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Capillarity Controlled Displacements in Sediments With Movable Grains: Implications for Growth of Methane Hydrates

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Abstract

Gas invasion of sediments is one mechanism by which methane hydrates are believed to form. As the capillary pressure exerted by an accumulated gas phase below the hydrate stability zone increases, it can exceed the entry pressure of the sediment within the hydrate stability zone, leading to a drainage displacement. Alternatively it can exceed the parting pressure of the sediment, leading to a gas-filled fracture propagating into the sediment. In unconsolidated ocean sediments, the capillary pressure may also be large enough to move grains apart during drainage. This motion alters the pore throat sizes which control subsequent drainage of the sediment. A model for the dynamics of this process is useful for assessing the competition between drainage (controlled by capillary forces) and fracturing (controlled by pore pressure and earth stresses). This in turn provides insight into the possible growth habits within the hydrate stability zone.

To model this process we consider immiscible displacements when fluid/fluid interfaces are controlled by capillary forces. The progressive quasistatic (PQS) algorithm based on the level set method readily determines the pore level geometry of these interfaces. Capillary pressure generally exerts a net force on grains supporting an interface. We extend PQS algorithm to implement a kinematic model of grain displacement in response to that force. We examine the changes in the drainage curve caused by this coupling. We compute the interfacial area associated with the bulk water phase, anticipating preferential growth of methane hydrate there.

When grains can move in response to net force exerted by the gas phase, small variations in an otherwise uniform distribution of pore throat sizes lead to self-reinforcing, focused channels of gas phase. In contrast to behavior in stationary grains, the drainage curve exhibits no clear percolation threshold. Displacements in materials with broad throat size distributions also exhibit self-reinforcing channels. Behind the leading edge of the displacement front, the net force exerted on the grains tends to push them together. This effectively seals off these regions from subsequent invasion. Thus hydrate growth tends to be localized along the channel of displaced grains.

1. Introduction

The Earth's crust contains a very large amount of carbon held as methane hydrates in relatively shallow sediments (Collett *et al*. 1999). Unfortunately the uncertainty regarding the amount is also large, and this hinders the task of assessing the potential resource. One way to reduce the uncertainty is to understand better the growth habit of hydrates, e.g., whether they occur as cement at grain contacts, as material filling pores between sediment grains, as a solid comprising part of the load-bearing framework, as veins or fractures, etc. Knowledge of the growth habit at the grain scale would enable improved inversion of standard logging measurements for hydrate saturation S_H, This knowledge would also inform methods and models of gas production from hydrate accumulations.

The growth habit of methane hydrates depends on the mechanism by which methane is brought into the hydrate stability zone (HSZ). (The HSZ refers to a range of depths, either below permafrost or below the ocean floor, within which the pressure and temperature are such that methane hydrate is thermodynamically stable.) Paradoxically, gas is observed to co-exist with hydrates in some hydrate provinces. Moreover, the solubility of methane in brine is two orders of magnitude smaller than the concentration of methane in hydrate. These observations have led us to examine the mechanisms by which a gas phase could enter the HSZ (Behseresht *et al*. 2007 and 2008b). There are two limiting cases (Behseresht *et al*. 2008a): drainage, in which gas displaces brine from the sediment after building up enough pressure to exceed the capillary entry pressure, and fracture propagation, in which the gas phase pressure builds up enough to exceed the least confining stress. In the latter case, the gas-water meniscus is assumed to form an "elastic membrane" that exerts a net force on the grains supporting the meniscus, but the gas phase capillary pressure does not lead to drainage into the walls of the fracture.