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Full Length Article

Fluid expulsion and microfracturing during the pyrolysis of an organic rich shale

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ABSTRACT

During progressive burial, low permeability organic-rich shale rocks evolve chemically and physically as the temperature and stress increase and organic matter matures. The transformation of organic matter into hydrocarbon, followed by its expulsion into secondary migration pathways along which it is conveyed into reservoirs rocks, is a coupled process that involves chemical reactions, changes in volume and stress leading to the nucleation and growth of microfractures, the opening and closing of these microfractures, and fluid transport through them. Primary migration was studied using an experimental setup that was designed to measure changes in fluid pressure, which are correlated with organic matter maturation and hydrocarbon expulsion. The setup consisted of a pressurized autoclave which was externally heated. Shale samples were confined, under an initially low confining pressure and an applied differential stress (0.18 MPa), and heated to temperatures of 210–320 °C. Changes in temperature, static pressure (pressure measured using a linear response transducer) and dynamic fluid pressures (measured using a piezoelectric differential transducer) in the autoclave chamber were monitored and recorded during each experiment. In the higher part of the temperature range, fluid produced by kerogen maturation and the concomitant formation of microfractures increased volumetric expansion of the shale. Power spectral densities of the fluid pressure signals were calculated and a conceptual model is proposed to explain the dynamics of fluid expulsions. While a power law distribution of frequencies of pressure burst amplitudes was identified, the frequencies of time intervals between successive expulsion events (waiting times) decrease monotonically with increasing waiting time. Co-generation of gas and liquid hydrocarbon was evidenced. Several samples were imaged after kerogen maturation using X-ray microtomography, and the data confirm the existence of a percolating network of microfracture that controls the primary migration of hydrocarbons.

1. Introduction

Identifying the processes that control the flow of hydrocarbons in tight rocks is important in understanding primary migration from source rocks into secondary migration pathways and how to increase the recovery of hydrocarbons from tight rocks formations [1]. Continuous burial of sedimentary rocks that are rich in organic content results in evolution of these materials and formation of organic fluids (oil and gas) and highly aromatic insoluble organic solids (matured kerogen and pyro-bitumen). As the temperature and pressure increase during progressive burial a complex mixture of fluids including hydrocarbons, carbon dioxide and water is produced. At first, the hydrocarbon produced by thermal decomposition (catagenesis) of the kerogen consists primarily of oil, but as the temperature and pressure continue to increase, the average molecular mass of the hydrocarbon produced from the kerogen decreases and eventually only natural gas is produced. In addition, oil that is retained in the source rock may be converted into natural gas and high carbon solids [2–8].

1.1. Maturation of organic matter in shales

The amount of oil and gas released during kerogen maturation depends on the chemical composition of kerogen, which depends in turn on the organic matter from which it was formed and the biochemical transformation that it underwent at shallow burial depths. Type I kerogen has the highest H/C ratio, it is formed from lipids and other organic matter (primarily in lacustrine sediments), and it has the highest oil generation potential. Type II kerogen is sourced primarily

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from planktonic marine organic matter. Type III kerogen, which has a lower H/C ratio than type II kerogen, is derived primarily from terrestrial organic matter, and it produces mainly natural gas. Type IV kerogen has the lowest H/C ratio, and it is not a significant source of hydrocarbon. Type II kerogen is the most important source of oil and natural gas. Methane is also produced by microbial activity at shallow burial depths. This is an important source of natural gas, but little of this gas is retained with the kerogen as it is buried to depths at which oil production occurs [7].

1.2. The onset of micro-fracturing and migration of organic matter

Several studies have correlated source rock maturation with petroleum migration, and early work is discussed in thorough reviews of primary migration [9–11]. Some investigators have used field observations to support the idea that microfractures serve as primary migration pathways [12–14]. Laboratory experiments also suggested that kerogen transformation leads to the formation of bed parallel microfractures. Propagation of these microfractures is controlled by the anisotropy of mechanical properties and the orientation of kerogen patches in the source rock [15,16]. Lash & Engelder [17] found microfractures that were filled with material which had chemical characteristics similar to those of decomposed kerogen. Observations of microfractures filled with calcium sulphate and organic materials [18] and horizontal microfractures at depths of 3.8–5 km have been reported [13]. Also, further studies of the conditions and processes that govern the dynamics of microfracture formation pointed towards a subcritical fracture propagation mechanism, because the transformation of kerogen to petroleum cannot increase the pressure in microfractures rapidly enough to drive critical fracture propagation. The rate of fracture propagation is governed by the chemical kinetics of fluid production during kerogen maturation [19], and while microscopic fracture propagation at high velocities, by a series of small jumps, has not been ruled out, chemically mediated fracture propagation (stress corrosion fracturing) appears to be more likely.

When kerogen is converted into oil, natural gas and other fluids, there is a net volume increase of about 10–20% under the prevailing temperature and stress conditions, and the resulting pressure is high enough to fracture the source rock and drive sub-critical microfracture propagation [20]. It has been proposed that microfractures play an important role in primary oil migration by providing pathways for fluid transport [13–15,17,18,21–23]. The microfractures formed by kerogen maturation tend to propagate along the laminations and bedding-parallel surfaces [16]. Based on linear elastic fracture mechanics theory, a mode I (opening mode) fracture propagates normal to the direction of the minimum principal stress, provided that the medium is isotropic [15]. At depth greater than ≈1 km, the largest principal compressive stress is usually the vertical lithostatic stress, and the least principal compressive stress lies more-or-less in the horizontal plane [24,25]. Since rocks are very weak materials under tensile stress, hydraulic fracturing is expected to occur preferentially along a vertical plane oriented perpendicular to the direction of the least principal compressive stress, and this is taken advantage of in high volume hydraulic fracturing to increase oil and gas production. However, on very small scales, strength effects become much more important and the local stress and pressure may deviate substantially from the large scale far field stress. Localized fluid production processes, such as the maturation of kerogen patches, changes the local stress state resulting in effective minimum principal stress that is perpendicular to the plane of lamination [26–28]. Because the kerogen concentration is higher in some laminae than others [17] and because of the high degree of structural and mechanical anisotropy that arises because of this lamination, orientation of anisometric particles such as stacked clay platelet aggregates during sedimentation and the increase in orientation that occurs during compaction, the strength and fracture toughness of many shales are much smaller for fractures parallel to the bedding plane than perpendicular to it [11,15,17].

1.3. Propagation of microfractures and primary migration

Propagating microfractures may coalesce, and when they reach pre-existing vertical fractures, that are open, partially healed or healed but weak, a three-dimensional fluid conductive fracture network that facilitates hydrocarbon primary migration may be formed. Because coalescence with pre-existing open or weak vertical fractures changes the stress field at the fracture tip, and the fluid pressure often decreases, propagation of the part of the horizontal fracture that reaches the pre-existing vertical fracture may cease [19]. A hydraulic fracture may propagate around a pre-existing fracture, and the parts of the fracture front that propagate around the pre-existing fracture may re-join behind it giving the false impression that the hydraulic fracture propagated through the pre-existing fracture. Microfractures formed by fluid production (natural micro-scale hydraulic fractures) may be expected to close when the fluid in them escapes to connected microfractures or pores more rapidly than the rate of fluid production within them. Even if microfractures become completely non-conductive because they become filled with minerals and/or bitumen, because of pressure solution creep or for other reasons, they may remain mechanically weak and, as demonstrated in analog experimental systems, they may become reopened as fluid production continues once enough fluid has penetrated into them and the pressure of the fluid becomes high enough to drive fracturing [29].

1.4. Experiments of primary migration

In the present study, we designed a system that enables very small hydrocarbon release events to be tracked during the maturation of immature Green River shale (a marlstone rich in type I kerogen) samples, by using pressure sensors with a time resolution in the order of 0.01–1 ms. The main goal was to experimentally characterize the fluid expulsion events, some of which are attributed to the appearance of microfractures at different heating temperatures. We determined whether weaker fluid expulsion events occurred at lower temperatures and whether these expulsions grew in size or in number as the temperature was raised. A persistent behavior in the fluid expulsion events that occurred at a constant elevated temperature was observed, and a conceptual model is proposed. We determined how much gas on average was released during the process. Preliminary analysis of the fluid expulsion data indicated that power law relationships might exist between several variables, and this was eventually verified for one of them (the probability distribution of burst amplitudes, where a burst consists of a set of pressure pulses closely spaced in time). We address how confinement affects the rock fracturing behavior. A series of specifically-designed experimental studies of fluid expulsion and development of microfracture networks and their contributions to the flow of hydrocarbons in the primary migration process are discussed.

2. Materials and methods

2.1. Sample preparation and sample holder

Cylindrical core samples, 25 mm or 28 mm in diameter and with aspect ratios (length/diameter) of 0.6 and 1 respectively, were drilled from a Green River Shale block. This rock is an immature marlstone, which contains type I kerogen [30]. Previous experiments have shown that kerogen maturation at atmospheric pressures occurs in this organic rich rock on time scales that are convenient for laboratory experiments (1–10 days) at temperatures in the 300–350 °C range [16]. The sample dimensions and experimental conditions that were used for system calibrations and kerogen maturation experiments are provided in Table 1. The smaller diameter samples were placed inside a sample holder (Fig. 1), which has the same dimensions as the inner space of the