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A perspective on Chinese petroleum geology

by

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Introduction

This paper represents the first attempt on the part of the U.S. Geological Survey (USGS) to report a perspective on Chinese petroleum geology based on the information gained on a recent trip to China in June 1979 and, as well, on at least some of the published information available to us. We are not yet able to present a new scientific paper on Chinese petroleum geology because most of the Chinese and Russian literature is unknown to us, and we neither really know the quality of data reported in the literature nor do we have sufficient independent observations to permit our judging the merit of conflicting data. As in any partly explored areas, the present spate of exploratory drilling will produce a massive amount of new information that will significantly modify whatever synthesis of data may be proposed now. We wish to emphasize that although some of the information presented is not consistent with information reported elsewhere, we are not now able to avoid inconsistency and uncertainty.

The first USGS involvement with Chinese petroleum interests was during a visit by a Chinese delegation hosted by the U.S. Department of Energy (DOE), when, at the specific request of the Chinese, the USGS was involved in certain briefings of our guests regarding the petroleum geology of the United States. Approximately 10 months later, in the fall of 1978, another delegation from the Chinese Petroleum Ministry visited the United States at the specific invitation of the U.S. National Council for China Trade. This delegation made a special request to review the petroleum research program of the USGS; we accommodated them by both field and laboratory tours in the Washington, D.C., and Denver locations of the USGS and at the EROS (Earth Resources Observation Satellite) Data Center at Sioux Falls, South Dakota. Shortly after their return to China and after normalization of diplomatic relations in January 1979, the USGS was invited to return the visit to China in the spring of 1979. The first substantial technical delegation of the U.S. Government to visit Chinese petroleum facilities spent 5 weeks in China during June and early July 1979. Our delegation consisted of 13 members (12 from the USGS and 1 from DOE), including a Chinese-born interpreter, now a scientist with the USGS, and various petroleum geologists, geophysicists, and geochemists. One member, M. J. Terman, had read a great deal about the general tectonic framework of China and had published various map compilations. At the request of the Chinese, made on their earlier trip to the United States, several U.S. experts in remote sensing had done some Landsat analyses of selected Chinese basins and went on the trip with the intent of focusing specific studies on the Qaidam (Tsaidam)[1] Basin of western China, the

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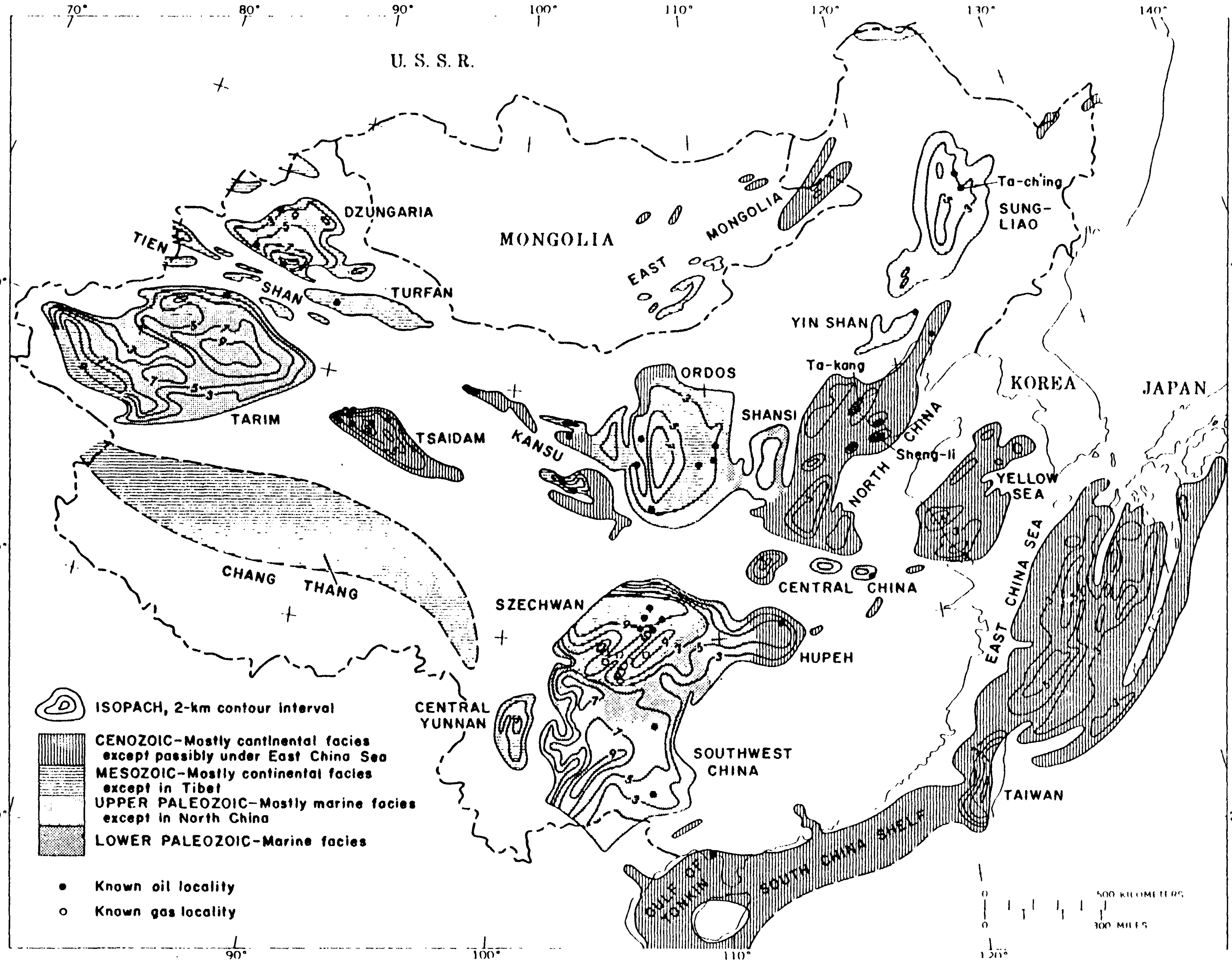
[1] Note: Throughout this paper the new official Pinyin transliteration is used, followed in the first usage by the Wade-Giles transliteration; the Pinyin spelling will not agree with the accompanying illustrations, which mostly use the now outdated Wade-Giles.

stratigraphy of which was thought to be similar to that of the Uinta Basin of Utah. The rest of the delegation had a range of interests, including sandstone and carbonate stratigraphy, organic geochemistry, structural geology, geophysics, and general petroleum geology. The senior writer served as the head of the delegation, and DOE International Affairs supported the travel to China. Our host was the Beijing (Peking) Scientific Research Institute of Petroleum Exploration and Development of the Ministry of Petroleum.

The Beijing Institute is a relatively newly named group, as of approximately early 1978; it is intended to provide a central focus for the research activities ongoing at each major oil basin. These activities run the whole gamut of petroleum research, including geology, production, drilling, technology, and information services. The general format of the visit was an agreed-upon agenda for delivering lectures, both by us and by the Chinese, interspersed with tours and visits to the various laboratories and work facilities in Beijing and later at the major oil fields. Most of our trip experiences, and hence our new geological understanding and insight, come from eastern China where most of China's production and exploration activities are located. Because of the regionalism of our experience, this paper will focus on eastern China.

The geography of China can readily be compared with that of the United States. China occupies about the same latitudes as does the conterminous United States, and it has almost the same physical dimensions. In China, as in the United States, the area of greatest rainfall is in the eastern third of the country, and most of the people live where the rain falls. Overall, the area receiving rainfall sufficient to support crops is small, and some three-quarters of a billion people live in that eastern agricultural region, which is about the same size as our country east of the Mississippi River. For comparison purposes, it is convenient to think of Beijing being located about where Washington, D.C., or Philadelphia is; you can visualize Manchuria, relatively, as New England; and Tibet is just about as remote from Beijing and Manchuria as Arizona and New Mexico are remote from Washington, D.C.

Figure 1, compiled by Terman in 1976, shows the locations of the various petroleum basins, isopachs of sediment thickness, and locations of some oil and gas fields. Most petroleum production and marketing are associated with the eastern basins - Sungliao and North China Basins; minor consumption in the western provinces is accommodated by local production. Whatever reserves have been established in the western basins are not yet fully exploited, however, because no economic way exists to transport petroleum products to a market. The only major pipeline in China brings oil from the supergiant Daqing (Ta-ch'ing) field (meaning Great Celebration) in the Sungliao Basin to Fushun where the line splits, one part going to Luda (Dalien) on Bohai (Pohai) for export and the other to the port of Qinhuangdao and on to Beijing for internal consumption. The other large producing area in China is the North China Basins, which


U. S. S. R.
MONGOLIA
EAST MONGOLIA
DZUNGARIA
TIEN SHAN
TURFAN
TARIM
TSAIDAM
KANSU
ORDOS
SHANSI
YIN SHAN
Ta-kang
Ta-ch'ing
SUNG-LIAO
NORTH CHINA
Sheng-li
KOREA
JAPAN
YELLOW SEA
EAST CHINA SEA
CENTRAL CHINA
CHANG THANG
SZECHWAN
HUPEH
CENTRAL YUNNAN
SOUTHWEST CHINA
TAIWAN
SOUTH CHINA SHELF
GULF OF TONKIN
ISOPACH, 2-km contour interval
CENOZOIC-Mostly continental facies except possibly under East China Sea
MESOZOIC-Mostly continental facies except in Tibet
UPPER PALEOZOIC-Mostly marine facies except in North China
LOWER PALEOZOIC-Marine facies
Known oil locality
Known gas locality
500 KILOMETERS
300 MILES
70°
80°
90°
100°
110°
120°
130°
140°
40°
30°
20°

includes Bohai and surrounding areas. The annual production of the country, of about 104 million metric tons or .75 billion barrels of oil, is split about equally between these two large producing areas.

Chinese petroleum geology is, in general, unique in the world, and its essential characteristics are well to keep in mind as one tries to grasp the complexity of petroleum geology in the enormous country:

(1) The land area of China comprises some 9.6 million km^2, half of which is covered with sedimentary rocks. In addition, China has a very wide Continental shelf characterized by many basins containing thick sedimentary deposits.

(2) The source rocks for oil are almost entirely nonmarine. At present, two lacustrine source-rock units, one of Cretaceous age and the other of Oligocene age, supply most of the oil. They have relatively high contents of organic matter (1-3 percent), and, in the eastern area, they have been subjected to extraordinarily high geothermal gradients ranging from 3°C/100 m to 5°C/100 m. These gradients are two to three times higher than those in most U.S. petroleum basins but are comparable with the gradients recorded in the Great Basin of the western United States.

3) Petroleum reservoirs are found in rocks of all geologic periods and in a wide variety of rock types, including metamorphic and volcanic rocks, but the principal reservoir rocks are upper Mesozoic-Cenozoic sandstones, dominantly of single-cycle origin. Primary porosity and permeability in the Sungliao Basin fields and in the North China Basins fields are excellent; porosity averages 20-35 percent, and permeabilities are in the hundreds of millidarcies or are a few darcies. However, outside the existing fields, the rocks are commonly tight, suggesting that preservation of good porosity and permeability may require the early migration of petroleum. Possibly where high heat flows do not produce early source-rock maturity, primary reservoir properties may be lost before oil migration. Upper Proterozoic (Sinian)-lower Paleozoic reservoirs in the North China Basins are entirely secondary in origin, owing to a long history of karst development or fracturing.

(4) The Pliocene marine shale that overlaps the earlier Cenozoic deposits of the North China Basins is an excellent seal, as are the Cretaceous shales in the Sungliao Basin; no oil seeps are reported in these basins, and no faults are known to break the regional seals. In basins of western and southwestern China, however, tectonic events have breached the regional sealing rocks, and oil seeps are common; the seeps are good for targeting exploration but are an obvious loss to the system.

(5) In the major Chinese producing localities, the source rock, effective reservoir-rock properties, and traps were produced almost concomitantly. In most places, the reservoir rock appears to be in juxtaposition with the source rock, suggesting only minimum necessary migration distance. The porosity, permeability, and topographic

traps in the Sinian and lower Paleozoic reservoirs, however, were formed by erosion (karst) or fracturing before Tertiary source-rock deposition. These traps are the so-called buried hills of Chinese petroleum geology. The analogy is quite precisely what we see in the Great Salt Lake today, where the lake sediments lap onto the blocks of Paleozoic rock now exposed as islands; surely the buried hills are one of the great examples of serendipity in the annals of petroleum geology.

(6) The trap types for petroleum in China are many and varied, but are in no way unique. Because most oil is associated with traps that formed at the same time as the source rocks were being deposited, sedimentation patterns are associated with the trapping phenomenon. The most common types of traps are drape folding over active basement blocks, rollover against growth faults, compressional anticlines, topographic cuestas or monadnocks (the famous buried hills), fault-bounded structural traps, onlap stratigraphic traps, and salt pillows (a phenomenon of eastern Bohai only).

(7) Though our technology people are commonly critical of the Chinese drilling equipment, our impression was that it is generally adequate for the given situation. Owing to high heat-flow conditions, drilling commonly has been to relatively shallow depths, 1,000-3,000 m, and, in many localities, the sediment is soft and drilling is easy. Fishtail bits are commonly used, and we were told at Daqing that a well to 1,000 m could be drilled in one day and completed in less than a week. Apparently, the equipment is as good as it needs to be, but certainly extreme drilling conditions cause trouble.

Although the general characteristics of Chinese petroleum geology are favorable and petroleum energy self-sufficiency has been attained by the discovery of at least one giant field, problems plague the Chinese. Nonmarine reservoirs are typically quite irregular, pay stackup is only locally good, and the reservoir rocks are mineralogically immature, rendering them subject to compaction damage by relatively shallow depth of burial if oil does not migrate early. Compaction damage may be a nagging problem in the western basins that may have lower geothermal gradients and, hence, relatively later migration. In addition to problems with the physical properties of the rocks, Chinese oil, derived from lacustrine source rock, has a high paraffin content (approximately 25 percent) and a high pour point (approximately 28°C or 85°F). Because of the high geothermal gradients (resulting commonly in reservoir temperatures of 100°-150°C), the high pour point does not present a production problem (as it does for similar oils in the Uinta Basin of Utah where the geothermal gradient is lower), but the transporting, marketing, and refining are more difficult than for oil containing less paraffin. Production is difficult from some traps where the oil has migrated along faults to overlying units and in so doing has lost volatile elements; their loss causes considerable deterioration of oil quality. The heavy-oil problem is particularly severe in Shengli and will hamper production wherever it is found.

In addition to geological problems, current administrative problems might limit attainment of present petroleum production quotas. Many common problems appear to exist in various petroleum basins, but communication among people in different locations is insufficient to promote common solutions; the Beijing Research Institute will mitigate this problem to some degree. Once oil is discovered in a basin by possibly quite imaginative thinking, the Chinese then begin to operate with more of an exploitation than an exploration mentality; a keen interest in exploitation is of course not surprising, but for long-term petroleum development, it must be balanced by continued vigorous exploration efforts. Finally, the Chinese may be literally burying themselves in data; certainly, they are being conscientious about data collection, but they do not seem to be devoting an equal effort to analysis of the data. China is largely in the precomputer era, so data management is a manual operation which is perhaps typified by a memorable remark we heard in Daqing from a young girl who was the team leader in charge of the production from eleven wells. She said: "To date, we have 960,000 pieces of information and all of it is accurate." We do not doubt that in the least; our concern is what do they want to do with the data.

With this discussion, we have intended to give a general perception of the petroleum geology and industry of China. We will turn now to more specific considerations of the geology as it bears on petroleum distribution; in addition, we will touch on the exploration history, discuss the unique characteristics of fluviolacustrine depositional conditions, describe the petroleum geology of various provinces, including the offshore, and finally give you some understanding of the reserves/production picture in China and the possible opportunities for western involvement in the People's Republic of China (PRC).

General Geology and Petroleum Exploration History

A regional historical synthesis of Chinese geology becomes so involved with theoretical and debatable plate tectonic interpretations that the petroleum explorationists are on much more solid ground when they simply focus on the individual platform blocks and leave their relationships to each other for future syntheses. Terman's Tectonic Map of China and Mongolia was published by the Geological Society of America (GSA) in 1972; a schematic version of his map is shown in figure 2. The map highlights the various platform areas where sedimentary basins developed and one can readily see the general structural grain that influences the particular platform area. Between platforms are areas of intense orogenic activity that, for purposes of this paper, will be ignored. A description of the general petroleum geology of China can be reasonably divided into eastern and western sectors, which are separated by a boundary line drawn just west of the Shaan-Gan-Ning (Ordos) and Sichuan (Szechwan) basins (figure 2). Following is a generalized description of those eastern and western sectors designed to give at least a broad understanding of the rocks and the tectonic activity; the reader, however, must be aware that many small basins and local areas differ from the broad theme we will present.

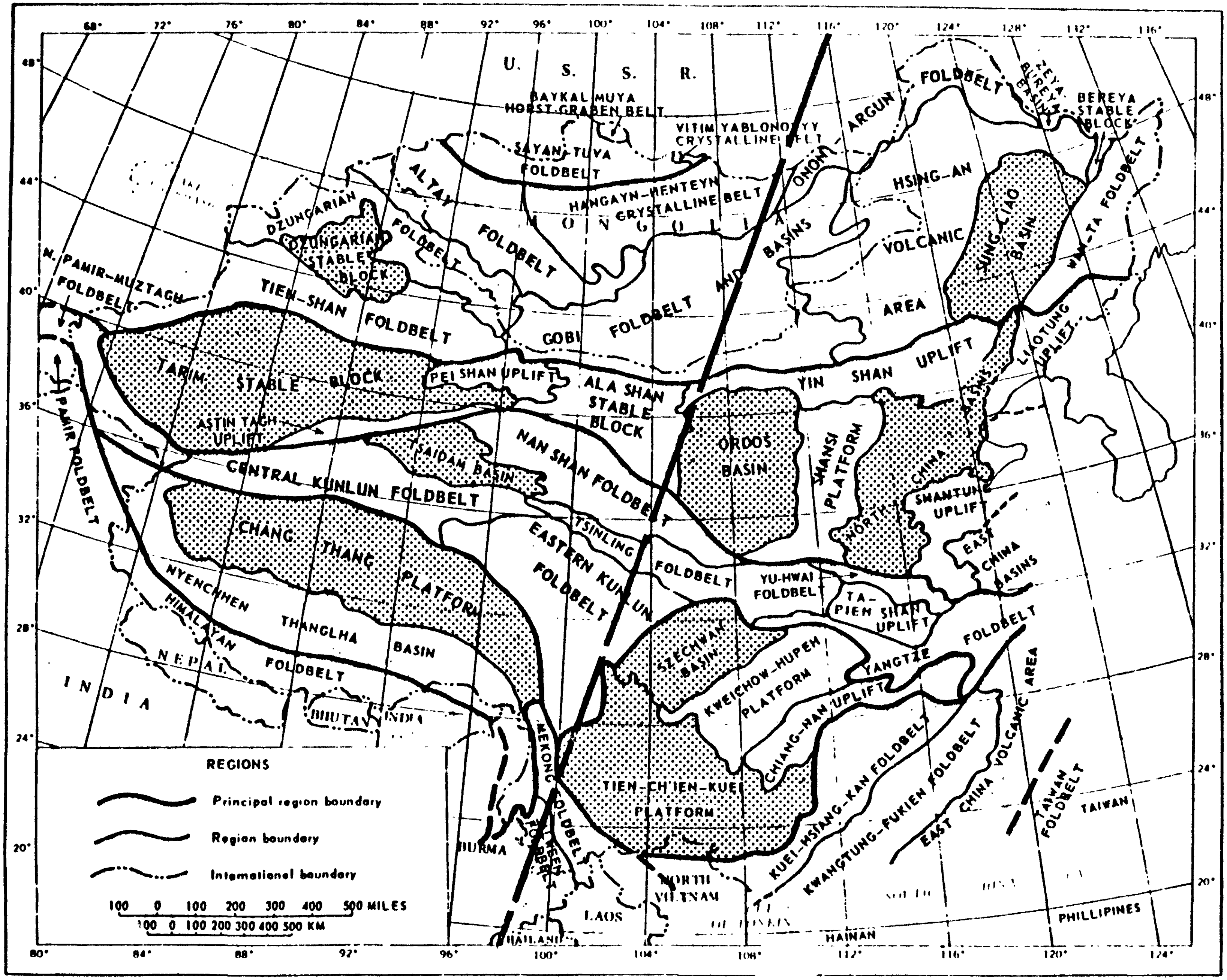


Figure 2.--Tectonic map of China and Mongolia, modified from Terman, 1972

The most obvious distinction between eastern and western China is the structural pattern and style. In the eastern region, a NNE-SSW orientation of structure predominates and, in the western region, the orientation is east-west. The style of the controlling structure pattern also differs in that extensional tectonism leading to block faulting dominates in the east, and compressional tectonism leading to overthrusts and foredeeps dominates in the west. Actually the sharp distinction in style is a phenomenon of the Tertiary period only; compressional tectonics also played a role in the eastern area during the Mesozoic and the Paleozoic. This change in style in the eastern area has produced very complicated structural patterns and erratic erosional remnants of certain stratigraphic units.

Eastern Area

In the eastern area, three distinct platform areas have been identified by Terman: the South China platform, including the Tian Qian-Gui (Tien-Ch'ien-Kuei) platform and the Sichuan Basin; the North China-Korea platform, including the Shaan-Gan-Ning and North China Basins; and the eastern part of the Central Asian fold system, including the Sungliao Basin (figures 2 and 3).

The first stratigraphic units containing oil and gas are the upper Proterozoic (Sinian) and the lower Paleozoic (Cambro-Ordovician) rocks of generally shallow-water marine carbonate facies. These rocks were widely distributed over the eastern platform areas, locally reaching thicknesses of as much as a few thousand meters. Today, their distribution is patchy owing to various subsequent uplift and erosion cycles, which left highly porous and permeable remnants to be covered by later sedimentary sequences. In the North China Basins, the final sedimentary cover was provided by Oligocene lacustrine source rocks giving rise to the buried-hills petroleum accumulations.

Middle and upper Paleozoic platform carbonate rocks are concentrated in the Tian-Qian-Gui area in thicknesses as great as 10,000 m. The rocks are truncated abruptly by major faults to the west and to the south, but onlap out gradually to the north into the Sichuan Basin and to the east onto the bordering high, where facies-equivalent coal deposits are presently being mined. This age rock is also common in the Shaan-Gan-Ning Basin, where it reaches a thickness of a few thousand meters of rich coal-bearing section. The principal coal-mining area of China is on the Shaonsi (Shansi) high on the east margin of the Shaan-Gan-Ning Basin.

Triassic marine carbonate rocks and shales are perhaps the thickest of anywhere in the world in the Tian-Qian-Gui platform and Sichuan Basin of the South China platform. The marine carbonate rocks are gas bearing in southern Sichuan, and the shale facies in the Tian-Qian-Gui provides a possible seal for underlying Paleozoic reservoirs; the seal is broken regionally by post-Triassic faulting but locally

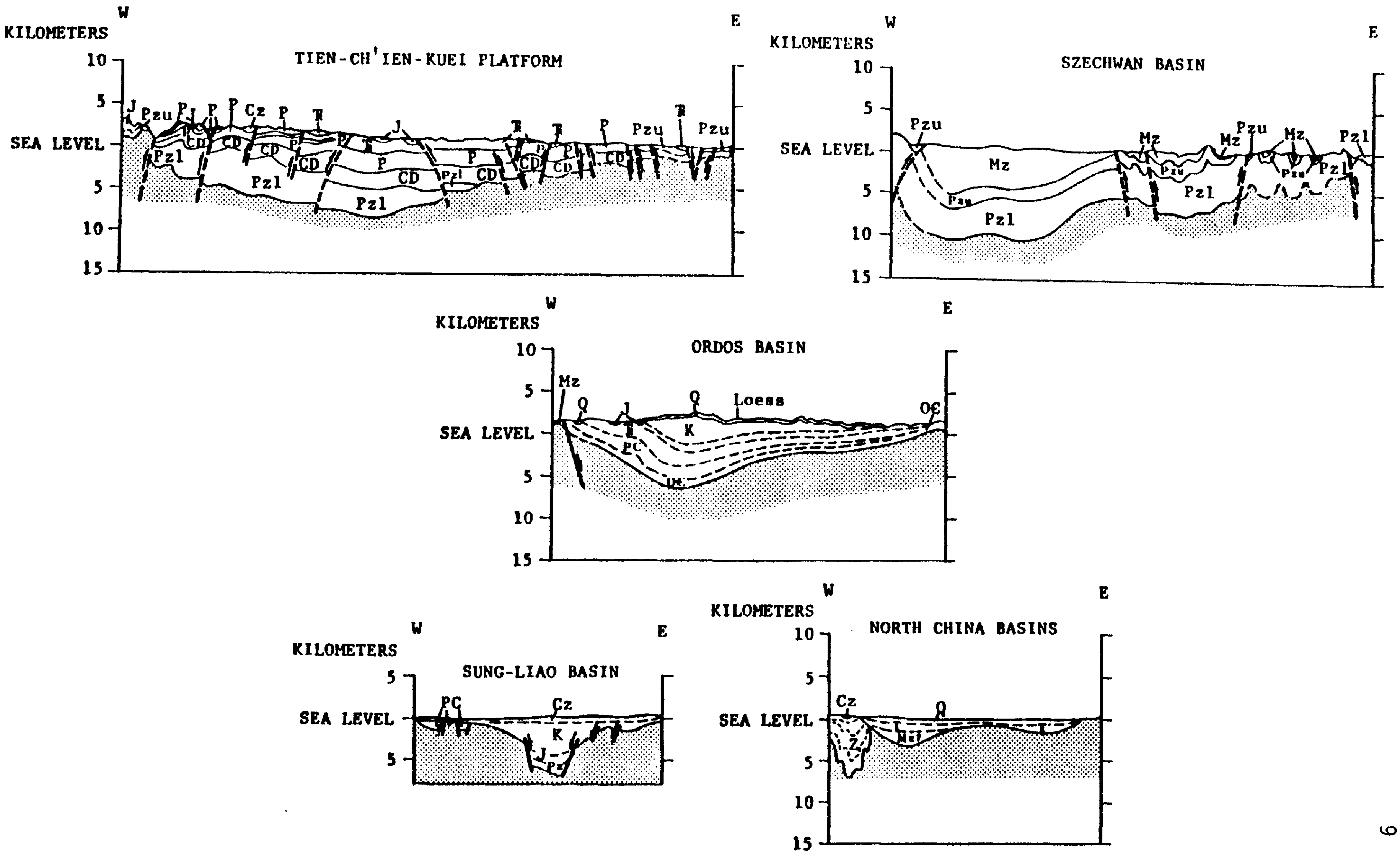


Figure 3.--Diagrammatic cross sections through basins in eastern China.

could be effective. An upper Triassic nonmarine red-bed facies is present in the Shaan-Gan-Ning Basin.

For the remainder of the Mesozoic and through most of the Tertiary, the depositional history in both eastern and western China is nonmarine. The late Triassic Indo-Sinian movement in southwestern China was synchronous with the regression of the seas from the platform areas which conditions prevailed until the Plio-Pleistocene marine invasion in the Bohai area some 150 million to 200 million years later. No equal exists in the world to such extensive and longlasting fluviolacustrine rock deposition.

Relatively thin Jurassic fluviolacustrine units were deposited in the Sichuan, Shaan-Gan-Ning, and Sungliao basins. Tectonic activity in the Jurassic appears to have resulted in only gentle basin downwarp, with the exception in the Sungliao Basin, where central basin grabens are recorded; the block faulting probably contributed to later drape-folding enhancement of Cretaceous compressional structures. Production has been established from the Jurassic (in eastern China) only in the Sichuan Basin.

Basin subsidence intensified during the Cretaceous in the Sichuan, Shaan-Gan-Ning and Sungliao basins. Rapid subsidence resulted in several kilometers of sediment accumulation in these three basins, but an extensive lake formed only in the Sungliao Basin, where concomitant compressional folding provided the traps and targets for successfull oil exploration.

Tertiary basins are confined to the North China Basins complex and to the offshore. After the formation of extensional grabens, a high rate of margin uplift and of yoked-basin subsidence evolved; the basins generally subsided faster than sediment was deposited, and widespread lakes formed. However, the rates of sedimentation were very high, about 0.1 to 0.2 mm/yr, and contributed to petroleum-favorable anoxic conditions. The extensional tectonic regime is inferred by the Chinese to have been caused by mantle upwelling, which is reflected in this area by a relatively shallow Mohorovicic discontinuity and by high geothermal gradients (commonly 3.0°-5.0°C/100 m). In spite of the modern earthquakes, this new Tertiary tectonic regime appears to be relatively quiescent now because an unbroken Plio-Pleistocene marine shale seals the underlying petroleum accumulations so well that no seeps are known in the North China Basins area. The Tertiary deposition locally took place on a basement of Sinian-lower Paleozoic rocks, which, being extensively weathered and fractured, provided one of the several excellent reservoirs for the overlying Tertiary source rocks.

Western area

In the western area, likewise, three distinct platforms have been identified by Terman: the Tibet platform on the south, the

Tarim stable block in central western China, and the Dzungarian stable block to the north in the Central Asian fold belt (figures 2 and 4). Little is known about the Sinian-Paleozoic sequence of rocks buried on these stable blocks. Because only minimum drilling has been done in the presumed platform-facies areas, much of the literature describes the rocks in the intervening fold belts, giving the distorted impression of a dominant eugeosynclinal facies in western China. Terman, to the contrary, predicted a shallow-water marine carbonate-sandstone facies on the western platforms, and he postulated considerable thicknesses, as much as 5-10 km, in the Tarim Basin. This hypothesis appears to have been confirmed by recent Chinese drilling and geophysical surveys, but we do not know the details. Elsewhere on the platforms in the western region, Paleozoic rocks are 2-4 km thick. The considerable thickness of Paleozoic marine, shallow-water platform facies will undoubtedly become a future exploration target.

Like that in eastern China, the Mesozoic-Tertiary geology in western China is mostly nonmarine fluviolacustrine; only the Tibetan platform has a marine Juro-Cretaceous cover. Triassic and Jurassic sedimentary rocks are commonly relatively thin, but the intensification of tectonic uplift in peripheral mountains and of downwarp in the basin foredeeps caused thick wedges of sediment to accumulate during the Cretaceous and Tertiary periods on the flanks of the Tarim and the Dzungarian stable blocks. High rates of sedimentation continued into the Neogene when 7,000 m of sediments were deposited. (This rate of sedimentation is analogous to that in the Neogene of California and of the central Gulf of Mexico.) Production in these basins is mostly from the Jurassic of Dzungaria and is modest. Jurassic organic matter must have been mostly herbaceous, because Dzungaria contains major coal deposits.

Sediments in the Qaidam Basin were deposited only during the Mesozoic and the Tertiary, and the Tertiary units, comprising some 5-7 km of sedimentary rocks, are by far the most likely to contain petroleum. Typical fluviolacustrine rocks are exposed in excellent outcrops on the surface, and we understand that in the subsurface a much broader lake facies is recognized in the northern part of the basin. The source rocks are dominantly Oligocene and Miocene, and the traps are of anticlinal or fault derivation. Pay sections as thick as 100 m are common, and several fields containing reserves of tens of millions of barrels to a few hundred million barrels of oil have been recognized; most of this oil will remain shut in, awaiting transportation and a market.

Petroleum Exploration History

The history of petroleum exploration, like everything else in China, goes back many years. Natural gas was discovered in eastern China 2,200 years ago, and wells were drilled with bamboo pipes to tap this resource 1,800 years ago. Petroleum for lamps became common 700 years ago. Modern exploration began during the first half of this

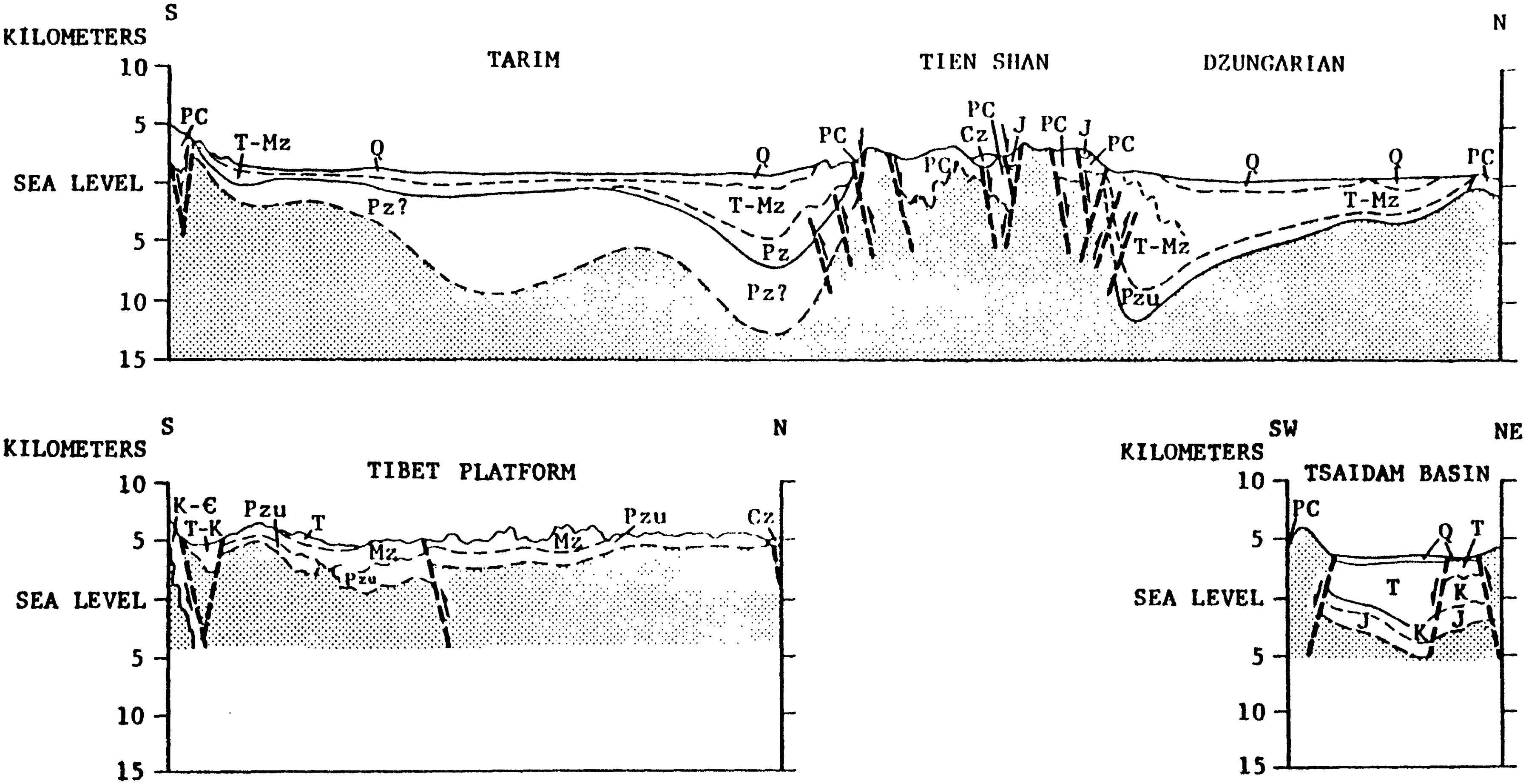


Figure 4.--Diagrammatic cross sections through basins in western China.

century and was focussed in the western areas on anticlines in the foredeeps in front of the rising mountain chains where oil seeps occurred. Probably the most notable was the field at Yumen in Gansu province.

After the revolution, which ended in 1949, exploration continued with Russian help but still only to a limited degree in the east presumably because of the known nonmarine conditions and the lack of experience by the Western world in finding oil in nonmarine basins. Only small fields continued to be discovered. In 1960, a break in relations with the U.S.S.R. led to the initiation of a truly Chinese petroleum industry. Because of market and logistics reasons, they decided it was better to look for the oil in the east where they needed it. Daqing was discovered, by the third exploratory well in Sungliao, and the petroleum worker and industry gained the respect that continues to date.

The Chinese quite properly believe that they significantly modified western petroleum philosophy with their unprecedented nonmarine discoveries, and they have worked hard and effectively to demonstrate the merit and the logic behind lacustrine basin petroleum genesis and exploration. After the great discovery at Daqing, another eastern platform basin, Shengli, quickly yielded its oil to the drill bit. Development in both areas was so rapid that by the middle 1960's, China could proclaim petroleum independence and begin to talk confidently of affecting trade by exporting petroleum. Serious export talk, however, is a product of successful offshore exploration, which began in Bohai in the mid 1960's and within the last few years has expanded to the South China Sea and will eventually extend to the East China Sea.

Oil in China, as in many other parts of the world, has greatly affected the way of life of those who search for and produce the resource. The discovery of oil in Sungliao has led to major community development and to the transfer of large numbers of technical people to create the support functions around the treasured resource. In that the major discoveries followed the Russian exodus, the industry is truly homegrown and operates very much on an each-one-teach-one philosophy. A legendary Chinese oil figure, iron-man Wang, came from Yumen to drill the first wells in Daqing literally with his bare hands. When the discoveries followed soon after in Shengli, 10,000 oil-field workers were transferred to that barren wasteland. The dimension of societal risk the Chinese took was staggering, but the success story that comes out of it literally supports the society with pride and with cash. They have created a tough act for themselves to follow, and therein lies some of the reasons for the western liaison--but more about that later.

Characteristics of Nonmarine Lacustrine Basins

The unique feature of Chinese petroleum geology is the regionally extensive and geologically long period of lacustrine-basin sedimentation. Certainly, one of the reasons Westerners have slighted the oil and gas potential of the nonmarine basins is that we have had only minimum experience with lacustrine environments, and that experience, in the Rocky Mountains, suggested that marine facies were more productive. Clearly, however, if the lakes were big enough and the right kind of organic matter accumulated, only an association with reservoir rocks and traps was needed. In China, the lakes were big enough; their average size was about 50,000 km^2, and the largest lakes were 200,000 km^2, which is like a fair-sized inland sea.

During Jurassic time, the climate was humid, and much of the organic matter deposited in the lakes was herbaceous, resulting in the organic transformation toward coal. Much of China's legendary coal resource is concentrated in Jurassic age rocks and most particularly in the Sinkiang province of northwest China. In the Cretaceous and on into the Tertiary, however, the climate became more arid, producing conditions necessary for deposition of sapropelic organic matter. Reservoir rocks were deposited in deltas, marginal to the oil source rock, and because of rapid marginal uplifts, substantial deltas built from many directions into the lakes that were obviously big enough and deep enough to accommodate the wave energy that resulted in at least minimum sorting of the sediments. The clastic sediments commonly are mineralogically and texturally immature, so that if oil had not migrated into them early, their porosity and permeability would likely have been significantly damaged by compaction; however, as is noted in the following discussion of particular basins, high heat flow contributed to early maturity and migration, thus preserving good reservoir properties. The deltas commonly have high constructional, lobate shapes and individual delta units may be several meters thick, extend 40-50 km into the lake, and be 10-20 km wide. (We had an opportunity to examine some cores from Shengli and were very impressed with the Chinese geologists' understanding of sedimentation processes and nuances of environmental interpretation.) When packaged through time by successive delta buildups, clastic sediment aggregations a few hundred meters thick become prime exploration targets. For analogies in the United States to this type of depositional setting, one can consider the Uinta Basin in Utah or the narrowly confined Tertiary basins of California. The latter of course had a marine setting, but the tectonic setting and rapid rates of sedimentation are very similar to the conditions described for the Chinese basins. On the other hand, the Uinta Basin matches the lacustrine environment, but the reservoir properties are not nearly as good as those we found in the Chinese basins.

Some Petroleum-Producing Areas of China

Bohai Area

The most rapidly expanding, and we think geologically interesting, petroleum-producing area of China is in the general Bohai area. Particular geographic localities included are: Dagang (Takang), Renjiu (Genchiu), offshore Bohai, and Shengli. Production from these basins comes from both Paleogene and Neogene rocks as well as from the lower Paleozoic buried-hills reservoirs that are charged by the enclosing Paleogene source rocks. The general Tertiary stratigraphic section is about 4,000-5,000 m thick, reaching a maximum of about 13,000 m, and it commonly contains some 2,000 m of Paleogene source rock; the source rock may be the age equivalent of the Fushun oil shale, which is being mined and retorted just north of Bohai. Simplistically, the structure stems from graben formation associated with growth faults and sediment drape. Marginally, onlap of the block-faulted high results in stratigraphic traps. At some distance from the source of sediments, isolated carbonate shoreline accumulations provide small traps. The regional seal for the North China Basins is a Pliocene-Pleistocene marine shale; it lies unconformably above Miocene (Neogene) fluvial sediments and is nowhere broken by faults. Oil migrates into the Miocene fluvial sediments along faults that extend downward into the underlying Paleogene source rocks; the oil from Neogene reservoirs commonly is relatively heavy owing to the loss of volatiles associated with the migration. An excellent discussion of the Gu-Dao oil field in the Bohai area was delivered by Chen Si Zhong and Wang Ping at the 1979 AAPG-SEPM Annual Convention (American Association of Petroleum Geologists-Society of Economic Paleontologists and Mineralogists Annual Convention, Houston, Texas, April 1-4, 1979, Program, p. 193). The wells having the highest production rates, as much as 1,000 tons/day, in this general area are from the buried hills at Genchiu. We do not know the longevity of these high production rates, but we were told repeatedly that rapid drawdowns were a very great problem, and certainly the nature of the reservoir suggests that the high flow rate might not last for long.

From an exploration perspective, we were impressed with the thorough geochemical, paleogeographic, and trap-model approach presented to us by the Chinese. Source-rock geochemistry is a major component of their exploration philosophy and, according to George Claypool of the USGS (personal communication, 1979), the Chinese are exceedingly competent. Paleogeographic reconstructions focus on the location of deltas and potential areas of source rock (figure 5); the Chinese concentrate their exploration where they get an optimum combination. At both Dagang and Shengli, the Chinese produced a series of paleogeographic reconstructions that were excellent and showed us in general the types of traps for which they were exploring. An interesting variant at Shengli, from that seen elsewhere in the basin, was a lower Tertiary salt zone some 1,000 m thick that controlled some production over broad salt pillows associated with normal growth faults; no salt domes have been recognized as yet.

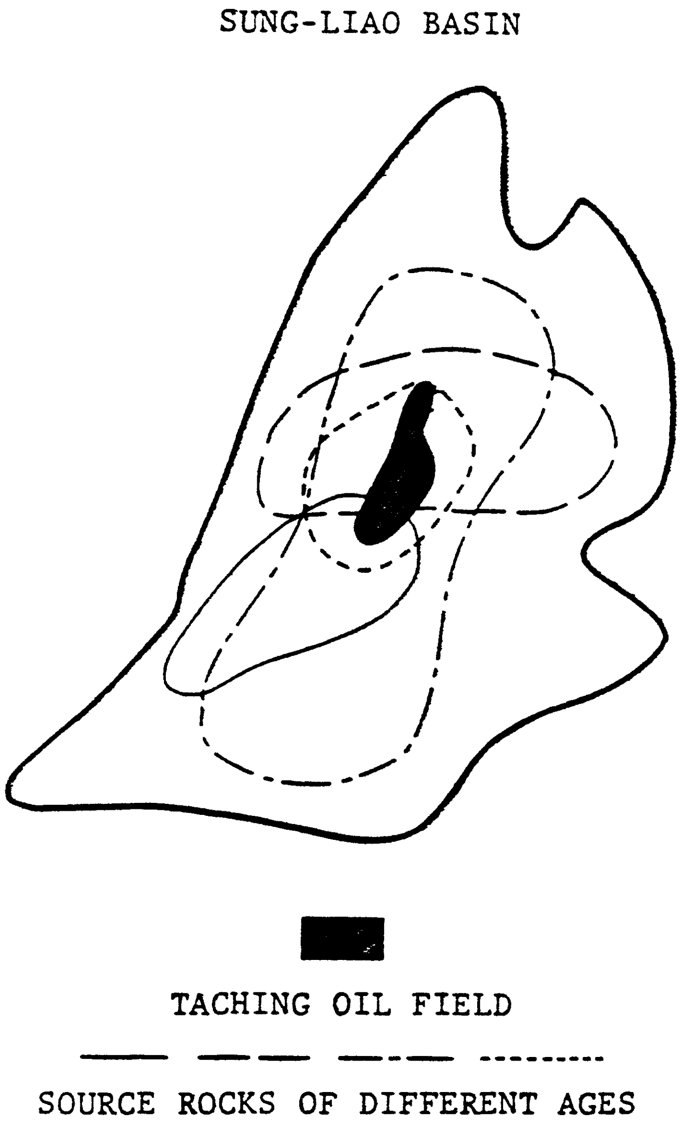


Figure 5.-- Source-rock distribution in the Sung-Liao Basin illustrating the geochemical technique used in Chinese oil exploration.

In offshore Bohai, the exploration problem is initially structural; some thirteen highs have been recognized and partly mapped by means of seismic surveys. Well control is as yet insufficient for paleogeographic reconstructions to be attempted, and the Chinese are very conscious of their lack of data on reservoir and source-rock distribution. Their model reconstructions and the geometry of potential targets in this area were quite sophisticated and showed an open-mindedness that will stand them in good stead for seismic interpretations. (The trap types thought to exist at Bohai are similar to those found in other fields in the North China basins.) The conceptual trap targets include buried hills, onlap reservoir sands, drape structures, fault traps, and rollover growth faults. Because the traps are so complexly faulted, the Chinese are having the same problems with this type of exploration that any of our explorationists do: all fault blocks do not produce; water levels are highly varied; pay stackups are not everywhere thick; and where oil has leaked up into the Miocene, heavy-oil production is a problem.

Northeastern China

The Sungliao Basin, location of the famous Daqing oil field, presents a completely different exploration and production situation from that at Bohai. The giant oil field is on a central basin arch having seven separate highs (the northernmost of which has a gas cap); the arch fortuitously coincides with an area of major Cretaceous lacustrine delta deposition. The field is about 100 km long and possibly 30 km wide. Though the individual sandstone reservoirs are highly irregular, sufficient communication exists among the 40-odd sandstones that make up the approximately 200 m-thick reservoir zone for a common water table to exist across the field. There is no active water drive, however, and production of the field derives from solution gas and an active water flood. Reservoir porosity and permeability exceed, respectively, 30 percent and a few hundred millidarcies. Owing to the very high geothermal gradient, 5°C/100 m, the oil window is in a depth range of 1,300 m to 2,200 m, and, fortunately, good reservoir and source rocks are included at about that level or shallower. Average production depths early in field development were less than 1,000 m, but deeper horizons are now sought.

The Chinese anticipate 50 percent ultimate recovery from their extensive and sophisticated water-flood operations and presently expect that 30 percent recovery will be achieved by 1985. Other smaller fields and prospects have been found marginal to Daqing and certainly the Chinese are optimistic about additional major discoveries. Petroconsultants reports one such field north of Daqing that may contain as much as 1 billion-1.5 billion barrels of oil. (This field may now be a part of Daqing proper.)

Central China

Still another type of exploration-production problem faces the Chinese in the Sichuan and Shaan-Gan-Ning Basins: low porosity and permeability and thin pay sections. In Sichuan, oil production has been established from two zones in the Jurassic, and dry-gas production has been an area mainstay for 2,000 years.[2] The Jurassic production we were apprised of comes mostly from a 100 m-thick section of thin lacustrine bioclastic limestones (three beds, 10-15 m each) interbedded with gray to black shales. Though commonly the literature suggests paralic sediments, no solid evidence for marine influence has in fact been recognized. The Permian and Triassic production, from marine carbonate rock on anticlines along the east and south margins of the basin, is dominantly dry gas containing no sulfur. Stratigraphically proximal coal horizons suggest the origin of the gas, and fracturing is probably responsible for the reservoir properties. World class reserves are not indicated from the data we were shown, but most published estimates indicate several fields with reserves in excess of 1 trillion cubic feet. We cannot meaningfully comment, however, on the reliability of those estimates.

The Jurassic reservoirs present an interesting exploration problem. The extremely low porosity and permeability of 1-3 percent and less than 1 millidarcy, respectively, must be overcome by finding maximum fracture zones, solution porosity, or high-pressure conditions. The Chinese development effort to date, since discovery in 1959, has focussed on fractures, but their exploration strategy is not obvious and may not be effective; the maximum fracture zones they showed us were not necessarily on the crest of arches or other mappable features. Possibly, more careful subsurface mapping may disclose trends of cleaner carbonate rocks that would be more subject to brittle fracture, but such rocks may not be present. A final possibility might be to conduct wildcat exploration in the deep high-pressure areas in the northwestern part of the basin.

Limiting factors in the future development of Sichuan are lack of thick source rock, low geothermal gradient, and mineralogically immature reservoir rock that may have lost, through compaction, most of its reservoir potential. (The Shaan-Gan-Ning Basin presents a similar problem in terms of known reservoir/source-rock conditions and is subject to the same limiting factors as the Sichuan Basin.)

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2 The Sichuan Basin is the principal agricultural region of China and, presumably, much of the gas production in this basin goes into the making of ammonia fertilizer.

South China

In addition to the Sichuan Basin, the South China platform also includes the Tian-Qian-Gui carbonate depositional basin. Here, some 6,000-12,000 m of marine sedimentary rock, ranging in age from Sinian to Triassic, was deposited. The thick Devonian through Permian section contains reef carbonate deposits intermediate between a platform facies and a deep-basin facies. The reef facies is readily recognizable by biohermal/biostromal accumulations or oolitic bank buildups; the platform facies is characterized by micritic limestone, skeletal carbonate sands, and widespread dolomites; and the basin facies comprises graptolitic shales, tuffaceous mudstones, siliceous shales, and thin limestones. The Upper Permian to Middle Triassic marine shales and evaporites provide a seal that overlies the section having a high exploration potential, but that regional seal has been breached in various localities, resulting in significant oil seeps with the oil now captured in vugular limestones. The Chinese have compiled an excellent folio of detailed paleoenvironment maps and are well on their way to planning a sophisticated exploration program. Fault scarps that formed as the basin developed controlled reef distribution. The Tian-Qian-Gui Basin has approximately the same general dimensions as the Permian Basin in the United States, and the very similar age and rock types make an excellent geologic analogue. In spite of the professional geologic analysis by the Chinese, exploration is going forward only slowly in the Tian-Qian-Gui Basin. The problem seems to be the lack of a drilling target defined by seismic surveys, which are difficult to obtain for technical reasons. Progress awaits a decision on a commitment to get better seismic data or to drill a hole to test the geologic concepts they have already evolved.

Offshore China

A final area of great interest to oil and gas explorationists in China is the offshore. Geologically, we can now say with some confidence that the general structural style, age, and stratigraphic section offshore will be very similar to those features in the Bohai area. Owing to drilling, this analogy has been rather better confirmed in the South China Sea-Tonkin Gulf area than it has in the East China Sea, but we know enough now to anticipate the drill in most localities. Geothermal gradients will be about 3°-4°C/100 m; overall sediment thickness in the graben basins may attain 6-10 km. Initial drilling has already established the presence of oil in two wells west of the Leighou peninsula, but production tests were only 30-40 tons of oil per day. Other wells in Tonkin have encountered gas shows, and a recent well about 200 km south of the Pearl River has been declared a discovery with an initial potential of approximately 300 tons of oil per day. Oil type in all the discovery wells has been paraffinic, and our Chinese colleagues have indicated to us the presence of nonmarine fluviolacustrine sediments. The extensional tectonism that we know existed here will no doubt have created trap types similar to those we have seen in Bohai: drape folds, growth faults, rollovers, and possibly reef structures to the south away from the principal source of sediments. Indeed, the Chinese visualize the possibility of an outer fringing ridge paralleling the coast which may have controlled reef growth. There is a certain comfort in discovering that the geologic occurrence of offshore oil may be similiar to that of the oil found onshore, but the complexity of nonmarine reservoirs in an extensional tectonic environment will not be easy to work with. United States company experience in the Gulf of Thailand (which is apparently structurally and stratigraphically similar to areas off China) should be helpful; certainly the high price of oil will add encouragement.

Reserves and Resources

The crucial questions, of course, in any petroleum analysis are what are the reserves and can we postulate significant resources? We, of course, are not in a position to answer either one of these questions, but we can tell you some of the things we have thought about. The two principal oil-producing areas are Sungliao and Bohai. In 1979, China produced 104 million tons or .75 billion barrels of oil. We were told that about half of the oil came from each of the two major producing areas (but certainly the old producing areas in western China deserve more than just trivial consideration) and that production was significantly levelling off from an early history of annual 20 percent growth rates. Because we have reason to believe that the Chinese are trying to get the oil out as fast as they can but at the same time we know of significant production problems, we assume that a 15/1 reserve/production ratio may be about right. That ratio is probably too high for Daqing, considering its extraordinary permeability and general deposit simplicity, whereas the ratio may be low for Bohai. However, considering 15/1 as at least a reasonable approximation, we suggest 11 billion barrels of oil reserve for these two major producing areas in eastern China and would argue that one should add only a very few more billion for the western China area, raising the total Chinese reserves to about 15 billion barrels of oil; if reserves in western China were significantly greater, we would probably see a pipeline under construction now. With respect to gas, we know even less and can only suggest that reserves of associated gas will be controlled by the generally low gas-oil ratio of about 250 cubic feet per barrel of oil and a rather limited regional source of nonassociated gas--mostly in the Sichuan Basin and to a lesser degree in the Qaidam Basin--the combination of which suggests overall modest gas reserves. As this report outlines, however, the potential for the growth of petroleum production is considerable, and we should anticipate continued Chinese oil and gas development. We do not believe, however, that the geology indicates that another Middle East is in the offing; indeed, China's potential petroleum reserves probably will not equal even those of the United States or the U.S.S.R. Rather, the geology suggests to us that China is good oil country that certainly has several tens of billions of barrels of oil yet to be discovered. This impression is well in line with various other published judgments on PRC oil potential.

The next several billion barrels of Chinese oil may not come quite as easily or as spectacularly as did the first 10 billion or 15 billion, but the Chinese are determined that it will come as rapidly as possible. Oil is the single major source of Western capital and the key to their modernization efforts. Just within 1979, the decisions to involve western technology and personnel in oil development have been firmly established. Our contacts suggest to us that they are aiming at the offshore to provide the quick oil for the export market. Production from those areas need not overly strain the logistic network of inland China and can be accomplished by western capital and technology, utilizing only minimum interface with the Chinese economic and cultural structure as a whole. Even more recent than the decision to seek help in exploring offshore, though, is the seeming willingness of the Chinese to consider western help onshore. We think this is a particularly significant show of confidence in the West, and we do not doubt that the exploration and development problems they face are similar to those with which we have wrestled for decades; our experience will be invaluable. We can expect, however, that onshore exploration will be a joint activity with the already established Chinese industrial capability. They have many competent geologists, engineers, and scientists who are perfectly capable of making a real contribution to human and world wellbeing; our entry at this stage into onshore operations will be and should be as equal partners seeking a common goal.