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Invited review

Characterization and development of natural gas hydrate in marine clayey-silt reservoirs: A review and discussion

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Abstract:
As a promising substitute for conventional fossil fuels with huge reserves, clayey-silt natural gas hydrate has been proved to be widely distributed in the continental margins of the marine environment. Characterization and development of this kind of natural gas hydrate reservoirs face unique challenges, compared with that of natural gas hydrate in marine sandy sediments. This review summarizes the basic methods for natural gas hydrate reservoir characterization and development, and discusses the applicability of these methods in marine clayey-silt natural gas hydrate reservoirs. Feasibilities of classical oil and gas reservoir characterization methods and models applied to hydrate-bearing strata remain elusive, let alone clayey-silt hydrate deposits. Current natural gas hydrate development methods are restricted by low gas productivity, potential geomechanical instability, and extremely high costs. Economically feasible technologies considering the influences of geotechnical issues are needed for the commercialization of natural gas hydrate contained in clayey-silt sediment.

1. Introduction

Natural gas hydrate (NGH) is a clathrate compound formed by water and natural gas molecules conditioned to relatively low temperature and high pressure. NGH is distributed worldwide with abundant reserves and is considered as one of the most promising substitution of conventional fossil fuels (You et al., 2019). Boswell et al. (2015) proposed a reserve pyramid to describe NGH distributions in different geological backgrounds including permafrost regions, marine permeable sandy sediments, and marine clayey-silt sediments. More than 90% of the total NGH reserve is supposed to distribute in marine clayey-silt sediments (Wu et al., 2017), featured with extremely low permeability (Liu et al., 2019a; Cai et al., 2020a), weak consolidation (Li et al., 2018; Dong et al., 2020), and relatively shallow burial depth. These characteristics raise the chanllenges of both reservoir characterization (Wang et al., 2011; Bu et al., 2019) and development (Liu et al., 2017). Moreover, NGH contained in the marine clayey-silt sediments is thought to be technically less feasible, compared with that contained in marine sandy sediments (Collett, 2019).

In the last two decades, great efforts have been made by China Geological Survey to survey and develop NGH in both permafrost and marine environments. Great advances have been achieved in fundamental characteristics of NGH (Wu et al., 2018), NGH accumulation mechanisms (Zhang et al., 2017), reservoir characterization (Wang et al., 2018), and production trials. Six expeditions have been conducted in the northern South China Sea to confirm the reserves of NGH (Liu et al., 2015; Zhang et al., 2015; Wei et al., 2019). However, the hydrate-bearing strata (HBS) reservoirs in the northern South China Sea have been proved to locate in unconsolidated clayey-silt sediments, which imposes significant difficulties for NGH development.

Two NGH production trials have been conducted in the Shenhu area of the northern South China Sea (Li et al.,

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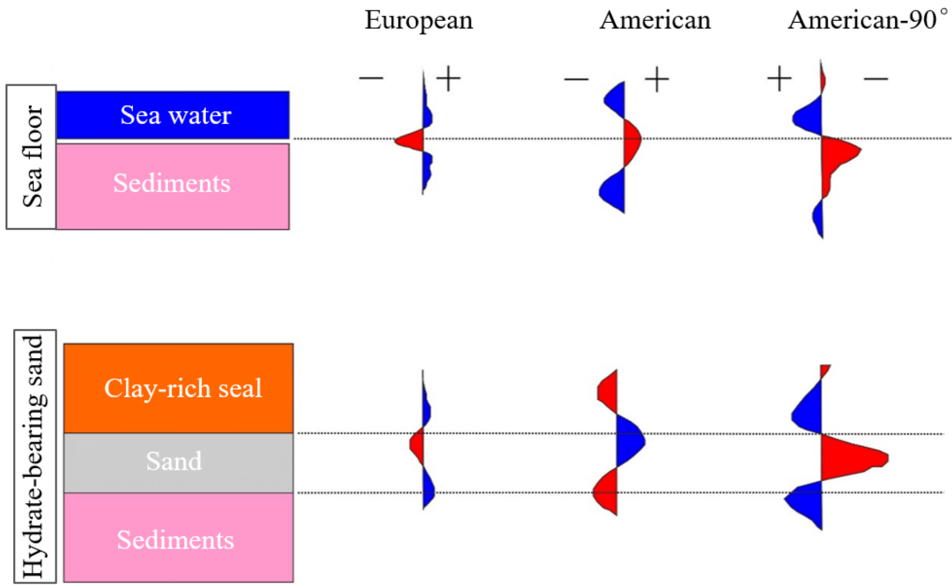

Fig. 1. Polarity convention (Shukla et al., 2019).

2018; Ye et al., 2020), which provided significant support for future studies, while the current gas production rates are far to reach the commercial standard (Wu et al., 2020). This review summarizes the basic methods for NGH reservoir characterization and development, and discusses the applicability of these methods in marine clayey-silt NGH reservoirs.

2. Marine clayey-silt HBS characterization

2.1 Identification of HBS according to seismic surveys

Seismic survey, a routine of marine NGH exploration, can indicate whether there is a prospect containing NGH in underlying accumulations by acquiring and interpreting seismic data. Seismic data include but are not limited to velocities and strengths of reflected seismic waves. The waves are normally generated underneath the sea surface and propagate downward into the deeper submarine sediments. When seismic waves encounter interfaces of different strata during propagation, some of the wave energy is reflected upward to the sea surface and subsequently measured. By analyzing the characteristics of the reflected seismic waves, geologists can build an accurate image of the submarine sediments and identify potential prospects of HBS.

The identification of NGH prospect basically requires a thorough understanding of the polarity convention applied to the seismic data (Boswell et al., 2015). For widely used European, North American 0°, and North American -90° polarity conventions in Fig. 1, the seafloor is represented as a trough-strong peak-trough, a peak-strong trough-peak, and a trough-peak, respectively, while the underlying HBS correspondingly responds as a peak-over-trough, a trough-over-peak, and a trough-peak (Shukla et al., 2019). These anomalous events of HBS is largely due to the presence of NGH with high saturations in the pore space changing the acoustic properties of the sediments (Konno et al., 2015; Bu et al., 2017, 2019). Similarly, gas-bearing sediments can also lead to anomalous events in seismic data. The polarity reflection model produced by gas-bearing sediments is quite different from that of HBS, and this decreases the difficulties in identification of NGH in marine sediments. However, it is much more challenging to distinguish HBS from water-bearing sediments since water-bearing sediments have the potential to produce the same seismic amplitudes with the presence of NGH.

The seismic amplitude of HBS increases with NGH saturation when the NGH saturation is larger than approximately 40%. Thus, high seismic amplitudes within the gas hydrate stability zone (GHSZ) are commonly viewed as convincing indicators of NGH occurrence, especially when the amplitude phase is the same as that of the seafloor. Besides, elevated interval velocities and appropriate changes in seismic reflection characteristics across the base for the GHSZ are also regarded as direct evidence of NGH presence in marine sediments. Identification of these potential seismic indicators, the depiction of the GHSZ, evidence recognition for gas sourcing and migration into the GHSZ, and evaluation of NGH occurrence are four major steps of a prospecting method developed by integrating traditional oil and petroleum system concepts into the NGH exploration system (Boswell et al., 2015), and this method has been successfully applied to the properly selected drill sites with high potentials of NGH occurrence (Boswell et al., 2012; Shukla et al., 2019).

Clayey-silt sediments with abundant foraminifers are widely distributed in the northern South China Sea (Liu et al., 2015; Zhang et al., 2015; Li et al., 2018), and the NGH occurrence in this area is normally identified by analyzing seismic characteristics of bottom simulating reflectors (BSRs) (Zhang et al., 2017; Wang et al., 2018). BSRs occurring in the upper few hundred meters of marine sediments are seismic reflections which are roughly parallel and have op-

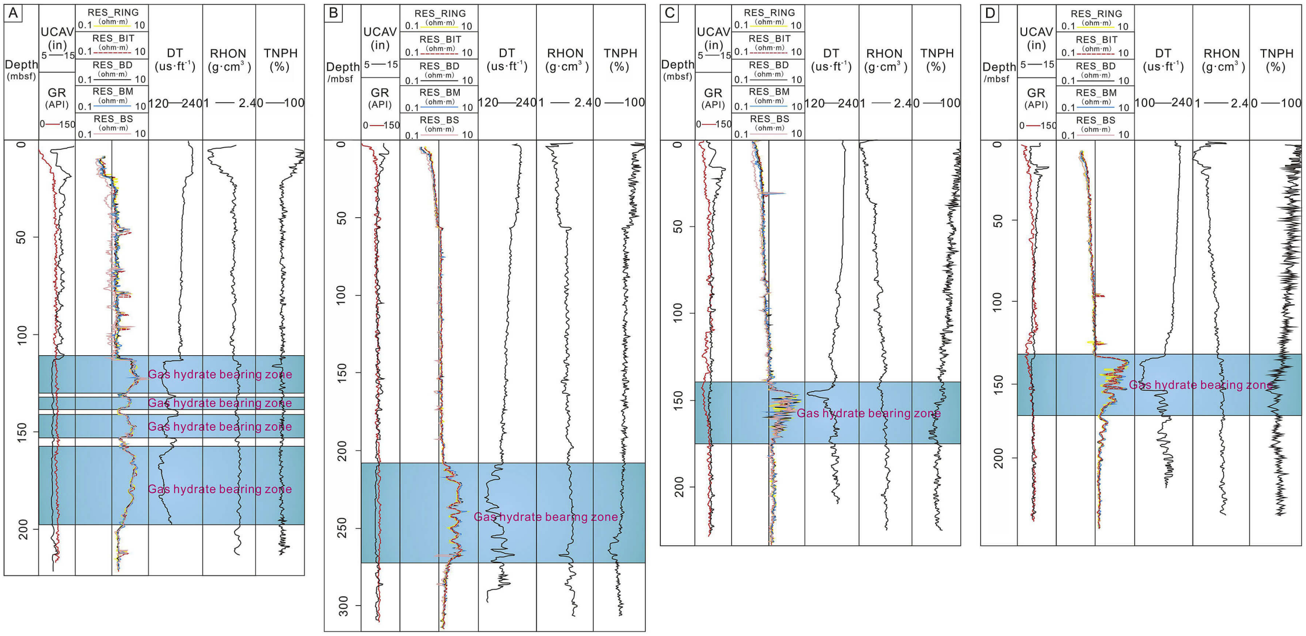

Fig. 2. Logging-while-drilling curves for drilling sites in the gas hydrate production test region in the South China Sea (Zhang et al., 2020).

posite polarity to the seafloor. Plenty of anomalous seismic events indicating various gas leakage structures (e.g., gas chimney and mud diapir) beneath BSRs facilitate identification of NGH occurrence with much more confidence (Sun et al., 2012). NGH related BSRs originate from large contrasts between the seismic impedances of NGH-bearing layers above and free-gas-bearing layers below. However, BSRs and NGH occurrences are not strictly relevant. Diagenetic-related BSRs inherently have no connections with the presence of NGH, while NGH extensively occurs in shallow (i.e., the depth below the seafloor is less than 100 m) marine sediments where BSRs can barely exist.

Identification of NGH occurrence in shallow marine sediments relies on analyses of high-resolution multi-beam seismic and sub-bottom profiling data rather than low-resolution traditional seismic data. These high-resolution seismic data are used to depict spatial distributions of gas leakage structures (e.g., mud volcano, mud diapir, gas chimney, and pockmark) which have great potential to produce extensive NGH with various morphologies in the GHSZ (Hachikubo et al., 2020; Xie et al., 2020). In addition to the depiction of gas leakage structures, geological bases of NGH accumulation in shallow marine sediments should be considered to further the process of NGH prospecting.

2.2 Characterization of HBS according to downhole loggings

Downhole loggings for assessments of NGH occurrence and concentration in marine sediments generally consist of standard wireline loggings and logging while drilling (LWD) (Shankar et al., 2014). Widely applied tools of the standard wireline loggings mainly include the triple combination tool string and the formation microScanner (FMS)/sonic tool string. The triple combination tools are composed of three tools that randomly selected from the hostile environment natural gamma ray sonde, the high-resolution laterolog array, the phasor dual induction-spherically focused resistivity tool, the accelerator porosity sonde, the hostile environment litho-density sonde, and the magnetic susceptibility sonde. While LWD tools normally include the geoVISION, the arcVISION, the adnVISION, the sonicVISION, the provision, and the EcoScope. By using these downhole logging tools, formation parameters such as natural gamma-ray spectroscopy, electrical resistivity, porosity, transverse, and shear wave velocities can be provided.

Standard wireline loggings are operated after a well was drilled, while LWD is synchronously performed with well drilling. The quality of data measured by standard wireline loggings can easily go worse when drilling mud invasion, borehole wall collapse, and/or irregular borehole geometry occur(s). In addition, standard wireline loggings cannot be done in shallow marine sediments since the casing and continuous measurements are quite difficult to deploy in the whole range of GHSZ. On the contrary, LWD has the capability of logging in any direction and any tough environments, and the spatial resolution is normally between 3cm and 15cm, which is much higher than that of standard wireline loggings (Zhong et al., 2020). This makes LWD a much more promising method to characterize HBS (Fig. 2).

Electrical resistivity logging and electrical resistivity tomography logging are effective methods to identify NGH occurrence in marine sediments since NGH with high saturations in the pore space can significantly increase the electrical resistivity of HBS (Ren et al., 2010; Zhang et al., 2021). Thus, HBS produces high anomalies in electrical resistivity logging curves (Sun et al., 2012; Wang et al., 2018; Waite et al., 2019). As stated above, enlarged borehole diameter and/or drilling mud invasion induced by NGH dissociation occurred during well drilling can separate shallow and deep electrical resistivity logging curves measured by standard wireline loggings but have no effects on those measured by LWD.

HBS in density logging curves are marked as low anomalies since the density of NGH is lower than that of the pore water. When porosities are the same, HBSs have higher neutron porosities than water-bearing and gas-bearing sediments, largely ascribed to the fact that the highest hydrogen content in NGH produces high anomalies in neutron porosities in logging curves. Nuclear magnetic resonance (NMR) logging data are also sensitive to the hydrogen content, while NMR porosities are lower than neutron porosities. Furthermore, NGH has density and hydrogen content similar to those of pore water, and their electrical resistivities are not distinguishable from those of natural gas. Thus, it is difficult to identify hydrate-bearing, water-bearing, and gas-bearing sediments by using single downhole logging curve, and comprehensively analyses by combining those downhole logging data are recommended.

Based on various downhole logging data, NGH saturation in marine sediments is commonly predicted by applying the Archie's law, a combination of porosity and NMR logging data, a series of three-phase acoustic models, and rock physics based sonic wave models. On the northern continental slope of Pearl River Mouth Basin in the northern South China Sea where both the first and the second production tests were conducted, NGH saturations calculated based on sonic wave models are consistent with those by combining neutron porosity and NMR logging data. NGH saturations within the HBS range from 0% to about 50%, while within the mixing layers, this value is approximately 0%-20% (Qin et al., 2020).

2.3 Comprehensive analyses by combining seismic and logging data

A combination of seismic data, well logging data, and pressure coring data is quite essential to identify and quantitatively estimate the prospective NGH accumulation in marine sediments (Wang et al., 2011, 2014a). Not only hydrate saturation but also hydrate morphology within marine sediments can be determined by performing comprehensive analyse on those data (Zhang et al., 2015). In clayey-silt sediments, NGH generally occurs in two major morphologies, i.e., pore-filling and fracture-filling, which are indicated by different well logging responses and seismic reflection characteristics. The fracture-filling HBS shows higher anisotropies in various properties than pore-filling HBS.

Clayey-silt sediments containing concentrated pore-filling NGH at the bottom of GHSZ are supposed to be affected by fluid migration. Under this condition, seismic reflections with high amplitudes and the same polarity with the seafloor reflection are indicators for the abundant presence of NGH (Wang et al., 2014b). The thickness and concentration of fracture-filling NGH in marine clayey-silt sediments are determined by faults and fluid migration conditions (Jin et al., 2020). Pull-up and weak-moderate amplitude seismic reflections are believed to be resulted from fracture-filling NGH with moderate saturation (Wang et al., 2014a). The geostatistical inversion by considering lithofacies constraints of gas hydrate presence can improve the spatial and concentration resolutions (Jin et al., 2020) which are promising in characterizing clayey-silt HBS in marine environment.

3. NGH Development from clayey-silt HBS

3.1 Development methods and field applications

NGH exists in a form of solid and is dissociated into water and gas phases by breaking the phase equilibrium conditons, i.e., lowering the pore pressure below the NGH equilibrium pressure, heating the ambient temperature above the hydrate equilibrium temperature, and shifting the NGH equilibrium state. Correspondingly, four hydrate dissociation methods (i.e., depressurization, thermal stimulation, chemical injection, and CO_2-CH_4 replacement) were experimentally and numerically investigated.

From the perspective of numerical simulation, hypothetical NGH reservoirs based on specific geological backgrounds were usually used to obtain practical conclusions. Nevertheless, it is impossible to develop a numerical model that is in 100% accordance with the pratical reservoirs (Liu et al., 2019b). The assumptions for mathematical equations might also significantly increase the gaps between numerical results and real applications. Thus, combinations of numerical and experimental approaches are expected to obtain more reliable conclusions.

To date, ten NGH development trials have been conducted worldwide both in the permafrost regions and marine environments. Depressurization, thermal stimulation, and CO_2-CH_4 replacement were deployed in previous production trials, among which the depressurization is regarded as the most promising approach (Nair et al., 2018). Gas productivity of the previous NGH production trials and their gaps toward commercialization are summarized in Fig. 3. The gas productivity from the NGH development trials are far to reach the commercialization standard in the current state.

It was supposed that the NGH contained in marine clayey-silt sediments accounts for more than 90% of the world's NGH reserves (You et al., 2019). However, the NGH contained in marine clayey-silt sediments is considered to be technically and economically less feasible, compared with NGH contained in sandy sediments. Only two NGH development trials were conducted in the clayey-silt HBS hrough deployment of a vertical well (Li et al., 2018) and a horizontal well (Ye et al., 2020), respectively. These two trials were organized by China Geological Survey and operated by CNPC Offshore Engineering Company Limited in the Shenhu area of the northern South China Sea, which confirmed the possibility of producing natural gas from clayey-silt HBS through an optimized depressurization method and provided great prospects for future commercialization.

The aforementioned laboratory researches and field trials yield some consensus. More importantly, key factors influencing production efficiencies for different production techniques differ. For instance, depressurization was proved to be restricted by heat supply (Zhang et al., 2019). Furthemore, depressurization is supposed to be more feasible for NGH contained in sandy sediments, as pressure transmission efficiency

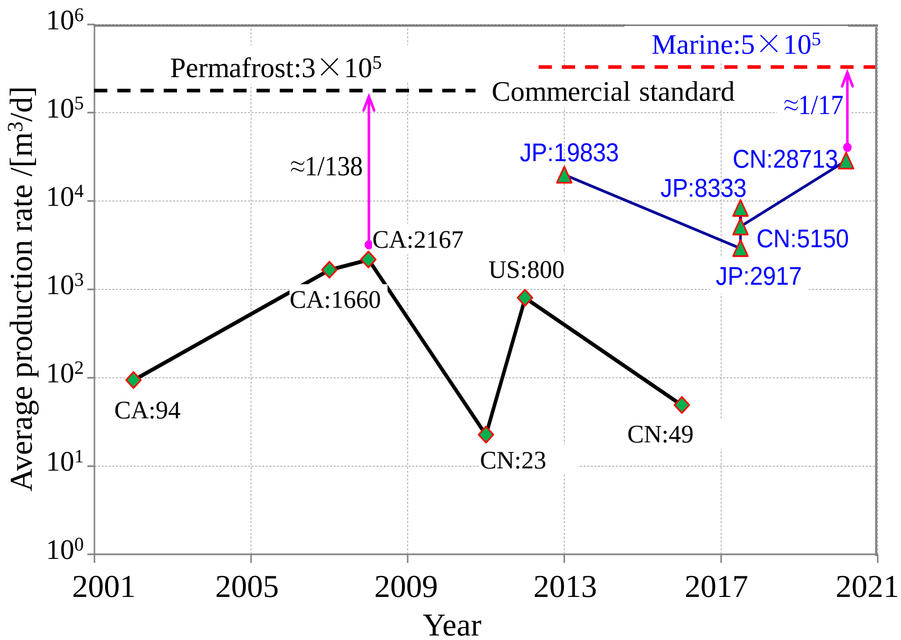

Fig. 3. The average gas production rate of the previous hydrate production trials. Here, CA represents Canada, JP represents Japan, CN represents China, and US represents the United State of America, modified from Wu et al. (2020).

in the sandy sediments is higher than that for the clayey-silt sediments.

Besides, chemical stimulation is dominated by permeability of the HBS; and CO_2-CH_4 replacement is restricted by slow replacement rate (Lim et al., 2016; Boswell et al., 2017). The reservoir permeability is viewed as the most important factor while selecting appropriate production setting and production method. Thermal stimulation is restricted by abundant heat loss, and hence, sediment with lower specific heat capacity and higher heat conductivity are more feasible for thermal stimulation. Last but not least, each of the aforementioned NGH dissociation techniques has its limitations for NGH development. Thus, a combination of certain techniques would help to reach a continuous and efficient gas extraction.

However, disagreement also arose with the advances in field trials. For example, field trials seem to approve that depressurization is a preferred method for marine NGH development. However, there is a lack of standards to quantitatively evaluate the applicability of each method for a specific geological setting (Wu et al., 2017). It remains uncertain whether the combination methods would work better in marine clayey-silt HBS. Furthermore, NGH development is coupled with various geotechnical and geomechanical issues, which would further induce potential geohazards and environmental problems (McConnell et al., 2012; Yoneda et al., 2015). Mechanisms, evolutionary behaviors, and their influences on safe gas extraction remain to be covered. These issues will be discussed in Section 3.2 and Section 3.3, respectively.

3.2 Gas productivity enhancement methods and mechanisms

Increasing gas productivity is the first step toward NGH commercialization. Wu et al. (2020) summarized four productivity-enhancing methods based on different stimulation mechanisms, which are complicated wellbore structures represented by long-reach horizontal well (Chen et al., 2020) and multi-branches lateral well (Li et al., 2019e), well netting method represented by dual-horizontal wells (Li et al., 2014) and well clusters (Yu et al., 2020), reservoir stimulation represented by hydraulic fracturing (Too et al., 2018), and combining applications of the aforementioned methods.

Numerous numerical and experimental studies have been conducted by previous scholars to evaluate the adaptability of the aforementioned gas productivity-enhancing methods. The current studies enlighten us the following gas productivity-enhancing mechanisms: (1) increasing NGH dissociation rate; (2) enlarging contact area between the wellbore and the HBS; and (3) increasing the gas-water two-phase flow field. Generally, increasing the NGH dissociation rate can be achieved by increasing the downhole pressure drop or increasing the temperature of injected agent. A combination of depressurization and thermal stimulation would overcome the drawbacks of individual method (Moridis et al., 2007; Guo et al., 2020). For this reason, a certain heat supply during NGH exploitation from clayey-silt sediments is necessary to overcome the energy loss due to hydrate dissociation, an endothermic chemical reaction (Li et al., 2020c).

Besides, there might exist other stimulation mechanisms that have not been covered. For example, Bhade and Phirani (2015) compared gas productivities with the same depressurization schedule for a hypothetical uniform reservoir and a heterogeneous reservoir. It was concluded that the gas productivity from the heterogeneous reservoir was lower than that form the uniform reservoir at the early stages of gas production. However, both the gas productivity and gas-water ratio were much higher for the heterogeneous reservoir in the later stages of production (Feng et al., 2019). This was attributed to the permeability anisotropy of the HBS. This enlightens us to set the directions of fractures once hydraulic fracturing is applied for an HBS. However, the mechanisms of permeability heterogeneity affecting the gas production process remains unknown.

As for the NGH contained in marine clayey-silt sediments, the field trials in 2017 (Li et al., 2018) and 2020 (Ye et al., 2020) conducted at the Shenhu area of the northern South China Sea have proved that it is possible to enhance gas productivity through specific techniques such as horizontal well. The complicated wellbore technique is currently viewed as the most promising technique for development of clayey-silt HBS, although the risk and cost for establishing a complicated wellbore pattern in HBS are extremely high. The complicated wellbore technique shall be combined with reservoir stimulation and thermal stimulation to for development of increase the gas productivity. Some novel and low-cost methods are greatly needed to reach NGH commercialization.

3.3 Geotechnical issues during NGH development

The marine clayey-silt HBS is usually characterized by shallow burial depth and non-diagenesis, which are the main inducement of geological disasters during natural gas extraction from the HBS. How to prevent or alleviate these underground risks is necessary for ensuring long-term, safe, and high-efficienct NGH production (Yan et al., 2020). Geotechnical issues related to NGH development include but are not limited to sand production (Li et al., 2016), borehole instability (Sun et al., 2018a), reservoir settlement (Yoneda et al., 2019), and seabed landslide (Zhang et al., 2018).

The aforementioned geotechnical issues are closely related to the geomechanical properties of HBS. A complete understanding of the geomechanical properties of HBS and their evolutionary behaviors during NGH dissociation is the basis of uncovering the potential geotechnical issues. Numerous studies have been conducted to investigate the influence of hydrate content on the mechanical properties of the sandy HBS (Yoneda et al., 2015; Dong et al., 2019; Cai et al., 2020b; Dong et al., 2020). As for clayey-silt sediments, in-situ piezocone penetration tests were introduced to evaluate the undrained shear strength of the shallow strata without hydrate (Li et al., 2019c, 2019d). A downscaling device was also developed to evaluate the piezocone penetration characteristics of HBS (Li et al., 2020a). However, laboratory results of the mechanical properties of clayey-silt HBS are rarely reported in the current state due to the difficulties of synthesizing NGH in clayey-silt sediments (Wei et al., 2020). THF is always used as a substitute to investigate the morphologies (Liu et al., 2019c) and mechanical properties of clayey-silt HBS (Li et al., 2020b). Fig. 4 shows a schematic diagram of the failure mode of clayey-silt HBS under triaxial shearing conditions, which significantly differs from that of the sandy sediments (see Fig. 5) (Yun et al., 2007; Dong et al., 2019).

Sand production refers to the detachment and outward migration of sand/fine particles from reservoirs and it has become one of the hotspots regarding NGH development (Li et al., 2020c). Most of the production trials (see Fig. 3) were terminated because of uncontrollable sand production (Li et al., 2016, 2021). From the academic perspective, tens of academic papers were published worldwide in the last decade to tackle sand production problems. Numerical simulation is currently the most cost-efficiency method for sand production predictions in NGH development (Zhu et al., 2020). It is widely accepted that sand production occurs because of the NGH dissociation-induced deterioration of formation strength (Li et al., 2019b). Most of the numerical models are based on fundamental understandings of the strength weakening effect. For instance, Uchida et al. (2013) proposed a thermal–hydraulic–mechanical–chemical coupled model to simulate sand detachment, migration, and production processes during NGH development (Fig. 5). In this model, the mass of sand particles is assumed to consist of three states: (a) standing particles that intact with the original soil skeleton (denoted as ssi); (b) flowing particles (denoted as fs); and (c) solids that are settled after flowing (denoted as sst). The

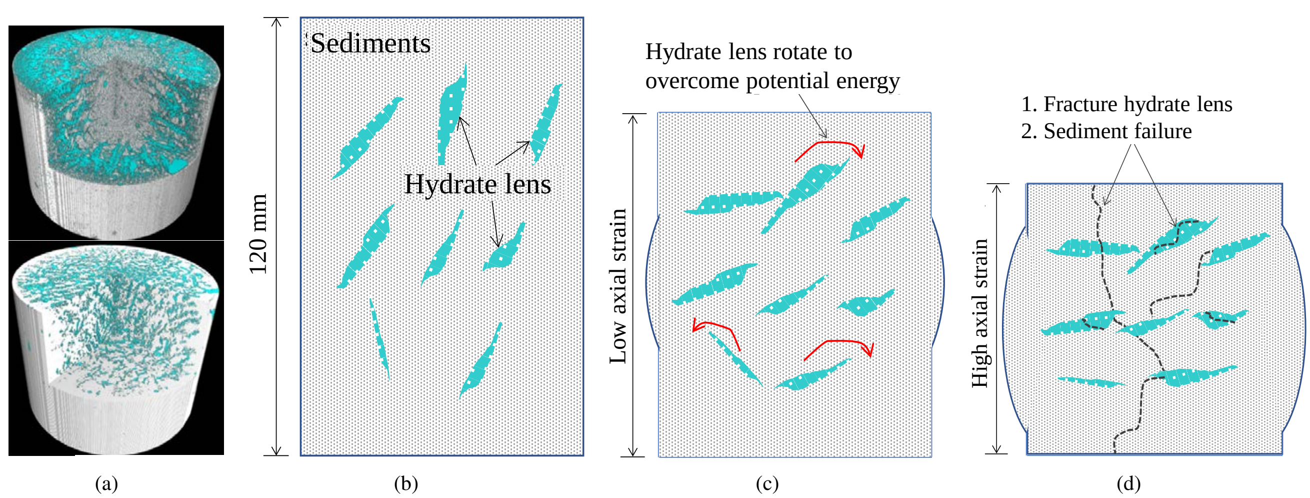

Fig. 4. Failure patterns of sediments containing hydrate lens, modified from Li et al. (2020b).

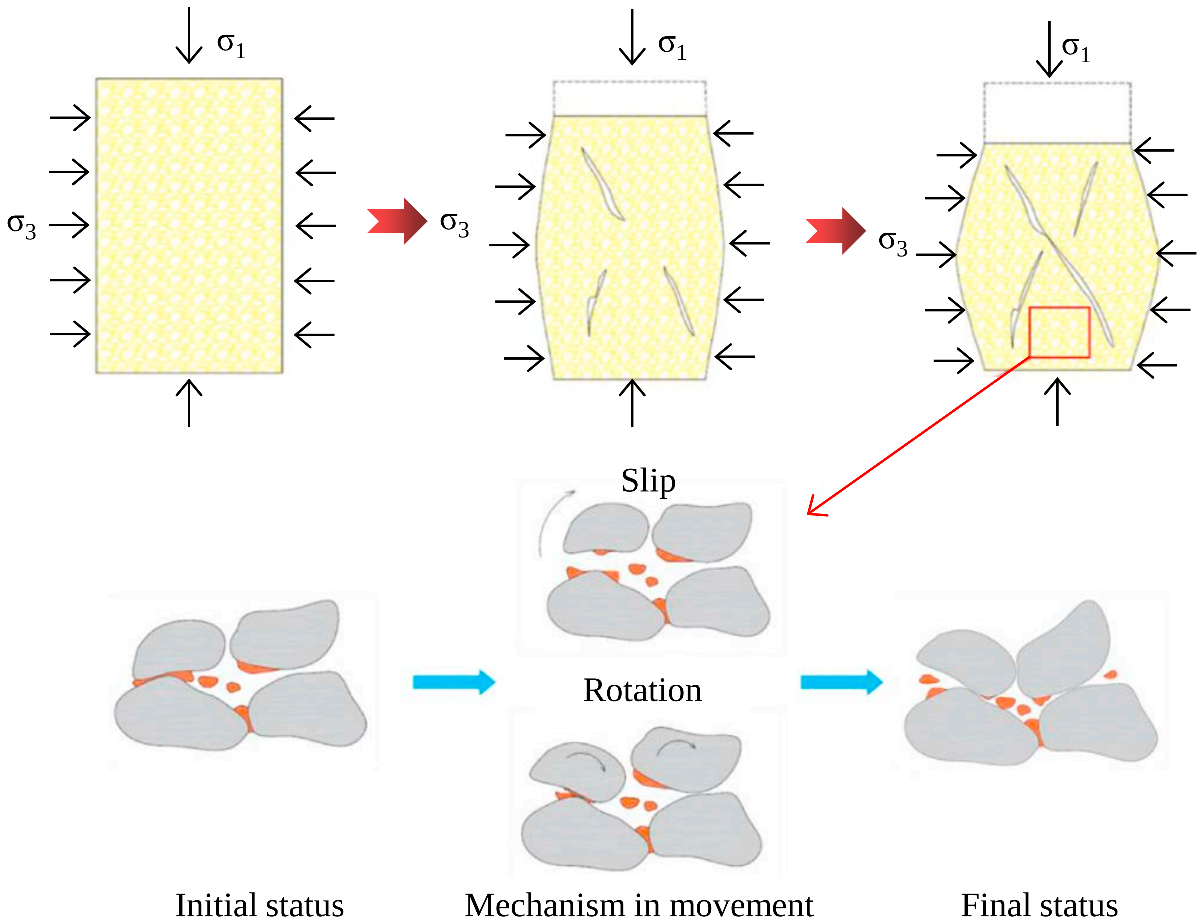

Fig. 5. Failure patterns of sandy HBS, modified from Dong et al. (2020).

solids mass balance model (Eq. (1)) was then incorporated with Darcy's law to demonstrate the flow behavior of solid. This model has been updated (Uchida et al., 2016) and widely accepted, although its applicability for clayey-silt HBS remains unknown.

$$m_s = m_{ss} + m_{fs} = (m_{ssi} + m_{sst}) + m_{fs} \tag{1}$$

where m_s, m_{ss}, m_{fs}, m_{ssi}, and m_{sst} represent different mass component of the solid per unit volume in HBS for stationary solid, flowing solid, intact solid, and settled solid, respectively.

Another important geotechnical issue induced from formation strength deterioration is borehole instability. Borehole instability in an NGH development wellbore would occur during drilling, completion, and production (Sun et al., 2018a, 2018b; Merey, 2019). During drilling, the frictional effect between the drill bit and the formation weakens the stability of NGH, and fluctuations of drilling mud enhance the fluid exchange between the wellbore and the vicinity of the borehole. As a result, borehole collapse, borehole fracture, or massive fluid loss would occur(s) (Merey, 2019). Borehole instability during NGH production is mainly caused by improper depressurization schedules (Yang et al., 2017; Lijith et al., 2019). Striking a balance between gas productivity and borehole instability is now the principal for natural gas extraction from marine clayey-silt HBS.

4. Discussion on Challenges with clayey-silt HBS development

4.1 NGH resource estimation

Well estimation of NGH resource in clayey-silt HBS based on proper reservoir characterization is the basis of gas extraction from HBS in an economically feasible way. However, how to improve current resource estimation methods to enhance the accuracy after a thorough understanding of the oil and gas system remains largely elusive due to several challenges in reservoir characterization. Examples include the challenges in well-logging data characterizing the mineralogy and the anisotropy of host sediments, the challenges in stratigraphic model developments to better consider complex structures and various components within clayey-silt HBS, and the challenges in comprehensive analyses of pressure core and well logging data.

In the gas hydrate community, current stratigraphic models used to estimate the NGH resource are almost the same as those widely applied in the oil and gas community, and some key parameters are directly valued based on the experience that came from oil and gas resource estimations. This will certainly lead to uncertainties and even errors in NGH resource estimation. A well-known example is Archie's law, and the values of the saturation exponent are site-dependent (Cook

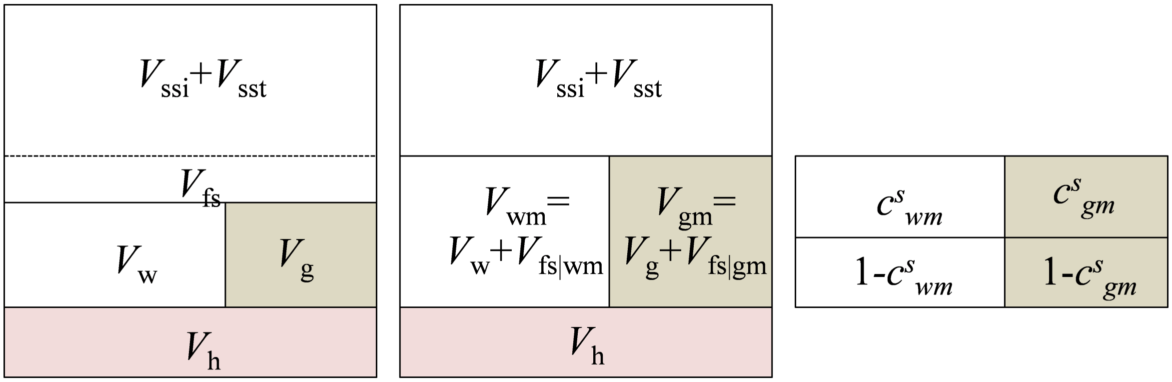

Fig. 6. A elementary volumetric cube representing solid statuses, mixture, and concentrations, modified from Uchida et al. (2013). Here, the subscripts *wm* and *gm* represent water-flowing solid mixture and gas-flowing solid mixture, respectively, and *c* represents the volumetric concentrations of the flowing solid.

and Waite, 2018; Zhang et al., 2021). Physical bases behind the saturation exponent are still not fully understood, and more experimental studies and various verifications should be performed in the future.

4.2 NGH development

Results from various experiments in the laboratory and field-scale numerical simulations show that the depressurization method is the most promising technique, and this method has produced exciting performances of gas production in marine sediments along the continental margin several times. In these field trials of gas recovery from hydrate deposits, particularly from clayey-silt hydrate deposits, various methods have been applied to enhance the gas production efficiency by increasing the depressurization area (e.g., a horizontal well or complex well groups) in HBS. However, the gas production efficiency still cannot satisfy the commercial production criterion, and fundamental researches focusing on the NGH production technique revolution should be dominated in the future. For these fundamental researches, several scientific challenges are summarized as follows.

(1) Pilot-scale experiments on NGH development simulations

Pilot-scale experiments can be the “bridge” connecting indoor experimental studies and field engineering applications. Large-scale experimental data is quite valuable for field-scale numerical simulator verifications (Liu et al., 2020), and this can facilitate the proper evaluation of production procedures before field NGH exploitations. In addition, with the increasing of sample scales, the dominated physical effect is changing. More specially, the NGH dissociation effect dominates in small samples, while the fluid flow through porous media dominates in a large sample. However, current pilot experiments just simulate HBS without upper and lower formations, and more complex formations should be considered. Furthermore, there is a clear lack of effective monitoring and measuring techniques, and this leads to difficulties in the characterization of various processes within samples, not even to mention proper analyses of details during experiments.

(2) Fine-grained sample preparation methods with high efficiencies

Fine-grained sediments just like clayey-silt host sediments for NGH have a poor ability to transfer water and gas, and this leads to very low efficiency in synthesizing NGH within fine-grained sediments. However, more than 90% of the total gas hydrate resource is stored in fine-grained sediments, and there are no sandy sediments hosting NGH in the northern South China Sea. This produces deep requirements to simulate fine-grained sediments in the laboratory in an efficient way. Current methods and techniques with low efficiencies should be modified and improved to enhance the continuous supply of gas and water through fine-grained sediments during NGH formation. In addition, methane hydrate pore habits should be the same as those in the field (Li et al., 2019a; Lv et al., 2020), and this determines that substitutes such as xenon hydrate, tetrahydrofuran hydrate, and carbon dioxide hydrate should be used carefully.

(3) New numerical modeling models coupling heat transfer, fluid flow, sediments deformation, and geochemistry phenomena

The geohazards potential in hydrate deposits would inevitably occur during NGH development, and field-scale numerical simulations need to properly consider sediments deformation with changing values and anisotropies in hydraulic and mechanical parameters. However, most of the previous numerical simulators are of low efficiencies to couple sediments formation with other physical and chemical effects, and the coupling ability and efficiency should be improved to simulate real hydrate deposits with more details (Moridis et al., 2019; Reagan et al., 2019). In addition, fine migration and production simulation are not well incorporated, and new coupling numerical simulators should consider changes of deposit properties due to the loss of fines and interactions between fines and pore fluids.

5. Conclusions and suggestions

Currently, commercial productions of NGH from clayey-silt HBS still face challenges in resource estimation, production technique development, deposit parameter refinement, and geohazard risk. Thus, fundamental studies in different scales by combining various research methods should be enhanced in the future, and some research interests are suggested here.

The key of NGH production efficiency enhancement to an economically feasible level relies on proper well designs and sufficient reservoir stimulation. Thus, scientific bases together with engineering techniques are suggested to be refined.

Enlargements of NGH dissociation front, enhancements of NGH dissociation rate, and improvements of fluid flowability through sediments are three important mechanisms guiding NGH production capacity enhancements. It should be clarified that how these three mechanisms control the NGH production process.

The strategy for NGH production in the future is cost minimization and productivity maximization, and deep cooperation among different institutes, universities, governments, and companies is encouraged to tackle key problems in experimental, numerical, and field studies on hydrate production methods and engineering strategies.

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Conflict of interest

The authors declare no competing interest.

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