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Research paper

Potential of porosity waves for methane transport in the Eugene Island field of the Gulf of Mexico basin

Ajit Joshi*, Martin S. Appold

Department of Geological Sciences, University of Missouri, Columbia, MO 65211, USA

A R T I C L E I N F O

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A B S T R A C T

The Eugene Island minibasin and hydrocarbon field in the northern Gulf of Mexico basin is a well-documented occurrence of anomalously rapid fluid migration. A variety of evidence suggests that hydrocarbons ascended through kilometers of very low permeability sediments separating source rocks and reservoirs at velocities up to kilometers per year. Previous research has shown that porosity waves could transport petroleum at millimeter per year velocities under a narrow range of low permeabilities. The purpose of the current research was to test the hypothesis that porosity waves could transport methane much more rapidly than oil.

To test this hypothesis, a one-dimensional numerical model of porosity wave behavior was constructed for Eugene Island sediments saturated with methane. The results show that gradual rates of pore fluid pressure generation typically caused by diagenesis are too slow for porosity waves to transport methane at kilometer per year rates. Instead, essentially geologically instantaneous pore fluid pressure increases are needed, which then could allow porosity waves to ascend 1–2 km at velocities >10's of m/year. Thus, porosity waves could only reach the lower reservoirs at Eugene Island, but could transport methane orders of magnitude faster than the background Darcian flow regime. Based on their predicted size, 10's of porosity waves would have been needed to charge these lower reservoirs with their original amount of methane. Whether a mechanism for instantaneous pore fluid pressure generation exists at Eugene Island is unclear. Earthquakes are capable of generating essentially instantaneous pore fluid pressure increases of order 1's of MPa or greater, although Eugene Island's seismic history is thought to have been relatively quiet. Thus, despite their high velocities, porosity waves are unlikely to have played a major role in transporting methane at Eugene Island, but could have in other more seismically active locations where required methane transport distances are smaller.

1. Introduction

The seeming ability of hydrocarbons to ascend quickly through thick sequences of low permeability sediments that separate hydrocarbon source rocks from reservoirs has been widely reported for the northern Gulf of Mexico basin (Anderson et al., 1994; Haney et al., 2005; Losh et al., 1999; Whelan et al., 2001; Young et al., 1977). One of the best documented examples is the Eugene Island minibasin and hydrocarbon field, where the principal hydrocarbon reservoirs are Plio-Pleistocene sands lying at depths of about 0.5–3 km, but the principal hydrocarbon sources are no younger than Early Tertiary sediments located at depths of at least 4.5 km. The hydrocarbon sources and reservoirs are separated by muds and shales whose permeabilities decrease with depth to perhaps as low as 10^{-24} m^2 at 4.5 km depth (Revil and Cathles, 2002). Despite such low permeabilities, a variety of geochemical and geophysical evidence suggests that hydrocarbons may have ascended through these sediments at rates of at least millimeters per year to as high as kilometers per year (Guerin, 2000; Haney et al., 2005; Losh et al., 1999; Nunn, 2003; Revil and Cathles, 2002; Roberts, 2001; Roberts and Nunn, 1995; Whelan et al., 2001) compared to rates of millimeters per million years predicted from Darcy's law (Joshi et al., 2012). This research and that of Lin and Nunn (1997) suggest that most of the hydrocarbon migration is likely to have been focused along the Red fault, a major growth fault along the eastern margin of the Eugene Island minibasin.

Previous researchers have proposed that porosity waves could be responsible for the anomalously rapid hydrocarbon migration

* Corresponding author.
E-mail address: aj2v4@mail.missouri.edu (A. Joshi).

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observed at Eugene Island. Porosity waves can arise in porous media that are deformable enough for porosity to dilate significantly in response to increases in pore fluid pressure and corresponding decreases in effective stress (Connolly and Podladchikov, 1998, 2015; McKenzie, 1987). The porosity waves travel as diffusion fronts toward regions of lower pressure, transporting fluids within their dilated porosity. The very rapid migration rates of porosity waves become possible if permeability increases sharply in response to increases in pore fluid pressure and porosity.

Appold and Nunn (2002) investigated the capability of porosity waves to transport oil in viscous sediments by building a one–dimensional numerical model that simulated the burial of an organic rich sedimentary layer and the conversion of kerogen to oil. Their results showed porosity waves to form as zones of elevated liquid fraction (i.e. fluid–filled porosity) where rates of hydrocarbon generation were high. In contrast to elastic porous media where porosity waves ascend along pressure gradients, in viscous porous media porosity waves ascend due to buoyancy at rates Appold and Nunn (2002) calculated to be up to about 1 mm per year. Revil and Cathles (2002) derived an analytical solution for porosity wave velocity from differential equations for fluid mass conservation in elastic porous media. They predicted that porosity waves traveling along the Red fault under high overpressures and whose pore space was saturated with a dense (e.g. 800 kg m^{-3}) fluid could reach velocities of 1's to 10's of km year^{-1}. Joshi et al. (2012) carried out a numerical modeling investigation of porosity wave behavior in highly overpressured, oil-saturated, elastic porous media. Porosity waves formed best where the hydraulic diffusivity was low relative to the rate of pore pressure generation, which was caused by compaction disequilibrium and hydrocarbon generation. Joshi et al. (2012) found that porosity waves having the greatest capability to transport oil formed under a narrow range of low permeabilities between 10^{-25} and 10^{-24} m^2, could only ascend distances of between one and 2 km before diffusing into the background, traveled at maximum velocities of millimeters per year, and had a low frequency of formation. Thus, they concluded that porosity waves are unlikely to have been an important mechanism for transporting oil at Eugene Island. However, Joshi et al. (2012) hypothesized that porosity waves may be much more effective at transporting methane because of methane's lower density and viscosity compared to oil.

The generation and velocity of porosity waves in elastic porous media is strongly affected by the ratio of the pressure generation rate (P_g) to the hydraulic diffusivity (D), where

$$D = \frac{k\rho_f g}{\mu_f S_s} \tag{1}$$

and k is the intrinsic permeability, ρ_f and μ_f are density and viscosity of the pore fluid respectively, g is the acceleration due to gravity, and S_s is the specific storage of the porous medium. Joshi et al. (2012) found that in order for porosity waves to reach velocities of at least millimeters per year in oil–saturated porous media, the P_g/D ratio must exceed about 10^8 Pa m^{-2}, which results in the formation of a discrete peak in amplitude in the porosity waves. When the P_g/D ratio is lower, then pore pressures diffuse away into the surroundings before pore pressure, porosity, and permeability can increase enough to form a rapidly moving porosity wave. Joshi et al. (2012) predicted an average pressure generation rate of about 30 Pa year^{-1} in the hydrocarbon source rocks at Eugene Island, caused primarily by compaction disequilibrium with minor contributions from hydrocarbon generation late in the history of the minibasin. This low pressure generation rate is why Joshi et al. (2012) found porosity wave formation to be limited to sediments with very low permeabilities on the order of 10^{-24} to 10^{-25} m^2, as noted above, in order to raise sufficiently the P_g/D ratio. If a similar P_g/D ratio were needed to form porosity waves in methane–saturated sediments (Joshi, 2015), then given the high hydraulic diffusivity of methane–saturated porous media, a pressure generation rate of ~2000 Pa year^{-1} would be required.

The purpose of the current research was to test the hypothesis that porosity waves could be more effective at transporting methane than oil from deep source rocks to much shallower reservoirs in the Eugene Island minibasin. To test that hypothesis, the research sought to answer the questions of how large porosity waves can get, how frequently they can form, how fast and far they can travel, and how much methane they can transport. The research results potentially have implications not only for Eugene Island but also for other locations where methane has apparently moved rapidly through low permeability, overpressured sediments.

2. Geological setting

The Eugene Island minibasin hosts one of the largest Plio–-Pleistocene oil and gas fields in the outer continental shelf of the Gulf of Mexico basin and has been extensively studied by previous researchers (Alexander and Flemings, 1995; Alexander and Handschy, 1998; Anderson et al., 1994; Gordon and Flemings, 1998; Haney et al., 2005; Hart et al., 1995; Holland et al., 1980, 1990; Joshi et al., 2012; Losh et al., 1999, 2002; Roberts, 2001). The minibasin is about 19 × 15 km in dimensions and is located about 270 km southwest of New Orleans, USA (Fig. 1). The minibasin formed during the time of maximum sedimentation in the Pliocene–Pleistocene that shifted the center of the deposition over 320 km southwestward from just west of the present mouth of the Mississippi River to 160 km south of the present shoreline of the Louisiana–Texas, USA state border (Woodbury et al., 1973). The rapid deposition of sediments caused the withdrawal of the underlying thick Miocene salt layer, leading to the development of listric normal growth faults and salt diapirs that bound the minibasin. Evidence from pore fluid chemistry, kerogen maturity indicators, hydrocarbon composition, borehole logging, fault-plane-section-analysis, and three dimensional seismic surveys indicates that the growth faults could have served as preferential conduits for the episodic ascent of fluids (Anderson et al., 1994; Haney et al., 2005; Lin and Nunn, 1997; Losh, 1998; Losh et al., 1999; Whelan et al., 2001). Some of the hydrocarbon fluids were trapped in rollover anticlines formed in the downthrown blocks of the growth faults (Holland et al., 1990).

Alexander and Flemings (1995) subdivided the structural and stratigraphic evolution of the Eugene Island minibasin into three phases: prodelta, proximal deltaic, and fluvial. During the early prodelta phase, the deposition of bathyal and prodelta shales, turbidites, and distal deltaic sands on top of the salt layer caused the salt layer to migrate outward laterally, creating more accommodation space above the layer for sedimentation. The principal sand reservoir deposited during this phase was the *Lentic* sand, which is overpressured. The proximal deltaic phase is characterized by the deposition of low stand, shelf–margin deltas that consist of alternating sequences of sand and mud in distributary channel, distributary channel–mouth bar, and delta–front environments. The sand reservoirs, such as OI, MG, LF, KE, JD and HB, deposited in this phase are moderately overpressured. During the late fluvial phase, the underlying salt layer was completely evacuated from the minibasin such that little further accommodation space for sedimentation was created. The deltaic system then prograded southward, forming an erosional unconformity on the exposed shelf. A major reservoir, the GA sand, was deposited early during the fluvial phase when faults were active and created structural closure for the