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National and Global Petroleum Resource Assessment Project

Assessment of Paleozoic Shale Gas Resources in the Sichuan Basin of China, 2015

Using a geology-based assessment methodology, the U.S. Geological Survey estimated a mean of 23.9 trillion cubic feet of technically recoverable shale gas resources in Paleozoic formations in the Sichuan Basin of China.

Introduction

The U.S. Geological Survey (USGS) quantitatively assessed the potential for unconventional (continuous) gas resources within organic-rich shales in three Paleozoic stratigraphic intervals in the Sichuan Basin of China (fig. 1). The stratigraphic intervals are the Lower Cambrian Qiongzhusi Formation, the Upper Ordovician and lower Silurian Wufeng and Longmaxi Formations, and the upper Permian Longtan and Dalong Formations (fig. 2). Organic-rich shales of these formations have been demonstrated to be the principal source rocks for conventional oil and gas fields in the Sichuan Basin (Ryder and others, 1994; Dai and others, 2008; Borjin and others, 2014). Since 2008, there have been numerous investigations and tests of shale gas potential of Cambrian, uppermost Ordovician, and lower Silurian shales in the Sichuan Basin (Zou and others, 2010). Commercial production of shale gas from the Silurian Longmaxi Formation in the southeastern foldbelt (east of Chongqing, fig. 1) has been ongoing since late 2012 (Guo and Zhang, 2014; Guo, 2015).

The organic-rich shales of the Qiongzhusi, Wufeng, and Longmaxi Formations were deposited in deep marine depocenters on the continental shelf off the South China continental block and near the early Paleozoic Gondwana margin. The shales presently contain up to 8 weight percent of Type II organic matter, averaging between 1 and 5.5 weight percent (Zou and others, 2010). The Longtan Formation is generally recognized as a coal-bearing marginal marine to deltaic source rock but has been demonstrated to contain a substantial organic-rich deep marine facies that contains Type II organic matter. The Longtan Formation has also sourced significant conventional oil and gas accumulations (Borjin and others, 2014). The overlying uppermost Permian Dalong Formation also contains organic-rich marine shale and was assessed with the Longtan. The Cambrian, Ordovician-Silurian, and Permian organic shales constitute three separate petroleum systems. The focus of this assessment is the potential for gas retained in these source rocks following oil generation and cracking. Conventional oil and gas resources of six Chinese provinces, including the Sichuan, were assessed by the USGS in 2011 (U.S. Geological Survey World Assessment Team, 2012).

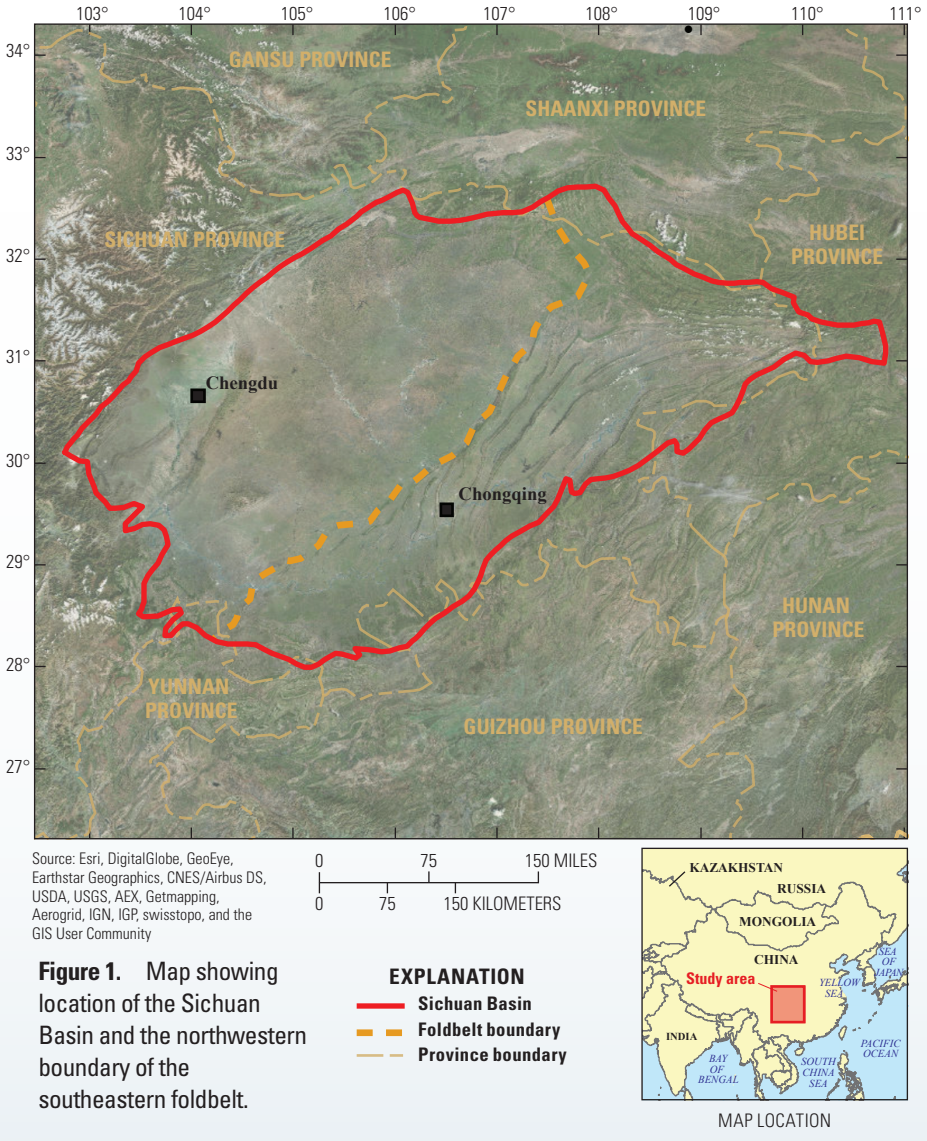

Figure 1. Map showing location of the Sichuan Basin and the northwestern boundary of the southeastern foldbelt.

U.S. Department of the Interior
U.S. Geological Survey

Printed on recycled paper

ISSN 2327-6916 (print) ISSN 2327-6932 (online)
http://dx.doi.org/10.3133/fs20153053

Fact Sheet 2015–3053
October 2015

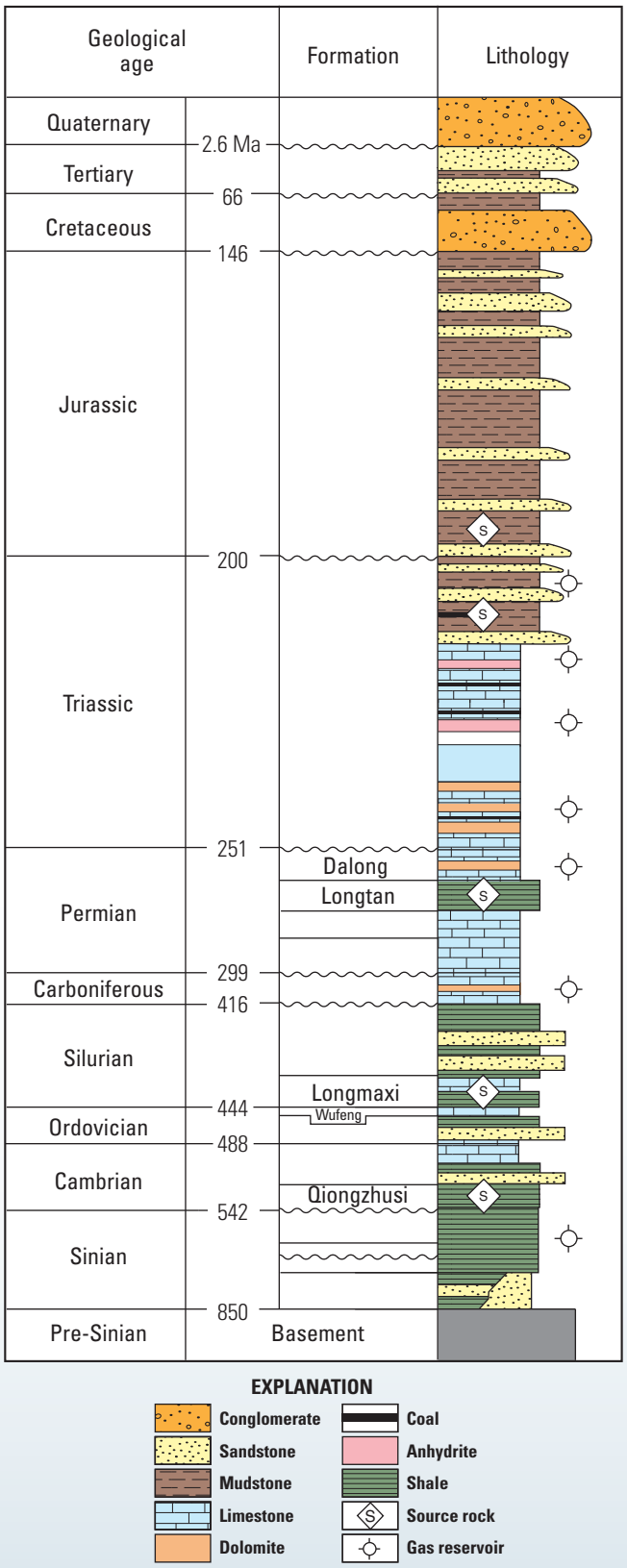

Figure 2. Simplified stratigraphic column for the Sichuan Basin, showing stratigraphic context of geologic formations that define the assessment units. Modified after Hao and others (2008), U.S. Geological Survey Geologic Names Committee (2010), and Zou and others (2010).

The USGS assessment methodology consists of a well-performance approach (Charpentier and Cook, 2011) that recognizes the geologic variability within assessed reservoirs. For non-U.S. assessments, the USGS assesses shale-gas reservoirs that (1) contain greater than 2 weight percent total organic carbon (TOC), (2) are within the proper thermal maturity window for gas generation, (3) have greater than 15-meter thickness of organic-rich shale, and (4) contain Type I or II oil-prone organic matter. Areas that do not meet these minimum criteria are unlikely to have significant resource potential without major technological improvements or major natural-gas price increases. Shale gas accumulations in the United States were used as analogs in this assessment. Analog data from U.S. accumulations included mean estimated ultimate recoveries from populations of shale gas wells and mean drainage areas of directionally drilled wells. Principal input data used in the assessment are listed in table 1.

We defined six assessment units (AUs): two each for the Cambrian, Silurian (including uppermost Ordovician), and Permian petroleum systems. For each of these stratigraphic intervals, we defined a relatively undeformed "platform" AU to the northwest of the southeastern foldbelt, and a "foldbelt" AU within the southeastern foldbelt (fig. 1). Accordingly, the AUs are: Cambrian Qiongzhusi Platform Shale Gas, Cambrian Qiongzhusi Foldbelt Shale Gas, Silurian Longmaxi Platform Shale Gas, Silurian Longmaxi Foldbelt Shale Gas, Permian Longtan Platform Shale Gas, and Permian Longtan Foldbelt Shale Gas. All AUs were quantitatively assessed.

Geologic Models for Assessment

The geologic models for the AUs parallel the tectonic history of the Sichuan Basin as follows: for the Cambrian and Silurian AUs, organic shale was deposited in deep basins associated with the passive continental margin of the south China block, which itself lay off the margin of the Gondwana supercontinent. As these basins accumulated greater thicknesses of sediment during the Paleozoic, the shale formations were deeply buried and generated oil. After the collision of the North and South China continental blocks in Triassic time, rapid and voluminous continental sedimentation accelerated the burial of shale formations and resulted in increased thermal maturity and cracking of oil to gas. Permian oil-prone organic-rich shale also accumulated in discrete basinal lows and generated oil (and later, gas) during Mesozoic continental sedimentation. Significant volumes of oil and gas from each of these Paleozoic source rocks migrated into shallower conventional traps; however, substantial volumes of gas remained in the shale formations to form the present shale gas accumulations.

Major Late Cretaceous and Tertiary uplift of the basin occurred in response to accretionary tectonics that included the Himalayan collision of India and Eurasia; related fracturing and faulting provided pathways for leakage of gas from shale reservoirs. In addition, development of widespread detachment folds and thrust faults in the southeastern fold belt likely produced the greatest gas leakage. In the AUs designated "foldbelt," the shale reservoirs are expected to be successful only in the least deformed

areas, such as the Silurian shale reservoirs in the successful wells in the Jiaoshiba gas field east of Chongqing (fig. 1; Guo and Zhang, 2014; Guo, 2015). In areas not affected by leakage along fault and fracture systems, overlying and underlying shales provide adequate roof and floor seals for the shale reservoirs. Exceptions might occur along the basal Cambrian unconformity beneath the Qiongzhusi Formation as well as mid-Permian and Permian-Triassic unconformities below and above the upper Permian shales, all of which would increase the risk of gas leakage. All shale reservoirs included in this assessment have sufficient brittle mineral content to be amenable to gas production by hydraulic fracturing.

Resource Summary

The USGS quantitatively assessed unconventional oil and gas resources in three Paleozoic shale sections in the Sichuan Basin of China. The mean total for unconventional gas resources is 23,900 billion cubic feet (BCFG), with a range from 4,505 to 58,382 BCFG. The mean total for natural gas liquids is 343 million barrels (MMBNGL), with a range from 50 to 920 MMBNGL (table 2). These resource estimates are for undiscovered technically recoverable volumes of gas and natural gas liquids and do not reflect volumes of economically recoverable resources.

Of the mean unconventional gas total of 23,900 BCFG, 68 percent (16,146 BCFG) is estimated to be in the Silurian Longmaxi Platform Shale Gas and Silurian Longmaxi Foldbelt Shale Gas AUs, 22 percent (5,349 BCFG) is estimated to be in the Cambrian Qiongzhusi Platform Shale Gas and Cambrian Qiongzhusi Foldbelt Shale Gas AUs, and 10 percent (2,405 BCFG) is estimated to be in the Permian Longtan Platform Shale Gas and Permian Longtan Foldbelt Shale Gas AUs.

Table 1. Key assessment input data for the Paleozoic shale gas assessment units in the Sichuan Basin, China.

[EUR (estimated ultimate recovery per well) and well drainage area are from U.S. shale gas analogs. BCFG, billion cubic feet of gas; AU, assessment unit; %, percent. The average EUR input is the minimum, median, maximum, and calculated mean]

Assessment Input Data–Continuous AUs	Cambrian Qiongzhusi Platform Shale Gas				Cambrian Qiongzhusi Foldbelt Shale Gas			
	Minimum	Mode	Maximum	Calculated mean	Minimum	Mode	Maximum	Calculated mean
Potential production area of AU (acres)	10,000	1,625,000	14,000,000	5,211,667	10,000	2,800,000	7,000,000	3,270,000
Average drainage area of wells (acres)	120	150	180	150	120	150	180	150
Success ratios (%)	5	20	50	25	5	15	40	20
Average EUR (BCFG)	0.2	0.4	1	0.431	0.2	0.35	0.8	0.373
AU probability	1.0				1.0			
	Silurian Longmaxi Platform Shale Gas				Silurian Longmaxi Foldbelt Shale Gas			
	Minimum	Mode	Maximum	Calculated mean	Minimum	Mode	Maximum	Calculated mean
Potential production area of AU (acres)	10,000	1,368,000	5,487,000	2,288,333	10,000	3,000,000	10,000,000	4,336,667
Average drainage area of wells (acres)	120	150	180	150	120	150	180	150
Success ratios (%)	10	45	90	48.3	10	40	90	46.7
Average EUR (BCFG)	0.2	0.8	2	0.856	0.2	0.7	1.5	0.734
AU probability	1.0				1.0			
	Permian Longtan Platform Shale Gas				Permian Longtan Foldbelt Shale Gas			
	Minimum	Mode	Maximum	Calculated mean	Minimum	Mode	Maximum	Calculated mean
Potential production area of AU (acres)	5,000	1,000,000	7,200,000	2,735,000	5,000	500,000	2,227,000	910,667
Average drainage area of wells (acres)	120	150	180	150	120	150	180	150
Success ratios (%)	5	20	50	25	5	15	40	20
Average EUR (BCFG)	0.2	0.4	1	0.431	0.2	0.35	0.8	0.373
AU probability	1.0				1.0			

Table 2. Assessment results for continuous gas resources in the Sichuan Basin, China.

[BCFG, billion cubic feet of gas; MMBNGL, million barrels of natural gas liquids; TPS, total petroleum system; AU, assessment unit. Results shown are fully risked estimates. For gas accumulations, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under assumption of perfect positive correlation]

Total Petroleum System (TPS) and Assessment Units (AU)	AU probability	Accumulation type	Total undiscovered resources							
			Gas (BCFG)				NGL (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean
Cambrian TPS										
Cambrian Qiongzhusi Platform Shale Gas AU	1.0	Gas	546	2,907	9,783	3,728	12	69	253	93
Cambrian Qiongzhusi Foldbelt Shale Gas AU	1.0	Gas	366	1,384	3,693	1,621	1	4	18	6
Silurian TPS										
Silurian Longmaxi Platform Shale Gas AU	1.0	Gas	1,183	5,089	15,290	6,271	27	123	405	157
Silurian Longmaxi Foldbelt Shale Gas AU	1.0	Gas	2,016	8,258	23,462	9,875	3	25	108	36
Permian TPS										
Permian Longtan Platform Shale Gas AU	1.0	Gas	307	1,530	5,054	1,953	7	37	131	49
Permian Longtan Foldbelt Shale Gas AU	1.0	Gas	87	368	1,100	452	0	1	5	2
Total undiscovered unconventional resources			**4,505**	**19,536**	**58,382**	**23,900**	**50**	**259**	**920**	**343**

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For Further Information

Assessment results are available at the USGS Energy Resources Program Web site, http://energy.usgs.gov/oilgas.

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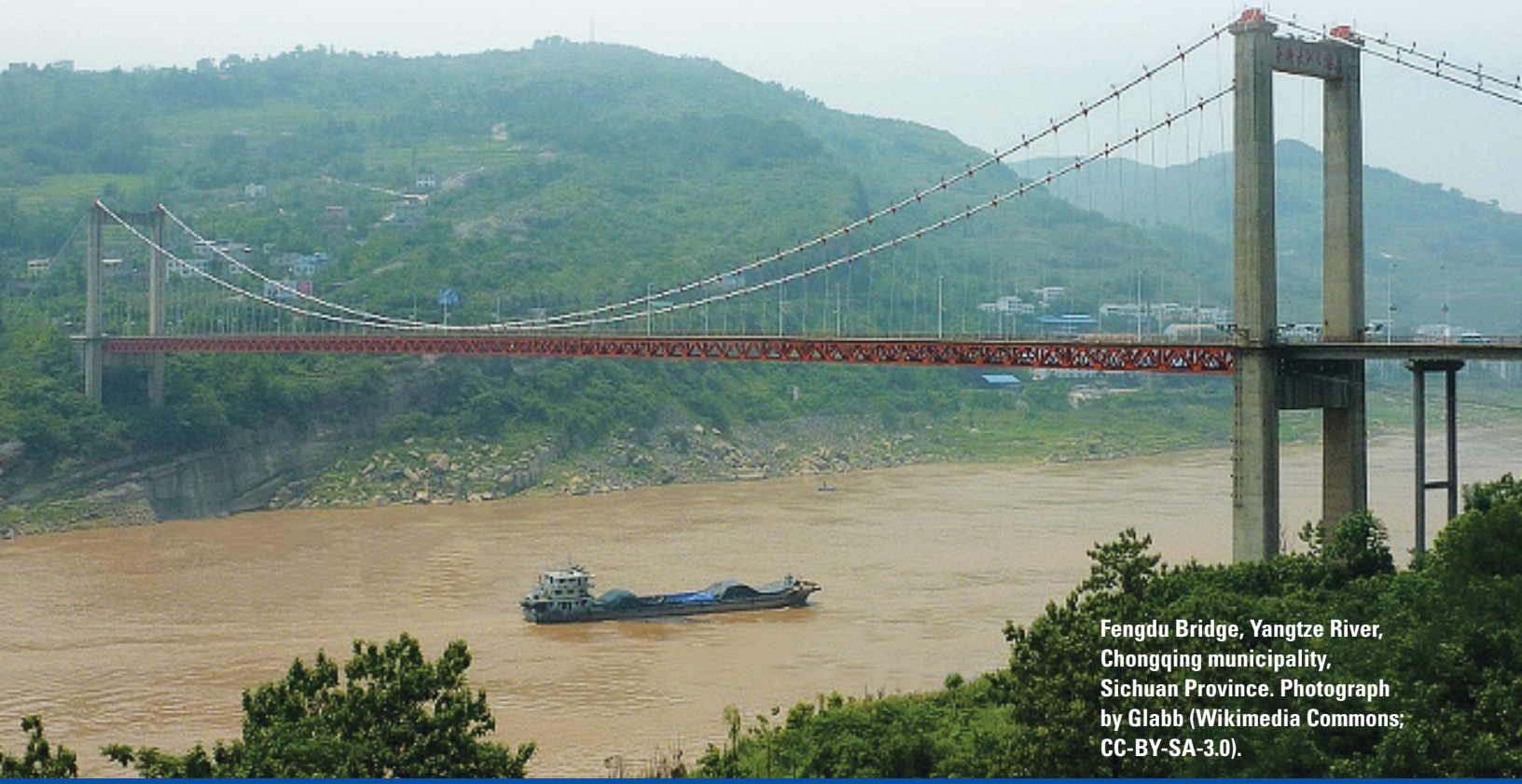

Fengdu Bridge, Yangtze River, Chongqing municipality, Sichuan Province. Photograph by Glabb (Wikimedia Commons; CC-BY-SA-3.0).