

Review

# Prevention of Potential Hazards Associated with Marine Gas Hydrate Exploitation: A Review

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Received: 20 August 2018; Accepted: 7 September 2018; Published: 10 September 2018



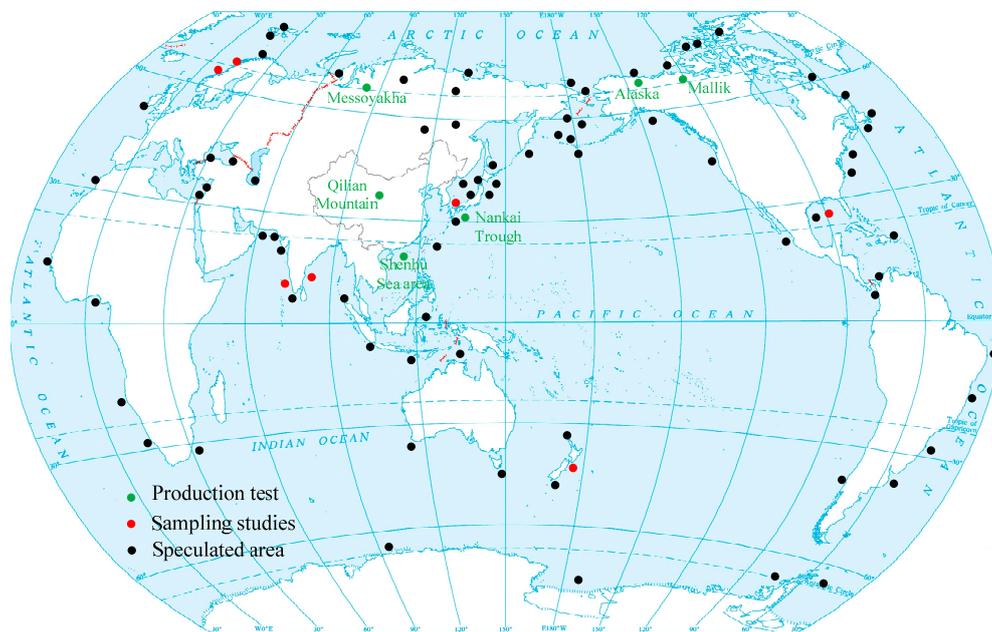
**Abstract:** Marine gas hydrates (MGHs), which have great potential for exploitation and utilization, account for around 99% of all global natural gas hydrate resources under current prospecting technique. However, there are several potential hazards associated with their production and development. These are classified into four categories by this paper: marine geohazards, greenhouse gas emissions, marine ecological hazards, and marine engineering hazards. In order to prevent these risks from occurring, the concept of “lifecycle management of hazards prevention” during the development and production from MGHs is proposed and divided into three stages: preparation, production control, and post-production protection. Of these stages, economic evaluation of the resource is the foundation; gas production methods are the key; with monitoring, assessment, and early warning as the guarantee. A production test in the Shenhu area of the South China Sea shows that MGH exploration and development can be planned using the “three-steps” methodology: commercializing and developing research ideas in the short term, maintaining economic levels of production in the medium term, and forming a global forum to discuss effective MGH development in the long term. When increasing MGH development is combined with the lifecycle management of hazards prevention system, and technological innovations are combined with global cooperation to solve the risks associated with MGH development, then safe access to a new source of clean energy may be obtained.

**Keywords:** marine gas hydrate; submarine landslide; greenhouse gas emission; lifecycle management; hazard prevention

## 1. Introduction

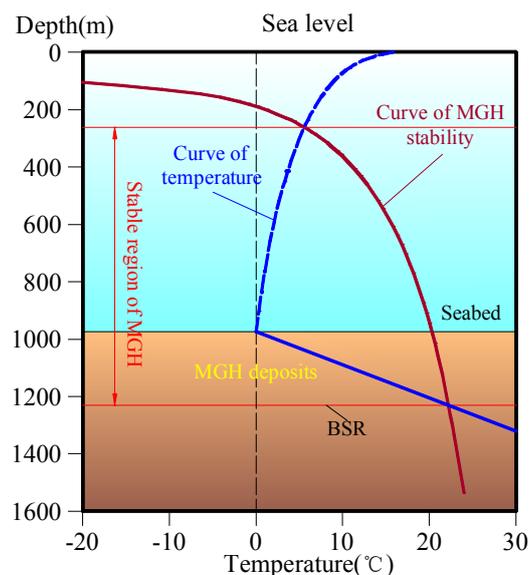
As the global economy develops, the demand for energy is increasing and with the resultant rise in consumption of fossil fuels, there is a need to find alternative forms of energy to maintain sustainable development [1,2]. As a non-traditional fossil fuel, natural gas hydrates (NGHs) are the subject of increasing research since their discovery in the 1960s [3,4], because of their high calorific value and potential utilization. NGHs (combustible ice) are non-stoichiometric crystalline compounds that form ice-like solid structures of gas (i.e., usually methane, ethane, propane and lower order hydrocarbons [5]) and water in a low-temperature (2–18 °C) or high-pressure (3.5–14.5 MPa) environment [6–8]. These conditions occur in near-surface, deep-water marine sediments and in terrestrial permafrost areas that are widely distributed around the world (Figure 1). Currently, NGH reserves are believed to be in the order of  $3.0 \times 10^{15} \text{ m}^3$  ( $3.0 \times 10^{12} \text{ t}$  oil equivalent), which is approximately twice the world’s known supply of fossil fuels (coal, oil, natural gas) [9]. Of the NGH reserves, marine gas hydrates (MGHs) account for more than 99% of these reserves, which if developed could provide many years

of production [10,11]. As a result, research on the development of MGHs has become an important research issue.



**Figure 1.** Distribution of NGH deposits on Earth [8]. (1) “Production test” represent the places where have been successfully tested NGH production; (2) “Sampling studies” represent the places just where the hydrate samples are taken but not production tested; (3) “Speculated area” represent the places where there may be hydrates under current prospecting technique.

NGHs are only stable within a specific range of temperature and pressure conditions (Figure 2) and understanding these is crucial to the development of NGH reserves. At present, there are five NGH production methods: depressurization, thermal activation, chemical agent injection, CO<sub>2</sub> replacement and solid fluidization [12,13].



**Figure 2.** Pressure-temperature equilibrium curves for MGHs [2].

There have been three important production tests of MGHs in the 21st century [14], namely within the Nankai Trough, Japan (2013, 2017) [15,16] and in the Shenhu area of the South China Sea (2017) [10].

Production tests of NGHs in terrestrial permafrost have been undertaken in the Mackenzie Delta, Canada (2002, 2007, 2008) [17] and the North Slope of Alaska, United States of America (2012) [18]; other countries such as Germany, India and South Korea have also conducted sampling studies on MGHs [19–21]. The results of the production tests and sampling studies have found that the crystal structure, sediment morphology and occurrence characteristics of NGHs show great diversity (Figure 3). This difference means that development of these resources will be complicated [6]. There is the potential for submarine landslides, climate warming, marine ecological damage and other hazards, if MGHs are not developed carefully. Current levels of technological development still face many technical and environmental challenges before the economic benefits of MGHs can be realized [10,14].



**Figure 3.** Occurrence characteristics of NGHs [6]. (a) Contained in the pore spaces of coarse-grained sand; (b) Massive lenses and nodules in muds; (c) Disseminated in muds; (d) Contained in the pore spaces of fine-grained marine sand; (e) Thin veins in muds; (f) Massive mounds on sea-floor.

This paper classifies and summarizes the different types of potential hazards in the development of MGHs based upon research to date, and proposes a comprehensive prevention and control strategy for these hazards, based on the concept of “lifecycle management”. Additionally, the key challenges and lessons learned from a production test in the Shenhu area of the South China Sea are presented.

## 2. Classification and Causes of Potential Hazards from MGHs

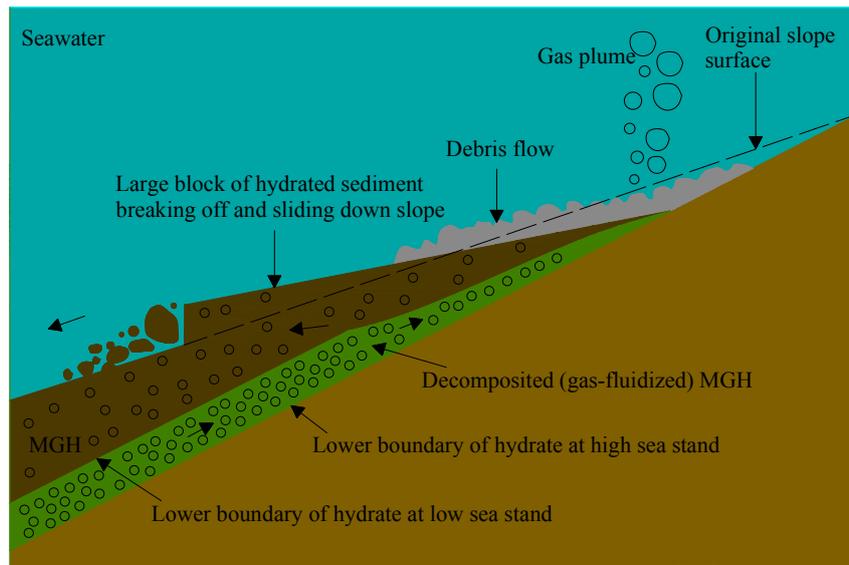
The development of MGH reserves is controlled by the environment and the geology of the sediments at the location, so development of these reserves is complex and the production methodology is location specific [14]. Four categories of potential hazards have been identified which may affect the development of MGHs: marine geohazards, greenhouse gas emissions, marine ecological hazards, and marine engineering hazards.

### 2.1. Marine Geohazards

#### 2.1.1. Submarine Landslide

Submarine landslides are the most important type of marine geohazard that may be encountered during the development of MGH reserves. As the pressure-temperature conditions change during development of MGH reserves, methane is released, and the filling and cementation of the reservoirs is reduced [22,23]. This results in a decrease of effective stress and an increase in pore pressure, which reduces the shear strength and bearing capacity of the sediments and can lead to reduced slope

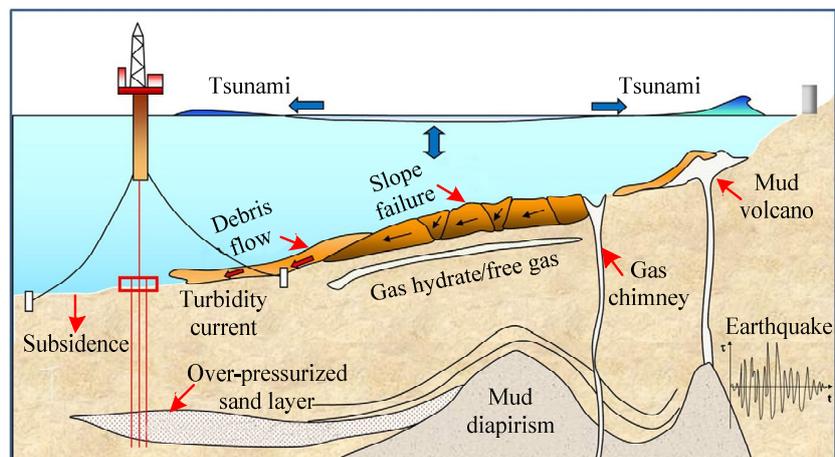
stability (Figure 4). Geohazards, such as sediment deformation, slumping, and even debris flows may occur. The submarine landslides of Storrega (Norway), at Cape Fear (USA) and in the Beaufort Sea (Canada) may have been related to the decomposition of MGHs [24–26]. Three criteria for the potential occurrence of submarine landslides have been identified [26,27]: (1) hydrates are widely distributed within the landslide areas; (2) the initial position of the landslide zone must be located at the phase boundary of the pressure-temperature field, (3) there is a low-permeability deposit under the hydrates which can maintain high pore pressure. The criteria suggest that submarine landslides caused by MGH decomposition are more likely to appear on shallow submarine slopes.



**Figure 4.** Schematic depiction of the mechanism that causes submarine landslides [23].

### 2.1.2. Earthquakes and Other Geohazards

The development of MGH reserves may cause other geohazards (Figure 5), such as earthquakes, active faulting, mud diapirism, and turbidity currents. Rapid venting of MGH reservoirs may cause the development of active faults which could provide a further conduit for methane escape, which would lead to a further decrease of reservoir pressure and thereby increase the rate of methane production [28]. Once the reservoir is drained, secondary hazards such as earthquakes may occur as a result of sediment settlement into the produced voids. Mud diapirism caused by plastic sediment flow around over-pressurized sand layers may also occur [22,29,30].

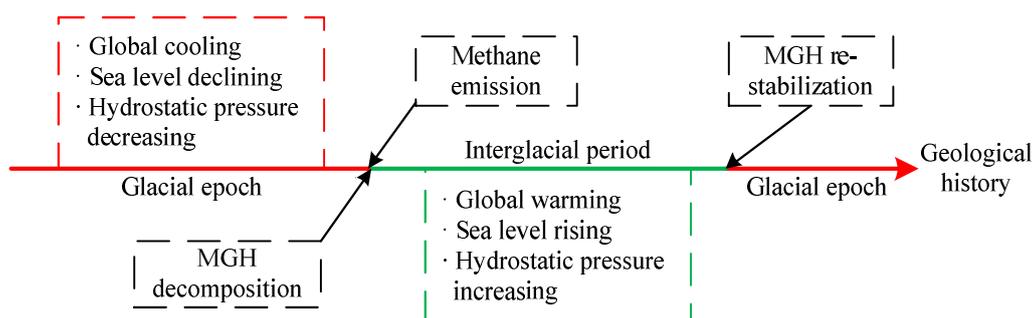


**Figure 5.** Sketch map of marine geohazards [22].

It should be noted that the release of MGHs and the associated marine geohazards triggered by this release are a normal process under natural conditions; the commercial development of MGHs could alter the balance and trigger these marine geohazards as an unnatural response [14]. Further studies are required to understand the causation of marine geohazards due to MGH development to ensure safe access to these resources.

## 2.2. Greenhouse Gas Emissions

One of the main impacts on the Earth's climate of increased greenhouse gases emissions is global warming. Methane is a greenhouse gas whose global warming potential index is twenty-five times that of carbon dioxide by unit mass and is an accelerator for environmental change [31,32]. Both the Paleocene-Eocene Thermal Maximum (PETM), with a global temperature rise of 4–8 °C that occurred 55.5 million years ago, and the global warming during the Quaternary interglacial periods were possibly caused by the large-scale decomposition of MGHs [23,33,34]. It suggested that during the Quaternary there was a cyclical link between the decomposition of MGHs (formation of methane) and global warming resulting in the glacial/intra-glacial cycle. As Figure 6 shows, (1) global cooling in the glacial epoch and sea-level decline leads to lower hydrostatic pressure, which results in the decomposition of MGHs as a result of the loss of stable pressure-temperature conditions; (2) the resulting methane enters the atmosphere which causes global warming, and an interglacial period ensues. As the glaciers melt as a response to the warmer conditions (interglacial period), the subsequent sea-level rise leads to increased hydrostatic pressure, and the MGHs restabilize until the next interglacial [35–37].



**Figure 6.** Relationship between gas hydrate decomposition and climate change.

At present, there is extensive research into establishing links between sudden releases of methane from MGH decomposition and specific changes in the global climate at certain times in the geological past, as well as the impact that these events had on geological history. One of the major problems with determining these effects is the fact that MGH-derived methane is dissolved and oxidized by seawater, so the amount entering the atmosphere is not representative of the release event or period [36]. Hence, the greenhouse gas emissions effect of MGH decomposition under normal conditions needs further observation and research [37].

## 2.3. Marine Ecological Hazards

In this paper, marine ecological hazards refer to the adverse effects on marine organisms and other components of the marine environment caused by the MGH decomposition. Under normal conditions, the gases from MGH decomposition reach the surface in a cold spring via a variety of means, including migration up fault planes and pore space expansion, where they form autotrophic chemosynthetic communities that consume methane, hydrogen sulfide, and other substances to provide the basic driving force for the entire marine community [38]. Inorganic carbon is also formed when MGH decompose and react with seawater to form carbonate minerals, providing a habitat for marine plankton and other biological communities (Figure 7). Uncontrolled releases from MGH may lead

to faulting, eruptions at the seabed, and the collapse of the carbonate deposits and chemosynthetic communities, which may adversely affect the health of the marine environment. Meanwhile, some of the methane derived from the MGH will be regenerated as new hydrates and return to the seabed while the rest will react with the dissolved oxygen in the seawater to form  $\text{CO}_2$ . If excessive amounts of methane enter the seawater, large volumes of oxygen are consumed to form  $\text{CO}_2$  so that the growth and evolution of marine animals and plants are prevented which could lead to extinction in extreme cases [39–41]. Marine faunal extinctions at the end of the Permian, Triassic, and Cretaceous may have been caused by the release of methane and subsequent changes to the marine environment [42,43].

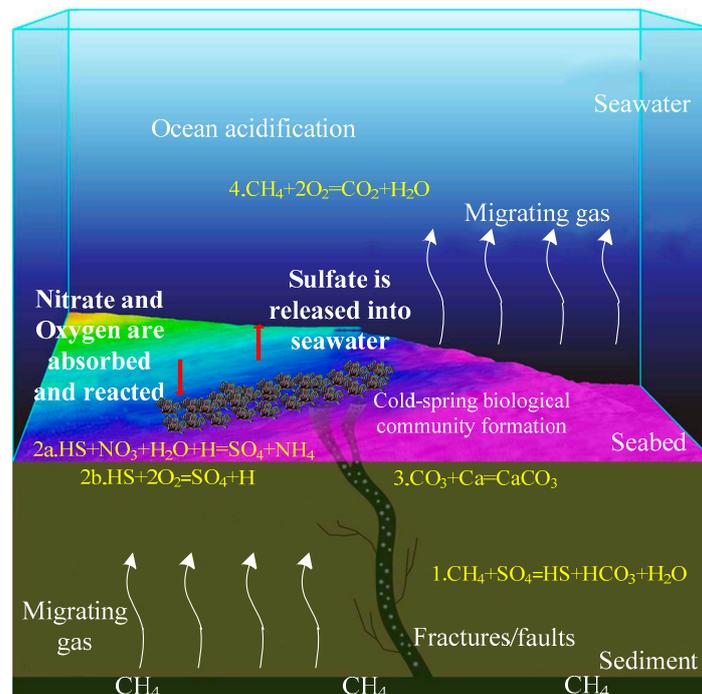


Figure 7. Chemical reaction after MGH decomposition [39].

Methane release by decomposition of MGH is a natural process and is part of the marine environment. Further research is needed into the effects on the marine environment that which might happen if MGH are developed as a commercial resource.

#### 2.4. Marine Engineering Hazards

Two types of marine engineering hazards can be caused by the development of MGH: (1) MGH instability induced during drilling, (2) the risks associated with drilling or installing submarine structures in MGH areas. These hazards are inter related and the links and differences are discussed below.

##### 2.4.1. MGH Stability Hazards

The MGH stability zone shown in Figure 2 is restricted to a limited temperature and pressure regime. Consequently, drilling through MGH is challenging as it involves changing the pressure regime and increasing the temperature profile of the sediments immediately surrounding the well bore (Figure 8). Furthermore, the use of organic alcohol hydrate thermodynamic inhibitors and inorganic salts in the drilling fluid can enhance the production of methane and barite precipitates, respectively [44]. On drilling into an MGH, large amounts of methane can be released that infiltrate into the drill pipe, resulting in a sharp increase in the mud pressure. As the methane rises and cools, it can reform as hydrate crystals that clog the drill pipe, potentially causing well abandonment. As drilling continues into the underlying free-gas zone, formation pressure can rise, causing increased release of

methane and the buildup of large amounts of high-pressure gas in the drill pipe, which could lead to a blowout [45]. With significant releases of methane, soil formation stability is reduced through the development of numerous voids, which could impact borehole stability if they collapse. Furthermore, poorly consolidated sediments can result in significant sand production, which can affect the operation of safety equipment such as blowout preventers [46].

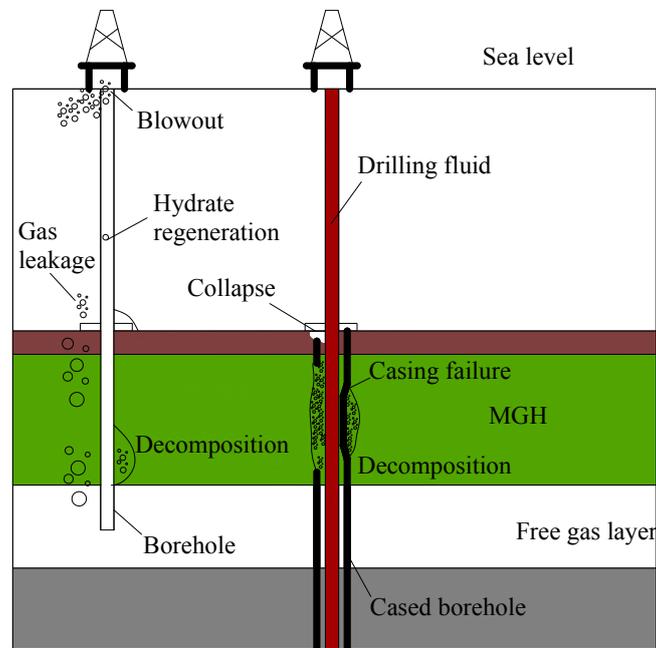


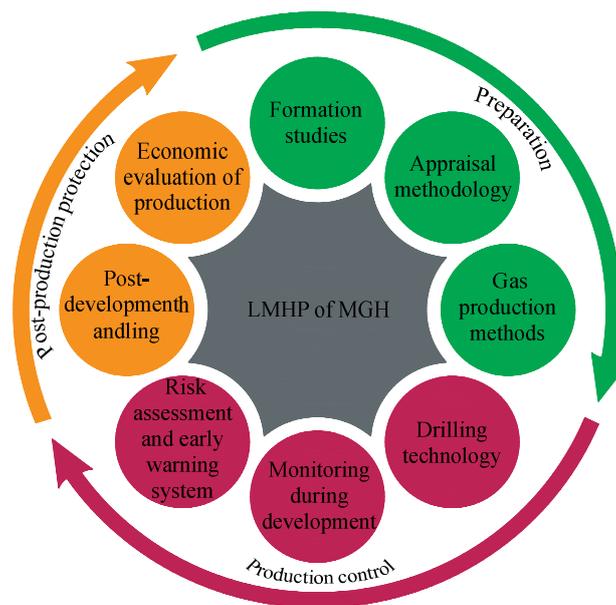
Figure 8. Sketch of drilling engineering hazards [38].

#### 2.4.2. Risks Associated with Drilling or Installing Structures in MGH Areas

Exploration and development drilling for hydrocarbons in deep water can involve drilling through MGH deposits, where decomposition and regeneration of MGH may occur [47]. When drilling through these deposits, the formation properties will change [48]. The risks such as changes in drilling fluid properties, borehole stability issues, well cleaning, and cementation problems will follow. However, these issues can be successfully mitigated by appropriate drilling techniques just like we can adjust the drilling fluid according to the formation properties change. Secondary generation of MGH within blowout preventers, as well as changes in the rheology of the drilling muds through the formation of barite scale and the subsequent blockage of pipework within the blowout preventer, may occur, but these effects can be reduced by appropriate composition of the drilling muds [49]. If foundations have to be piled into or laid on top of these deposits, then the seabed stability can be reduced if the pressure–temperature regime is disrupted with the subsequent damaged to the structures, associated pipelines, and communication cables [50].

### 3. Control and Prevention of Potential Hazards in MGH Development

Many methods have been proposed to reduce the potential hazards associated with the development of MGH as a resource. A concept of “lifecycle management of hazards prevention” (LMHP) in the development of MGH is proposed to cover the different stages of MGH development. These stages are: preparation; control during development; and post production protection. Each stage requires research into specific issues (Figure 9) and these are discussed below.



**Figure 9.** Lifecycle management schematic.

### 3.1. Preparation

The preparation phase is the primary step and the LMHP covers the mechanism of MGH formation, appraisal methodology and gas production methods.

#### 3.1.1. MGH Formation Studies

A comprehensive study of the formation, migration, accumulation, and storage of methane within the MGH, in conjunction with expected pressure-temperature conditions, gas source, gas migration, and the presence of suitable reservoirs within the MGH accumulation are the main factors to be determined [51]. The characteristics of each MGH accumulation depend on the interaction of all these factors [52]. The degree of difficulty for the development of NGH reservoirs can be represented in pyramidal form (Figure 10). The difficulty of developing MGH reservoirs varies in a continuum from low in sandy reservoirs, then permeable clay reservoirs, then cold spring-related massive reservoirs, to high in non-permeable clay reservoirs. Each reservoir-type can be subdivided into three types according to recoverable value: Class I, Class II and Class III [6,12]. Class I is that one hydrate bearing layer covers on a two-phase fluid zone with free gas which is considered to be the most suitable reservoir for natural gas production. Class II is that one hydrate bearing layer covers on a mobile water zone and Class III is that there is only one hydrate bearing layer, which are still not well defined as gas production targets [53]. The successful production test of high-saturation diffusion-sourced hydrates in a viscous siltstone reservoir in the Shenhu area of the South China Sea demonstrates that production can be successfully obtained from complex MGH reservoirs [54].

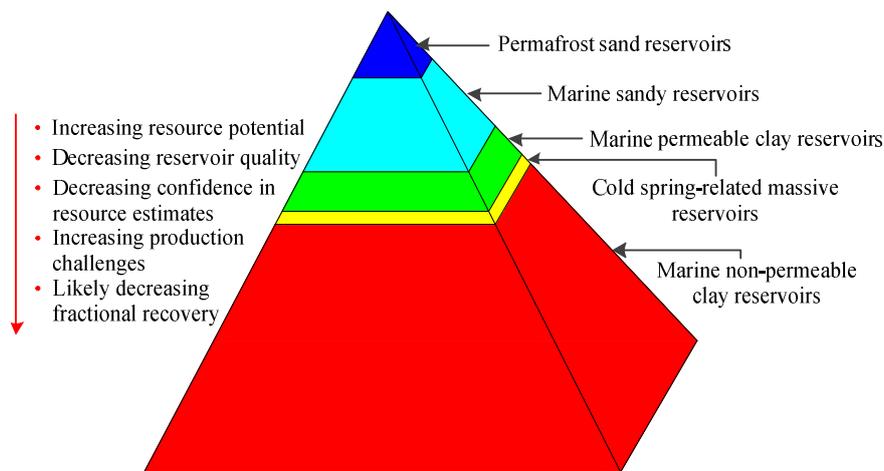


Figure 10. The pyramid of NGH exploitation difficulty [53].

### 3.1.2. Appraisal Methodology

An efficient appraisal methodology is a prerequisite for effective economic development of MGH reserves. The appraisal methodology involves the elimination of prospects with insufficient reserves, as well as reserves which are deemed risky or too complex to develop [14]. Resources can be defined as the total quantity of gas stored in the MGH reservoir (the sum of discovered and undiscovered gas as well as economically recoverable and non-economically recoverable gas), while reserves can be defined as the amount of gas that can be recovered at a reasonable level of economic return [55,56]. Currently, appraisal methodology involves four methods for volumetric estimation: (1) area/depth method, (2) volumetric method, (3) probability statistics, and (4) material balance method, of which the volumetric method which most widely used [57]. Figure 11 shows that as geological certainty and economic cut-offs improve, the reserves gradually decrease. At present, the concept of “natural gas hydrate petroleum system” [58] based on volumetric method has been proposed by researchers, which combines the accumulation mechanism with the actual occurrence conditions, and has a higher feasibility in the management of MGH resource appraisal system in the future [59].

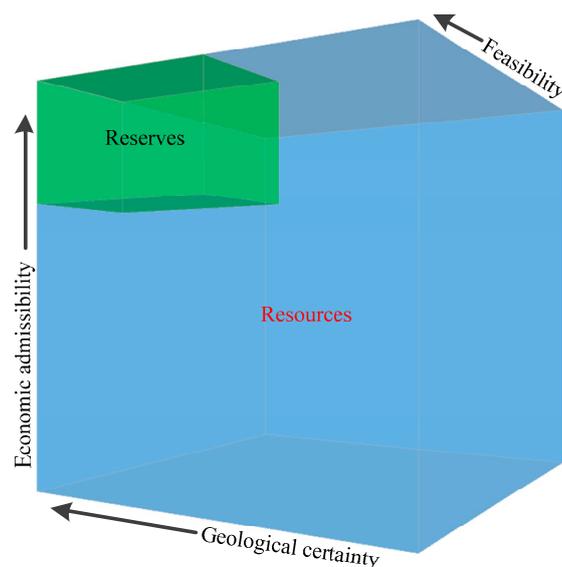


Figure 11. Volumetric method in resource appraisal [56]. (a) the “blue cube” represents “Resources”; (b) the “green cuboid” represents “Reserves”; (c) the “arrows” indicates an increase in each element.

### 3.1.3. Gas Production Methods

Choosing the most effective method for gas production from MGHs involves assessing a variety of factors to achieve the simplest, most practical, and environmentally safe method of production. Five methods are mentioned in the Introduction, their production benefits and risks are presented here as follows [6,60]:

- (1) Chemical agent injection, used in permafrost NGH developments, is expensive and toxic and application in MGH development will damage marine ecological environments.
- (2) Depressurization operations of MGHs do not require continuous operation so have lower costs, and are appropriate for large-scale production.
- (3) Thermal activation methods can be used in situations of complex geology; however, these methods require high levels of energy consumption as well as having low heat exchange efficiency.
- (4) CO<sub>2</sub> replacement methods are environmentally friendly, but are technically difficult and require a steady supply of CO<sub>2</sub>.
- (5) Solid fluidization is only applicable to deep-sea reservoirs at shallow depths, with limited-diagenesis and poor cementation. It has only been applied in the Liwan area of the northern South China Sea [35].

Production tests using a combination of depressurization and thermal activation methods have been successfully applied at the highest ranked offshore prospects (the Shenhu area of the South China Sea and the Nankai Trough of Japan) [10,15,16], and the CO<sub>2</sub> replacement method is the most effective onshore method to avoid potential hazards in the future (production test of permafrost in the North Slope of Alaska, USA) [18,61].

## 3.2. Production Control

Production control during MGH development is the key priority for LMHP and involves using appropriate drilling technology, hazard monitoring during drilling and production, and suitable monitoring systems to provide early warning of systems failure.

### 3.2.1. Drilling Technology Management

Drilling technology management is one of the core parts of MGH development which can avoid potential hazards if applied correctly. There are three aspects involved: drilling, cementing, and completion [62]. The drilling system includes drilling technology, fluid, and equipment, and their effective integration to ensure efficient drilling. The preferred method of drilling is selected to inhibit decomposition of MGHs by maintaining pressure or using casing. Cased drilling has been used on all the production tests because it is quicker, cheaper, and less prone to failure. Well cementation provides protection and support to the wellbore casing, particularly across the reservoir section. Well completion provides further stability to the wellbore and to prevent accidents caused by excessive sand production. Drilling has been done to date using semi-submersible drilling rigs or drill ships (Figure 12) and downhole gas-liquid-solid separation devices [63]. The Shenhu production test used the “Blue Whale I” semi-submersible drilling rig and a Chinese gas-water-sand tri-phase separator. The Nankai Trough production tests used the “Chikyu (Earth)” deep ocean drilling vessel and a Japanese gas-liquid separator. Both these systems proved effective during the respective production tests [64,65]. During the drilling of these production wells, drilling fluids had significant quantities of thermodynamic inhibitors added to the drilling mud to suppress or retard the regeneration of hydrates. This also had a significant effect on the prevention and control of marine geohazards. Special cements were used which had the following properties: low temperature, low density, low hydration heat, high early strength, low filtrate loss, good densification, and anti-channeling in order to ensure efficient completion of cementing operations. Appropriate well completion measures, such as mechanical sieve

tubes and gravel packing, were used during the production tests [66]. Research is needed to improve sand control methods during well completion to reduce sand abrasion and enhance abrasion resistance.

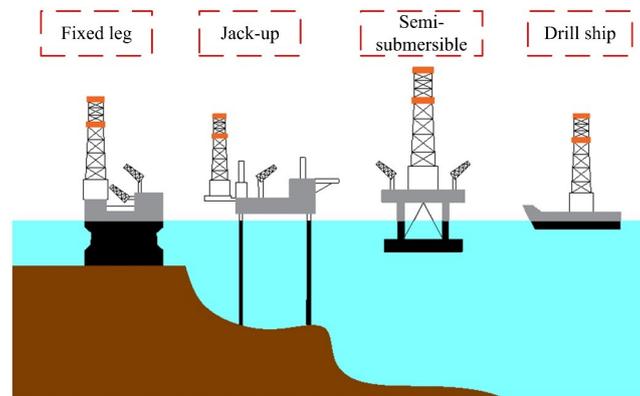


Figure 12. Different platforms for offshore drilling [10].

### 3.2.2. Monitoring during Development

Monitoring the changes in the submarine environment is an important part of the MGH development process (Figure 13). This ensures that potential hazards can be prevented during development, as well as establishing a baseline for monitoring changes in the marine environment during production and throughout development. Baseline monitoring is performed to detect changes in reservoir parameters, such as temperature, pressure, permeability, porosity, saturation, as well as in environmental parameters, such as seawater composition and submarine life that result from the development of MGHs. It is important to obtain baseline data before production commences in order to analyze the changes relating to production and development in the surrounding environment; these data can be collected along with other monitoring data in the planning stage. During production and development, it is important to have real time monitoring of seabed deformation, reservoir stability, and methane leakage; this was undertaken during the production test in the Nankai Trough of Japan and in the Shenhu area of the South China Sea [11,67,68]. Therefore, it is important to carry out long term, real-time, extensive, multi-parameter, in-situ monitoring to evaluate the impact that MGH production has on the marine environment during production, development, and afterwards.

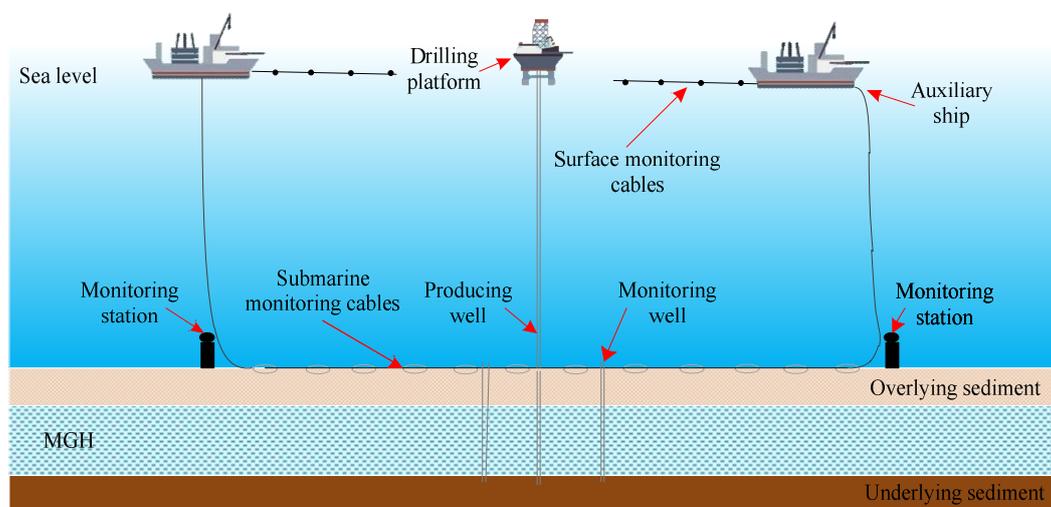


Figure 13. Submarine in-situ monitoring system [67].

### 3.2.3. Risk Assessment and Early Warning System

The purpose of a risk assessment system is to estimate and assess the scale and impact levels that potential hazards would have throughout the entire life cycle of a MGH development, and then establish a quantitative assessment and early warning system for potential hazards. This paper suggests a fuzzy comprehensive evaluation method [69] to quantitatively evaluate different types of hazards. First, a set of assessment object factors ( $U$ ) is determined (Table 1), and then a comment set  $V = \{\text{High risk, medium risk, low risk, minimal risk}\}$  is determined.

**Table 1.** Assessment object factors set.

The First Index $U_i (A_i)$	The Second Index $U_{ij} (A_{ij})$	The Third Index $U_{ijk} (A_{ijk})$
Climate and environmental hazards $U_1 (A_1)$	Greenhouse gas $U_{11} (A_{11})$	—
	Biocoenosis hazards $U_{12} (A_{12})$	
	Submarine landslide $U_{21} (A_{21})$	
Marine geohazards $U_2 (A_2)$	Active fault $U_{22} (A_{22})$	—
	Mud diaper $U_{23} (A_{23})$	
	Sea quake $U_{24} (A_{24})$	
	Turbidity current $U_{25} (A_{25})$	
	Well blowout, leakage and borehole instability $U_{311} (A_{311})$	
Marine engineering hazards $U_3 (A_3)$	Drilling engineering hazards $U_{31} (A_{31})$	Sand production, well plugging and hydrate secondary generation $U_{312} (A_{312})$
	Deep-sea drilling hydrate crossing and other accidents $U_{32} (A_{32})$	Disused well $U_{313} (A_{313})$
		submarine line accidents $U_{321} (A_{321})$
		Oil-gas well accidents $U_{322} (A_{322})$
Note: the sum of $A_i$ is 1	Note: the sum of $A_{ij}$ is 1 ( $i$ is the same)	Note: the sum of $A_{ijk}$ is 1 ( $i, j$ all are the same)

Next, a second set ( $A$ ) of assessment object factors is derived using a variety of methods including expert estimation, Delphi method, and characteristic value, although they all involve subjective analysis. The fuzzy relation matrix  $R$  is determined using a single factor fuzzy assessment. The appropriate fuzzy synthesis operator  $M$  is selected to combine the weight set  $A$  and the matrix  $R$  to create a weight set  $B$ . Then by comparing the weight set  $B$  with the comment set  $V$ , the potential risk level for each potential hazard can be determined. As a result of this analysis of potential hazards, a quantified risk assessment for potential hazard levels during MGH development can be established and a set of corresponding early warning measures be established. Using appropriate technologies, personnel, and equipment in a prudent way to form a complete risk assessment and develop early warning system for hazards will prevent hazards occurring and provide a solution pathway when they occur.

### 3.3. Post-Production Protection

It is important to evaluate the post-production restoration cost of the environment surrounding an MGH development as part of the overall evaluation of the economic value of developing an MGH resource.

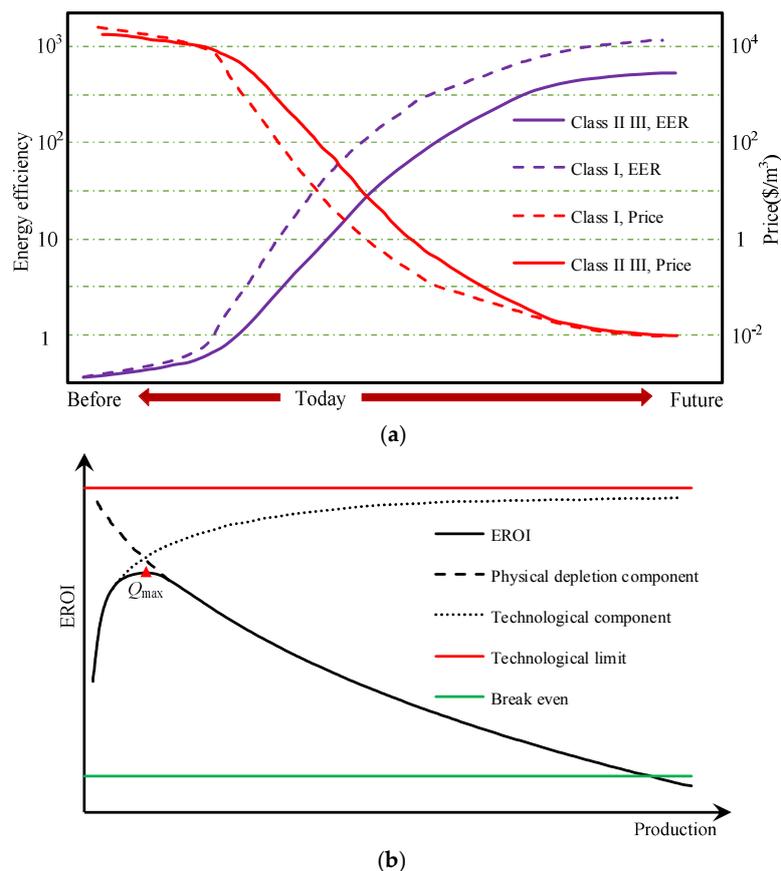
#### 3.3.1. Post-Development Handling

The cessation of production at MGH developments involves a variety of issues such as well abandonment, reservoir protection, and monitoring of the surrounding environment. Well abandonment is similar to that of traditional deep-sea gas production and monitoring of the surrounding environment is concerned with whether there are anomalies in strata, seawater, or the atmosphere. These processes can be undertaken during the risk assessment process. Post production reservoir remediation is important to maintain seabed stability. During MGH production, large numbers of voids may appear in the reservoir, resulting in reduced sediment strength and problems relating to sediment collapse. A method to inject the produced voids with high-water content sediments

under high-pressure and low-temperature is proposed, which would improve sediment stability and remediate the marine environment after production has ceased.

### 3.3.2. Economic Evaluation of Production

The economic evaluation of production considers the problem of coordination between input and output, technology and efficiency. One of the main purposes of developing MGHs is to maximize the economic benefit by using suitable technology in a safe environment. The two important parameters involved in the economic evaluation are the energy efficiency ratio (EER, ratio of combustion heat to decomposition heat in unit) and the energy return on energy invested (EROI, ratio of energy output to energy input during production) [70]. On the one hand, EER is affected by the production method, with the depressurization having the maximum energy efficiency; on the other hand, the reservoir type (Section 3.1.1) is also an important factor. The changes in reservoir energy efficiency and expected production cost trends are shown in Figure 14a. EROI is mainly influenced by the technical level and the amount of resources used during production. Generally speaking, the higher the resource value used, the higher the hydrate production efficiency that can be achieved. The continuous improvement in technology and constant consumption of resources indicates that the EROI has a peak value  $Q_{max}$  and then declines to the breakeven line (Figure 14b). Therefore, low-efficiency technology will inevitably consume large amounts of high-quality resources and shift the peak forward. One of the important uses of economic evaluation of the production costs associated with technological breakthrough and innovation is to ensure that these lie within a reasonable range on the EER and EROI graphs [71,72].



**Figure 14.** Economic evaluation indices of production [70]. (a) Changes of EER and production cost with time; (b) Change of EROI with production. The “Physical depletion component” means the trend of gas hydrate resource depletion; the “Technological component” means the trend of technology development; the “Technological limit” means the maximum that the technology can achieve; the “Break even” means that the EROI is maintained at a lower level and is no longer developed.

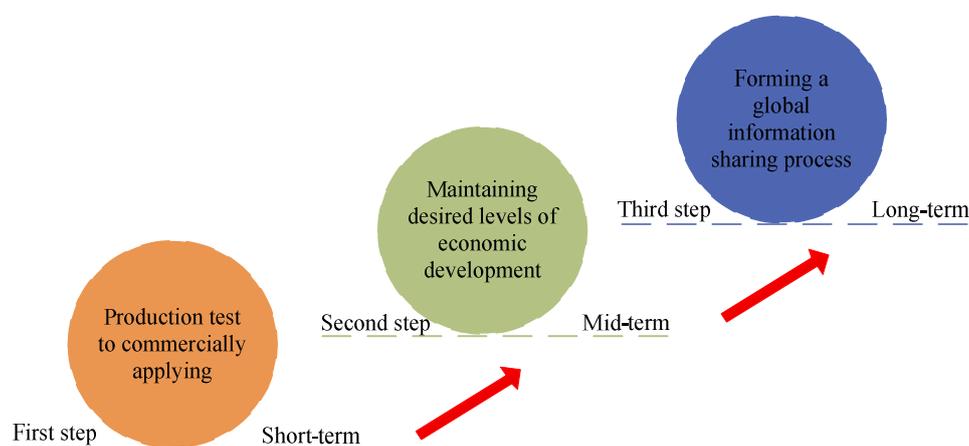
Based on the above analysis, all stages of LMHP are dynamic and interlinked processes. Effective integration of these will enable MGH development to be undertaken in a safe and effective fashion; ignoring small details may lead to significant problems during the project life cycle.

#### 4. Key Challenges and Prospects

The development and exploitation of MGHs is undergoing rapid evolution. Between May to July 2017, China successfully tested in the Shenhua area of the South China Sea, where natural gas was extracted from silty clay reservoirs at a depth of 203 to 277 m below the seabed, in water depths of around 1266 m below sea level [10,35]. The production test was carried out by the “Blue Whale I” semi-submersible drilling rig. Firstly, the MGH in the silty clay reservoirs is decomposed by the depressurization, and then the natural gas developed by the hydrate sediment is taken out smoothly by using a gas-water-sand tri-phase separator which independently developed by China [10,73]. During the 60-day stable production test, the cumulative gas production exceeded  $30.9 \times 10^4 \text{ m}^3$ , with an average daily output of  $5151 \text{ m}^3$  and a maximum daily production of  $3.5 \times 10^4 \text{ m}^3$ . The maximum methane content in the produced gas was 99.5% [10,72]. Several major technical breakthroughs were achieved during this production test, such as the longest sustained production time and the maximum volume of gas production, the duration of stable air flow and environmental safety, as well as establishing two new world records for the gas production time and volume. However, these production test successes are only an initial step in the process of MGH development where all involved countries, including China, are still facing great challenges and difficulties.

##### 4.1. Key Challenges

The potential hazards and the implementation of the prevention and control measures within LMHP are all challenges. In this section, these are summarized into the “three-step” strategy (Figure 15) reflecting the importance that these problems have within the different development stages of MGH development.



**Figure 15.** The “three-step” strategy of development.

The first step: short-term challenges. This stage contains most of the major problems that needs to be dealt with from production testing to development. These include target zone (s) selection, the mechanism and method of increasing production, flow security mechanisms, sand control methods, solid-gas-liquid multiphase flow monitoring, reservoir deformation and monitoring, in-situ bio-environmental analysis, risk assessment and establishment of an early warning system. This step is the bottleneck for the development of MGHs as large investments are required to drive technological innovation to increase production and development breakthroughs.

The second step: mid-term challenges. These challenges are more associated with ensuring that the economics of development are maintained to ensure successful development. Production levels

can be maintained to ensure that costs associated with the exploration and development, production monitoring, technological innovation, and environmental monitoring and remediation are covered. This requires that a long-term comprehensive solution is found to guarantee the effective utilization of MGHs.

The third step: long-term challenges. A global resource management mechanism similar to that used in developing petroleum resources needs to be created at this stage. As a new source of energy, MGHs have the potential to change global consumption patterns. Their successful development and achieving maximum return on investment requires international cooperation, and exchange of ideas, as well as developing a scheme to allow global production and shared access to these resources.

#### 4.2. Prospects

As world energy patterns change and environmental issues become more important, the identification and development of a new unconventional source of energy is becoming a global issue. MGHs are possibly a great source of potentially clean energy with large reserves, wide global distribution, and a high energy density. Production tests results from the Shenhu area of the South China Sea and the Nankai Trough of Japan demonstrate the accumulation and application of drilling technology to develop these reserves. The potential risks, the formation of MGHs, as well as the production and prevention hazards during development are the key issues to solve the economic utilization of MGHs, will be major research topics for scientists from around the world for many years.

### 5. Conclusions

- (1) Four inter-related hazards which may occur during MGH exploitation were identified as follows: marine geohazards, greenhouse gas emissions, marine ecological hazards, and marine engineering hazards.
- (2) Lifecycle management of potential hazards prevention in the exploitation of MGHs (LMHP) was proposed firstly. It has three stages: preparation, which involves investigating the accumulation mechanism, appraisal methodology and gas production methods; production control, which includes drilling techniques, monitoring during production risk assessment and early warning system; and post-production protection, including post-production remediation and economic evaluation of production. All these factors are inter-related and need to be systematically evaluated.
- (3) A “three-step” strategy for the development of LMHP is proposed, which consists of commercially applying the results of MGH research in the short-term, maintaining desired levels of economic development in the mid-term and forming a global information sharing process associated with hydrate in the long-term. Understanding this “three step” strategy will allow the successful development of MGH resources.
- (4) The production test in the Shenhu area of the South China Sea showed that the development of MGHs is a complex and constantly changing problem with difficult challenges. Safe and efficient development and production of MGHs can be achieved by innovation and breakthroughs in the use of technology as well as through extensive international cooperation and exchange of information around the world.

**Author Contributions:** The concept of LMHP and “three-step” strategy for MGHs development was proposed by F.W. and he also wrote the conclusions and abstract. The specific classifications of the two strategies were carried out by B.Z. and data collection during the revision of the paper was completed by G.L.

**Funding:** This research was funded by the [Independent Research Project of State Key Laboratory of Coal Resources and Safe Mining, CUMT] grant number [SKLCRSM18X012], the [Independent Innovation Project for Double World-class Construction, CUMT] grant number [2018ZZCX07] and the [China Scholarship Council] grant number [201802180034].

**Acknowledgments:** This work was supported by the Independent Research Project of State Key Laboratory of Coal Resources and Safe Mining of CUMT (SKLCRSM18X012), the Priority Academic Program Development of

Jiangsu Higher Education Institutions, the Independent Innovation Project for Double World-class Construction of CUMT (No.2018ZZCX07) and the visiting scholarship funded by the China Scholarship Council (No.201802180034). The authors gratefully acknowledge financial support of the above-mentioned agencies.

**Conflicts of Interest:** The authors declare that they have no conflicts of interest.

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