JGR Solid Earth

INTRODUCTION TO A SPECIAL SECTION
10.1029/2019JB018186

Special Section:
Gas Hydrate in Porous Media: Linking Laboratory and Field-Scale Phenomena

Introduction to Special Issue on Gas Hydrate in Porous Media: Linking Laboratory and Field-Scale Phenomena

C. D. Ruppel[1], J. Y. Lee[2], and I. Pecher[3]

[1]U.S. Geological Survey, Woods Hole, MA, USA, [2]Korean Institute of Geoscience and Marine Resources, Daejeon, South Korea, [3]School of Environment, University of Auckland, Auckland, New Zealand

Abstract The proliferation of drilling expeditions focused on characterizing natural gas hydrate as a potential energy resource has spawned widespread interest in gas hydrate reservoir properties and associated porous media phenomena. Between 2017 and 2019, a Special Section of this journal compiled contributed papers elucidating interactions between gas hydrate and sediment based on laboratory, numerical modeling, and field studies. Motivated mostly by field observations in the northern Gulf of Mexico and offshore Japan, several papers focus on the mechanisms for gas hydrate formation and accumulation, particularly with vapor phase gas, not dissolved gas, as the precursor to hydrate. These studies rely on numerical modeling or laboratory experiments using sediment packs or benchtop micromodels. A second focus of the Special Section is the role of fines in inhibiting production of gas from methane hydrate, controlling the distribution of hydrate at a pore scale, and influencing the bulk behavior of seafloor sediments. Other papers fill knowledge gaps related to the physical properties of hydrate-bearing sediments and advance new approaches in coupled thermal-mechanical modeling of these sediments during hydrate dissociation. Finally, one study addresses the long-standing question about the fate of methane hydrate at the molecular level when CO_2 is injected into natural reservoirs under hydrate-forming conditions.

Key Points:
- The arc of laboratory and modeling research focused on hydrate-bearing sediments has been based on the findings of major field programs
- The Special Section highlights hydrate formation from vapor phase methane in porous media and the role of fines in hydrate reservoirs
- The Special Section underscores the importance of coupled mechanical and thermodynamic models for tracking gas hydrate reservoir evolution

Correspondence to:
C. Ruppel,
cruppel@usgs.gov

Citation:
Ruppel, C., Lee, J. Y., & Pecher, I. (2019). Introduction to special issue on gas hydrate in porous media: Linking laboratory and field-scale phenomena. *Journal of Geophysical Research: Solid Earth*, *124*, 7525–7537. https://doi.org/10.1029/2019JB018186

Received 12 JUN 2019
Accepted 3 JUL 2019
Accepted article online 29 JUL 2019
Published online 14 AUG 2019

1. Introduction

The past decade has seen a marked increase in the number of laboratory and numerical modeling studies focused on porous media phenomena related to hydrate-bearing sediments (HBS), which are defined as sediments containing gas hydrate at any saturation. This research trend has been driven in part by steady progress toward conducting more frequent and longer-duration field tests of methane extraction from gas hydrate deposits (Konno et al., 2017; Kurihara et al., 2005, 2010; Moridis et al., 2011; Schoderbek et al., 2013; Uddin et al., 2012; Yamamoto et al., 2014). Designing such tests and interpreting the results require refinements in reservoir modeling to appropriately account for the response of sediments, hydrate, pore fluid, and gas during production processes. Laboratory studies, whether reliant on idealized sediments or natural samples, provide most of the raw data to support the refinement of reservoir models.

An additional motivation for the increased number of HBS studies over the last two decades has been the recognition that the complexities of HBS vary across all spatial scales and that processes at all spatial scales contribute to the bulk behavior of HBS. Thus, continued studies to define the nature and behavior of HBS are valuable at all scales, from the subpore to the scale of recovered cores (maximum of a few meters) and entire boreholes and up to the field scale that characterizes seismic or other types of shipboard geophysical imaging (Waite et al., 2009).

To capture some of the recent developments in porous media studies related to gas hydrates, the *Journal of Geophysical Research* compiled contributed papers in a Special Section between late 2017 and early 2019 (Table 1). The resulting 21 papers cover a wide range of topics but are organized around the central themes of hydrate formation and dissociation in porous media and laboratory physical properties. This paper provides an overview of the Special Section and introduces connections between past research and the current state of the art in some disciplines relevant to HBS.

2. Background

In nature, gas hydrate forms when low molecular weight gases like methane (CH_4), ethane (C_2H_6), H_2S, or CO_2 combine with water to produce an ice-like solid under conditions of moderate pressure (generally 0.5

Table 1
Papers in the Special Section, in Order of First Citation in This Commentary

Citation	Title
	Hydrate formation mechanisms
VanderBeek and Rempel (2018)	On the importance of advective versus diffusive transport in controlling the distribution of methane hydrate in heterogeneous marine sediments
Lei and Santamarina (2018)	Laboratory strategies for hydrate formation in fine-grained sediments (*also fines)*
You and Flemings (2018)	Methane hydrate formation in thick sandstones by free gas flow
Meyer, Flemings, and DiCarlo (2018)	Effect of gas flow rate on hydrate formation within the hydrate stability zone
Meyer, Flemings, DiCarlo, You, et al. (2018)	Experimental investigation of gas flow and hydrate formation within the hydrate stability zone
Sahoo et al. (2018)	Presence and consequences of coexisting methane gas with hydrate under two phase water-hydrate stability conditions
Almenningen et al. (2018)	Upscaled anisotropic methane hydrate critical state model for turbidite hydrate-bearing sediments at East Nankai Trough
Ge et al. (2018)	Laboratory investigation into the formation and dissociation process of gas hydrate by low-field nuclear magnetic resonance technique
	Role of fines
Han et al. (2018)	Depressurization-induced fines migration in sediments containing methane hydrate: X-Ray computed tomography imaging experiments
Hyodo et al. (2017)	Influence of fines content on the mechanical behavior of methane hydrate-bearing sediments
Jang et al. (2018)	Impact of pore fluid chemistry on fine-grained sediment fabric and compressibility
Taleb et al. (2018)	Hydromechanical properties of gas hydrate-bearing fine sediments from in situ testing
	Geomechanical and hydraulic properties
Spangenberg et al. (2018)	A quick look method to assess the dependencies of rock physical sediment properties on the saturation with pore-filling hydrate
Madhusudhan et al. (2019)	The effects of hydrate on the strength and stiffness of some sands
Kossel et al. (2018)	The dependence of water permeability in quartz sand on gas hydrate saturation in the pore space
Gil et al. (2019)	Numerical analysis of dissociation behavior at critical gas hydrate saturation using depressurization method
Cook and Waite (2018)	Archie's saturation exponent for natural gas hydrate in coarse-grained reservoirs
Zhou et al. (2018)	Upscaled anisotropic methane hydrate critical state model for turbidite hydrate-bearing sediments at East Nankai Trough
	Coupled numerical modeling
Sánchez et al. (2018)	Coupled numerical modeling of gas hydrate-bearing sediments: From laboratory to field-scale analyses
Kim et al. (2018)	Methane production from marine gas hydrate deposits in Korea: Thermal-hydraulic-mechanical simulation on production wellbore stability
	CO_2-CH_4 hydrate dynamics within the reservoir
Schicks et al. (2018)	From microscale (400 μl) to macroscale (425 L): Experimental investigations of the CO_2/N_2-CH_4 exchange in gas hydrates simulating the Iğnik Sikumi Field Trial

to 30 MPa) and low temperature (generally less than 30 °C). Excluding Antarctic gas hydrates (Wadham et al., 2012), which are poorly characterized, more than 98% of the estimated methane (McIver, 1981; Ruppel, 2015) trapped in gas hydrate probably exists in marine sediments on continental margins at water depths greater than ~500 m (as shallow as 300 m at high latitudes). Most of the remaining gas hydrate has formed within or beneath ice-bearing permafrost at high latitudes, particularly in sediments that overlie major thermogenic basins (Ruppel, 2015). Minor components of the global gas hydrate system are found beneath the Tibetan Plateau (Gong et al., 2015) and Lake Baikal (Scholz et al., 1993) and in locations that would have been beneath ice sheets at the Last Glacial Maximum (e.g., Portnov et al., 2016). Exhaustive recent reviews of the different environments for gas hydrate occurrence, the global amounts of sequestered methane, and the susceptibility of gas hydrate to degradation due to oceanographic and climate change can be found in Boswell and Collett (2011) and Ruppel and Kessler (2017).

In some cases, gas hydrate concentrates to form relatively pure deposits in voids or fractures within the sedimentary section; however, the hydrate that forms within the matrix of porous sediments is probably the most important volumetrically. A focus on the bulk hydrate-bearing porous medium, instead of single crystal or pure hydrate (e.g., Stern et al., 2000), is therefore critical to advancing understanding of natural gas hydrate systems. Hydrate-bearing porous media combine sediment with multiphase pore fill, which can be gas hydrate, vapor phase (free gases such as methane, higher-order hydrocarbons, and CO_2), and/or fluid (water, brine, or liquid hydrocarbons). Fine-grained particles that are mixed with coarser sediments can be mobilized under certain conditions and are also considered a component of pore fill in some cases.

Porous media studies have long been plagued by the difficulty of transferring findings derived from a specific field setting, laboratory setup, or modeling approach to more general circumstances, and this situation is only exacerbated for HBS. For low saturation (<40%, which is the threshold below which gas hydrate formed from dissolved phase methane does not significantly stiffen the sediments; Yun et al., 2007), the properties of the porous media can exercise the primary control on the behavior and physical properties of the HBS. For higher saturations, explicit consideration of the relationship between hydrate and the sediment grains/interstitial fluid is usually necessary to elucidate the mechanisms associated with the sediments' response to deformation, thermal perturbation, or other phenomena.

3. Special Section Themes

The 21 studies in this Special Section adopt a range of approaches for elucidating porous media phenomena in HBS and making the links between small-scale investigations and the field scale that is appropriate for reservoir characterization. The papers contributed to the Special Section can be roughly divided among several themes: (a) the impact of multiphase (particularly vapor phase) pore-filling materials and/or flow on the formation/dissociation of gas hydrate in porous media, (b) the role of fines, (c) the physical properties of HBS, and (d) full thermal-hydraulic-mechanical coupled modeling of HBS subject to perturbations associated with dissociation. This section describes the different classes of studies in the Special Section and places the new contributions in the context of historical developments in understanding HBS.

3.1. Free Gas Within the Hydrate Stability Zone

A major theme of the Special Section is the role of the vapor (free gas) phase in the formation of hydrate in natural reservoirs and the resulting HBS properties. At the end of the twentieth century, the paradigm for the evolution of hydrate in deep water marine sediments was largely driven by findings from Ocean Drilling Program (ODP) Leg 164, which was the first research drilling expedition designed specifically to study gas hydrates (Paull et al., 1996). In 1995, ODP Leg 164 completed a series of boreholes in the Blake Ridge sediment drift deposit on the U.S. Atlantic margin and inferred low hydrate saturations within relatively homogeneous fine-grained sediments at locations with and without a bottom simulating reflector (BSR), which is the negative impedance contrast seismic feature that separates underlying gas-charged sediment from overlying HBS in some marine settings.

In the years following ODP Leg 164, two major classes of studies emerged that have particular relevance to HBS issues. First, a pair of seminal papers examined the physics and thermodynamics related to pore-scale interaction of sediments and gas hydrate (Clennell et al., 1999; Henry et al., 1999), setting the stage for the explosion of related research in the subsequent years. Second, numerical modeling studies (Xu & Ruppel, 1999; Zatsepina & Buffett, 1998) advanced a framework for the formation of gas hydrate within the gas hydrate stability zone (GHSZ) from dissolved phase methane and without a role for free gas (vapor phase). We examine each of these developments in turn.

The Clennell et al. (1999) and Henry et al. (1999) studies were among the first to ever consider the interaction of gas hydrate and sediments at the grain scale from the standpoint of soil physics and thermodynamics. The research explained how capillary effects in fine-grained sediments could inhibit the formation of gas hydrate and how microenvironments related to variations in pore water salinity could also play a role in the ultimate distribution of gas hydrate in the sediment matrix. Motivated in part by observations on ODP Leg 164, these studies demonstrated that capillary effects alone could not explain the apparently anomalous depth of the base of the GHSZ (Ruppel, 1997) on the Blake Ridge. Clennell et al. (1999) and Henry et al. (1999) postulated that other types of physical and thermodynamic interactions among hydrate, sediment grains, and pore fluid likely played a role in governing the fine-scale distribution of hydrate in the ODP Leg 164 area.

In the wake of ODP Leg 164, numerical and analytical models (Davie & Buffett, 2001; Xu & Ruppel, 1999; Zatsepina & Buffett, 1998) that posited the formation of gas hydrate from dissolved gas also played a key role in HBS research around the turn of the century. Although formulated as multiphase models, the models truly considered only two phases simultaneously: hydrate and dissolved methane within the GHSZ and dissolved methane and free gas in the underlying zone. At depths where the concentration of methane in pore space exceeded local methane solubility within the pressure and temperature (P-T) field for gas hydrate stability, gas hydrate was presumed to form from the excess methane. The same solubility and concentration

conditions at reservoir depths where the P-T conditions were not conducive to gas hydrate stability (e.g., below the GHSZ) were predicted to lead to the accumulation of free gas in the sediments. Under some conditions, a BSR would be predicted if gas existed just below the base of the GHSZ (Xu & Ruppel, 1999).

Hydrate formation in homogeneous porous media from dissolved phase methane supplied from below provided a ready explanation for several key observations from ODP Leg 164, including (a) the existence and lateral discontinuity of BSRs that separate HBS from underlying free gas (Holbrook et al., 1996; Paull et al., 1996); (b) the evolution of high-saturation gas hydrate deposits in locally more permeable sediments, including sediments with diatoms or fine-scale fractures (Daigle & Dugan, 2010; Kraemer et al., 2000; Nimblett & Ruppel, 2003; Wood & Ruppel, 2000); and (c) the finding of higher hydrate saturations near the base of the GHSZ (Holbrook et al., 1996). The focus on dissolved phase methane as the precursor to hydrate formation also underscored that the growth of hydrate in sediments was generally slow and acutely sensitive to advective flux (Xu & Ruppel, 1999). The advective flux in turn depends on both sediment permeability (linking back to Clennell et al., 1999) and the rate at which fluids migrate through sediments due to processes such as compaction, hydraulic pressure differentials, and thermal and chemical gradients.

In the Special Section, VanderBeek and Rempel (2018) develop sophisticated extensions of dissolved phase models with an application to high-saturation (>60%) hydrate deposits in the Gulf of Mexico. Their results demonstrate that coarse-grained layers exercise a feedback effect that enhances both advection and diffusion, leading to the evolution of higher gas hydrate saturations in these sediments. When hydrate formation from dissolved phase methane is dominated by diffusion, saturations tend to increase in localized zones. Advection leads to a wider distribution of gas hydrate, but at lower saturations, in the more permeable strata.

When the focus on hydrate formation from dissolved phase methane emerged in the gas hydrates literature, it also challenged the prevailing laboratory protocols for studying HBS. At the time, researchers often vigorously bubbled methane through sediments maintained within the P-T conditions for hydrate stability to form synthetic hydrate in the lab (Helgerud, 2001; Helgerud et al., 2000). This procedure led to rapid nucleation and growth of gas hydrate at gas-fluid interfaces and often little hydrate formation within the porous media. Gas sometimes displaced sediments, creating voids that then clogged with hydrate, and hydrate was often observed to nucleate in undesirable places, such as on inlets or at the sediment-water interface.

The recognition that the formation of hydrate from dissolved phase methane produced load-bearing hydrate and fundamentally different bulk HBS physical properties (Kleinberg & Dai, 2005; Lee, Francisca, et al., 2010; Spangenberg & Kulenkampff, 2006; Waite et al., 2009) than if hydrate forms on gas bubbles and at menisci between grains increased the urgency of ensuring that laboratory hydrate formation methods more closely aligned with those presumed to be important in nature. However, forming hydrate from dissolved phase in the laboratory posed major challenges. For example, synthesizing gas hydrate to saturations of more than a few percent of pore space from dissolved phase methane can require days to months, depending on the size of the experimental cell, sediment grain size, how far within the P-T stability field the experiments are conducted, and other factors. To make the timescales conducive to laboratory study, researchers turned to alternate hydrate formers (e.g., Lee et al., 2007) like tetrahydrofuran, which is completely miscible in water and forms Structure II hydrate at P-T conditions closer to ambient than does methane, a Structure I hydrate-former.

Difficulties forming hydrate from dissolved phase methane in porous media on reasonable timescales are particularly pronounced for fine-grained sediments owing to high capillary pressures (Clennell et al., 1999), low permeability, and electrical charges that interfere with hydrate nucleation (Lei & Santamarina, 2018). Waite and Spangenberg (2013) proposed changes in the process for supersaturating water with methane prior to its being circulated through the porous media pack. With their approach, gas hydrate saturations of several percent per day could be grown in fine-grained media from dissolved phase methane.

While advances were being made in studying HBS properties using gas hydrate formed from dissolved phase gas, observations in several gas hydrate provinces (Gorman et al., 2002; Hübscher et al., 2004) and during ODP Leg 204 drilling on Hydrate Ridge (Liu & Flemings, 2006; Milkov et al., 2004; Tréhu et al., 2004) renewed the focus on the existence of free gas within the GHSZ, an apparent contradiction of equilibrium thermodynamics (Fu et al., 2018). In permafrost areas, it had long been known that gas migrating upward from deeper conventional reservoirs and freezing in place during glacial epochs is likely the predominant mechanism for hydrate formation (e.g., Collett, 1993, 2002; Dai et al., 2011; Majorowicz & Osadetz, 2001;

Ruppel, 2015). In deep water provinces, methane seeps supplied by chimneys that feed gas through the GHSZ are widespread on continental margins (Greinert et al., 2000; Hornbach et al., 2007; Pecher et al., 2010; Römer et al., 2012; Sassen et al., 2003; Skarke et al., 2014; Westbrook et al., 2009), hinting at the importance of gas hydrate formation from a vapor phase in some locations (Smith et al., 2014).

Liu and Flemings (2007) provide the critical study for hydrate formation on gas bubbles within the porous medium of the GHSZ in water-limited settings or those dominated by pore-filling brines that can inhibit gas hydrate formation and stability. A new modeling study in the Special Section (You & Flemings, 2018) expands on this earlier work to demonstrate that hydrate formation from a free gas phase can concentrate hydrate in coarse-grained layers within the GHSZ. Thus, this single Special Section has numerical modeling studies showing that hydrate formation from both dissolved phase methane (VanderBeek & Rempel, 2018) and from gaseous methane (You & Flemings, 2018) can lead to high saturations of hydrate in coarse-grained layers, underscoring the long-recognized role of permeability in controlling hydrate distributions (e.g., Nimblett & Ruppel, 2003).

The role of a vapor phase in the nucleation and accumulation of gas hydrate in porous media is the focus of several laboratory studies in the Special Section as well (Meyer, Flemings, & DiCarlo, 2018, Meyer, Flemings, DiCarlo, You, et al., 2018; Sahoo et al., 2018). Both Meyer, Flemings, DiCarlo, You, et al. (2018) and Sahoo et al. (2018) describe experiments in which gas hydrate does not form to saturations as high as are predicted based on thermodynamic equilibrium for the three phase system (gas-pore fluid-gas hydrate). Meyer, Flemings, DiCarlo, You, et al. (2018) start with methane migrating through the sediment sample already held within the P-T conditions for hydrate stability, whereas Sahoo et al. (2018) inject methane gas and then allow the system to equilibrate before lowering the temperature, following a method first described by (Waite et al., 2004). These studies and Meyer, Flemings, and DiCarlo (2018) postulate that gas hydrate initially forms as a film or skin around gas bubbles in pore spaces.

These findings are similar to those of Jain and Juanes (2009), who used a multiphase modeling approach, and also to those of Fu et al. (2018), who describe bubble armoring phenomena in liquids, instead of porous media. In the Special Section papers, the hydrate skin forms a physical barrier that can cause local differential pressures to develop between the pore fluid and the hydrate-encased gas. This may limit further hydrate growth to that which can be accomplished with (slow) diffusion of methane alone. In some cases, the differential pressures are high enough to rupture the hydrate skins, allowing renewed advection of hydrate-forming components through the porous media.

Meyer, Flemings, and DiCarlo (2018) add a sensitivity study to this framework by varying the rate at which gas flows through a brine-saturated porous specimen held within the P-T conditions for gas hydrate stability field. They then maintain upstream methane pressure for 800 hr after stopping brine withdrawal. For their experimental configuration, lower gas flux leads to much higher final saturations of gas hydrate, a result that may seem counterintuitive. Meyer, Flemings, and DiCarlo (2018) interpret this finding by noting that lower methane flux allows more time for hydrate growth and the formation of thicker hydrate skins on gas bubbles, but also larger pressure differentials. The laboratory studies (Meyer, Flemings, & DiCarlo, 2018, Meyer, Flemings, DiCarlo, You, et al., 2018; Sahoo et al., 2018) imply that gas bubbles may sometimes be stranded within pore space, armored by hydrate skins, and therefore unconnected to the flow of pore fluid and gas through the medium. Like the dissolved phase models of VanderBeek and Rempel (2018), the laboratory experiments conducted by Meyer, Flemings, & DiCarlo, (2018), Meyer, Flemings, DiCarlo, You, et al., (2018) and Sahoo et al. (2018) with a free gas phase can provide an explanation, albeit with a different physical grounding, for high saturations of gas hydrate forming far above the base of the GHSZ.

Hydrate is also formed from vapor phase methane in the Special Section paper by Almenningen et al. (2018), who use micromodels to simulate porous media for their study of the synergistic relationships between gas hydrate dissociation and pore water salinities within the model. Micromodels typically consist of a transparent material that is precisely etched to mimic a porous medium and that has added inlets and outlets to allow fluid flow through the mock sediment. Micromodels can be two- or three-dimensional and can exactly duplicate the arrangement of pores and grains within a real sediment sample. The models have become widely used in gas hydrate studies within the past few years (e.g., Almenningen et al., 2017; Cao et al., 2018; Hauge et al., 2016; Mahabadi et al., 2016) building on an early studies by Tohidi et al. (2001, 2002) and Katsuki, Ohmura, et al., (2008), Katsuki, Ebinuma, et al., (2008).

In the Special Section, Almenningen et al. (2018) form interstitial gas hydrate in the presence of briny pore fluids within the micromodel and produce both massive (solid) hydrate and hydrate on the surface of bubbles. Dissociation releases fresh water (Hesse & Harrison, 1981), leading to the development of local salinity gradients. The local variations in pore fluid chemistry in turn produce an inhomogeneous pattern of hydrate dissociation (e.g., more dissociation where pore fluids are briny and less where pore fluids are fresher). In some cases, new gas hydrate may form in the porous medium even though the overall P-T regime should be characterized by dissociation (Almenningen et al., 2018).

Using a more traditional laboratory configuration, Lei and Santamarina (2018) also consider the role of free gas (vapor phase) in hydrate formation but focus on fine-grained sediments. Their laboratory study includes hydrate formation from gas migrating through and sometimes lifting up cohesive sediments or from gas stored in anomalously large pores (e.g., diatoms) set within the fine-grained matrix. The importance of large pores is also highlighted in the nuclear magnetic resonance imaging study of Ge et al. (2018), who use free gas to produce hydrate in natural sediment samples that are predominantly coarser grained (e.g., sandstone). They infer that hydrate preferentially forms and also more rapidly dissociates in larger pores.

3.2. Role of Fines

Fines—the vernacular term used to describe the fine-grained component of bulk sediment—have become a major focus of gas hydrates research over the past decade (e.g., Cao et al., 2018; Jung et al., 2012; Priest et al., 2008). The presence of fines affects permeability and thus methane flux, which in turn control how and where gas hydrate concentrates and the saturations achieved. Fines can also govern the physical properties of bulk HBS and the response of sediments during production of methane from dissociating gas hydrates (Bahk et al., 2013; Cha et al., 2016; Jung et al., 2012; Lee, Santamarina, et al., 2010b). Mobilized fines can clog pathways for gas or fluid flow through the reservoir (reduced permeability) or foul the screened intervals in extraction wells, making it more difficult to drive additional hydrate dissociation in the reservoir or to recover fluids and gas (Han et al., 2018). Fines also migrate during other types of sediment deformation (e.g., compression and shearing; Hyodo et al., 2017), leading to denser sediments, changes in stress distribution, and altered hydrate formation patterns.

Fines, which include both silt and clay particles (nominally less than 75 μm in the engineering literature according to Jang et al., 2018), also have particular characteristics that affect their interaction with pore fluids, other grains, and gas hydrate. For example, fine particles carry an electrical charge that influences the development of sediment fabric and governs some physical properties of bulk sediments (e.g., compressibility) as pore fluid ionic content changes (Jang et al., 2018). This Special Section paper also explains how mobilization of fines during hydrate reservoir depressurization is a consequence not only of their entrainment in pore fluid flows, but also of changes in electrical interactions between the fine particles and freshening pore fluid.

Even in the absence of gas hydrate, visualizing the distribution of fines in porous media is a challenge for analyzing fines migration mechanisms. The image analysis methods devised by Han et al. (2018) expand the use of X-Ray computed tomography (CT) technology to track the locus of mobilized fines in multiphase flow experiments.

The Special Section also includes a rare field study that uses in situ measurements to constrain hydraulic, geomechanical, and other properties of fine-grained sediments in a rapid gas flux setting in the Gulf of Guinea (Taleb et al., 2018). The in situ data imply that seafloor hydrate-bearing clays are in a contractive state, which contrasts with the dilative state of coarser-grained HBS and also the findings of Yun et al. (2007) for a range of sediments that includes clays. The Taleb et al. (2018) study also infers the relative hydraulic diffusivity of hydrate-bearing clay sediments by measuring pore water dissipation. Increased hydrate saturation leads to the expected decrease in hydraulic diffusivity, but the relationship does not persist beyond 20% saturation. Higher hydraulic diffusivity for larger gas hydrate saturations is explained as a consequence of fractures or a decrease in compressibility.

3.3. Geomechanical and Hydraulic Properties

Studies of the mechanical, electrical, hydraulic, geotechnical, and thermal properties of HBS are now relatively routine. A decade ago, a major review compiled all the HBS physical properties results (Waite et al., 2009). This followed the completion of an exhaustive parametric study that for the first time systematically

measured a wide range of physical properties for sands, silts, and clays with closely controlled saturations of a Structure II hydrate former (tetrahydrofuran) that does not have a free gas phase Santamarina and Ruppel, 2010. Because such proxy hydrates form from dissolved phase in the same way as methane hydrate can and in the same loci within the sediment-pore space complex, these studies were useful for advancing understanding of physical properties other than electrical (Lee et al., 2007). In the Special Section, Spangenberg et al. (2018) show that water ice can also be used as an analog for gas hydrate for certain physical properties (e.g., electrical resistivity and compressional wave velocity) and under specific conditions.

During the first decade of the 21st century, researchers published physical properties results for HBS using natural samples and samples with synthetic hydrate, samples composed of a single sediment and mixtures, samples with different pore fluids (including gas), and samples with various saturations of Structure I or Structure II gas hydrate (Cortes et al., 2009; Hyodo et al., 2002, 2005; Kingston et al., 2008; Lee et al., 2007, Lee, Santamarina, et al., 2010a, Lee, Francisca, et al., 2010; Priest et al., 2005; Santamarina & Ruppel, 2010; Soga et al., 2006; Waite et al., 2009; Winters et al., 2007; Yun et al., 2007). With the advent of new methods for hastening methane hydrate formation from dissolved gas (e.g., Waite & Spangenberg, 2013), an increased focus on hydrate formation from free gas (section 3.1), and frequent recovery of natural HBS in pressure cores that maintain reservoir pressure over long periods, detailed studies of physical properties in the presence of methane hydrate are now routine and explore an even broader parameter space.

A new contribution in the Special Section focuses on the mechanical properties of a suite of hydrate-bearing sands, particularly during dissociation (Madhusudhan et al., 2019), in samples having excess gas. Such a scenario might be applicable within the GHSZ during production of methane or in ocean warming scenarios. The situation might also apply at the base of the GHSZ, which is assumed to be the thermodynamic triple point (coexistence of vapor phase methane, hydrate, and dissolved methane). Just as specific surface plays a role in the locus of hydrate formation for fine-grained sediments, the Madhusudhan et al. (2019) study demonstrates that the specific surface, grain morphology, and grain size affect the details of hydrate formation and cementation in various sands and thus differences in the behavior of these sands following hydrate dissociation.

Four papers in the Special Section focus on HBS properties but include aspects other than laboratory measurements. The study by Kossel et al. (2018) highlights the critical issue of the water permeability of HBS, long considered one of the most critical unknowns for reservoir modeling studies. Starting with methane hydrate formed from dissolved phase in sand, they acquire three-dimensional magnetic resonance images of the HBS. They then use this information to calculate flow parameters from finite element models and compare the results to those predicted using widely applied permeability formulations, calibrating the exponent that relates intrinsic to relative permeability in most of these models.

A similar approach is adopted by Gil et al. (2019), who use numerical modeling to interpret X-Ray CT imagery of experiments on HBS under conditions of hydrate formation and dissociation. Hydrate is formed in the porous sample from the free gas phase, and hydrate saturations in some experiments were in excess of 50%. At 50% hydrate saturation, depressurization during laboratory production testing results in a fairly homogeneous pressure distribution in the cell. By 60% saturation, the hydrate substantially interferes with fluid permeability, resulting in slow propagation of the depressurization signal. At even higher hydrate saturations (70% and 80%), production is not stable or became impossible, respectively.

A calibration study is also provided by Cook and Waite (2018), who determine hydrate saturations from electrical resistivity measurements via Archie's equation. Instead of focusing on laboratory resistivity studies on a variety of HBS (e.g., Du Frane et al., 2015; Lee, Santamarina, et al., 2010a; Priegnitz et al., 2015; Santamarina & Ruppel, 2010; Spangenberg & Kulenkampff, 2006), Cook and Waite (2018) use borehole logs from permafrost and deep water gas hydrate reservoirs to constrain the Archie's exponent for high-saturation deposits. By combining compressional velocity and resistivity logs, their empirical study shows that this exponent is 2.5 ± 0.5 for high-saturation gas hydrate reservoirs.

A third nonlaboratory study relevant for sediment behavior in hydrate reservoirs is focused on the development of a realistic critical state model for turbiditic sediments in the Nankai Trough, where the Japan Oil, Gas and Metals National Corporation conducted the first deep water gas hydrate production test in 2013 (Yamamoto et al., 2014). Instead of directly measuring sediment physical properties, Zhou et al. (2018)

use borehole logs and the results of laboratory geomechanical analyses that constrain these properties in order to calibrate a sophisticated anisotropic model. They report that application of this new model within a thermal-hydraulic-mechanical (THM) reservoir simulator more closely reproduces the production pattern for water and gas from the 2013 test than does an older, isotropic critical state model.

3.4. Numerical Modeling Focused on Coupling Geomechanics and Gas Hydrate Dynamics

In the past decade, the THM framework mentioned by Zhou et al. (2018) for reservoir simulation has become widely applied in the hydrates community. The THM approach builds on original work by Rutqvist and Moridis (2007) and Rutqvist (2011), who used variations of the TOUGH+HYDRATE for the thermal and hydraulic components and FLAC for the mechanical part of early generation coupled models of the gas hydrate reservoir. Sometimes called THMC (where the *C* stands for coupled), this type of modeling seeks to understand the complete behavior of gas hydrate reservoirs, particularly during production of gas from hydrate. Some contemporary researchers still use versions of TOUGH, while others use different codes for the thermal/hydraulic and/or mechanical components. Coupling geomechanics to other aspects of gas hydrate dynamics has now become such an important issue that an international code comparison study is conducting side-by-side comparisons of THM hydrate simulators (White et al., 2017).

Writing in the Special Section, Sánchez et al. (2018) apply THMC to both laboratory experiments and simulations of field production testing. One of their key findings is that mechanical perturbation (shearing) can destabilize shallowly buried gas hydrate that has accumulated to high saturations, confirming an earlier laboratory result (Jang & Santamarina, 2016). Sánchez et al. (2018) also derive an analytical solution for the production of gas from a depressurized cylindrical hydrate reservoir and show that the solution closely matches that produced by the THMC code.

Kim et al. (2018) also use a THMC approach but rely on the more classic framework of Rutqvist and Moridis (2007). The Kim et al. (2018) study of wellbore stability for a simulated gas hydrate production test at one site in the Ulleung Basin shows that low bottom hole pressure (in this case, 5 MPa) induces large depressurization and thermal perturbations in the formation and thus more dissociation at greater distances from the wellbore. Low and intermediate bottom hole pressures also cause compressive stress conditions to respectively exceed or be close to the yield strength of wellbore casing.

3.5. CO_2-CH_4 Hydrate Dynamics Within the Reservoir

One Special Section study defies classification with the others. In their experimental study, Schicks et al. (2018) reexamine the physical mechanism responsible for release of methane from gas hydrates when CO_2 with nitrogen is injected into a hydrate-bearing reservoir. The Ignik Sukumi trial in 2012 (e.g., Boswell et al., 2017) involved such an apparent exchange of CO_2 for methane within the gas hydrates in a permafrost-associated reservoir near Prudhoe Bay, Alaska. Both CO_2 and CH_4 form Structure I gas hydrates, and some studies have suggested that replacement of methane by CO_2 in the reservoir's gas hydrates may occur without dissociation of the original methane hydrate (Falenty et al., 2016; Ota et al., 2005). The results of Schicks et al. (2018) indicate that methane hydrate underwent conventional depressurization-driven dissociation during injection of CO_2 and N_2 in the Ignik Sukumi test and imply that a mixed hydrate containing all three gases may have formed in the reservoir.

4. The Future of HBS Studies

The contributions in the Special Section capture a snapshot of HBS research ~25 years after ODP Leg 164 and at the end of a decade marked by the first deep water production tests (Li et al., 2018; Yamamoto, 2013). The contributions are not representative of the full range of HBS research currently underway and particularly miss the critical role of pressure cores (cores maintained at their in situ pressure during recovery and analysis) in providing constraints on reservoir properties (e.g., Boswell et al., 2018; Dai et al., 2017; Holland et al., 2018; Lee et al., 2013; Priest et al., 2018; Santamarina et al., 2012; Yamamoto, 2015; Yoneda et al., 2017, 2018; Yun et al., 2010, 2011). In recent years, most studies focused on pressure cores are published in scientific report volumes that document individual drilling expeditions (e.g., Collett, 2014; Collett et al., 2019; Ryu et al., 2013; Yamamoto & Ruppel, 2015). Even without pressure coring, many of the advances in understanding HBS properties at multiple spatial scales are now spawned by drilling expeditions and associated

laboratory and reservoir modeling research. Such projects have also been a key driver for investments in geophysical site survey, advanced logging-while-drilling, and innovative methods for sampling real HBS.

The Special Section papers also highlight a range of techniques—micromodels, THMC modeling, and certain in situ measurements—that are becoming more widely used in HBS studies. None of these approaches is new; however, technical developments, such as 3-D printing that allows less expensive production of micromodels or new and more powerful coupled flow models for THMC approaches, have led to more widespread interest in these kinds of studies for the analysis of HBS properties.

Much of the research published in the Special Section was motivated by the energy resource potential of gas hydrates, meaning that most studies focused on coarse-grained sediments, improved reservoir modeling, and processes that concentrate gas hydrate or prevent the extraction of methane from reservoirs. Although not important for energy resource studies, low (<5%) saturation gas hydrate in fine-grained marine sediment remains the most widespread natural form. On a global basis, the impact of oceanographic or climate change on gas hydrate could be dominated by the response of these widespread deposits, which will likely receive renewed focus in the future.

Future HBS studies will continue to include laboratory, field, and modeling components. Pressure coring will continue to become more routine and reliable over the next decade, and more tools and approaches will be adopted to image and interrogate pressure cores. Field methods for measuring HBS physical properties from conventional ships (Taleb et al., 2018) are likely to continue evolving alongside techniques to directly constrain HBS geotechnical properties using borehole instrumentation. The synergy between reservoir models and HBS property studies will likely continue and should yield increasingly refined models for potential production from high-saturation deposits, particularly in well-studied deep water marine gas hydrate provinces.

Acknowledgments
C. R. was supported by the U.S. Geological Survey's Energy Resources Program and the Coastal/Marine Hazards and Resources Program, as well as by DOE Interagency Agreement DE-FE0023495. C. R. thanks W. Waite and J. Jang for discussions and suggestions that improved this paper and L. Stern for a helpful review. J. Y. Lee was supported by the Ministry of Trade, Industry, and Energy (MOTIE) through the Project "Gas Hydrate Exploration and Production Study (19-1143)" under the management of the Gas Hydrate Research and Development Organization (GHDO) of Korea and the Korea Institute of Geoscience and Mineral Resources (KIGAM). Any use of trade, firm, or product name is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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