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Granular experiments of thrust wedges: Insights relevant to methane hydrate exploration at the Nankai accretionary prism

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ABSTRACT

The accumulation mechanism of methane hydrates has been a central issue in previous hydrate research regarding the Nankai accretionary prism, southwest of Japan. Expulsion of formation fluids is significant during the prism accretion process, and the migration of these methane-bearing fluids exerts a strong control on the accumulation of hydrates. Two types of fluid pathways, inter-granular porosity and faults, need to be evaluated to understand hydrate accumulation. Fluid migration along faults can be partly modeled by examining faulting activity. Our study modeled the accretion process by using two granular methods that approximated the geologic body as an assemblage of particles: (1) analog experiments using granular materials, and (2) a numerical simulation based on the distinct element method. The analog experiments closely reproduced the prism geometry observed in seismic profiles across the Nankai accretionary prism. Digital image correlation analysis indicated that the frontal thrust is generally active but older structures are also frequently reactivated. The numerical simulations produced prism geometries similar to those of the analog experiments. The velocity distributions of the particles showed evidence of episodic faulting and reactivation, but the internal stress field exhibited little change in the deeper part of the prism during deformation. The frequent and substantial changes in fault activity displayed by the models indicate episodic fluid flow along fault surfaces. Active frontal thrusting suggests that formation fluids generally migrate from deep within the prism to the deformation front, but may move along reactivated older faults. Inter-granular permeability also fluctuates, as it is controlled by temporal and spatial variations in the internal stress field. However, fluid flow is likely to be relatively stable in the deeper segment of the prism.

1. Fluid flow and methane hydrates in accretionary prisms: an introduction

Vast quantities of methane hydrates are present in accretionary prisms around the world (Collett, 2002). The distribution of hydrates has been examined through the regional development of bottom simulating reflections (BSRs) on seismic profiles (e.g., Aoki et al., 1983; Minshull and White, 1989; Davis et al., 1990; Ferguson et al., 1993; Delisle et al., 1998; Ashi et al., 2002; Baba and Yamada, 2004). Allison and Boswell (2007) reported an estimated 400 × 10^6 trillion cubic feet (TCF) of methane gas in hydrates worldwide, which is at least 2–10 times greater than the confirmed conventional natural-gas reserves. Industrial and scientific drilling projects have confirmed the presence of methane hydrates in accretionary prisms in the Middle American Trench (Kvenvolden and McDonald, 1985), offshore Costa Rica (Shipboard Scientific Party Site 1041, 1997), the Cascadian margin, USA (Tréhu et al., 2003; Expedition 311 Scientists, 2005), and the Nankai Trough (Taira et al., 1992; Matsumoto, 2002; Tsuji et al., 2005; Kinoshita et al., 2008).

These studies have revealed many uncertainties regarding methane hydrates that require further examination. For example, although the existence of methane hydrates in accretionary prisms has been confirmed at several locations, the occurrence and accumulation of methane hydrate deposits are not fully understood. A recent geophysical investigation showed that the characteristics of BSRs in seismic profiles are strongly dependent on the method of data acquisition, in particular the type of seismic source used

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(Kamei et al., 2005). Our understanding of the rock physics of hydrate reservoirs is still relatively simple, with a focus on the microscale (e.g., Dvorkin et al., 2000), though efforts to measure flow velocities have been undertaken in a laboratory setting (e.g., Priest et al., 2005; Yun et al., 2005). Accurate methods for the detection of hydrates and evaluation of their regional volumes have not been established to date, other than that used in a study in the eastern Nankai area (Japan Oil, Gas and Metals National Corporation (JOGMEC), 2011), as detailed below.

Depressurization appears promising as a production method for methane gas from hydrates. This follows significant success at the Mallik test site for continental natural-gas hydrates in the Mackenzie Delta in the northwestern Canadian Arctic (Research Consortium for Methane Hydrate Resources in Japan, 2008). The methods for production of offshore hydrates are, however, still being examined exclusively in laboratories, except for one offshore experiment in the Nankai Trough (JOGMEC, 2011).

Hydrate research has clarified several aspects of the formation and accumulation of methane hydrates. The formation of methane hydrates is primarily controlled by the chemical conditions of hydrate stability and methane solubility in the formation water (e.g., Claypool and Kaplan, 1974; Pecher et al., 1998; Clennell et al., 2000). The gas hydrate stability zone (GHSZ) in ocean-floor sediments is located between the ocean floor and the maximum depth below the ocean floor at which gas hydrates are stable, as defined by temperature and pressure. In a typical accretionary prism, where heat flow is usually low (e.g., Yamano et al., 1982; Ashi et al., 2002), the base of the GHSZ is a few hundred meters below the ocean floor. As accretionary prisms are tectonically active, pressure conditions are not always static, meaning that the depth of the base of the stability zone also fluctuates. For example, when sediments are uplifted by thrust movement, the base of the stability zone migrates upward due to the reduction in pore fluid pressure. This upward migration causes dissociation of hydrates at the former base of the GHSZ, and subsequent upward migration of the dissociated gas. The migrated dissociated gas then re-forms gas hydrates at the base of the new stability zone—this may be the mechanism that causes methane hydrate concentration near the base of the stability zone (e.g., Bangs et al., 2005). Actual methane hydrates are distributed in the gas hydrate occurrence zone (GHOZ) where the concentration of methane exceeds its solubility in the formation water (Tréhu et al., 2006). This occurrence zone generally occupies the lower–middle part of the stability zone.

Methane can be classified as biogenic or thermogenic, based on the processes by which it formed. Biogenic methane is generated by the biological activity of methane-producing bacteria in sediments at shallow depths below the ocean floor (Claypool and Kaplan, 1974). The generation of thermogenic methane usually occurs in deeply buried sediments, typically greater than 2 km below the ocean floor (Tréhu et al., 2006), and may be the result of the same processes that produce hydrocarbons in sedimentary basins (Hyndman and Davis, 1992). Although the content of organic carbon in the accreting sediments is sometimes less than 1% (e.g., Nankai; Taira et al., 1992; Waseda, 1998), BSRs can still be observed in such regions, suggesting some uncertainty in the generation mechanism of methane at convergent margins.

The two modes of methane generation suggest that the distribution patterns of biogenic and thermogenic methane hydrates are likely to be significantly different. Microbial methane can be generated wherever sediments contain organic carbon (Davie and Buffett, 2001). The average concentration of biogenic methane hydrates is generally equivalent to a small percentage of the total porosity (e.g., Lorenson, 2000; Tréhu et al., 2004), and such hydrates tend to accumulate near the base of the hydrate occurrence zone. In contrast, thermogenic methane migrates from deeply buried sediments along fluid pathways, driven by the advection of formation fluids. Thermogenic methane may be periodically expelled from the formation zone, and subsequently migrates to the GHOZ. Therefore, thermogenic methane hydrates are frequently concentrated in faults and high-permeability layers that form the migration pathways for the fluid. The concentration of hydrates in the GHOZ increases over time, as long as the ‘petroleum system’ of thermogenic methane generation and migration is maintained. The concentration of thermogenic methane hydrate is generally much higher than that of sparsely distributed biogenic methane hydrates. We suggest that these concentrated thermogenic hydrates are the best candidates for commercial methane hydrate exploration.

To clarify the accumulation mechanism of thermogenic methane hydrates in accretionary prisms, the migration of formation fluids needs to be examined in detail (Baba and Yamada, 2004). The fluid pathways in accretionary prisms can be classified into two types: migration through inter-granular pore spaces, and migration along faults (Fig. 1). Given that the accreted sediments are weakly consolidated, inter-granular porosity is expected to be extremely high (e.g., 61% recorded by Dugan and Flemings (2000)). This is particularly significant in shallower sediments where fluid flows through inter-granular pore spaces. This type of fluid flow, called ‘diffusive flow’ (Baba and Yamada, 2004), is primarily controlled by the stress field, including the overburden pressure, which affects the volume and geometry of the inter-granular pore space. Fluid flow along faults, termed ‘focused flow’ (Baba and Yamada, 2004), plays a more important role in deeper sediments, which are relatively consolidated and less permeable. The occurrence of focused fluid flow in accretionary prisms has been confirmed by isotope analysis, heat-flow measurements, and analyses of hydrates (e.g., Sample, 1996; Suess et al., 1999). Fluid flow in accretionary prisms is a combination of these two flow types (Fig. 1). In deeper parts of the prism, fluid expelled by the overburden pressure predominantly migrates along faults (focused flow). Most of the fluids then migrate to shallower horizons through inter-granular pore spaces (diffusive flow) to form hydrates in the occurrence zone.

Qualitative modeling of diffusive flow is possible through the use of conventional reservoir simulators, but no universal method has been established to model focused flow (Hickman et al., 1995; Wilkins and Naruk, 2007). Sibson (1990) proposed a model of focused flow in which fluid flow occurs along a fault surface coeval with fault displacement, driven by the hydromechanical behavior of the fault. This fault-valve model requires a large amount of high-

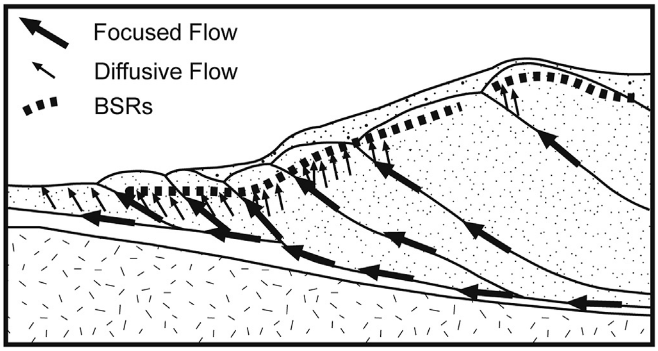

Figure 1. Model of fluid flow within an accretionary prism (after Baba and Yamada, 2004). The fluid pathways can be classified into two types: diffusive flow through inter-granular pore spaces, and focused flow along faults. The total fluid flow is the sum of these two types.