Putting the Deep Biosphere and Gas Hydrates on the Map

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ABSTRACT

Microbial processes in the deep biosphere affect marine sediments, such as the formation of gas hydrate deposits. Gas hydrate deposits offer a large source of natural gas with the potential to augment energy reserves and affect climate and seafloor stability. Despite the significant interdependence between life and geology in the ocean, coverage of the deep biosphere is generally missing in most introductory oceanography textbooks, so there is a need for instructional materials on this important topic. In response to this need, a course module on the deep biosphere with a focus on gas hydrate deposits was created. The module uses Google Earth (Google, Mountain View, CA) to support inquiry-based activities that demonstrate the interaction of the deep biosphere with geology. The module was tried as both a series of in-class exercises and as an out-of-class assignment in an introductory, undergraduate oceanography course. The students took short, preactivity and postactivity quizzes to determine the effectiveness of the module in improving student knowledge about gas hydrates. The module was effective at increasing student knowledge about the basic environmental and biological controls on the formation of gas hydrates on the seafloor. Students showed a consistently low initial comprehension of the content related to gas hydrates, but most (>80%) of the students increased their quiz scores for all module activities. This module on gas hydrate deposits increases the available teaching resources focused on the deep biosphere for geoscience educators. *© 2016 National Association of Geoscience Teachers*. [DOI: 10.5408/15-136.1]

Key words: deep biosphere, gas hydrate, oceanography, Google Earth

INTRODUCTION

The ocean is essential for life on our planet. It covers 71% of the Earth's surface, is the source of the water we drink, the air we breathe, and much of the food we eat. However, based on informal student evaluations from our introductory oceanography course at Miami University, it was clear that our students had deficiencies in ocean literacy that affected their ability to recognize the significance of Earth's largest geologic feature—the ocean. Specifically, our students struggled to identify ways (beyond pollution) that the ocean and humans are inextricably connected (principle 6, Ocean Literacy, 2013). One formal study of college student knowledge of the ocean found similar results, with students being more aware of ocean pollution than other connections to the ocean, such as oxygenation of our atmosphere or climate change (Cudaback, 2006). Broader surveys show that the American public overall demonstrates a similar low awareness of the ocean (Steel et al., 2005; The Ocean Project, 2009, 2011). An ocean-literate public is essential for the survival of our planet, including humans, yet most American voters don't have access to formal science courses beyond high school or a few college courses. This means that introductory oceanography college courses may be the last chance to positively affect voter ocean literacy through formal education (Cudaback, 2006). We describe a module that was built out of the need to develop strategies that could bring some of the richness of the oceanography community into the college classroom to help our students develop deeper connections to the ocean (Kobilka and Sikorski, 2013). The developed module uses cutting-edge research about microbial life in ocean sediments (that is, the deep biosphere) as a case study to illustrate the connectivity between society and the ocean, as well as to introduce the students to additional forms of marine life and ecosystems. Specifically, the created module provides both introductory material on the deep biosphere and inquiry-based activities that demonstrate the interdisciplinary nature of this science with authentic gas hydrate data displayed in the educator-friendly software of Google Earth (Google, Mountain View, CA).

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BACKGROUND

For years, deep marine sediments were considered completely void of life because of the harsh conditions present (e.g., cold, high pressure, few nutrients). It wasn't until the mid-1990s that technology progressed enough to provide uncontaminated samples of the marine sediments, which allowed scientists to assess the presence of life. Scientists quickly realized that these deep marine sediments contained abundant and diverse microbial life, which has been termed the deep biosphere. Microbial processes in the deep biosphere can have profound effects on the chemical and even the geological features in marine sediments. For example, gas hydrates are composed of methane (mainly produced by microbes) locked in an ice-like clathrate. Hydrates are a defining feature along most continental margins, where temperature, pressure, and methane concentrations support hydrate formation and are, therefore, relatable to the geology of the ocean basins.

Gas hydrates have the potential to greatly affect society. The potential amount of methane in gas hydrate deposits is around 500 to 2,500 Gt of methane carbon, which is equal to, or more than, all other fossil fuel deposits (Milkov, 2004). When the ice melts, the methane (natural gas) is released and can be ignited for use as an energy source. In fact, several countries (i.e., the U.S., Japan, India, Korea) are investigating how to harvest natural gas hydrates from the seafloor. Gas hydrates are also a potential source of geohazards. For example, the melting of gas hydrates would release large volumes of methane, a greenhouse gas, into the atmosphere. Large-scale releases of methane associated with gas hydrate deposits might explain ancient periods of major climate warming that are documented in the marine sediment record (Dickens, 2003). In addition, the melting of gas hydrate is also potentially associated with large-scale slope instability on the seafloor (Maslin et al., 2004).

Life present in deep subsurface marine environments is inextricably interconnected to the study of the ocean, yet the deep biosphere is not typically covered in most undergraduate oceanography textbooks. Although three reviewed textbooks (Garrison, 2011; Pinet, 2011; Sverdrup and Kudela, 2014) did mention that gas hydrate deposits are found on the seafloor, these texts provided no additional discussion on the role microbial processes have in the formation of these deposits. In fact, a review of the most-recent editions of introductory oceanography textbooks found only one direct reference to the deep biosphere (i.e., Trujillo and Thurman, 2017). Recent, significant advances in the understanding of the deep biosphere warrant induction of this topic into undergraduate oceanography courses; thus, there is a significant need for course materials on this subject.

Inquiry-based learning refers to a set of strategies that actively involves students in the process of learning, which includes engaging students with scientific data and the process of doing science (Anderson, 2002). Geoscience educators recognize several potential benefits of engaging students with scientific data, including improved ability to think quantitatively, as well as improved ability to communicate in verbal, written, and graphical formats (Manduca and Mogk, 2002). When directly engaged with geologic problems, students are exposed to the types of experiences (Kolb, 1984) that can lead to an increase in student comprehension and retention of course material because inquiry-based learning uses all regions of the brain, providing both a direction and a context for course content (Zull, 2002). In fact, there are a number of examples within the geosciences that demonstrate positive learning outcomes when students actively engage with their course work (Yuretich et al., 2001; McConnell et al., 2003; Kortz et al. 2008; McNeal et al., 2008; Drennan and Evans, 2011; Kim et al., 2013; Grissom et al., 2015). However, typically, the use of authentic geoscience data within classrooms is hindered by limited access to data and lack of familiarity with discipline-specific data formats and/or specialized software (Taber et al., 2012). These challenges are starting to be addressed (Ledley et al., 2012; Ellwein et al., 2014; Gold et al., 2015). The benefits of asking students to engage with scientific data could extend beyond mastering content knowledge. Engaging with complex, real-world problems also requires students to confront their own beliefs about learning and knowledge and helps to foster their ability to think critically and to transfer their existing knowledge to new situations (Bransford et al., 2000; Baxter Magolda and King, 2004; Feinstein et al., 2013), which are skills that are required for responsible citizenship (Manduca and Mogk, 2002; Ledley et al., 2012).

MODULE DESIGN

We created a new instructional module on the deep biosphere focused on gas hydrate deposits. The course module was developed for use in an introductory oceanography course at the undergraduate level but would also be appropriate for use in any introductory geology or marine biology course. Although this module was developed with a general education student audience in mind, it is helpful if students have some background knowledge of seafloor topography and marine sediments before completing this module.

The module uses Google Earth to support inquiry-based activities that demonstrate the interaction of the deep biosphere with geology. Google Earth is a popular application for geoscience educators and researchers (Bailey et al., 2012). In fact, Google Earth has been used by geoscience educators to generate, share, and analyze a variety of geologic data, including block diagrams, buoy data, field notes, and satellite imagery, with students in both traditional and online classrooms, as well as in the field (Kluge, 2009; Whitmeyer et al., 2009; Clary and Wandersee, 2010; Eusden et al., 2012; Hochstaedter and Sullivan, 2012; Monet and Green, 2012; Giorgis, 2015). To our knowledge, however, no similar resource for teaching about the deep biosphere is currently available. The development of this module required the creation of new KML (Keyhole Markup Language) layers for use in Google Earth. Building on the previous efforts of Dr. Thomas D. Lorenson (from the U.S. Geological Survey [USGS]), a KML file of all known marine gas hydrate locations was created (supplemental material, S1; available in the online journal and at http://dx.doi.org/10.5408/15-136s1). Cellular abundance data in marine sediment from Kallmeyer et al. (2012) was also modified to create a KML file (supplemental material, S1). These two created layers are used in conjunction with the ocean-related layers (e.g., chlorophyll, sea surface temperatures, and human impact) that are already provided in Google Earth (supplemental material, S1; available in the online journal and at http://dx.doi.org/10.5408/15-136s1).

The course module has three activities (supplemental material, S2; available in the online journal and at http://dx.doi.org/10.5408/15-136s2). Each activity provides all the necessary background information, identifies the ocean literacy principles and learning outcomes addressed in each activity, and provides short-answer questions to help guide student exploration of each topic. Each activity also includes multiple-choice assessment questions designed to be used at the conclusion of each activity. Specific student-learning outcomes for the entire module are provided in Table I.

Overview of Activity 1: Environmental Controls of Gas Hydrate Formation

The purpose of Activity 1 is to explore the temperature and pressure controls on the spatial distribution of gas-hydrate deposits in marine sediments. In Activity 1, students first have to estimate the range of conditions that promote

TABLE I: Learning objectives for each of the three activities that comprise the gas hydrate teaching module, as well as, any addressed ocean literacy principles (Ocean Literacy, 2013).

Activity	Student Learning Outcomes	Ocean Literacy Principles
1	1. List and describe two factors that determine gas-hydrate formation in deep marine sediments.	7c.
	2. Predict the location of gas hydrates on the seafloor based on known environmental factors.	
	3. Calculate the size of the gas-hydrate stability zone at an assigned seafloor location.	
	4. Develop an explanation for any discrepancies between the theoretical and observed locations of gas hydrate deposits.	
2	1. Use newly acquired knowledge to evaluate your previous understanding of the controls on the distribution of gas hydrates in the ocean.	5e.
	2. Explore and interpret four authentic data sets, including surface water chlorophyll concentrations, sea-surface temperature, cell abundance, and human impact values in ocean sediments.	7b.
	3. List and describe two distinct processes that microbes use to produce methane in the ocean.	
	4. Develop an accurate explanation for the current distribution of gas hydrates in deep marine sediments.	
3	1. Interpret $\delta^{13}C$ data to determine the origin (i.e., thermogenic or biogenic) of methane found with marine hydrate deposits.	

the formation of gas hydrate. This range is known as the gas hydrate stability zone (GHSZ). In general, the GHSZ extends from the depth within the ocean that temperature is low enough and pressure is high enough to form gas hydrate (Trehu et al., 2006). Next, the students are asked to analyze generalized data sets to evaluate the likelihood of gas-hydrate formation on the seafloor at four different locations. The activity concludes with the students learning the results of the scientific drilling efforts at each of the four study locations and then developing an explanation for any discrepancy between their drilling predictions based on GHSZ thickness and the actual drilling outcomes (i.e., the presence or absence of gas hydrate). A more detailed description of Activity 1 is listed below.

Activity 1, Part A: What Environmental Conditions Produce Gas Hydrates?

The first part of this activity asks students to review the general factors that control the formation of gas hydrates, which include water and sediment temperature and pressure. Students are provided with a gas-hydrate stability diagram (supplemental material, S2; available in the online journal and at http://dx.doi.org/10.5408/15-136s2) and are given several short-answer questions to help to orientate them to the data set and to identify key features of the stability diagram, specifically the GHSZ. Once the students have gained some familiarity with the figure, they are asked to evaluate a set of environmental conditions that allow gas hydrates to form (supplemental material, S2; available in the online journal and at http://dx.doi.org/10.5408/15-136s2). This part of the activity concludes by asking students to apply what they have just learned to the entire ocean by identifying places that are potential targets for gas hydrate extraction.

Activity 1, Part B: Virtual Data Collection From Four Different Marine Locations

Once students have gained some familiarity with the gas-hydrate stability diagram, the students are then instructed to open the Activity 1 KML file (supplemental material, S3; available in the online journal and at http://dx.doi.org/10.5408/15-136s3) in Google Earth, which shows the locations of four, authentic, deep-sea drilling sites, such as NGHP-01-17A in the Andaman Sea (Fig. 1). For each of the four sites, the students click on the placemark icon to reveal a text box that provides authentic facts about the site, including location (name of ocean or sea), geologic feature (e.g., continental margin, midocean ridge, or deep-ocean basin), and the depth to the seafloor (Fig. 1). Students are asked to record their observations. This exercise serves as an intermediate step that provides students with physical locations where they can now apply their conceptual knowledge about gas-hydrate stability.

Activity 1, Part C: Are Gas Hydrates Stable Here?

In this part of the module, students are asked to apply their newly acquired knowledge about gas hydrate stability to determine the size of the GHSZ at the same four localities just explored in Part B. The students are provided with four generalized data sets, such as the chart shown in Fig. 2A for sediment core NGHP-01-17A from the Andaman Sea. To successfully complete this part of the activity, students label and calculate the size of the GHSZ for each seafloor site on the provided chart (Fig. 2B). Again, students are asked to record their results. Based on their GHSZ calculations, students must then predict whether gas-hydrate formation is likely at each locality. After being provided with the results of drilling, however, the students are confronted with a discrepancy between their predicted and the actual drilling results. Despite having large GHSZs, some localities lack gas hydrate. Activity 1 concludes by asking students to provide two different explanations why gas hydrate may not form in an area of the seafloor despite having favorable environmental conditions (i.e., what other factors might also be important).

Overview of Activity 2: Biological Controls on the Formation of Gas Hydrates

At the conclusion of Activity 1, students discover that temperature and pressure alone cannot fully explain the

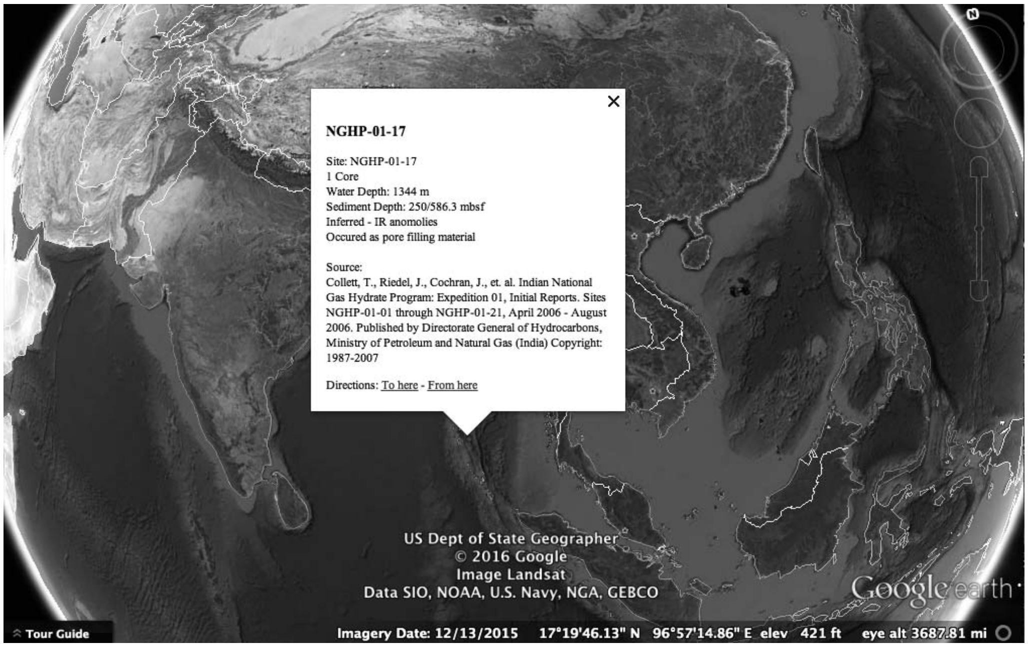


FIGURE 1: A screenshot image of the gas-hydrate Google Earth KML layer (modified from Dr. Thomas D. Lorenson, USGS) used in the gas-hydrate module, which shows the location and characteristics of known gas-hydrate deposits. Note that this example of site NGHP-01-17 shows the type of information provided to students about each locality.

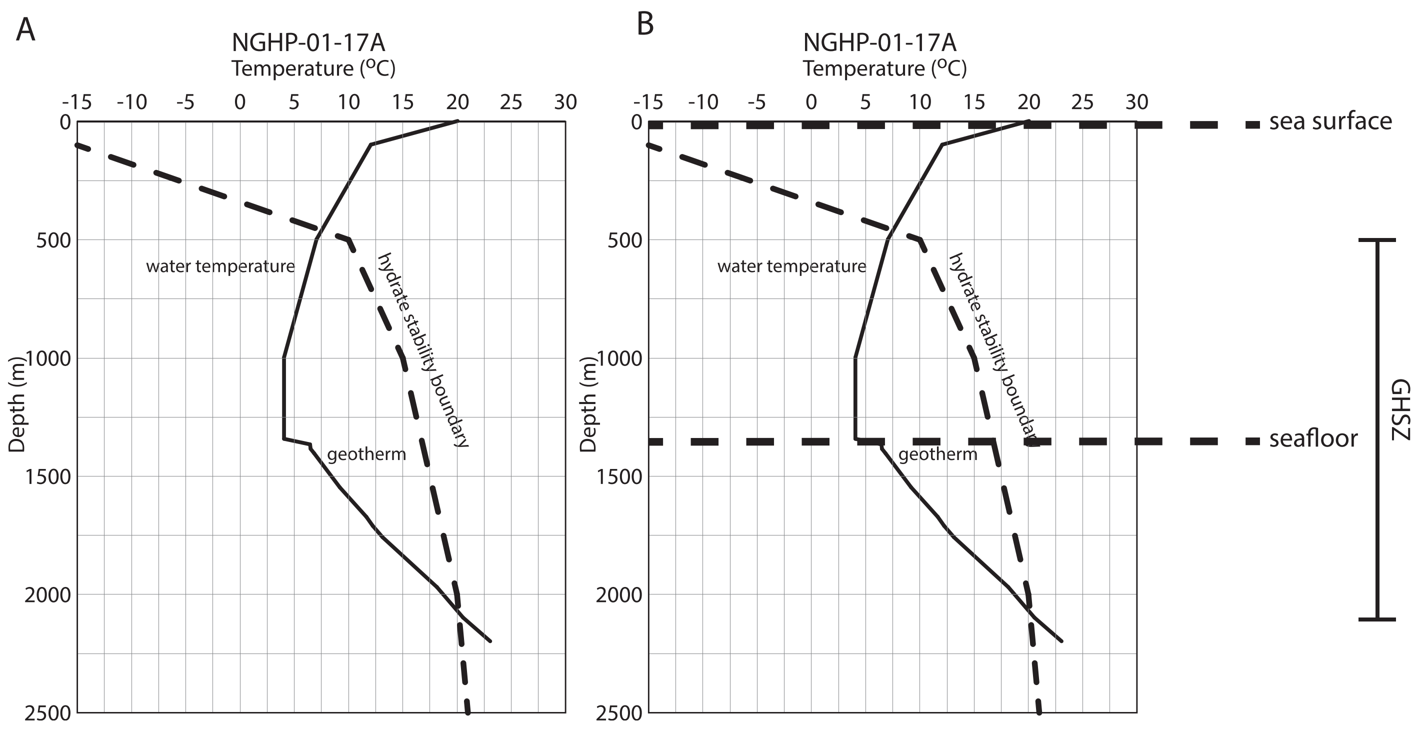


FIGURE 2: In Activity 1, students were provided several generalized data sets, such as the chart shown for sediment core NGHP-01-17A from the Andaman Sea (A). The black line shows how temperature changes with depth, and the dashed line represents the hydrate stability boundary. In general, gas hydrates should be stable under pressure and temperature conditions located to the left of this dashed line. (B) Same graph as part (A), but the students were asked to label the depth of the sea surface and seafloor for each data set (students drew the dashed horizontal lines) and used their newly acquired knowledge about gas-hydrate stability to determine the size of the GHSZ (students drew the solid vertical line) at each locality.

existence of gas hydrates. Additional factors must contribute to the formation of gas hydrates. The purpose of Activity 2 is to explore the biologic controls on the distribution of gas hydrate deposits in marine sediments. In Activity 2, students compare the distribution of marine gas hydrates to four different marine data sets, including microbial cell abundance in marine sediments, sea surface temperature, surface chlorophyll, and human impacts (supplemental material, S1; available in the online journal and at http://dx.doi.org/10.5408/15-136s1) to determine whether any of these data sets positively correlate to the distribution of gas hydrates. Based on their observations, the students develop a more-complete explanation for the distribution of gas hydrates on the seafloor. A more-detailed description of Activity 2 is listed below.

Activity 2, Part A: Biological Controls on Gas Hydrate Formation

This activity begins with students exploring the locations of known marine gas hydrate deposits. This is a critical part of the overall module because this is the first time the students are actually shown gas hydrate locations. Up to this point, students only speculated on hydrate locations based on temperature and depth data for a few drilling sites. Students then summarize any general patterns or trends they notice about the locations of gas hydrates on the seafloor (i.e., gas hydrate deposits are mostly located along continental margins). Students are then asked to reflect on how their previous predictions of hydrate locations compare to the actual distribution. The remainder of this activity has students systematically evaluate any relationships among the location of known marine gas hydrates and several additional marine data sets. For example, students are first asked to examine only the sea-surface temperature layer in Google Earth (supplemental material, S1; available in the online journal and at http://dx.doi.org/10.5408/15-136s1). These data represent the average sea-surface temperature for the observational period of 1985 to 2007. Sea surface temperature is the temperature of the top millimeter of the ocean's surface. Students are then asked to answer some basic questions about the layer. After students reflect on the key characteristics of the sea-surface temperature layer they are then asked to upload the gas-hydrate location layer, so at that point, the locations of known gas hydrate deposits are superimposed over sea-surface temperature data. Students are then asked to compare and contrast the location of gas-hydrate deposits to average sea-surface temperatures. Students should realize that there is no correlation between these two data sets because gas-hydrate localities are distributed across the globe, regardless of sea-surface temperature.

Next, students are asked to examine only the cell-abundance layer (supplemental material, S1; available in the online journal and at http://dx.doi.org/10.5408/15-136s1) in Google Earth. These data represent the estimated distribution of microbial cells in marine sediments (modified from Kallmeyer et al., 2012). Students are also provided with additional information related to the deep biosphere and the main metabolic pathways used by methanogens, a type of microorganism that can produce methane from either carbon dioxide (CO_2) or acetate (CH_3COOH). Again, students are then asked to answer some basic questions about the layer and to decide whether any correlation exists between these two layers. This time students should conclude that a correlation exists between cell abundance and gas-hydrate locations. Cell counts are highest in regions where gas hydrates are found. This process is repeated for the remaining two data sets (human impact and chlorophyll). The activity concludes with students developing a hypothesis for the distribution of gas hydrates in relationship to several environmental variables.

After completing this activity, students should conclude that a correlation exists between the locations of gas-hydrate deposits, chlorophyll, and cell abundance; specifically, in areas of high surface-chlorophyll concentrations, there are also higher levels of microbes on the seafloor, and those areas are where gas-hydrate deposits are found. By completing this activity, students conclude that biological activity in the ocean is another important factor controlling the distribution of gas-hydrate deposits.

Activity 3: What Is the Source of Methane in Gas Hydrates?

This part of the module focuses on carbon isotopes and how the study of carbon isotopes in marine sediments can help researchers to determine the source of the methane found in gas-hydrate deposits. Methane (CH_4) contains carbon (C). However, there are three different isotopes of carbon that exist naturally on our planet (i.e., ^{14}C, ^{13}C, and ^{12}C). ^{13}C and ^{12}C are stable isotopes and are more common than the radioactive ^{14}C. Each methane source has its own isotopic fingerprint or different relative proportions of these two stable-carbon atoms (i.e., $\delta^{13}C$). The presence of other hydrocarbon gases, such as ethane and propane, can also provide insight into the type of processes responsible for forming a gas-hydrate deposit. Thus, by studying the carbon atoms present within a gas-hydrate sample, a scientist can deduce the origin of the methane. A similar, but more extensive and systematic, explanation of carbon isotopes and their role in determining the source of methane in gas hydrates is provided to the students as part of this activity (supplemental material, S2; available in the online journal and at http://dx.doi.org/10.5408/15-136s2). After such a review, the students are given two scenarios and then asked to interpret the carbon isotopic data to determine the origin of the methane for each gas-hydrate sample.

ASSESSMENT OF LEARNING

The gas-hydrate module was tested in three sections of an introductory oceanography course primarily instructed by J.J.S. at Miami University during the 2014–2015 academic year. Dr. Brandon Briggs was a frequent guest lecturer in the course. The combined enrollment was 188 students (51 students in the first section and 48 students in the second section during the fall semester, and 89 students in a single section during the spring semester). Students who enrolled in this course were mostly nonscience majors taking the course to fulfill a general education requirement. There are no prerequisites for this course; however, many of the students had taken at least an introductory geology course. The students enrolled in this course were mostly second-through fourth-year undergraduates. It is a 3-credit hour lecture course with no associated laboratory. The course traditionally meets twice a week with 75-minute class periods. In general, the course is centered on three main themes: (1) ocean exploration, (2) ocean features and processes, and (3) human interactions with the ocean. Students completed the gas-hydrate module during the second unit of the course (approximately wk 10), which includes topics such as ocean bathymetry and ocean sediments.

To determine the effectiveness of the instructional module, the students were asked to take a short, multiple-choice, preactivity and postactivity quiz. The authors wrote all questions used on the quizzes (supplemental material S4; available in the online journal and at http://dx.doi.org/10.5408/15-136s4), which have not been externally validated. The quizzes addressed concepts directly related to the environmental controls on gas-hydrate formation and to the biological controls on gas-hydrate formation. J.J.S. graded the assessment questions as *incorrect* or *correct*. In all cases, student participation in the assessment process was voluntary. Students who opted to participate were given the opportunity to earn extra course credit based on their highest prequiz and postquiz scores for both quizzes. Students were also instructed to complete each quiz on their own, during class, without outside assistance (e.g., classmates or the Internet). Students were given 5–10 min to complete each quiz, which was immediately collected upon completion.

Preassessment and postassessment quizzes were analyzed using normalized learning gain, where gain was measured by the following equation: (*Posttest* % − *Pretest* %)/(100 − *Pretest* %) (Hake, 1998). A value of zero indicated that the student's pretest and posttest scores were the same. Students who scored a 100% on the postquiz were indicated by a value of 1. Students who scored lower on their postquiz were represented by a value less than 0. We chose this assessment approach because Hake (1998) showed that using normalized learning gain produces results that appear to be independent of the student population or the pretest scores. Thus, this approach should also allow for easier comparison of student learning among different student populations. In addition, we only calculated normalized learning gains for students who took both the pretest and posttest to avoid inflating the gain by including the prescores of students who dropped, stopped attending class, or chose not to participate in the postmodule assessment. During the fall semester, the authors conducted a preliminary evaluation of the course module that involved teaching it as a series of in-class exercises (i.e., Trial 1). The following spring semester, the authors deployed the entire module as an out-of-class homework exercise (i.e., Trial 2). A summary of the instructional setting and procedures for each semester is provided below for additional clarification. Regardless of the semester the course was taught, the same preactivity and postactivity quizzes were used to assess student learning gains.

Trial 1: Module as an In-Class Exercise

During Trial 1, Activity 1 (environmental controls) was completed during the first class period and Activities 2 and 3 (biological controls) were completed during the next class period. Students were informed in advance through an announcement on the online course site and during class that they should bring their laptops to these two class periods. Students were also provided instructions on how to download Google Earth to their computer. If a student didn't have access to a laptop, then he or she was allowed to share a laptop with a group member. Each class period began with the voluntary short assessment previously described. Once all the assessment quizzes were collected, the authors provided the class with a 10–15 min introduction to the topic via lecture and explanation of the activity learning outcomes (Table I). Students then worked within small (approximately four people) groups to answer the questions on the activity worksheets provided to them. The students had access to their personal laptops, and there was a computer and projector within the classroom. The authors walked around the room and helped to direct students through any problems or questions they had about the assignments. Once all groups had completed their worksheets, the authors brought the groups together to clarify any remaining student confusion, to reflect on the purpose of the activity, and to summarize the significance of their results in understanding the controls on gas-hydrate formation. Student worksheets were then collected for evaluation. The postassessment quiz was then passed out to the students. In Trial 1, students completed an activity and were assessed on that activity within a single 75-min class period.

Trial 2: Module as Homework

Having the opportunity to interact with students live within the classroom the previous semester as they worked through the gas-hydrate module provided the authors with invaluable feedback on how to improve the activities to increase student satisfaction and understanding of module content. During Trial 2, the authors deployed an updated module as a single, out-of-class homework assignment in a larger section (89 students) of the same introductory oceanography course taught in Trial 1. On the first day of class, students were asked to participate in the assessment of the gas-hydrate module by taking 10–15 min to answer all 10 multiple-choice assessment questions (i.e., five questions from environmental controls plus five questions from biological controls). Completed quizzes were collected, graded, and stored for later comparison to the postquiz scores. As in Trial 1, the gas-hydrate module material (Activities 1–3) was assigned after covering seafloor topography and marine sediments, but this time, the module was assigned as homework. Students were given 1 wk to complete the activity and submit it to the course Web site by the given deadline. During the class meeting, immediately after the posted module deadline, students were once again encouraged to participate in the assessment process by taking the postmodule quiz. In this format, students still took the prequiz before any classroom exposure to the topic of gas hydrates and the postmodule quiz after completing the module activities. The major difference between Trials 1 and 2, however, was that students were asked to take on more responsibility for their learning of the material outside of class during Trial 2.

Learning Gains

A paired *t*-test was performed on the prequiz and postquiz results using R statistical software (R Development Core Team, 2012; R Foundation for Statistical Computing, Wien, Austria). A p-value <0.05 was considered significant (Table II). The results of this analysis

TABLE II: A summary of statistical analysis on prequiz and postquiz results using a paired *t*-test.

Trial	Activity	Average Prequiz Score (%)[1]	Average Postquiz Score (%)[1]
1 ($n = 95$)	1	61 ± 18	90 ± 16
	2 and 3	59 ± 17	86 ± 13[2]
2 ($n = 84$)	1	29 ± 19	80 ± 21
	2 and 3	31 ± 18	51 ± 22[2]

[1]*p*-values were <0.05 between average prequiz and postquiz scores.
[2]*p*-value were <0.05 between Trial 1 and Trial 2.

indicate that students during both trials started with the same level of knowledge about gas hydrates. A comparison between postquiz scores for Activity 1 showed no significant difference between trials; however, postquiz scores for Activities 2 and 3 were significantly different between trials. Specifically, Trial 2 students had lower postquiz scores than did Trial 1 students on Activities 2 and 3. Regardless of the presentation mode of the module (in-class exercise versus homework), however, most (>80%) of the students showed positive and statistically significant learning gains (Fig. 3 and Table II).

DISCUSSION

The positive learning gains indicate that the gas hydrate module was effective at increasing student knowledge about the basic environmental and biological controls on the formation of gas hydrates. However, students who completed the module outside of class did not demonstrate the same level of comprehension about the biological controls by the end of the activity as compared with those students who completed the activity in class. In particular, most (75%) of Trial 2 students answered one assessment quiz question (question 9, supplemental material S4; available in the online journal and at http://dx.doi.org/10.5408/15-136s4) incorrectly after completion of the homework. The information for this question was presented in a figure provided to the students in the homework. but the students were not asked to directly engage with the figure. This result indicated a need to revise the homework and ultimately led to subsequent revision to the assignment. In addition, student feedback from Trial 1 indicated that students were uncomfortable with basic biological concepts and had no prior exposure to microbiology. During Trial 1, the authors scheduled class time to present the core concepts students would need to understand the metabolic pathways used by life in the deep biosphere. Time constraints prevented the authors from presenting the same material in class during Trial 2. Instead, the authors distilled the necessary background information and included it as part of the background information provided to students along with the homework assignment.

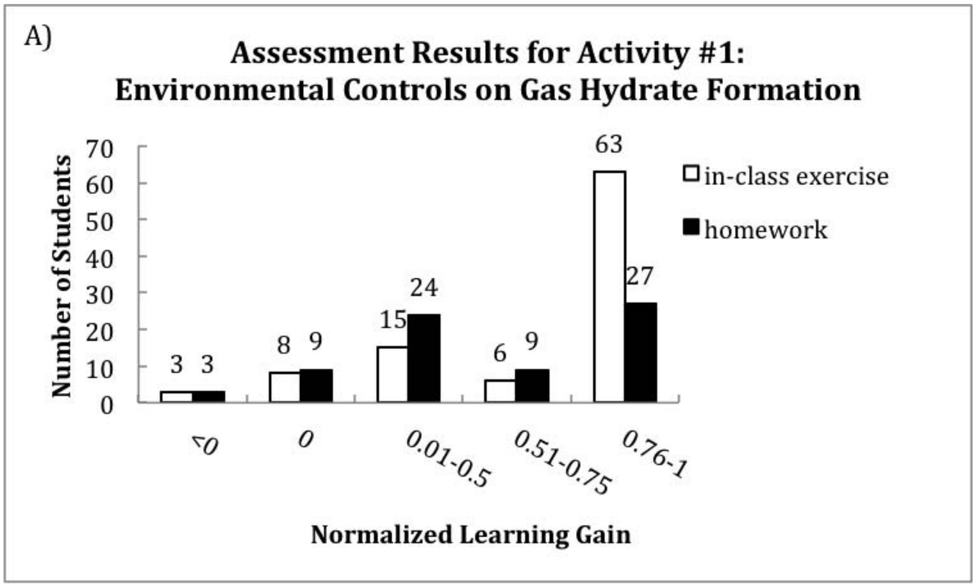
Unlike Trial 1 students, Trial 2 students who completed this assignment for homework, in general, asked fewer questions about the module content. The authors received only a handful of electronic mails, and fewer than 10 students stopped by instructor office hours to ask for help. Completing the assignment outside of class placed a greater responsibility on the students to learn the material on their own. The results of the Trial 2 assessment quizzes indicated that students might benefit from more supporting materials for the biological portion of the activity, especially if they are unable to seek direct instructor help outside of class. In response to this concern, additional background material on bacteria respiration pathways was added to the module after Trial 2 and is available for future students in the supplemental files (supplemental material, S4; available in the online journal and at http://dx.doi.org/10.5408/15-136s4).

Students in this study were not formally surveyed to discover their experience with gas-hydrate deposits before completing the module or what outside of class experiences related to module topics they had between the prequiz and postquiz in the case of Trial 2 students. This information would have helped to identify any additional factors beyond completion of the module that might have contributed to the positive leaning gains recorded in our study. The results of Trial 1, however, provided some evidence that most of the learning was the direct result of the module because students were given the prequiz and postquiz during the same class period in which the activity was being completed. Thus, students received no additional outside input into content related to the module.

From an instructional viewpoint, the module can be successfully used both within and outside of the classroom. The use of Google Earth within the module does require student and faculty access to computers and a reliable Internet connection; however, the module could be modified to use color printouts of the Google Earth layers instead of interacting with the data sets online. A limitation of this approach would be that students would have to consider one ocean basin at a time. In Google Earth, students also have the ability to overlay various layers to look for spatial correlations among the data sets; however, printing off the maps on transparency paper would produce an equitable experience. Although the module activities were designed to be used together, they can also be used as stand-alone activities with minimal modification. This aspect provides instructors the option to use only the aspects of the module they find to be most relevant to their students and their classroom setting.

CONCLUSIONS

The developed instructional module on gas hydrates, as a case study for the deep biosphere, is appropriate for use in any oceanography, marine biology, or introductory geology course. It is recommended that students receive some background knowledge of seafloor topography and marine sediments before completing this module. Each activity can be completed as an in-class activity or as homework. The module was evaluated within three sections of an introductory oceanography course at Miami University during the 2014–2015 academic year using prequiz and postquiz results. The assessment results indicate that the gas-hydrate module is effective at increasing student knowledge about the basic environmental and biological controls on the formation of gas hydrates in marine sediments, although lower gains in the biological controls were recorded when the activity was completed as homework. A simple modification to the module, however, should help to increase student learning



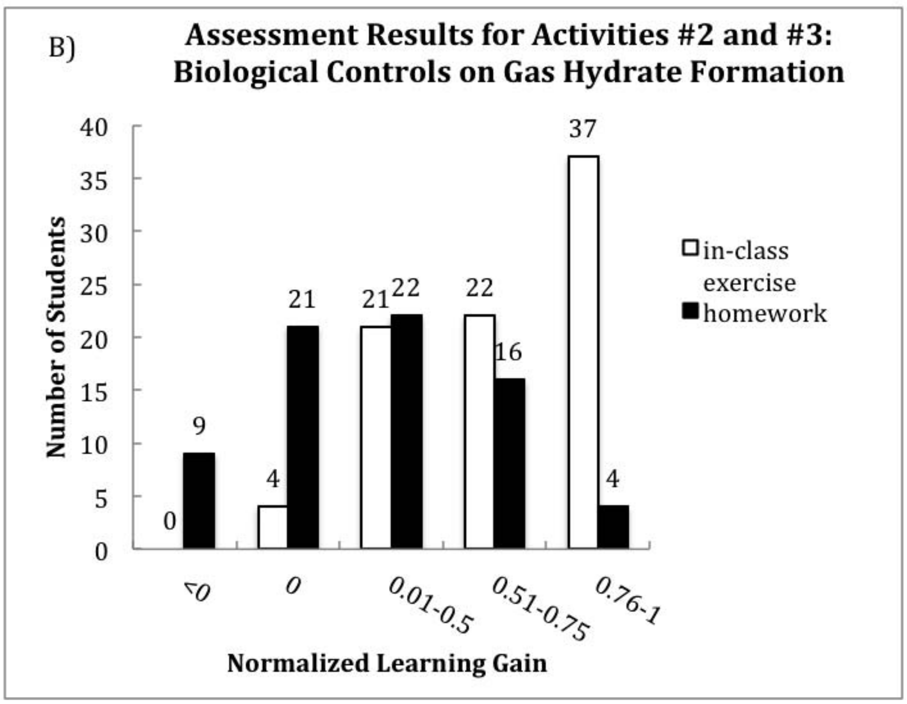


FIGURE 3: Normalized learning gains of students who completed the gas-hydrate module either as an in-class activity or as homework. (A) Results for environmental control questions. (B) Results for the biological control questions.

for those that complete the activity outside of the classroom. Overall, the developed teaching module on gas hydrate deposits adds to the available user-friendly, data-driven teaching resources focused on the deep biosphere for geoscience educators.

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