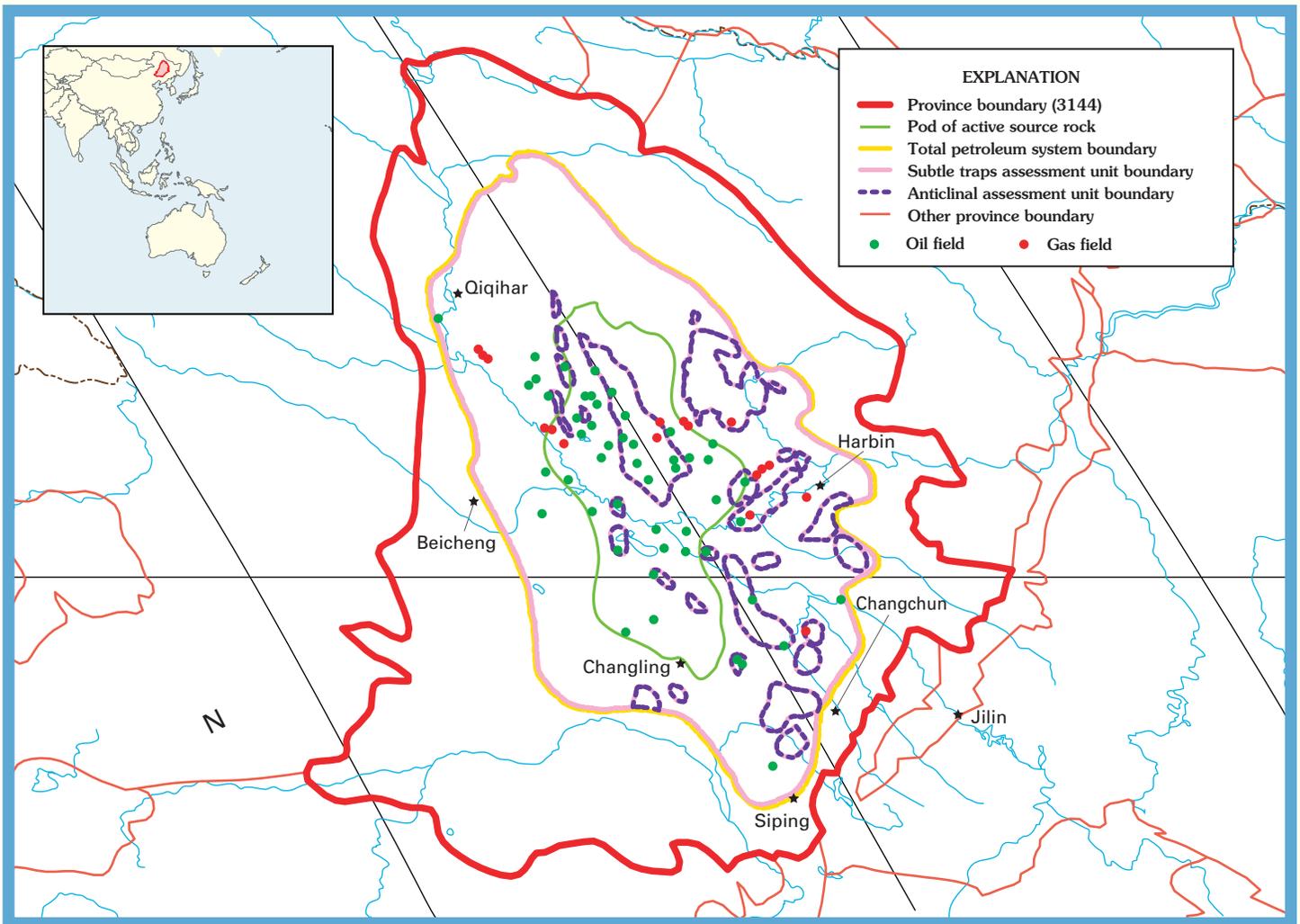


Qingshankou-Putaohua/Shaertu and Jurassic Coal–Denglouku/Nongan Total Petroleum Systems in the Songliao Basin, China



U.S. Geological Survey Bulletin 2203-A

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By Robert T. Ryder, Jin Qiang, Peter J. McCabe, Vito F. Nuccio, and Felix Persits

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Qingshankou-Putaohua/Shuertu and Jurassic Coal–Denglouku/Nongan Total Petroleum Systems in the Songliao Basin, China

By Robert T. Ryder,¹ Jin Qiang,² Peter J. McCabe,³ Vito F. Nuccio,³ and Felix Persits³

Foreword

This report was prepared as part of the World Energy Assessment Project of the U.S. Geological Survey. For this project, the world was divided into 8 regions and 937 geological provinces. The provinces were then ranked according to the discovered oil and gas volumes within each (Klett and others, 1997). Then, 76 “priority” provinces (exclusive of the United States and chosen for their high ranking) and 52 “boutique” provinces (exclusive of the United States and chosen for their anticipated petroleum richness or special regional economic importance) were selected for appraisal of oil and gas resources. The petroleum geology of these priority and boutique provinces is described in this series of reports.

The purpose of this effort is to aid in assessing the quantities of oil, gas, and natural gas liquids that have the potential to be added to reserves within the next 30 years. These volumes either reside in undiscovered fields whose sizes exceed the stated minimum-field-size cutoff value for the assessment unit (variable, but must be at least 1 million barrels of oil equivalent) or occur as reserve growth of fields already discovered.

The total petroleum system constitutes the basic geologic unit of the oil and gas assessment. The total petroleum system includes all genetically related petroleum that occurs in shows and accumulations (discovered and undiscovered) that (1) have been generated by a pod or closely related pods of mature source rock and (2) exist within a limited mappable geologic space, along with the essential mappable geologic elements (source, reservoir, seal, and overburden rocks) that control the fundamental processes of generation, expulsion, migration, entrapment, and preservation of petroleum. The minimum petroleum system is that part of a total petroleum system encompassing discovered shows and accumulations together with the geologic space in which the various essential elements have been proved by these discoveries.

An assessment unit is a mappable part of the total petroleum system in which discovered and undiscovered fields constitute a single, relatively homogeneous population such that the chosen methodology of resource assessment based on estimation of the number and sizes of undiscovered fields is applicable. A total petroleum system may equate to a single assessment unit. If necessary, a total petroleum system may be subdivided into two or more assessment units if each assessment unit is sufficiently homogeneous in terms of geology, exploration considerations, and risk to assess individually.

A graphical depiction of the elements of a total petroleum system is provided in the form of an events chart that shows the times of (1) deposition of essential rock units; (2) trap formation; (3) generation, migration, and accumulation of hydrocarbons; and (4) preservation of hydrocarbons.

A numeric code identifies each region, province, total petroleum system, and assessment unit; these codes are uniform throughout the project and will identify the same type of entity in any of the publications. The code is as follows:

Example

Region, single digit	3
Province, three digits to the right of region code	3144
Total petroleum system, two digits to the right of province code	314401
Assessment unit, two digits to the right of petroleum system code	31440101

The codes for the regions and provinces are listed in Klett and others (1997).

Oil and gas reserves quoted in this report are derived from Petroconsultants’ Petroleum Exploration and Production database (Petroconsultants, 1996) and other area reports from Petroconsultants, Inc., unless otherwise noted.

Figures in this report that show boundaries of the total petroleum system(s), assessment units, and pods of active source rocks were compiled by using geographic information system (GIS) software. Political boundaries and cartographic representations were taken, with permission, from Environmental Systems Research Institute’s ArcWorld 1:3 million digital coverage (1992), have no political significance, and are displayed for general reference only. Oil and gas field

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Abstract

The Qingshankou-Putaohua/Shuertu petroleum system involves the generation of oil and gas from a mature pod of lacustrine source rock near the center of the Songliao Basin in northeastern China. The primary source rock is the Lower Cretaceous Qingshankou Formation, and a secondary source rock is Member 1 of the Lower Cretaceous Nenjiang Formation. The most productive of six sandstone reservoirs are the Putaohua reservoir (Member 1 of the Lower Cretaceous Yaojia Formation) and the Shaertu reservoir (Members 2 and 3 of the Yaojia Formation and Member 1 of the Nenjiang Formation). Most oil and associated gas generated from the Qingshankou Formation and Nenjiang Formation (Member 1) are trapped in large faulted anticlines, fault blocks, and faulted anticlinal noses in combination with facies-change and (or) diagenetic stratigraphic traps. Two assessment units are defined in the petroleum system: (1) an anticlinal assessment unit; and (2) a subtle-traps assessment unit consisting of (a) anticlinal noses in combination with fault or stratigraphic traps, (b) stratigraphic traps, and (c) unconventional reservoirs. Undiscovered conventional oil and gas resources are expected in both assessment units in small (5–10 million barrels of oil; 30–60 billion ft³ gas) and medium (10–25 million barrels of oil; 60–150 billion ft³ of gas) fields. Also, undiscovered conventional oil and gas resources are expected in several large fields (25–73 million barrels of oil; 150–173 billion ft³ of gas).

The Jurassic coal–Dengloukou/Nongan petroleum system involves the generation of natural gas from multiple pods of mature source rock in graben structures at the base of the Songliao Basin. Sandstone and conglomeratic sandstone in the Lower Cretaceous Dengloukou Formation and the Lower Cretaceous Quantou Formation are the major reservoir rocks. Most of the known natural gas is trapped in anticlines, anticlinal noses, and fault blocks. This petroleum system is largely unexplored in comparison to the Qingshankou-Putaohua/Shuertu petroleum system and has good potential for undiscovered gas in the structural traps assessment unit. Undiscovered conventional gas is expected in small (30–60 billion ft³ of gas), medium (60–150 billion ft³ of gas), and large (150–395 billion ft³ of gas) fields.

The U.S. Geological Survey World Energy Assessment Team (2000) estimated that the Songliao Basin has, at a mean value, about 1.03 billion barrels of undiscovered conventional oil resources and 5.71 trillion ft³ of undiscovered conventional gas resources.

Acknowledgments

Data on ultimate recovery, cumulative production, and selected characteristics of oil and gas fields used in this report

were obtained from an unpublished volume (Anonymous, 1996) for Songliao Basin oil and gas fields and from the Petroconsultants, Inc. (1996) database. An English translation of the volume, “Songliao Basin—History of the Daqing Oil Field” (Yang Wanli, ed., 1984), contained many fundamental facts and interpretations used in this report. Susan Walden produced and (or) revised most of the figures and illustrations.

Introduction

The Songliao Basin (3144) in northeastern China is the second largest petroleum-producing region in China (Klett and others, 1997). Oil was first discovered in this intracratonic rift basin in 1959 at the giant Daqing complex and the large Fuyu field. Through 1996 approximately 17.6 billion barrels of oil equivalent (BBOE) of recoverable hydrocarbons (largely oil) had been discovered in the basin, of which about 13.4–14.9 BBOE are from the Daqing complex. A Lower Cretaceous lacustrine black shale and mudstone unit, representing one of several stages of maximum expansion of a basin-centered lake, is the major source rock. Reservoir rocks consist of very fine grained to fine-grained Lower Cretaceous sandstone in deltaic and fluvial sequences that flanked the lake.

The Qingshankou-Putaohua/Shuertu total petroleum system (314401) contains about 99 percent of the discovered oil and gas in the Songliao Basin. This petroleum system is named for the Qingshankou Formation, the major source rock, and the Putaohua and Shaertu reservoirs, the most productive of six reservoir intervals. Another total petroleum system recognized in the basin is the Jurassic coal–Dengloukou/Nongan gas system (314402) (Guan, 1991; Wu and others, 1991; Jin and McCabe, 1998), the name referring to a deeply buried sequence of Upper Jurassic coal beds and associated volcanic and terrigenous clastic rocks, the source-rock interval, and the productive Lower Cretaceous Dengloukou Formation and Nongan reservoir of the Quantou Formation.

Province Geology

The Songliao Basin (fig. 1) is a large ($\approx 260,000$ km²), oval (800 km long and 360 km wide) intracratonic rift basin defined in outcrop by unconsolidated Quaternary sediments and locally by Cretaceous and Neogene sedimentary rocks (fig. 1). Complex block faulting in the subsurface has little, if any, surface expression. The basin is underlain and flanked by igneous and metamorphic basement rocks, predominantly Paleozoic and Mesozoic in age, that represent an accretionary complex of Hercynian foldbelt terranes, microcontinents, and the Great Hingan Mesozoic magmatic arc (Tian and others, 1992; Sengör and Natal'in, 1996).

The basin is situated in Heilongjiang, Jilin, Nei Mongol, and Liaoning Provinces of northeasternmost China. Russia is within 150 km of the north end of the basin, and Mongolia is

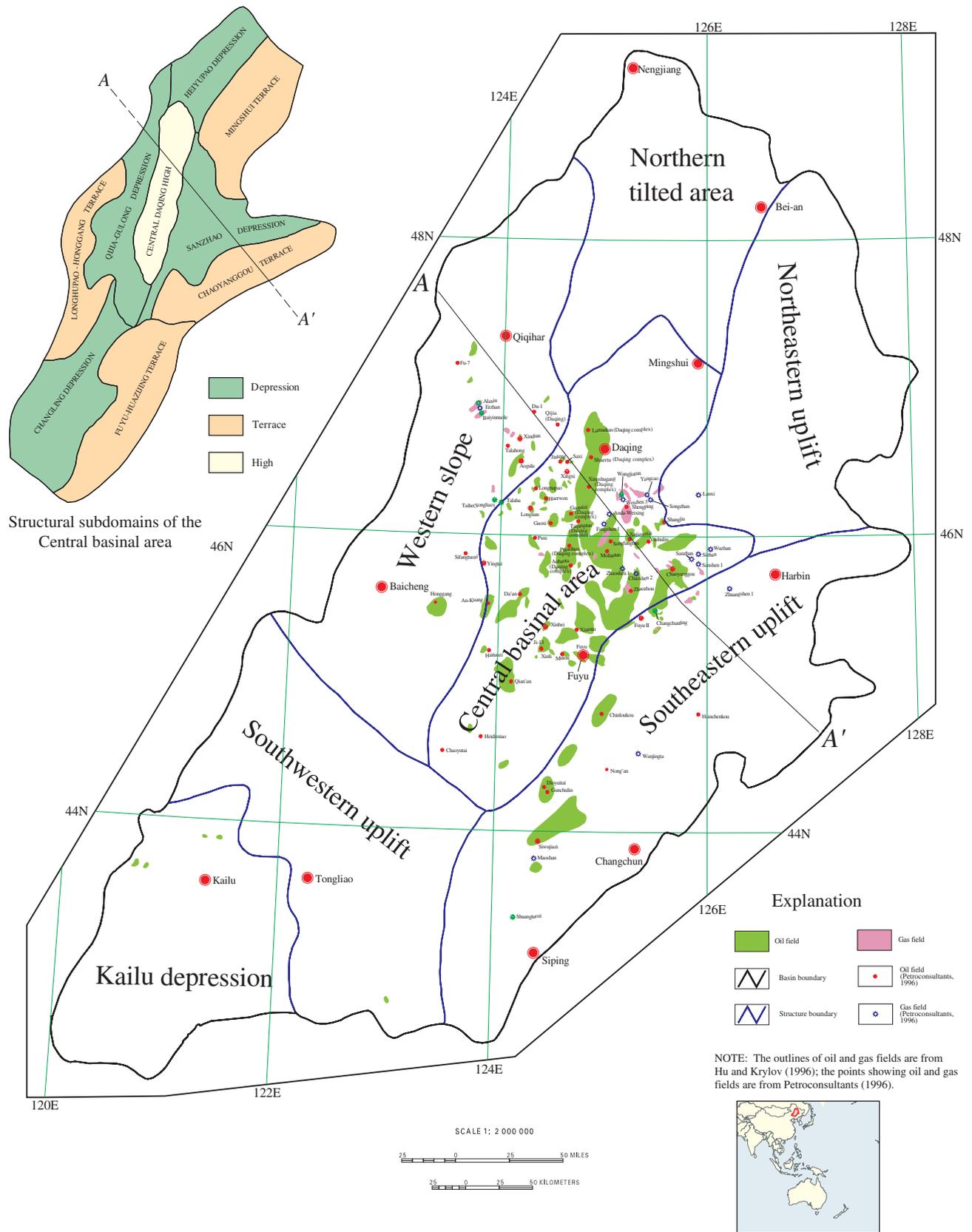


Figure 1. Oil and gas fields and structural domains of the Songliao Basin, China. Cross section A–A' is shown on figure 2. (For a larger version of this figure, [click here](#).)

4 Total Petroleum Systems, Songliao Basin, China

within 250 km of the west side. A nearly featureless landscape having less than 50 m of relief and numerous lakes, swamps, and rivers characterizes the present-day topography. Temperatures are hot ($>20^{\circ}\text{C}$) in the summer and cold ($<0^{\circ}\text{C}$) in the winter.

Basin evolution involved a complex tectonic history including (1) Late Jurassic–Early Cretaceous(?) rifting, volcanism, and sedimentation (155–144(?) million years ago (Ma)); (2) short-term uplift and erosion (144–140 Ma); (3) Early Cretaceous to early Late Cretaceous post-rift subsidence and Denglouku through at least Sifangtai sedimentation (140–75 Ma); (4) Early Cretaceous gentle, short-term rifting during early Qingshankou sedimentation (Song, 1997; Hu and others, 1998); (5) Late Cretaceous to Tertiary (Paleogene) late-stage compression, partial basin inversion, and uplift (75–65 Ma); and (6) minor post-inversion readjustment by differential subsidence and uplift (65 Ma to present day?). These tectonic events are broadly related to interactions of the crust and mantle caused by the westward subduction of the Pacific plate and the southward subduction of the Mongol–Okhotsk plate beneath the Asian plate (Ma and others, 1982, 1989; Li, 1995; Yin and Nie, 1996). An abnormally thin continental crust (29 km) beneath the Songliao Basin is 5–9 km thinner than the crust of the adjoining uplifts, a difference that emphasizes the magnitude of the crustal extension perhaps caused by subduction.

The Songliao Basin is divided into seven structural domains: (1) western slope, (2) northern tilted area, (3) central basinal area, (4) northeastern uplift, (5) southeastern uplift, (6) southwestern uplift, and (7) Kailu depression (Yang W., 1985; Yang J., 1985) (fig. 1). Moreover, the central basinal area is subdivided into nine structural subdomains: (1) Qijia–Gulong depression, (2) Sanzhao depression, (3) central Daqing high, (4) Longhupao–Honggang terrace, (5) Chaoyanggou terrace, (6) Mingshui terrace, (7) Heiyupao depression, (8) Changling depression, and (9) Fuyu–Huazijing terrace (inset, fig. 1). These structural domains and subdomains are shown along with locations of oil and gas fields in figure 1, and selected normal faults are shown on the geologic cross section of figure 2.

Sedimentary fill between 6 and 7.5 km thick is preserved in the Qijia–Gulong depression along the west side of the central Daqing high (figs. 1, 2). In ascending order, the major stratigraphic units in the Qijia–Gulong depression as recognized by Yang (1984) and Li (1995) (inset, fig. 1), their age (Li, 1995) and thickness (Yang, 1984; Li, 1995) are (1) Upper Jurassic ($\approx 1,100$ m); (2) Lower Cretaceous (Neocomian) Denglouku Formation ($\approx 1,900$ m); (3) Lower Cretaceous (Aptian) Quantou Formation ($\approx 1,600$ m); (4) Lower Cretaceous (Aptian) Qingshankou Formation (≈ 400 m); (5) Lower Cretaceous (Albian) Yaojia Formation (≈ 200 m); (6) Lower Cretaceous (Albian) Nenjiang Formation ($\approx 1,100$ m); (7) Upper Cretaceous (Cenomanian) Sifangtai Formation (≈ 400 m); (8) Paleogene and Neogene Mingshui [we use a Danian age here as assigned by Li (1995) rather than a Maastrichtian age assigned by Ma and others (1989)],

Yian, Daan, and Taikang Formations (≈ 400 m); and (9) unconsolidated Quaternary sediments (≈ 100 m). The ages and thicknesses of these rocks are used to construct the burial and petroleum generation history of the Qijia–Gulong depression described later in the report. Slightly different ages and thicknesses were assigned to the Qijia–Gulong sedimentary fill by Hu and Krylov (1996) (fig. 2); in particular, they assigned an Early Cretaceous age to the lower 2,400 m of the fill (Huoshiling and Shahezi Formations) and did not recognize fill of Late Jurassic age. Although not labeled on their cross section, the Lower Cretaceous Yingcheng Formation is implied as part of the lower 2,400 m of the fill (Hu and Krylov, 1996). Another difference is that Hu and Krylov (1996) assigned a Late Cretaceous age to the Quantou, Qingshankou, Yaojia, and Nenjiang Formations.

Unconformities were recognized by Hu and Krylov (1996) at the base of the Upper Cretaceous Sifangtai Formation, at the top of the Upper Cretaceous Mingshui Formation, and at the base of the Lower Cretaceous Denglouku Formation (fig. 2), but their magnitude is uncertain because of disputed ages based on nonmarine fauna and terrestrial flora (Gao, 1984). Ages used by Li (1995) indicated that the Upper Cretaceous sequence is thin (only Cenomanian-age strata are present), and this implies that there was perhaps extensive Late Cretaceous erosion (fig. 3A) even though no unconformity was recognized by Li (1995) between the top of the Cenomanian Sifangtai Formation and the base of the Danian (Paleocene) and (or) Maastrichtian Mingshui Formation (fig. 3A). Ma and others (1989), on the other hand, assigned a Late Cretaceous age to the Qingshankou, Yaojia, Nenjiang, Sifangtai, and Mingshui Formations, which could be interpreted to indicate that little Late Cretaceous erosion took place (fig. 3B).

Whether or not a regional unconformity is present at the top of the Sifangtai Formation has significant implications for reconstruction of the burial and petroleum-generation history of the Songliao Basin. Without a regional unconformity between the Sifangtai Formation and the overlying Mingshui Formation (or between the Mingshui Formation and the Paleogene Yian Formation), representing uplift and erosion of 500–1,000 m of unnamed Upper Cretaceous strata, it is difficult to account for significant oil generation from the Qingshankou Formation source rock. Otherwise, an unusually high geothermal gradient ($>50^{\circ}\text{C}/\text{km}$) or thermally immature oil are necessary to account for the large volume of oil in the basin. Using the stratigraphy of Li (1995) (fig. 3A) and the large hiatus implied by Danian-age strata overlying Cenomanian-age strata, we tentatively propose that a regional unconformity representing a period of 29 million years exists between the Sifangtai and Mingshui Formations (fig. 3C). Late Cretaceous–Tertiary tectonic inversion in the Songliao Basin documented by Song (1997) and by Hu and others (1998) supports either this proposed unconformity or one of similar magnitude between the Mingshui and Yian Formations. Either unconformity could account for the erosion of 500–1,000 m of Upper Cretaceous strata.

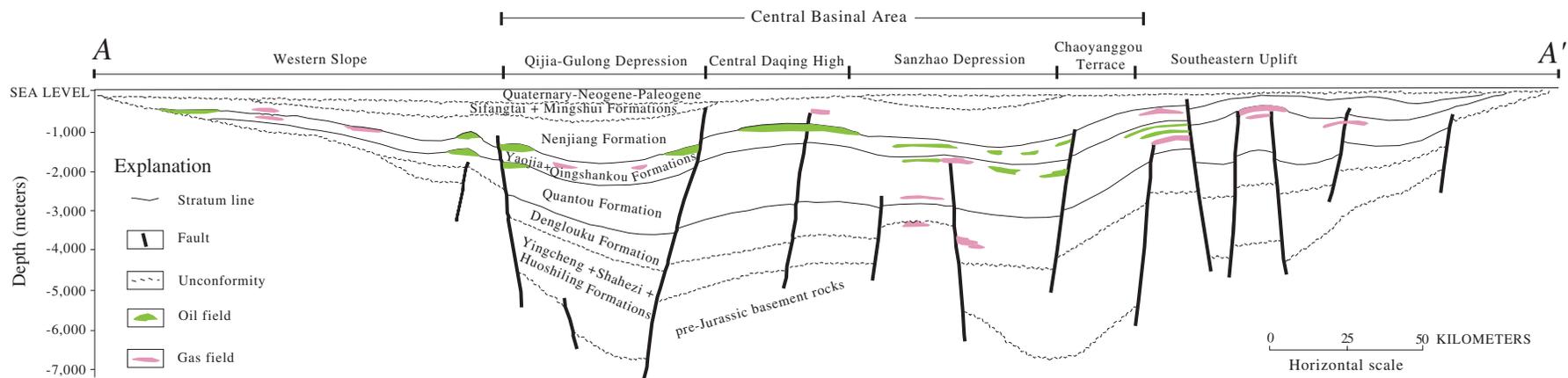


Figure 2. Cross section through the Songliao Basin, China (modified from Hu and Krylov, 1996).

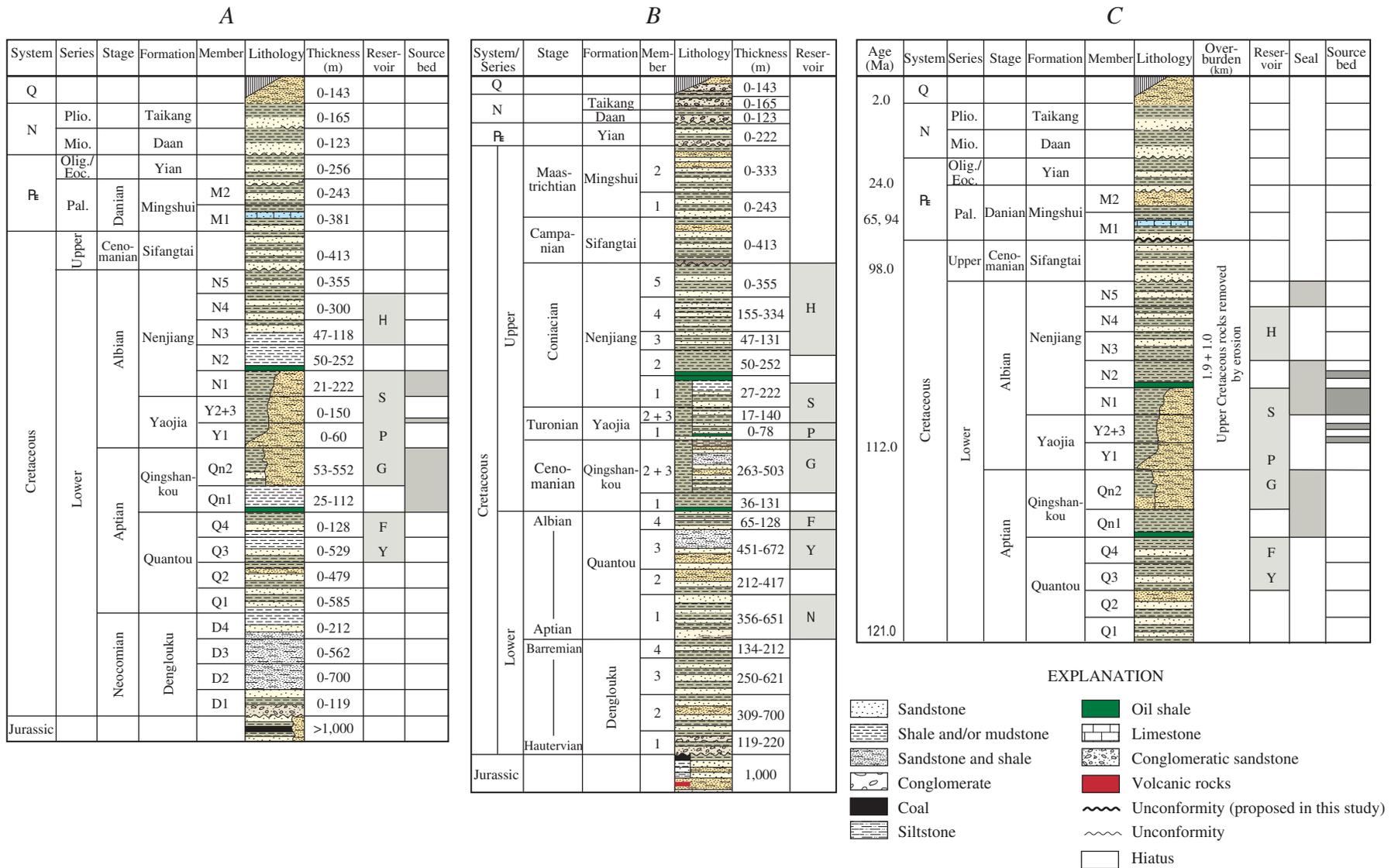


Figure 3. Stratigraphic column for the Songliao Basin, China: *A*, from Li (1995); *B*, from Ma and others (1989); *C*, modified from Li (1995) to show the essential elements of the Qingshankou-Putaohua/Shaertu petroleum system. Reservoir groups: H, Heidimiao; S, Shaertu; P, Putaohua; G, Gaotaizi; F, Fuyu; Y, Yangdachengzi; N, Nongan. Symbols or abbreviations for geologic time: Q, Quaternary; N, Neogene; P_e, Paleogene; Plio., Pliocene; Mio., Miocene; Olig., Oligocene; Eoc., Eocene; Pal., Paleocene.

Exploration History

Petroleum exploration began in the Songliao Basin in 1955. Oil was discovered in 1959 at Daqing-Gaotaizi and Fuyu fields, where accumulations are trapped in large faulted anticlines. Within the next four years the remaining six oil fields in the giant Daqing complex were discovered, in addition to several major fields in the central basinal area and some small fields in the western slope (fig. 1; table 1). These discoveries, most of which occurred in faulted anticlines, were the result of an intensive exploration program between 1958 and 1963 that included the acquisition of 42,000 line km of seismic data and the drilling of approximately 240 exploration wells (Zhang, 1984). Many of the exploration wells drilled in the next 20 years (1964–83) tested subtle traps, particularly faulted anticlinal noses in combination with sandstone pinchouts. Consequently, approximately 29 oil and gas fields were discovered in the central basinal area, western slope, and southeastern uplift (fig. 1; table 1). In the last decade and a half approximately eight small gas fields and five large to small oil fields have been discovered, mainly in the central basinal area (tables 1, 2). Several of these oil and gas fields produce from Lower Cretaceous sandstone reservoirs (for example, Nongan) that are older and deeper than the usual reservoirs in the basin (table 2). Exploration in the 1990s, in addition to drilling for older and deeper targets, began a shift to structural domains outside the traditional central basinal area, such as the Kailu depression (fig. 1). To date, approximately 81 oil and (or) gas fields have been discovered in the Songliao Basin (fig. 1; tables 1, 2). An estimated 17.6 BBOE of ultimately recoverable oil and associated gas (<0.3 BBOE) had been discovered through 1996 (tables 1, 2). Exploration and production programs in the basin are divided between the Daqing Petroleum Administrative Bureau (north half of the basin) and the Jilin Petroleum Administrative Bureau (south half of the basin). The Liaohe Petroleum Administrative Bureau is responsible for oil and gas exploration in the Kailu depression (southwestern end of the basin).

Ulmishek (1993) suggested that numerous small undiscovered oil fields remain in the Songliao Basin, but the expected increase in total resources would be no more than several percent of those discovered to date. In the 1994 U. S. Geological Survey World Energy Assessment (Masters and others, 1998), undiscovered conventional oil and gas resources in the Songliao Basin are estimated, at a mean value, to be 2.3 billion barrels of oil and 13 trillion cubic feet of gas, respectively.

Qingshankou-Putahua/Shuertu Total Petroleum System (314401)

Petroleum Occurrence

Of the approximately 81 oil and (or) gas fields discovered to date in the Songliao Basin (fig. 1; tables 1, 2), at

least 63 are associated, either fully or in part, with the Qingshankou-Putahua/Shaertu petroleum system (tables 1, 2). The majority of the 63 fields are located in the central basinal area (48), with the remainder located in the western slope (8), southeastern uplift (6), and northeastern uplift (1). Reservoir intervals, listed in ascending order, are the Yangdachengzi, Fuyu, Gaotaizi, Putahua, Shaertu (Saltu), and Heidimiao (fig. 3A–C). All are stratigraphically within about 650 m of the Qingshankou Formation and Nenjiang Formation (Member 1) source-rock complex. The 65- to 100-m-thick Fuyu reservoir interval directly underlies the Qingshankou Formation source rock, whereas the 250- to 500-m-thick Gaotaizi reservoir rocks intertongue with the upper part of the Qingshankou Formation. Both reservoir intervals are in conformable contact with the Qingshankou Formation source rock. The 450- to 650-m-thick Yangdachengzi reservoir interval is transitional with, and directly underlies, the Fuyu reservoir. The ≈10- to 78-m-thick Putahua reservoir, one of the primary reservoirs in the petroleum system (Xu and Wang, 1980; Yang, 1985), disconformably overlies the Gaotaizi reservoir interval and the top of the Qingshankou Formation source rock (fig. 3). The other primary reservoir, the 50- to 350-m-thick Shaertu reservoir (Xu and Wang, 1980; Yang, 1985), has a lower part that conformably underlies the Nenjiang Formation (Member 1) source rock and an upper part that is a lateral equivalent (fig. 3A, B). The Heidimiao reservoir, youngest of the reservoir intervals, conformably overlies Member 2 of the Nenjiang Formation approximately 50–250 m above the Nenjiang (Member 1) source rock (fig. 3A, B).

Reasonably consistent API gravity values (≈30–35°), sulfur content (≈0.05–0.23 percent), high paraffin content (≈12–30 percent), and gas-oil ratios (GOR ≈50–300 ft³ of gas/barrel of oil) (Meyerhoff and Willums, 1976; Yang and others, 1984; Petroconsultants Inc., 1996) indicate that oils in the Songliao Basin are similar to each other. Moreover, about 50 crude oils in the basin—analyzed by a variety of geochemical techniques—show similar triterpane, sterane, pristane/phytane, n-alkane, and δ¹³C distributions (Gao and Liu, 1984; Kong, 1984; Li and others, 1987). The majority of these analyzed Songliao Basin crude oils are distributed among the Yangdachengzi, Fuyu, Gaotaizi, Putahua, Shaertu, and Heidimiao reservoirs and appear to have been derived from the same or geochemically similar source rocks.

Two distinct petroleum systems (Qingshankou-Putahua and Nenjiang-Shuertu) are implied by the investigation of Li and others (1987), based on subtle biomarker distributions from 23 crude oils. Li and others (1987) suggested there has been little mixing between stratigraphic levels of the Songliao Basin oils because of an observed positive correlation between the thermal maturity of these oils, based on biomarker distributions, and the age of the associated reservoirs. They (Li and others, 1987) speculated that the mature oils were generated from the Qingshankou Formation (Member 1) source rock, whereas the least mature oils were generated from the Nenjiang Formation (Member 1) source rock. Oil generated from the Qingshankou Formation source rock is thought to have migrated stratigraphically downward into the Fuyu and

Yangdachengzi reservoirs and stratigraphically upward into the Gaotaizi and Putaohua reservoirs, and possibly into the Shaertu reservoir; in contrast, most of the oil in the Shaertu reservoir and all of the oil in the Heidimiao reservoir is thought to have migrated from the Nenjiang Formation (Member 1) source rock (Li and others, 1987).

The Qingshankou and Nenjiang (Member 1) Formations are considered in this report to be excellent source rocks, but whether or not they constitute separate, easily recognizable petroleum systems cannot be established because of subtle geochemical differences between the oils (Gao and Liu, 1984; Li and others, 1987) and the small number of published analyses. At least 100 additional oil analyses, distributed among the six reservoirs and numerous fields, probably would be required to supplement the excellent data set of Li and others (1987) before the Qingshankou-Putaohua/Shuertu of this report can be realistically subdivided into Qingshankou-Putaohua and Nenjiang-Shuertu petroleum systems. Even if these petroleum systems could be separated on the basis of oil geochemistry, their fundamental processes of generation, expulsion, migration, entrapment, and preservation of petroleum are so similar that the assessment of the basin's oil and gas resources probably would not be improved.

Most of the oil in the Qingshankou-Putaohua/Shuertu petroleum system was generated in the Qijia-Gulong, Sanzhao, and Changling depressions of the central basinal area of the Songliao Basin and migrated updip into the growing central Daqing high and adjoining western slope and southeastern uplift (fig. 1) (Yang, 1985). Migration paths were relatively simple and appear to have involved minimal vertical and downward movement of oil into sandstone reservoir beds before short-range, lateral secondary migration occurred (Yang, 1985; Li and others, 1987). The distance of lateral migration commonly ranged from 10 to 50 km (Yang, 1985), but numerous traps probably were filled directly by locally derived oil.

Approximately 99 percent (≈ 17.4 BBOE) of the known, ultimately recoverable 17.6 BBOE in the Songliao Basin is in the Qingshankou-Putaohua/Shuertu petroleum system. Of this total amount, approximately 12.1 BBOE (69 percent) has been identified in the Putaohua and Shaertu reservoirs.

Source Rocks

The Qingshankou Formation, the primary source rock in the Qingshankou-Putaohua/Shuertu total petroleum system, is Early Cretaceous (Aptian) in age and represents about 5 million years of geologic time (figs. 3C). Also, because of its fundamental importance to the total petroleum system, the Qingshankou Formation source rock is identified on the events chart (fig. 4). Member 1 of the Nenjiang Formation, the second most important source rock, is Early Cretaceous (Albian) in age and represents about 3 million years of geologic time (figs. 3C, 4). Minor source rocks are thin black shale and mudstone units in Members 1–3 of the Yaojia Forma-

tion and Member 2 of the Nenjiang Formation (Zhang, 1984; Yang and others, 1985; Li, 1995) (fig. 3C). The Qingshankou Formation and Nenjiang Formation (Member 1) source rock units extend across about 87,000 km² and 100,000 km² of the Songliao Basin, respectively (Yang and others, 1984), which areas include most of the central basinal area and major parts of the western slope, northeastern uplift, and southeastern uplift (fig. 5). Black shale and mudstone of deep-water, eutrophic lacustrine origin constitute most of these source rock units. Ye and Wei (1996) and Schwans and others (1997) suggested that marine water invaded the lacustrine environment during maximum stages of lake expansion and partly influenced the deposition and composition of the lacustrine black shale and mudstone. Abundant organic matter in the source rocks is dominated by algae and bacteria that accumulated in the deeper anaerobic parts of the lake (Yang and others, 1985). Terrestrial plants thrived in the areas surrounding the lake and contributed additional organic matter to its shallow-water margins. The thickness of the Qingshankou Formation source rock exceeds 500 m (fig. 5), whereas the thickness of the Nenjiang Formation (Member 1) source rock ranges from about 27 to 222 m (Lee, 1986; Li, 1995) (fig. 3C).

Total organic carbon (TOC) content of the Qingshankou Formation (Qn1+Qn2) and Nenjiang Formation (N₁) (fig. 3A) ranges from 1.5 to 8.4 percent and averages 2.5 percent (Qn1), 1.5 percent (Qn2), and 2.9 percent (N₁) (Zhang, 1984; Yang and others, 1985; Li and others, 1987; Li, 1995). The hydrogen index (HI), in milligrams of hydrocarbons per gram of organic carbon (mgHC/g orgC), for Qn1, Qn2, and N₁ ranges from about 200 to 900 (Yang and others, 1984; 1985). Type I (>650 HI) and type IIA (450–650 HI) varieties constitute 85–90 percent of the kerogen in the Qn1, Qn2, and N₁ source rocks (Yang and others, 1985). The pod of thermally mature source rock (%R_o=0.5–2.0) associated with the Qn1 and Qn2 source rock is confined to the central basinal area and a small part of the western slope (Yang, 1984) (fig. 6). Because the Nenjiang Formation (N1) is less deeply buried, its thermally mature part is located within the pod of mature source rock shown for Qingshankou Formation (figs. 6 and 7).

Oil-source rock correlations based on biomarker distributions (isoprenoids + others) and $\delta^{13}\text{C}$ data indicate that the Qingshankou Formation is the predominant source rock for oils in the Yangdachengzi, Fuyu, Gaotaizi, and Putaohua reservoirs, whereas the Nenjiang Formation (Member 1) is the predominant source rock for oils in the Heidimiao reservoir (Gao and Liu, 1984; Kong, 1984; Li and others, 1987). There is some disagreement regarding the predominant source rock for oils in the Shaertu reservoir, with Gao and Liu (1984) and Li and others (1987) favoring the Nenjiang Formation (N1) as the source and Kong (1984) favoring the Qingshankou Formation. On the basis of the available geochemical data, we consider both the Nenjiang and Qingshankou Formations to be important source rocks for Shaertu reservoir oils, but we suggest that the Qingshankou Formation was predominant because of its overall higher thermal maturity. Additional factors favoring both formations as major active source rocks in the Songliao Basin

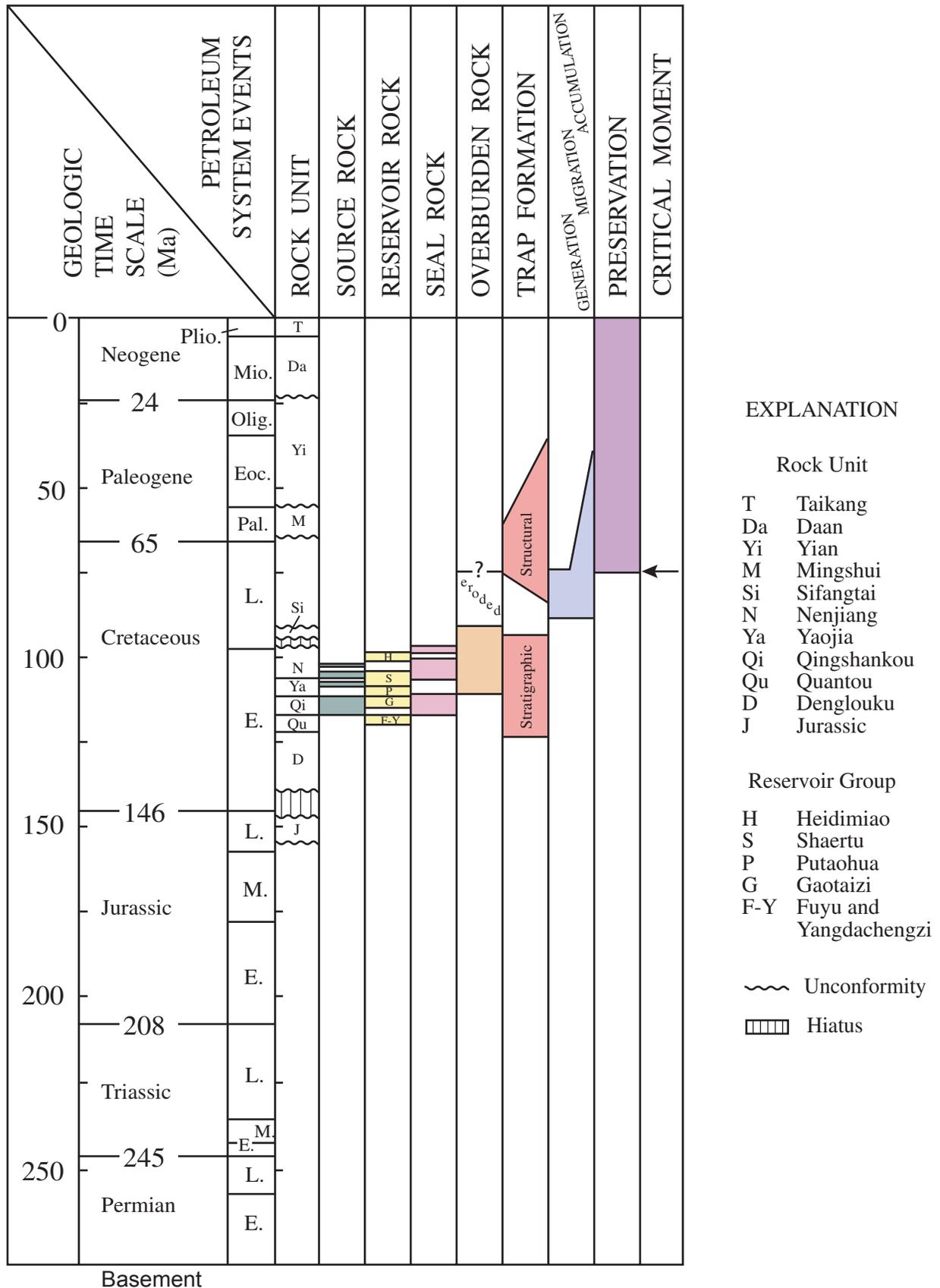


Figure 4. Events chart for the Qingshankou-Putahua/Shuertu total petroleum system. Abbreviations: Plio., Pliocene; Mio., Miocene, Olig., Oligocene; Eoc., Eocene; Pal., Paleocene; E., Early; M., Middle; L., Late.

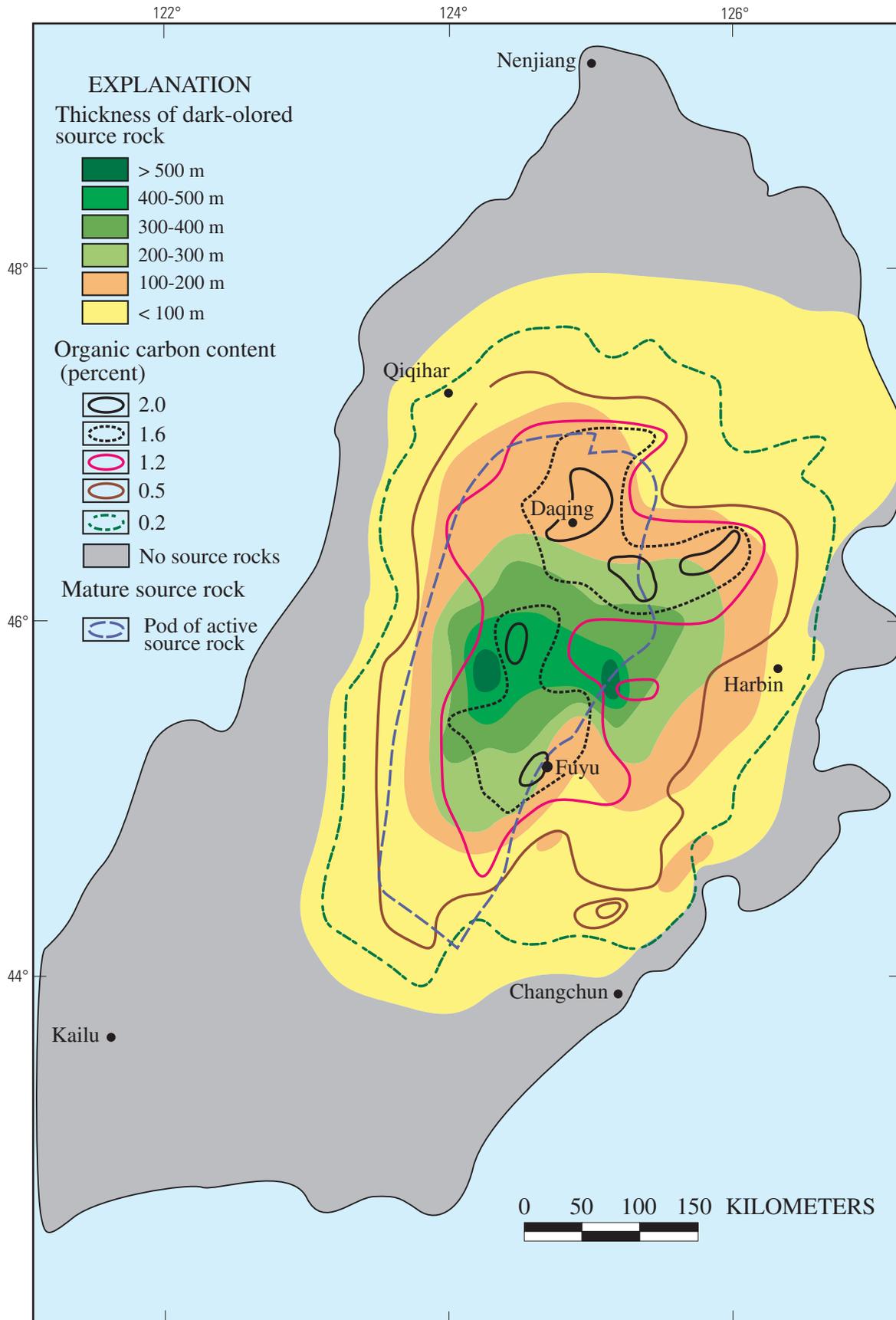


Figure 5. Distribution, thickness, and organic carbon content of the Qingshankou Formation source rocks.

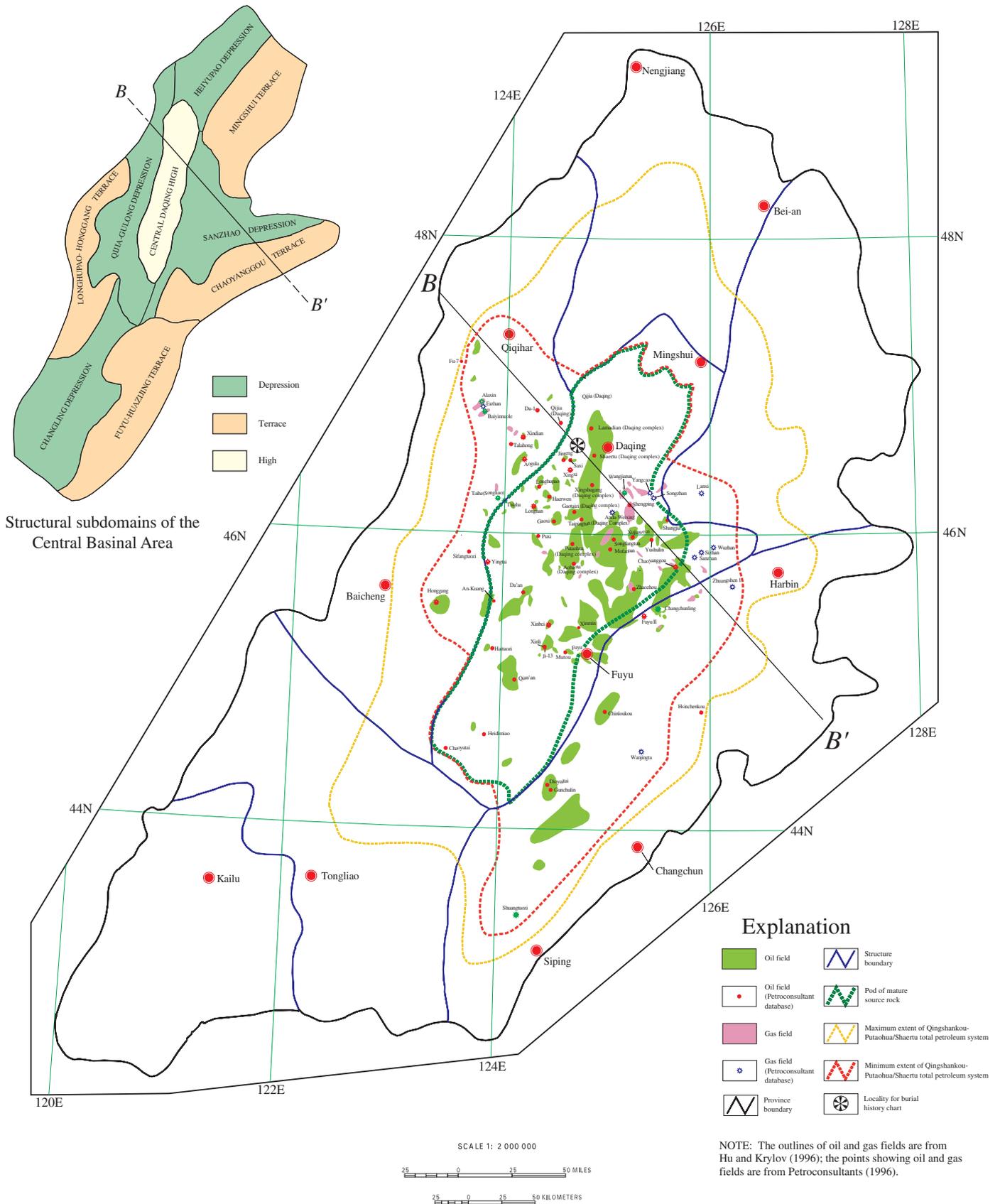


Figure 6. The Qingshankou-Putahua/Shuertu total petroleum system in the Songliao Basin, China. Cross section B–B' is shown on figure 9. (For a larger version of this figure, [click here.](#))

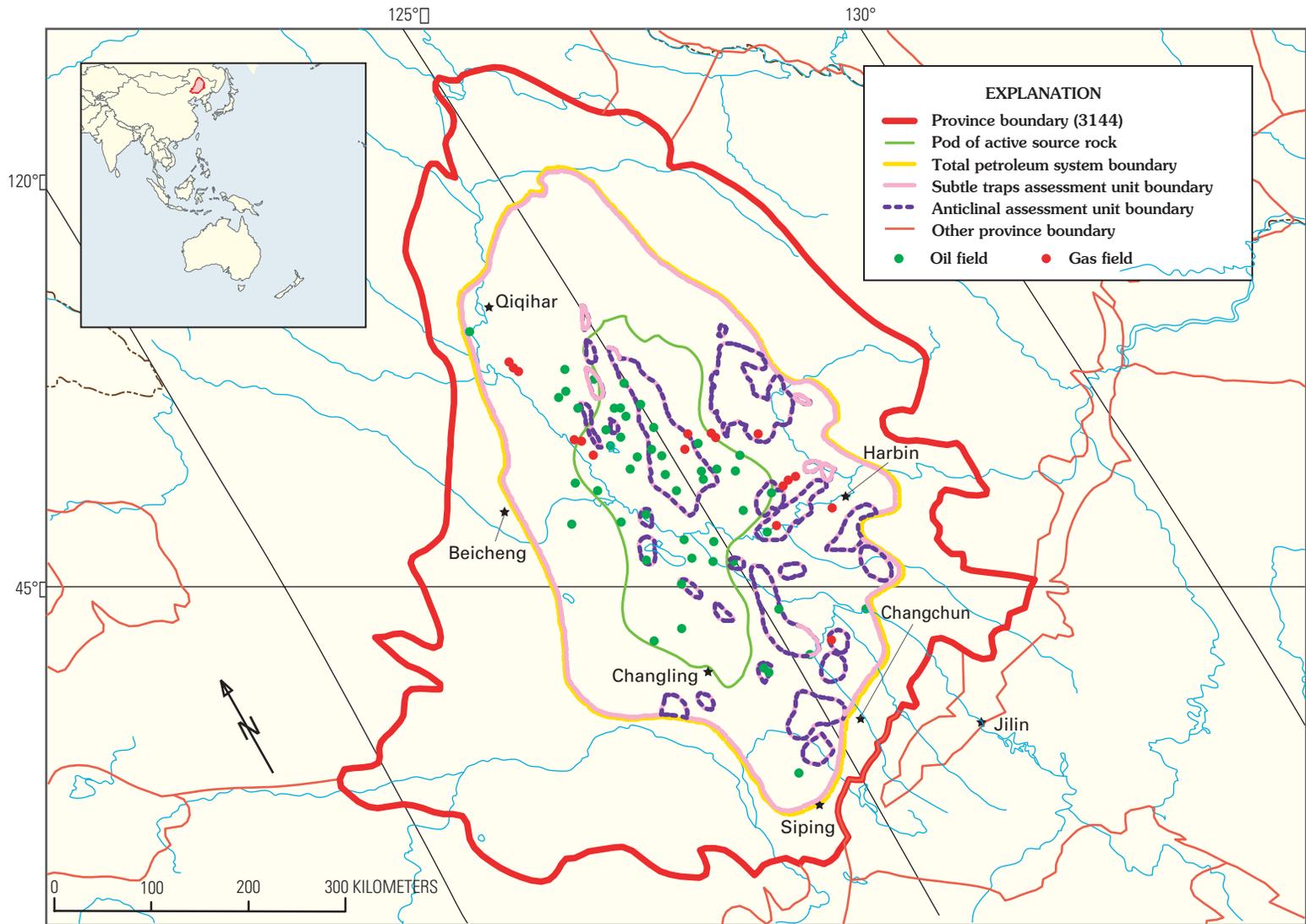


Figure 7. The Qingshankou-Putaohua/Shuertu total petroleum system in the Songliao Basin province 3144 with anticlinal assessment unit 31440102 (regions of anticlinal closure) and subtle traps assessment unit 31440101 (entire region between anticlines).

are their high HI values, thermal maturation indices in the oil-generation “window” ($\%R_o=0.5-1.0$), and close proximity to large oil fields (Yang and others, 1985). As discussed in the “Petroleum Occurrence” section, these source rocks probably belong to separate petroleum systems, but as yet there is insufficient analytical data on oils and source-rock extracts to adequately define them. In this report the Qingshankou Formation is recognized as the predominant source rock in the Qingshankou-Putahua/Shaertu petroleum system.

Overburden Rocks

On the basis of a model for burial history and hydrocarbon generation, we conclude that the critical moment for the Qingshankou-Putahua/Shaertu petroleum system occurred in late Campanian time (≈ 75 Ma) (figs. 4, 8; table 3). The critical moment would be slightly younger if the onset of the Nenjiang Formation (N1) oil generation were accounted for in the burial history chart (fig. 8). Overburden rocks at the critical moment for the Qingshankou Formation, in ascending order, consist of the Yaojia, Nenjiang, and Sifangtai Formations (fig. 3) and unnamed Upper Cretaceous strata removed by post-Late Cretaceous uplift and erosion. The Lower Cretaceous Yaojia and Nenjiang Formations were deposited in, and peripheral to, a large lacustrine system that expanded and contracted across the center of the Songliao Basin. Dark-gray to black shale and mudstone, commonly containing abundant organic matter, characterize the deposits near the center of the lake, whereas coarse-grained siliciclastic rocks (siltstone, sandstone, and conglomerate) and associated mudstone characterize the deltaic, interdeltic, and littoral deposits along the margins of the lake and braided fluvial, alluvial-plain, and alluvial-fan deposits at the basin margins. The siliciclastic rocks vary from gray to green to red; in general, red beds are most common in alluvial-plain and alluvial-fan settings where prolonged subaerial exposure occurred. The Upper Cretaceous Sifangtai Formation, deposited during the waning stages of the basin-centered lacustrine system, is characterized by green, gray, and red mudstone, siltstone, and local sandstone.

Overburden rocks at the critical moment for the Qingshankou Formation source rock reached a maximum thickness of about 3,000 m in the Qijia-Gulong depression (figs. 8, 9). Moreover, approximately 2,500 m of overburden rock accumulated above the Qingshankou Formation in the Sanzhao depression (figs. 8, 9). An estimated 1,000 m of overburden rock, now removed because of a 10-million-year-old period of Late Cretaceous (mid-Campanian through Maastrichtian) uplift and erosion, constitutes about one-third of the total overburden rock in the Qijia-Gulong and Sanzhao depressions (figs. 3, 8; table 3). The overburden rock thins to less than several hundred meters at the outer margins of the western slope and southeastern uplift because of depositional thinning and erosional truncation.

According to one of the models for burial history and petroleum generation produced for this study, the presence

of 1,000 m of Upper Cretaceous strata in addition to what is now present, combined with a 45 °C/km geothermal gradient, would result in the expected high rates of oil and gas generation from the Qingshankou Formation source rock occurring between 85 and 75 Ma. In contrast, another model using only 500 m of eroded Upper Cretaceous rocks but with the same geothermal gradient results in much less oil generation and no gas generation. Similar conclusions were reached by Yu and others (1997) in their burial and thermal history models of the Songliao Basin. Also, the 45 °C/km geothermal gradient used in the model for burial history and petroleum generation (fig. 8) is consistent with the 46.6 °C/km geothermal gradient calculated by Wang and Xing (1991) from fluid inclusions in the Sanzhao depression.

Not all investigations have concluded that $\approx 1,000$ m of Late Cretaceous uplift and erosion are necessary to account for major oil generation from the Qingshankou Formation. For example, using biomarker distributions, Li and others (1987) reported that Songliao Basin oils have an unusually low maturity and that the source rocks for the oils do not exceed a $\%R_o$ value of 0.7. Thus, peak oil generation may have occurred at a lower thermal maturity than predicted by normal kinetic reactions. Hou and others (1999) suggested that a stage of relatively high salinity in the deposition of the Qingshankou Formation may account for the apparent lower maturation levels in its oils. One problem with the idea of immature Qingshankou oils is that $\%R_o$ values at least as high as 0.93 have been reported for the Qingshankou Formation (Zhou and Littke, 1999). In another example, Zhou and Littke (1999) simulated significant oil generation from the Qingshankou Formation in early Tertiary time (Paleocene-Eocene) by using kinetic parameters different from those used in this study (fig. 8) and variable heat flow/time across the basin. Although that model permits oil generation without significant removal of overburden, it does not account for the large volumes of oil found in the basin (Zhou and Littke, 1999). Thus, the thickness of overburden rock at the time of major oil generation (critical moment) from the Qingshankou source rock remains conjectural. The key question is whether or not large volumes of oil can be generated from Type I kerogen at a burial depth of about 2,000 m combined with a slightly elevated geothermal gradient.

Trap Styles for Oil and Gas Fields

Late Cretaceous and early Tertiary compressional tectonics in the Songliao Basin created numerous faulted anticlines, domes, and anticlinal noses, and also produced discreet fault blocks (Song, 1997; Hu and others, 1998). These structures, either by themselves or in combination with pinchouts of nearshore lacustrine and fluvial sandstone, formed most of the traps in the Qingshankou-Putahua/Shaertu petroleum system. Additional anticlines were formed by differential compaction over horst blocks and to a lesser extent by differential compaction over high concentrations of sandstone. The largest

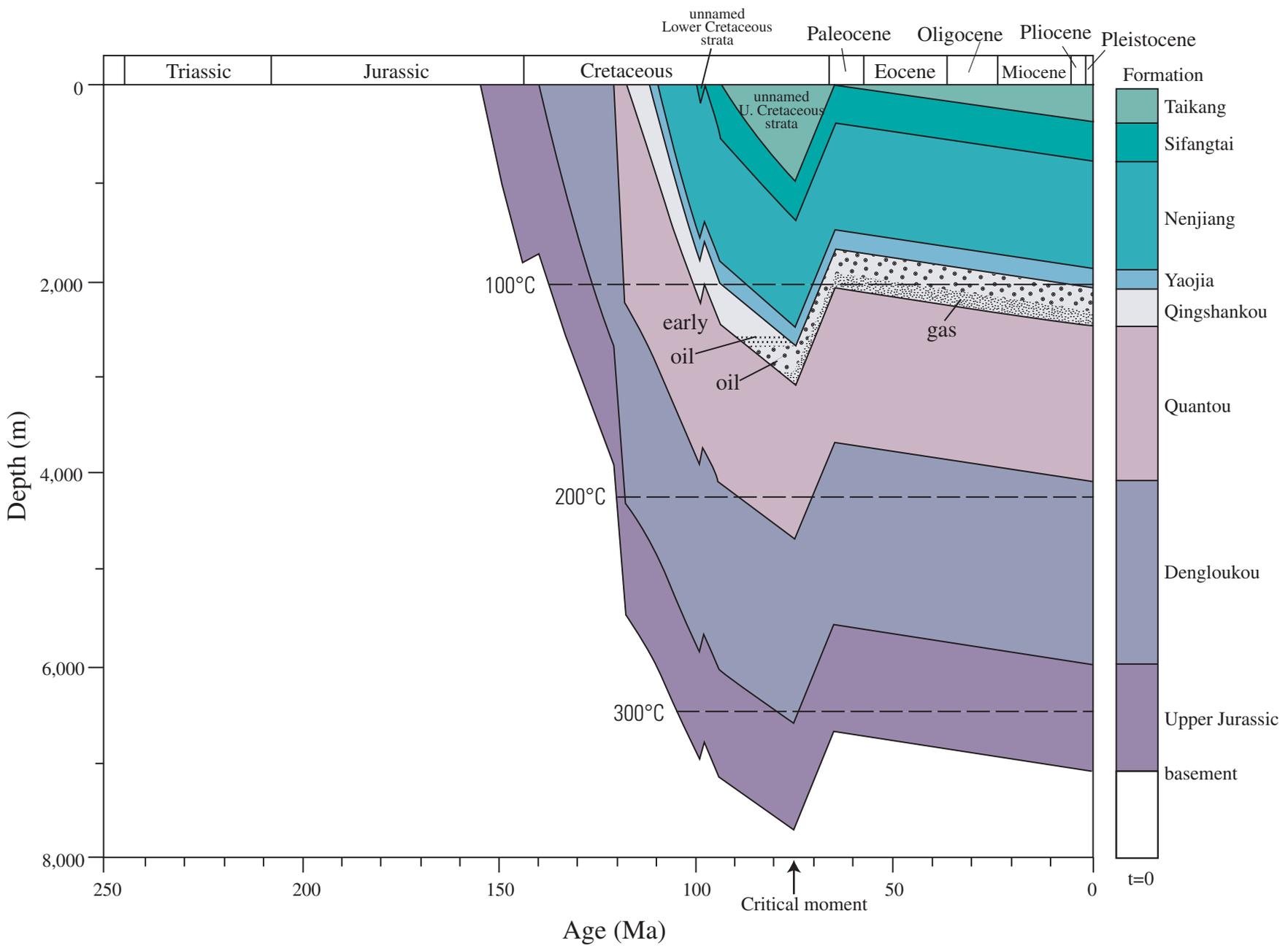


Figure 8. Burial history chart for the Qingshankou-Putaohua/Shuertu total petroleum system, Qijia-Gulong depression, Songliao Basin, China.

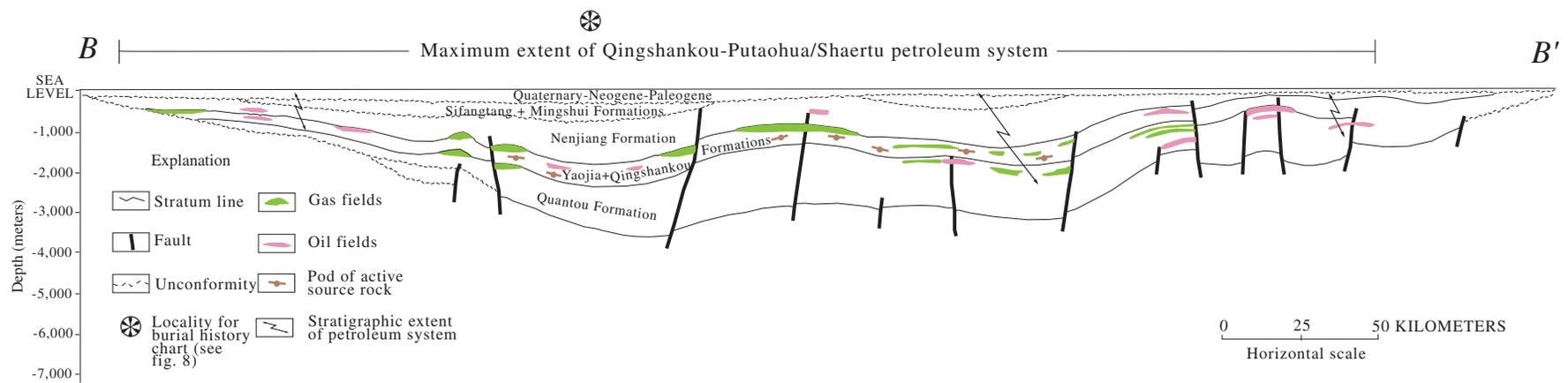


Figure 9. Cross section through the Qingshankou-Putahua/Shuertu total petroleum system in the Songliao Basin, China (modified from Hu and Krylov, 1996).

structural traps have retained their integrity since they formed in Late Cretaceous and early Tertiary time. Locally, structural traps probably were modified by minor Neogene compression causing remigration of hydrocarbons and new sites of entrapment. Stratigraphic traps were established by the end of the Early Cretaceous, but optimum trapping conditions probably were not established until lateral seals were more deeply buried in the Late Cretaceous. Overall, such traps as those formed by facies changes, paleotopography, unconformities, and diagenesis are small and subtle in comparison to the structural traps and, thus, are of secondary importance in known and undiscovered fields.

Oil and (or) gas fields discovered to date in the Qingshankou-Putaoehua/Shaertu petroleum system are shown in figure 6. The trap type for each field is noted in table 1. These fields and the pod of active source rock define the minimum extent of this petroleum system, an approximately 65,000-km² area that covers much of the central basinal area and parts of the adjoining western slope, southeastern uplift, and north-eastern uplift (fig. 6). About 118,000 km² is our estimated maximum extent of the petroleum system, based on (1) presence of large anticlinal structures, (2) favorable reservoir and seal rock, (3) areas of low to moderate groundwater recharge, and (4) a relatively short migration distance (within ≈100 km) from the pod of mature source rock.

Most of the major anticlines and domes in the Songliao Basin were likely drilled in the early (1959–70) and middle (1971–82) phases of exploration. Thus, future oil and gas discoveries are expected to occur mainly in anticlinal noses in combination with subtle fault blocks and in stratigraphic traps, such as those formed by facies changes and diagenetic processes, that are difficult to image with reflection seismic methods. Drilling depths to potential traps are less than 2,500 m.

Reservoir Rocks

Reservoir rocks in the Qingshankou-Putaoehua/Shaertu petroleum system primarily consist of very fine grained to fine-grained sandstone deposited in fluvial and deltaic systems on the margins of a large basin-centered lake (Ma and others, 1982; Xia, 1984; Zhang, 1984). Typically, the reservoir sandstone is arkosic arenite (Xia, 1984; Li, 1995) and primary intergranular porosity is the predominant porosity type. The largest of the fluvial and deltaic depositional systems was located at the north end of the lake, where south-flowing rivers discharged coarse-grained detritus derived from uplifted plutonic and metamorphic terranes. This north- to north-north-east-trending, elongate, teardrop-shaped clastic depocenter is aligned with the axial trough of the basin. In general, the narrow northern end of the depocenter is represented by the fluvial-dominated subaerial part of the deltaic depositional system whereas the wider southern end is represented by the lacustrine-dominated part.

In ascending order, six reservoirs are recognized in this petroleum system: Yangdachengzi, Fuyu, Gaotaizi, Putaoehua, Shaertu, and Heidimiao (figs. 3, 4). These broadly defined reservoirs (Ma and others, 1989; Li, 1995) or pay zones (Yang, 1985) are 200- to 500-m-thick sandstone-bearing intervals that coincide with one or more formal stratigraphic units (fig. 3). Net sandstone and pay thickness for each reservoir interval averages about 100–150 m and 20–50 m, respectively. The Putaoehua and Shaertu reservoirs are the primary reservoirs, whereas the Yangdachengzi, Fuyu, Gaotaizi, and Heidimiao reservoirs are secondary.

The majority of the sandstone bodies in the six reservoirs are products of the northern fluvial and deltaic depositional system. Secondary fluvial and deltaic depositional systems are located along the western and southern parts of the lake (Zhang, 1984). Fan deltas are present along the west side of the basin where short, high-gradient streams drained tectonically active uplands (Ma and others, 1982). Few fluvial and deltaic depositional systems are present along the east side of the lake where littoral to shallow-water deposits of siltstone, shale, and mudstone predominate (Ma and others, 1982). General properties of the six reservoirs in this petroleum system are presented in table 4.

Putaoehua reservoir sandstone was deposited unconformably on the Qingshankou Formation across most of the Songliao Basin (Ma and others, 1982, 1989). This marked basinward shift of deltaic and associated littoral, shallow-water lacustrine sandstone across a low-relief erosion surface likely was caused by an abrupt lowering of the lake level (Xue and Galloway, 1993). Detritus from northern and southern fluvial and deltaic depositional systems gradually covered parts of the erosion surface and later was redistributed by an advancing lacustrine shoreline. The northern depositional system contributed the greatest volume of sand to the Putaoehua reservoir. Reworked Putaoehua sandstone in close proximity to underlying lacustrine source rock are important factors that account for its primary reservoir status. The net thickness of the Putaoehua reservoir ranges from 0 to 78 m (Ma and others, 1989; Li, 1995), with a net thickness of sandstone ranging from ≈5 m to 30 m; the thickest sandstone units are found in the northern and southern fluvial and deltaic systems (Ma and others, 1982). The Putaoehua reservoir in the northern fluvial and deltaic system is divided by Ma (1985) into a lower unit (net sandstone ≈0–10 m) and an upper unit (net sandstone ≈0–18 m). Both units consist of fluvial, deltaic, and littoral shallow-water lacustrine facies. In order of basinward progression, subdivisions of the major depositional environments consist of (1) river-mouth subfacies, (2) subaqueous distributary channel subfacies, (3) subaqueous interdistributary channel subfacies, and (4) sheet sandstone subfacies (Ma, 1985). Across most of the southeastern uplift, the Putaoehua reservoir is dominated by siltstone units deposited in a littoral to shallow lacustrine setting (Ma and others, 1982). In the Putaoehua pay zones, porosity ranges from 14 to 33 percent (average ≈27 percent) and permeability ranges from 1 to 1,637 md (average ≈800 md) (Li, 1995; table 4).

Shaertu reservoir sandstone units were deposited in delta-plain and delta-front settings at the margins of a deep perennial lake. This reservoir conformably overlies the Putahua Formation (Member 1 of the Yaojia Formation) and, in turn, is conformably overlain by Member 2 of the Nenjiang Formation. Basinward, the Shaertu sandstone units intertongue with, and gradually are replaced by, source rock deposited in the adjoining perennial lake. The primary source rock interval that intertongues with the upper part of the Shaertu reservoir rocks constitutes Member 1 (N1, fig. 3) of the Nenjiang Formation. Net thickness of the Shaertu reservoir ranges from 44 to 362 m as reported by Ma and others (1989) and from 21 to 372 m as reported by Li (1995). The net thickness of sandstone beds in the lower part of the Shaertu reservoir (Members 2 and 3 of the Yaojia Formation) ranges from 0 in the offshore parts of the lake to between 20 and 50 m in the northern fluvial and deltaic system (Ma and others, 1982). Porosity ranges from 16.5 to 29.4 percent (average \approx 24 percent) in the pay zones, and permeability ranges from 27 to 1,109 millidarcies (md) (average \approx 300 md) (table 4).

Although the six reservoir intervals in the Qingshankou-Putahua/Shuertu petroleum system have been thoroughly explored in the central basinal area and adjoining uplifts, additional exploration is believed to be warranted because (1) the lenticularity and complex intertonguing of the sandstone bodies has made it difficult to map all potential reservoir units; (2) previous drilling has focused on high-quality reservoirs of the northern fluvial and deltaic system and, consequently, many lower-quality reservoirs in the distal parts of the depositional system may have been bypassed; (3) the fluvial and deltaic depocenters along the western and southern parts of the basin, and perhaps even the eastern part of the basin that is dominated by siltstone, are believed to be underexplored; and (4) the older and deeper Yangdachengzi and Fuyu reservoirs have not been explored as intensely as the Gaotaizi, Putahua, Shaertu, and Heidimiao reservoirs.

Seal Rocks

The regional seal rocks in the Qingshankou-Putahua/Shuertu petroleum system consist of widespread lacustrine black shale and mudstone of Member 1 of the Nenjiang Formation (Ulmishek, 1993) and overlying Member 2 of the Nenjiang Formation (Yang, 1985) (figs. 3, 4). Other important seal rocks, consisting of widespread lacustrine black shale and mudstone, are Member 1 and parts of Members 2 and 3 of the Qingshankou Formation (figs. 3, 4). Secondary seal rock of moderately extensive shale and mudstone are located between the Putahua and Shaertu reservoirs and at the top of the Heidimiao reservoir (figs. 3, 4). Also, most seal rocks in this petroleum system are source rock. Numerous local mudstone and siltstone units serve as seals for oil and gas trapped in lenticular sandstone bodies, commonly segregating oil, gas, and water into variously sized discrete pools that have no unified oil-water or gas-water contact (Ma and others, 1982; Ma

1985). Local seals are important for creating updip traps in isolated fault blocks.

Assessment of Undiscovered Petroleum by Assessment Unit

Two major assessment units are defined in the Qingshankou-Putahua/Shuertu petroleum system: (1) an anticlinal assessment unit (31440102) consisting of conventional reservoirs and (2) a subtle traps assessment unit (31440101) consisting of (a) anticlinal noses in combination with fault and stratigraphic traps, (b) stratigraphic traps, and (c) conventional reservoirs. An assessment unit of unconventional reservoirs consisting of low-permeability sandstone, siltstone, and fractured shale may also exist; however, too few reservoir, well, and production data are available for specific definition.

The anticlinal assessment unit consists of oil, associated gas, and nonassociated gas trapped in large anticlines and domes that have structural closure of at least 30 m (fig. 7). Commonly, the crests of the anticlines are cut by numerous transverse, normal faults. Oil fields in the Daqing complex (ultimate recovery = 13.4–14.9 BBOE), whose anticlines exhibit \approx 60 to \approx 310 m of closure, contain approximately 85 percent of the discovered oil in the petroleum system and about 93 percent of the discovered oil in the assessment unit. Other known oil fields of significant size are the Haitouzi, Fuyu, Daan, and Chaoyanggou fields (table 1), several of which (for example, Daan and Qianan; table 1) are in part controlled by facies changes and fracture networks.

The subtle traps assessment unit, the extent of which is shown in figure 7, involves the trapping of oil and (or) gas in anticlinal noses in combination with fault or stratigraphic traps. These anticlinal noses range from subtle to well defined, and they commonly are associated with numerous transverse normal faults. Oil and local gas fields discovered to date in the assessment unit have an ultimate recovery of approximately 1.3 BBOE. Oil fields in anticlinal noses (for example Shenping, Honggang, Yushuling, and Longnan fields; table 1), range in size from 5 to 125 million barrels of oil equivalent (MMBOE) with most being discovered in the middle (1971–82) to late (1983–94) phases of the basin's exploration history. Probably most large and medium accumulations in the anticlinal nose part of the assessment unit have been identified, but undiscovered smaller fields should remain in subtle traps formed by faults and stratigraphic pinchouts with anticlinal noses; such traps should be identifiable on high-resolution 3-D seismic records.

Stratigraphic traps in the subtle traps assessment unit contain oil and (or) gas that accumulated in a variety of stratigraphic traps (facies-change, truncation, diagenetic, and paleotopographic varieties). Such traps are expected to have formed in synclinal structures, or homoclinal structures on the flanks of anticlines, where few exploration holes have yet been drilled. Combination-trap fields such as Daan, Xinli, Qianan, Gaoxi, and Halwen fields have a strong stratigraphic imprint,

which supports the view that the complex facies patterns characterizing the sandstone reservoirs in the Qingshankou-Putaohua/Shuertu petroleum system resulted in the development of traps that are largely stratigraphic. Particularly noteworthy exploration targets are narrow and thick ($\approx 10\text{--}20$ m) sandstone bodies that could have filled deeply incised channels during extreme lake-level lowstands (Xue and Galloway, 1993). These types of sandstone bodies might be most common in the Putaohua reservoir interval.

Low-permeability sandstone and siltstone in the assessment unit of unconventional reservoirs form poor-quality reservoirs at the distal ends of the fluvial and lacustrine delta depositional systems. Reservoir porosity is less than 12 percent (Xia, 1984), and permeability is usually less than 1 md (Xia, 1984). Abnormal fluid pressures (low and high) are common (Wang and Liu, 1997). Wells drilled into these reservoirs typically do not yield natural flows of oil and (or) gas unless they are hydraulically fractured. Also, oil and gas accumulations have poorly defined oil-water and gas-water contacts (Ma and others, 1982). Xia (1984) and Guiming and Yuxin (1996) recognized that the Yangdachengzi and Fuyu reservoirs near the deepest parts of the Songliao Basin (for example, the Sanzhao depression) have the same characteristics and, thus, probably are unconventional reservoirs. Xia (1984) recognized that as recovery technology improves and energy needs increase, unconventional resources eventually will be developed. Very likely, low-permeability sandstone and siltstone reservoirs exist in other reservoir intervals of the Qingshankou-Putaohua/Shuertu petroleum system, including the vast region of littoral and shallow lacustrine siltstone on the southeastern uplift.

Self-sourced oil trapped in fractured lacustrine shale and mudstone constitute an additional part of the assessment unit of unconventional reservoirs. Many of the tectonic fractures probably resulted from rejuvenated fault zones and anticlinal flexures formed during partial basin inversion. Local commercial oil flows from tectonic fractures have been reported in the Talaha, Yingtai, Putaohua, Sanzhao, Xinli, Xinbei, and Daan fields (Ma and others, 1982; Cheng, 1984; Qian, 1984; Petroconsultants, 1996). Although not yet identified in the basin, open fractures caused by tensional stresses accompanying oil-generation processes may be present in structurally low areas such as synclines and troughs.

Because the largest fields in the anticlinal assessment unit were discovered early in the exploration history of the Songliao Basin (1959–63) and because most anticlinal structures already have been drilled, this assessment unit probably has much less remaining potential for conventional undiscovered oil and gas resources than has the subtle traps assessment unit. The majority of the conventional undiscovered oil and gas resources are expected to be in small to medium fields in the subtle traps assessment unit. Undiscovered conventional oil and gas resources in the subtle traps assessment unit (31440101) were estimated by the U.S. Geological Survey World Energy Assessment Team (2000), at the mean value, to be about 735 million barrels of oil and 1.79 trillion ft^3 of gas

(0.24 trillion ft^3 of gas in oil fields and 1.55 trillion ft^3 of gas in gas fields). In comparison, the anticlinal traps assessment unit (31440102) is estimated to contain, at a mean value, about 291 million barrels of oil and 0.71 trillion ft^3 of gas (0.10 trillion ft^3 of gas in oil fields and 0.61 trillion ft^3 of gas in gas fields) (U.S. Geological Survey World Energy Assessment Team, 2000).

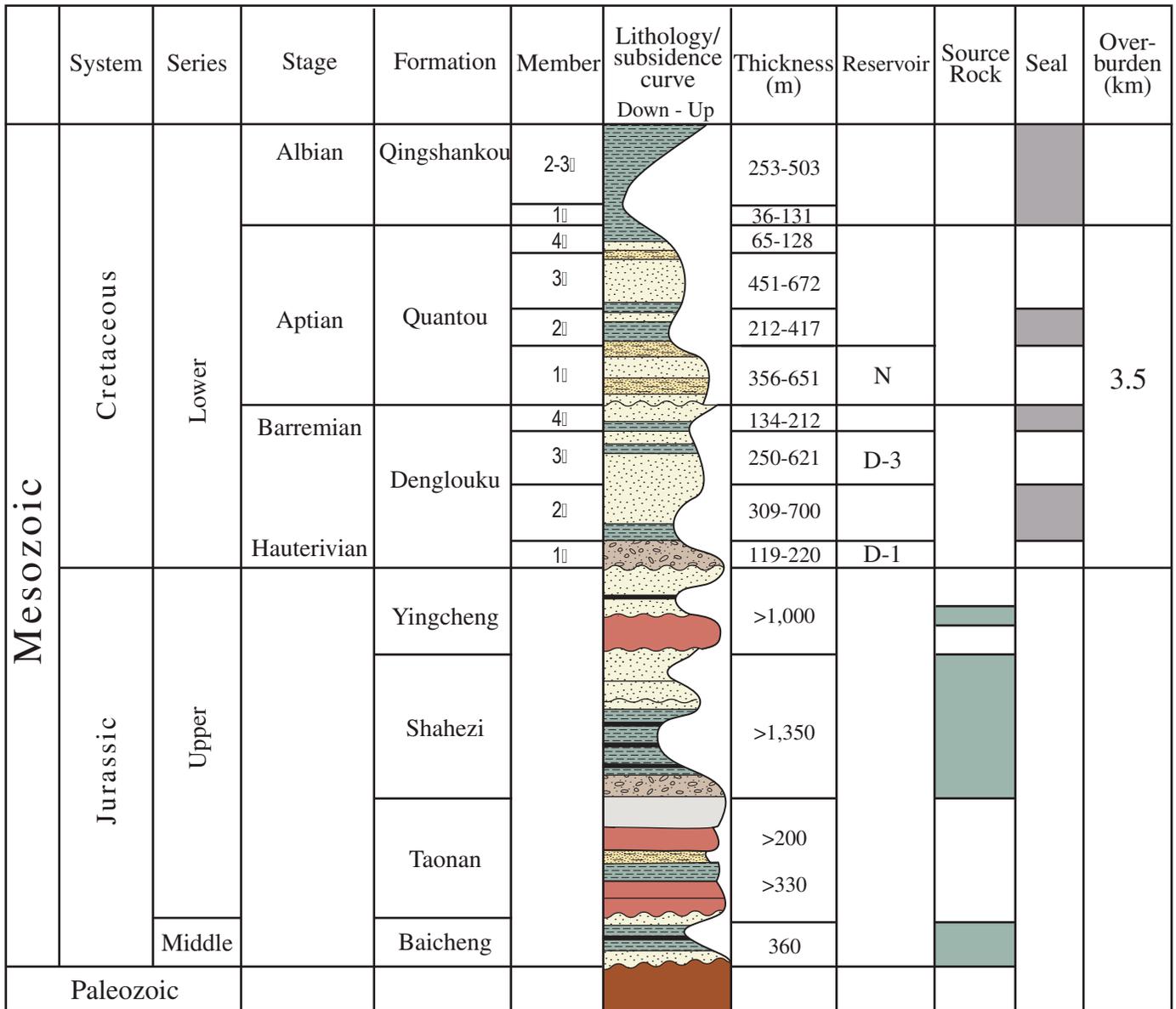
Jurassic Coal–Denglouku/Nongan Total Petroleum System (314402)

Petroleum Occurrence

Of the approximately 81 oil and (or) gas fields discovered to date in the Songliao Basin, at least 10 are affiliated, either fully or in part, with the Jurassic coal–Denglouku/Nongan petroleum system (table 2). Gas fields in the Denglouku Formation, lower part of the Quantou Formation, and pre-Jurassic basement rocks, shown in figure 2, belong to this petroleum system. Coal-bearing sequences of Late Jurassic age, which are the source rocks, are part of the Shahezi and Yingcheng Formations (figs. 2, 10). In this report, a Late Jurassic age (Cao and others, 1990) is adopted for the Shahezi and Yingcheng Formations rather than an Early Cretaceous age (Hu and Krylov, 1996). Of the 10 fields identified in table 2, 7 are in the central basinal area and 3 are in the northeastern uplift (fig. 1). Reservoir intervals, listed in ascending order, are Member 1 of the Denglouku Formation (D–1), Member 3 of the Denglouku Formation (D–3), and Member 1 of the Quantou Formation (N, Nongan reservoir) (fig. 10). The 120- to 220-m-thick D–1 reservoir interval unconformably overlies Upper Jurassic coal-bearing volcanic and sedimentary rocks. The bases of the D–3 and Nongan reservoirs are as much as 900 and 1,700 m, respectively, above the top of the Upper Jurassic coal-bearing sequence.

As noted by the fields listed in table 2, the Jurassic coal–Denglouku/Nongan petroleum system is dominated by nonassociated natural gas that we believe was derived from Jurassic coal beds. Although oil in Jurassic rocks in the Nongan field area suggest that Jurassic oil-prone source rock is present in the basin, Li and others (1987) concluded that probably they were derived from the overlying organic-rich Qingshankou Formation (figs. 3, 5) and migrated downsection or across fault blocks.

Natural gas was generated in numerous north-trending grabens and half-grabens filled with Jurassic coal-bearing volcanic and sedimentary rocks (Yang, 1981; Hu and others, 1998) (fig. 11) and migrated vertically upward, largely along fault zones, into overlying Lower Cretaceous sandstone reservoirs. The close proximity of known gas fields in this petroleum system to the Jurassic coal-bearing grabens indicates minimal lateral migration of the gas (fig. 11). Compressional



EXPLANATION

- | | | |
|-------------------------|-------------------------|--------------------------------|
| Reservoir Group | Sandstone | Volcaniclastic rocks |
| N Nongan | Shale and (or) mudstone | Basalt and (or) andesite flows |
| D-3 Denglouku, Member 3 | Siltstone | Coal |
| D-1 Denglouku, Member 1 | Conglomeratic sandstone | Metamorphic rocks |
| | Unconformity | |

Figure 10. Partial stratigraphic column for the Songliao Basin showing the essential elements of the Jurassic coal–Denglouku/Nongan total petroleum system (314402) (modified from Cao and others, 1990).

structures were not formed until Late Cretaceous and Paleogene time, so much of the coal-derived gas initially accumulated in paleostructures and (or) in stratigraphic traps. Late Cretaceous and Paleogene compression or transpression redistributed a large part of the earlier trapped gas into anticlines and structurally inverted fault blocks.

Less than 1 percent (≈37 MMBOE) of the known ultimately recoverable 17.6 BBOE in the Songliao Basin is in the Jurassic coal–Denglouku/Nongan petroleum system. However, the system is underexplored and additional gas resources are expected to be discovered in deeper, undrilled parts of the basin.

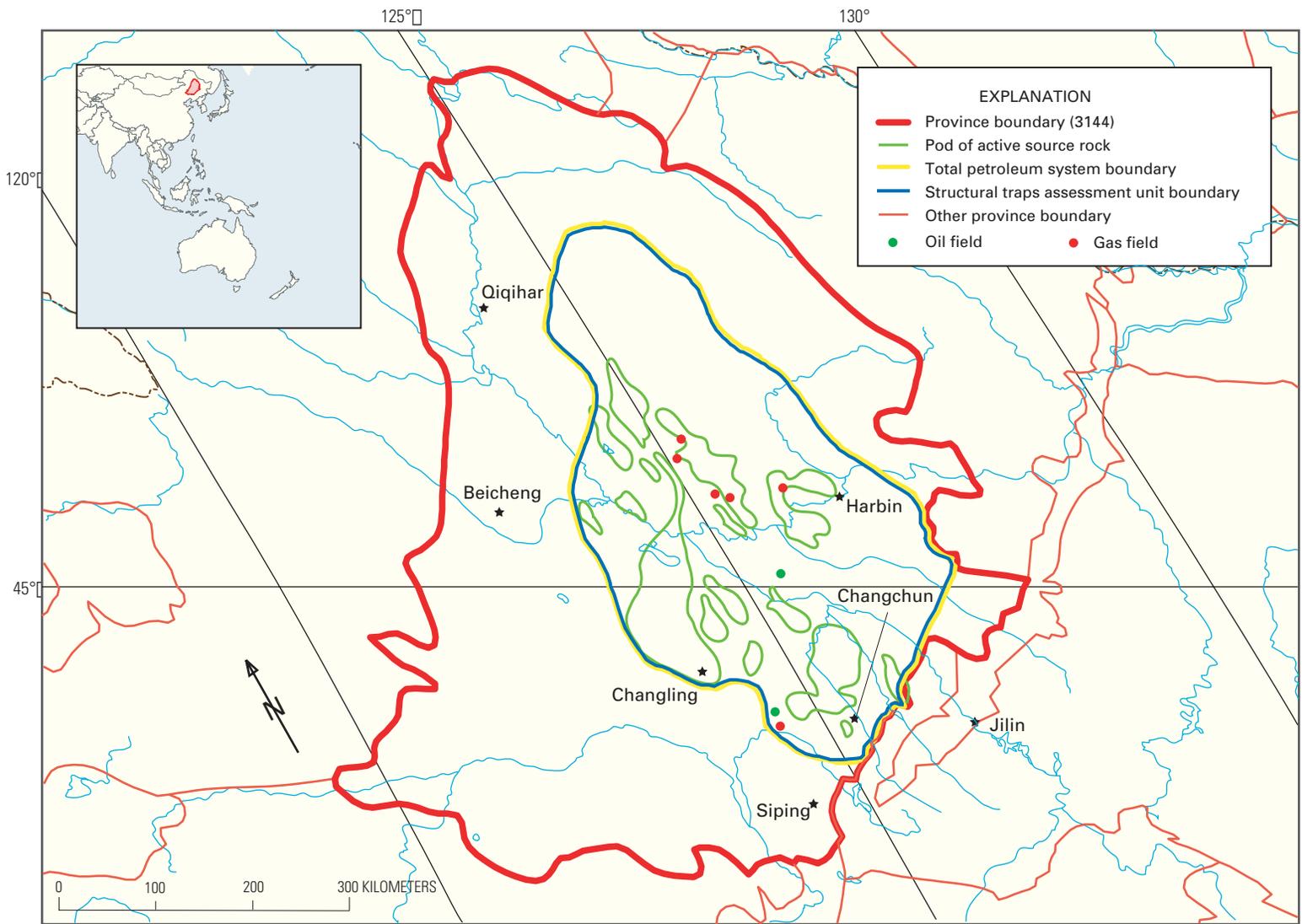


Figure 11. The Jurassic coal–Denglouku/Nongan total petroleum system (314402) in the Songliao Basin province 3144 with structural traps assessment unit 31440201.

Source Rocks

Coal beds in the Upper Jurassic Shahezi and Yingcheng Formations are believed to be the major source rocks in the Jurassic coal–Denglouku/Nongan petroleum system (figs. 10, 12). Because few wells have penetrated Jurassic rocks in the Songliao Basin, the presence of coal in the deep subsurface is largely inferred from commercial coal beds in outcrops of Jurassic rocks on the flanks of the basin (Yang and Shen, 1986; Wang and Hu, 1993; Cheng and others, 1997; Lu and others, 1997). Although petrographic and geochemical data are not readily available, these coal beds are assumed to consist of gas-prone type III kerogen. On the basis of coalification gradients derived from five boreholes, vitrinite reflectance values (R_o) for Jurassic coal beds are predicted to range from 3 to 5 percent in the deepest parts of the Songliao Basin (Wu and others, 1991). Predicted vitrinite reflectance values range from 1 to 3 percent on the flanks of the basin.

Overburden Rocks

The critical moment for the Jurassic coal–Denglouku/Nongan petroleum system occurred approximately in late Aptian time (≈ 118 Ma) (fig. 12). This interpretation is based on the time that the top of the Upper Jurassic sequence reached the 200 °C-isotherm as shown in the burial history chart for the Qijia-Gulong depression (fig. 8). Overburden rocks at that time were the Denglouku and Quantou Formations (fig. 12).

The Lower Cretaceous (Neocomian) Denglouku Formation consists of 1- to 3-km-thick nonmarine, terrigenous clastic strata deposited in a north-trending central graben system that approximately coincides with the present-day central basinal area (Yang, 1981; Zhou and others, 1985) (fig. 1). The basal member of the formation (Member 1) unconformably overlies Jurassic rift deposits and consists of a thick sandy conglomerate sequence of alluvial-fan and fluvial origin, Member 2 contains alternating beds of lacustrine mudstone (locally dark gray) and thick, braided fluvial sandstone, and Members 3 and 4 consist of interbedded massive, braided fluvial sandstone and multicolored (green, gray, purple, black) alluvial-plain mudstone and shale (Yang, 1981; Cao and others, 1990). In addition to being part of the initial post-rift deposits above the central graben system, Members 3 and 4 extended across the east flank of the graben as much as 100 km east of the main depocenter (Yang, 1984; Zhou and others, 1985).

The Lower Cretaceous (Aptian) Quantou Formation is composed of 1- to 2-km-thick, nonmarine, terrigenous clastic strata deposited in a post-rift sag setting. The depocenter coincides with Late Jurassic and earliest Cretaceous (Denglouku Formation) rift-controlled depocenters; however, overall, the Quantou Formation is more widespread and oval shaped in plan view than underlying units of the Denglouku Formation. The progressive expansion of successive members

of the Quantou Formation across the flanks of the basin indicates the beginning of the downwarping stage (post-rift) of the Songliao Basin (Yang, 1981). Members 1 through 3 are dominated by sandstone and conglomeratic sandstone of fluvial and alluvial-fan origin (Cao and others, 1990). The upper member (Member 4) is dominated by finer grained, basin-centered playa and shallow-water lacustrine deposits (Cao and others, 1990).

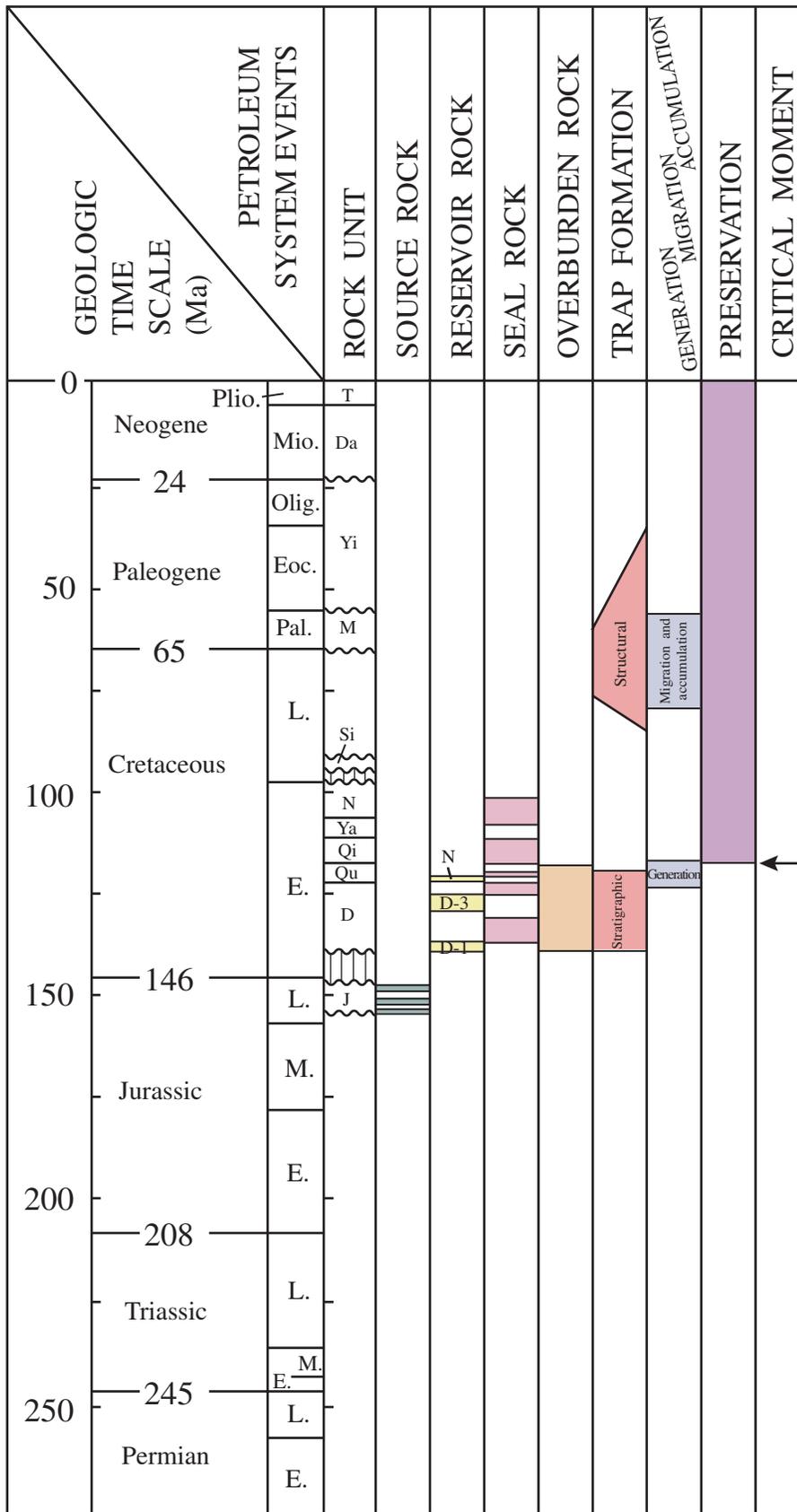
Overburden rocks at the critical moment for the Jurassic coal beds reached a maximum thickness of about 3,500 m ($\approx 4,400$ m uncompact) in the Qijia-Gulong depression (Yang, 1984) (fig. 10; table 3). Moreover, about 2,500 m (3,100 m uncompact) of overburden rock accumulated above the Jurassic coal beds in the Sanzhao depression (fig. 2). The overburden rock sequence thins to less than several hundred meters at the outer margins of the western slope and southeastern uplift because of depositional thinning and erosional truncation.

Trap Styles for Oil and Gas Fields

Late Cretaceous and early Tertiary compressional tectonics in the Songliao Basin created numerous anticlinal and fault-block structures (Song, 1997; Hu and others, 1998) (fig. 12). Such structures, either by themselves or in combination with fluvial sandstone pinchouts, provide most of the traps in the Jurassic coal–Denglouku/Nongan petroleum system. The largest structural traps have retained their integrity since forming in Late Cretaceous and early Tertiary time. Stratigraphic traps were established by the end of Aptian time (fig. 12), but optimum trapping conditions probably were not established until lateral seals were more deeply buried in the Late Cretaceous. Overall, facies-change, paleotopographic, and unconformity types of stratigraphic traps are small and subtle in comparison to the structural traps and, thus, are of secondary importance.

Gas fields discovered to date in the Jurassic coal–Denglouku/Nongan petroleum system are shown in figure 11. The trap type for each field is noted in table 2. These fields and the pods of active source rock define the minimum extent of the petroleum system, an approximately 55,000-km² area that coincides with much of the central basinal area and the adjoining southeastern uplift (fig. 11). About 125,000 km² is our estimated maximum extent of the petroleum system, based on (1) the presence of large anticlinal structures, (2) the presence of favorable reservoir and seal rock, and (3) a distance within ≈ 100 km of the pods of active Jurassic source rock (fig. 11).

Because most of the major anticlines in the Songliao Basin probably have not been drilled into or through the Denglouku Formation, this petroleum system has good potential for undiscovered gas fields. Drilling depths to potential traps are between 2,500 and 4,500 m.



EXPLANATION

- Rock Unit
- T Taikang
 - Da Daan
 - Yi Yian
 - M Mingshui
 - Si Sifangtai
 - N Nenjiang
 - Ya Yaojia
 - Qi Qingshankou
 - Qu Quantou
 - D Denglouku
 - J Jurassic
- Reservoir Group
- N Nongan
 - D-3 Denglouku, Member 3
 - D-1 Denglouku, Member 1
- Unconformity
 Hiatus

Figure 12. Events chart for the Jurassic coal-Denglouku/Nongan total petroleum system. Abbreviations: Plio., Pliocene; Mio., Miocene; Eoc., Eocene; Pal., Paleocene; E., Early; M., Middle; L., Late.

Reservoir Rocks

Reservoir rocks in the Jurassic coal–Denglouku/Nongan petroleum system consist of fine- to coarse-grained sandstone and conglomeratic sandstone deposited in alluvial-fan and braided-fluvial systems associated with the rift stage of basin development. Sandstone reservoirs in the Denglouku Formation and lower part of the Quantou Formation are feldspathic litharenite and lithic arkose (Yang and Li, 1991). Both primary and secondary intergranular and intragranular porosity types characterize the reservoirs, but at depths exceeding 3 km secondary porosity begins to equal or exceed primary porosity (Xing and Jiang, 1990; Yang and Li, 1991).

In ascending order, three reservoirs are recognized: Denglouku, Member 1 (D–1), Denglouku, Member 3 (D–3), and Nongan (N) (figs. 10,12). The basal reservoir (D–1) is between 100 and 200 m thick (Cao and others, 1990), consists of coarse-grained sandstone and conglomeratic sandstone of alluvial-fan and braided-fluvial origin, and is confined to a north-trending graben system near the center of the basin. Coarse detritus was derived from nearby high-standing horst blocks that flanked the central graben system. The D–3 reservoir is a fluvial-sandstone-dominated unit between 250 and 620 m thick (Cao and others, 1990). Most of the D–3 sandstone units occupy the same central graben system that controlled the deposition of the D–1 reservoir. The Nongan reservoir (Member 1 of the Quantou Formation) is a 350- to 650-m-thick, fluvial-sandstone-dominated unit that represents a transition from the rift stage to the downwarping stage of the basin (Cao and others, 1990). The Nongan reservoir covers a slightly larger part of the basin than the Denglouku reservoirs and consists of deposits of two major fluvial systems — one fluvial system drained a northerly source area whereas the other system drained a southerly source area. The Yangdachengzi and Fuyu reservoirs in Members 3 and 4, respectively, of the Quantou Formation may contain natural gas derived from Jurassic coal beds (Hu and others, 1998; table 1). However, until more definitive geochemical data are available we consider natural gas in the Yangdachengzi and Fuyu reservoirs to be largely derived from the Qingshankou Formation (figs. 3, 5).

Gross reservoir interval thickness for the three reservoirs ranges from about 60 to 250 m, whereas pay thickness ranges from about 3 to 44 m (table 5). Porosity ranges from about 5 to 16 percent in the Denglouku Formation reservoirs, and permeability ranges from about 0.03 to 10 md (table 5). In contrast, porosity ranges from about 9 to 20 percent in the Nongan reservoir, and permeability ranges from about 1 to 260 md (table 5). Because of the compositional immaturity of these sandstone reservoirs, they are prone to unusually high porosity destruction, particularly at depths greater than 3,500 m. Xing and Jiang (1990) reported that reservoir porosity at these depths is about 5 percent or less. Thus, natural fractures may be required to improve reservoir quality.

Seal Rocks

The regional seal rock for the Jurassic coal–Denglouku/Nongan petroleum system is the widespread lacustrine black shale and mudstone of the Lower Cretaceous Qingshankou Formation (figs. 10, 12). Other important seal rocks are the mudrock- and shale-dominated Members 2 and 4 of the Denglouku Formation and Member 2 of the Quantou Formation (figs. 10, 12). These fine-grained terrigenous clastic intervals are dominated by floodplain and possibly shallow-water lacustrine deposits.

Assessment of Undiscovered Petroleum by Assessment Unit

A structural traps assessment unit (31440201) is defined in the Jurassic coal–Denglouku/Nongan petroleum system (fig. 11). The unit consists of natural gas trapped in anticlines, domes, anticlinal noses, and fault blocks. Commonly, anticlinal crests and noses are cut by numerous fault systems. Known fields, most of which have been discovered since the middle 1980s, are small (median = 3.3 MMBOE) and have an estimated total ultimate recovery of about 37 MMBOE (Petroconsultants, 1996). As exploration focuses on deeper parts of the Songliao Basin, more gas fields are expected to be found, mostly being small to medium, but some large. Undiscovered conventional gas resources in the structural traps assessment unit (31440201) are estimated by the U.S. Geological Survey World Energy Assessment Team (2000), at a mean value, to be about 3.21 trillion ft³ of gas.

Summary

Approximately 99 percent of the ≈17.6 BBOE of known petroleum in the Songliao Basin are defined by the Qingshankou-Putaoehua/Shaertu total petroleum system. The Lower Cretaceous Qingshankou Formation, consisting of 500–600 m of lacustrine black shale and mudstone, is the primary source rock. The Lower Cretaceous Nenjiang Formation (Member 1), consisting of about 200 m of lacustrine black shale and mudstone, is the second most important source rock. Fine-grained to very fine grained feldspathic sandstone deposited in fluvial and deltaic depositional settings around the margins of the lake constitute the reservoirs. The primary reservoirs are the Lower Cretaceous Putaoehua and Shaertu reservoir intervals, and additional ones are the Lower Cretaceous Yangdachengzi, Fuyu, Gaotaizi, and Heidimiao reservoir intervals. Most of the known oil and gas resources in the petroleum system are trapped in large anticlines (15–16 BBOE) and in anticlinal noses in combination with fault and facies-change stratigraphic traps (1 BBOE). Nearly 15 BBOE trapped in large anticlines of the Daqing complex account for about 85 percent

of the known oil and gas. Two oil and gas assessment units are identified in the Qingshankou-Putaohua/Shuertu petroleum system: (1) an anticlinal assessment unit and (2) a subtle traps assessment unit consisting of anticlinal noses and stratigraphic traps. The anticlinal and subtle traps assessment units involve conventional reservoirs. The U.S. Geological Survey World Energy Assessment Team (2000) estimated, at a mean value, the following undiscovered conventional oil and gas resources for the Qingshankou-Putaohua/Shuertu petroleum system: subtle traps assessment unit (735 million barrels of oil, 1.79 trillion ft³ of gas); anticlinal assessment unit (291 million barrels of oil, 0.71 trillion ft³ of gas).

Less than 1 percent of the ≈17.6 BBOE of known petroleum in the Songliao Basin is defined by the Jurassic coal–Denglouku/Nongan total petroleum system. However, this petroleum system is underexplored and therefore is considered to have good potential for future discoveries of natural gas. Coal-bearing Jurassic sequences are the major source rocks, and the primary reservoirs are the Lower Cretaceous Denglouku Formation (Members 1 and 3) and the Nongan reservoir (Member 1 of the Lower Cretaceous Quantou Formation). Most of the known natural gas in this petroleum system are trapped in anticlinal and fault block fields whose median size (3.3 MMBO) and total ultimate recovery (≈37 MMOE) are small. Approximately 3.21 trillion ft³ of undiscovered conventional gas is expected, at a mean value, in the structural traps assessment unit (U.S. Geological Survey World Energy Assessment Team, 2000).

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