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Origin of condensates and natural gases in the Almond Formation reservoirs in southwestern Wyoming, USA

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ABSTRACT

Condensates and natural gases are significant resources that frequently occur together in many petroleum systems. Unraveling their origins is crucial for effective petroleum exploration and exploitation. This is often a challenge because light crudes are volatile, deficient in biomarkers, and commonly altered. The origin of condensates and natural gases in the Upper-Cretaceous Almond Formation in southwestern Wyoming was unraveled through use of improved analytical and interpretative geochemical approaches constrained by regional geologic perspectives and basin modeling. Here, an improved GC–MS/MS method allowed simultaneous determination of saturate and aromatic biomarkers, diamondoids, and organosulfur compounds in the whole crudes. Furthermore, basin-specific calibration of diamondoid-based thermal maturity parameters, through correlation of measured indices for diamondoids in rock extracts versus measured reflectance of vitrinite from the same rocks, allowed reliable interpretation of maturity of the most likely source rocks. Modified interpretation schemes for C_7-hydrocarbon distributions, and compositions of C_1-C_{30} alkanes, aromatic and organosulfur compounds, and $\delta^{13}C_1$-C_5 together indicated that the condensate and natural gas from each well are likely co-generated and thermogenic products from non-marine source rocks, although methane is partially biogenic. The bulk thermogenic petroleum are too mature to have originated in the rocks adjacent to the producing reservoirs. The geochemical, geologic, and modeling interpretations collectively indicate that the condensates and associated natural gases were most likely generated, expelled, and migrated from the downdip, highly mature, nearshore/transitional humic source rocks of the Almond Formation/Mesaverde Group in the Washakie Basin and Great Divide Basin at >1.3% Ro and ~30 Ma.

1. Introduction

The Almond Formation in the Eastern Rock Springs Uplift in southwestern Wyoming is a major reservoir for condensate and natural gas accumulations (García-González et al., 1997; Johnson et al., 2005; Tobin et al., 2010). Unraveling the origins of these resources is crucial for effective exploration and exploitation. Although a significant number of studies have been reported on the geologic setting of the play, only a few relevant geochemical studies are reported, and these focus primarily on petrographic examination and hydrous pyrolysis experiments on the source rocks (García-González et al., 1997; Ko, 2010). Deciphering the origin of the petroleum fluids and tracing their migration pathways are hindered by the absence of comprehensive studies that document the molecular and isotope geochemistry of both the accumulated petroleum fluids within the reservoirs and the organic matter in the source rocks within the basin.

This task is complicated because condensates and natural gases are products of numerous processes that can occur simultaneously, sequentially, or independently from each other. Condensates can be products of: (i) normal thermal maturation of hydrogen-rich coals/shales within the "oil window" (0.67–1.3% Ro); (ii) advanced thermal degradation of kerogen and crude oil within the condensate thermal stability zone (1.3–2.0% Ro); or (iii) evaporative fractionation-migration from a normal, single-phase crude (Thompson, 1987, 1988, 2010). Furthermore, natural gas can be microbial in origin under relatively low thermal stress or thermogenic under high thermal stress. When thermogenic, it may or may not be co-generated with liquid petroleum (Clayton et al., 1991; Bissada et al., 1993; Odden et al., 1998; Huang et al., 2014; Zhang et al., 2015). The task is further complicated because condensates often display a paucity or absence of biomarkers, high molecular volatility with consequent tendency towards natural

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fractionation, and susceptibility to volatiles lost during routine multi-step group-type separation in preparation for GC–MS analysis of the diverse group-types (Bissada et al., 2016a, 2016b; Mei et al., 2018). These leads to ambiguities associated with common interpretation schemes for the light hydrocarbon distributions.

The primary purpose of this study is to decipher the origin of the condensates and natural gases in the Almond Formation reservoirs in southwestern Wyoming despite the aforementioned shortcomings. To accomplish this, several improved geochemical methods were used. (a) A single-step GC–MS/MS analytical method (Mei et al., 2018) with enhanced resolution and sensitivity was used for simultaneous determination of saturated and aromatic biomarkers, organosulfur compounds and diamondoids in whole crudes. (b) A modified diamondoid-based maturity inference approach was developed and calibrated using correlation of molecular characteristics (both absolute concentrations and compound ratios) of diamondoids measured in solvent extractable organic matter (EOM) from conventional cores in the area versus measured reflectance of vitrinite from the same cores. (c) Revised interpretation schemes for the C_7 hydrocarbon distributions were used for clearly inferring source facies, degree of thermal maturity, and extent of alteration. Moreover, to uncover the most likely source kitchen and understand the probable generation and migration histories for the petroleum systems in the Washakie Basin and Great Divide Basin of the southwestern Wyoming province, it was necessary to integrate the geochemical inferences with reasonable basin modeling scenarios and constrain the conclusions with the prevailing geologic perspective. Although the methods and interpretation schemes deployed here were custom-designed to study the condensate and natural gas petroleum system of the southwestern Wyoming province, the approaches and the workflow can be applied elsewhere around the world to understand petroleum origins.

2. Materials and methods

2.1. Regional geology

The southwestern Wyoming province (Greater Green River Basin) is a large scale foreland basin consisting of five subbasins: Hoback Basin, Green River Basin, Great Divide Basin, Washakie Basin, and Sand Wash Basin (Johnson et al., 2005). Tectonically, this configuration evolved by eastward propagation of the Late Jurassic to Early Eocene (~140–50 Ma) thin-skinned Sevier orogeny and the Late Cretaceous to Early Eocene (~80–50 Ma) thick-skinned Laramide orogeny (Law, 1988; Decelles, 2004). The

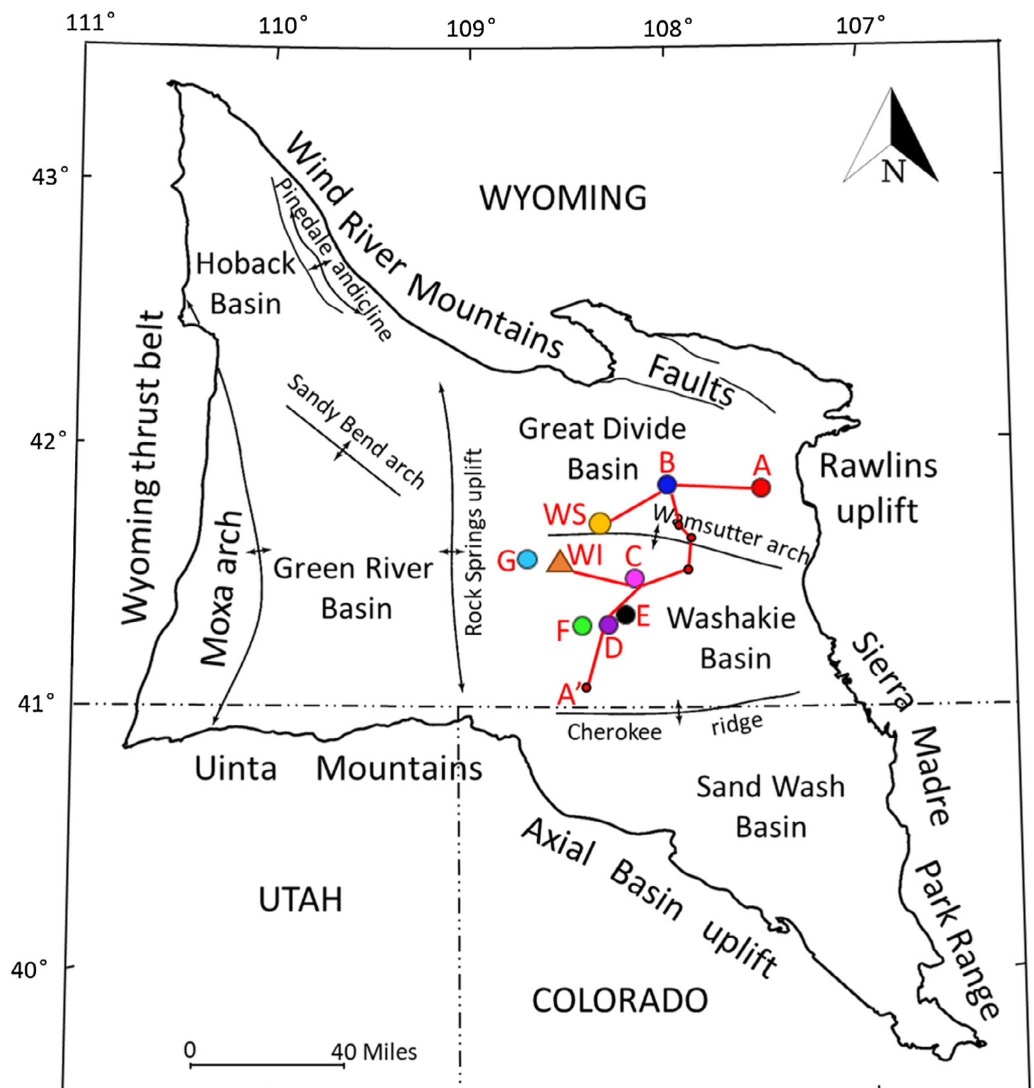

Fig. 1. Structure map of southwestern Wyoming showing study area, sample locations, and cross section lines (modified from Johnson et al., 2005). For sample and well information see the tabulated data.