ARTICLE IN PRESS

Marine and Petroleum Geology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Source rock heterogeneity and migrated hydrocarbons in the Triassic Shublik Formation and their implication for unconventional resource evaluation in Arctic Alaska

Inessa A. Yurchenko[a,*], J. Michael Moldowan[b], Kenneth E. Peters[a,c], Leslie B. Magoon[a], Stephan A. Graham[a]

[a] Department of Geological Sciences, Stanford University, Stanford, CA 94305, USA
[b] Biomarker Technologies, Inc., 638 Martin Avenue, Rohnert Park, CA 94928, USA
[c] Schlumberger Information Solutions, 18 Manzanita Place, Mill Valley, CA 94941, USA

A R T I C L E I N F O

Keywords:
Shublik Formation
Source rock
Arctic Alaska
North Slope
Biomarkers
Diamondoids
Heterogeneity
Migrated hydrocarbons

A B S T R A C T

This organic geochemical study of the Triassic Shublik Formation aims to investigate source rock heterogeneity, facies variation, and source and maturity of migrated hydrocarbons in the Tenneco Phoenix-1 well (OCS-Y-0338), drilled in offshore Arctic Alaska in 1986. Recovered continuous core is nearly 90 m thick continuous section throughout the entire Shublik Formation. Guided by previously published analyses of the Phoenix-1 core by Robison et al. (1996), this study provides the most detailed core-based analysis of the Shublik Formation to date. Analysis of biomarkers and diamondoids combined with Rock-Eval pyrolysis results indicates evidence of mature migrated hydrocarbons that may have affected previous interpretations of organic matter type and maturity of this core. Despite the variable lithology, four identified source rock intervals contain oil-prone type I kerogens with maturity ranging from immature to marginally mature. Biomarker analysis indicates the presence of two organic facies deposited under anoxic clay-poor and suboxic clay-rich environments that likely generated genetically distinct oils.

1. Introduction

It is widely recognized that petroleum source rocks can have significant spatial variability in lithology, and the quality, quantity and thermal maturity of the organic matter, which impact resource potential and the composition of expelled petroleum. However, most oil-source rock correlation studies focus on only a few selected rock samples that may not be representative of the entire source-rock interval. In practice, most conventional cores target reservoir rocks, and most source rock analyses use cuttings and/or outcrop samples, thus creating interpretive pitfalls. Recent success in shale-oil and shale-gas exploration and production shifts the research focus from reservoir to source rock and elevates the importance of recognizing geochemical and lithologic heterogeneity. Moreover, this sparked scientific interest to identify new unconventional hydrocarbon facies within the source rock and to better understand the distributions of their reservoir and source rock properties for a more accurate resource assessment (Jarvie, 2012; Schneider et al., 2013). Source rock cores are now an essential part of the unconventional shale resource exploration procedure providing many opportunities for advanced shale research.

Despite much work, the nomenclature for unconventional shale resource systems remains poorly defined and sometimes misleading. Shale, mudstone, and source rock are terms often used interchangeably despite fundamentally different lithologic and geochemical characteristics. A shale resource system is an organic-rich mudstone that serves as both source and reservoir rock for generated oil and gas (Jarvie, 2012). It can also charge and seal petroleum in juxtaposed organic-lean facies. Thus, all of the elements and processes in a conventional petroleum system (Magoon and Dow, 1994) also apply to shale resource systems. The pod of active source rock remains a key component of both conventional and unconventional systems.

The primary objective of this research is to understand how lithologic heterogeneity relates to the distribution of source rock properties and to quantify its impact on resource potential. To fulfill this objective, a thorough core-based investigation was conducted on the Triassic Shublik Formation source rock in Arctic Alaska.

* Corresponding author. Geological Sciences Department, 450 Serra Mall Bldg. 320 Rm.118, Stanford, CA 94305-2115 USA.
E-mail address: inessa@stanford.edu (I.A. Yurchenko).

https://doi.org/10.1016/j.marpetgeo.2018.03.033
Received 29 August 2017; Received in revised form 26 March 2018; Accepted 27 March 2018

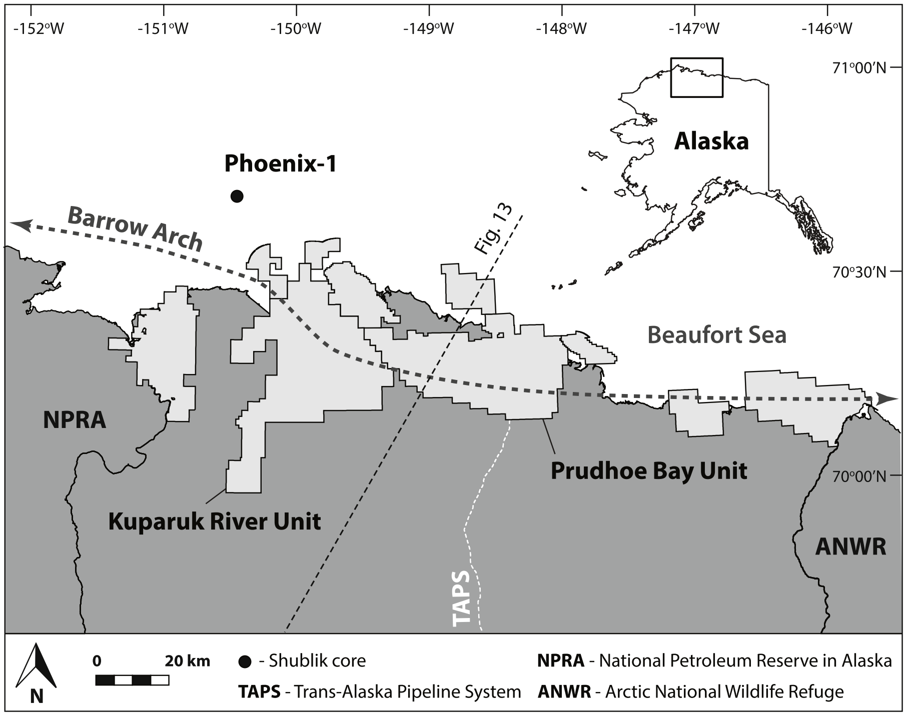

Fig. 1. Map of part of Arctic Alaska showing the study area, location of the sampled data (Phoenix-1 well) and cross section (Fig. 13). Main producing oil field units (light grey) are located in the northern part of the central North Slope (area between NPRA and ANWR) along the structural axis of the Barrow Arch (grey dashed line).

2. Geological background

Arctic Alaska is one of the world's most petroliferous regions, containing a great share of U.S. energy resources (Bird and Houseknecht, 2011). Nearly all petroleum-producing fields are located in the central North Slope between the National Petroleum Reserve in Alaska (NPRA) to the west and the Arctic National Wildlife Refuge (ANWR) to the east (Fig. 1). Most of the petroleum production is from the northern part of the central North Slope, whereas the area to the south remains a risky exploration frontier. The origin of North Slope petroleum has been debated and discussed in numerous publications since the discovery of the supergiant Prudhoe Bay Field in 1967. It is widely recognized that crude oil accumulations in the North Slope commonly represent mixtures of oil derived from several source rocks (Seifert et al., 1980; Wicks et al., 1991; Masterson, 2001; Peters et al., 2008). Key petroleum source rocks include Triassic Shublik Formation, Jurassic Kingak Shale, and Cretaceous gamma ray or highly radioactive zone (GRZ) (Magoon and Bird, 1985; Bird, 1994; Masterson, 2001; Houseknecht and Bird, 2004; Peters et al., 2006) (Fig. 2). Other source units proposed in the North Slope include, but are not limited to: the Carboniferous to Permian Lisburne Group; the Cretaceous Seabee and Torok formations; and the Tertiary Canning Formation (Claypool and Magoon, 1985; Lillis et al., 1999; Lillis, 2003; Magoon et al., 1999; Peters et al., 2007).

The Middle to Upper Triassic Shublik Formation is a key source rock in the North Slope of Alaska and the greater Prudhoe Bay Field area. Although it has been recognized that organic-rich Shublik rocks show variable lithology, the majority of the research historically focused on organic geochemical assessments of Shublik oil types, rather than the source rock itself.

2.1. Shublik Formation lithostratigraphy

The Shublik Formation is a laterally continuous (over 400 km) and vertically variable (20–150 m) (Bird, 1994) unit that has been widely described in both outcrop and in the subsurface. Since it was first described by Leffingwell (1919), mapped by Keller et al. (1961), and measured by Detterman (1970), the Shublik Formation has been divided into different facies, units, and zones (Dingus, 1984; Parrish, 1987; Kupecz, 1995; Hulm, 1999; Parrish et al., 2001; Kelly et al., 2007; Hutton, 2014). The Middle to Upper Triassic Shublik Formation is interpreted to have been deposited under fluctuating oceanic upwelling conditions (Parrish, 1987; Kupecz, 1995; Parrish et al., 2001). As described by Parrish et al. (2001), the Shublik Formation contains a characteristic set of lithologies that include glauconitic, phosphatic, organic-rich, and cherty facies, consistent with deposition in a coastal upwelling zone. Its organic-rich intervals are often recognized by abundance of impressions and shells of distinctive Triassic bivalves *Halobia* and *Monotis* (Dingus, 1984; Hulm, 1999). Perhaps the most widely-used subclassification of the Shublik Formation is the zonation scheme employed within the Prudhoe Bay unit (Kupecz, 1995), which subdivides the Shublik Formation into four zones (from A, shallowest to D, deepest). These zones show different gamma-ray log signatures, which reflect the lithologic contrast between phosphatic sandstone (zone D), interlaminated black shale and limestone (zone C), phosphorite and phosphatic carbonate (zone B), and interlaminated shales and carbonate grainstone (zone A). Hulm (1999) extended this interpretation regionally outside of the Prudhoe Bay unit and into the NPRA area, and provided a detailed conventional core description for 10 wells, that allowed the subdivision of the Shublik Formation into 11 depositional facies, 8 of which were observed in the Phoenix-1 core. Hulm's facies classification and some core descriptions were adopted and six most commonly occurring facies were sampled as part of this study (Figs. 3 and 4).

2.2. Shublik source rock geochemistry

Although lithological heterogeneity and thickness variability of the Shublik Formation is widely recognized, most of the literature refers to it as one source rock unit. Several studies consider the Middle to Upper Triassic Shublik Formation to be the major source rock for oil in the North Slope (Seifert et al., 1980; Magoon and Bird, 1985; Bird, 1994; Masterson, 2001; Peters et al., 2008). Magoon and Bird (1985) reported that average richness for Shublik Formation is 1.7 wt%, and that it contains type II/III (hydrogen index, HI = 200–300 mg hydrocarbons/g TOC) organic matter in the west and type I (HI > 600 mg hydrocarbons/g TOC) in the Prudhoe Bay area. Bird (1994) showed that total