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Origin, properties, and implications of solid bitumen in source-rock reservoirs: A review

Maria Mastalerz[a,*], Agnieszka Drobniak[a], Artur B. Stankiewicz[b]

[a] Indiana Geological and Water Survey, Indiana University, Bloomington, IN 47405-2208, USA
[b] Schlumberger, 6350 West Sam Houston North, Houston, TX 77041, USA

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ABSTRACT

This paper reviews the significance of solid bitumen with emphasis on source-rock reservoirs. We discuss difficulties and discrepancies with terminology, especially those terms related to the origin of solid bitumen and its physical and chemical properties. Various definitions of solid bitumen have their own justifications and can be used provided there is clarity about which defining criteria are being considered. Difficulties in conforming to chemical-, solubility-, or origin-related definitions lead us to suggest adapting the reflectance of solid hydrocarbon as a practical choice for placing the boundary between solid bitumen and pyrobitumen, and 1.50% is proposed as the boundary value. It has to be noted that this boundary may be shifted down to 1.3% for sulfur-rich kerogen. Recently, much progress has been made by combining imaging and physical adsorption techniques in porosity studies, and so the porosity of solid bitumen is given special emphasis. Comparing pore characteristics obtained from SEM versus those generated by gas adsorption, mercury intrusion, or neutron scattering techniques indicates that the SEM pore inventory fails to account for the smallest pores (< 5 nm in size) present in organic matter. Therefore, low-pressure CO_2 adsorption is still the most effective technique to assess microporosity (pores < 2 nm in diameter) in shales. We conclude that combining observational in situ techniques with techniques based on physical principles is necessary to make progress toward a better understanding of porosity systems in organic matter, including solid bitumen.

We review the implications of the abundance of solid bitumen on reservoir quality, porosity, permeability, and producibility, based on examples of selected sequences. One of the difficulties in predicting the influence of solid-bitumen-bearing horizons on reservoir quality arises from the problems with detecting organic phases using various logging techniques. The use of specialized techniques such as NMR logging that allows two-dimensional T_1 and T_2 measurements should be expanded, and other potential techniques need to be further researched and tested. Certain aspects of the properties of solid bitumen that are not as well understood, such as its hydrocarbon generation potential or its role in hydrocarbon migration are also discussed with the aim of identifying further research that could lead to a better understanding of the role that solid bitumen plays in unconventional reservoirs.

1. Introduction

There are two types of organic matter (OM) in source-rock reservoirs: 1) primary organic matter that comes from the depositional setting (e.g., Tissot and Welte, 1984; Hunt, 1996; Vandenbroucke and Largeau, 2007); and 2) secondary organic matter formed from the transformation of the primary organic matter (e.g., Jacob, 1985; Jarvie et al., 2007, Fig. 1). Primary organic matter includes (a) non-extractable fraction referred to by organic geochemist as kerogen and called macerals by organic petrologists and (b) original soluble organic matter that is not a product of generation/expulsion (Fig. 1). Secondary organic matter also includes both extractable and non-extractable material that is referred to by organic geochemists as bitumen and pyrobitumen, respectively. In organic petrology terminology, secondary organic matter includes oil, solid bitumen, and pyrobitumen (Figs. 1 and 2). Solid bitumen and pyrobitumen are often the prevalent OM component of rock sequences of late oil window and dry gas window maturities (Rippen et al., 2013; Kondla et al., 2015; Emmanuel et al., 2016; Hackley and Cardott, 2016; Liu et al., 2018) and in the exploitation of OM-rich shales they influence, to a large extent, reservoir quality (Wood et al., 2015). In addition, the presence of solid bitumen and pyrobitumen and their reflectance are often used to assess maturity

* Corresponding author.
E-mail address: mmastale@indiana.edu (M. Mastalerz).

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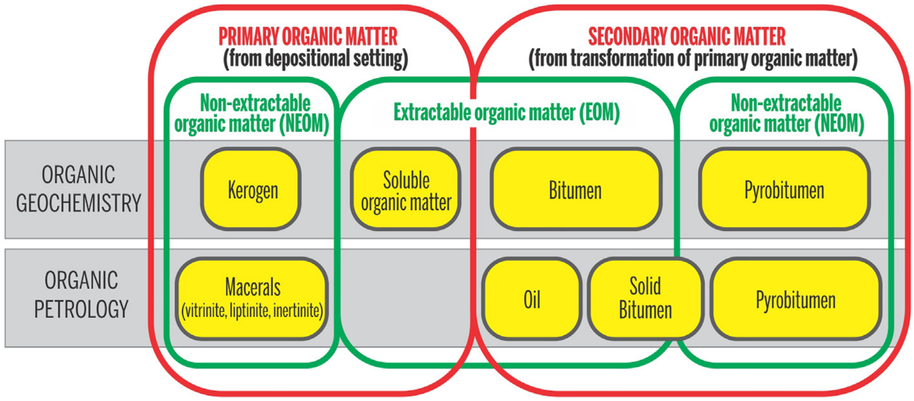

Fig. 1. Comparison of basic nomenclature of organic matter used by organic geochemists and organic petrologists.

level in the absence of reliable vitrinite particles (Jacob, 1989; Gentzis and Goodarzi, 1990; Bertrand, 1993; Landis and Castaño, 1995; Schoenherr et al., 2007; Mählmann and Le Bayon, 2016; and many others).

Although awareness of the role of solid bitumen in source-rock reservoirs is growing, many discrepancies still exist related to its definition, nomenclature, and classification. These inconsistencies result from differing criteria used to classify bitumen by various disciplines. Specifically, organic geochemists define bitumen as an organic fraction extractable with organic solvents (Hunt, 1996; Killops and Killops, 2005, Fig. 1), whereas organic petrologists identify solid bitumen based dominantly on morphological features and void-filling occurrence (Landis and Castaño, 1995). There are also various approaches to classifying solid bitumen in general, from the strictly generic (Abraham, 1960; Jacob, 1989) to the genetic (Curiale, 1986). Furthermore, definition of bitumen is further blurred by application of laboratory analytical techniques (Rock-Eval, solvent extraction, etc.) to match/define signals obtained by various logging tools.

The need for unequivocal recognition and identification of solid bitumen in source-rock reservoirs has become even more pressing recently because researchers have increasingly been using ion-milled surfaces and scanning electron microscopy (SEM) techniques to document OM pores, and attempting to apply OM terminology developed for reflected light microscopy (Loucks et al., 2009; Curtis et al., 2011; Fishman et al., 2012; Milliken et al., 2013; Schieber, 2013). Although OM can be easily differentiated from minerals using SEM owing to its low backscatter electron intensity, SEM cannot reliably identify individual components of OM or distinguish kerogen from solid bitumen; all this can be easily accomplished using oil immersion and reflected light microscopy. Therefore, attempts to use the nomenclature of organic petrology (Fig. 2) by nonorganic petrologists in SEM studies can result in imprecise or incorrect use of the terms "solid bitumen," "pyrobitumen," "kerogen," or "bituminite" (e.g., Milliken et al., 2013; Schieber, 2013). In fact, because of the similarities in terms, "bituminite" (primary maceral) and "bitumen" are at times confused even among organic petrologists (e.g., Mählmann and Le Bayon, 2016; Mohnhoff et al., 2016). In addition, the vast literature of engineering is adopting various definitions of bitumen or introducing their own terms to correlate log-based responses (e.g., nuclear magnetic resonance [NMR]) in bitumen-bearing sequences. Bitumen producibility and its influence on porosity and permeability are key questions when discussing reservoir quality (e.g., Hogue et al., 2015; Crousse et al., 2015).

The purpose of this paper is to provide a review of the current understanding of the properties, origin, and implications of the occurrence of solid bitumen in unconventional plays. By reviewing these aspects in the literature we hope to: a) clear the confusion about the use of terms; b) point out some controversial and poorly understood issues related to solid bitumen's properties that are relevant to the geology of unconventional systems; and c) suggest further research to improve the understanding of the influence of solid bitumen on reservoir quality in unconventional plays.

2. Definitions and classifications of solid bitumen

The term "bitumen" is usually applied to naturally occurring liquid or solid petroleum that is soluble in organic solvents such as, for example, toluene, dichloromethane, or carbon disulfide (Hwang et al., 1998; Killops and Killops, 2005). Bitumen is predominantly a secondary product generated from the breakdown of kerogen during diagenesis. In contrast, kerogen is defined by geochemists as the fraction of OM preserved in sedimentary rocks that is insoluble in organic solvents (Durand, 1980; Tissot and Welte, 1984, Fig. 1). Kerogen is derived from the breakdown and diagenesis of the original plant and animal organic material. Confusing aspects of the relationships between kerogen, and bitumen and oil have been recently discussed by Burnham et al. (2018).

Solid bitumen (solid petroleum) has been studied extensively because of its common occurrence and applications (Abraham, 1960; Khorasani et al., 1979; Robert, 1988; Gentzis and Goodarzi, 1990; Khorasani and Michelsen, 1993; Mastalerz et al., 1995; Wilson, 2000; Hackley and Cardott, 2016; and many others). Consequently, many terms have been used to describe solid bitumen, introducing uncertainties about the relationships and correspondences among these terms. "Migrabitumen" (Jacob, 1989), "pyrobitumen" (Hunt, 1996), "tar mats" (Dahl and Speers, 1986), "dead oil," and "reservoir bitumen" (Hwang et al., 1998; Cheng et al., 2016) are only a few examples of terms used to describe solid petroleum in rocks.

In the field of organic petrography, solid bitumen is defined as a secondary maceral, to distinguish it from the primary macerals (Figs. 1 and 2). As a product of petroleum generation/expulsion from kerogen and, often, subsequent migration, solid bitumen is recognized dominantly using reflected light microscopy based on its pore and fracture-filling form, without having its own defined shape (e.g., Jacob, 1989; Landis and Castaño, 1995; Cardott et al., 2015; Wei et al., 2016). Because, as discussed later, the properties of solid bitumen, including its solubility, change with maturation, and because the solubility is not a parameter easily defined under microscope, in the organic petrography-based definition, solid bitumen may be at least partially insoluble, which differs in that aspect from the geochemistry-based definition of bitumen (Fig. 1).

"Pyrobitumen" is another term used by both organic geochemists and organic petrologists to describe the largely insoluble residue remaining after cracking of oil to gas.

(Tissot and Welte, 1984; Hunt, 1996; Suárez-Ruiz et al., 2012). However, in fact pyrobitumen is more than just insoluble residue from cracking of oil – rather, it is insoluble solid bitumen that developed molecular cross-linking and, thus, insolubility) (e.g., Tissot and Welte,