Marine and Petroleum Geology 73 (2016) 392–404

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Effect of kerogen on rock physics of immature organic-rich chalks

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ARTICLE INFO

Article history:
Received 5 January 2016
Received in revised form
17 March 2016
Accepted 19 March 2016
Available online 22 March 2016

Keywords:
Organic-rich chalk
Source rock
Porosity
Kerogen
Acoustic velocity
Poroelasticity
Tensile strength
Compressive strength

ABSTRACT

We study the rock physics of organic-rich chalk from the Shefela basin, central Israel, based on laboratory measurements of core material from the Zoharim well. This deposit is an immature source rock that includes the Late Cretaceous Ghareb and Mishash formations. The studied rock is composed of three dominating phases: minerals, kerogen, and pores. We investigate how porosity and kerogen influence the physical behavior of the rock, based on measurements of porosity, density, acoustic velocities, elastic moduli, tensile strength and compressive strength. We find that the dynamic bulk modulus and the static Young's modulus decrease with increasing kerogen content as well as with increasing porosity. To describe the stiffness of the solid skeleton we use two different poroelasticity models for fluid substitution assuming material isotropy: Biot-Gassmann model and Marion's BAM model. The obtained poroelasticity coefficients indicate a soft matrix composed of kerogen-micrite mixture, characterized by a low BAM normalized stiffness factor ($w \sim 0.2$) and a high Biot coefficient ($\beta \sim 0.9$). These values appear to vary with changes in kerogen content, grain size and degree of cementation. Porosity, which typically decreases with depth in the studied basin, does not show a clear correlation with kerogen content. Moreover, both compressive and tensile strengths decrease linearly with increasing porosity, regardless of kerogen content. We use a density–kerogen relationship to create a porosity depth profile, by combining data from continuous cores and density well logs. By comparing sonic logs with laboratory measurements of P-wave velocities on fully-saturated cores, we are able to detect a gas zone in the shallow interval of the sequence in the studied well.

1. Introduction

Organic-rich sediments are widely known as source rocks due to their high potential within the organic matter to produce oil and gas. These rocks are typically fine-grained sediments that include organic matter in solid and fluid states. Kerogen is solid, and is the most abundant organic phase in thermally immature source rocks. The physical properties of source rocks are strongly influenced by kerogen properties such as density, maturity level, chemical composition, elastic moduli and acoustic velocities. The advance in production technologies allows now to produce oil and gas from immature source rocks via in situ methods for inducing maturation. Moreover, tight source rocks may also contain producible hydrocarbons. These aspects, among others, motivate the study of rock physics of immature organic-rich rocks.

Several studies of rock physics of source rocks have been conducted (e.g. Bisnovat et al., 2015; Carcione, 2000; Pinna et al., 2011; Sayers, 2013; Vernik and Nur, 1992). These rocks often exhibit low permeability, low density, slow acoustic waves, mechanical softness, and porosity typically ranges from 0.5% to 45% (e.g. Bisnovat et al., 2015; Vernik and Nur, 1992). The mineralogical phase of source rocks is frequently occupied by shales, with illite being the most abundant mineral (Carcione, 2000). A model proposed by Vernik and Landis (1996) suggests that kerogen is isotropic whereas shales are transversely isotropic, thus suggesting that the entire medium is transversely isotropic. This may not be the case where the clay content is low, and the predominant minerals are quartz or carbonates (Carcione et al., 2011). Anisotropy stems from different origins, such as interlayering of lithologies, preferred orientation of minerals, and cracks induced by stresses or hydrocarbon expulsion (Vernik and Nur, 1992). Chalks are among the less studied organic-rich sediments, specifically in the field of rock

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http://dx.doi.org/10.1016/j.marpetgeo.2016.03.023
0264-8172/

physics, because rarely have they been identified as potential source rocks. Anisotropy in chalks is different than in shales due to differences in mineralogy and fabric. Consequently, the physical behavior of organic-rich chalks combines characteristics of non-organic chalks and organic-rich shales.

Organic-rich shales typically exhibit strong velocity anisotropy, low velocity in the bedding-normal direction, and relatively low density and porosity (Vernik and Milovac, 2011). These rocks are transversely isotropic with the symmetry axis in the bedding-normal direction, and can be described by five elastic constants: C_{11}, C_{33}, C_{55}, C_{66}, and C_{13} (for full definitions see Pinna et al., 2011; or Sayers, 2013). The Bakken shale is a case in point of rock physics of transversely isotropic source rocks (e.g. Carcione et al., 2011; Sayers, 2013; Vernik and Nur, 1992). Shale fabric is conceptualized as lenticular grains of illite rather than continuous sheets (Vernik and Landis, 1996; Vernik and Milovac, 2011). Sayers (2013) concluded that the kerogen in the Bakken reduces elastic stiffnesses when forms an interconnected network instead of discrete inclusions. Carcione et al. (2011) indicated that if kerogen is treated as part of the solid skeleton, it is optional to model the effective moduli using Hashin-Shtrikman bounds (Hashin and Shtrikman, 1963). Although Gassmann's theory is frequently used for predicting elastic moduli, it is noteworthy that organic-rich rocks do not obey some basic assumptions of that theory (Gassmann, 1951; Mavko et al., 2009). For example, not all skeletal components have the same bulk and shear moduli, and usually organic-rich rocks contain clays that may exhibit matrix anisotropy and non-negligible hygroscopy. Furthermore, Gassmann's theory assumes the pore pressure is equilibrated throughout the pore space, and that might not be the case where wave frequencies are higher, such as in laboratory ultrasonic devices or sonic well logs (Mavko et al., 2009). However, modifications of Gassmann's theory can lead to more accurate results, for example in cases of mixed mineralogy (Brown and Korringa, 1975) or by empirical models for specific lithologies (Krief et al., 1990).

Anisotropy of high-porosity chalks may be exhibited by parameters such as permeability, strength, elasticity and acoustic velocities. Korsnes et al. (2008) studied the Stevns Klint and Liege outcrop chalks, and reported isotropic permeability (1–4 mD) and tensile strength (0.5–0.58 MPa), but anisotropy in compressive strength and bulk modulus. Stevns Klint chalk exhibits greater stiffness parallel to bedding but the Liege chalk is stiffer normal to bedding. Talesnick, Hatzor and Tsesarsky (2001) found that compressive strength in the bedding-parallel direction is ~1.5 times greater than in the bedding-normal direction in the high-porosity transversely isotropic Marasha chalk, regardless of the water content in the range of 0-50%. Bisnovat et al. (2015) studied the mechanical and petrophysical properties of the organic-rich chalk in the Shefela basin which is also studied here, using cores from the Aderet well. They found that tensile strength ratios parallel/normal to bedding are 1.7 and 2.2 in the Ghareb and Mishash formations, respectively. Compressive strength was found to be positively correlated with total organic carbon (TOC), but porosity, permeability, tensile strength and static elastic moduli were not, despite of the high organic content (TOC up to 20%). It was also noted that the chalk exhibited brittle behavior at room conditions.

Chalks are typically highly porous, with a small pore size at the micro to nano meter scale, so that chalk physics depends strongly on pore-scale mechanisms. The Niobrara chalk in Denver basin contains a type II kerogen with TOC amounts of ~3.2% (Rice, 1986). There, the porosity decreases consistently with depth, from 45% at 300 m depth to ~5% at 2100 m (Lockridge and Pollastro, 1988). High porosity in chalks can be found even at great depths, as in the Tor and Ekofisk formations from the North Sea (Japsen et al., 2004), where porosity of 45% at 3 km depth is caused by ~15 MPa overpressure. At the high porosity range (35–42%), the Ekofisk chalk has a bulk modulus of about 3-8 GPa and shear modulus of 3.5–6 GPa (Røgen et al., 2005). Røgen (2002) showed that the acoustic properties of North Sea Chalk manifest isotropy. Olsen (2007) described in detail the poroelasticity of North Sea chalk. He found that the Iso-Frame model and the Marion's bounding average method (BAM) are more consistent than the self-consistent model by Berryman when both dry and water-saturated chalks are modelled. The derived poroelasticity coefficients are related to the degree of cementation and thus may also provide a proxy for Archie's cementation factor (Archie, 1942).

The studied Late- Cretaceous organic-rich chalk in the Shefela basin is situated in a syncline associated with the “Syrian Arc” folding system (Meilijson et al., 2014). This NE–SW elongated structure is about 90 km long and about 35 km wide (Fig. 1), and includes organic-rich sections with minimum thickness of 150 m (Gvirtzman et al., 1985). The sequence may be as thick as 550 m (Minster, 2009), and it constitutes the largest known organic-rich deposit in Israel, perhaps even in the Levant region. The kerogen classification is type IIS, due to its deep marine origin and high amounts of sulfur (Spiro, 1980). This thick sequence is located in the Shefela basin at shallow depths (several hundreds of meters), and was never exposed to significantly high temperatures. Consequently, the organic-rich chalk in the Shefela basin is an immature source rock. The kerogen-chalk mixture results in a high porosity, fine grained, dark brown rock, which contains mostly fine grained components (kerogen and micrite), some micron-scale foraminifers, and in some places large visible fossils and thin marl beds (Bisnovat et al., 2015; Burg et al., 2010). There are hardly any open fissures and bedding directivity is barely recognized in the naked eye. *In situ* stress measurements show that the stress field in the region is characteristic of “normal faulting” (e.g. Zoback, 2010), with maximum horizontal stress acting in ESE-WNW direction (Gersman et al., 2012).

In this study we performed laboratory measurements on cores from Zoharim well. The extensive research previously performed on Aderet well (Bisnovat et al., 2015) provides us with a good background for the mechanical and petrophysical behavior of this rock type. Enhancements obtained in the current study include ultrasonic velocities and dynamic elastic moduli, together with some modifications in the experimental methodology. Moreover, here the poroelasticity of the chalk is being thoroughly investigated, in order to improve interpretation of field tests (well logs and surface surveys), mainly regarding porosity, TOC, and fluid saturation. At this stage, the dynamic elasticity moduli of the organic-rich chalk are assumed to be isotropic, an issue we plan to further explore in the future. The main goal of this study is to obtain a deep understanding of the effects kerogen has on the physical nature of immature organic-rich chalks.

2. Methods

2.1. Petrophysical properties and ultrasonic velocities

Porosity, permeability and solids density were measured using Coreval30 poro-permeameter system, manufactured by Vinci Technologies, using Nitrogen gas. The measurements were performed on 1 inch length and 1 inch diameter oven-dried core plugs. Overall 65 samples from Ghareb formation and 24 samples from Mishash formation were measured. The plugs were subjected to 400 psi confining pressure during the tests. Geochemical analysis of the organic material focused on TOC measurements of cores, using an SC632 LECO for organic carbon and sulfur. TOC measurements were performed by Israel Energy Initiatives (IEI Ltd).

Ultrasonic velocities of core plugs, 1 inch length and 1 inch diameter, were measured using the Acoustic Velocity System