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Experimental study on a pressure-coring technology based on a freeze-core valve for marine hydrate-bearing sediment sampling

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ABSTRACT

Recovery of hydrate-bearing sediments under near in situ conditions remains a topic worthy of investigation. To avoid the frequent sealing failures of mechanical valve-based samplers, a freeze-core-valve-based sampler is proposed for pressure-coring sampling in submarine sediment. A series of preliminary experiments were conducted to characterize the freeze-core valve, including the performance of retaining pressure and adaptation to different sediments. The results show that the freeze-core valve exhibited a strong performance in retaining pressure and can be to various sediments without limitations due to sediment conditions, including pore water salinity, clay mineral content, particle size and grain grading. The retained pressure for a 58-mm nominal diameter and 80-mm-long freeze-core valve formed at −40 °C can reach 43 MPa without leakage, which can meet the requirement of the pressure-coring sampling. The pressure retaining performance can be further improved by lowering the freezing temperature or increasing the length of the freezing-core valve. According to the preliminary tests, the sampling technique based on the freeze-core-valve has the potential to solve the problem of the low recovery success rate of gas hydrate sediment cores in the future.

1. Introduction

In the past few decades, natural gas hydrates, especially oceanic gas hydrates, have received significant attention as a potentially substantial unconventional natural gas resource and for their effects on marine geologic hazards and global climate (Konno et al., 2013; Jing et al., 2015; Hedeo et al., 2004). A number of hydrate reservoirs have also been found in submarine areas, such as Hydrate Ridge (Cao et al., 2013), the Gulf of Mexico (Francisca et al., 2005; Boswell et al., 2012), the Cascadia Margin (Malinverno, 2010; Malinverno et al., 2008), Nankai Trough (Stern and Lorenson, 2014), Ulleung basin (Rose et al., 2014), the Shenhu area (Winters et al., 2014), Krishna Godavari basin and Andaman basin (Uchida et al., 2009; Ryu et al., 2013; Wang et al., 2011). Nevertheless, gas hydrates tend to dissociate with relatively rapid gas exsolution in the case of no pressure (Dai and Santamarina, 2014; Waite et al., 2008). Most commonly, more than 95% of hydrocarbons were lost during the non-pressure recovery process (Paull and Ussler, 2001; Paull et al., 2000), which seriously impacted the accurate quantification of gas hydrate reserves (Schultheiss et al., 2008).

Until now, several attempts have been undertaken to develop pressure-preserving samplers to retrieve gas hydrate-bearing sediments at near in situ pressures. A variety of pressure-coring tools are well-known and have been successfully applied: the Pressure Core Barrel (PCB) from the Deep Sea Drilling Project (DSDP) (Peterson, 1984), the Pressure Core Sampler (PCS) from the Ocean Drilling Program (ODP) and the Integrated Ocean Drilling Program (IODP) (Dickens et al., 2000; Riedel et al., 2006), the HYACE Rotary Corer (HRC) and the Fugro Pressure Corer (FPC) used in the ODP and IODP (Trehu et al., 2003; Expedition 311 Scientists, 2005; Schultheiss et al., 2009), the Pressure Temperature Core Sampler (PTCS) and the Hybrid Pressure-Coring System (Hybird PCS) used in the Nankai Trough (Takahashi et al., 2001; Kubo et al., 2014), the Multiple Autoclave Corer (MAC) and the Dynamic Autoclave Piston Corer (DAPC) from Germany (Abegg et al., 2008),

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the Hydraulic Pressure and Temperature Preservation corer (HPTP) deployed in the South China Sea (Zhu et al., 2011), etc. The above pressure corers have accomplished the task of retrieving samples while maintaining pressure; however, failures of maintaining pressure have often occurred due to the wear or malfunction of mechanical valves, such as the flapper valve and ball valve (Fig 1)(Luo et al., 2015a,b). To avoid this problem, an ice-valve-based pressure-core-sampling system used in permafrost regions was proposed (Luo et al., 2015a,b). Distinct from the mechanical valves, this coring method utilized an ice valve made out of drilling fluid to retain pressure. Relevant tests presented the desirable capability of retaining pressure and its potential to improve the success rate of pressure coring. However, considering the pollution of the drilling fluid and costs of casing, the ice-valve based corer using conventional drilling fluid seems to be less suitable for sampling in a seafloor environment.

Hence, a freeze-core-valve-based corer utilizing the artificial freezing of a very small part of sediment to act as a seal is proposed for sampling in marine sediment. With respect to the artificial ground freezing (AGF), a number of successful applications have been recorded on various occasions. Dash recommended a ground freezing method utilizing the seal characteristic and thermal stability of freezing soil to address hazardous waste (Dash, 1994, 1997). Hu et al. proposed a Freeze-Sealing pipe roof method, which made the most of the advantages of frozen soil, such as tightness and sealing (Hu and Tao, 2015). Through artificial ground freezing for the Dusseld subway in Germany, Peter et al. stated that the freezing soil would achieve a higher strength and resistance to deformation when the soil saturation was over 60% (Jordan and Heb, 1994). As marine sediments are always saturated (Liu et al., 2013; Wang et al., 2006), it is inferred that the frozen sediments could be available for retaining pressure. Based on the mature application of AGF, freezing on a very small scale for sealing is probably much easier. Several preliminary laboratory tests for the freeze-sediment-valve are presented, and the capability of retaining pressure and its adaptability to different seafloor sediments are also discussed in this paper.

2. Concept of the freeze-core-valve pressure coring system

Different from mechanical valves and the ice valve, the freeze-core valve is made from a fraction of in situ sediment. As a wireline coring sampler, the freeze-sediment-valve-based corer can be used to sample at a deeper layer from the seafloor. As shown in Fig 2, the corer mainly consists of a bi-stable fluidic amplifier, a pump head, two dewars and a core tube. An actuation ball, similar to PCS, is designed as the controller of the bi-stable fluidic amplifier. The fluidic amplifier is employed to control the seawater to flow into the chamber to drive the reciprocating piston. The plunger connected with the piston drives the pre-stored low-temperature alcohol to circulate from the upper dewar to the lower dewar. A continuous cooling process is made by low-temperature alcohol at the heat exchangers. The influence of heat transfer on the other parts is eliminated by means of thermal insulation. Finally, the freeze-core valve and ice valve are formed to retain pressure. Then, the pressure-core sampler is pulled up with cores to the ground, thereby completing the coring process.

Fig. 1. The stuck ball valve of PTCS (Aumann and Associates, 2003).

With the in situ freezing, there is no need to lift the core barrel like the ice-valve pressure corer. Additionally, using seawater instead of conventional drilling fluid can solve the problem of marine pollution and additional costs. Hence, this system not only inherits the advantages of the ice-valve-based pressure corer, such as permitting a larger coring diameter, less working surface requirements, and no jamming or abrasion, but is also simpler and more suitable to sample in seafloor sediment compared with the ice-valve-based corer.

It is worth noting that the hydrate-bearing sediment can be obtained from the valve if pressure is maintained. Similar physical properties have previously been reported for frozen soil and hydrate-bearing sediment (Liu et al., 2013), and the substitution of hydrate-bearing sediments by ice-bearing sediments was also regarded as an efficient method to simplify experiments (Luo et al., 2015a,b). In some respects, the frozen hydrate-bearing sediment is exactly like the frozen sediment on the condition that the effect of the hydrate can be neglected. The hydrate acts as cement between sediment grains, presenting similar adhesive properties with ice in frozen soil (Li et al., 2010; Sung et al., 2004). A few authors have confirmed that hydrates had higher mechanical strength than ice (Helgerud, 2001, Helgerud et al., 2009). Their strengths increased more obviously than ice during the load process (Stern et al., 1996, 1998). Moreover, hydrate can achieve higher strength than ice by lowering temperature, and even a twenty-fold distinction was observed at 0 °C; at lower temperatures, a greater difference between hydrate and ice can be observed (Stern et al., 1996, 1998; Durham et al., 2003). Apparently, hydrate-bearing sediment can effectively maintain pressure if the frozen sediment meets the requirement of pressurization and if the frozen sediment valve is at a very low temperature. To verify the pressurizing ability of the freeze-core valve, several preliminary experiments were conducted using frozen sediment.

3. Description of the experimental method

3.1. Materials

Seawater is a salt solution of nearly constant composition (Metcalf and Eddy, 2008). Artificial seawater is prepared as shown in Table 1. The particle sizes of quartz grains for tests are classified and listed in Table 2. The median size of clay minerals was 0.002 mm. All of the samples were prepared using a grain skeleton, and the clay minerals were mixed proportionally. The amounts of materials were measured by an accurate analytical balance (ME104E) with a resolution of 0.1 mg.

3.2. Lab apparatus and test procedure

The schematic experimental layout is shown in Fig 3. The test devices mainly include a freeze-core-valve tube with a bore diameter of 58 mm, a digital refrigerated circulator bath, an air compressor and a booster pump. The whole experiment is divided