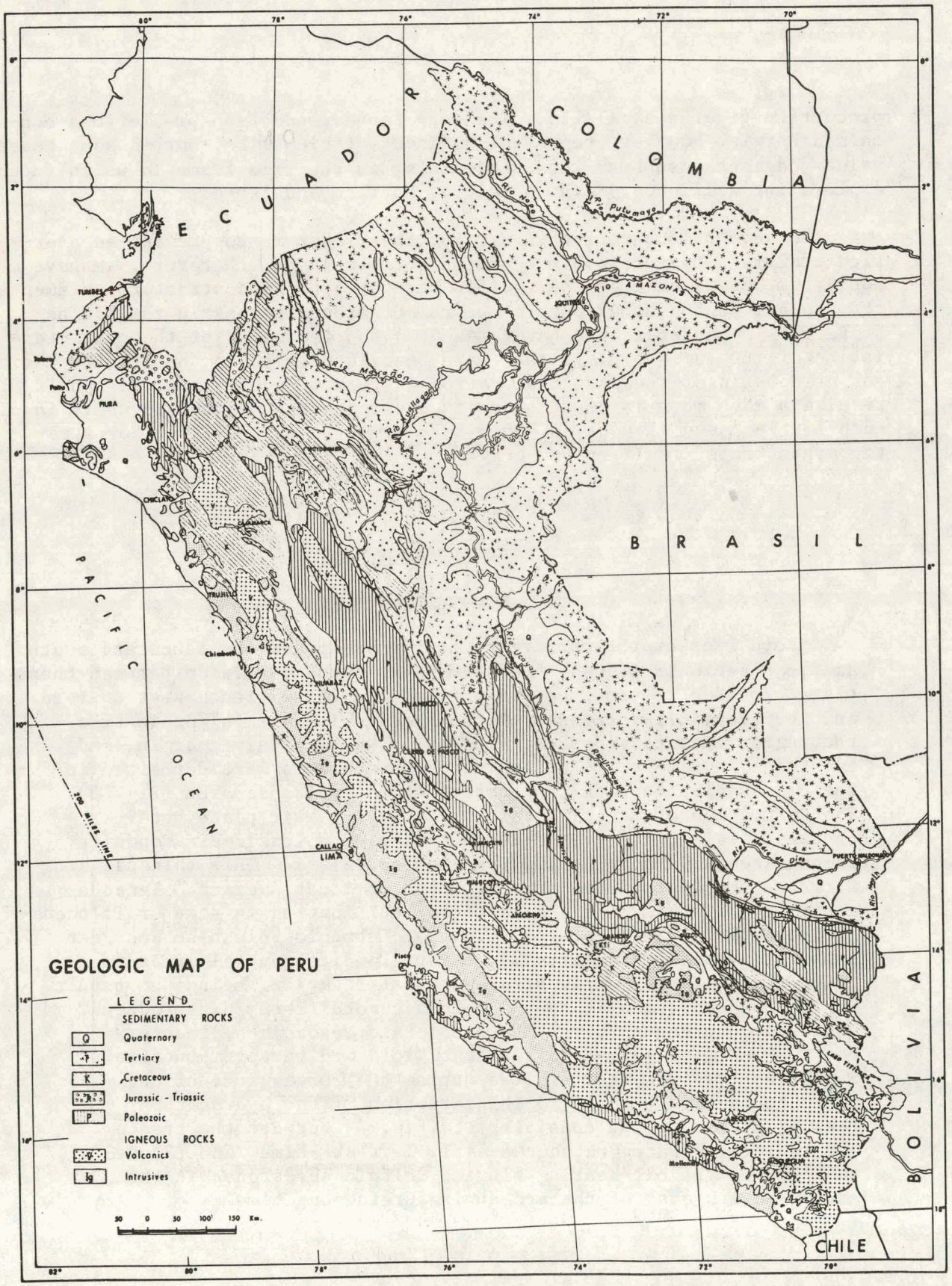


Figure 3. Geologic map of Peru. From: PetroPeru, 1975.

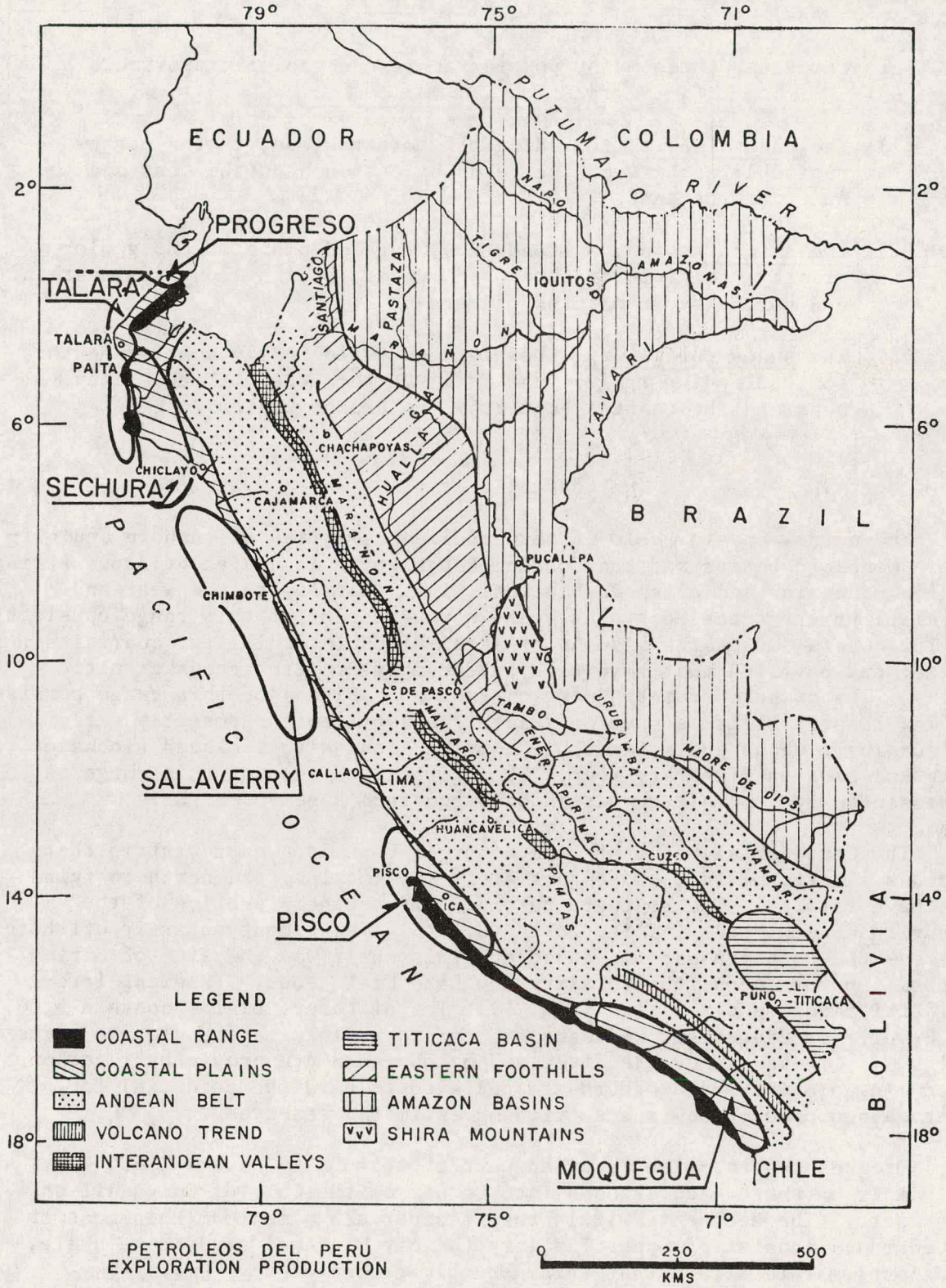


Figure 4. Morpho-structural map of Peru.

From: Travis and others, 1976.

Peru comprises three major physiographic and geologic provinces (fig. 4).

(1) The coastal belt, including offshore regions, is the narrow region lying between the Peru-Chile trench on the west and the Andes on the east.

(2) The Amazon region, a broad, low, jungled plain which, geologically, consists of three sedimentary basins along the eastern and northeastern margins of Peru.

(3) The Andes Cordillera, the high and geologically complex north-south trending ranges that form the backbone of Peru. They separate the coastal belt from the Amazon region.

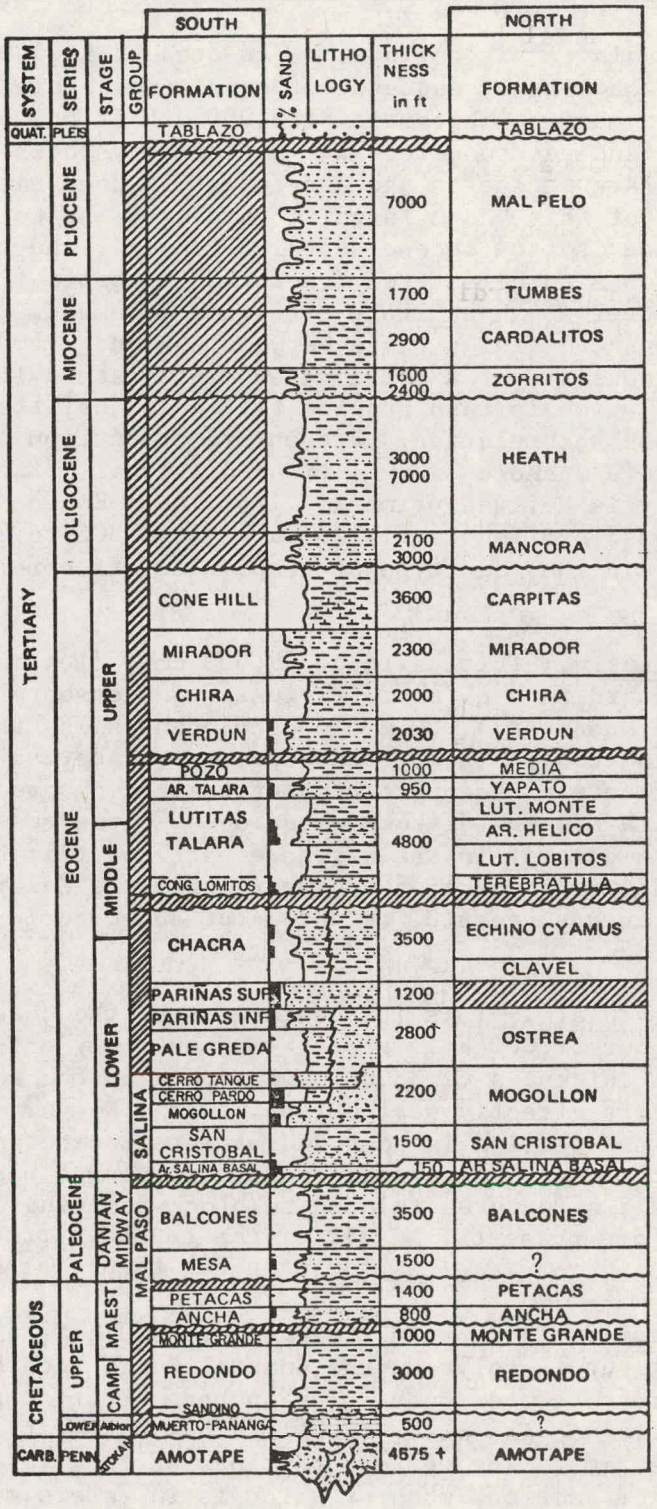
Coastal belt

The narrow coastal belt of Peru includes a series of onshore and offshore Cenozoic basins and the Coastal Range which is a discontinuous string of low mountains and offshore basement highs that lie to the west and parallel to the Andes Mountains. The northern part of this range consists of low coastal mountains made up of late Paleozoic argillite, quartzite, slate, and phyllite that have been intruded by Pre-Cretaceous granitic rocks. The onshore southern portion (south of Pisco) of this range consists of low coastal hills made up of a late Precambrian (and possibly early Paleozoic) igneous and metamorphic complex along with isolated blocks of late Paleozoic sedimentary rock. The offshore portion of this range is represented by a persistent trend of subsurface basement highs.

The Continental Shelf off the coast of Peru is a narrow strip that reaches a maximum width of approximately 100 km along the northern third of the coastline. The southern part of this northern section of the Peruvian coastal belt (latitudes 5° to 14°S) lies almost entirely offshore, whereas the northern part is onshore. This shelf was the site of marine deposition throughout the Tertiary and Late Cretaceous. Basement irregularities define six basins (fig. 4). The different basins contain 5,000 to 8,000 m of Cretaceous and Cenozoic strata, mainly marine clastic rocks (fig. 5). These basins are discussed below--some are proven hydrocarbon producing provinces and others are believed to have the potential for hydrocarbon production (see section on estimated reserves).

Progreso basin.--The Peruvian part of this basin covers 2,500 km^2, is mainly offshore, and extends into Peru from the Gulf of Guayaquil on the north. The sediments within this basin reach a maximum thickness of 6,000 m and consist of upper Tertiary (mainly Miocene) sandstone, shale, and conglomerate strata that thin abruptly to the east as they change from marine to fluvial facies. Numerous normal faults, gravity slides, and domal and anticlinal structures have been interpreted in seismic records.

Figure 5. GENERALIZED STRATIGRAPHIC COLUMN - NW COASTAL AREA - PERU



From: PetroPeru,
unpublished data.

Although this basin is relatively small, oil has been discovered in clastic rocks of Miocene age in Peru and Ecuador (fig. 4).

Talara basin.--This basin, has an area of 16,500 km^2, lies mostly offshore and contains a sequence of sandstone, shale, and conglomerate that reaches a maximum thickness of 8,000 m. It has produced the bulk of Peru's oil and gas to date. The sedimentary rocks of this basin are Campanian to late Eocene in age and represent deep marine to fluvial facies. The structure of this basin is quite complex owing to severe faulting (fig. 6). Production is from Eocene deltaic, fluvial, and turbidite sandstones. Some production also comes from fractured Paleozoic (Pennsylvanian) rocks which otherwise constitute effective basement. Depths to producing horizons in onshore fields range between 450 and 2,500 m. The northwestern onshore area consists of a complicated, intricate system of high-angle normal faults which in turn provide tilted and uplifted fault-block traps for hydrocarbon accumulation. Presently, production of 34,000 bbl/day comes from PetroPeru's onshore oilfields. Additional offshore production of about 30,000 bbl/day is derived primarily from lower Eocene sandstones. Depths to pay horizons in offshore fields range from 300 to 3,000 m. Tilted fault blocks are again the main type of trap. The offshore fields are operated by Belco.

Sechura basin.--This basin of 29,000 km^2, lies mainly onshore but extends southward into offshore regions. The onshore portion contains a maximum thickness of 3,000 m of post-Eocene silty shale and soft argillaceous sandstone. These rocks are representative of marine to brackish water environments. Phosphate beds of commercial grade are present and are associated with Miocene diatomaceous rocks. Numerous faults and closed structures are present in the offshore parts of this basin. Attempts to extend oil and gas production southward from the Talara basin to the Sechura basin have been unsuccessful to date, but subeconomic gas deposits have been identified.

Salaverry basin.--This is the largest of the coastal basins, having an area of about 54,000 km^2, and it lies entirely offshore. This basin has a maximum thickness of 3,000 m of strata in the northern part and 4,000 m in parts directly west of the Coastal Range. Sparse well data suggest that the section is composed of late Eocene and post-Eocene marine shale, siltstone, and calcareous rocks overlying a basal sandstone unit. Numerous closed structures related to block faulting and broad flexures or low folds are present. No oil or gas has been produced from this basin, although, to date, exploration has been sparse.

Pisco basin.--This basin, covering 25,000 km^2, lies offshore in its northern part but is split by the Coastal Range into both offshore and onshore portions to the south. The onshore strata consist of as much as 2,500 m of Miocene diatomite, fossiliferous shale, fine tuffaceous sandstone, and phosphate beds. The western portions of this yet untested basin contain over 3,000 m of section, much of which is in waters more than 1,000 m deep.

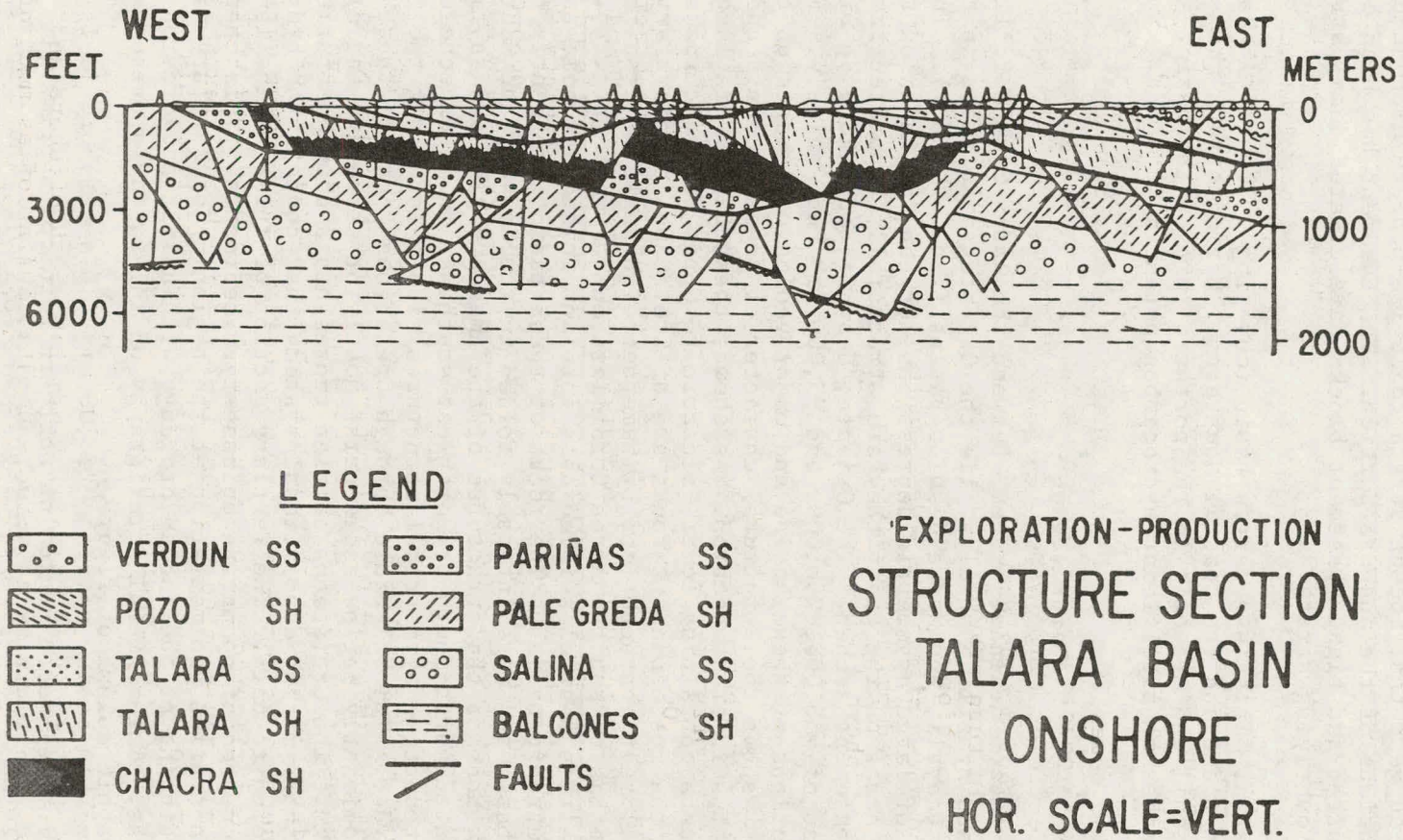


Figure 6. Structure section of onshore Talara basin.
From: PetroPeru, 1975.

Seismic surveys suggest that Eocene strata could lie beneath Miocene beds in seaward extensions of the onshore portion. The basement has been extensively block faulted and higher basement blocks have created domal structures with closure in overlying strata.

Moquegua basin. This is a narrow basin (covering 19,000 km^2) that lies between the Andes and the Coastal Mountains. Marine strata are volumetrically small and are only in the northern part of the basin. This basin thus possesses no significant hydrocarbon potential.

Amazon region

Within the Amazon drainage system, between the Andes East Cordillera and the Guyana and Brazilian shields, lie the Oriente (also known as the Maranon basin), Ucayali, and Madre de Dios basins (figs. 7 and 8). These basins are part of large asymmetric depressions between the Andes on the west and shield areas on the east; they are structurally separated from one another by basement arches. The Oriente, Ucayali, and Madre de Dios basins have areas of 458,000, 200,000, and 95,000 km^2 respectively. Figure 7 shows the locations of these basins and major geologic elements of the region. Figure 8 shows the structural character of these elements and their relationships in cross section. As shown, these basins are large sedimentary troughs containing lower Paleozoic to Upper Cenozoic rocks. Volumetrically, the most abundant rocks are of Cretaceous and Tertiary ages. A foothill belt characterized by numerous high-angle reverse faults lies between the basins and the Andes Cordillera on the west (fig. 7). This foothill belt is best classified as a foreland foldthrust belt and the basins as retroarc basins. The rocks of these basins are gently folded in the Oriente basin and more intensely folded in the Ucayali and Madre de Dios basins. Most of the structures of the Amazon basins are asymmetric anticlines oriented north-south or northwest-southeast in an en echelon arrangement. Productive symmetrical structures also exist along the Peru-Ecuador border. The Paleozoic through Cretaceous rocks of these basins are predominantly marine and consist mostly of carbonate and clastic sedimentary rocks. The Cretaceous section represents a complex of fluvial deltaic and offshore marine depositional systems that contain the hydrocarbon reserves discovered to date. The Tertiary section of these basins is predominantly composed of nonmarine molasse-type sediments. This change from marine to nonmarine sedimentation at the beginning of Tertiary time reflects the beginning of the Andean orogeny, with uplift and erosion of Andes cordilleras. The regional stratigraphy of this area is presented in the stratigraphic column of figure 9.

Production in the Amazon region of northern Peru comes primarily from fields in the Oriente (Maranon) basin (table 3; fig. 10). The traps are predominantly faulted anticlines, located primarily by seismic surveys. Reservoir rocks are Upper Cretaceous sandstone of the Vivian and Chonta Formations that are parts of deltaic complexes. The sandstone beds were

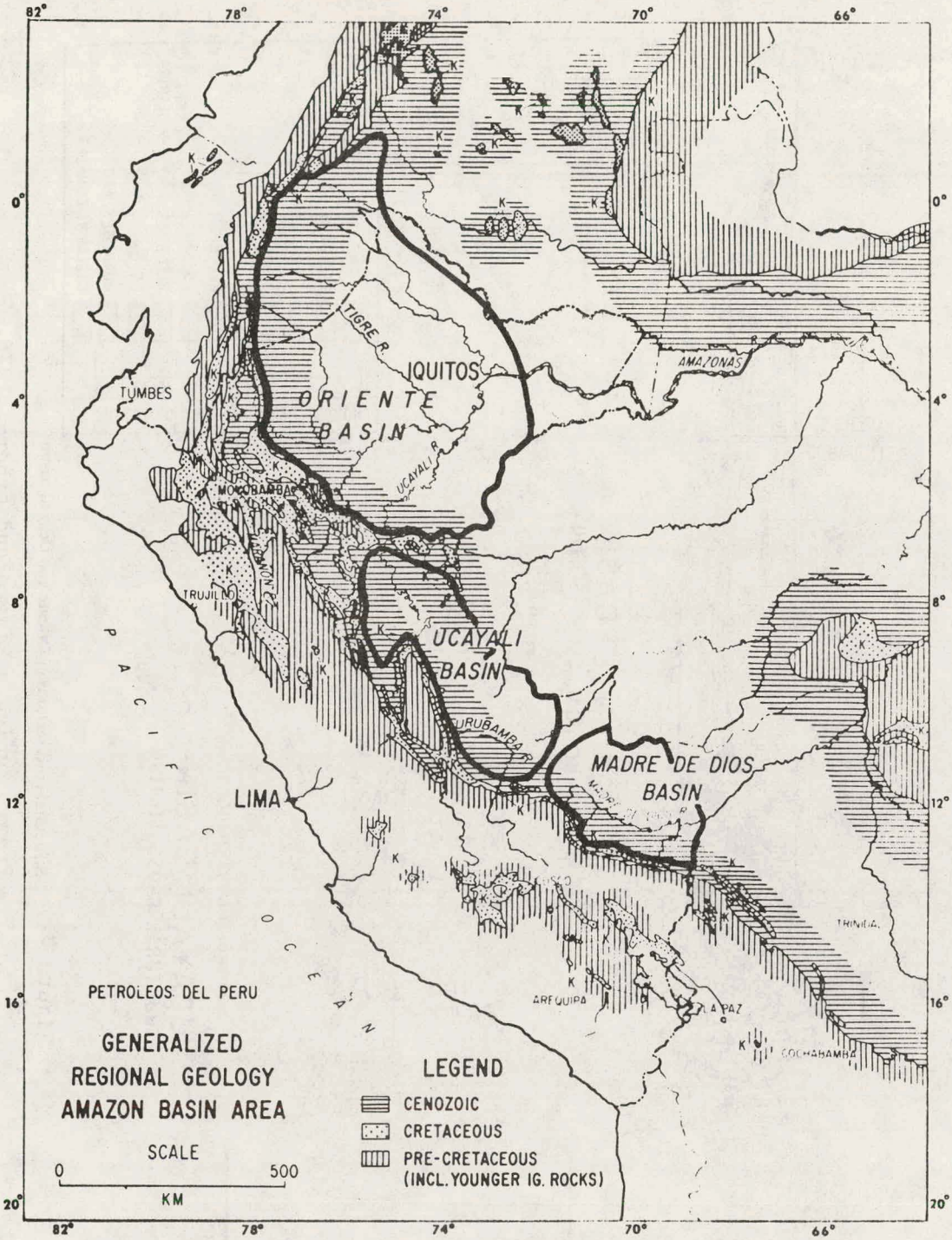


Figure 7. Generalized regional geology of Amazon basin area.

From: Zuñiga y Rivero and others, 1976.

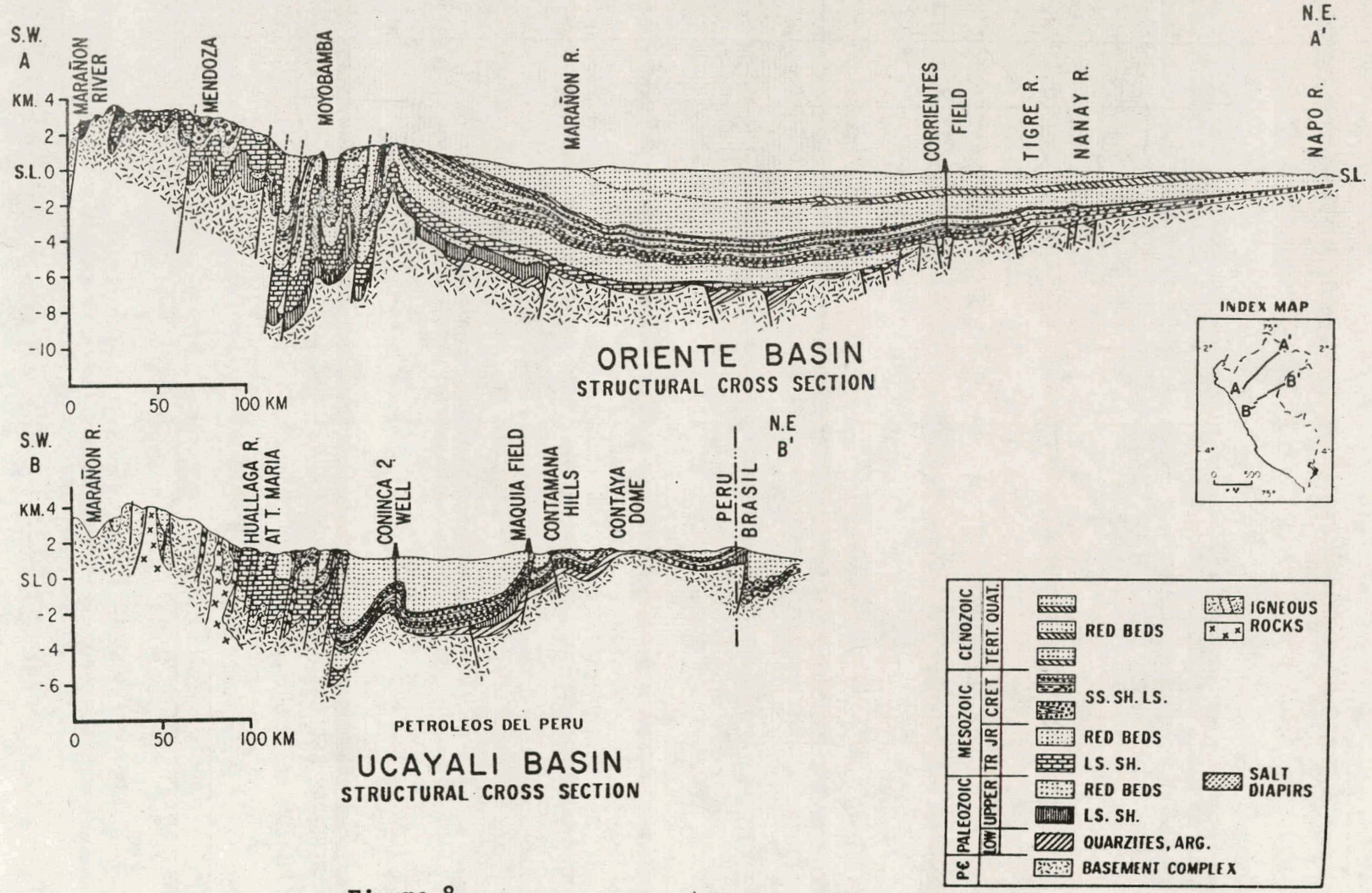


Figure 8. Structural cross sections of Oriente and Ucayali basins.

From: Zuñiga y Rivero and others, 1976.

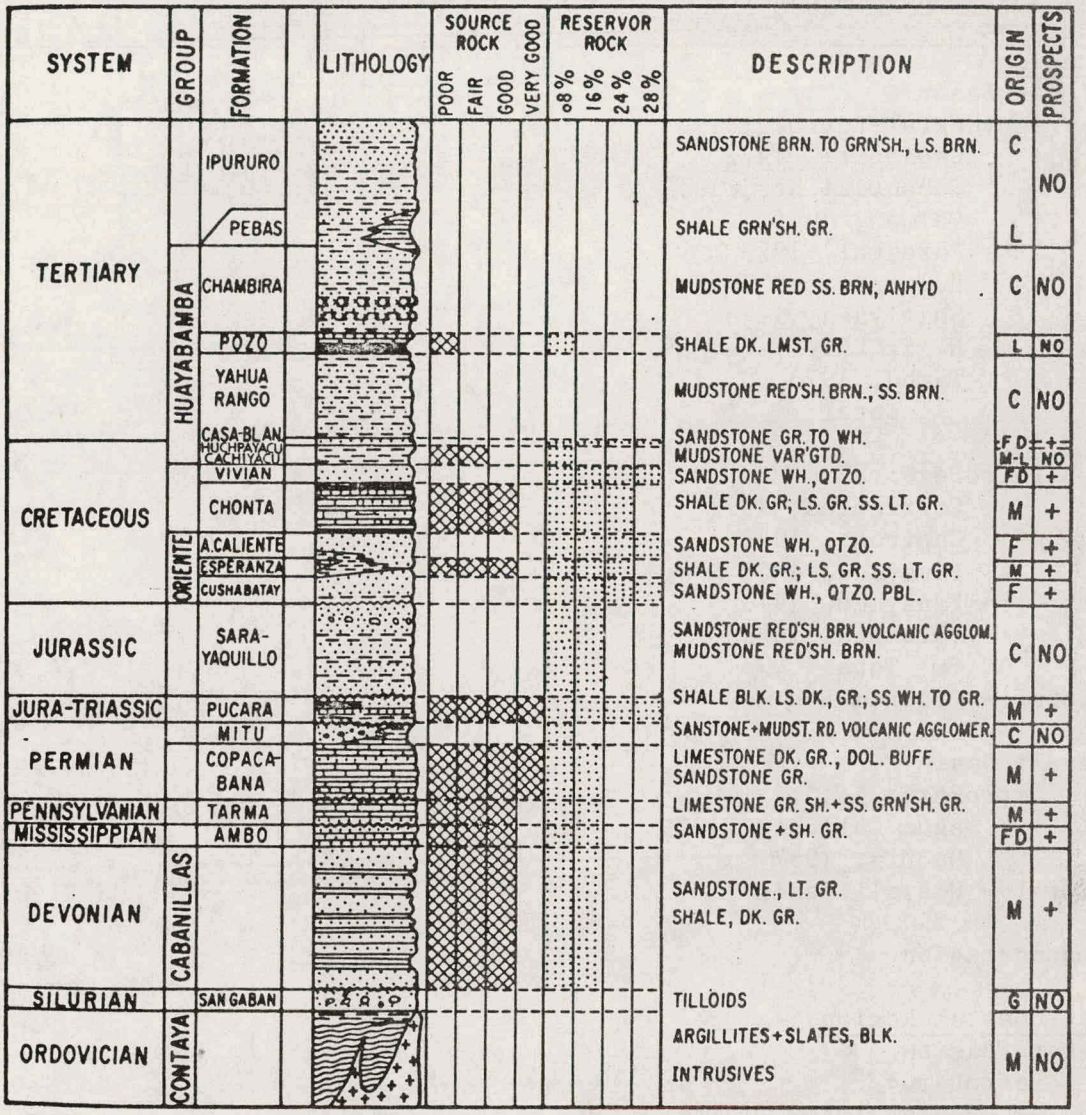


Figure 9. Composite stratigraphic column, eastern Peru.

From: Zuñiga y Rivero and others, 1976.

Table 3. Oil production in Peru
(Oil and Gas Journal, 1977c.)

Region, basin, company, field, and discovery date	Production (barrels) Daily average 1/1/77 to 7/1/77	Total cumulative 7/1/77
Amazon Region		
Oriente Basin		
Occidental-PetroPeru:		
Capahuari, 1972	a	a
Capahuari Sur, 1973	a	a
Carmen, 1975	a	a
Forestal, 1973	a	a
Huayuri Sur, 1977	a	a
Shiviyaca, 1973	8,867	6,040,720
N. E. Shiviyaca, 1977	a	a
Tambo, 1973	a	a
Total	8,867	6,040,720
PetroPeru:		
Corrientes, 1971	14,419	4,943,728
Capirona, 1972	b	b
Pavayacu, 1972	b	b
Yanayacu, 1974	b	b
Valencia, 1975	b	b
Total	14,419	4,943,728
Total - Oriente Basin	23,286	10,984,448
Ucayali Basin		
PetroPeru:		
Agua Caliente, 1939	339	13,505,156
Maquia, 1957	984	7,771,928
Total - Ucayali Basin	1,323	21,277,084
Total Amazon region	24,609	32,261,532
Northwest Coastal Region		
Onshore Basins		
PetroPeru:		
Talara area fields, 1869	8,714	542,471,441
Lima area fields, 1905	24,157	296,713,414
Total	32,871	839,184,855
Offshore Basins		
Belco - Petroperu:		
Humboldt, 1960	25,200	69,807,000
Litoral, 1955	2,300	25,875,000
Providencia, 1967	1,100	10,827,000
Other (c)	--	509,000
Total	28,600	107,018,000
Total Northwest Coastal region	61,471	946,202,855
Total Peru	86,080	978,464,387

a shut-in until early 1978
b shut-in until mid-1977
c includes Zocala, Rincon, Humboldt Norte, and Parcela fields

derived from shield areas to the east, and they interfinger with deeper-water, more open marine deposits toward the west. Average depths to producing horizons are between 3,000 and 3,300 m. Occidental Petroleum and PetroPeru are the only operators in this basin. Total cumulative production from the Oriente basin to July 1, 1977 was nearly 11 million bbl (table 3). Production in the Ucayali basin (table 3) comes from Lower and Upper Cretaceous sandstones of the Cushabatay, Agua Caliente, and Vivian Formations. As in the Oriente basin, these sandstones are parts of shield-derived fluvial-deltaic complexes that interfinger with marine shales toward the west. The two producing fields in this basin, Maquia and Agua Caliente (fig. 10), both under the control of PetroPeru, have anticlinal traps. Depths to pay horizons range from 450 to 730 m. Cumulative production from the Ucayali basin to the middle of 1977 was about 21.3 million bbl (table 3).

Andes Cordilleras

The Andes of Peru contain two subparallel north-south trending fold belts: the late Paleozoic Eastern Cordillera, and the Mesozoic-Tertiary Western Cordillera. In southern Peru (southeast of Cusco) these fold belts are separated by the Altiplano basin (also known as the Titicaca Basin), an intermontane plateau filled with late Cretaceous and Tertiary molasse deposits (fig. 4). North of Cusco a jog in the trend of the Western Cordillera brings the two fold belts into juxtaposition with each other while pinching out the Altiplano intermontane basin. The East and West Cordillera fold belts are both structurally and compositionally distinct features. The Eastern Cordillera takes the form of an anticlinorum in which structures are fan shaped and have a flow cleavage in the axial region giving way to fracture cleavage at the margins. The Western Cordillera on the other hand rises above the gentle upwarps of its underlying Precambrian basement, the Arequipa massif. Within this belt exists a relic Mesozoic-Tertiary retroarc basin.

The Coastal batholith lies within the Western Cordillera and comprises middle Cretaceous to early Tertiary intrusive rocks that become progressively younger to the east. Cenozoic and Holocene volcanic rocks cover parts of the western and southwestern segments of the Andes (fig. 4).

The hydrocarbon potential of the Andean region appears low. The now abandoned Pirín Field is located in the Altiplano basin. Additional small fields may be discovered in this region. Some prospects may also exist in the Western Cordillera, where tar seeps from Mesozoic rocks are reported, and beneath the late Cenozoic Andean volcanic rocks. The complexity of the geology probably precludes serious exploration efforts in the foreseeable future.

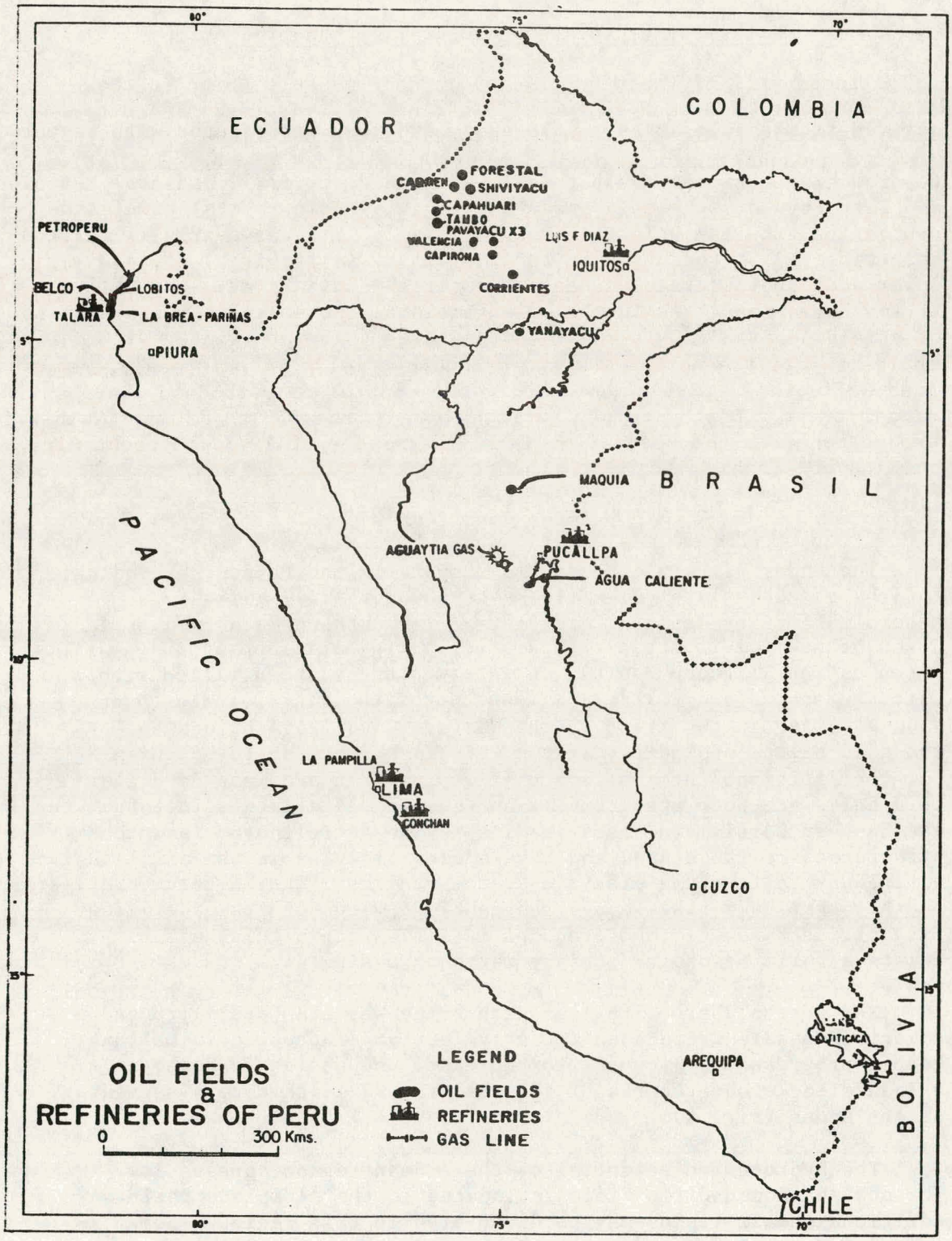


Figure 10. Oil fields and refineries of Peru. From: PetroPeru, 1975.

History of hydrocarbon exploration and production

The Incas utilized seepage oil and asphalt in Peru prior to the Spanish conquest, and such surface indications of hydrocarbons led to drilling as early as 1864. Reports of the first production in the northwestern coastal part of Peru date from 1874, and by 1900 cumulative production was estimated to have reached 275,000 bbl from the Negritos, Lobitos, and Zorritos fields (figs. 11 and 12). For the past 100 years most exploration and production has been concentrated in this northwestern coastal region, although in 1875 the now depleted Pirín field on the shores of Lake Titicaca was discovered on the basis of surface oil seeps.

Also stimulated by known oil seeps, exploration in the Amazon basins of eastern Peru began in 1919. The first discovery in this region was made in 1937, based on drilling of a surface anticline that was initially recognized during areal reconnaissance, but it was another 20 years before the second discovery was made in this remote and inaccessible jungle region.

Exploration in all of Peru lapsed during the 1940's, but the enactment of Law 11780 in the early 1950's and the advent of gravity and seismic surveys generated a surge of leasing and exploration by private operators in the 1950's and early 1960's. Gravity surveys led to the discoveries of the Tunal and Carpitas fields in the northwest coastal region during the mid 1950's, and seismic surveys were responsible for discovery of the Portachuelo field in the same region in 1954. Photogeology and seismic surveys located the anticlinal traps of the Maquia and Aguaytia fields of the Amazon region in 1957 and 1962. Seismic surveys eventually became the standard method of exploration and are credited with leading to the discovery of seven new offshore fields in Peru's northwestern region in the 1950's and 1960's (fig. 11).

These discoveries, however, were paired with a number of discouraging events. Attempts to extend the coastal production southward into the Sechura basin began early in the 1950's but ended without success in 1956. Lack of continued success in the Amazon region led to substantial decreases in exploration there. Finally, increasing political instability in the 1960's culminated in the revolution of 1968, following which the oil fields and other property of the International Petroleum Company in the Talara area were nationalized. A 1969 law prohibited the granting of new concessions to private firms, and in the same year the new state oil company, PetroPeru, was created by restructuring and expanding its predecessor, Empresa Petrolera Fiscal.

The situation changed once again in 1970 with implementation of the so-called "Peru Model" in which private companies were invited to act as operators but were required to enter into partnerships (under

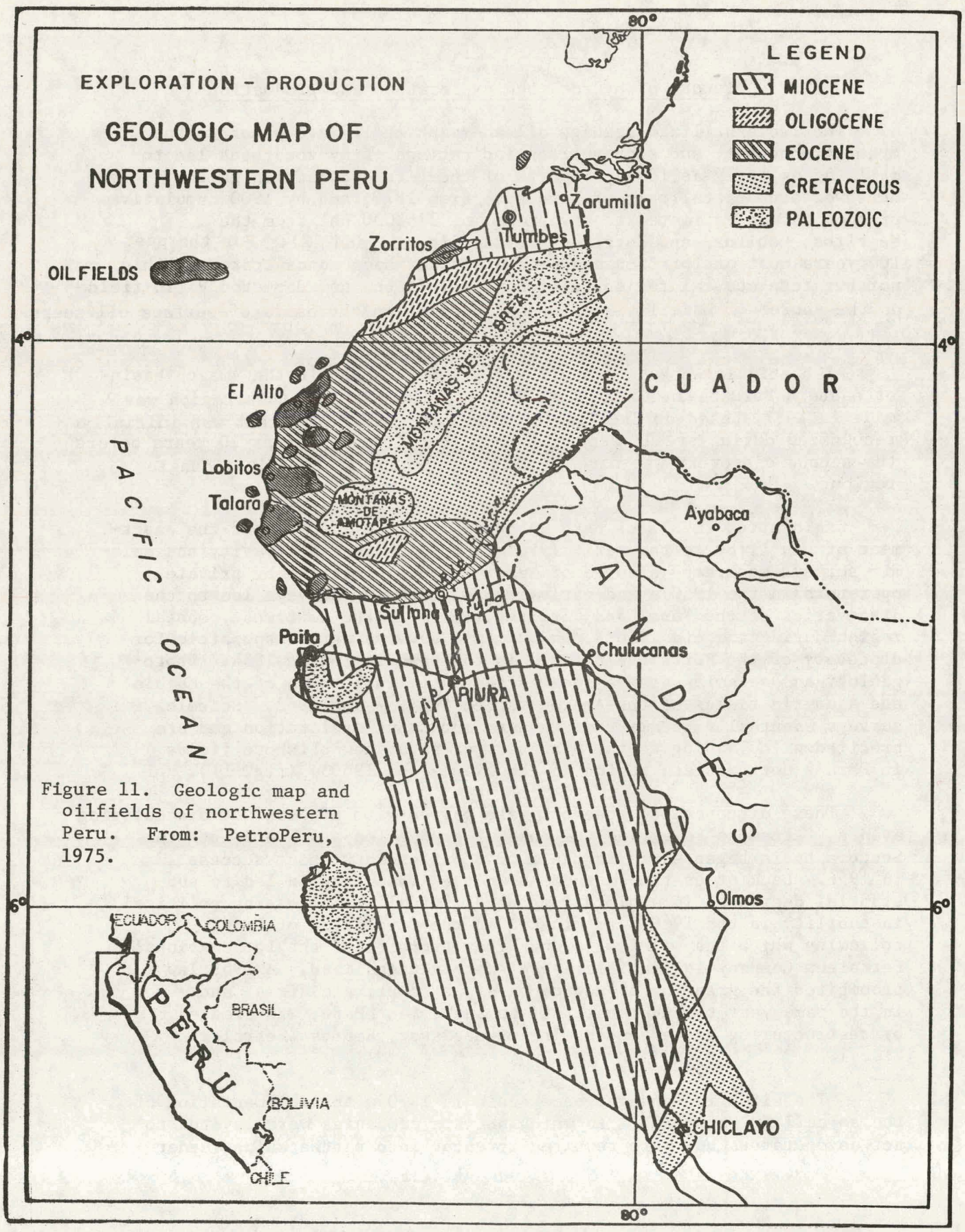


Figure 11. Geologic map and oilfields of northwestern Peru. From: PetroPeru, 1975.

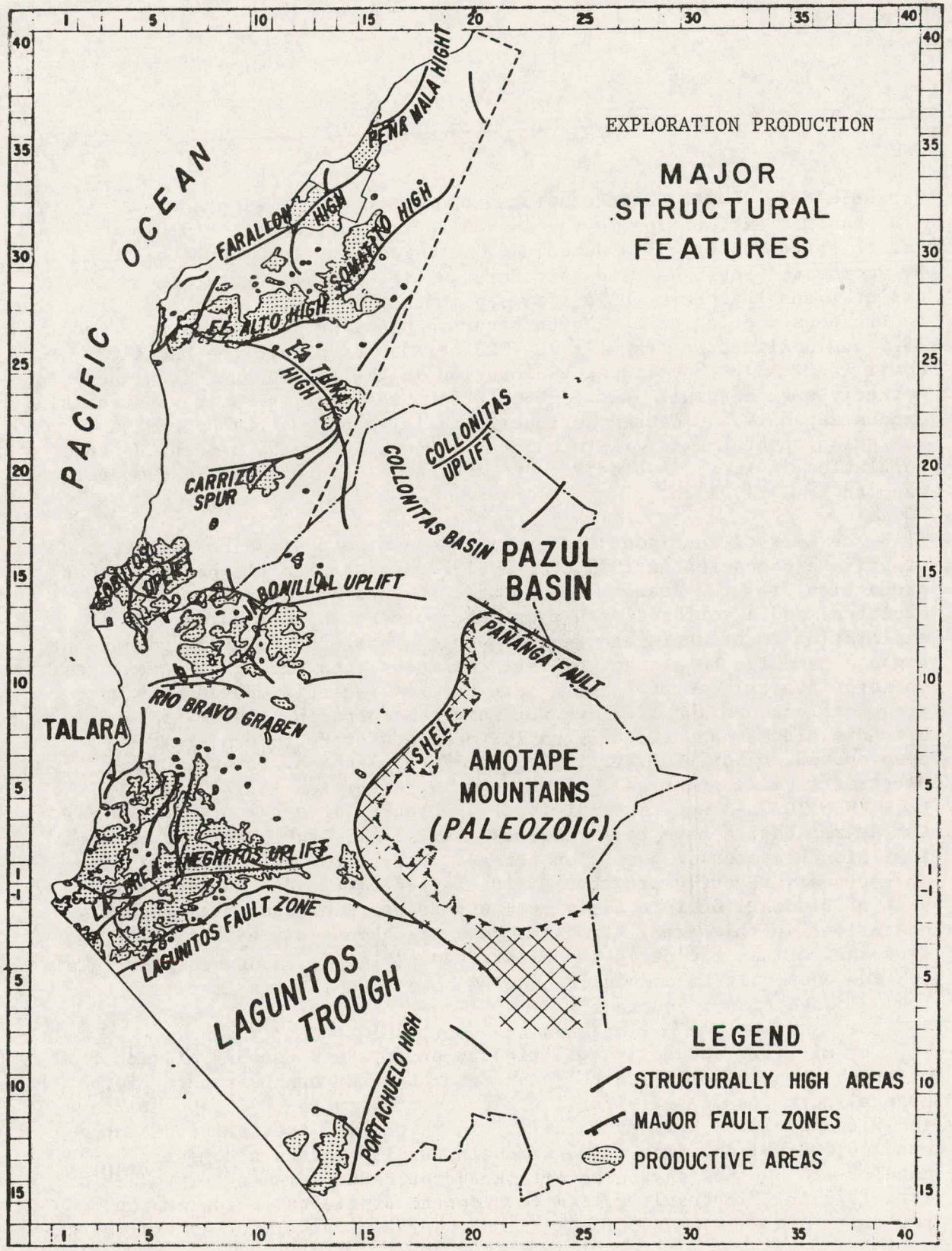


Figure 12. Structural features of northwestern Peru.
From: PetroPeru, 1975.

variable terms) with PetroPeru for exploration and development. A new phase of exploration in the Amazon region in the early 1970's led to the discovery of a dozen new oilfields in the Oriente basin by Occidental Petroleum and PetroPeru. This, in turn, generated expectations that Peru would become a major oil exporter and led to the construction of the North Peruvian pipeline, completed in 1977 and designed to transmit 200,000 bbl/day of oil to the Pacific coast (fig. 13). Subsequent exploration in the Amazon basins, however, was markedly unsuccessful. Although this left the pipeline with substantial excess capacity and caused serious financial problems for PetroPeru, transmission of Amazon oil to coastal regions, where 90 percent of the population resides, enabled Peru to attain self sufficiency and modest exports by early 1978.

The lack of continued success in the Amazon basins led to an exodus of private companies in 1975-76. By 1977, faced with the prospect that production from the Amazon basins would be substantially less than expected, and also faced with mounting costs for both imports and exploration in offshore and remote jungle areas, the Peruvian government began a campaign to attract private companies into exploration ventures on more favorable terms. The government has recently opened up a vast area both onshore and offshore for service contracts. Twenty-five offshore blocks, an area originally reserved for PetroPeru, have been opened up for bidding (fig. 13). Each block covers 400,000 hectares (1 million acres), of which a large portion is in water less than 200 m deep. An additional 47 blocks for service contracts in the Amazon basins have been reopened (fig. 13). Each block encompasses 1 million hectares (2.5 million acres). PetroPeru has called for bids on secondary-recovery projects on the Talara oilfields and, as a result of bidding, Occidental Oil Company is starting secondary-recovery operations in this area. Programs have also been initiated for the La Brea and Parinas fields in the Talara area (fig. 10), but bids for this job are open only to companies based in one of the Latin American Free Trade Association countries.

By mid-1977 cumulative oil production for Peru was 978 million bbl. of which most, 946 million bbl, came from the northwestern part of the coastal belt (table 3). Total oil production averaged 76,400 bbl/day in 1976 and 91,100 bbl/day in 1977. In March 1978 average production was 140,000 bbl/day from 2,495 producing wells (versus a domestic demand of 126,000 bbl/day. Most of the 90 percent increase in production from 1976 to 1978 resulted from development of fields in the Amazon region.

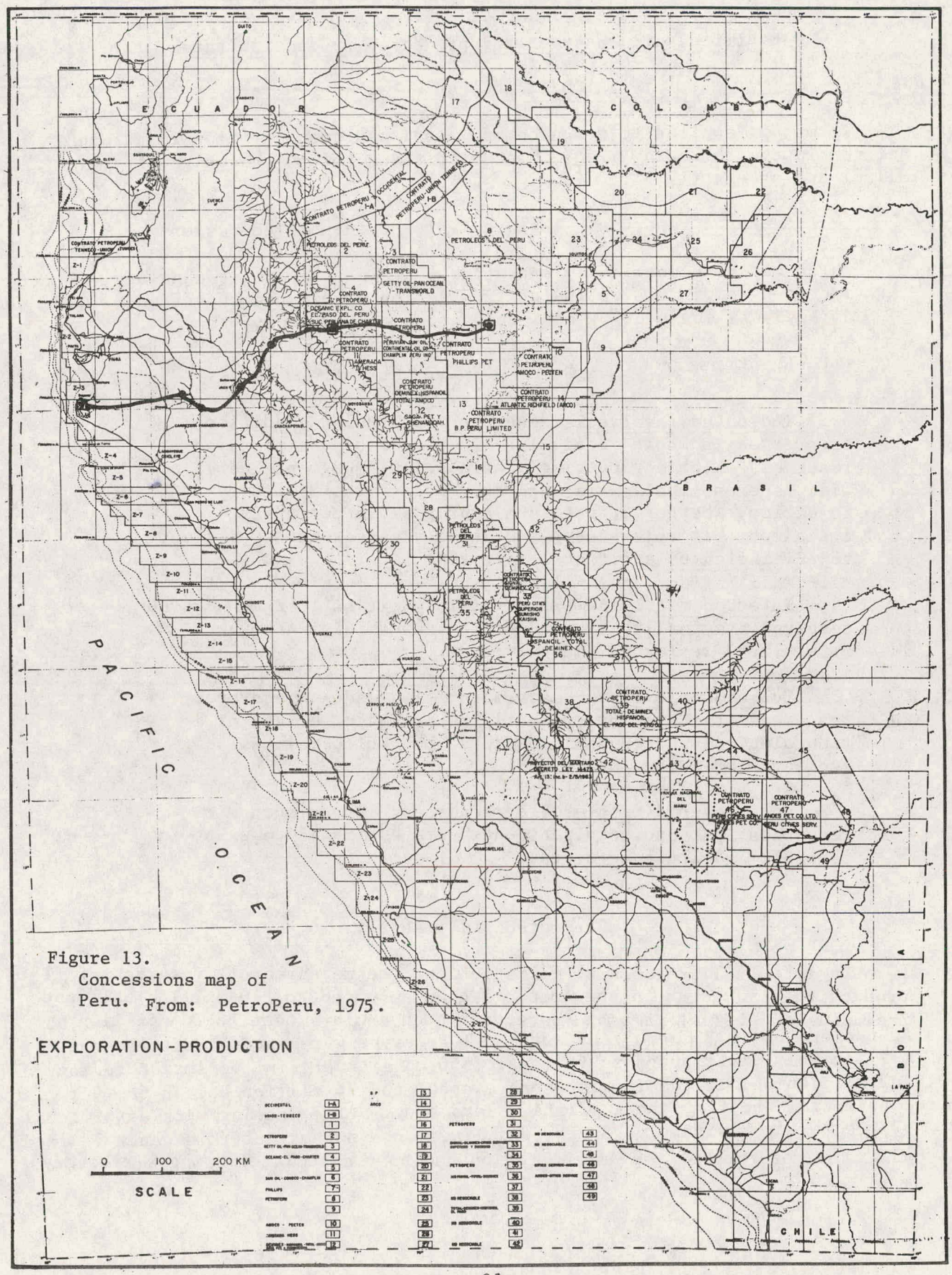


Figure 13.
Concessions map of
Peru. From: PetroPeru, 1975.

Estimated oil reserves and projected production rates

Definitions

Terms, as applied to resource appraisal and used in this study, are defined in the following list. The definitions follow the usage of Miller and others (1975).

Measured reserves. That part of the identified resource which can be economically extracted by using existing technology, and whose amount is estimated from geologic evidence supported directly by engineering measurements. In this study, they are considered to be equivalent to API (American Petroleum Institute) and AGA (American Gas Association) proved reserves.

Indicated reserves. Reserves that include additional recoveries in known reservoirs (in excess of the measured reserves) which engineering knowledge and judgment indicate will be economically available by application of fluid injection, whether or not such a program is currently installed. In this study, indicated reserves are equivalent to API indicated additional reserves.

Inferred reserves. Reserves in addition to demonstrated reserves eventually to be added to known fields through extensions, revisions, and new pays.

Sub-economic resources. Identified and undiscovered resources that are not presently recoverable because of technological and economic factors, but which may be recoverable in the future.

Undiscovered recoverable resources. Those economic resources, yet undiscovered, which are estimated to exist in favorable geologic settings.

Estimated oil reserves

In late 1975, PetroPeru indicated that the measured oil reserves of 11 productive structures in the Amazon region amounted to 546 million bbl, not including additional probable reserves which could amount to 204 million bbl. At the end of 1977, Peru's measured oil reserves were estimated to be 756 million bbl, distributed as follows: 550 million bbl in the Amazon region, 132 million bbl in the Talara onshore area, and 74 million bbl in the Continental Shelf offshore of the Talara area. At a meeting with an official of the Peru's Ministry of Energy and Mines, the authors of this paper learned that the reserves of the Amazon region had been calculated using a recovery

factor of 40 percent and that more recent calculations indicate the measured oil reserves of that area are 385 million bbl. This revision for the measured oil reserves of the Amazon region was calculated using a recovery factor of 28 percent.

Belco Petroleum under a service contract with PetroPeru is developing its Zocala II area on the continental shelf offshore of Talara. By the end of 1976, Belco had drilled a total of 435 wells on the shelf between Sechura and Zorritos, 285 of which are presently producing, 110 closed, and 40 abandoned. As of December 31, 1976 measured oil reserves in the Zocala II area were estimated to be 74 million bbl. The authors calculate that production since that time, about 30,000 bbl/day, has probably reduced the measured reserves to about 60 million bbl.

Petroleum production from the Talara fields on the northwest coast are operated by PetroPeru and have been in a declining trend. During 1976, output of 12.9 million bbl, a decrease of 7 percent from the previous year, was considerably below the output of 20.2 million bbl in 1966. Officials of PetroPeru and the Ministry of Energy and Mines indicated to the authors that measured oil reserves of the onshore Talara fields presently are about 120 million bbl.

In addition to measured oil reserves discussed above, indicated oil reserves of about 500 million bbl were identified. These indicated reserves are expected to be produced by secondary recovery methods from the onshore part of the Talara basin. Primary recovery methods have produced about 1 billion bbl of oil, and officials of PetroPeru and Occidental indicate that secondary methods could recover about 50 percent of that amount. The Talara area has been divided into two sections: La Brea-Pariñas and Lobitos-El Alto-Los Organos. In December 1977, the joint bid of Occidental Peruvana, Inc., and a joint venture partner was selected by PetroPeru for a contract to conduct secondary recovery operations in the second Talara section. The contract was signed on March 31, 1978, and according to officials of Occidental, drilling for secondary recovery will start in the latter part of 1978. Additional secondary recovery operations in the LaBrea-Pariñas area will begin in 1983, according to officials of PetroPeru.

Inferred oil reserves of Peru are estimated by the authors to be about 30 million bbl. These reserves represent deposits of heavy crude (17° API) believed to exist in Block 1B. Officials of Occidental indicate that the heavy crude can be recovered by mixing with lighter oil recovered from Block 1A.

In summary, the total of Peru's measured, indicated, and inferred oil reserves are estimated to be 1,095 million bbl. These data are summarized as follows:

	Oil (millions barrels)
Measured reserves (Amazon region)	385
Measured reserves (Talara offshore)	60
Measured reserves (Talara onshore)	120
Indicated reserves (secondary recovery, Talara	500
Inferred reserves	30
Total	1,095

Undiscovered oil resources

Estimates of Peru's undiscovered recoverable oil resources have been large--especially for the Amazon basins. For instance, Zuniga y Rivero and others (1976) have estimated the undiscovered oil resources of the Amazon basins as follows:

Basin	Undiscovered oil reserve (billions barrels)
Maranon	20
Ucayali	5-10
Madre de Dios	6-12
Total	31-42

However, Zuniga y Rivero (personal communication) has indicated that, on the basis of more recent exploration, these figures should be, perhaps, halved.

Travis and others (1976) have estimated the undiscovered oil resources of the coastal basins as follows:

Basin	Undiscovered oil reserves (billions barrels)
Progreso	0.35
Talara	1.0
Sechura	0.1
Salaverry	0.5
Pisco	0.1
Moquegua	none
Total	2.05

These estimates do not include potential reserves from the Lima and Arequipa basins--deep water basins of large areal extent that lie seaward of the Continental Shelf.

The objective of this paper, however, is not to estimate Peru's potential hydrocarbon reserves. Rather, it is to estimate production for the years 1978 through 1985 as well as for the year 2000. Therefore, the authors judged the above estimations to be insufficient. For purposes of this report we would categorize significant undiscovered reserves as those that possibly could be exploited within the time frame covered by this study. We attempted, therefore, to eliminate from consideration undiscovered reserves believed to exist both in water depths beyond the Continental Shelf and in stratigraphic traps in the Amazon region. The technology for producing hydrocarbons seaward of the Continental Shelf is not fully developed and will probably not be fully operational for another 10 years. The search for stratigraphic traps in the Amazon basins must follow extensive accumulation of more subsurface information from drilling and be aided by seismic stratigraphic studies.

With these considerations in mind, the authors discussed the undiscovered resources of the coastal basins with scientists of Petro-Peru, Belco, Occidental, and Geopet (a Peruvian consulting company based in Lima, Peru). Our estimates of the undiscovered recoverable oil resources of Peru are listed, by basin, in table 4. For coastal basins, high and low estimates are shown. These values bracket the estimates made by scientists with whom we talked. The estimates of undiscovered resources of the Amazon basins (table 4) were made by us on the basis of areal extent. That is, the total oil resources of Blocks 1A, 1B, and 8 (the present producing areas of the Amazon region) were estimated by the authors to be 560 million bbl (identified plus undiscovered). The amount of undiscovered resources contained in remaining Amazon region blocks (those that are as yet relatively unexplored by drilling) was assumed to be proportional (based on areal extent). These resulting amounts of oil per block were then reduced by a "richness factor." The richness factors, generated by the authors, were 0.75, 0.50, and 0.50 for the Maranon, Ucayali, and Madre de Dios basins respectively. The richness, or reducing factors, are less than 1.00 because southward from the main producing areas of the Amazon region (Blocks 1A, 1B, and 8), structures of the type from which oil is presently being produced are few and the organic content of potential source rocks is reduced (Zuñiga y Rivero, personal commun., 1978). It should be noted that oil production to date from Blocks 1A, 1B, and 8 has been limited to structural traps located by standard seismic methods. We assume, therefore, that our estimates of undiscovered oil resources in the remaining areas of the Amazon basins (table 4) include only those resources contained in structural traps that can be located by standard seismic methods; i.e., the estimates do not include potential resources that could be contained in stratigraphic traps.

Table 4.--Estimates of Peru's undiscovered recoverable oil resources listed by basin. Note: estimates for the Amazon basins (Marañon, Ucayali, and Madre de Dios) do not include potential resources that may exist in stratigraphic traps. Estimates for the remaining basins do not include potential resources believed to exist in water depths beyond the Continental Shelf.

Basin	Oil (Millions barrels)
Progreso	150 - 350
Talara (onshore)	50 - 500
Talara (offshore)	150 - 200
Sechura	50 - 100
Salaverry	150 - 500
Pisco	20 - 100
Marañon	880
Ucayali	330
Madre de Dios	280
TOTAL	2,060

Oil production through 1985

Estimates of oil production in Peru for the years 1978-1985 are shown in table 5. These estimates were generated by the authors through discussions with officials of the Ministry of Energy and Mines and with officials and scientists of PetroPeru, Occidental, and Belco. Our basic assumption when making these estimates was that the rate of oil production, at least through 1985, would not be affected by significant new discoveries. Exploration for new oil deposits has all but ceased in most areas of Peru; and, owing to the time lag between exploration and production phases, a renewal of exploratory ventures probably would not be reflected in production increases until after the middle 1980's.

As shown in table 5, oil production in Peru can be placed in 5 categories: (1) Amazon region operated by Occidental; (2) Amazon region operated by PetroPeru; (3) primary recovery from the Talara onshore area; (4) secondary recovery from the Talara onshore area; and (5) Talara offshore area operated by Belco. Each is discussed separately in the following paragraphs.

Table 5.--Estimates of future yearly and daily production of oil in Peru for the years 1978-1985. [Oxy, Occidental; pp, PetroPeru]

Year	*Amazon region Oxy	*Amazon region Oxy new fields	*Amazon region pp	*Talara onshore primary recovery	*Talara onshore, secondary recovery Oxy	*La Brea-Parinas secondary recovery	*Talara offshore Belco	Total (Million barrels per year)	Total (Thousand barrels per year)
**1978	25.5	-	10.0	12.0	0.6	-	11.0	59.1	162
1979	40.0	-	10.7	11.4	3.0	-	10.8	75.9	208
1980	40.0	-	10.7	10.8	9.8	-	10.6	81.9	224
1981	35.3	-	10.0	10.3	12.0	-	10.4	78.0	214
1982	29.0	-	9.2	9.8	12.0	-	10.2	70.2	192
1983	26.0	1.8	8.6	9.3	12.0	3.0	9.9	70.6	193
1984	21.5	3.6	7.5	8.8	11.4	9.8	9.5	72.1	196
1985	17.0	3.6	6.3	8.4	10.0	12.0	9.2	66.5	182

* Yearly production rates in millions of bbl/yr

** 1978 production rates refer to latest quarter of year

Note: Projected production figures provided to the authors by the Ministry of Energy and Mines, in thousands of bbl/day, were as follows: 214 (1979), 213 (1980), 207 (1981), 210 (1982), 202 (1983), 186 (1984), and 163 (1985).

Amazon Region (Occidental)--Occidental Petroleum Corporation presently operates 8 fields (table 3) in Block 1A located in northern Peru near the Ecuadorian border (fig. 13). Five of these fields are producing oil, one field produces only small amounts of gas (Carmen), and the remaining two (Huayuri and Tambo) are not yet on-line. Occidental's first discovery in this area was in 1972. Full output was delayed because of insufficient transportation facilities. In early 1978, a spur oil pipeline with a capacity of 80,000 bbl/day was completed. This spur line extends from the main Trans-Andean pipeline to Occidental's gathering station on Andoas. According to a spokesman for Occidental, the company is installing new pumps on the spur line to raise delivery capacity to 120,000 bbl/day. In addition to this delivery capacity, Occidental's new river terminal on Rio Tigre, east of Shiviyacu, has made it possible to barge over 15,000 bbl/day to the main pipeline station at Saramuro (in June 1978 Occidental's barge delivery to Saramuro was 18,000 bbl/day).

Total oil production from Block 1A on May 10, 1978, was 72,000 bbl. This production was from five fields as follows:

Forestal	6,000	bbl
Northeast Shiviyacu	400	bbl
Shiviyacu	11,000	bbl
South Capahuari	49,000	bbl
North Capahuari	5,600	bbl
Total	72,000	bbl

Officials of Occidental indicate that oil production could reach 110-120,000 bbl/day in the latter part of 1978. The increase in production is expected chiefly from South Capahuari. By the use of added gas lift and the drilling of two more wells, its production could reach 70,000-75,000 bbl/day. Also in the latter part of 1978, plans are to put Huayuri field on-line with a production capability of perhaps 20,000-25,000 bbl/day. According to officials of Occidental, additional production in 1979 of about 1,000 bbl/day could come from Block 1B. Occidental recently acquired this block previously operated and later abandoned by Union Oil Company after the discovery of heavy oil (17° API). Occidental plans to produce some of this heavy oil by mixing with lighter oil from Block 1A. Other production in 1979 could come from Tambo or the yet untested Torisa field. The authors estimate that small, new discoveries, perhaps of light oil in 1B, will increase production by 5,000-10,000 bbl/day in the 1982-1983 period (table 5). We estimate that without other significant discoveries, Occidental's production will peak at 110,500 bbl/day in the 1979-1980 period and slowly decline.

Amazon region (PetroPeru)--In 1976 PetroPeru drilled 79 development wells in Block 8. Sixty-two of these wells gave positive results, and oil production from PetroPeru's four production areas in Block 8 (fig. 13) was 56,000 bbl/day by mid-1977. By June of 1978, however, average daily production had declined to about 27,800 bbls as follows:

Corrientes	25,000 bbl
Pavayacu	2,600 bbl
Yanayacu	200 bbl
Capirona	small amounts
Total	27,800 bbl

According to a PetroPeru spokesman, Corrientes has produced 12 million bbl of oil over the past several years and its production rate is presently declining. Recent drilling at Pavayacu is expected to raise production from that area to about 5,300 bbl/day, and the installation of new pumps could raise Yanayacu's heavy oil production (17° API) to 300 bbl/day. PetroPeru officials expect that in 1979 daily production of oil from Block 8 will be as follows:

Corrientes	20,000 bbl
Pavayacu	5,300 bbl
Yanayacu	300 bbl
Capirona	2,500 bbl
Total	28,100 bbl

The increase in production from Capirona is expected as a result of new drilling.

During the years 1978-1985, additional PetroPeru oil production of about 1,000-1,500 bbl/day will probably come from the company's two producing fields in the Ucayali basin. Total cummulative production from 1939 to mid-1977 from the Agua Caliente and Maquia fields, in the Ucayali basin, has been 21 million bbl (table 3). Total average daily production from these two fields was about 1,300 bbl during the first 6 months of 1977 (table 3).

The authors expect PetroPeru's Amazon production to be about 29,400 bbl in the 1979-1980 period, followed by a rapid decline (table 5).

Talara onshore (primary recovery)--This region was the cradle of the South American oil industry as the first commercial well was drilled there in 1863. As of mid-1977, cumulative production was 839 million bbl (table 3). Daily production of about 33,000 bbl comes from some 2,100 wells (table 3). Maximum oil production from a well in this area is about 800 bbl/day, but most are making 4-5 bbl/day.

Output of oil in the year 1966 was 20.2 million bbl, in 1975 about 13.9 million bbl, and in 1976 about 12.9 million bbl. Over the 10 year period 1966-1976, the average yearly decrease in oil production was 3.6 percent, whereas, between 1975 and 1976, the decrease rose to almost 7 percent. On the basis of these statistics, the authors estimate that between 1978 and 1985, the average yearly decline in oil production from primary recovery in the Talara onshore area will be about 5 percent (table 5).

Talara onshore (secondary recovery)--For purposes of secondary recovery operations, the Talara area has been divided into two sections: Lobitos-El Alto-Los Organos, and La Brea-Pariñas. Occidental Peruvana, Inc., and its joint venture partner, Bridas Exploraciones y Produccion S.A., were selected to conduct secondary operations in the first Talara section. According to information received by the authors from officials of Occidental and the Ministry of Energy and Mines, secondary operations are expected to begin in the 1978-79 period and peak oil production, of perhaps 33,000 bbl/day, will be reached in about 1982 (table 5).

Secondary recovery operations are expected to begin in the La Brea-Pariñas section in the 1980-81 period and it is estimated that peak production will be reached in about 1985 (personal communication, 1978, official of Ministry of Energy and Mines). The authors estimate that peak production from these operations will be about 33,000 bbl/day (table 5).

Talara offshore--Belco Petroleum, the only operator in this area, is developing its Zocalo II area on the continental shelf offshore of Talara. In the years 1971-77, Belco made 15 discoveries and by mid-1977 was producing oil at the rate of 28,600 bbl/day (table 3). By the end of 1976, Belco had drilled a total of 435 wells in the Continental Shelf between Sechura and Zorritos. Of these wells 285 are presently producing, 110 are closed, and 40 were abandoned. Discovery of offshore fields was largely an extension of onshore work. As in the onshore area, production from individual wells is small.

The authors estimate that yearly oil production rates for the offshore Talara area will remain relatively constant during the years 1978-1985, with only a small decline of perhaps 1-3 percent (table 5).

Oil production in year 2000

Presently producing Peruvian oilfields (table 3) will be depleted or nearly depleted by the year 2000. If we assume that no new additions (above those shown in table 5) are made to Peru's measured oil reserves, the authors calculate that Peru's total oil production, at the turn of the century, will range from 10 to 15 million bbl. It is unlikely, however, that this situation will come about. More likely, as future world oil demands and oil prices increase, exploration in the Amazon basins will become more attractive. If we assume that one-half of Peru's undiscovered oil resources (table 4) are moved into the measured reserve categories during the 1990's (a reasonable assumption we believe), it is possible that the production rate in the year 2000 will reach 116 million bbl/yr. In making this estimate, the authors used a ratio of 10:1 for yearly production rates versus measured reserves.

Realization of the latter production rate by the turn of the century requires that an active and continuing exploration program be initiated in Peru before about 1985. To date, producing fields in Peru have proved to be associated with relatively small structures and the few tests made by foreign oil companies several years ago in the Amazon basins suggest that future production will not come from giant fields. The search for small traps will require extensive exploratory ventures.

Gas production and gas reserves

Natural gas plays a smaller part in Peru's total energy situation than oil, supplying 6.4 percent of total needs. Output of natural gas over the past decade has been relatively flat. After a peak of 77.1 billion cubic feet in 1969, output declined steadily, and in 1975 production was 64.9 billion cubic feet. In 1976 production moved upward to 71.7 billion cubic feet and in 1977 increased slightly to 72.8 billion cubic feet. On the basis of discussions with officials of PetroPeru and the Ministry of Energy and Mines, gas production in Peru is expected to remain relatively constant at about 72 billion cubic feet per year with, perhaps, a small (5 percent) decline per year.

Natural gas in Peru is produced chiefly from the Talara area, both onshore and offshore. The gas is used primarily for the production of fertilizer and this usage is expected to continue through 1985. Water flooding for secondary recovery operations in the Talara area probably will increase the reservoir pressure, thereby causing some of the gas to dissolve in the oil, resulting in increased oil production but decreased gas production. We can expect gas production in the areas under secondary recovery to decline somewhat after flooding gets underway.

In the Amazon region most oilfields have a water drive, and gas production is small. The produced gas is used for injection, gas lift, and local fuel; small amounts are being flared. This will probably continue to be the case through 1985. In the Ucayali basin, one gas field, Aguaytia, has been discovered. PetroPeru estimates that it has subeconomic reserves of 317.8 billion cubic feet of gas. more drilling will be done in Aguaytia gas field, but production of the Aguaytia reserves is not expected before 1985.

Gas reserves of the Marañon basin of eastern Peru are believed to be small. The oilfields in the Maranon basin are producing medium gravity oil (20° to 45° API) from Cretaceous reservoirs. All these reservoirs have a water drive and produce very little gas. The produced gas is either reinjected, flared, or used for fuel in the immediate vicinity.

Because of its remoteness, little exploration drilling has taken place in the Madre de Dios basin, and its gas potential remains unknown.

In the Talara basin of northwestern Peru, the measured gas reserves are estimated by PetroPeru to be one trillion cubic feet. However, it is all but impossible to make a reasonable gas estimate because of the complexity of the area. In addition to the structural complications resulting from the block faulting, there are stratigraphic problems. Some blocks produce only oil, others only gas. Sands are lenticular, and there appears to be no order in the sequence of fluids. A water sand may overlie a gas sand, etc. This makes it impossible to establish gas-water or gas-oil contacts and thereby impossible to calculate the volume of gas. Gas is produced from from both gas caps and solution gas.

In the Progreso basin of Peru, a wildcat drilled offshore from Tumbes was completed with initial production of 5,246 barrels of oil per day and 18 million cu ft of gas per day. An offset was dry. The gas reserves of this basin are unknown but are thought to be considerable. The portion of the Progreso basin in Peru is small in comparison with the part in Ecuador.

In the Sechura basin two wildcats found gas, but not in economical quantities.

The gas potential of the Salaverry and Pisco basins is unknown, but because of the thin sedimentary sections and the scarcity of structures, the gas potential is probably low.

Prospects and recommendations for increasing production

The probability for achieving major increases in Peru's oil production rates predicted for the years 1978-1985 (table 5) is small. Production rates for these years are relatively fixed by the present size of Peru's measured reserves. The normal lag time between exploration and production is 3 to 5 years. In Peru, where resources are suspected to lie in remote regions, the lag time would be even higher. Exploration at this time apparently has all but ceased throughout much of the country and new exploratory ventures appear to be several years away. The chances, therefore, of making significant new discoveries that would affect the pre-1985 production rates are slim.

Accelerated exploitation of present reserves, by the drilling of large numbers of wells in the already producing fields could raise yearly production over the next several years; but, the total average yearly production for the years 1978-1985 would not be significantly changed. This is due to the rate at which production from these fields is expected to decline (table 5). The only exception appears to be the secondary recovery operations scheduled for the La Brea-Parinas area (table 5). If the timetable for the start of these operations were moved ahead 2 to 3 years, production would still peak during the mid-1980's and production rates for the year 1980-1984 would increase.

Prospects for increasing the predicted production rate for the year 2000 appear good. The amount of increase will depend on the quantity of undiscovered reserves that can be moved into the measured reserve category within the next 10 to 15 years by exploration and test drilling. We also should stress again that without a vigorous renewed exploration program, oil production rates beyond 1990 will be substantially below today's production rates.

Despite recent disappointments, the Amazon basins contain the best long-term prospects for increased production in Peru. The geological circumstances of hydrocarbon accumulations there appear to be much more complicated than believed earlier, and exploration consequently will be more difficult and extended than previously thought. Although Peru is presently in the stage of searching for and drilling structural traps in the Amazon basins, long-term production rates will probably depend on the amount of petroleum contained in stratigraphic traps. Evaluation of these types of traps must await more detailed subsurface information from drilling and must be aided by studies of depositional environments as well as seismic stratigraphic studies.

Immediate exploration efforts should concentrate on anticlinal structures in the Amazon basins. These were a factor in the early assessments of the region which later proved over-optimistic when several major structures turned out to be dry. Many of these structures may have been formed rather late in geologic time, e.g., during the Pliocene Epoch. They thus may post-date the time of hydrocarbon migration and are understandably barren. An important phase of exploration in these basins will be the precise reconstruction of the deformational history of the individual structures. Feininger (1975), in a study of the Ecuadorian part of the Oriente basin, has suggested that oil in Cretaceous reservoirs there was squeezed from source beds to the west in the Andean region during Late Cretaceous time. He postulates that in some parts of the Andes, Cretaceous deformation was so intense that oil could not migrate. Basinal areas in the Amazon region to the east are consequently unproductive. This factor may explain the lack of success in certain parts of the Peruvian Amazon basin.

To date producing fields in the Amazon region have proved to be relatively small anticlinal structures. The early unsuccessful tests by many foreign oil companies apparently were confined to larger structures. New exploratory ventures, therefore, should be aimed at highly detailed surveys.

In the offshore basin, structural traps will continue to be the main targets, and seismic methods the main exploration tool. Lower Cenozoic clastic rocks, the main reservoirs in the Talara basin, will be a major objective in the other coastal basins as well. The estimates of reserves in several of the basins (e.g., Sechura and Pisco basins) are relatively low because their onshore parts of Eocene sections are thin or nonexistent. The lower Cenozoic part of the stratigraphic succession may possibly exist in the offshore areas, along with potentially prospective clastic units of Cretaceous age.

The most attractive targets within the post-Eocene succession are in the Miocene. In the Sechura and Pisco basins, Miocene sections include phosphatic and diatomaceous rocks that are nearly identical to the organic-rich Monterey Formation, a major source for oil and gas in California. In the onland parts of these two basins, the diatomaceous sediments apparently were never buried deeply enough to generate hydrocarbons. Thicker and more favorable upper Cenozoic sequences probably exist in offshore regions. Sandstone beds that overlie or interfinger with the diatomaceous rocks in the offshore areas may be expected to contain hydrocarbons, as they do in the Monterey Formation of California.

As oil prices increase and deep-water-production technology advances, potential traps in basins beyond the Continental Shelf (Lima and Arequipa basins) could prove to be attractive targets.

PRELIMINARY REPORT ON COAL DEPOSITS OF PERU

By Wilds W. Olive and Robert G. Hobbs

Introduction

This report is based partly on information contained in published reports and unpublished reports of the Banco Minero del Peru, MINEROPERU, INCITEMI, CENTROMIN, and SIDERPERU. Many pertinent data were also obtained from conversation with the following individuals: Ing. Raul Eyzaguirre Parra, Gerente, MINEROPERU; Ing. Abel Castañaga Coll, Jefe, Dpto. de Carbón, SIDERPERU; Ing. Gustaveo Luyo Velit, Jefe de la Unidad Operativa de Oyón, SIDERPERU; Jose Olcese DiGianvito, Doctor Geólogo, SIDERPERU; Alberto Benavides, Chairman, Cia. de Minas Buenaventura, S.A.; Guillermo Abele C., Director Departamento de Exploraciones, and Ing. Reuben A. Palao, Gerente, CENTROMIN; Ing. Cesar Sotillo Palomino, Director General, INCITEMI, Ing. Flavio Estrada Ch., Jefe Investigaciones Metalogenesis, INCITEMI, Julio Escudero Ratto, Geologo Direccion de Minería y Geología, and Ing. Jose Cruzado Castañada, PetroPeru. Unpublished reports from the files of the Banco Minero del Perú were made available by Juan Luis Sayan Miranda, Coordinador. The able assistance of Blanca de Huaco, Minerals Section, U.S. Embassy, Lima, was invaluable. All persons contacted were most helpful and cooperative in providing pertinent information from the various organizations which they represented.

Coal deposits are reported from 18 of Peru's 24 Departments. The deposits range in age from Late Jurassic to late Tertiary and include coal that ranges in rank from lignite to anthracite. At most localities, particularly in departments south of the Department of Huancavelica, the deposits are generally considerably less than a meter thick, are of limited areal extent, and have little or no economic value. However, in central and northern Peru, coal beds with thicknesses greater than one meter are reported at numerous localities, some of which are sites of formerly active mines or are in areas of active exploration.

Jurassic-Cretaceous coal deposits

Coal that has the greatest potential as a source of future energy occurs in rocks of Late Jurassic and Late Cretaceous ages. For the most part, the coal is found in areas of rugged terrain at altitudes above 2,000 meters and as high as 4,600 meters. Although many of the coal deposits are accessible by railroad and road, others can be reached only by foot or on horseback.

General geology.--The Upper Jurassic and Lower Cretaceous coal measures consist largely of continental, fine to coarse clastic sedimentary rocks that were deposited in lacustrine and palustral environments along the Andean trough. Deposition of the coal measures in most areas extended from Jurassic into the Cretaceous without interruption. As indicated by the coal beds in rocks of the same age in many parts of the country, conditions favorable for accumulation of coal existed contemporaneously in large areas of Peru and may

have given rise to coal beds that formerly were continuous over many hundreds or even thousands of square kilometers. Many of the areas now designated as coal basins are within boundaries that are largely defined on the basis of geographic or structural features. Whether these areas were part of large depositional basins is, on the basis of present knowledge, a matter of conjecture.

Structure.--In most parts of Peru, the Jurassic-Cretaceous coal-bearing sequence is folded and faulted, and in many areas it is intruded by igneous rocks. As a result of heat and pressure generated by tectonism and from igneous intrusive bodies, much of the coal has been metamorphosed. In some areas, coal beds, being the weakest member in the stratigraphic sequence, mark the positions of bedding-plane faults. As a result of differential movements, the coal has been pulverized, contorted, squeezed, and caused to flow in a manner that might be expected of asphalt. Such coal is commonly referred to as cisco. It forms beds of highly variable thickness and at places is injected along planes of faults that offshoot from the fault that follows the coal bed. A bed 2 meters thick may thin to less than 2.0 centimeters within a distance of 3 meters, or it may disappear altogether.

Thickness of coal beds.--Coal beds of minable thickness, that is, thicker than 0.6 meter, are reported at numerous localities in the central and northern parts of Peru. In the Departments of Cajamarca, La Libertad, and Ancash in northern Peru, coal beds 1.5 to 6.0 meters thick have been noted, and some have been traced along the outcrop for several kilometers. In the northernmost part of the Department of Ancash, 35 coal beds ranging in thickness from 0.1 to 1.5 meters are reported within a measured stratigraphic interval of 170 meters. Twelve of the beds are more than 0.6 meter and some are as much as 1.5 meters thick. In central Peru, in the Departments of Pasco, Lima, and Junín, coal beds rarely exceed 1.5 meters in thickness.

Rank and quality of coal.--The rank of Jurassic and Cretaceous coal ranges from subbituminous to anthracite, but in approximately two-thirds of the areas of coal deposits, the coal is reported to be anthracite. On the basis of a limited number of analyses from widely separated localities, the anthracite has a low ash content, a low to moderate sulfur content, and heat values that range from 6,000 to 7,500 kilocalories. Ash content of subbituminous and bituminous coal from central Peru, where most of these types of coal are found, is highly variable, ranging from 7 percent to as high as 41 percent.

Analyses of subbituminous coal from three thin beds (0.20 to 0.40 m) in the Jatunhuasi area of Pasco Department indicate 6 to 20 percent ash, 40 to

60 percent fixed carbon, and 0.6 to 2.0 percent sulfur. Heating values range from 5,000 to 7,000 kilocalories.

Much of the bituminous coal forms a weak coke that is suitable for lead smelting furnaces, but it is not suited for the blast furnaces of steel mills unless mixed with strongly coking coal from other sources.

Coal reserves.--Measured, indicated, and inferred reserves (more commonly reported as proven, probable, and possible reserves) are given in reports, mostly unpublished, on areas of former mine sites or on areas that are currently under investigation; however, no attempt has been made to classify reserves on a nation-wide basis according to widely accepted standard procedure.

An estimate of 1,060 million tons of coal reserves for Peru is given by Escudero (1977, p. 8). This figure appears excessive considering the scarcity of data on which it is based. According to standards adopted by the U.S. Geological Survey, measured coal reserves are those deposits within a one-fourth mile (0.4 km) radius of a point at which the thickness of a coal bed has been accurately measured. Indicated reserves include coal within an area that extends one-half mile (0.8 km) beyond the area of measured reserves, and inferred reserves include coal that extends 6 miles (9.6 km) beyond the limit of indicated reserves providing geologic evidence indicates persistence of coal beds. Thus, indicated and inferred reserves are a consequence of measured reserves.

Of the 1,060 million tons of reserves presented by Escudero, 142 million tons are classified as "measured" and "estimated"; however, information on which these estimates are based are not given, and thus these reserve figures cannot be interpreted as to their significance in terms of economically recoverable coal.

Areas having potential for coal production

Although little or no coal is currently being produced in Peru, four coal fields (fig. 14) appear to hold potential as possible sources of fuel for producing energy and as sources of coking coal. These include the Alto Chicama and Santa Valley coal fields in northern Peru and the Oyon-Gazuna, and Jatunhuasi coal fields of central Peru. These and other coal areas are discussed separately below.

Alto Chicama coal field

The following discussion is for the most part from a report on the Alto Chicama field prepared by MINEROPERU (1977).

Geography

The Alto Chicama coal field includes an area of about 750 km^2 in Otuzco and Santiago de Chuco Provinces, La Libertad Department. From Trujillo the field

Base 76870 3-70

Figure 14. Peruvian coal fields that have potential for economic development.

is 135 km by a road that passes through Otuzco, Usquil, and Mina Los Andes. The area is in the Cordillera Occidental. It is traversed by deep narrow valleys that are bordered by steep slopes that rise to a gently rolling upland surface known as the altiplano. Altitude ranges from about 1,950 m in the deepest valleys to 4,200 m at the crests of the highest peaks.

Geology

Stratigraphy

Rocks exposed in the area include sedimentary and igneous rocks that range in age from Early Cretaceous to Quaternary. The sedimentary rocks of Early Cretaceous age include the Chimú, Santa, Carhuaz, and Farrat Formations of the Goyllarisquizga Group. The total thickness of the group is about 2,000 m. The sequence is largely composed of sandstone, quartzite, mudstone, shale, and minor amounts of limestone and coal. Coal occurs only in the Chimú Formation.

The Goyllarisquizga Group is unconformably overlain by a sequence of volcanic rocks, about 1,000 m thick, that belong to the Calipuy Formation of Late Cretaceous and early Tertiary age. Quaternary rocks consist of fluvioglacial deposits that form a thin veneer above older rocks at altitudes above 3,800 m, and of alluvial deposits along the valleys of the major streams.

Small igneous bodies of andesite and dacite are intruded into stratigraphic units of all ages.

Structure

As a result of the Andean orogeny during Late Cretaceous and Tertiary time, the area was subjected to intense tectonism, and the strata were deformed and offset by north-northwest-trending folds and reverse and overthrust faults. At a later stage the strata were offset by normal faults that trend transverse to earlier structures. Throughout most of the area, the coal-bearing sequence is steeply dipping, and at places, the strata are overturned.

Coal beds

The coal beds of the Alto Chicama area are within a 500-m interval in the upper part of the Chimú Formation which has a total thickness of about 1,000 m. The coal beds are interstratified with orthoquartzite, sandstone, mudstone, and shale that were deposited in deltaic and lagoonal environments. Altogether, 10 coal beds have been identified, 2 of which have a minable thickness of 2.0 m or more. One of the beds locally attains a thickness of 4.0 m. Escudero (1977, p. 4) reports that the cisco coal bed in the south sector of the coal field is 6 m thick. The economic thickness of other coal beds ranges from 0.8 to 1.5 m; average thickness of all beds is about 1.6 m.

Most of the coal is anthracite, although a little more than 12 percent is reported to be "hulla magra," which as literally translated means "lean hard pit coal," here interpreted as bituminous coal. Average analyses of samples from many coal beds in different sections of the coal field are presented in table 6. Other values based on analyses of coal from the southern sector of the field, presented by Escudero (1977, p. 4), are as follows: moisture, 5 to 8 percent; volatile material, 2.5 to 12 percent; ash, 6 to 10 percent; fixed carbon, 80 to 85 percent; sulfur, 1 to 2.5 percent; heating value, 7,000 to 7,500 kilocalories.

Plans for future development

MINEROPERU and ELECTROPERU are proposing to develop the reserves of the Alto Chicama field for generation of thermal-electric energy. A mine that will ultimately produce 4,000 tons of coal per day is planned. The coal will be used to fire a 480-megawatt thermal-electric power plant at the mine mouth. Although water is available from the Alto Chicama River and several of its tributaries, the supply will be limited and as a conservation measure, recycling of water, where possible, will be required.

Reserves

Reserve estimates given by MINEROPERU for the Alto Chicama field are based on information obtained from geologic mapping of coal beds, trenching, tunneling, and diamond-core drilling. The method of computation appears to be comparable with that used by the U.S. Geological Survey, and therefore reserve estimates are accepted as reliable. "Proven," "probable," and "possible" reserves, reported in the following table, are believed to correspond to "measured," "indicated," and "inferred" reserves of USGS terminology.

	Reserves, metric tons
Proven	25,222,741
Probable	34,478,764
Possible	211,137,134
Total	270,838,639

Additionally, about 11 million tons of "noneconomic reserves" are reported; however, if they are noneconomic, they cannot be considered as reserves.

Assessment

The approximate 60 million tons of "proven" and "probable" reserves is adequate to proceed with further investigations directed toward establishing a 4,000 ton per day coal mine in the area. However, before the most economic and efficient means of mining and power generation can be determined, much additional work needs to be done, such as core drilling to block out reserves, and systematic sampling and analysis of coal to obtain information needed to determine boiler design and construction.

Table 6. Coal quality and preparation (from Bennett, 1957, p. 48-50).

1. ANALYSES.	Galgada Mine Run-of-mine coal	Galgada Mine Clean coal	Ancos Mine Run-of-mine coal	Ancos Mine Clean coal	Limeña Mine Run-of-mine coal	Limeña Mine Clean coal
TYPICAL PROXIMATE ANALYSIS. Percent (O)						
Moisture	4.4	4.6	3.8	4.2	4.4	4.8
Dry Basis						
Volatile	4.0	4.0	4.3	3.2	6.4	6.5
Fixed Carbon	66.4	85.3	65.6	85.2	69.5	80.9
Ash	29.6	10.7	30 1	10.6	32.1	12.6
Sulphur	0.8	0.9	0.7	0.8	0.6	0.5
Btu/lb (O)		12,685		12,900		12,463
K-cal/kg		7,044		7,166		6,980
Ash fusion, Initial, C		1,275		1,260		1,220
Ash fusion, Softening		1,470		1,440		1,350
Ash fusion, Fluid		1,500		1,500		1,430
Size: (Percent)						
+ 1 5/8 inch		16.9%		16.7		35.7
1 5/8 x 9/16 inch		17.3%		18.5		23.3
9/16 x 3/64 inch		39.9%		45.8		23.9
3/64 x 48 mesh		11.4		7.3		8·1
48 x 200 inch		10.8		8.7		6.0
- 200 inch		3.7		3.0		3.0

(o) These analyses are reasonably representative as to run of mine and clean coal. Btu and k-cal. values are calculated from a table of A-M free values based on the averages of a large number of bomb tests. Ash fusion tests are the average of all known tests for each coal, including some tests which are probably unreliable.

Ultimate Analysis Per cent (1) (Dry Basis)							
H					1.9	0.7	1.5
C					78.4	64.0	78.1
N					(8.5)	0.3	(9.1)
O						2.7	
S					0.7	0.6	0.3
Ash					10.5	31.6	11.0
Ash Analyses Per Cent (1)							
SiO_2			60.7		64.1		53.5
Al_2O_3			29.3		23.4		28.7
Fe_2O_3			4.6		3.7		7.1
CaO-MgO			2.6		1.7		2.9
P_2O_5			0.07		0.01		0.02
GeO_2			0.12		0.25		0.08
SO_3			0.54		0.34		0.72
Sink Float Tests (1)							
	9/16x3/16		9/16x5/16		9/16x3/16		
	%wt.	Ash%	%wt.	Ash%	%wt.	Ash%	
160 float	40.6	5.2			0.5	3.9	
160 x 170	34.6	10.2	58.6	7.4	13.3	8.0	
170 x 180	4.7	23.5	35.1	11.4	35.4	14.7	
180 x 190	7.7	31.7	1.8	25.6	11.5	23.1	
190 x 200	3.1	41.1	0.7	35.5	8.4	35.4	
200 x 210	2.5	50.6	0.8	44.7	13.9	53.5	
210 sink	6.8	71.7	3.0	66.4	17.0	75.5	
	100	16.6	100	11.4	100	32.1	

(1) Note that these tests are on different samples than those above noted, and due to different ash contents are not strictly comparative between the mines.

Flotation Tests.	Coal from Galgada Mine	Coal from Ancos Mine	Coal from Limeña Mine
% Ash, Heads (2)	26.9	16.5	22.3 (3)
% Ash, Concentrate	10.5	10.1	12.7
% Ash, Refuse	58.6	61.3	53.8
% Recovery, Coal	68.5	84.5	76.6
% Recovery, Carbon	84.0	90.1	86.1
% Size: (Percent)	100%-50m	100%-50m	100%-48m
	28%-200m	33.5%-200m	30.5%-200m

Galgada, "Rey de Carbón" (4)

Proximate analysis	
Moisture	2.0
Dry basis	
Volatile	8.8%
Fixed Carbon	81.8%
Ash	9.4%

Size: (Percent)	%Wt.	%Ash
+1 5/8 inch	51.2	11.4
1 5/8 x 9/16 inch	13.4	7.7
9/16 x 3/64 inch	28.7	6.9
- 3/64 inch	6.7	11.4

Sink Float Test

3/32 x 3¼" (86.6%)	% Wt.
1.70 float	0
1.70 - 1.75	79.8
1.75 - 1.80	17.7
1.80 sink	2.5
	100.0

(2) This sample was particularly high in clay-slime content.

(3) Actual run in flotation plant, of 1416 Tons in Apr. '54

(4) Channel sample, taken under Dr. Olive's supervision. Seam is 10 meters wide with 2.5 meters parting of shale, which was not included in the sample. Sample, therefore, represents 7.5 meters of coal.

MINEROPERU anticipates that the proposed mine and thermal-electric plant will cost on the order of $300 million, including cost of transmission lines. Before such an investment is committed, all aspects relating to minability of the coal, environmental effects of coal mining and power generation, water supply, and other factors will need to be thoroughly investigated. It is unlikely that investigations preliminary to establishing a power-generation plant could be completed prior to 1985; however, chances appear favorable that plans proposed by MINEROPERU can be realized by the year 2000.

Santa Valley coal field

Geography

The Santa Valley coal field is in Santiago de Chuco Province, La Libertad Department, and is 100 to 110 km from the port of Chimbote. The surface is intensively dissected by stream erosion. Tributaries characteristically have short steep courses and occupy deeply incised narrow trenches that head against narrow ragged divides. Slopes are generally very steep, and talus throughout much of the area is resting at or near the angle of repose. Altitude ranges from about 1,000 m to more than 2,500 m.

Geology

Stratigraphy

The coal-bearing rocks of the area are of Early Cretaceous age and are part of an elongate, north-trending wedge of Cretaceous sedimentary rocks about 35 km long and 15 km wide. The wedge is bounded on the west by intrusive igneous rocks and on the east by volcanic rocks.

The Lower Cretaceous sequence is divided into the Chimú Sandstone and the Carhuaz and Goyllarisquizga Formations which comprise a stratigraphic section of more than 3,000 m of continental, brackish water, and marine sediments that consist mostly of shale, sandstone, orthoquartzite, and a few thin limestone beds. Coal occurs in the Chimú Sandstone and in the lower part of the Goyllarisquizga Formation.

The Chimú Sandstone, which is more than 500 m thick, is the oldest formation exposed in the area. It is well exposed in the western half of the coal field where it contains numerous coal beds. The Chimú is overlain by the Carhuaz Formation which is about 2,000 m thick and consists largely of shale and a few beds of sandstone and limestone.

The Goyllarisquiza Formation, which overlies the Chimú, is the youngest of the Cretaceous units exposed in the area. The upper part of the unit has been removed by erosion, and its remaining thickness is no more than 550 m. It is extensively exposed in the northern and western parts of the area.

The formation consists mostly of sandstone, but in its lower part it contains a few thin beds of shale and one to three coal beds of considerable thickness. Intrusive rocks on the west are Cretaceous and Tertiary in age, and volcanic rocks on the east are Tertiary and Quaternary in age. Small intrusive bodies in the form of stocks, sills, and dikes cropout throughout the area of Cretaceous sedimentary rock; most of those reported are in the area of outcrop of the Carhuaz Formation.

A north-trending granodiorite intrusion about 1 1/2 km wide is exposed along the Santa River Valley in the southern part of the coal field where it forms the core of a sharply folded, northerly trending anticline. Numerous sills and dikes, apophyses from the intrusive body, penetrate the adjacent sedimentary rocks for distances as much as 2 km on either side.

Structure

The sedimentary strata are intensely folded and are broken into numerous blocks that are bounded by faults that trend in various directions. The strata in the central part of the area strike almost due north, whereas, in the northwestern part they strike northwesterly and in the southeastern part the strike is northeasterly. In general the strata are more intensely deformed in the western part of the area, which is also the area where exposed intrusive bodies are more numerous. The coal field is traversed by a large, faulted anticline whose axis trends northerly about 25 km from the intrusive mass in the southern part of the field. Its northern limit is terminated by an east-trending fault. Superimposed on this large structure are numerous small local folds and dip reversals, probably induced by bedding-plane slippage and squeezing of the Carhuaz shale which is extensive at the surface throughout most of the area of the anticline. In its northern part, the structure is traversed by north-trending faults which have largely destroyed the eastern limb of the fold. In general, the north-trending faults east of the crest of the anticline are down to the west, whereas, those on the opposite side are down to the east, thus producing a complexly faulted graben, the axis of which coincides in position with the crest of the anticline. This relation suggests that the anticline was produced by vertically acting forces, more than likely by the granodiorite intrusion that is exposed in the southern part of the area.

Northeast- and northwest-trending faults divide the northeastern part of the area into a mosaic of blocks. Most of the faults are down to the west.

Coal

Coal beds

Most coal beds in the area are in the Chimú Formation. As many as 35 beds ranging in thickness from 0.1 to 1.5 m have been identified within a stratigraphic interval of 170 m (SOFREMINES, written communication, 1958?). Within this interval, they are grouped in five zones that are 14 to 25 m apart. Twelve of the beds are more than 0.6 m thick and, thus, have economic potential.

Coal beds of two formerly active mines, the Ancos and Galgada mines, in the northern part of the field are in the Chimú Formation. At each mine, nine coal beds are reported; however, only three of the beds at each mine have been exploited. At the Galgada Mine, six coal beds ranging in thickness from 0.60 to 1.20 m are within a stratigraphic interval of 43 m; and at the Ancos mine, about 4 km to the south, three beds with thicknesses of 1.80, 0.70 and 0.70 m are within an interval of 14 m (Bennett, 1957, p. 19 and 21). Coal beds between the two mines are probably continuous, though beds exploited at the two mines may not be the same.

Coal of the Goyllarisquizga Formation is exposed in the northern part of the coal field and at the Limeña mine in the southern part of the area. All the outcrops are near the base of a thick sandstone and are believed to be in approximately the same stratigraphic position. The coal bed in the northern area is referred to as the "Rey de Carbón." It crops out in the vertically dipping limbs of a small tight fold. An overturned syncline at the base of a thrust block occurs about 300 m to the north and on the strike of the coal outcrop, but this structure may be separated from that at the coal outcrop by a fault of undetermined magnitude that follows a west-trending valley between the two localities. The Rey de Carbón, striking northwesterly, also is exposed a short distance east of these localities where it occurs near the base of a thrust block. Engineers of the Galgada mine have mapped the coal bed in this area for a distance of 4 or 5 km. The bed is about 10 m thick and has a 2 1/2 m-thick shale parting near the middle. The Rey de Carbón is again exposed at three closely spaced localities about 1 km northeast of Ancos. All outcrops are adjacent to faults. At one locality, a coal bed at least 12 m thick and possibly as much as 24 m thick was penetrated in two tunnels driven into fault blocks. Coal at the Limeña Mine strikes northeasterly and dips 20° N. The coal is of variable thickness, ranging from about 1 1/2 to 6 m, and contains partings of limestone, shale, and sandstone, which in some areas of the mine comprise as much as 40 percent of the total thickness of the bed (Bennett, 1957, p. 23).

All the outcrops of coal beds in the Goyllarisquizga Formation are at approximately the same stratigraphic position, which suggests a continuity of the coal-bearing horizon throughout the area of distribution of the Goyllariquizga Formation. However, no Goyllarisquizga coal has been reported from the west-central and southwestern parts of the coal field. In the southwestern part, carbonaceous shale occurs at about the stratigraphic position of the coal-bearing horizon, and may indicate that the coal grades into carbonaceous shale westward.

Coal of the Chimú Formation is a high-quality anthracite that is comparable to Pennsylvanian anthracite (Morfitt & Associates, 1944, p. 7, 51) and is "... of the highest quality for blast furnace fuel and other uses." The coal is low in ash, sulphur, and phosphorus and has a high fixed-carbon content.

Coal of the Goyllarisquizga Formation, as indicated by tests of coal from the Limeña mine, is much slower burning and, thus, is not suited

for use in plants requiring high burning rate per unit area or volume; however, it would be suited for coal-burning electric power generating plants (Bennett, 1957, p. 23-24).

Quality and preparation characteristics of coal from the Galgada and Ancos Mines, which are in the Chimú Formation, and coal from the Limeña Mine in the Goyllarisquizga Formation are presented in table 6.

Reserves

Data are insufficient to provide a reasonable estimate of reserves for the entire area of the Santa Valley coal field. Reserves estimates by mining engineers have been mainly for planning mining operations. For the most part, such estimates include reserves that are indicated by various stages of mine development. By comparison with estimates derived by the U. S. Geological Survey method, estimates by the mining engineers are ultraconservative. For example, Morfitt & Associates (1944, p. 39-41) calculated reserves for properties of the Ancos and Galgada Mines and included only that coal that was in close proximity to tunnels at different levels. The length of the area considered did not exceed the longest tunnel, which was 1390 m. The following reserve estimates were derived for the Galgada and Ancos mining operations: 643,800 metric tons proven, 3,418,000 tons indicated, and 2,702,100 probable. Morfitt & Associates (1944, p. 3) conclude that an "... estimate of possible reserves would require much additional exploration and development. It is safe to assume, however, that such reserves are extensive and, when proven, will show tonnages considerably in excess of those herein classified as proven, indicated, and probable coal."

SOFREMINES (1958 ?) estimate 4 million tons of "positive" reserves for the Limeña mine and state that combined "positive" and "posssible" reserves could be as much as 8 million tons.

The areas for which reserves have been estimated represent only a very small part of the coal field. Coal beds more than one meter thick and as much as 10 m thick occur in outcrops and small mines throughout much of the area. This distribution, along with the large amount of reserves contained in the relatively small areas of the Galgada, Ancos, and Limeña concessions, suggests that total coal reserves of the Santa Valley coal fields are large, possibly in excess of 100 million tons.

Assessment

To date coal of the Santa Valley has been considered principally as a source of blast-furnace and metallurgical coal to supply the steel mill at Chimbote, and also as a possible export product. Little attention has been given to the possibility of using it to generate electric energy.

Production of coal appears to have been hampered by the small size of mine concessions which do not contain reserves adequate to justify the amount of investment needed for installation of a profitable operation. Also, the railroad that serves the area can haul no more than about 2,000 tons of coal per day, which limits large-scale development.

It seems probable that the coal could best be used to produce thermal-electric energy. Transmission lines from the generating plant could possibly be tied in with lines leading from the hydroelectric generating plant now in operation at Huallanca, 25 km south of the Limeña mine. However, the first step toward developing or restimulating the coal industry in this area should be to conduct an exploration program that will include mapping the geology, determining the continuity, thickness, and quality of the coal beds, and calculating reserves.

Time required for gathering basic data would require several years, and it is unlikely that a coal-fired generating plant could be established in the Santa Valley prior to 1985.

Oyón-Gazuna coal field

Geography

The Oyón coal field and its northward extension, the Gazuna area, are in Cajatamba Province, Lima Department, and about 150 km by road and 50 km in direct line from the port of Huacho. It is an area of rugged relief with steep-walled, narrow valleys and craggy peaks, the highest of which are snow capped. Altitudes range from about 3,600 to 5,100 m above sea level.

Geology

Stratigraphy

The sedimentary sequence exposed in the area consists of clastic and carbonate rocks of Late Jurassic to Late Cretaceous age. The clastic sequence is represented by the Goyllarisquizga Group which consists of the Oyón, Chimú, Santa, Carhuaz, and Farrat Formations. The Oyón is Late Jurassic in age and all other formations of the group are Cretaceous.

The Goyllarisquizga Group is succeeded by a sequence of carbonate sediments represented by the Parihuanca, Chulec, Pariatamba, Jumasha, and Celendín Formations. Coal beds of minable thickness occur in the Oyón Formations (Cerna Nongrados, 1977).

In many parts of the Oyón area the strata are intruded by small igneous bodies most of which are elongate and trend northerly. An intrusive body, much larger than any in the Oyón area, is intruded into the strata of the Gazuna part of the coal field.

Structure

As a result of the Andean orogeny during Late Cretaceous and Tertiary time, the area was uplifted and the strata were folded and faulted, producing steep-limbed anticlines and synclines that are paralleled by overthrust faults and traversed by high-angle normal and reverse faults. The major folds and faults trend north-northwesterly. The coal-bearing strata in the Oyón area are exposed on the flanks and at the crest of one of these anticlines, which is bordered on the west side by a west-dipping overthrust fault. Coal beds on either flank of the structure dip generally 35° to 40°, but in some areas, owing to secondary folding and faulting, the beds are near vertical and at places are probably overturned. In the Gazuna area the anticline is broader and dips are more gentle.

Coal beds

Coal beds in the Oyón Formation occur within a zone about 100 m thick. Three crosscut tunnels, each about 330 m long, have been driven across the zone at intervals of about 400 m along the anticline in the central part of th Oyón area. One of the tunnels penetrated the coal-bearing section on the east flank of the anticline, and two penetrated all or a part of the section on both sides. As revealed in the walls of the tunnels there are at least six coal beds. All consist mostly of cisco, and all are highly contorted. Thicknesses vary markedly within short distances. One bed that is 2 m thick on one side of the tunnel diminishes to a thickness of 20 cm on the opposite side, only 2 1/2 m distant. Some beds thin and disappear, and at places cisco as much as a meter thick is injected along fault planes. The thickest bed penetrated is on the order of 10 m. However, thicknesses of such beds, unless measured at numerous localities over a large area, can have little relevance to true or average thicknesses.

The number of coal beds, their quality, and rank vary from one sector of the Oyón-Gazuna coal field to another (Cerna Nongrados, 1977). In the Oyón area the number ranges from 1 to 6 with average thickness ranging from 1.0 to 1.5 m as determined from available data, whereas in the Gazuna area there are 11 coal beds with average thicknesses ranging from 0.08 to 2.00 m.

Physical and chemical composition

The coal of the Oyón area is of subbituminous and bituminous rank, whereas the coal of the Gazuna area, due largely to heat from igneous intrusion, is mostly anthracite and semianthracite, although some in the southern part of the area is bituminous. Percentage of sulphur and ash in coal from both areas is generally low, but percentages in Gazuna coal are lower than in Oyón.

Much of the coal from Oyón is cokeable or is well suited for mixing with other coals to produce coke, whereas, only a small part of the Gazuna coal is suited for making coke. Analyses of coal from the Oyón and Gazuna areas give the following values (Vilchez Salazar and Angeles Figuero, 1977, p. 15-16):

	Oyón coal	Gazuna coal
Humidity	6 percent	6 percent
Volatile material	16 to 22 percent	6 to 14 percent
Ash	6 to 12 percent	5 to 10 percent
Fixed carbon	65 to 75 percent	70 to 85 percent
Sulphur	0.5 to 1 percent	0.5 to 1 percent
Calorific value	7,000 to 7,600 kcal/kg	7,000 to 7,600 kcal/kgr
Swelling index	2.5 to 9 percent	
Expansion	0 to 10.0 percent	
Contraction	0 to 26 percent	

Reserves

The reserves of the Oyón area have been estimated as 42,300,000 metric tons (Cerna Nongrados, 1977, p. 15) which includes 2,835,000 tons of "non-washable coal" and 4,860,000 tons of coaly shale. The remaining 34,605,000 tons consist of 3,645,000 tons cokeable coal, 18,022,500 tons of coal suited for mixing with other coal to produce coke, and 11,475,000 tons of non-cokeable coal, and 1,462,500 tons of unknown coking quality. The reserves are not classified according to degree of certainty or thickness.

Reserves of the Gazuna area are estimated as 107,800,000 metric tons of which 25,400,000 tons are classified as proven and probable.

Assessment

Coal of the Oyón area is currently being explored by SIDERPERU for the purpose of providing a source of coking coal and coal suitable for mixing with other coal to produce coke in order to supply the needs of the steel mill at Chimbote. Robert Hobbs of the U.S. Geological Survey visited the area during September 1978, and on the basis of his appraisal of exploration efforts as of that time, he expressed the opinion that the coal possibly could be economically exploited, but that before a mine should be considered, much additional drilling and sampling of coal would be needed to determine thickness and continuity of the beds and the quality and quantity of the coal. Only with a thorough knowledge of these factors can the economics of mining in the area be determined.

The Gazuna area is a potential source of coal for generation of electricity; however, before the coal can be considered as more than a potential source, much additional exploration effort is needed.

Jatunhuasi coal field

Geography

The Jatunhuasi coal field is a rectangular area of 1,500 hectares in Concepcion Province, Junin Department. It is about 70 km southeast of La Oroyo and 40 km east of Huancayo, and is just 200 m east of the Continental Divide which is at an altitude of about 4,600 m.

The surface throughout most of the area is part of the altiplano of the Andes and is gently sloping to moderately rolling. Local relief is generally less than 150 m, but in the southeastern part of the area the surface is dissected by the east-flowing Cachi River, which at places has incised its course as much as 400 to 450 m below upland areas. A number of small lakes are in the upland areas, and many are aligned along the outcrop area of the coal-bearing strata.

Geology

Stratigraphy

Sedimentary rocks exposed in the area consist of an alternating sequence of marine and continental deposits that range in age from Jurassic to Tertiary. A generalized description of the stratigraphic sequence is presented in the table below.

In different parts of the field several persistent diabase sills have intruded the sedimentary sequence. Many follow coal beds which most commonly are the weakest members of the sequence.

The coal-bearing section is in the Negro Bueno Member of the Goyllarisquizga Formation and is about 65 m below the top of the member which is also the top of the formation. The thickness of this section ranges from about 8 to 20 m.

Structure

The Jatunhuasi coal field is on the northeast flank of a northwest-trending anticline that is bordered on the northeast by a broad syncline and on the southwest by two north-dipping thrust faults that are short distances beyond and parallel to the axis of the anticline. At places the anticline is traversed by high-angle faults that trend N. 60° E. to N. 85° E., and have displacements of as much as 20 m. Also, bedding-plane faults follow coal beds, and as a result of differential movements, the coal is highly fractured and slickensided.

Coal beds

Throughout much of the area the coal beds are concealed beneath a layer of soil that is generally shallow on the crests of hills but is as much as 10 m thick in swales. Because of general concealment, coal beds can be traced at the surface for only short distances.

Much of the knowledge pertaining to the characteristics of the coal beds is largely from underground workings, trenches, and test holes. During the early 1900's coal was mined from numerous underground workings in many parts of the area, and early investigators of the geology of the area had access to an abundance of data that have not since been available as the mines were long ago abandoned and are now caved in.

Generalized description of sedimentary rocks exposed in the Jatunhauasi coal fields (from Page, 1962)

Probable age	Formation	Member	Description	Thickness (meters)
Tertiary	Casapalca		Terrestrial red beds, Sandy shale, fine sandstone, thin limestone and limestone conglomerate	300
Middle Cretaceous	Machay	Chulec	Marine limestone with black shale and calcareous sandstone	800
			Massive sandstone, red sandy shale	65
Lower Cretaceous	Goyllarisquisza	Negro Bueno	Coal, sandstone, sandy fireclay, mudstone, shale	15
	Jatunhuasi		Massive sandstone with platy sandstone and argillaceaus beds	400
		Manca	Fine platy sandstone, red sandy shale	220
		Chaucha	Marine limestone	85
			Massive sandstone	75
			Fine sandstone, red sandy shale	215
Lower Jurassic Upper Triassic			Marine limestone	700 +

In general the coal beds are lenticular and are rarely of minable thickness for distances of more than a few hundred meters (Gerbracht, 1962). Commonly beds of minable thickness occur in pairs, but at places there are three beds; however, the beds are not everywhere the same. Beyond the limits of minable coal are smaller lenses of coal that give a false impression of continuity and large reserves.

According to Gerbracht, a traverse along the outcrop from one end of the field to the other will reveal the following pattern which repeats itself each 4-5 km:

1. Carbonaceous shale
2. Increase in percentage of coal in shale
3. Seam reaches maximum thickness and is entirely coal
4. Seam decreases in thickness, and number and thickness of shale partings increase
5. Seam splits and disappears.

Coal having economic potential forms in three seams designated, from oldest to youngest, as the Z, XY, and AB seams. The Z seam is as much as 83 cm thick and is generally thicker than the AB seam. The coal is dirty and it commonly contains bands of shale. It is much affected by bedding-plane faulting, and when handled it breaks readily into slickensided flakes.

The XY bed generally is 4 to 6 m above the Z bed, but at places is almost in contact with the Z bed. The XY bed is as much as 90 cm thick, but it is very thin or missing over large areas. It commonly contains a parting of variable thickness.

The AB seam is usually 8 to 12 m above the XY bed but locally is as much as 19 m (Page, 1962). At places it is split by a thick clay parting and occurs as two benches. In such areas the coal is not considered minable (Gerbracht, 1962). Its average thickness is about 75 cm; locally, it is as much as 1.4 m thick (Ramón, P., 1978, p. 28).

Although as many as six different coal beds have been identified in the sequence, beds other than those described above are too thin to have economic value.

Physical and chemical properties

Jatunhuasi coal is classified by Vilchez S. and Angeles F. (1977, p. 18) as subbituminous and bituminous with a high content of volatile material. According to Gerbracht (1962), coal of the AB seam, as mined, contains about 40 percent ash. It produces a good strong coke and is good for blending with other coals to produce coke. On the other hand, Page (1962) considers the AB coal to be inferior in quality to that of the XY bed. The XY, according to Gerbracht, contains a higher percentage of fixed carbon and is noncoking. Coal of the Z bed usually contains a high percentage of ash and a low percentage of fixed carbon. It also is noncoking.

Sulphur content in coal from all beds is rarely less than one percent or more than 5 percent. All seams contain pyrite (Page, 1962).

Analyses of coal from each bed are presented in the following table:

Analyses of coal samples from Jatunhuasi coal field
(from Ramon P., 1978, p. 28)

Sample Number	Type of sample	Bed	Thickness (meters)	Volatile materials (percent)	Fixed Carbon (percent)	Ash (percent)	Sulphur (percent)	BTU/16
28	Outcrop	AB	1.40	24.0	48.9	27.1	1.8	10,400
29	Outcrop	XY	0.82	28.5	49.7	21.8	1.4	10,400
30	Outcrop	AB	1.25	22.1	60.1	17.8	1.6	10,930
31	Outcrop	(XY)X	0.70	28.0	48.3	23.7	018	9,840
32	Outcrop	(XY)Y	0.30	17.0	12.0	71.0	0.8	3,600
33	Outcrop	Z	0.50	17.9	17.3	64.8	0.4	3,330
34	Trench	AB	0.80	27.0	58.2	14.8	0.8	11,470
35	Trench (oxidized)	XY	0.50	17.0	20.2	62.8	0.3	3,810
36	Gallery at 130-m depth	AB	1.30	30.1	53.5	16.4	1.4	9,870
37	Cross cut in mine	XY	0.50	27.9	40.6	31.5	2.1	8,980
38	Outcrop	XY	0.90	31.1	47.7	21.2	1.1	9,600
39	Outcrop	Z	0.40	24.0	30.9	45.1	0.4	5,280

Coal in most parts of the coal field is highly fractured owing to tectonic activity and when mined will produce a high percentage of fines. Also, lenses of soft clay or "muki," which are present in the coal at places, and clay partings that cannot be removed during mining will require that the coal be washed.

Reserves

Coal reserves have not been calculated for the entire area of the Jatunhuasi coal field. Only for an area in the vicinity of the Nueva Selica

mine in the northwestern part of the area are meaningful reserve figures available. Based on an investigation by Page (1962) involving geologic mapping, core drilling, trenching, and tunneling, recoverable reserves of coal according to coal beds are estimated as follows:

Bed	Dry short tons
AB	433,400
XY	269,600
Z	525,000
Total	1,228,000

In calculating reserves Page included all coal beds 50 cm or more thick. Although he does not classify reserves according to degree of certainty, the data on which his estimates are based seem adequate to place the estimates in the categories of measured and indicated. Escudero R. (1977, p. 6) estimates reserves for the area as 60 million tons of inferred coal, but data on which this figure is based are not cited.

Coal beds in the Jatunhuasi field are exposed over a distance of 25 km. The area for which Page provides reserve estimates extends only 5 km of this distance. Coal resources in the remaining parts of the field are probably large but to classify them as reserves will require further exploration.

Assessment

The coal beds in the Jatunhuasi field are thin and mining will be costly. Also mining problems can be anticipated due to subsurface water at shallow depth. However, because of a serious need for coking coal at the nearby Cerro de Pasco mine at La Oroyo and because of the high cost of importing coking coal from foreign sources, coal in the area probably can be economically exploited if adequate reserves can be blocked out. Currently, Cerro de Pasco imports about 60,000 metric tons of coking coal per year at a cost of $70 per ton. Investigations conducted during the early 1960's indicated that Jatunhuasi coal could be profitably mined. However, due to economic changes, this may no longer be the case.

Investigations currently in progress indicate that coal beds are thickest in the southeastern part of the area near the Cachi River. Because of greater relief and therefore better drainage conditions, problems encountered in mining will probably be fewer than in poorly drained areas to the northwest. This area, which is considered to have the best potential by geologists of CENTROMIN, should be further explored by core drilling, trenching, and tunneling in order to obtain data necessary for classifying reserves.

Other areas

The Goyllarisquizga coal mine, a short distance from La Oroyo, was a source of coking coal for lead blast furnaces of the Cerro de Pasco Corp. until 1971, when the mine was shut down due to depletion of reserves. However, development work is now underway to reopen the mine and to produce coal from beneath areas that were formerly occupied by shops and maintenance buildings. An estimated 300,000 metric tons remain in such areas. The planned production rate is 100 metric tons per day. A coal-preparation plant of 100-ton-per shift capacity will be installed. The capacity that is in excess of that required to prepare coal from the mine will be used to prepare coal that it is anticipated will be supplied by local small mines.

Beds of lignite, bituminous coal, and anthracite more than 2 m thick are reported to exist in several other areas in northern and central Peru. Additionally, numerous beds of lignite at a depth of about 460 meters are described from wells drilled for oil approximately 230 km east of Iquitos. Large inferred reserve estimates, as much as 100 million tons, are given for some of these areas; however, neither the method nor data used for deriving reserve estimates are reported. Therefore, figures for such estimates must be regarded as highly speculative.

As much as 100 million metric tons of lignite in beds 1 to 4 m thick have been reported in Tumbes Province, northern Peru. The area was visited during September 10 to 12, 1978, by W. W. Olive and Robert Hobbs of the U.S. Geological Survey and by Jose Cruzado C. of PetroPeru. The thickest lignite bed observed did not exceed 10 cm. Examination of well records in the files of PetroPeru indicated lignite beds possibly as thick as 1 m but at depths of 10,000 to 13,000 feet.

Lignite beds in Tumbes Province are reported to exist in rocks of middle Miocene age. These rocks for the most part consist of very coarse sediments and do not suggest environmental conditions favorable to accumulation of thick lignite deposits. Further, the area of reported lignite is part of a melange in which the strata are highly contorted to the extent that it is rarely possible to correlate strata exposed in one hill with those of an adjacent hill. Such conditions would pose serious mining problems.

Recommendations

The seeming lack of basic data at the coal fields discussed in the report points to the great need for a well-planned exploration program with the following objectives:

1. Map coal outcrops at a scale of 50,000 or less,
2. Determine the thickness of the beds at regular intervals,
3. Determine the quality of the coal,
4. Classify reserves according to their degree of certainty, quality, and thickness by using consistent established standards.

Information presently available on coal localities in most parts of Peru is inadequate to judge whether economic deposits exist, either in terms of the present or of the future economy.

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GEOTHERMAL ENERGY

By Robert O. Fournier

Introduction

Using the terminology of U.S. Bureau of Mines-U.S. Geological Survey Bulletin 1450-A (1976) and U.S. Geological Survey Circular 726 (White and Williams, 1975), the geothermal energy resource base of Peru is all the heat above 15° C to a depth of 10 km, the greatest depth from which thermal energy is likely to be economically extracted in the foreseeable future. Because thermal gradients and heat flow are poorly known throughout Peru, data are insufficient to estimate whether the geothermal resource base for Peru is relatively large or small, compared to the world average. According to Uyeda and Watanabe (1970), thermal gradients in South America generally are relatively low in the Pacific coast area; are relatively high in the Andes area; and are normal to subnormal in most other places. Because the Andes occupy a relatively large area of Peru, the geothermal resource base of Peru probably is relatively large compared to the world average. For the purposes of this report, the important consideration is the quantity of heat (thermal energy) that can be economically extracted using present and probable future technology. In this regard, Peru has no demonstrated economic reserves. There are, however, demonstrated subeconomic resources, as shown by the emergence of warm and boiling springs in many parts of the country. Based on the chemical and physical character of the hot springs, a broad knowledge of the geologic characteristics where economic geothermal resources tend to occur, and analogy with demonstrated geothermal energy reserves in northern Chile, economic reserves and subeconomic resources can be inferred for Peru. The inferred 1/ reserves all are in southern Peru in areas of recent and active volcanism (Zone V in fig. 15). Inferred resources and speculative 2/ resources and reserves exist in central and northern Peru, generally in a narrow belt of hot spring activity within the Cordillera Occidental (Zones I, II, III, and IV in fig. 15) and in a zone extending from Cuzo to Puno (Zone VI, fig. 15) The reserves in central and northern Peru are termed speculative because it has not been demonstrated that significant amounts of geothermal energy can be economically extracted from the particular type of geologic environment encountered there.

Utilization requirements with present technology

In order to utilize geothermal energy economically for the production of electricity, minimum underground temperatures of about 170° C to 200° are required at depths less than 3 km (preferably less than 2 km). Furthermore, hot water or steam must be found in permeable zones (reservoirs) in the hot rock because the thermal energy must be transferred to the surface by withdrawing that water or steam. This means

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1/ See footnote 1, table 7.

2/ See footnote 2, table 7.

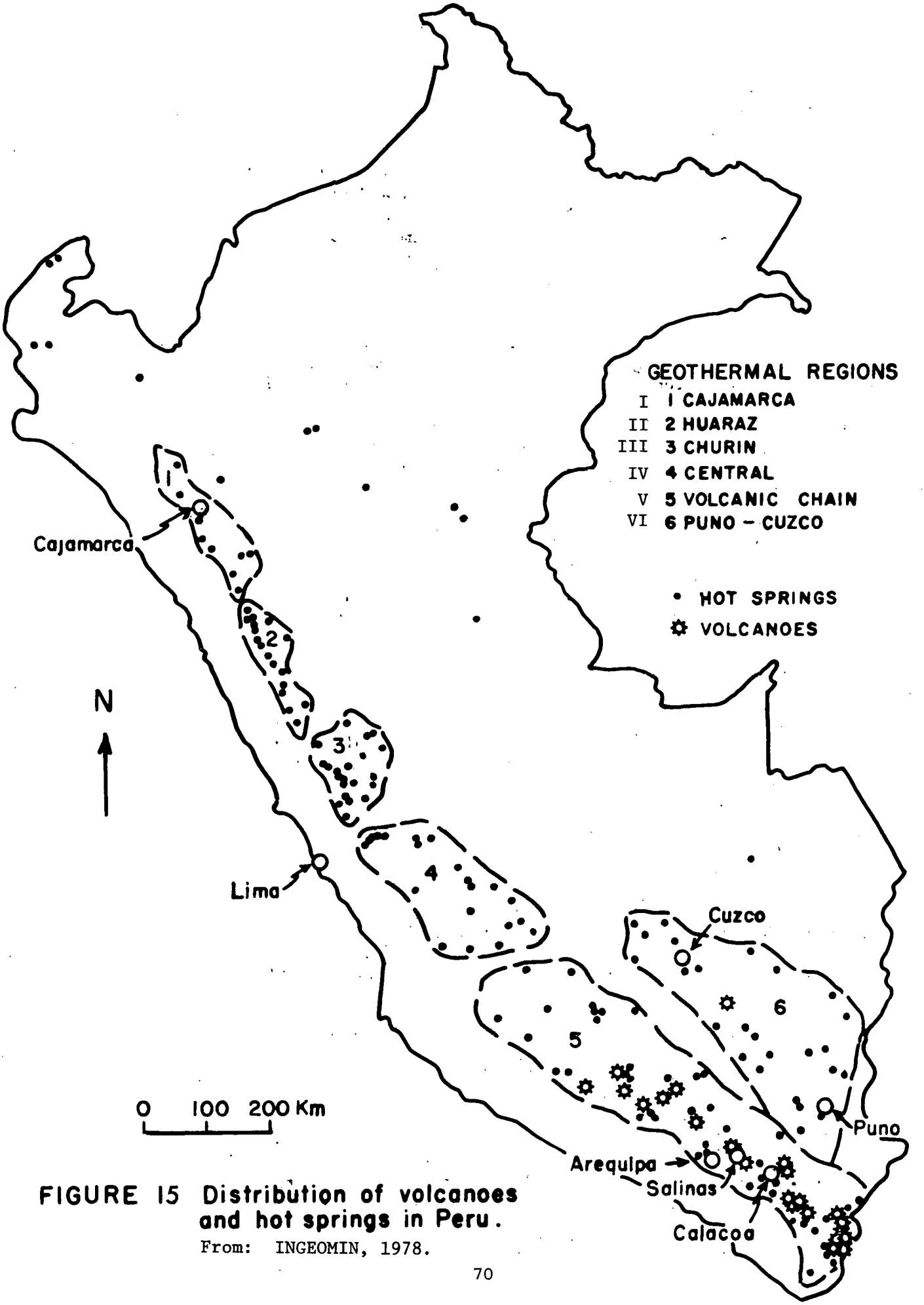

FIGURE 15 Distribution of volcanoes and hot springs in Peru.
From: INGEOMIN, 1978.

known. This information on depths, sizes, and permeabilities must come from detailed geologic, hydrologic, and geophysical studies of specific places and, ultimately, from deep drilling.

Preliminary detailed geologic studies have been made of two geothermal areas by MINERO PERU: one of Calacoa (Vargas and others, 1975) and the other of Salinas (Morgan and Quintacailia, 1976). No geophysical studies were done as part of this work. Some geochemistry was done only at Calacoa, but chemical analyses are incomplete and cannot be used with confidence to estimate reservoir temperatures.

Over a 17-day period, a team of Japanese geothermal energy experts (GERD, 1976) conducted studies (mainly geochemical) of the geothermal potential of hot spring localities near the towns of Sicuani, La Raya, and Quisocollo, which are located in Puno-Cuzco geothermal region VI (fig. 15). They concluded that 20-30 MW (72 x 10^9 to 108 x 10^9 million joules) could be produced from geothermal energy in that region. That estimate appears to be on the optimistic side because the underground hot water reservoirs feeding the springs probably have lower temperatures than those estimated by the Japanese team 3/.

Estimated geothermal resources at temperatures greater than 180° C

The estimated geothermal resources of Peru in table 7 are subdivided into inferred and speculative economic reserves and subeconomic resources. All these resources must be considered undiscovered because temperatures 180° C or greater have not been demonstrated by drilling.

Given the available information, only the Calacoa area is considered to have inferred economic reserves. The general character of the hot spring activity there is indicative of a hot-water-dominated reservoir with temperature greater than 180° C. In other places in the world, hot-water-dominated reservoirs yield about 30 to 250 MW (1.1 x 10^{11} to 9.0 x 10^{11} joules). We have arbitrarily assigned a value of 100 MW (3.6 x 10^{11} joules) for Calacoa. The subeconomic resources include thermal energy in relatively impermeable hot rock at shallow depths and thermal energy in rocks at depths between 3 and 10 km.

The numbers in table 7 for the speculative economic reserves and resources were derived by assuming that at least four of the nine large active volcanoes of Peru are associated with active hydrothermal systems and that at least 8 to 10 other hydrothermal systems are present near volcanoes that are no longer considered to be active. Additional study

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3/ Recent unpublished work by R. O. Fournier has shown that a magnesium correction must be applied to the Na-K-Ca geothermometer. This correction lowers the estimated temperature at La Raya to 130° to 140° C and at Quisicollo to 80° to 90° C. These corrected temperatures are in good agreement with the silica temperatures for these localities (120° to 135° C at La Raya and 87° to 92° C at Quisocollo). These temperatures are too low for economic electrical production using present technology. In addition, the high calcium and CO_2 contents of water are likely to cause calcite scaling problems that would make exploitation difficult.

of the many relatively insignificant hot springs in region V may elevate many of the speculative reserves to inferred reserves. However, it is likely that many exploitable geothermal systems in Peru have no hot spring or fumarole surface expression, either because the systems are too young, or because abundant, cold, shallow groundwater completely masks the deep hot water. The systems having no surface hot spring might be located by geologic and geophysical methods.

TABLE 7. Estimated geothermal reserves and resources of Peru sustained over a 5-year period.

Temperature	Economic (Reserves)		Subeconomic (Resources)	
	MW	Joules	MW	Joules
Over 180° C				
Inferred 1/	100	3.6×10^{11}	1000	3.6×10^{12}
Speculative 2/	2000	7.2×10^{12}	20,000	7.2×10^{13}
Under 180° C				
Inferred 1/	300	1.1×10^{12}	Large	
Speculative 2/	6000	2.2×10^{13}	Large	

1/ Inferred reserves or resources are based largely on broad knowledge of the geologic character of the deposits and for which there are few, if any, samples or measurements. The estimates are based on assumed continuity or repetition, for which there is geologic evidence; this evidence may include comparisons with deposits of similar types. Bodies that are completely concealed may be included if there is specific geologic evidence for their presence (U. S. Geological Survey Bulletin 1450-A, 1976).

2/ Speculative resources are undiscovered resources that may be present either in known types of deposits in a favorable geologic setting where no discoveries have been made, or in as yet unknown types of deposits that remain to be recognized (U.S. Bureau of Mines-U.S. Geological Survey, 1976).

Estimated geothermal resources at temperatures less than 180° C

The subeconomic resources at temperatures less than 180° C are probably very large. However, with the present state of knowledge, it would be meaningless to make a numerical estimate and, for the purpose of this report, the subeconomic resources less than 180° C can be ignored.

In region V of figure 15, the inferred economic resources at temperatures below 180° C should be larger than the inferred resources at temperatures greater than 180° C (table 7). This is because there should be more low-temperature rock than hot rock, and shallow rocks generally are more permeable than deep rocks.

The low-temperature economic resources of regions I, II, III, IV, and VI in figure 15 are difficult to evaluate with the available information. Most of the springs appear to lie on or near major faults, and it is likely that meteoric waters have become heated to moderate temperatures by deep circulation along these structures. Limestone is abundant throughout the region. Limestones generally are highly fractured and dissolve easily; they make good reservoir rocks. However, waters that dissolve limestone at moderate temperatures deep underground become rich in dissolved calcium and CO_2. Such waters deposit calcium carbonate when they lose CO_2 upon reaching the surface, and this scaling poses a major problem in their utilization for geothermal energy.

Ample recharge water is available from the rain and snow that fall on the nearby mountains. However, this situation also could allow dilution and cooling (mixing of warm and cold waters) hundreds of meters underground. No published data on natural hot spring discharge rates were available for this report. Data on discharge rates are necessary to estimate the natural convective discharge of heat at the surface. In general, about 4 to 5 times the natural heat discharge can be sustained under production conditions.

Four of the better known hot spring localities in region II (fig. 15) were visited to gain an impression of the magnitude of hydrothermal activity present there. The hot springs at three localities were little more than travertine-depositing seeps and the fourth (Monterrey) discharged a few tens of liters per minute at 45° C from a 3-meter-deep well. It is probable that the surface discharge of hot spring water is impeded by the deposition of travertine underground. It is also possible that there may be substantial undetected discharges of hot spring waters directly into the bottoms of rivers and streams.

The general conclusion is that in regions I, II, III, IV, and VI wells several hundred meters deep usually would be necessary to attain temperatures and flow rates appropriate for significant non-electrical utilization. However, even with sufficient temperature and flow rates from relatively shallow wells, carbonate scaling is likely to be a major problem. For these reasons, the geothermal resources in most parts of regions I, II, III, IV, and VI probably are subeconomic.

Potential installed capacity in 1985 and 2000

The estimated potential installed geothermal capacity in 1985 and 2000 is shown in table 8, assuming (1) present technology only, and (2) present technology augmented by future worldwide technology developments that might be applicable in Peru. The installed capacity in 1985 will be limited in part by the long lead time necessary for exploration, reservoir evaluation, plant design, financing, and construction (5 to 6 years), and in part by the limited number of qualified people available to carry out the work. Increased funding is not likely to immediately affect the number of available qualified people.

Future technology should have no impact by 1985 and only limited impact by 2000, when it may allow greater utilization of a given system than is possible now.

Future technologies that may have the greatest impact upon the utilization of geothermal energy in Peru include methods of economically utilizing 120° to 150° C water for the production of electricity and methods of stimulating hot water flow into wells by creating artificial permeability. There is even a chance that geopressured hot water and gas may be found in some of the deep sedimentary basins. At present, geopressured hot water resources have not been proven to be economic.

If the first one or two deep exploration wells are not successful, it is possible that a geothermal program could be terminated, and there would be no installed capacity by 2000.

Non-electrical utilization will probably be insignificant in 1985 and still relatively small in 2000, even though the resource is very large. Calcium carbonate scaling problems will be one of the major factors impeding the development of the low-temperature geothermal resources; calcite scaling will prevent relatively untrained people from drilling shallow wells and setting up hot water distribution systems at low cost. Heat exchanges or other sophisticated and expensive methods are likely to be required to deal with the calcite problem. Also, the available government money and manpower can be more effectively used in efforts to find and produce the high-temperature resources of the country. It should be kept in mind, however, that relatively low temperature water (70° to 100° C) is a by-product of geothermal energy utilization for electrical production and that such water might be used for non-electrical purposes.

TABLE 8. Potential installed capacity in 1985 1/ and 2000

	1985	2000
Electrical		
Present Technology	36 MW	200 MW
Future Technology	0	200 MW
Non-electrical		
Present Technology only	Insignificant	Insignificant
Future Technoloby	Insignificant	Insignificant

1/ The minimum time necessary from the start of specific site appraisal to the production of electricity by a geothermal power plant is 5 to 6 years. Therefore, if there is to be any geothermal production by 1985, a vigorous geothermal program must begin almost immediately.

Investment required

The investment required to develop geothermal energy can be subdivided into a succession of investments, starting with the cost of regional exploration and progressing through a specific site evaluation, site development (drilling and testing), power plant construction, and finally fuel supply and power plant operation (including waste disposal). It is relatively easy to estimate the general range in total costs required to

produce electricity from geothermal resources because the major investment is in the plant and its operation, relatively standard items varying mainly with the rate of inflation. The exploration and specific site evaluation costs are more nebulous because different geologic, topographic, and access conditions require different exploration techniques for various lengths of time and effort at greatly different costs. Another consideration is the total area to be covered in regional exploration and the number of specific sites to be evaluated before selecting one or more for development testing. At this time, the number of specific sites that should be evaluated is unknown. In the United States, geothermal exploration companies hope to find one area worth deep drilling for every four areas evaluated in detail. Of the deep wells drilled, three out of four are likely to be failures. The success ratio should be higher in a situation such as that at present in Peru, where the better prospects have not already been drilled.

Comparative costs for the generation of electricity for various types of geothermal resources and for oil, coal, and nuclear materials are shown in table 9. These costs were calculated by geothermal energy economist Bob Greider who formerly headed the Chevron Oil Company's geothermal energy division. Greider made use of Stanford Research Institute projections for oil, coal, and nuclear materials and included all aspects of the costs including fuel production, transportation, plant construction and operation, and environment protection. Greider concluded that electrical production from geothermal energy hot-water systems at temperatures above about 200° C is about 20 percent cheaper than nuclear electricity costs, the next most competitive fuel. Greider did not consider hydroelectric, solar, or other technologies.

There are no set costs for developing a geothermal field because each power plant must be engineered to accommodate the particular reservoir temperature, salinity, noncondensable gas content, production pressure, rate of production that can be sustained by the reservoir, ambient conditions at the field, etc. In 1977, hot-water flash plants had an extremely wide cost range, about $400 per KW (111 dollars per million joules). Double flash 45-MW (162 x 10^9 joules) power plants operating on fluids with low solids and low noncondensable gas contents at temperatures about 230° C could be constructed for about $450 to $475 per net KW, or $125 to $132 per million joules. Plants operating with fluids at about 175° C cost about $550 to $575 per net KW or $153 to $160 per million joules.

According to Greider (reported in Geothermal Report, 1977), recent experience at Hilo, Hawaii, shows that the cost of developing a small, 3-well geothermal prospect now runs between $2.5 and $4.75 million, providing for limited failure and follow-up costs, but not including other exploration failures and land costs. About $12 to $13 million would be required to expand the search to attain 200 MW (720 x 10^9 joules). These figures do not include the cost of power plant facilities. By comparison, Ronald Barr (1975) concluded that $4.69 million would be required to run a geothermal energy exploration program for 3 years with a total of four deep exploration wells drilled (only one successful) at different geothermal prospects. This does not include the cost of land acquisition.

Approximate costs of some of the exploration techniques are given in table 10. These costs apply to exploration in the western United States and could differ considerably from the costs that would apply in Peru.

Table 9. Comparative costs of electricity production estimated by Bob Greider (reported in Geothermal Report, 1977) for the period 1977 - 1980 (one mill = 0.1 cent).

Fuel	Cost: mills/kWh	Cost: mills/million 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 - 14
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

Table 10. Approximate costs of geothermal exploration techniques.

Geology -- salary, office, field expenses per geologist per month	$3,500	$4,000
Geochemistry -- 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 -- per specific site	12,000	14,000
Seismic (passive) -- per specific site	25,000	50,000
Airborn magnetics -- per km flown	7	9
Shallow wells for temperature of hydrology --	20,000	50,000
Deep wells (1,500 meters or deeper) --	450,000	750,000

Labor requirements

The following labor functions will be necessary in geothermal energy exploration and development program:

1. Regional exploration to select sites for detailed studies. Mostly geology and geochemistry.
2. Specific site studies to determine whether or not to do deep drilling and, if so, where to drill and how deep. Geology, hydrology, geochemistry, geophysics (many options), and shallow drilling may be required.
3. Deep drilling and reservoir evaluation.
4. Power plant design.
5. Power plant construction.
6. Maintenance of geothermal fuel supply to power plant and disposal of waste products.
7. Operation of electrical generation equipment.

Functions 4, 5, and 7, related to power plant design, construction, and operations, are beyond the scope of this section on geothermal resources and the labor requirements are not discussed further here. It is expected that there would be a considerable overlap of personnel in carrying out functions 1, 2, 3, and 6.

The Instituto de Geologia y Mineria (INGEOMIN) now has the main responsibility for geothermal energy exploration in Peru, although in the past, MINERO PERU has mapped two geothermal prospects. At present, INGEOMIN has a few geologists and one analytical chemist assigned to its geothermal program, but, because of lack of funds, no field work can be done and no equipment purchased. The exploration program now consists of library research and photointerpretation. None of the personnel are specifically trained or experienced in geothermal exploration techniques.

Many of the regional exploration functions can be carried out effectively by the present INGEOMIN personnel. The geologists would benefit by early contact with one or more geologist-volcanologists who have had experience in geothermal exploration. The analytical chemist should be given one or two months training out of Peru, in a laboratory where a variety of geothermal waters have been analyzed. Additional analytical equipment also will be required in INGEOMIN in order to analyze a large number of water samples quickly, cheaply, and accurately (additional atomic absorption lamps, a spectrophotometer, automatic titrator, specific ion electrodes and meter and various laboratory supplies). It will be necessary to have oxygen and deuterium isotopic analyses and isotopic age dating of rocks performed by foreign laboratories (cost/sample?).

Also, a geochemist experienced in geothermal exploration should be involved early with some of the hot spring collection work and with interpretations of the results.

There are various ways that specific site studies and reservoir evaluation could be accomplished. Probably the quickest and most effective would be to contract out the work to a private company that could carry all the way through to function 6, supplying fuel to a power plant. Alternatively, a project manager having broad knowledge and experience in geothermal assessment might be recruited to oversee the specific site studies. The project manager would decide what exploration techniques to use and when (using expert consultants when necessary to help formulate the program and evaluate the results). Presumably, foreign contractors would have to be used for many of the geophysical techniques that might be required. The deep drilling would be handled in a manner similar to that now used in oil and gas exploration in Peru. In the above process, Peruvian personnel should be involved with all phases of the operation to gain the necessary experience to act as their own project managers.

The specific number of professionals and support people required to carry out a geothermal exploration and development program is somewhat flexible depending upon how many specific sites are to be evaluated simultaneously and upon the techniques being employed at a certain time. In general, 20 to 60 people might be involved at a given time.

Suggested program

A region where detailed studies should be undertaken soon is at Salinas, near Arequipa. As yet, there is no direct evidence for a high temperature geothermal system at Salinas. However, the general geologic environment appears to be favorable. Hydrologic and geochemical studies (including shallow drilling) should be carried out at Salinas to see if the existence of a high-temperature hydrothermal system can be confirmed. If so, additional geophysical work should be initiated to determine the probable distribution of the hot water.

URANIUM

By Edwin A. Noble

Introduction

Peru is part of a subcontinent-size region that has not been adequately assessed for its uranium potential. Past exploration has been neither comprehensive nor intensive and has almost completely lacked coverage by modern aeroradiometric reconnaissance. Peruvian geologists and other competent explorationists have made local investigations throughout readily accessible parts of the country but have hardly scratched the surface of the large, poorly accessible area that they all believe most favorable for uranium. No economic deposits have been found.

Scope and results of past exploration

Uranium investigations apparently began in 1953 with the initiation of a joint program by the Junta de Control de Energia Atomica del Peru (JCEA) and the U.S. Atomic Energy Commission (USAEC). The cooperative program extended through 1960. The first phase of the program, from 1954 to 1957, consisted of examination of specimens from mines and mills to identify those exhibiting radioactivity. Next, more than 200 mines and prospects were examined; some of these yielded uranium minerals or measurements of anomalous radioactivity, but no economic concentrations were found. The uranium was usually found associated with other metals, but was also identified in otherwise barren hydrothermal localities. Host rocks included pegmatite, granite, diorite, rhyolite pyroclastics, and black shale. Practically all this work was concentrated in the western and central Andes, where mining activity provided a relatively dense network of roads.

In 1956 and 1957, extensive carborne-scintillometer surveys were made on traversable roads outside the active mining districts. Although no strong anomalies were noted, the surveys were not believed conclusive because of possible widespread leaching of uranium from surface rocks. In 1957 and 1958, emphasis of the USAEC-directed project was transferred to a search for Peruvian analogues of environments productive in the United States. Studies of rocks, environments, and mineral zoning yielded some information on the distribution of anomalous radioactivity but did not lead to ore discoveries.

The last phase of USAEC involvement, from 1958 through 1960, was devoted to an attempt to demonstrate the reality of hydrothermal zoning around major intrusive centers, a conviction long held by Gabelman, the USAEC's principal investigator in Peru (Gabelman and Beach, 1962). Gabelman believed that uranium would not be found in appreciable amounts in the major metal districts of Peru but was more likely to be found in outer, cooler zones parallel to the high-temperature zones of the western slope of the Andes. He concluded that the bleached and pyritized Mesozoic and Tertiary sedimentary

rocks of the eastern Andes and Amazonas basin were the most likely hosts for uranium deposits. This area was largely unexplored, but Gabelman noted that a cursory examination showed radioactivity to be more widespread here than elsewhere.

A German scientific mission, specializing in geology, geophysics, and geochemistry, aided JCEA in 1961. In 1970, reconnaissance-type aeroradiometric prospecting of a limited area (less than 1 percent of Peru's 1,285,000 km^2) was conducted through an International Atomic Energy Agency (IAEA) aid program; the maximum anomalies detected had radioactivity of only about four times background. A more detailed aeroradiometric prospecting program in a small area was carried out in 1971-72, also supported by IAEA. Coco, the IAEA expert who conducted the aeroradiometric projects in 1970 and 1971-72, recommended continuation of aerial prospecting by fixed-wing plane, using helicopters where needed. He (Coco, 1972) suggested supplementary use of geochemical prospecting but cautioned that the technique might lead to misinterpretations in regions where physiographic extremes bring about abrupt differences in rainfall in closely adjacent areas.

In 1973 and 1975, the IAEA, through a United Nations Development Program (UNDP), gave technical assistance to the Instituto Peruano de Energía Nuclear (IPEN) for project work and training in geochemical prospecting. The geochemical expert, Santomero, who directed this program for IAEA, recommended additional geochemical exploration with special attention to the eastern Andes where continental sedimentary rocks cropout on the flanks of basins near silicic plutonic rocks (Santomero, 1977).

Geologists for IPEN and UNDP agree in general with the final recommendations of Gabelman and the IAEA experts. They also add recommendations of two additional areas. One includes the sediments and associated volcanics of the Puno district in the vicinity of Lake Titicaca (area V-I in fig. 16). The other includes a radioactive Paleozoic granite (as much as 120 ppm uranium) and associated sedimentary rocks in east-central Peru (area III-6 in fig. 16).

Present program

As a part of Peru's Nuclear Plan for 1976-1981, a team of about 15 IPEN and UNDP geologists, with support from chemists and subprofessionals, has been delineating areas according to favorability for the occurrence of uranium resources. The information presented below was obtained through personal contact with geologists and engineers of IPEN and UNDP in August 1978. The IPEN-UNDP group developed an "index of geologic favorability" by attributing numerical values to geologic features possessed by classic uranium ore deposits elsewhere in the world. Based on similarities in geology, the entire country was divided into seven generalized "belts." These belts were further subdivided into smaller "prospecting units" (fig. 17) for purposes of more detailed assessment of

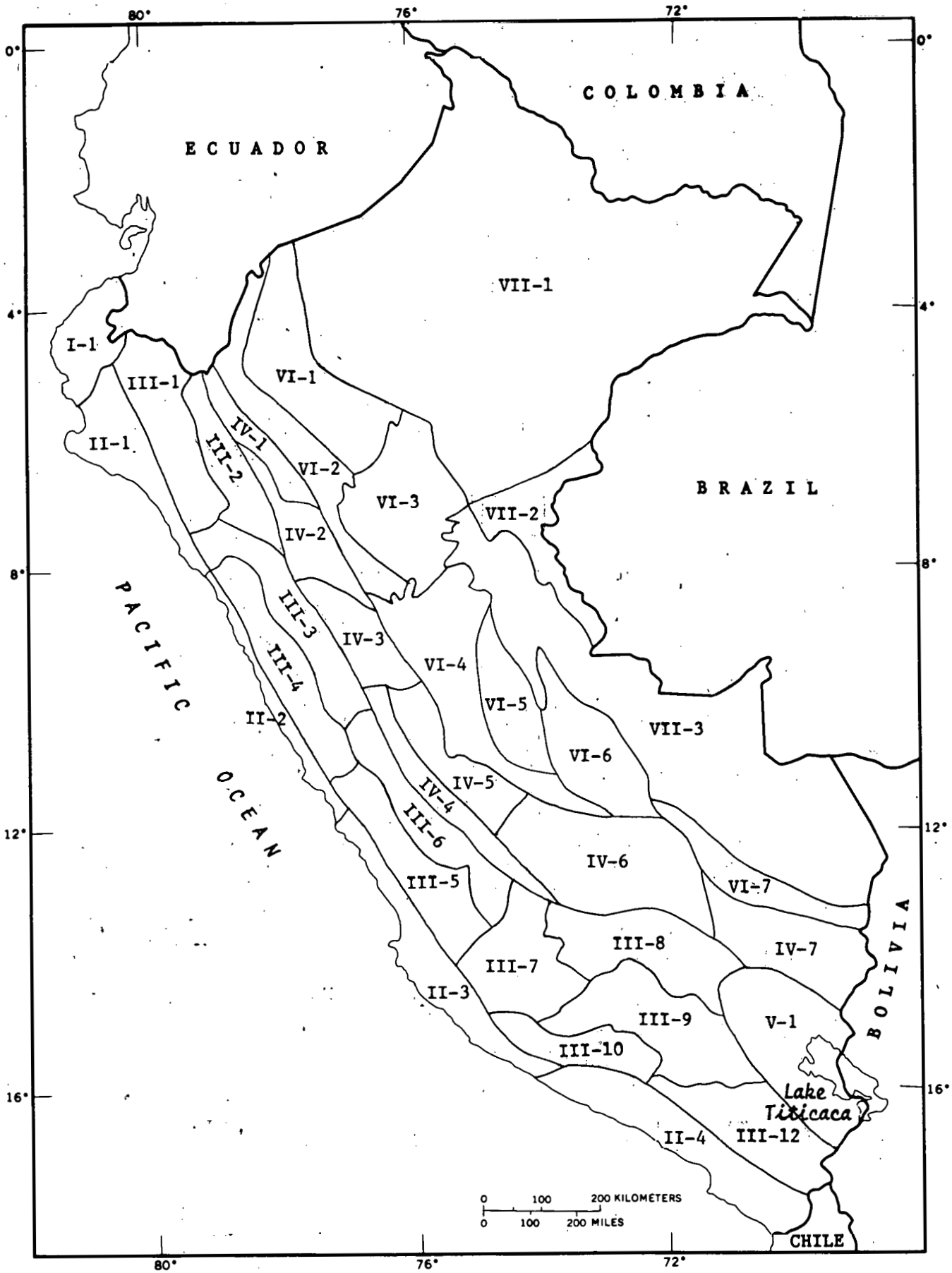

Figure 16. Subdivisions representing areas of similar geologic environments in Peru. Simplified from Instituto Peruano de Energia Nuclear, unpublished map.

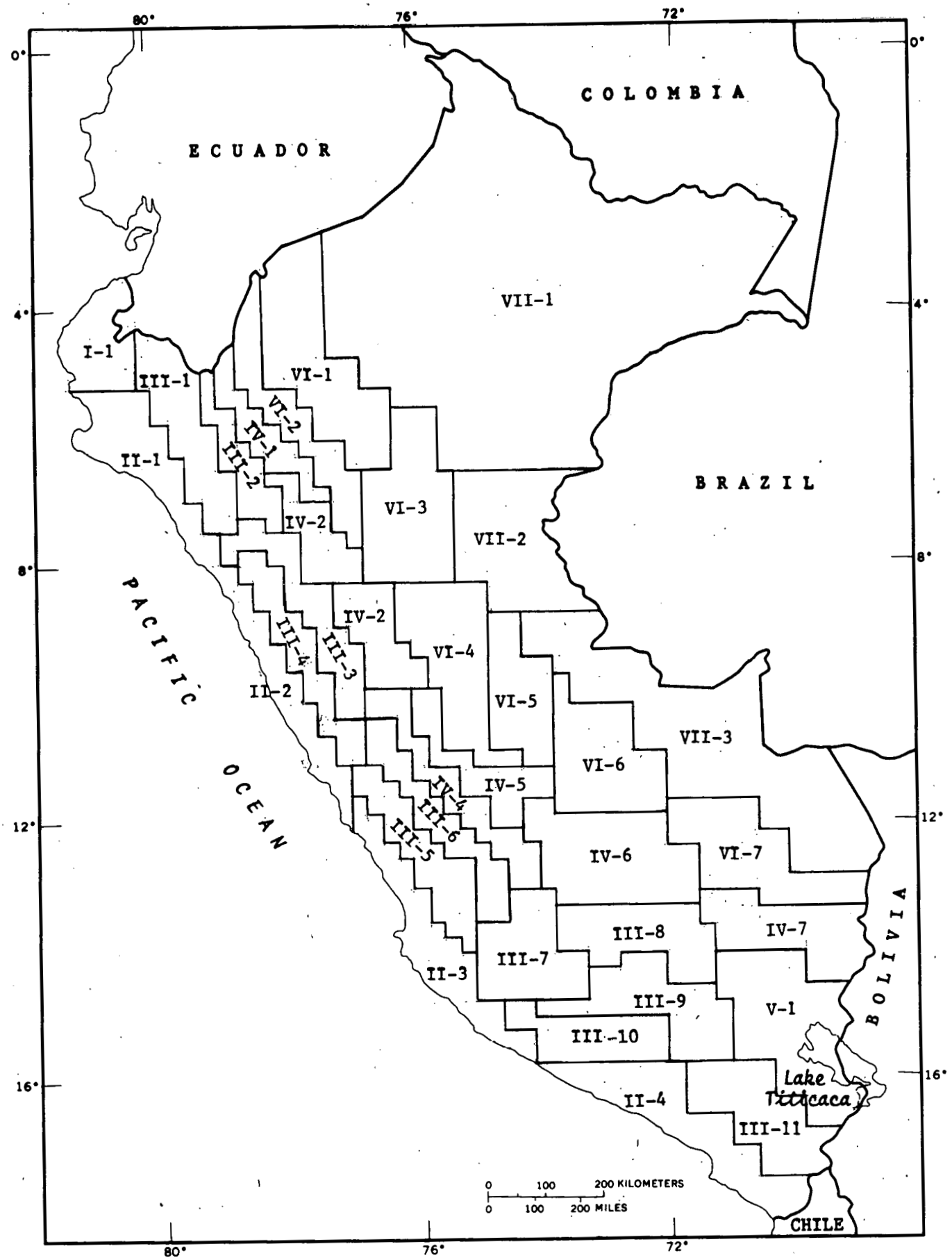

Figure 17. Uranium prospecting units for leasing purposes in Peru. Simplified from Instituto Peruano de Energia Nuclear, unpublished map.

favorability for uranium. A prospecting unit is intended to be of a size and character that will permit completion of the prospecting phases within 2 or 3 years. For the purpose of leasing, the boundaries of the prospecting units are modified to conform to a latitude-longitude grid (fig. 17). A law that will allow leasing of land for exploration is expected to be passed in 1979.

Observations and recommendations

Although not situated in a widely recognized uranium province, Peru has a variety of rock types, rock environments, rock ages, and climate that conceivably could provide for source, transport, and concentration of uranium. However, neither theory nor investigation has yet answered fundamental questions concerning the crustal occurrence of uranium and its behavior throughout the past geologic-hydrologic events in the region. On the optimistic side, worldwide research on uranium and its relation to geologic processes is progressing rapidly, and improved geologic models are being constructed to aid in the assessment of uranium potential. These advances in understanding, along with vastly improved methods of regional reconnaissance, can be applied to exploration in Peru as soon as outside capital is permitted to participate.

Recent work by the Peruvian/UN geologic team reinforces an earlier conclusion, reached by the U.S. team in 1960 and by IAEA personnel in the early 1970's, that the most favorable areas for uranium search lie along the foothills of the Eastern Cordillera and in the adjoining jungle area that extends toward the geologically attractive Brazilian Shield. Peruvian geologists point out that the foothills belt is a geological continuation of the known uranium province similarly situated in Argentina; they add that access in Peru is more difficult and that the climate mandates different approaches to exploration which are not yet well developed.

The difficulty of access and remoteness from sources of supplies will make any drilling program difficult and costly. This emphasizes the need for the best possible basic geologic-geochemical-geophysical analysis prior to a drilling effort. The role of IPEN is obvious; intensive geologic work and good data presentation can provide attractive targets for outside capital to explore. Logs of near-surface portions of oil wells would help, and the availability of reliable laboratory analysis could also encourage potential explorationists.

It should be reemphasized that geological-geochemical theory has not reached the point from which one can safely predict Peru's uranium potential. Until more is known about uranium's distribution and its behavior under a wide range of conditions, exploration should continue in Peru and in other underexplored areas of South America.

MISCELLANEOUS SOURCES OF ENERGY

By Ralph L. Miller

Oil shale

The following generalized description of oil shale has been summarized from more detailed descriptions in various publications of the U.S. Geological Survey:

> Oil Shale is a very fine grained sedimentary rock, containing enough organic matter (hydrocarbon) to yield at least 10 gallons of oil per ton when properly processed. Some shales yield much more oil, however, and in the United States some thin layers have been reported to yield 140 gallons of oil per ton. Most shales of commercial interest yield from 25 to 65 gallons of oil per ton, though some foreign deposits yielding between 10 and 25 gallons per ton have been mined on a large scale. Many other organic-rich shales yield less oil (1 to 10 gallons per ton), but because of their low grade, they usually are not called oil shale.
>
> When shale is heated in a retort to a temperature of about 900° F, some of the organic material melts, and when this liquid is heated to higher temperatures, gases form. The vapors can be condensed to form oil, with part remaining as hydrocarbon gas. From 25 to 75 percent of the organic matter in oil shale can be converted to oil and combustible gas. The remaining carbon forms combustible char or coke.

Oil shale has been processed commercially in a number of countries, including Estonia, Sweden, and South Africa. Until recently inexpensive oil, particularly from the Middle East, has made these industries economically marginal at best. However, with the huge increases in the price of petroleum since 1973, many countries including the United States are again assessing or reassessing this possible source of liquid hydrocarbon to meet future needs.

We are not aware of any reports of oil shale deposits in Peru, but with considerable sections of the country still very little known geologically, oil shale deposits may exist, and might have some input into Peru's energy scenario in the future. Even if oil shale deposits were found, they certainly would not be in production by 1985, and probably not before the year 2000.

Bitumen-bearing rocks (tar sands)

The following brief description on bitumen-bearing rocks is excerpted from an article by W. B. Cashion (1973, p. 99).

"Nonfluid petroleum occurs as interstitial deposits in numerous types of rock. These rocks and their associated hydrocarbons *** have been referred to as tar sands, oil-impregnated rocks, asphalt-bearing rocks, oil sands, bitumen-bearing rocks, and petroleum-impregnated rocks. *** the term "bitumen-bearing rocks" *** is defined as follows: Consolidated or unconsolidated rocks whose interstices contain viscous to semisolid to solid petroleum which in its natural state cannot be recovered by primary petroleum-recovery methods. This definition includes vein, dike, and asphalt-lake deposits, as well as disseminated deposits, but it excludes pyrobitumens (such as coal and oil shale)) and fluid bitumens.

Nonfluid bitumen occurs principally as disseminated deposits in small pore spaces spread throughout rock material. Bitumen content may be as much as 20-25 percent by weight, but is normally much less."

* *

"The Athabaska tar sands in Canada are being mined and processed by GCOS (Great Canadian Oil Sands, Ltd.) to produce crude oil. *** Other companies also plan to add new installations.

In 1967, tar-sand deposits in Albania, Rumania, and Russia and an asphalt-lake deposit on the Island of Trinidad were also being exploited; ***"

We do not know of any tar sand deposits in Peru, but this may be due to lack of knowledge, rather than lack of deposits. In either case, an industry based on crude petroleum from tar sands is not likely in the near future nor as long as liquid petroleum meets domestic needs.

Ocean thermal energy conversion (OTEC)

Energy production based on the temperature differential between surface and deep ocean waters has attracted some attention and may hold potential for the future, particularly for countries fronting on an ocean where deep waters are present close to shore. The technology to exploit this source of energy is still not developed, however.

A recent world-wide chart published by the U.S. Department of Energy shows the temperature differential of the world's oceans for depths of water shallower than 1,000 meters. A differential greater that 20° C is considered to be possibly favorable from a temperature standpoint for energy from this source. Peru, however, is shown on the chart, on the basis of measurements so far available, to have a differential of less than 15° C. On this basis, energy conversion from surface-subsurface temperature differential does not seem to be prospective for the foreseeable future in Peru.

ENERGY-RELATED MINERALS

By Wilds W. Olive

An increase in the production of energy from traditional sources the development of new energy sources will result in an increased demand for minerals and rock materials used in the production, generation, and transmission of energy. The mineral wealth of Peru is legend; it is well endowed with most materials that are essential to energy production; however, economic sources for some materials, such as aluminum, vanadium, and cobalt are either nonexistent or are marginally economic.

The following information on the occurrence and reserves of energy-related materials was provided by Ing. Manuel Velasquez, Director General, Hierro Peru (iron and cobalt), and by Ing. Edgardo Ponzoni S., Director de Geología Minera, Instituto de Geología y Minería (metallic and nonmetallic minerals):

Iron.--All iron produced in Peru comes from the Marcona mine which is operated by Hierro Peru, a government-owned company. The mine, which is an open pit, is about 500 km south of Lima by way of the Pan-American Highway.

The mineralized area extends over 150 km^2, and within this area the iron minerals, principally hematite, martite, limonite, and magnetite, occur in tabular bodies that traverse metasedimentary rocks of Paleozoic age, and interbedded sedimentary and volcanic rocks of Jurassic age.

The following reserve estimates (tons) were reported in 1976:

	Proven	Probable	Total
Ore from oxidized zone	81,015,000	30,257,000	111,272,000
Ore from transitional zone	119,388,000	146,632,000	266,020,000
Primary ore	414,018,000	725,658,000	1,139,676,000
Total	614,421,000	902,547,000	1,516,968,000

The ore contains an average of 54.2 percent iron, 2.40 percent sulfur, and 0.10 percent copper. Additionally, headings contain about 0.5 lb of colbalt per ton. Analysis of tailings indicate a content of 0.3 percent copper and 1 lb/ton of cobalt. About 4 million tons per year of tailings are produced.

The company is currently developing plans to extract copper and cobalt from the tailings and anticipates that within 4 or 5 years it will be able to recover about 9,000 tons per year of copper and 3 1/2 to 4 1/2 million pounds of cobalt.

Copper.--Copper occurs in large concentrations at many places throughout the Cordillera Occidental; however, in the Cordillera Oriental concentrations in which it is the principal metal are small. Reserves, are reported as follows:

Proven reserves	3,733,339,000 metic tons;
Potential reserves	7,532,000,000 metric tons;
Potential-hypothetical reserves	2,800,000,000 metric tons.

The proven reserves are based on measurements of ore at 46 mines, and potential reserves are estimates from 16 mines. Potential-hypothetical reserves are based on estimates derived from geological and geophysical investigations of 11 porphyritic copper prospects.

Silver.--Silver, as a principal product or as a byproduct is relatively abundant in the Cordillera Occidental. It is less abundant in the Cordillera Oriental. Reserves (presently of all classes) are estimated as 22,739 metric tons. These reserves pertain to 82 mines, 5 of which produce more than 100 tons of silver per year.

Lead and zinc.--These two metals always occur together in mineralized areas and are commonly associated with silver, copper, and other metals. They are known to occur in greater abundance in the Cordillera Occidental. Reserves of lead for 72 mines operating in the country are given as 3,214,000 tons. About one half the reserves are for one mine which has a production rate of more than 20,000 metric tons of lead per year.

Zinc reserves are reported as 7,318,300 metric tons more than two-thirds of which pertain to 6 mines that produce more than 20,000 tons per year.

Tungsten.--Tungsten is found in the Cordillera Occidental, principally in sedimentary rocks where they are in contact with silicic igneous stocks. It is the principal product in some deposits and a byproduct in others. Principal deposits are in the Pasto Bueno and Mundo Nuevo zone in Northern Peru. Reserves of tungsten ore containing an average of 0.46 percent WO_3 are reported as 17,200,000 tons of which 7,200,000 tons are in Ancash Department and 7,500,000 tons are in Junín Department.

Vanadium.--Since the early 1900's asphalt deposits in central Peru have been known to contain comparatively high concentrations of vanadium. As much as 3 percent vanadium content is reported for some samples. The most important vanadiferous asphalt deposit is that at the Ragra mine (now inactive) where vanadium compounds formerly were concentrated by burning the asphalt and recovering the ash for shipment at Marcapomacocha, and other places. Reserves of asphalt containing more than 0.05 percent V_2O_5 are estimated at 66,000 metric tons.

Aluminum.--No economic deposits of aluminum ore are known in Peru.

Bentonite.--The largest known bentonite deposits are in the Pacific coastal zone, principally in the departments of Piura, Tumbes, Lima, Ica, and Arequipa. The deposits in all areas are associated with marine Tertiary sedimentary deposits. A deposit near the Marcona mine in Ica Department is being exploited for use in pelletizing iron ore. Reserves are estimated as 26,500,000 metric tons proved; 13, 137,000 tons probable, and 68,702,000 tons potential. Bentonite is also produced in the Department of Tumbes for use by PetroPeru as drilling mud.

Barite.--Barite, a common constituent in drilling muds of the oil industry, is present in veins and is a gangue mineral in metallic deposits in many parts of Peru. Proven reserves are reported as 6,900,000 metric tons, and potential reserves are 10,000,000 tons.

Fluorite.--Although fluorite has been found in many parts of the country, it does not occur in sufficient quantity or concentration for economic exploitation.

Graphite.--Information pertaining to graphite is very scanty. A deposit is reported in the vicinity of the Llagen Hacienda near Trujillo. No reserve estimates for this mineral are available.

Limestone and dolomite.--Limestone and dolomite form thick stratigraphic units that are extensively exposed in all areas of Peru except in the forested area east of the Andes. Limestone for manufacture of cement and concrete aggregate is obtained principally from Cretaceous rocks. Reserves of limestone and dolomite have not been determined; however, it is safe to assume they are adequate to meet all needs for the foreseeable future.

WATER RESOURCES AND ENERGY IN PERU

by

Stuart L. Schoff

Introduction

This report summarizes the presently available information regarding the water resources of Peru. 1/ It is part of an assessment seeking to identify the interactions of various energy strategies and options, and their potential effects on Peru's energy future. It is based on information obtained through interviews with Peruvian officials and supporting data compiled by the U.S. Departments of Energy, State, and Interior and by others. This study has not produced new data but instead assembles existing data from several sources. It does not deal with hydroelectric power, inasmuch as others are reporting on that subject.

Acknowledgements

The author acknowledges here and is grateful for the help of his colleagues of the U.S. Geological Survey and the U.S. Energy Team in Peru who shared information with him and freely discussed various problems. Special thanks go to Blanca de Huaco, of the American Embassy, Lima, for efficient help in scheduling appointments, to hydrologist Timothy Wyatt of Lahmeyer International, to Engineer Samaniego of Belco Petroleum Co., and to the following officials of the Peruvian government: Axel Dourojeanni, Director, and Javier Cuellar, Sub-director, of the Direccion de Aguas; Engineer Barra, Chief, and Santiago Stucchi E., of the Dirección General de Irrigaciones; Engineer Santiago Chinchay, of Petroperu; and Emilio Chaparro, Guillermo Vilela, and Arturo Rosell, of Electroperu.

Water and energy

Water and energy are inevitably related. Water both helps to produce energy, as in a hydroelectric power plant, and consumes energy, as in a pump used to lift water from a well. Water is essential in the boiler of a thermal-electric power plant, and it may well have been used to wash the coal that fires the boiler. Water may also be used in transporting the coal by steam-powered locomotive or by a pipeline slurry. Water cools nuclear generators and diesel-powered generators. Once the power becomes available, people use it in all sorts of ways, creating a lot of needs for water that would not exist otherwise.

1/ The reader will note some differences between the water-resource data presented in the main Report and this Annex. This is a result of the inaccessability of some areas in Peru, the preparation of estimates and measurements by different organizations at different times, and the difficulties of obtaining accurate data. Notwithstanding these differences, however, the conclusions in the main Report and the water resources Annex remain unchanged because the differences are small when compared to the Peruvian total water resource.

Geography

Peru fronts on the Pacific Ocean on the west coast of South America. Its Pacific coastline is more than 2,000 km long, from about 18° to about 3½° S lat. The most northerly part of the country, however, is not on the coast, but in the Amazon basin very nearly at the equator. Lima, the national capital, is near the coast and at about 12° S lat and 77° W long. It is directly south of Washington, D.C. The Andes Mountains, which rise to more than 6,000 m in altitude, extend the full length of the country, southeast to northwest, and divide the country into three major topographic units: the Pacific coastal lowland, the mountains themselves (the Sierra), and the Amazon lowland (the Selva).

In terms of watersheds, Peru's 1,285,000 km^2 are divided, draining into the Atlantic, the Pacific, and a small area drained radially into Lake Titicaca (table 11).

Table 11. Area of watersheds of Peru.

Watershed	According to -			
	OAS (1)		Lahmeyer (2)	
	Km^2	Pct.	Km^2	Pct.
Pacific	279,689	21.7	229,095	17.8
Atlantic	956,751	74.5	1,024,450	79.4
Titicaca	48,775	3.8	35,514	2.8
Total	1,285,215	100	1,289,059	100

(1) Organization of American States (OAS), Plan Nacional de Ordenamiento de los Recursos Hidraulicos, Republica del Peru, 1976, p. 55.

(2) Lahmeyer International, data supplied 8-23-78.

For this report, the Pacific watershed is regarded as consisting of two subdivisions: (1) the west flank of the Andes Mountains, descending from the continental divide at altitudes of 5,000 m and more; and (2) the lowland at the foot of the mountains, stretching at many places to the seashore but at others separated from the coast by a coastal mountain range. The lowland, therefore, is not strictly a coastal plain. For convenience, it will be called the Pacific lowland, although some parts of it, notably those behind the coastal mountains, are many meters above sea level. Some of these high parts are called pampas; for example, the pampas of Majes and la Joya.

The definition used here covers a smaller area than the official government definition of the coastal area as extending to altitude 2,500 m. It is doubtless the larger area that is reported to include 45 percent of the population and more of the economic activities of the country (OAS, p. 86).

The Atlantic watershed is here considered to be subdivided into two parts. These are (1) the mountain ranges of the Andes east of the continental divide and their included valleys, canyons, and high plateaus, known collectively as the Sierra, and (2) the Amazon lowland, known as the Selva and by some subdivided into "high" and "low" parts.

No topographic subdivisions need be noted for the Titicaca watershed, which, however, is divided politically. About half of Lake Titicaca and 20 percent of the drainage area are Bolivian territory.

Climate

Climate is the key to the distribution of water in Peru. The climate is determined in large measure by ocean currents and the Andes Mountains.

The climate of the coastal area is dominated by the influence of the Peru (Humbolt) current, which is a cold ocean current that flows northward along the Peruvian coast from the Antarctic. It consists of two parts, a cold coastal current and a somewhat warmer, wider but less well defined oceanic current. The coastal current flows northward along the coast of Chile, receives an upwelling of cold water at temperatures of 14 to 18° C near northern Chile, and continues northwestward along the coast of Peru. It supports

abundant marine life, and it holds the average annual air temperature of coastal Peru in the range of 19 to 24° C, lower than the temperature on the Brazilian coast at the same latitude. The warmer oceanic part of the current is 80 to 160 km wide, and supports little marine life.

Prevailing southwest winds blow the cold, moisture-laden air from above the cold current across the Peruvian coast, where it is warmed, its relative humidity is decreased, and it rises. Then as a static cloud layer, it is held by a temperature inversion. Warm air above presses down on the cool layer below, at about 750 m of altitude. Lateral movement is prevented by the nearby mountains, and thus, from June to October, clouds lie above the land and extend far out to sea. The clouds produce a fine mist, which provides some moisture by condensation where it comes in contact with the earth. Near Lima this condensation ordinarily occurs at altitudes of 800 to 1,400 m, although occasionally it may reach down to sea level. Rain seldom falls below the 1,500 m level on the slopes of the Andes. The sun is rarely seen in winter at Lima, but in summer the temperatures are high enough to prevent the formation of fog. To the north in Peru, where a coastal mountain range is lacking and the Andean foothills are farther from the coast than at Lima, the sun shines most of the day, even in winter, rain almost never falls, and little vegetation can grow naturally.

The climate east of the continental divide is determined by a combination of easterly prevailing winds and by the towering bulk of the Andes Mountains. Warm, moist, easterly winds from the Atlantic ocean retain some moisture and pick up some from evaporation as they travel until they reach the Andes, which deflect them upward. The cold of high altitudes causes condensation and heavy downpours. Even on the high western slopes of the Cordillera Occidental, most of the rain comes from the east, and mostly from January to March. Some high valleys and deep gorges between the western and central and eastern cordilleras receive extremely heavy precipitation. Here the season of heavy rain is summer, September to April. A marked dry season prevails in winter in most of the mountains.

Above altitudes of 3,400 m, some snow falls during winter, and above 4,600 m, all precipitation is snow. Frosts do not occur below about 3,000 m, but above about 4,000 m, frost occurs in winter on an average of about 25 days per month. The line of permanent snow ranges from about 4,600 m in the Cordillera Blanca to about 5,200 m in the south.

Average temperatures in the mountains of Peru range widely with altitude, but local average temperatures show only small seasonal variations. At Cuzco, for example, the seasonal temperature range is only 42° C. At such places, however, the diurnal temperature range can be great--from 24° C to 0° C in a few hours.

The lowlands east of the main body of the Andes are often divided for description into "high" and "low." Tingo María, in the high part, gets 3,962 mm of precipitation annually, on average, and has hot days but cool nights. The low part averages about 2,500 mm of precipitation annually and 200 rainy days a year; it has no dry season. At Iquitos, on the Amazon River, the daily mean temperature throughout the year is virtually constant at about 27° C. The midday reading often reaches 35° C and occasionally exceeds 38° C.

Precipitation and runoff

Annual precipitation in Peru ranges from virtually zero on the Pacific coastal lowland to moderate in the high mountains to abundant on the Amazon lowlands. In table 12, which classifies selected precipitation stations by watershed, it takes only a glance to see that the Atlantic watershed gets vastly greater precipitation than the Pacific, and that the Titicaca watershed gets precipitation comparable to the lower range for the Atlantic watershed. Cerro de Pasco, Cuzco, and Huancayo of the Atlantic watershed and Puno of the Titicaca watershed, all above 3,000 m in altitude, get between 600 and 1,000 mm per year. Iquitos, Juanjuí, San Ramón, and Tingo María, all of them low in valleys of major rivers or on the Amazon lowland, get more than 1,450 mm. On the other hand, the stations of the Pacific watershed receive less than 100 mm except Imata, which gets 620 mm.

Imata is not out of place. It is near the headwaters of the Río Sumbay and near the continental divide, where it benefits from the rain clouds coming from the Atlantic side. It demonstrates that more water is available in river basins of the Pacific watershed than is suggested by the records of precipitation stations on the Pacific lowland.

Estimates of mean annual precipitation, basin by river basin, have been made by Lahmeyer International for the Federal Republic of Germany, which in turn is cooperating with the government of Peru in an appraisal of Peru's hydroelectric potential. Each

Table 12. Mean annual precipitation for selected stations in Peru (from Wernstedt, 1972, as quoted by Willmore and Steele, 1978; here converted to millimeters).

Station	Precipitation (mm)	Station	Precipitation (mm)
Pacific watershed		Atlantic watershed	
Arequipa	94	Cajamarca	782
Cartavio	8	Cerro de Pasco	926
Imata	620	Cuzco	749
Lambayeque	25	Chachapoyas	815
Lima	26	Huancayo	749
La Molina	20	Iquitos	2,718
Piura	72	Juanjuí	1,476
Tacna	41	San Ramón	1,942
Vítor	22	Tingo María	3,409

Titicaca Watershed

Station	Precipitation (mm)
Puno	625

river basin was studied in detail by segments. Its area, altitude, length of channel, and other characteristics were compared with those of other basins in order to reach an estimated average mean annual precipitation for the basin. This estimate then was extended to an estimate of the runoff of the basin. Such estimates were made for 53 river basins of the Pacific watershed, 49 in the Atlantic watershed, and 8 in the Titicaca watershed. The estimates for the individual river basins are not pertinent to this report but could become important in later planning. They and the totals by watershed are given in table 13.

Table 13. Estimated mean annual precipitation and runoff of Peruvian river basins (Lahmeyer International as summarized by Willmore and Steele, 1978, table 4).

River basin	Area (Km^2)	Mean alt. (m)	Mean annual precip. (mm)	Mean annual runoff (mm)	Mean annual runoff (10^6 M^3)
PACIFIC WATERSHED					
Zarumilla	817	279	369	214	175
Tumbes	2729	362	422	198	540
Chira	11564	960	550	193	2232
Piura	10475	539	377	87	911
Cascajal	4147	227	219	22	91
Olmos	965	730	385	23	22
Motupe	1951	665	279	92	179
LaLeche	1578	1255	584	199	314
Chancay-Lambayeque	4906	1509	669	207	1015
Zaña	2080	1069	514	93	193
Chaman	1248	671	370	63	79
Jaquetepeque	4257	2220	731	161	685
Chicama	4454	1772	558	201	895
Moche	2161	2221	496	124	268
Virú	1967	2015	429	43	85
Chao	1443	1433	324	75	108
Santa	12478	3410	651	378	4717
Lacramarca	685	1560	161	2	1
Nepeña	1885	2034	266	21	40
Casma	3064	2309	315	47	144
Culebras	671	1615	191	2	1
Huarmey	2343	2488	353	64	150
Fortaleza	2342	2434	330	20	47
Pativilca	4908	3078	480	307	1507
Supe	1078	2165	302	42	45
Huaura	4483	3061	592	225	1009
Chancay-Huaral	3382	2665	410	189	639
Chillón	2364	2478	361	155	366

(continued)

Table 13. Estimated mean annual precipitation and runoff of Peruvian river basins (continued).

River basin	Area (Km^2)	Mean alt. (m)	Mean annual precip. (mm)	Mean annual runoff (mm)	(10^6 M^3)
Rímac	3134	3157	520	317	993
Lurín	1600	2456	326	88	141
Chilca	798	1589	170	56	45
Mala	2522	2999	427	218	550
Omas	1741	1702	188	70	122
Cañete	5981	3645	541	303	1812
Topara	494	1993	216	78	38
San Juan	5333	2567	353	120	640
Pisco	4054	3049	468	136	551
Ica	7366	1756	183	68	501
Grande	10522	2138	285	46	484
Acarí	4082	3013	438	114	465
Yauca	4589	2757	380	80	367
Chala o Indio Muerto	1284	2072	234	42	54
Chaparra	1387	2776	332	60	83
Atico	1425	2239	226	34	48
Caravelí	2009	2516	286	49	98
Ocoña	15908	3719	768	138	2195
Majes-Camaná	17141	3509	552	110	1885
Quilca O Chili	13254	3422	343	65	861
Tambo	12697	3472	351	91	1155
Osmore o Moquegua	3595	1971	108	37	133
Locumba	5316	2599	176	25	133
Sama	4809	2260	107	16	77
Caplina	1629	3095	167	37	60
Subtotal	229,095				29,949
ATLANTIC WATERSHED					
Alto Marañon	28500	3009	815	815	23227
Chrisnejas	4660	3150	762	251	1170
Llaucano	2852	2572	1030	525	1497
Chamaya	3380	1682	1035	476	1609
Huancabamba	3448	2122	688	261	900
Chotano	1694	2298	1068	577	977
Chinchipe	7155	1434	1074	569	4071
Tabaconas	3792	1941	1234	716	2715
Cenepa	7360	732	939	441	3246
Santiago	33000	692	2655	1699	5607

(continued)

Table 13. Estimated mean annual precipitation and runoff of Peruvian river basins (continued).

River basin	Area (Km^2)	Mean alt. (m)	Mean annual precip. (mm)	Mean annual runoff (mm)	Mean annual runoff (10^6 M^3)
Marañon Medio	24225	368	1177	553	13396
Morona	16070	526	2534	1571	25246
Pastaza	40997	1077	2389	1457	5972
Tigre	34120	386	2964	1838	6271
Bajo Marañon	44730	176	2376	1164	5207
Utcubamba	7507	1903	840	512	3844
Chiriaco	4125	1755	803	458	1889
Nieva	4330	711	603	247	1070
Huallaga Sup	75130	1515	1403	744	5590
Huallaga Inf.	17433	255	1430	715	12465
Urubamba	7272	4366	753	392	2851
Vilcanota	52041	1577	1253	677	3523
Apurímac Sup	13538	4237	732	337	4562
Santo Tomás	3072	4196	909	600	1843
Punanqui	793	4103	903	605	480
Vilcabamba	2575	4356	932	634	1633
Pachachaca	5608	4157	993	596	3342
Apurímac Inf.	15356	2960	948	645	9905
Pampas	23742	3821	853	324	7692
Mantaro Sup	9190	4333	810	308	2830
Mantaro Med	18580	3958	782	336	6243
Mantaro Inf.	6823	3078	763	572	3903
Pachitea	26960	857	2303	1428	3850
Aquaytía	11540	600	2392	1244	14356
Ene	7576	945	1691	1099	8326
Tambo	5171	700	1780	1121	5797
Ucayali	111928	289	2081	1145	12815
Perené	20552	2229	1176	694	14263
Amazonas	55658	113	2734	1422	7913
Napo	44822	228	2769	1689	7570
Putumayo	40138	160	2747	1428	5730
Yavari	59170	370	2811	1799	10645
Purua	16900	414	1888	963	16275
Madre De Dios	37600	1297	3358	1813	6817
Inambari	20355	2261	3118	1621	32995
Tambopata	14710	990	1624	893	13136
Acre	3230	454	1859	948	3062

(continued)

Table 13. Estimated mean annual precipitation and runoff of Peruvian river basins (continued).

River basin	Area (Km^2)	Mean alt. (m)	Mean annual precip. (mm)	Mean annual runoff (mm)	(10^6 M^3)
Los Piedras	15550	396	1895	966	15021
Yurua	9492	329	1935	967	9179
Subtotal	1,024,450				362,526
TITICACA WATERSHED					
Suches	1453	4656	601	222	323
Huancané	3557	4259	692	242	861
Ramis	14444	4307	676	183	2643
Coata	4757	4338	854	265	1261
Illpa	1165	4133	737	206	240
Ilave	7977	4333	462	134	1069
Maure	1687	4542	403	64	108
Zapatilla	474	4011	598	263	125
Subtotal	35,514				6,630
SUMMARY					
Pacific	229,095				29,949
Atlantic	1,024,450				362,526
Titicaca	35,514				6,630
Total	1,289,059				399,105

Table 13 shows a total of 29,949 x 10^6 m^3 of total runoff for the Pacific watershed. A previous estimate for the same watershed by the Economic Commission for Latin America (ECLA, 1968) differs considerably in detail of areas and runoffs but comes close to the Lahmeyer estimate of total runoff, with 32,741 x 10^6 m^3. Hence, in round numbers, 30,000 x 10^6 m^3 may be taken as the annual runoff of the Pacific watershed. This is the amount of water annually available.

in that watershed. This is the amount that must be shared by all users. Only by importing water from another basin--the Atlantic watershed or the Titicaca basin--or by distilling sea water can it be increased. That second alternative--distillation--presumably is possible, but in the present state of the technology promises to consume large amounts of the very thing that now should be conserved: energy.

Theoretically, the total usage of water in the Pacific watershed might exceed the available 30,000 x 10^6 m^3 because in appropriate sequence, water can be used several times: first in a hydroelectric plant or two, then taken from the river channel as surface water for irrigation, and later withdrawn from wells for one purpose or another. Whether the total water usage can really exceed the amount of water physically available is problematical, because re-use tends to increase the salinity of the water. It is necessary that part of the water pass through and out of the area of use in order to carry away the dissolved salts. Perhaps a statistical excess of water use over water availability can best be achieved by running part of the water through several hydroelectric plants, which cause little adverse effect on the water.

The Andean cordilleras and their included valleys receive moderate to abundant precipitation, but its uneven distribution through the year can mean disastrous drought. Impounded water could alleviate drought but might not be economical. In narrow canyons having steep gradients even a high dam may not impound much water. In the up-and-down world that is the Sierra, steep slopes can mean fields too small for efficient irrigation. Furthermore, frequent frosts at high altitudes inhibit agriculture, and so considerable attention is directed to raising animals. Perhaps more important to the inhabitants of the Sierra than quantity is the quality of the water, because some streams have been contaminated by the dumping of mine wastes into them. The thinking in the national capital seems to be not so much on providing water for the Sierra as it is on diverting water from the Sierra under or over the continental divide for use on the Pacific lowland.

The Amazon lowland can be said not to have a water problem, unless it is too much water. The rivers flowing eastward from the Andes bring great quantities of water to an area that receives abundant rain and is sparsely populated. The supply of water vastly exceeds the demand for it.

Physiographic and geologic provinces

Peru is made up of three major physiographic and geologic provinces: the coastal belt, the Amazon basin, and separating these two, the Andean cordillera. The geology is highly diverse and complicated, and a few paragraphs can hardly do it justice.

The coastal belt of Peru is made up of a series of onshore and offshore Cenozoic basins and a low, discontinuous coastal mountain belt.

The coastal range is a discontinuous string of low mountains and offshore basement highs, are west of and parallel to the Andes Mountains. The northern part of this range consists of low coastal mountains made up of late Paleozoic argillite, quartzite, slate, and phyllite, which have been intruded by pre-Cretaceous granitic rocks. The "onshore" southern part (south of Pisco) consists of low coastal hills made up of a late Precambrian (and possibly early Paleozoic) igneous and metamorphic complex along with isolated blocks of late Paleozoic sedimentary rock. The offshore part of this range is represented by a persistent trend of subsurface basement highs.

Coastal basins are defined by basement irregularities of the Continental Shelf, which is a narrow strip reaching a maximum width of approximately 100 km along the northern third of the Peruvian coastline. The submerged and emerged shelf was the site of marine deposition throughout Tertiary time, and the six structural basins contain 5,000 to 8,000 m of Cretaceous and Cenozoic strata, which are mainly marine clastic rocks. These basins are described in the chapter on hydrocarbon (Mattick and Yenne, this volume). The ground-water potential of the rocks in the coastal basins is problematical, although in the several thousand meters of thickness represented there, some water-bearing strata could reasonably be expected.

Almost every imaginable kind of rock can be found in the Andes Mountains of southern Peru. Shale, quartzite, mica schist, and phyllite occur in the undifferentiated Paleozoic rocks of the Vilcabamba, Vilconota, and Carabaya cordilleras. Rocks of Carboniferous age include friable sandstone, black shale, reddish conglo-

merate, and limestone. Permian strata include continental arkose, sandstone, shale, thick volcanic clastic rocks, andesitic and rhyolitic flows, thick tuffs, and marl. The Jurassic rocks include shale, quartzite, sandstone, and limestone and the Jurassic-Cretaceous sequence contains basalt, andesite flows, trachyte, tuffs, agglomerates, argillite, quartzite, and limestone. No doubt the rocks in the northern part of the Andes are equally diverse. With such variety of lithologic types, a wide range of hydrogeologic conditions is inevitable. Surely among the thousands of meters of rock in the Andes some strata must be porous, permeable, and saturated--hence, aquifers.

Springs are the best indication that aquifers exist in the mountains, inasmuch as little has been done to develop ground water by means of wells. Large towns and small ones in the mountains depend on springs for part or all of their public water supplies.

Estimates based on rather sparse data have been made of main rock units of southern Peru. These are shown on a map covering the departments of Ayacucho, Apurímac, Arequipa, Cuzco, Puno, Moquegua, and Tacna in terms of high, low, and medium yields expectable per well (Schoff and Sayán, 1959, mapa hidrogeologico).

Water regimen of the Pacific watershed

The western slope of the Andes Mountains and the Pacific lowland make up the Pacific watershed of Peru. They are a hydrologic unit in the sense that all the water they receive together is the precipitation--rain and snow--on the high parts of the mountains. Part of this water enters the canyons and rushes down their steep channels. The bedrock of the sides and bottoms of the canyon generally is not notably permeable and so does not take in much water. The boulders, sand, and gravel in the canyon bottoms are in intermittent transit downstream. They are an alluvial deposit of small width and no great depth and therefore have small capacity to store water. Hence the water from high places rather quickly reaches the coastal lowland, except that the part of the precipitation received as snow lies in storage for a time and serves to minimize the floods and extend the season of flow. Yet some of these streams do not reach the ocean and some are dry through long stretches of channel for a considerable period (Willmore and Steele, 1978, table 5).

The streams descending the west flank of the Andes have unloaded much of their sediment on the coastal lowland, and then have carved channels across their deposits. Some of these channels are hundreds of meters deep, and a kilometer or more wide at the bottom, and road cuts in their sides expose the boulders, cobbles and gravel of which the deposits are made. The Sihuas and Vítor rivers in the south are notable in this respect. In places they have cut through the gravel into the bedrock below.

Not all the rivers have carved such spectacular canyons as have the Sihuas and Vítor. The Río Chancay, in the north, divides at the apex of its alluvial fan into two distributaries, which at most are entrenched only about 10 m (Schoff and Sayán, 1969, pp. F12-14).

The rivers as they cross the Pacific lowland lose water to the adjacent alluvial deposits, which can constitute ground-water reservoirs of great capacity. Water taken from the rivers and spread on fields is partly used by plants, partly evaporated, and partly sinks into the ground, adding to the underground water supply. It may return to the river channel downstream or be pumped from wells one or more times. Thus the same water may be taken several times, although at the cost of progressively increasing salinity. The amount of water that can be beneficially recycled is practically unknown because it is difficult to keep track of water use where many users are involved.

Water in deserts

Much of the west slope of the Andes Mountains is desert. The aridity decreases with increasing altitude, giving way gradually to the increasing humidity that ultimately feeds the main streams. The mountain flank between those main streams is creased by innumerable dry canyons, which seem never to contain water but by their very presence testify to the long-range potency of rare flash floods, or to a humid past, however remote. The aridity and the ruggedness of the west flank of the mountains discourage economic activity, and a need for water is not likely to develop there unless and where useful mineral deposits are found.

Similarly forbidding are the segments of the coastal lowland between the valleys of the main, life-giving rivers. They stand

from a few to many meters above the valley bottoms and bear the load of debris washed onto them in ages past from the now dry canyons of the west flank of the mountains. Known as "pampas," they are in aggregate many times greater in area than the valley bottoms, and they are mostly vast, absolute desert, receiving no significant precipitation, and little if any flow from the mountains. They are practically unoccupied and unused, and appear to have no prospect of being occupied or used. Water could hardly be brought to them from the rivers, for the cost of canals, pipes, and pumping could be excessive, even if water were available. Water from wells, if present, would probably have to be lifted too far to be economically advantageous. For example, an attempt to tap ground water on the Pampa de la Joya in 1956 (Schoff and Sayán, 1959, p. 142) ended as a dry hole at a depth of about 87 m. This depth at that time was considered to be uneconomical in irrigation pumping.

The Pampa de la Joya test hole, however, is not enough to eliminate ground water as a possible source of water for the pampas. It is only one test hole on one pampa, and altogether too little is known of what is under those desert areas. One or more of them may contain a trapped supply of "fossil" water--water stored, captive, from some rainy epoch of the remote past. Such a deposit, receiving no replenishment, could be exploited to exhaustion, just as a mineral deposit is mined out. Some deserts, too, may conceal permeable conduits through which water moves between the major valleys. But these are speculations, as yet without proof.

Water use in coastal valleys

Water--both surface water and ground water--is used in large quantities and for many purposes in the valleys that cross the Pacific lowland to the ocean. The quantities used have increased through the years as population and economic activity have grown. A report prepared under the auspices of the Organization of American States (OAS, 1976, p. 73) states, in translation:

> The cultivated area along the cost of Peru less than 50 years ago was about 300,000 ha, whereas now it exceeds 800,000. With the increase in land under cultivation have come the construction of dams at some places and the pumping of ground water at others. At present nearly 10,000 wells in the coastal valleys withdraw annually more than 1,100 x 10^6 m^3 of water. The dams and wells have increased the dependability of the water supply, making it profitable to grow sugar cane, cotton, rice, corn, grains, legumes, citrus fruits, and grapes.

Estimates by Lahmeyer International of the water annually available in Peru, in millions of cubic meters, are 29,949 in the Pacific watershed, 362,526 in the Atlantic watershed, and 6,630 in the Titicaca watershed (table 13). Based on detailed analysis of each river basin, these estimates should be the most accurate yet made. Estimates of water use by the Oficina Nacional de Evaluación de Recursos Naturales (table 14) show a total of 15,878.78 x 10^6 m^3 of water used to irrigate 731,082 ha in the coastal area. About 9 percent of this water (1,394.6 x $10^6 m^3$) is ground water.

Table 14. Land and water in agricultural use in Peru (Oficina Nacional de Evaluación de Recursos Naturales, 1978).

	Pacific watershed (10^6 m^3)	Atlantic watershed (10^6 m^3)	Titicaca watershed (10^6 m^3)
A. Available water.....	33,971.83	1,437,001.46[a]	23,705.4[a]
B. Ground water used....	1,733.07	.52	.05
Agriculture.....	1,394.6	.....	.....
Cattle.....	2.47	.....	.....
Industry.....	122.63	.....	.....
Public supply.....	194.69	.....	.....
Unspecified.....	18.68	.....	.....

	Coastal area	Andes mountains	Amazon basin
C. Land under irrigation (ha)	731,082	357,351	43,102
D. Total water used in irrigation (10^6 m^3)	15,878.78	6,187.44	992.77

E. Water demand in agriculture, coastal area: 20,000-25,000 m^3/ha/yr.

[a]Lahmeyer International estimates only 362,526 X 10^6 m^3 for the Atlantic and 6,630 X 10^6 m^3 for the Titicaca watersheds--23 and 28 percent as much, respectively. Cause of the differences is not apparent. The Lahmeyer estimates, based on detailed studies are used elsewhere in this report.

The area under irrigation differs from source to source: 800,000 ha in the quotation above, 731,000 ha in table 14, and 750,000 ha as reported orally by Stucchi (8-16-78). The differences between these reports, however, are not great and probably are due to variations in the circumstances under which they were determined and reported. Perhaps the figure 750,000 ha is a reasonable and acceptable compromise. It apparently should apply to the valleys of the coastal lowland, inasmuch as Calderón (oral, 8-24-78) pointed out that another 300,000 ha above the lowland to altitudes of 3,000 m also are irrigated. Thus his total estimate is about 1,000,000 ha for the Pacific watershed.

The water demand is said by Calderón to range from 20,000 to 25,000 m^3/ha/yr. At the lower of these rates, 750,000 ha would require about 15,000 x 10^6 m^3/yr, which is close to the total water used in irrigation as reported in table 14.

Role of ground water

A partial inventory of wells and pumpage in Peru is given in table 15, which includes, in addition to wells in 40 of the valleys of the coastal lowland, 111 wells in the mountains and the Amazon lowland. Made between 1968 and 1977, this inventory also includes many wells used for domestic and public supply, for cattle raising, and for industries and unspecified purposes. Of 6,898 wells listed, 2,689 (39 percent) are irrigation wells yielding a total of 874.2 x 10^6 m^3/yr--about half the total amount given as "total water used in irrigation" in table 14.

Ground water plays an important part in the economy of the Pacific lowland, but it is not a limitless resource independent of the rivers. Quite to the contrary, it is only a hidden part of the total water supply in any of the coastal valleys. It is replenished by the water brought by the rivers from high in the mountains. Without that replenishment, it would sooner or later be exhausted.

Problems that arise in connection with the use of ground water are declining water levels and, especially in irrigation, increasing salinity of the water.

Table 15. Distribution of water wells by uses and agricultural area with annual pumpage (from Direccion General de Aguas y Suelos.) (Inventoried 1968-1977)

Location	Domestic supply		Public Supply		Cattle raising		Irrigation		Industries		Unspecified		Totals	
	Wells	Pumpage (m^3/yr)	Wells	Pumpage (m^3/yr)	Wells	Pumpage (m^3/yr)	Wells	Pumpage (m^3/yr)	Wells	Pumpage (m^3/yr)	Wells	Pumpage (m^3/yr)	Wells	Pumpage (m^3/yr)
Agr. area 1	72	17,117,310	2	61,000	798	42,873,103	247	80,214,775	3	735,000	10	868,000	632	141,869,188
Zarumilla	2	117,000	1	48,000	.....	.....	47	10,789,163	.....	.....	3	.....	53	11,014,163
Tumbes	.....	.....	.....	.....	.....	.....	...	.....	.....	.....	2	.....	2	.....
Piura	53	15,038,310	.....	.....	297	42,862,103	152	53,305,612	3	735,000	.....	.....	505	111,941,025
Mancora	2	886,000	.....	.....	1	11,000	4	588,000	.....	.....	1	260,000	8	1,745,000
Namuc	15	1,016,000	1	13,000	.....	.....	44	15,532,000	.....	.....	4	608,000	64	17,169,000
Agr. area 2	248	21,664,658	5	934,400	21	196,392	524	215,465,179	16	3,886,183	20	4,552,000	834	246,698,812
Olmos	3	463,000	.....	.....	.....	.....	7	2,471,000	.....	.....	1	260,000	11	3,194,000
Motupe	2	704,000	.....	.....	.....	.....	52	26,280,100	.....	.....	14	3,640,000	68	30,624,100
La Leche	20	821,860	.....	.....	.....	.....	58	29,994,800	.....	.....	....	.....	78	30,816,660
Chancay-Lambayeque	85	12,311,414	5	934,400	8	83,720	383	152,689,360	11	3,352,364	5	652,000	497	170,023,258
Saña	26	1,712,125	.....	.....	.....	.....	...	.....	.....	.....	....	.....	26	1,712,125
Chaman	53	464,064	.....	.....	6	75,264	10	1,190,859	1	219	....	.....	70	1,730,406
Jequetepeque	59	5,188,195	.....	.....	7	37,408	14	2,839,060	4	533,600	....	.....	84	8,598,263
Agr. area 3	893	46,899,256	39	3,480,807	94	1,465,442	843	272,467,551	117	33,244,701	6	436,900	1,992	357,994,657
Chicama	303	7,404,983	19	2,015,100	27	537,966	527	181,662,672	62	17,562,188	....	.....	938	209,182,909
Moche	361	29,241,589	12	759,229	55	186,884	161	21,666,737	23	1,874,195	....	.....	612	53,728,634
Santa	16	296,343	1	462,000	.....	.....	...	.....	14	10,148,500	1	260,000	32	11,166,843
Lacramarca	49	6,660,279	.....	.....	.....	.....	...	.....	10	988,359	....	.....	59	7,648,638
Nepeña	44	1,929,620	.....	.....	10	717,542	73	56,330,812	3	2,236,320	....	.....	130	61,214,294
Casma	59	1,120,961	4	235,500	2	23,050	75	11,554,250	1	285,000	5	176,900	146	13,395,661
Culebras	1	155	.....	.....	.....	.....	1	18,000	1	79,000	....	.....	3	97,155
Huarmey	60	245,326	3	8,978	.....	.....	6	1,235,080	3	71,139	....	.....	72	1,560,523
Agr. area 4	1,289	129,623,000	59	20,461,028	259	4,457,021	498	79,142,572	294	53,463,276	9	262,850	2,408	287,409,747
Fortaleza	12	3,772,865	.....	.....	1	91,800	21	8,236,050	8	8,062,000	2	.....	44	20,162,715
Pativilca	45	2,003,919	4	16,120	1	3,940	...	.....	7	170,520	2	129,850	59	2,324,349
Supe	18	131,670	.....	.....	.....	.....	13	3,696,848	.....	.....	....	.....	31	3,828,538
Huaura	118	5,207,620	2	35,000	13	693,600	19	3,854,000	8	3,143,240	3	132,000	163	13,065,660
Chancay-Huaral	214	1,957,222	7	13,749	71	967,594	36	6,910,600	6	.....	....	.....	334	10,001,056
Chillón	41	18,373,428	6	815,280	13	365,607	29	6,413,391	6	2,015,290	1	.....	96	27,982,996
Rimac	463	93,014,412	29	19,226,447	36	537,070	59	16,903,940	238	36,922,337	....	.....	825	166,604,206
Lurín	220	2,719,833	3	41,812	101	1,240,482	173	12,017,685	8	963,570	....	.....	505	16,983,382
Chilca	16	913,810	.....	.....	14	72,498	137	13,304,538	3	3,974	....	.....	170	14,294,820
Mala	52	437,572	.....	.....	2	1,675	4	650,300	6	1,685,500	1	1,000	65	2,776,047
Cañete	90	1,090,649	8	312,620	7	482,755	7	7,155,000	4	344,954	....	.....	116	9,385,978
Agr. area 5	207	16,758,873	10	810,500	65	1,165,949	450	205,079,654	28	1,796,990	....	.....	760	225,611,966
Topara	1	16,400	.....	.....	9	18,166	6	1,054,000	.....	.....	....	.....	16	1,088,566
San Juan	150	2,940,883	2	46,500	47	1,042,533	210	86,892,054	21	1,337,990	....	.....	430	92,259,960
Ica	56	13,801,590	8	764,000	9	105,250	234	117,133,600	7	459,000	....	.....	314	132,263,440
Agr. area 6	9	22,700			1	7,490	11	138,764	7	1,013,611	....	.....	28	1,182,565
Caravelí	.....	.....	.....	.....	.....	.....	6	96,000	1	180,000	....	.....	7	276,000
Chili	9	22,700	.....	.....	1	7,490	5	42,764	6	833,611	....	.....	21	906,565
Agr. area 7	5	2,180,650	.....	.....	2	15,560	116	21,674,712	6	1,017,700	4	.....	133	24,888,622
Moquegua	4	1,549,650	.....	.....	2	15,560	60	1,210,312	5	1,017,700	....	.....	71	3,793,222
Locumba	.....	.....	.....	.....	.....	.....	...	.....	.....	.....	...4	.....	4	.....
Sama	.....	.....	.....	.....	.....	.....	...	.....	1	.....	....	.....	1	.....
Caplina	1	631,000	.....	.....	.....	.....	56	20,464,400	.....	.....	....	.....	57	21,095,400
Agr. area 8	75	364,985	3	.....	1	.....	...	.....	3	27,340	3	.....	85	392,325
Ucayali	75	364,985	3	.....	1	.....	...	.....	3	27,340	3	.....	85	392,325
Agr. area 12	20	35,360	2	.....	.....	.....	...	.....	4	16,200	....	.....	26	51,560
Puno	20	35,360	2	.....	.....	.....	...	.....	4	16,200	....	.....	26	51,560
Total	2,818	234,666,792	120	25,747,735	741	50,180,957	2,689	874,183,207	478	95,201,001	52	6,119,750	6,898	1,286,099,442

Water levels decline progressively when the amount of water withdrawn consistently exceeds the amount of replenishment. The decline can be arrested by reducing the pumpage or by bringing in water to recharge the aquifer artificially.

The mineral content of the water increases as the water travels seaward because each kilometer of travel provides new opportunity for contact with soluble minerals. It increases also with the use and reuse of water, because each use involves some evaporation, or evaporation plus transpiration, which leaves less water to contain the same or increased mineral matter. Some combination of these causes is probably seen in the Lambayeque Valley, where the dissolved solids in ground water were found to increase from 261 to 1,240 meq in about 50 km in the downstream direction (Schoff and Sayán, 1969, p. F 50, fig. 20, and table 12). The extent to which the valleys of the coastal lowland have been affected by this sort of increase in salinity is not known.

Another cause of increasing salinity of ground water is the advance of sea water into fresh-water aquifers where wells near the coast are heavily pumped. This can happen, of course, if the aquifer extends under the sea and makes contact with the sea water. Pumping at the wells reduces the head, permitting the sea water to push into the aquifer toward the point or points of reduced pressure. Increases in salinity of ground water due to this cause may have occurred at a few places in Peru, among them Callao, but are not well documented.

Water in the Atlantic watershed

The data provided by Lahmeyer International (table 13) show that the Atlantic watershed, with about 4.5 times the area of the Pacific watershed, has about 12 times as much runoff. Per square kilometer, the Atlantic watershed has about 350,000 m^3 annually whereas the Pacific watershed has 130,000 $m^3/km^2/yr$. In some places, the difference is between too much and too little.

The water problems in the mountains seem to be mainly problems of uneven seasonal distribution of precipitation, together with local contamination from mine wastes dumped into streams. Water is needed for public supply in the cities and towns, for raising animals, for human consumption, for some industries, for mining, and, as

indicated in table 14, for irrigation. Some of the water is taken from streams and from lakes, and some is ground water. Indeed, many mountain towns, large as well as small, in the 1950s were getting their public water supplies from springs, which are ground water returning to the land surface. Among them were Abancay, 2 springs, 9 lps (liters per second) each; Andahuaylas, 2 springs, 60 lps; Arequipa, 1 spring, 220 lps; Ayacucho, 40-50 lps; Cuzco, 5 springs, 130 lps total; and Sicuani, 28 lps (Schoff and Sayan, 1959, pp. 64-104). Changes may have been made in places, but most of these towns probably still use spring water.

Population is sparse in the Amazon lowland and the towns are small, except Iquitos, the Amazon River port. The demand for water is so small in relation to the supply that any water problems are likely to be matters of equipment and distribution.

Water use by cities

The per capita daily consumption of water, in liters, is presented for 16 major cities of Peru in table 16. The lowest rate, 79 lpd, is for Puno, which is high in the mountains. The highest rate, 475 lpd, is for Piura, which is on the arid coastal lowland in the north. Lima with 470 lpd is a close second. The unweighted average for the cities listed in table 16 is 265 lpd.

Table 16. Per capita daily water consumption, in liters, in some principal cities in Peru (including industries). (Oficina Nacional de Evaluación de Recursos Naturales, 1978.)

Tumbes	138	Cajamarca	227	Huánuco	336	Ilo	222
Piura	475	Chachapoyas	253	Huancayo	361	Tacna	229
Sullana	174	Chimbote	100	Ayacucho	292	Puno	79
Chiclayo	250	Lima	470	Arequipa	196	Cuzco	441
			Average	265			

Both surface water and ground water are used by the cities. Lima was reported by Cuellar (oral communication, 8-17-78) to be taking in 1978 about 8.4 m^3/sec from the Rio Rimac and about 2.9 m^3/s from wells in the Lima-Callao area. Calderon (oral, 8-24-78) stated that about 3 m^3/s is taken from a lake (Marcapomacocha) in the headwaters of the Río Mantaro of the Atlantic watershed and is sent through a tunnel under the divide into the Río Rimac, and thence to Lima. This is the "Mantaro" water presently being received by Lima. The frequently mentioned Mantaro project is a proposal for pumping water from the Río Mantaro at a point about midway between the lake and the rail junction, La Oroya. The water would be boosted to the lake and thence through the tunnel. This project apparently awaits financing. Other cities, among them Trujillo, Tacna, and Chiclayo, rely solely on water pumped from wells, and a partial inventory shows 120 wells in 19 localities yielding 25.7 x 10^6 m^3 for public supply (table 15). This figure includes small amounts for Puno and Ucayali in the Atlantic watershed; all the rest is in the Pacific watershed. In addition, 2,818 wells yielding 234.7 x 10^6 m^3/yr are reported as used for domestic supply. Trujillo pumps from a locality where 600 irrigation wells are said to be in use (Chaparro, oral communication, 8-23-78) and Tacna's supply is reported to be in danger of exhaustion (Stucchi, oral communication, 8-16-78). According to Perez (1978) Tacna has a shortage of 400 lps, and to meet it, is having to divert water from agricultural use. He suggests investigating the possibilities of the Maure formation, which like the Capillume Formation consists of re-worked lacustrine volcanic materials. Ground water in the Capillume, he says, proved to be the answer to a water problem at Moquegua, where yields were as muchas 140 lps.

If the average per capita water consumption remains 265 lpd in urban areas to the year 2000, and 80 lpd in shanty towns and rural areas (table 17), the population projections can be restated as water consumption (m^3 x 10^6/yr):

Table 17. Consumption of water projected to 1985 and 2000.

	1976	1985	2000
Urban (265 lpd)	570	865	1,940
Shanty towns and rural (80 lpd)	290	366	373
Total	860	1,231	2,313

This is a conservative estimate. Per capita water consumption of 265 lpd is very modest in comparison with consumption in highly industrialized societies, and 80 lpd is only about six or eight generous sized bucketsful. It is likely that the use of water would grow even if population remained static because urbanization tends to raise living standards, adding to the ways in which water is used, and hence to per capita consumption. The same tendency probably would extend to rural areas, although not to the same degree. Hence, the total water consumption, especially in the cities, is likely to grow faster than the population.

If Lima grows to 12,000,000 inhabitants by the year 2000 and holds its per capita consumption of water to 470 lpd, it will need 2,058.6 x 10^6 m^3/yr, whereas the combined runoff of the Rimac and Chillon river basins, to both of which it has access, is only 1,359 x 10^6 m^3/yr (table 13). The deficit would be 699 x 10^6 m^3. It can be met by importing water from the Atlantic watershed, or by cutting per capita consumption of water.

Water use by industry

Some industries use much water but others use little; some that use significant quantities of water have their own wells, or sometimes surface sources, but others buy city water. The purchased water is counted as part of the municipal water use and is included in the figures for per capita consumption. The water from company-owned sources may or may not be included in statistical summaries. Hence the reported industrial use of water is likely to be considerably less than the actual total, although much of it is counted in the municipal statistics. The Dirección General de Aguas y Suelos has identified 478 wells as primarily used for industry, and credits them with 95.2 x 10^6 m^3/yr of water (table 15).

Water for use in petroleum production

The water demand of petroleum companies seems to be small to the point of unimportance. Belco Oil Co. operates off shore, uses sea water in drilling wells, and does no refining of oil. Its use of fresh water is confined to about 3,000 liters per day for human consumption on its four offshore drill platforms, plus 160 to 240 m^3/day for its camp on shore (Samaniego, oral communication, 8-22-78).

Petroperú operates on land and uses both fresh and salty water in its drilling operations, but the amounts are small (Chinchay, oral comm., 8-23-78) because drilling mud is recycled so far as possible. The cost of materials used in mixing makes it imperative that the drilling mud be saved and trucked from one drill site to another. The quantity of water used in refining is likewise said to be small. Petroperú's largest use of fresh water is for human consumption in the company town, Talara, which has a population of about 8,000. The water comes by pipeline from Piura.

The average quantity of water consumed per million Btu (British thermal units) by U.S. refiners is 6.7 gallons (table 18).

Petroperú is interested in the possible development of a phosphate deposit near Bayovar, which will require considerable water, depending on the choice of method of extraction. Petroperu would supply from the Sechura field the natural gas for processing the phosphate.

Table 18. Water consumption in refining processes and electrical generation.

Process and product	Consumptive use (gal/10^6 Btu)	Remarks
Uranium.....	14.34	Reactor fuel for 1,000 MW nuclear plant annualized for 80 percent load factor. Includes water consumed at power plants supplying electricity for processing.
Oil.....	6.7	Average for U.S. refineries.
Pipeline gas from coal.....	....	Lurgi gasification followed by methanation stage. Product about 1,000 Btu per standard cubic foot.
a. Water cooling (90 percent load factor).	72-158	Consumption varies with amount of blowdown required; directly proportional to mineral content and turbidity of cooling supply.
b. Partial air cooling (90 percent load factor).	37-79	Assumes 85 percent of cooling demand met by nonevaporative air cooling.
Synthetic oil from coal.....	31-200	General estimate based on several potential processes using pressure hydrogenation technology.
Oil from shale.....	19-29	Includes water requirement for spent shale disposal.

(continued)

Table 18. Water consumption in refining processes and electrical generation (continued).

Average water consumption in electrical generation (Most efficient design assumed; at 80 percent load factor)		
Process	Water consumption (gal/kWhr)	Water consumption (gal/10^6 Btu)
Fossil-fueled.....	0.5	146
Nuclear.....	.8	234
Geothermal.....	1.8	527

Water use and thermal electric energy

Thermal electric energy is produced by burning oil, gas, or coal to produce steam, which drives generators. The process requires water for boilers, for cooling evaporative condensers, for boiler blowdown, for scrubbing stack gasses, and for steam leakage. Cooling is the greatest consumptive use in this process, and it creates problems in quality of water as evaporation increases the mineral content of the water left behind. The more energy is developed, the greater will be both the consumption of water and the effect on water quality. Heated water and boiler waste dumped into rivers and lakes can spoil them for downstream use.

Thermo-electric plants are used at several places in Peru, producing a total of 2,515.8 MW (table 19), but the national agency for electric power, Electroperu, seeks to emphasize hydroelectric power, which is regarded as abundant and far from fully developed. Electroperú has one major steam plant in the planning stage, the Alto-Chicama plant, which would burn locally mined anthracite coal to produce 480 MW. The water problem of this plant is that 700 lps will be needed for boiler,

cooling and other uses, but the minimum (dry-season) flow of the Chicama River drops to 300 lps. To meet the deficiency, one or more dams about 20 m high are proposed for impounding the needed reserves of water. This move would lead to the next problem, which is siltation in the reservoirs.

Table 19. Electric generating capacity in Peru (MW), 1976. (Energy Team ref. data.)

	Hydro-electric	Steam generator	Gas turbine	Diesel generator	Total
Public.....	1,156.0	14.5	143.9	180.6	1,495.0
Private producers....	249.8	387.5	87.9	295.6	1,020.8
Total	1,405.8	402.0	231.8	476.2	2,515.8

At 700 lps for production of 480 MW, the water requirement of the Alto-Chicama plant would be 1.5 lps/MW. If this rate is applicable to all the new steam generating plants shown in table 20, the water requirement would be 1,623 lps; or, at 18,500 m^3/yr/MW and an 80 percent load factor, about 16.3 x 10^6 m^3/yr.

Table 20. Planned electric generating plants in Peru, excluding hydroelectric plants (summarized from Energy Team ref. data).

Project	Date of readiness	Net increase in capacity (MW)	Totals (MW)
A. Steam plants			
Alto Chicama	1985	480	
Pulpa Blanqueada	....	190-202	
Siderperú	1988	200	
Ilo	1979	6	
			876-888
B. Combustion-turbine plants			
Bayovar	1983	60	
Chilina	1978	10	
Cerro Verde	1980	33	
			103
C. Diesel generators			
Chiclayo	1982	25	
Bayovar	1981	72	97
		Total	1,076-1,088

Water use and nuclear power

The generation of electric power in a heavy-water nuclear reactor requires about 50 percent more cooling water than a power plant of equal capacity fired by oil, gas, or coal. Nuclear plants also raise awkward problems of waste disposal. These include the discharge of heated water into rivers or lakes where an increase in heat may be undesirable; the discharge or leakage of water containing radioactive contaminants into other bodies of water; and the seepage of surface waters through buried radio-

active solid wastes and thence into ground water. Some of the problems may be avoided by locating plants where sea water can be used for cooling, but even here damage to the environment needs careful consideration. Such plants in Peru would necessarily be along the Pacific coast--a convenient location with respect to the major cities and industries of the country. An average of 14.34 gal per million Btu is estimated to be needed in processing fuel for a 1000 MW nuclear plant and 0.8 gal/kWhr is needed in the generation of electricity (table 18).

Nuclear power is not yet a reality in Peru. No uranium mines are being worked, and the prospects for locating uranium deposits of commercial value are remote (Noble, Edwin, oral comm. Aug. 1978). Hence no water for uranium mines or nuclear power plants is used at present. The impact of nuclear energy on future water demand is therefore conjectural.

Water use and solar and wind energy

Solar energy for such uses as heating water or buildings seems to require little water directly. If water is heated, the water is chargeable to whatever use is made of hot water. If the water heats a building and is recirculated, the consumption of water can be small, although at some point the water may have to be discharged to waste and replaced. Where solar energy heats air as a medium for heating a building, the water requirement seems to be negligible. The generation of electricity by means of photovoltaic devices also seems to have little or no direct impact on water resources.

Wind power is another source of energy that needs little water, if any. In fact, wind power is widely used to pump water on farms and ranches, and none of the water is used in the operation. As regards water use, turning an electric generator is the same as turning a windmill.

Water and diesel-electric power

Some cities in Peru, among them Chiclayo, depend on diesel-electric generators, and several expansions of such systems are planned. Their water requirements are restricted to the amount used in cooling the diesel engines, which may be recirculated repeatedly. Hence, the total amount consumed usually is very small.

Water and geothermal energy

Geothermal energy has yet to be tapped commercially in Peru, and the magnitude and useful potential of this energy source are still in the realm of speculation based on comparisons with Chile. Volcanoes in the southern part of the Andes Mountains in Peru seem to offer the greatest potential. Nearby in northern Chile, in the provinces of Antofagasta and Tarapacá, three localities are estimated to have energy potentials of 50 MW each, or more, and plans are reported to be under way for developing 25 MW from one of them (El Tatio field). The volcanic activity evident at 17 volcanoes in Chile extends into Peru, where nine volcanoes are considered to be active. Among these, Ubinas volcano (alt. 5,672 m) is regarded as the most promising, although samples of steam from it have not been taken, nor have temperatures been measured (Parodi, 1975, pp. 107-8).

The quantity of water that might be used in a developed thermal-energy field cannot plausibly be estimated, and may not become important before the year 2000. If hot water or steam delivers the energy to the land surface, the water may come from underground reservoirs, or cold water may be introduced to hot rocks through wells. The difference in procedure can be considerable from the viewpoint of providing water for a geothermal-energy project. Other needs for cold fresh water might be cooling and personal use by operating personnel, and could be similar from one project to another, but they obviously would depend on the size of the project. Project size in turn could be partly governed by accessibility, which seems to mean remote locations in mountains at altitudes of 3,000 to 4,000 m. An average figure for water consumption in geothermal generation of electric power is 1.8 gal/kWhr, or 527 gal/10^6 Btu (table 18).

In view of the lack of present development and the magnitude of the problems involved, the use of geothermal energy may come about so slowly that by the year 2000 the quantity of water needed to sustain it will still be minimal.

Water law

Water in Peru is now administered under the Ley General de Aguas, 1969. All water without exception is the property of the state, which is to control its use, preservation and development

for the good of the nation. Users have no rights to water no matter what the source of the water may be, but as water is vital, it is available to all to meet primary needs (OAS, 1976, p. 79). The Dirección General de Aguas y Suelos administers the law, and issues permits for the use of water. It can also change the terms or revoke a permit.

Recommendations

As the demand for water in the Pacific coastal area approaches the limits of the supply of water, the following actions could be advantageous:

Refine estimates of runoff. Good as the estimates by Lahmeyer International are, they are necessarily based on information that is sketchy, even erroneous at many places, and can be improved as new information becomes available.

Maintain records of the principal uses of water and identify the places where heavy use is likely to create problems.

Continue to emphasize the development of hydroelectric power. It makes energy available and leaves the water in condition for additional use.

Adjust rates charged for irrigation water so that users will be encouraged to apply water economically and efficiently.

Promote economical use of water generally through educational campaigns to inform the public, including irrigators, on the importance to the nation and to them of using water efficiently.

Monitor irrigated areas so as to identify early stages of water logging or the accumulation of salts in the soil.

Identify localities that may be subject to encroachment of sea water in heavily pumped aquifers, and monitor them so that they may be given prompt attention, if needed.

Monitor water levels in areas of heavy pumping of ground water for early identification of overdraft.

Encourage the use of mineralized water, where available, for purposes that do not require fresh water.

GEOLOGIC HAZARDS

By A. F. Espinosa

Geologic hazards are those disturbances that take place in the environment owing to certain natural or manmade conditions and that have the potential for creating future hazards. The mitigation of geologic hazards can be accomplished only if appropriate steps are identified and implemented. Because of their very nature, studies of geologic hazards must be based on interdisciplinary effort.

Geologic hazards in general can be classified by their principal status, by their associated hazards, and by the byproducts of these hazards. For example, the main hazard is the "cause;" the associated hazard is a "spreading of the cause" to other hazards; and the byproduct is the disruption to lifelines, the permanent damage to the environment, and the effects on manmade constructions and on human activities.

Table 21 identifies 18 main hazards that in Peru are directly associated with earthquakes. Some of the effects attributed to these hazards have been reported in the literature. Selected sources of data on studies performed in Peru or about Peru and its hazards, are given in alphabetical order and numbered from 1 through 124 at the end of this section.

The 18 hazards in table 21 are matched in table 22 with the identifying reference numbers to studies of the hazard in question. In table 22, item 18 represents, from the seismological point of view, studies performed on earthquakes in general.

The epicenter locations of some earthquakes having magnitude 5.3 or greater, and which have been recorded on strong-motion instruments in Lima, Peru, are shown in figure 18. Some of these earthquakes have caused widespread damage in Peru; for example, the May 31, 1970, earthquake, at 7.8 magnitude, caused severe damage to the country. Some of the existing geologic hazards caused by the 1970 earthquake are shown in figures 19-21. In the town of Yungay 18,000 people lost their lives. Debris avalanches, sand-boils in water-saturated unconsolidated sediments, and earth flow in water-saturated, grass-covered glacial lake deposits were physical manifestations resulting from the earth shaking. Other earthquakes in Peru have been accompanied by similar phenomena.

The landslide potential in Peru is high. This geologic hazard causes great concern, especially in areas or towns (fig. 18) that could be in the path of landslides or may have their routes of transportation disrupted.

Types of damage sustained during the 1970 earthquake by adobe construction in Huaraz and to a paved road west of Chimbote are shown in figures 22 and 23. From these photographs one can appreciate the hazard problems in Peru.

Table 21. Hazards associated with earthquakes in Peru.

Number	Main hazard	Associated hazard(s)	Byproduct(s)
1.	Fault rupture and fissures.....	subsidence	damage to structures, " " environment.
2.	Liquefaction.....	ground failure, shaking	ditto
3.	Lateral spreading...	liquefaction, shaking	ditto
4.	Sink holes, and flows.....	sliding, flooding	-----
5.	Subsidence.....	ground failure	damage to highways, railroads, structures.
6.	Overflow on river...	sediment transport, erosion, lateral spreading, flooding.	damage to lifelines.
7.	Ground-water flooding.....	-----	damage to airports, structures, lifelines.
8.	Flooding due to subsidence.....	further subsidence	-----
9.	Landslides.....	impounding of water, obstruction of river flow, roads overflow, soil collapse, etc.	damage to lifelines, structures, environment, roads, etc.
10.	Rockfalls/slides....	landslides, obstruction to river, water waves in lakes, etc.	damage to lifelines, reservoirs, etc.
11.	Soil failure.....	sliding, landsliding, consolidation, compaction, etc.	damage to wharfs, ports, roads, etc.
12.	Snow avalanche(s)...	burial	damage to towns, roads, lifelines.
13.	Debris avalanche(s).	burial.	ditto
14.	Subsidence over mines, soil failure over mines, etc.....	collapse burial	damage to man-made structures.
15.	Tsunami.....	coastal region hazard effects.	damage to lifelines, structures, ports, etc.
16.	Lava flow.....	fire, heavy ash covers, burial.	damage to environment, " " structures.
17.	Ashfalls.....	burial	ditto
18.	General hazards due to earthquake effects.....	-----	-----

Table 22. Key to references to hazard studies.

Hazard number (See table 21)	Reference number (see references at end of this section)
1	15, 16, 22, 31, 33, 33A, 38, 50, 98, 99, 102, 103, 122
2	33, 98, 99, 103
3	22, 32, 33, 33A, 47, 84, 98, 99, 103
4	33A, 100, 101
5	23, 24, 31, 33, 33A, 36, 47, 103
6	33A, 55
7	33A
8	55
9	4, 5, 10, 11, 22, 31, 33, 33A, 41, 44, 47, 54, 56, 71, 72, 77, 81, 82, 83, 85, 96, 98, 99, 99B, 120
10	9, 22, 31, 33, 56, 80, 98, 99, 99A, 99B, 103
11	22, 31, 33, 56, 96, 98, 99, 99A, 99B, 103
12	33, 33A, 56, 98, 99, 119
13	33, 33A, 56, 98, 99
14	
15	95, 106B
16	69, 70, 90, 91, 114
17	90, 91
18	1, 2, 3, 6, 7, 8, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 25, 26, 27, 28, 29, 30, 31, 34, 35, 36, 37, 38, 39, 40, 42, 43, 45, 46, 48, 49, 50, 51, 53, 58, 59, 61, 62, 63, 64, 65, 66, 67, 74, 75, 76, 78, 79, 80, 84, 88, 89, 92, 93, 94, 97, 101, 102, 103, 104, 106, 108, 109, 110, 111, 112, 113, 115, 116, 117, 118, 121

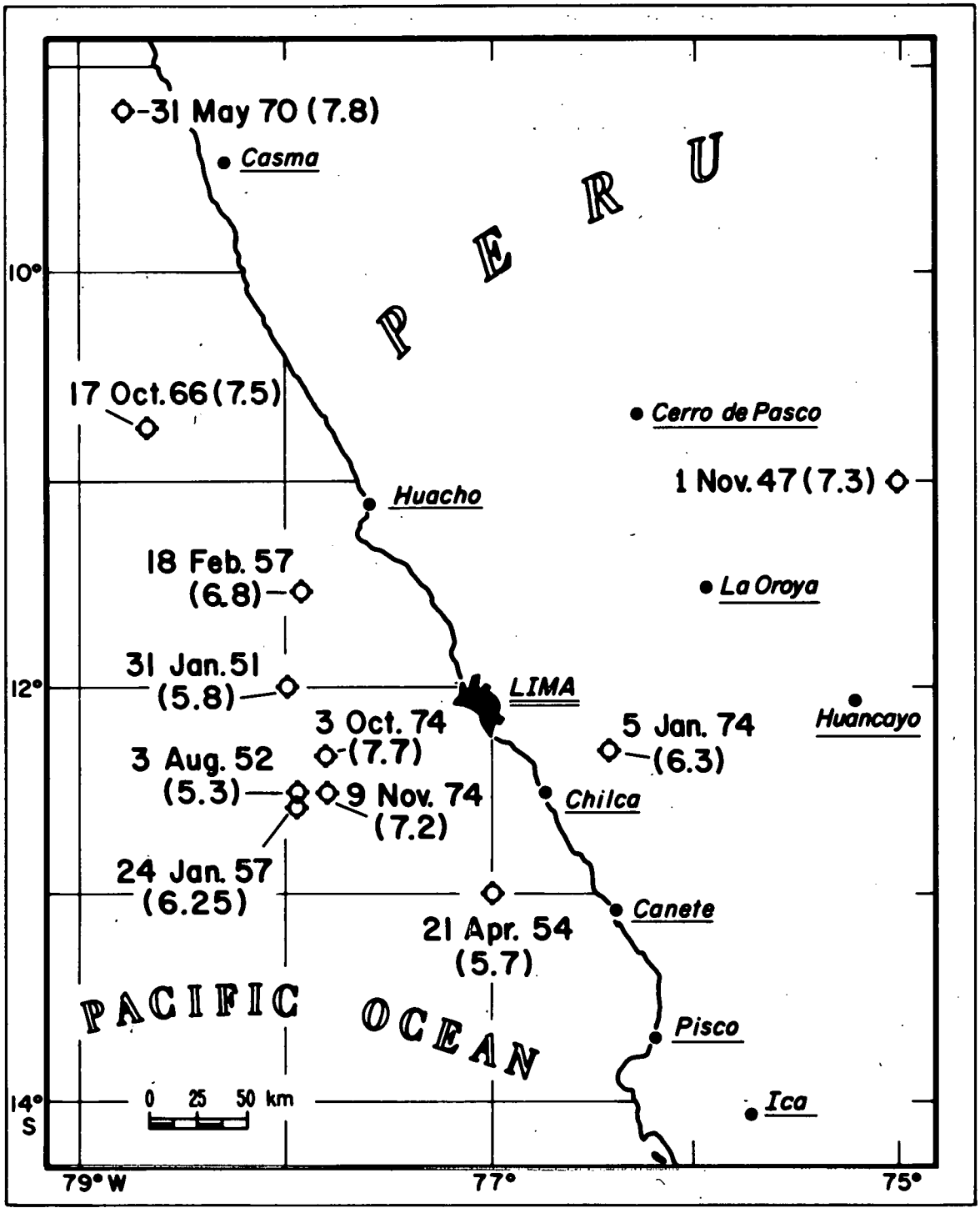

Figure 18. Locations of epicenters for Peru earthquakes having magnitudes of 5.3 and higher, recorded on strong-motion accelerograph systems at the Geophysical Institute of Peru.

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Figure 19. Oblique aerial view of Nevados Huascaran and the debris avalanche area (light colored) (photography courtesy of the Servicio Aerofotografico Nacional del Peru, June 13, 1970). Vertical drop from summit of Nevados Huascaran (6654 m) to Rio Santa (2510 m) is 4144 m and horizontal distance is 16 km.

Figure 20. Sand boil in water-saturated unconsolidated sediments of the Casma Valley; during the earthquake jets of muddy and sandy water squirted from the two pits. The mound of ejected sand is more than 1 meter in diameter.

Photo by author.

Figure 21. Earth flow in water-saturated grass-covered glacial lake deposits in terrain underlain by glacial outwash deposits. Note the irregularities in topography due to former slumps and earth flows. During the earthquake the fine-grained sediments liquefied and flowed down the hill to the level of the Rio Santa, which is near the toe of the flow.

Photo by author.

Figure 22. Typical street scene in a 100-block area of central Huaraz where nearly all adobe-block buildings were destroyed. Most buildings were 2 or 3 stories high and had heavy tile roofs. Thousands of people were buried here in the narrow streets as well as in collapsed houses.

Photo by author.

Figure 23. Slumping and fissuring of paved road near the bay shore in western Chimbote due to liquefaction and lateral spreading of water-saturated beach sediments.

The geologic hazard potential existing in Lima and vicinity is portrayed by figure 24, which shows distribution of intensity (modified Mercalli intensity scale) attributed to the October 3, 1974, earthquake. Damage distribution in the capital of Peru, owing to the 1974 earthquake, is shown in figure 25. The epicentral distance from Lima for this earthquake was 80 km. Liquefaction, ground compaction, subsidence, and small landslides were observed in Lima. At greater distances from the epicenter, near San Luis (fig. 24), liquefaction took place in cultivated fields, and slumping was observed on the Pan-American highway south of Lima in several places. These types of geologic hazards are associated with earthquake vibrational effects.

The geologic hazards found in Peru are summarized in tables 21 and 22. The byproducts of most of the main and associated hazards, as listed in table 21, have direct impacts on lifelines: these effects are very important because they disrupt the normal trend of life and the economy of the nation.

The extensive destruction from most earthquakes to cities, towns, and villages is attributed largely to the poor construction of buildings, which are chiefly adobe. Adobe material has little shear resistance to lateral forces imposed by the vibrational effects of earthquakes. Other types of damage and destruction that are often caused in some areas of Peru are due to differential compaction, liquefaction, and rock slides. Extensive damage to roads and railway routes is a potential hazard that can impair lifelines in Peru.

Lima and other cities are in continual danger of damage from earthquakes. To understand the attenuation of seismic short-period waves and their corresponding level of ground motion is a problem that should be addressed in the near future. This type of understanding is of utmost importance in seismic-risk studies and seismic zonation procedures. A network of strong-motion accelerograph systems would provide the short-period wave and ground-motion measurements needed for writing or revising the building code of Peru. Such an effort will help to mitigate earthquake hazards in urban and industrial areas.

It would be desirable and advisable to initiate an extensive geologic mapping program in Peru with special attention to mapping of surficial materials. As Peru is a large country, systematic mapping of the entire country on a quadrangle basis is an impossibly large task. For this reason, guidelines should be drawn for selecting the more critical areas of the country. The so-called "critical areas" would include those having heavy concentrations of population, important industrial and other structures, major transportation routes, and so forth. Much of the information for hazard evaluation of landslides, mud flows, rock falls, and related phenomena can be effectively interpreted from aerial photographs. In addition, much information is already available for some areas, but this information would need to be evaluated in terms of geologic hazards.

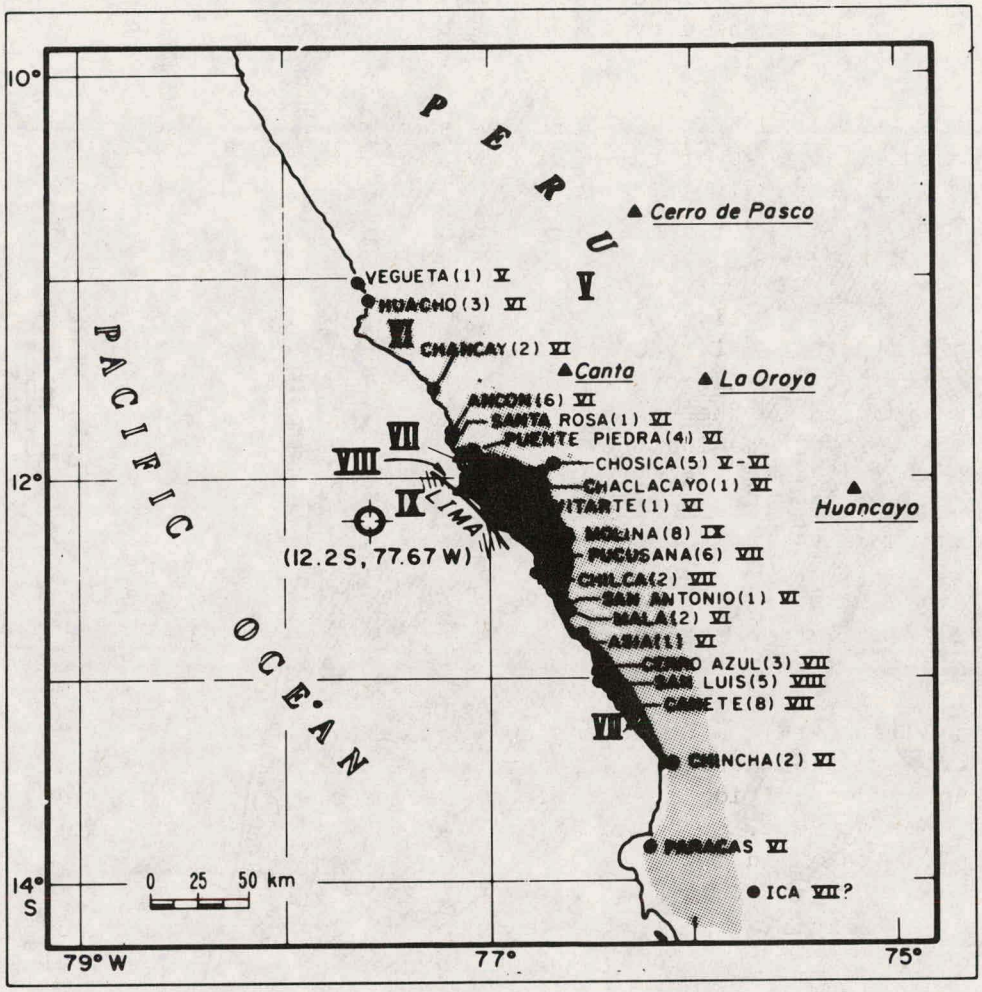

Figure 24. Distribution of intensities of the October 3, 1974, earthquake. Modified Mercalli Intensity Scale shown by Roman numerals; arabic numbers in parentheses indicate number of observations at each indicated town; circle with cross is epicentral location of the October 3, 1974, earthquake.

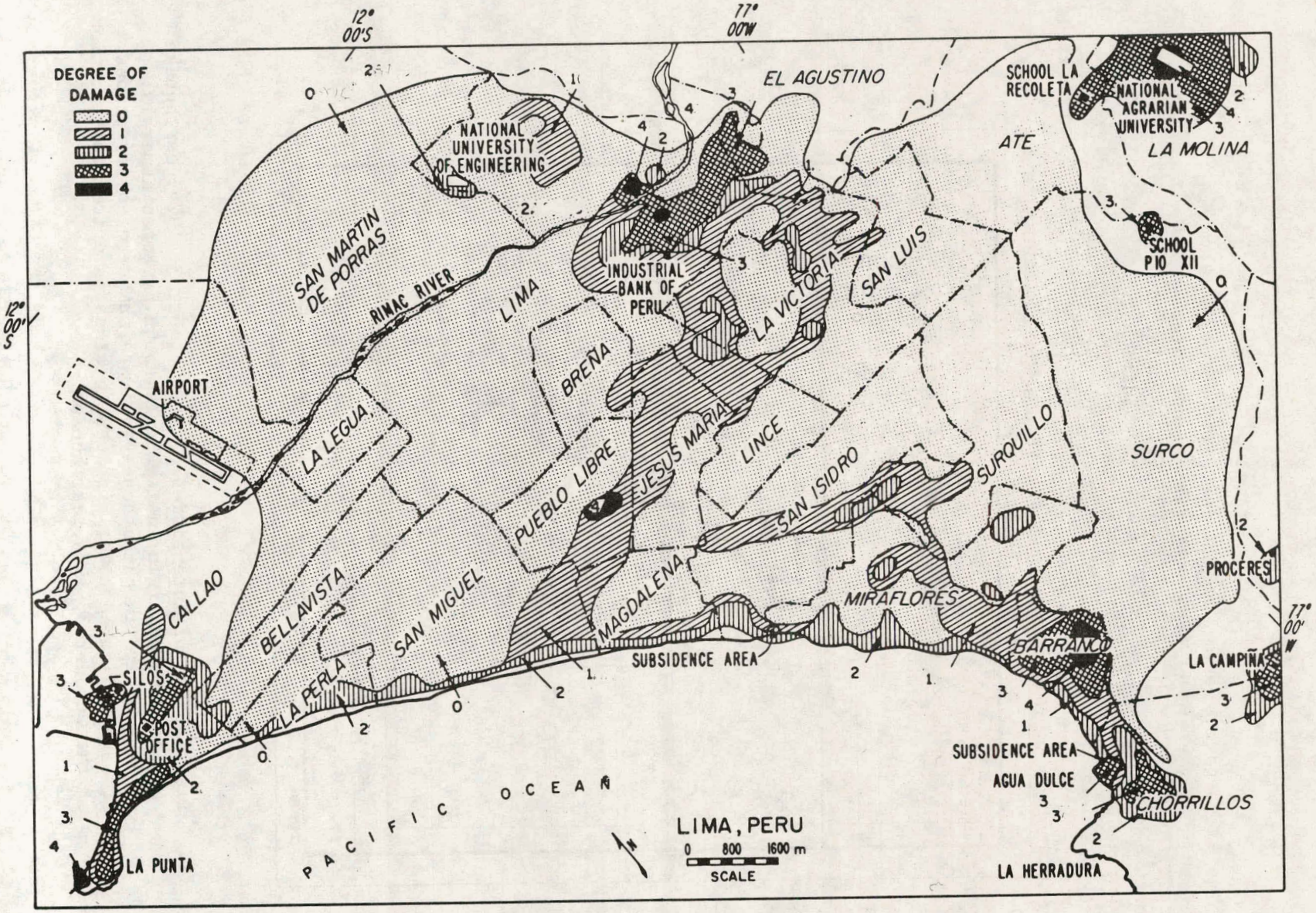

Figure 25. Degree of damage distribution in Lima due to the October 3, 1974, earthquake.

Lake deposits should be studied critically for liquefaction hazard. The location, distribution, composition, and water content of the lake deposits is particularly important. For example, the Cuzco airport is located on lake beds; even under static conditions, problems have been experienced in building airport foundations. The principal hazard in this case would be ground-surface deformation (table 21, main hazard numbers 2, 3, and 7). Thus, the airport facility could be immediately damaged after a strong earthquake, and the service of this facility would be lost for assistance for rescue and relief measures.

At the present time (1978), there is a memorandum of understanding on earthquake hazards between the U. S. Geological Survey and the Instituto Geofisico del Peru. The program has dealt with the evaluation of natural hazards in the Bayovar site in northern Peru. USGS geologists have participated in this program by evaluating, on a reconnaissance basis, the engineering geology, soil engineering, and faulting at the Bayovar site. Similar studies are needed in numerous other urban and industrial areas.

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RECOMMENDATIONS

Energy requirements of Peru to meet future needs are expected to expand year by year, as population increases, industrialization progresses, and the standard of living for its people is enhanced. To meet these future needs, Peru should explore all promising channels for enlarged or new energy production, both in the renewable and non-renewable categories. The following recommendations treat the non-renewable potential sources of energy, commonly called the fossil fuels. Geothermal energy is here included in this group.

Measures of a general nature to improve Peru's knowledge of and quantification of potential resources of the fossil fuels include the following:

1. Graduate-school education and practical training for a larger number of earth scientists. The administrators of earth-science agencies in Peru are almost without exception highly educated and capable scientists, but there is a dearth of well trained and widely experienced workers in the ranks.

2. Development of an intensified program of reconnaissance geologic mapping of the country, accompanied by detailed geologic mapping of the more critical or promising regions.

3. Development of guidelines or a methodology for assessing reserves and resources of fossil fuels (and minerals), so that consistency exists in the quantification of these resources. Included in the methodology should be the concept of realism, so that the quantities of measured, indicated, and inferred reserves for the future are neither inflated above nor downgraded below a level justified by the facts and reasonable geologic inferences.

4. Increased coordination of effort and collaboration between governmental bureaus working in the area of energy resources.

In addition to the above recommendations, the following specific projects are proposed to properly assess and stimulate exploration for the fossil fuels in Peru.

Petroleum

The hope for large increases in reserves of petroleum (and gas) for the future center on the jungle region of Peru. Only the northernmost of the three sedimentary basins there has been drilled extensively, and exploration there has been limited to structural targets. Two projects for immediate implementation to renew interest and stimulate exploration of this region are recommended:

Basin studies (Amazon area)

This study is aimed at preparing and publishing a series of geologic and geophysical maps (page size) for each of the jungle basins. The purpose of publication is to stimulate economic and geologic interest in the hydrocarbon potential of Peru. Items to be published include: lease block maps showing locations of all fields and wells; basement maps, structure and isopach maps for several prominent reflectors; lithologic and geophysical logs of selected wells; geologic cross sections; and gravity and magnetic maps (if available). PETROPERU has most of this data on hand and publication at page size would not affect the proprietary nature of some of this data.

Stratigraphic and geochemical studies of jungle basins

This project involves source rock and reservoir rock studies for Cretaceous and older rocks in the Amazon basins. Adequate samples from previous surface investigations and drilling should be readily available. Maturation and geochemical properties of potential sources rocks should first be investigated, followed by study of the physical properties and depositional history of potential reservoir rocks. Some new data may need to be collected, and seismic stratigraphic studies should be made. The results of this project should be published to attract new explorationists.

Computerized petroleum data system

The data that are produced in petroleum exploration and production are so abundant that manipulation and analysis of the data is excessively difficult and time-consuming. For this reason a program is proposed to develop a computerized petroleum data system which will incorporate available geological, engineering, and production information on Peruvian oil and gas resources. Program design and data capture will be directed towards providing an information base which can then be utilized for the evaluation of present reserves, potential reserves from secondary and tertiary recovery, and ultimate oil and gas resource potential. The proposed program will be incorporated with exisitng physical measurement data bases within PETROPERU for purposes of developing an overall resource assessment of both known and potential areas of oil and gas for Peru.

Coal

A considerable potential exists for meeting a part of Peru's needs for electrical energy and for coking coal in the known coal deposits. These deposits have not, however, been adequately assessed as to quantity, quality, and minability of the coal.

Coal basin studies

Other than Alto Chicama and Oyon, which are actively being explored, the two most important coal fields in terms of possible exploitation are Jatunhuasi and Santa Valley, but information is not available to appraise their potential adequately. A three-phase exploration program is recommended, consisting first of geologic mapping at 1/50,000 scale to determine sequence and structure of coal beds, then a drilling program to determine thicknesses at depth and to obtain fresh samples of the coal beds for analysis, and finally based on information from the first two, calculation of the coal reserves in each field that are available for development.

Geothermal energy

Little attention has been paid to geothermal energy as a source for electric power in Peru. There does exist, however, a good possibility that exploitable resources of geothermal energy are present, especially in the southern part of Peru in the volcanic belt.

A project should be initiated to assess and hopefully to develop geothermal energy in this region. The Calacoa and Salinas areas should be studied in detail to select specific sites for deep exploratory drilling. Simultaneously regional geological and geochemical exploration should be undertaken to find other localities in the zone of recent volcanoes where it is likely that geothermal energy can be exploited economically. The goal is to put the first geothermal-powered turbine into operation by 1985-87 and to produce 200 MW of electricity by the year 2000.

Uranium

The potential for nuclear energy in Peru is still unknown. Studies that have been made have been almost entirely confined to the more accessible western part of the country. Uranium specialists agree, however, that the geologically most favorable areas for uranium lie along the foothills of the Eastern Cordillera and the adjoining jungle area. Reconnaissance surveys, both surface and airborne, should be extended into these regions to determine if favorable areas do exist for more detailed studies.

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