Marine and Petroleum Geology 56 (2014) 255–265

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Review article

Lacustrine basin unconventional resource plays: Key differences

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ARTICLE INFO

Article history:
Received 29 October 2013
Received in revised form
16 February 2014
Accepted 20 February 2014
Available online 6 March 2014

Keywords:
Cracking kinetics
Fracability
Generation kinetics
Lake level
Shale gas
Shale oil
Waltman Shale
Wind River basin

ABSTRACT

There has been a revival in hydrocarbon source rock characterization and development associated with growing interest in unconventional resources, where these fine-grained organic-rich rocks act as both source and reservoir. To-date, the exploration focus on shale reservoirs has been largely on marine systems. Lacustrine source rocks for conventional resources are geographically important, dominating regions such as China, Indonesia, and Brazil's resource-base. However, they have been generally untested for unconventional resources.

There are a number of key differences in the nature of these hydrocarbon systems that should be considered when assessing whether lacustrine systems may represent future unconventional opportunities in areas where the conventional resource-base is dominated by lacustrine-sourced oil. Among the key differences between these depositional systems is the greater sensitivity to high frequency climatic variability within lacustrine systems. Lacustrine systems are highly sensitive to changes in the balance between precipitation and evaporation, which may lead to rapid changes in lake level, potentially exceeding 600 m. These changes in depositional conditions are geologically rapid and may occur over periods of thousands of years. Such changes can reduce the areal extent of potentially thick source rock intervals to only those portions of a basin where a permanent deep lake was present. Thus the core unconventional target area may be geographically limited compared with their marine counterpart. Although potentially areally limited, a review of many lacustrine source rocks suggests that their thicknesses are often significantly greater than marine source rocks. An examination of the more distal portions of lacustrine systems, where better source rock potential is present reveals that there is generally limited connectivity between source and conventional reservoir. In these settings, such as the Wind River basin (Waltman Shale), the hydrocarbons remain trapped within the shales, potentially leading to over-pressured hydrocarbon charged systems. Such conditions suggest that although areally limited, viable unconventional targets may exist, if suitable reservoir conditions are present. Finally, the character of the oils produced is different in these settings, with lacustrine oils being waxy and displaying different hydrocarbon generation and cracking kinetics. High wax oils display distinct flow characteristics, being more viscous, and may offer different production challenges than their non-waxy marine equivalents. Additionally, differences in their cracking kinetics may indicate that the timing of gas generation for shale gas plays may differ significantly from marine systems.

1. Introduction

Unconventional resource plays have become an increasingly important component of the global hydrocarbon endowment. In North America, drilling of a suite of Paleozoic and Mesozoic marine systems such as the Barnett Shale (Montgomery et al., 2005), the Marcellus Formation (Engelder and Lash, 2008), and the Haynesville Shale (Hammes, 2009) has expanded the availability of gas reserves. Similarly, drilling in the Bakken Shale (LeFever, 2005) and the Eagle Ford Formation (Martin et al., 2011) has expanded the hydrocarbon liquids resource. Estimates have suggested that technically recoverable shale gas exceeds 6600 tcf (trillion cubic feet) globally (U.S. Energy Information Administration, 2011a), while estimates of recoverable resources of the unconventional Bakken play alone may exceed 3.65 BBO (billion barrels of oil) (Pollastro et al., 2008) and that of the Eagle Ford play are approaching 3 billion bbl oil (U.S. Energy Information Administration, 2011b). Although these resource estimates are considered by some as minimums (Dong et al., 2011), it remains largely unknown how much of this resource-base will ultimately be

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http://dx.doi.org/10.1016/j.marpetgeo.2014.02.013
0264-8172/

converted to reserves and produced. Monetization of the resource will, at least in part, be driven by: 1) economic and environmental considerations; 2) ability to identify core areas, where production rates will be high; and 3) advancements in drilling and completion technology in order to more effectively recover the resource.

The potential reserve addition could significantly alter the distribution curves relating effective source rock age to global reserves as presented by North (1979a, b) and Tissot (1979), increasing the available resources attributable to the Paleozoic portion of the stratigraphic column. Historically, this portion of the curve has been limited as a result of advanced thermal maturity coupled with the lack of preservation of conventional trap, seal, and reservoir section (Thompson, 1976; Bois et al., 1982; Dewey and Obermajer, 2009). The nature of these unconventional hydrocarbon systems reduces the impact of advanced thermal maturity and preservation of pre-existing accumulations, although post-generation basin inversion and structural deformation may still remain negative factors (Pryvalov et al., 2011) even when targets are returned to attractive depths (Jarvie et al., 2007).

Growth in North America's resource-base has not gone unnoticed by the rest of the world. Shale gas plays have now been suggested to exist globally. For example, the Silurian shale play of Poland (Dittrick, 2011) has become an active test region, where a number of companies are in the midsts of active drilling campaigns. China is also aggressively examining its unconventional resource potential targeting both shale gas and shale oil plays (Guo and Zhao, 2012; Zou et al., 2011). In fact, unconventional gas was mentioned in China's most recent "5-year plan", with the China National Energy Administration publishing specific target goals of 6.5 billion m^3/yr (229 bcf/yr).

Expansion of exploration for unconventional resources beyond the borders of North America has raised a number of questions both geologic and infrastructure related. The questions associated with infrastructure are beyond the scope of this paper (see for example Hsieh, 2011). This paper deals with a specific suite of the geologic questions that have been raised – those dealing with the viability of lacustrine systems as unconventional resource plays. This is a key question for areas where non-marine, lacustrine source rocks dominate and marine source rocks may be absent. Specifically, this paper addresses the key differences between marine and lacustrine systems and the associated implications on unconventional resources. Such an understanding may provide a foundation for determining whether lacustrine systems could prove to contain significant volumes of recoverable unconventional resources.

The global conventional resource base is dominated by marine petroleum systems, independent of whether the organic matter is autochthonous or allochthonous, oil- or gas-prone. Lacustrine systems, however, are still important, accounting for about 20% of the conventional global oil endowment (Bohacs et al., 2000). Within certain regions, such as China, Indonesia, and Brazil, the resource-base is dominated by lacustrine or hybrid (lacustrine source and marine reservoir) petroleum systems (Katz, 1990). In these countries more than 85% of the reserves are lacustrine derived, with individual fields having lacustrine source rocks potentially exceeding a billion barrels (Hasan et al., 1979; Li, 1995). A key question remains: should it be anticipated that lacustrine unconventional systems can provide a hydrocarbon resource-base proportional to their marine counterparts, or do the depositional systems differ so much that their ultimate resource potential differs?

Shale gas and oil systems have been defined as fine grained reservoirs in which either gas or oil are self-sourced and some of the gas is stored in the sorbed state (Bustin, 2005). These fine grained reservoirs are often petroleum source rocks for conventional hydrocarbon systems. Source rocks may be geochemically defined and it is important to note that they are unique and not ubiquitous. Source rocks are those rocks that: 1) contain above-average quantities of organic carbon (TOC > 1.0%), generally greater than 2.0% TOC, prior to achieving thermal maturity levels consistent with or greater than the main stage of hydrocarbon generation and expulsion (vitrinite reflectance [R_o] equivalent to 0.7% or greater); and 2) are capable of yielding above-average quantities of hydrocarbons (>2.5 mg HC/g rock) (Bissada, 1982), typically greater than 10 mg HC/g rock, upon pyrolysis. Thermal maturity must be taken into consideration because at maturities equivalent to the main stage of generation or beyond, organic carbon content may be reduced by more than 60% depending on kerogen type (Daley and Edman, 1987), with the greatest reduction occurring in more oil-prone source rocks. The loss in organic hydrogen is even greater than the loss of organic carbon.

Satisfying these source rock criteria alone does not equate to the establishment of viable exploration targets for shale gas or shale oil. Thermal maturity is another critical factor. Not all source rocks contain commercial quantities of hydrocarbons. The appropriate level of thermal maturity needs to have been obtained and the timing of generation and/or cracking needs to be consistent with trapping and/or retaining of the hydrocarbons. For example, if basin inversion followed generation, hydrocarbons may be lost from the source rock as a result of fracturing and changes in pressure. Alternatively, the lack of commercial production may be related to how hydrocarbons are distributed both stratigraphically and areally and the relationship of this distribution to "fracability" of the unit, a key component of reservoir potential (Britt and Schoeffler, 2009). For example, if the most organic-rich portion of the shale is associated with a clay-rich section, high ductility of the interval will reduce its fracability and limits its potential.

2. System sensitivity

Among the key differences between marine and lacustrine systems are their sensitivity to climate change and the associated sea level or lake level change (Bohacs et al., 2000). Lacustrine systems appear much more sensitive to climate changes than marine systems both in magnitude of base level change and timing. Bohacs et al. (2000) suggest that these differences make it inappropriate to apply sequence stratigraphic models directly to lacustrine settings. Changes in the magnitude of lake level can be significantly greater than observed in marine systems and occur over much shorter timeframes. For example, Talbot (1988) and Scholz and Soreghan (1999) reported changes in lake level for the larger East Africa rift lakes in excess of 300 m occurring over the past 15,000 years. In Lake Tanganyika lake level changes exceeded 600 m (Scholz and Rosendahl, 1988). These changes in lake level were climatically induced, reflecting changing patterns of evaporation and precipitation, and therefore the availability of water within the catchment area (Burnett et al., 2011). This contrasts with sea level changes where changes on the order of 300+ meters may have occurred over a period of ~100 million years (Pitman, 1978). These long-term sea level trends are typically a result of global tectonic events, including the increase in mid-ocean ridge volume (Turcotte and Burke, 1978). High frequency sea level changes also occur. These higher frequency changes in sea level are climatically induced and associated with changes in ice volume (Shackleton, 1987). Although the temporal character of these sea level changes may appear similar to those of lake level, their magnitude is quite different. The marine changes are on the order of only about 130 m (Lambeck, 1990), significantly less than that of lacustrine systems.

Among the consequences of sea/lake level variability are differences in stratigraphic fabric and character. Although far from homogenous, deepwater marine source rock systems appear to