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Geologic characteristics of hydrocarbon-bearing marine, transitional and lacustrine shales in China

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ABSTRACT

Organic-rich shales spanning in age from Pre-Cambrian to Quaternary were widely deposited in China. This paper elaborates the geology and unique characteristics of emerging and potential hydrocarbon-bearing shales in China. The Pre-Cambrian Sinian Doushantuo to Silurian black marine shales in the intra-shelf low to slope environments were accumulated in South China and Tarim Platform in Northwest China. These marine shales with maturity (Ro) of 1.3–5% are in dry gas window. During Carboniferous to Permian, the shales associated with coal and sandstones were mainly deposited in coastal swamp transitional setting in north China, NE China, NW China and Yangtze platform in South China. These transitional shales are generally clay rich and are potential gas-bearing reservoirs. Since Middle Permian, the lacustrine shales with total carbon content (TOC) up to 30% and Ro mainly in oil window are widely distributed in all the producing basins in China. The lacustrine shales usually have more clay mineral content than marine shales and are characterized by rapid facies change and are interbedded with carbonates and sandstone. The high quality shale reservoir with high TOC, hydrocarbon content and brittle minerals content is usually located at transgressive systems tract (TST) to early highstand systems tract (EHST) interval deposited in anoxic depositional setting. Recent commercial shale gas production from the Silurian Longmaxi marine shale in the southeastern Sichuan Basin, preliminary tight oil production associated with lacustrine hydrocarbon-bearing shale intervals and hydrocarbon shows from many other shales have proven the hydrocarbon-bearing shales in China are emerging and potential shale gas and tight (shale) oil plays. Tectonic movements could have breached the early hydrocarbon accumulation in shales and tectonically stable areas are suggested to be favorable prospects for China shale plays exploration and production.

1. Introduction, data and methodology

The successful shale gas and shale oil revolution in the U.S. is evident in the current U.S. energy portfolio (Curtis, 2002; EIA, 2013) and is largely due to the growing understanding of self-sourced reservoirs, hydraulic fracturing advancements, and improvements in horizontal drilling technologies specifically developed for shale reservoir systems. China looks forward to replicating the U.S. experience to produce shale gas to power its economy and reduce coal consumption based on having largest shale gas resource in the world and a huge internal demand (EIA, 2011, 2013). Comparing to shales developed in foreland marine setting in U.S., the challenges for China shale gas include the more complex geology in marine, transitional and lacustrine settings, harsh ground conditions, lack of advanced

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shale gas technologies and experience, insufficient infrastructure, environmental issues, water shortages, etc. (Jiang, 2014). In 2011, the U.S. Energy Information Administration (EIA) assessed that China could have 36 TCM or 1275 TCF of technically recoverable shale gas. In March 2012, the China Ministry of Land and Resources (MLR) announced that China had 25.08 TCM (886 TCF) of technically recoverable shale gas resources in marine, transitional and lacustrine geologic settings in onshore China (excluding the Qinghai-Tibet Plateau area) (Zhang et al., 2012). In June 2013, the EIA reduced their assessment of China's recoverable shale gas resource to 31.48 TCM or 1115 TCF. Even with this reduction, both estimates indicate that China's shale gas resource is most likely the largest in the world and comparable to that of the updated U.S. recoverable shale gas reserves of 665 TCF. In addition to the shale gas resource, the EIA (2013) predicted that China had 32 billion barrels of technically recoverable shale oil and PetroChina predicted that China had about 3000–6000 million tons of technically recoverable shale oil (25–50 billion barrels) spread across various lacustrine basins ranging in age from Permian to Cenozoic (Zou et al., 2013). These huge shale gas and shale oil resources represent a vast, long-term and very important energy resource for China and will provide a great opportunity for China to mirror the shale energy revolution in the U.S. 400 wells have been drilled in the last few years and almost half of the drilled wells have good shale hydrocarbon show. The Sinopec's Jiaoshiba Shale Gas Field in the southeastern Sichuan Basin (Fuling area, Chongqing) announced early 2014 to become the first commercial shale gas production outside North America. The Jiaoye8-2HF well in this shale gas field was reported to produce 547,000 cubic meters (19.1 million cubic feet) per day from Silurian Longmaxi marine shale. For lacustrine shale, Sinopec sped up lacustrine shale gas and tight (shale) oil exploration in the Sichuan Basin targeting the Jurassic organic-rich lacustrine shale intervals interbedded with carbonate. PetroChina has reported preliminary success of tight (shale) oil from Permian lacustrine shale and carbonate interbeds in Junggar and Santanghu Basin in Northwest China.

Recognizing that many papers have introduced basic geological information, reported values for shale gas resources and identified properties of China shales (Zhang et al., 2008; Zou et al., 2010, 2013, 2014; Hao et al., 2013; Ju et al., 2014; Tan et al., 2014), a thorough, detailed and high confidence summary for the geology of the organic-rich marine, transitional and lacustrine shales in China is still lacking. The missing components are shale gas and shale oil resource potentials across different ages of shales and across various geographic and geologic regions outlining key properties of representative shale gas and shale oil plays.

This paper employed the historical oil industry data, outcrop and subsurface core samples and recently drilled shale gas and shale oil wells as database to characterize the geology of China shales. Lab test results of petrology, geochemistry, mineralogy, rock fabrics and petrophysics for 109 core and outcrop shale samples representing marine, transitional and lacustrine environments in China were used to characterize shale properties. The distribution of shales in time and space was systematically summarized based on the geologic history of China and synthesis of literatures and industry data. Robust comparisons between hydrocarbon-bearing marine, lacustrine and transitional shales were revealed based on the analysis of geochemical, mineralogical, petrophysics, rock fabrics test results and integrated shale reservoir heterogeneity characterization within sequence stratigraphic framework. The classic third-order sequence stratigraphic analysis follows the sequence stratigraphic division methodology introduced by Vail et al. (1977) for siliciclastic sediments and Slatt and Rodriguez (2012) for shale. The sequence stratigraphic framework of shale formation was built integrating regional geology, lithofacies description of cores and outcrops, well logs analysis, geochemistry, mineralogy, etc. The high quality hydrocarbon-bearing shale reservoir is then predicted within sequence stratigraphic framework. Some advice for exploration of shale gas and shale oil in complex depositional and tectonic settings in China were lastly given through correlation between tectonic settings and shale gas production, unique geological characteristics of hydrocarbon-bearing China shales and lessons learned from shale exploration and production in U.S. and China.

2. Geologic setting of marine, transitional and lacustrine shales in China

The main tectonic units of China comprise three primary continental platforms/blocks and/or ancient cratons and other smaller paleo-continents and massifs (i.e. Qiangtang, Qaidam, Songneng, etc.): the Sino-Korea platform in northern China, the Tarim Platform in northwestern China, the Yangtze Platform in central south China, a deformed paleo-continent (Cathasia) in southern and southeastern China, and orogenic belts of various ages between platforms and massifs (Wang and Mo, 1995; Wang et al., 2005; Wan, 2011; Ren et al., 2013). China's sedimentary basins have developed since 2500 Ma years ago in Sino-Korea Platform in northern China. The shales in China span in age from Proterozoic to Quaternary. The organic-rich shales began to accumulate during the Proterozoic e.g., the Meso-Proterozoic Hongshuizhuang marine shale was deposited across a wide swath in northern China (Qin et al., 2010). After the breakup of the Rodinia supercontinent, the Pre-Cambrian aged Sinian Doushantuo Fm marine shale was deposited in shelf to slope settings in the Yangtze Platform around 700 Ma years ago (Qin et al., 2010). After the breakup of Rodinia supercontinent, the Pre-Cambrian aged Sinian Doushantuo marine shale was deposited in the shelf to slope settings in the Yangtze Platform around 700 Ma years ago during a period of sea level rise (Jiang et al., 2011, Fig. 1). Between the early Cambrian to Silurian, marine shales were deposited primarily in passive margin settings to foreland settings as a consequence of compression from the Late Ordovician Caledonian orogeny. These deposits are present in the Yangtze Platform region in southern China and the Tarim Platform in northwestern China (Wang and Mo, 1995; CPGC, 1989; Zhang et al., 2008; Zou et al., 2010, Figs. 1 and 2). During the Carboniferous (Mississippian and Pennsylvanian) to Permian periods, the Hercynian orogeny and accretion of Pangaea resulted in vast coastal plains, peat bogs and coastal swamp transitional settings in most areas across China. This resulted in vast deposits of shales interbedded with coal across much of today's Yangtze Platform in southern China, northwestern China and the Sino-Korea Platform in northern and northeastern China e.g. Ordos, Songliao and Bohai Bay Basins (Figs. 1 and 2). During the late Paleozoic (Middle Permian) after the Hercynian Orogeny, the lacustrine basins started to form in northwest China, e.g. Junggar and Turpan-Hami basins (CPGC, 1989; Wang and Li, 2004; Zou et al., 2010, Figs. 1 and 2). Since the Mesozoic, the continent of China experienced a period of intra-continental tectonic events when Indosinian, Yanshanian and Himalayan Orogenies were the predominant forces in China (Wang et al., 2005). The sea retreated in most regions and the depositional systems were dominated by a preponderance of fluvial-lacustrine environments leading to the high number of lacustrine basins throughout China (e.g. Triassic lacustrine systems in the Ordos and Sichuan basins, Jurassic lacustrine in Junggar and Qaidam basins, Cretaceous Songliao Basin, Paleogene Bohai Bay Basin, and the Subei basin). The organic-rich, lacustrine shales in China were formed in semi- to deep lake settings or in lakeshore-swamp environments during this period and comprise the majority of China's source rocks related to oil production (Hu et al., 1991; Carroll et al., 1992; Zou et al., 2010, 2014, Figs. 1 and 2). These organic-rich shales span in age from the