CrossMark

Geochemical and petrophysical source rock characterization of the Vaca Muerta Formation, Argentina: Implications for unconventional petroleum resource estimations

Maria-Fernanda Romero-Sarmiento[a,*], Sebastian Ramiro-Ramirez[b], Guillaume Berthe[a], Marc Fleury[a], Ralf Littke[c]

[a] IFP Énergies nouvelles (IFPEN), Direction Géosciences, 1 et 4 avenue de Bois-Préau, 92852 Rueil-Malmaison Cedex, France
[b] The University of Texas at Austin, Institute for Geophysics, United States
[c] Institute of Geology and Geochemistry of Petroleum and Coal, Energy and Mineral Resources Group, Lochnerst 4–20, RWTH Aachen University, 52056 Aachen, Germany

ARTICLE INFO

ABSTRACT

The Vaca Muerta Formation is currently regarded as the most prolific source rock interval for unconventional petroleum exploration in Argentina. In this study, we integrate recent CT-scanner, nuclear magnetic resonance (NMR) T_1-T_2 and Rock-Eval Shale Play® analytical techniques, combined with classical geochemical, petrological and petrophysical methods to characterize Vaca Muerta source rocks along a vertical profile. The proposed analytical workflow was tested here on 4 samples derived from one core: the LJE-1010 borehole drilled in the lowermost Jurassic Vaca Muerta member (Neuquén Basin – Argentina), to evaluate the unconventional hydrocarbon potential and pore network attributes. First, entire rock samples were analyzed by dual energy CT scanner to evaluate possible heterogeneities; this also helped in the selection of representative samples. Then the organic matter properties were investigated by open-system pyrolysis techniques, organic petrography and biomarker analyses as a function of the core depth. A comparative approach between open-system pyrolysis methods (e.g. Rock-Eval Basic/Bulk-Rock & Shale Play® methods vs. Source Rock Analyzer) is also illustrated in this work. Finally, petrophysical characteristics and pore network attributes in shale were estimated by gas permeability (steady-state method corrected for Klinkenberg effect), porosity and NMR methods. The investigated samples have oil-window maturity and are characterized by a network of solid bitumen. Based on new Rock-Eval Shale Play® data, the potentially producible oil present in the rock samples was estimated using the modified oil saturation index (OSI = Sh0 + Sh1 peaks × 100/TOC). Results indicate that the oil crossover effect and potential productive oils occur within intervals showing higher TOC values (~3 to 8 wt%). We also illustrated here that, for unconventional shale play perspectives, Rock-Eval Shale Play® parameters (Sh0 & Sh1) allow to obtain both a better quantification of free and retained hydrocarbons in source-reservoir rock samples and correct original oil *in place* (OOIP) estimations in early exploration campaign for shale oil and shale gas assessment. For Vaca Muerta rock samples, OOIP estimations range from 60 to 160 bbl oil/acre-ft, approximately. We also demonstrated that the solid bitumen, oil and organic matter are clearly distinguished in the studied samples using advanced NMR T_1-T_2 maps obtained at different temperatures. The solid bitumen was clearly evidenced as a peak with T_1/T_2 ratio ~ 14 on NMR T_1-T_2 maps. Concerning the matrix bulk rock permeability, the obtained results showed that the most deep sample is characterized by a permeability of about 140 nanoDarcy (nD) whereas the shallower sample containing also higher amounts of organic matter is more permeable (~213 nD), indicating that TOC values play a main control on Vaca Muerta poromechanical characteristics. The maximum total porosity values range between 6.5 and 21.8% and were calculated in this work integrating NMR and helium porosity values. Finally, global interpretations of these obtained results suggest that the Vaca Muerta Formation could be considered as a prolific shale play interval for unconventional petroleum exploration in the near future.

* Corresponding author.
  E-mail address: maria-fernanda.romero-sarmiento@ifpen.fr (M.-F. Romero-Sarmiento).

1. Introduction

During the last 20 years, for "conventional" petroleum system perspectives, several studies have been focused on the geochemical characterization of the Vaca Muerta source rocks and their correlated oil samples at the basin scale (e.g. Villar and Talukdar, 1994; Rodríguez Monreal et al., 2009; Legarreta and Villar, 2011; Sylwan, 2014; Legarreta and Villar, 2015; among others). Today, with the increasing interest on unconventional resources (when "shale plays" are considered simultaneously both source and reservoir rocks), it is necessary to evaluate, for a correct economic assessment, (1) porosity and permeability including the organic porous network (nature and distribution of pore structures in organic matter and the relationship with the mineral matrix), (2) the gas and oil trapping mechanisms, and (3) the hydrocarbon composition, quality and quantity in these source-reservoir rock samples (e.g. Loucks et al., 2009, 2012; Curtis et al., 2012; Romero-Sarmiento et al., 2013, 2014a, 2014b, 2016a, 2016b).

A more accurate quantification of the oil and gas *in place*, within these "unconventional" petroleum systems, is now essential. In this context, classical geochemical and petrophysical techniques have been combined to characterize different shale oil and shale gas systems worldwide (e.g. Uffmann et al., 2012; Ghanizadeh et al., 2015). Among the organic geochemical techniques, current open-system pyrolysis devices like Rock-Eval 6, Source Rock Analyzer and HAWK have been widely used to reproduce, at the laboratory scale, the thermal cracking of organic matter in rock samples to generate hydrocarbons and to estimate their petroleum generation potential (e.g. Tissot and Espitalié, 1975; Espitalié et al., 1977; Espitalié et al., 1986; Peters, 1986; Lafargue et al., 1998; Behar et al., 2001; Jarvie, 2012; among others). However, several questions still remain, such as the reliability of the classical S_1 peak (well-known as free hydrocarbons) obtained from these methods and their corresponding extrapolation/signification to the geological conditions.

Recently, in order to obtain a better assessment of these free and/or sorbed hydrocarbons still present within organic-rich rock samples, a specific pyrolysis program for characterization of unconventional shale resource systems has been developed by IFPEN (France): the Shale Play method® (Romero-Sarmiento et al., 2014a, 2016a, 2016b; Pillot et al.,

2014). This method provides the hydrocarbon content index (HCcont = Sh0 + Sh1 peaks; mg HC/g of initial rock; Fig. 1) that can be used to estimate the total available free and/retained hydrocarbons occurring in unconventional source rock samples. It has been also demonstrated that this method determinates more accurate Rock-Eval T_{max} values for initial oil-impregnated or non-extracted samples, indicating that the position of the new Sh2 peak is not affected by either the presence of hydrocarbons in place or the improved thermo-vaporization stage (Fig. 1; Romero-Sarmiento et al., 2014a, 2016a, 2016b).

Now, the purpose of this paper is to integrate Shale Play® analyses with recent CT-scanner and Nuclear Magnetic Resonance (NMR T_1-T_2) techniques, combined with other geochemical, petrological as well as petrophysical analytical workflows such as open-system pyrolysis (Rock-Eval vs. Source Rock Analyzer), organic petrography, bio-markers, He and NMR porosity, and gas permeability methods to evaluate the unconventional hydrocarbon potential and pore network attributes in source rocks as a function of both core depth and similar thermal maturity. To do that, we investigated here the geochemical, petrological and petrophysical source rock properties of four well-preserved organic-rich samples derived from one core: the LJE-1010 borehole drilled in the lowermost Jurassic Vaca Muerta Formation in the Neuquén Basin, Argentina (Fig. 2), in order to estimate potentially producible oil intervals. We also tried to obtain a better discrimination between solid bitumen, organic matter and liquid hydrocarbons (free and sorbed) still present in the selected rock samples using both Shale Play and NMR techniques.

2. Material and methods

2.1. Samples: the Vaca Muerta Formation (Argentina)

The investigated samples correspond to an exploration well (LJE-1010) drilled in the Neuquén Basin, Argentina (Fig. 2A). The Neuquén Basin covers an area of approximately 120,000 km^2 in West-Central Argentina (Yrigoyen, 1991), and can be subdivided into the Andean mountain range in the west and the Neuquén embayment in the east (Howell et al., 2005). In terms of reserve ranking, it is the most
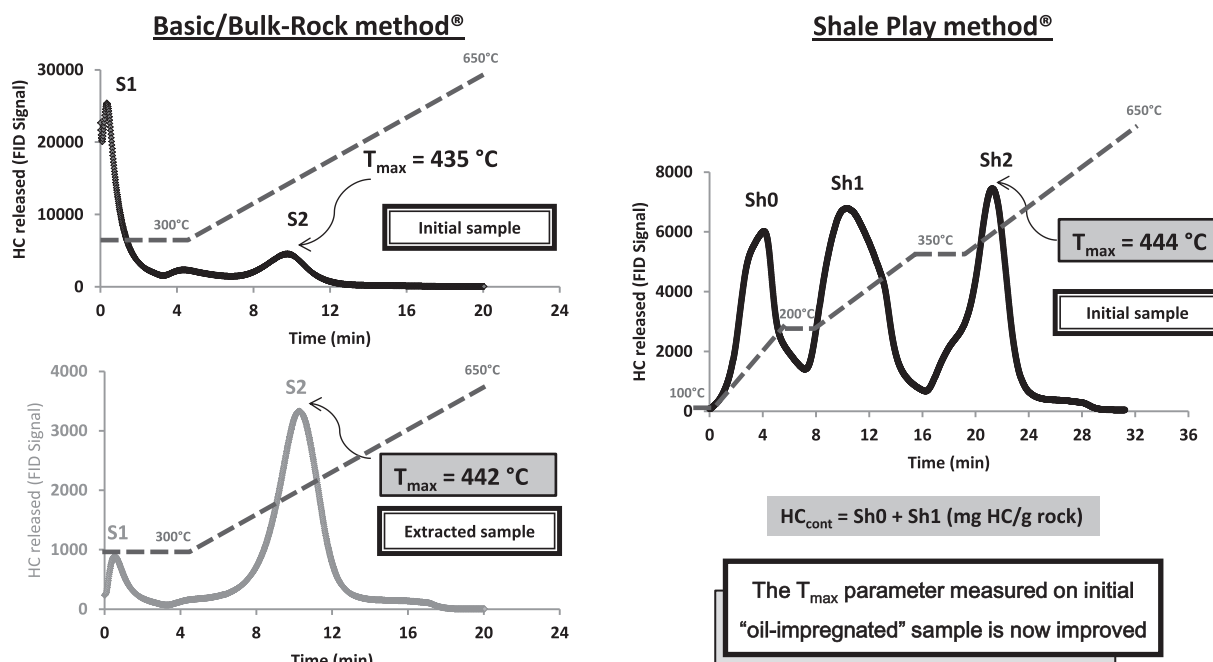

Fig. 1. Examples of Rock-Eval T_{max} values obtained from the classical Basic/Bulk-Rock® method (initial vs. extracted sample) and the Shale Play® method (initial sample): Late Jurassic Bazhenov Shale (data from Romero-Sarmiento et al., 2014a, 2016b).