

Development in the Gulf of Maine: *Avoiding Geohazards and Embracing Opportunities*

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Mapping for marine-spatial planning is crucial if Maine is to safely develop its offshore resources, especially wind and tidal energy. Laura Brothers and her coauthors focus on shallow natural gas (methane) deposits, an important and widespread geohazard in Maine's seafloor. They describe the origin, occurrence, and identification of natural gas in Maine's seafloor; explain the hazards associated with these deposits and how to map them; and discuss what Maine can learn from European nations that have already developed their offshore wind resources. Because the U.S. gives states a central role in coastal management, Maine has the chance to be proactive in delineating coastal resources and demarcating potential seafloor hazards. 🐚

INTRODUCTION

A growing appreciation for the Gulf of Maine's potential for wind and tidal power generation and its use as an energy corridor, offers the state of Maine a multitude of research and development opportunities (Baldacci 2008; OETF 2009). As of this publication, Maine's federal delegation has acquired funding for researchers to assess the feasibility of developing tidal power in Cobscook Bay, and already Maine has identified three potential sites for construction of wind turbine prototypes (University of Maine 2009; Cousins 2009). Success in these budding sectors depends upon the identification of available coastal resources and the demarcation of potential hazards. The most widespread potential geohazard in the coastal Gulf of Maine is natural gas, or methane, found in Maine's seafloor.

Although it does not occur in economic quantities, natural gas is prevalent throughout Maine's muddy coastal embayments and within the Gulf of Maine's deep basins (Figure 1, page 48) (Rogers et al. 2006). In recent geologic history, fluid-escape events occurred, and giant craters have formed in the seabed (Figure 2, page 49). The frequency and magnitude of these escape events are uncertain as are the mechanisms responsible for crater formation. Without considering these potential hazards, offshore development may be at risk. In this paper, we describe the origin and occurrence of shallow natural gas in Maine's seafloor; explain how we identify natural gas; outline the hazards associated with these deposits; offer recommendations on how to effectively delineate this hazard as part of a comprehensive marine-spatial plan based on seafloor mapping; and briefly describe how European nations have developed their offshore wind resources and what Maine can learn from them. We suggest that if Maine is to compete effectively for federal funding or to competitively attract private investment for ocean energy development, ocean mapping for marine-spatial planning is imperative.

WHERE DOES NATURAL GAS ORIGINATE?

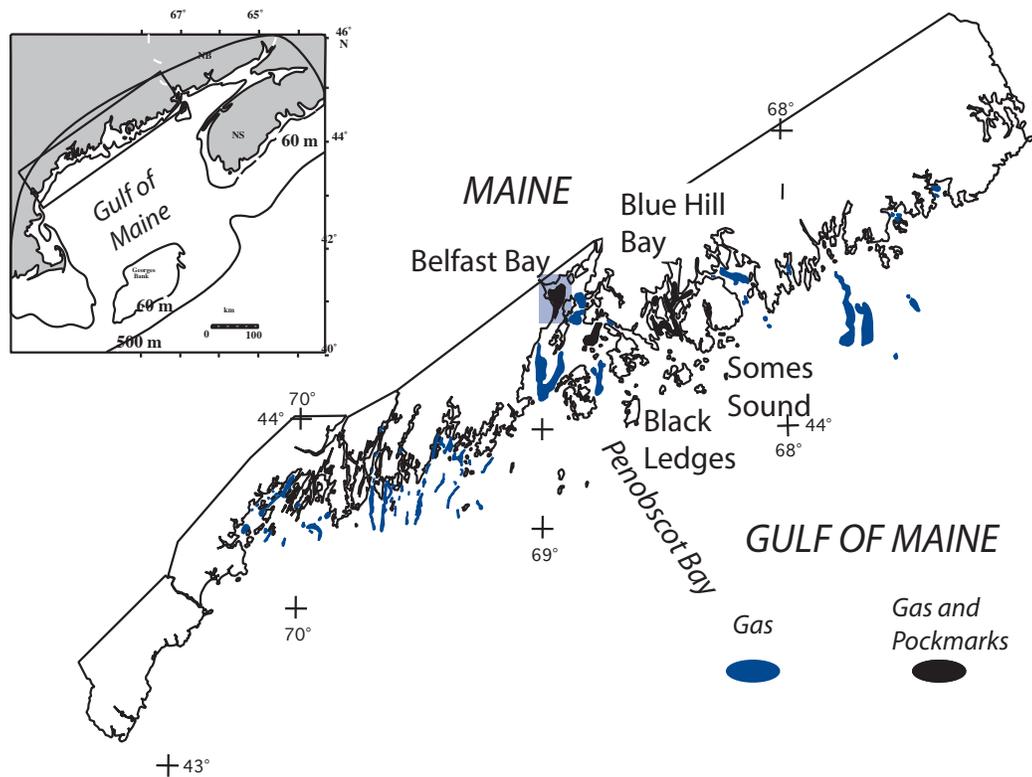
Methane found near the coastline has origins in the rich biological productivity of Maine's coastal region. Although no one has yet pinpointed

the specific source of methane in estuarine and coastal sediments, subsurface gas likely originates from organic matter deposited in marshes, lakes, and bogs between approximately 12,000 and 10,000 years ago, when sea level was as much as 200 feet lower than it is today (Belknap et al. 2002). Following this low-sea-level interval, Maine experienced a rise in sea level, with the ocean washing inland and depositing tens of feet of mud and sand over these former marshes and bogs (Barnhardt et al. 1995; Kelley et al. 1998). Buried under a growing mass of mud, the organic material became deprived of oxygen. Anaerobic bacteria decomposed the organic matter and produced methane as a byproduct in a manner similar to how methane is produced in landfills today (Judd and Hovland 2007).

WHERE IS NATURAL GAS IN THE SEABED?

Gas is identified in geophysical surveys, specifically from seismic reflection profile data. In a seismic reflection survey, a vessel tows an instrument that issues a precisely tuned acoustic pulse that sounds like a "click" to human ears. As specific instrumentation varies per survey, we generically refer to this instrument as the "seismic source." This acoustic energy travels through the water column, and the sound reflects off the seafloor. Some of the sound energy continues into the seafloor and reflects off deeper boundaries between layers with different physical properties. We refer to these surfaces as "reflectors." Bedrock, sand, mud, and gravel have distinctive properties and form reflectors in the seismic record. A second instrument, called a hydrophone, receives the reflected sound at the water surface. The receiver measures the length of time the acoustic energy takes to reflect, along with the

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FIGURE 1: **Distribution of Subsurface Gas and Pockmarks along Maine's Coast**

In addition to the coast, gas and pockmarks have also been observed in Gulf of Maine basins. This map represents a conservative estimate of gas and pockmark distribution.

Source: Modified from Rogers et al. 2006

intensity of the echo. Since the speed of sound in water is known, the receiver calculates the water depth and depths to buried layers. The intensity of the return provides a measure of the relative hardness (rock or gravel) or softness (mud) of the seafloor. The resulting record provides a vertical “slice” through the seafloor that shows where layers of differing materials exist, but does not specifically identify what the materials are (Figure 3, page 50). Scientists familiar with regional geology interpret these records. Petroleum companies use a similar method to identify hydrocarbon resources. They must employ much more acoustic energy, however, to identify oil and natural gas thousands of feet deep in hard rock than is needed to explore shallow sediments in the Gulf of Maine.

economically recoverable (Gontz 2005).

Bathymetry data are collected simultaneously with seismic reflection data to more fully understand the structure of the seabed. Modern swath-bathymetry data resolves the seafloor topography with remarkable three-dimensional precision, allowing characterization of navigation hazards, seafloor habitats, shipwrecks, and other features on the scale of feet. Also acquired as a byproduct of swath-bathymetry data are data that indicate relative hardness of the seafloor. In this way, we can remotely determine if the seafloor is rocky, sandy, or muddy. Once acquired, these data are used to create maps of the seafloor. From these compilations scientists map the distribution of seafloor substrate and natural gas fields (Figures 1 and 2).

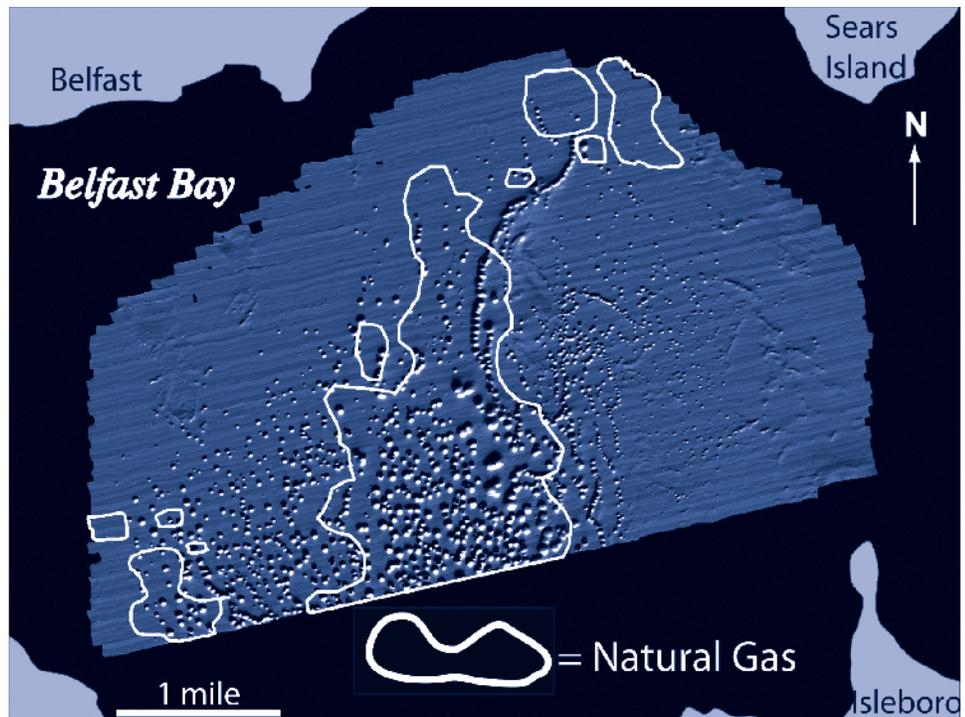
Natural gas has a distinct acoustic return from sediment or rock (Schubel and Schiemer 1973), and this signature has been observed throughout coastal Gulf of Maine (Figure 1). The presence of methane in Maine's offshore areas has also been verified using direct methods such as seafloor chemical analyses and the ignition of gas collected in sediment cores (Christian 2000; Barnhardt et al. 1997). Although shallow biogenic methane exists in Maine's seafloor, we must be clear that there are no petroleum fields along Maine's coast. Simple calculations based on conservative estimates of volume, pressure, and temperature indicate that the amount of methane held in Maine's muddy embayments is not

FIGURE 2: **Belfast Bay, Maine, Pockmark Field and Subsurface Gas Disruption**

WHERE IS GAS KNOWN TO EXIST?

As we have already discussed, our knowledge of subsurface natural gas deposits comes from geophysical surveys collected throughout the Gulf of Maine (Figure 1, Figure 3, page 50) (Barnhardt et al. 1996, 1998). For the past 25 years, state and university researchers have conducted these surveys in areas of specific interest, many in accordance with particular research objectives funded by federal research agencies. These efforts produced several graduate theses and detailed information for approximately 12 percent of the seabed in Maine's nearshore coastal waters (Barnhardt et al. 1998). Most of the Gulf of Maine's seabed sediments remain unmapped in any systematic detail, and there is no comprehensive subsurface map of Maine's coastal zone.

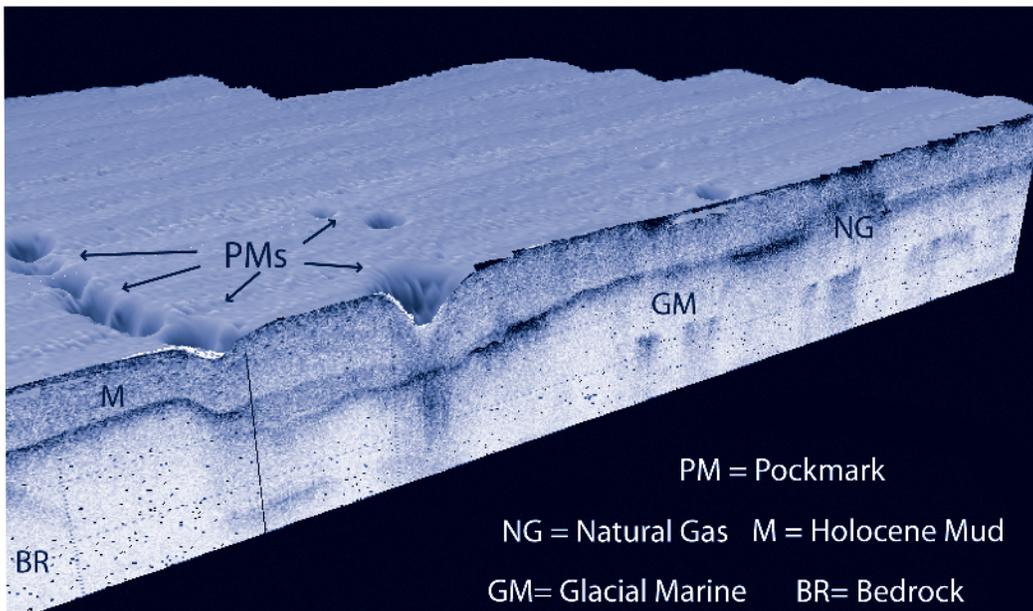
Regional disparities also exist in survey coverage. For example, southern Maine with its comparatively high population density and popular sandy beaches attracted more research attention than Downeast Maine. Geophysical data collected in southern Maine's sandy embayments indicate that no gas presently occurs in the seabed subsurface. The limited data collected in Downeast Maine's muddy embayments, however, positively indicate the presence of shallow natural gas. Without total survey coverage, less-than-certain geological and physical characteristics are used to infer where additional gas deposits may occur. For example, we expect gas in most shallow, muddy embayments along Maine's Downeast coast based on extrapolations of surveys collected in similar muddy embayments (Figure 1) (Barnhardt et al. 1996). Partial mapping coverage of the Gulf of Maine means that the known distribution of natural gas is a conservative estimate of total shallow gas deposits.



A plan view of Belfast Bay bathymetry, or water depth, illustrating how thousands of pockmarks can dominate a seafloor. Belfast Bay has some of the world's largest and most well studied pockmarks. This image is the result of seafloor mapping conducted by the U.S. Geological Survey using swath bathymetry (interferometric sidescan sonar) and seismic reflection profile data (Chirp sonar).

SEAFLOOR FEATURES ASSOCIATED WITH NATURAL GAS DEPOSITS

Massive seafloor depressions associated with fluid escape, called pockmarks, are commonly observed in the vicinity of gas deposits in Maine (Figure 2, Figure 3, page 50). These types of features are found worldwide and frequently exist above oil and gas fields, where the gas is rising from deep below the surface. But pockmarks also occur in previously glaciated areas, such as Maine, where no extensive petroleum fields exist. Pockmarks are abundant along the New England coast and continue up to Newfoundland, but are not found in non-glaciated areas along the East Coast of

FIGURE 3: **What's Underneath a Pockmark Field?**

Swath-bathymetry data (top) draped over seismic reflection profile data form a composite image of Belfast Bay, Maine's seafloor and subsurface. Seismic reflective profile data show distinct geologic units like layers in a cake. This cross-section through the earth shows an example of natural gas (NG) imaged in the seafloor's subsurface. Adjacent to the gas is the crater-like fluid-escape feature called a pockmark (PM). Although no scale is possible for an oblique image, Holocene mud (modern mud, M) thickness ranges between 16 feet and 32 feet across this short distance. Complex subsurface and seafloor relief is typical of coastal Maine and the lower geological units, BR (bedrock) and GM (glacial-marine mud), occur on nearby land.

Source: Modified from Andrews et al. in review

the United States south of New York City (e.g., Delaware Bay or Chesapeake Bay).

Pockmarks may occur as singular features, or in fields numbering thousands of depressions. Maine's pockmarks range in size from nine to 1,000 feet in diameter and may be up to 120 feet deep. The largest pockmarks in the Gulf of Maine could contain the entire University of Maine football stadium or the governor's mansion (Figure 4). Belfast Bay, Maine, contains more than 2,000 pockmarks. Curiously, these features occur in soft muddy seafloors and exhibit uncommonly steep slopes on the order of 20° to 44° (Andrews et al. in review). One untested hypothesis suggests that deeper, stronger sediments stabilize pockmark slopes.

HOW DO THESE LARGE, UBIQUITOUS FEATURES FORM?

Many hypotheses address-
 ing the formation of pockmarks have been proposed, including: cratering from WWII depth charges, whale feeding, sea-level changes, and ground-water escape or ice disturbance. These hypotheses, however, cannot explain the distribution and number of pockmarks in Maine's waters. We propose that fluid escape (gas and pore water) created Maine's pockmarks. Seafloor fluid escape can occur steadily or abruptly. Evidence collected in Maine supports each of these pathways, so both may happen. For example, seafarers occasionally report bubbles and sediment plumes in Maine's coastal embayments (Rogers et al. 2006). One geophysical survey imaged an expulsion event (Kelley et al. 1994). A later

geochemical survey, however, found little methane in the same field, suggesting that Maine pockmarks are not actively venting gas (Ussler et al. 2003). To reconcile these observations, we hypothesize that these features may form episodically with changes in environmental conditions such as changes in ocean temperature, storm- or tsunami-related sea-level changes, or by physical vibration from earthquakes or other sources. Pockmarks, particularly those that occur in shallow water such as the Gulf of Maine, remain one of the world's most enigmatic seafloor features. Changes to the seabed, either naturally occurring or those resulting from human-made development, could influence pockmark occurrence. A fuller understanding of the origin(s) of pockmarks and the ability to predict seafloor expulsion events requires more study.

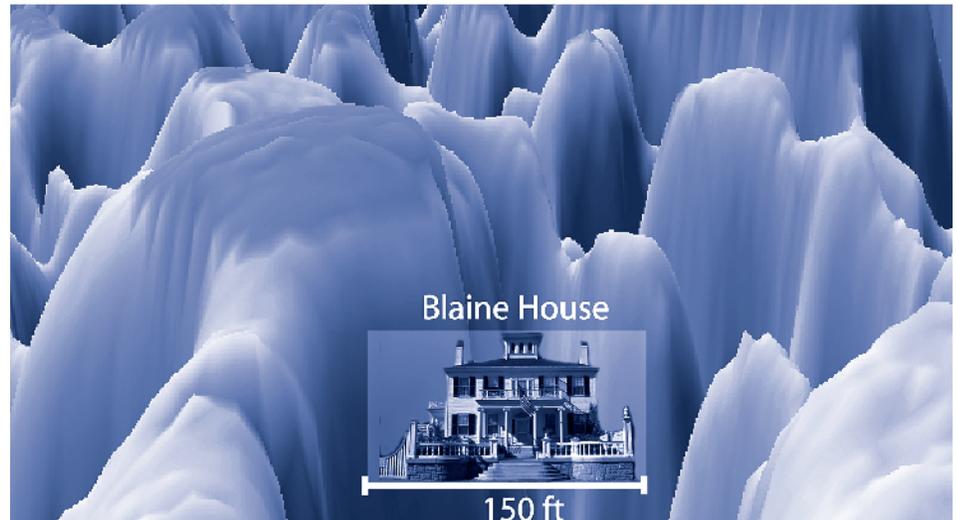
FIGURE 4: **How Big Is a Pockmark?**

WHAT ARE THE IMPLICATIONS OF SHALLOW GAS DEPOSITS FOR COASTAL DEVELOPMENT?

Seafloor construction on sediments that contain natural gas requires special engineering approaches. Activities such as seafloor loading or excavating affect seafloor stability. Examples of seafloor loading include the installation of infrastructure (e.g., foundations, pipelines, and utilities, cables or moorings), and deposition of dredge spoils. An example of seafloor excavation is seafloor dredging. Upon loading, soft muddy gas-bearing sediments are more easily compressed and subject to settlement than non-gas-bearing sediments, so the seabed sinks. Sediment strength also depends upon pressure exerted by natural gas within the seafloor and past loading and excavation history (Sills and Gonzalez 2001). As a rule, the presence of gas decreases sediment strength.

If a gaseous seafloor is not actively venting gas or settling, we say that the sediment and natural gas are in equilibrium. A principal physical assumption for equilibrium is that sediment weight, and the impermeable nature of the overlying sediments, impedes the escape of the gas. Thus the seafloor confines the gas. We cannot know where the tipping point occurs (i.e., the point where gas buoyancy overcomes sediment weight). It is possible that certain types of marine use may physically alter this equilibrium relationship. Understanding seabed changes and stability may be critical to some types of coastal development.

The Troll A gas production platform, located in the Norwegian sector of the North Sea, exemplifies change in seafloor equilibrium. Geophysical surveys at the platform site and adjacent pockmark field before construction did not identify the presence of subsurface gas. After nearly a decade of operation, however, engineers found large amounts of gas accumulating in and around the platform foundations. This unanticipated buildup of gas warranted concern because an excess of seafloor gas can compromise the type of



An oblique view of the Belfast Bay pockmark field with the Blaine House for scale. Vertical slopes are exaggerated, but it is clear how extensively pockmarks dissect the seafloor. Bathymetry collected by the U.S. Geological Survey.

foundation used in Troll A. After subsequent surveys, investigators determined that increased sediment temperatures, resulting from operation of the warmer deep-production wells, led to the expansion of previously unidentifiable gas (Tjelta et al. 2007). To address this hazard, engineers installed venting modifications to the Troll A foundation systems. These modifications were successful, and the platform continues operation to this day. Although Maine sediments and proposed infrastructure could not be subject to the deep heat sources that affected Troll A, the possibility for seafloor activities to facilitate gas migration exists. The Troll A case study illustrates (1) the need to identify potentially gassy sediments before development; (2) the need to monitor development, even after initial construction, for gas migration; and (3) that with understanding, mitigation of the problem can be successful.

While Troll A did not result in catastrophe, significant gas-related hazards have been reported. Judd and Hovland (2007) report rapid formation of pockmarks during oil and gas installation construction and operation. Human activities are not the only trigger for pockmark formation. Naturally occurring events, such as temperature changes or earthquakes, can certainly affect the gas-sediment equilibrium.

Types of activities undertaken in pockmarked and gassy seafloor regions must either be constrained or appropriately designed for gas. For instance, pipeline or cable installations in pockmarked areas are infeasible due to the lack of structural support over these depressions. Additionally, jetting for cable placement and dredging in gassy areas has the potential to disturb equilibrium and induce gas migration. These activities should be conducted with caution. Lastly, sediments below proposed locations for infrastructure (e.g., offshore liquid natural gas terminals and foundations/moorings for floating tidal and wind turbine foundations) should be investigated for evidence of seafloor gas.

WHAT ARE EUROPEAN NATIONS DOING, AND HOW DOES MAINE COMPARE?

Nations that are leading offshore wind energy production include the United Kingdom, Denmark, Norway, Sweden, Germany, and the Netherlands. These countries have already mapped their seafloors through national and European Union efforts (see the Web site www.unesco-ioc-marinesp.be/msp_around_the_world). Several of these countries are oil-producing nations and are well acquainted with the hazards of subsurface gas and pockmarks (e.g., Troll A). Although U.S. petroleum and offshore foundation industries also have expertise in dealing with gas-associated geohazards, these industries have no historical presence in the Gulf of Maine. In addition, these European nations have a generally supportive regulatory and business community for renewable offshore energy.

According to the European Wind Energy Association's Web site (www.ewea.org/index.php?id=180), much offshore wind power generation in Europe takes place in extensive, shallow, sandy shelves. This is generally a less physically challenging environment for infrastructure development than the coastal Gulf of Maine. Maine's immediate offshore environment is characterized by varying bathymetry and seafloor substrate. These geological differences influence how wind resources are developed. For example, some of Denmark's wind farms are located 18 miles offshore in 15 to 50 feet of water. The turbines are secured to the sandy seabed with monopiles or gravity-

base foundations. In Maine, proposed wind turbines will be located three miles offshore, but water depths will be in the hundreds of feet and the seafloor could be muddy, gravelly, rocky, or some combination of all three, and gas may be present in the mud. Because of these water depths, Maine scientists and engineers are pursuing floating turbine platforms. These platforms can be moored and anchored at great depths. Currently, there is only one floating wind turbine in the world, located in the Norwegian sector of the North Sea (Statoil 2010).

Anchoring a platform is more challenging with a heterogeneous seafloor. Although an anchor can be designed for almost any seafloor environment, the extent and cost of site investigations and resulting anchor design are dependent on the nature of the seafloor. Generally, non-uniform and complex seafloors, such as those in the Gulf of Maine, require more extensive, and therefore more costly, site investigations. Energy developers and engineers must weigh the costs of development within certain areas with the financial rewards of the energy generated from within these regions; this is true for both oil and gas and renewable energy investment sectors. Seafloor and subsurface characteristics are fundamental criteria in determining the economic viability of a site for offshore wind-power development.

Maine's complex seafloor has not been deemed cost prohibitive, but its heterogeneity underscores the need for mapping and marine-spatial planning. The international Society for Underwater Technology (SUT) lists an assessment of public domain resources and regionally available data as critical steps in initial selecting renewable energy sites. An analysis of planning and development of eight offshore wind farms from Europe found that spatial planning and proper site selection were the most important factors in mitigating environmental impacts, preventing conflicts among users, and contributing to overall economic viability of production sites (POWER 2007).

NEXT STEPS: MANAGEMENT RECOMMENDATIONS

Offshore development carries with it significantly more risk and cost than near-shore and land-based operations. Gas migration can cause unanticipated

instability of the seafloor and costly setbacks during construction and operation. Further, there is a potential for gas-related catastrophic failures, which could greatly affect Maine's chances at successful offshore energy development. Because safe development is entirely possible with appropriate measures, we urge large-scale hazard demarcation and advocate following established guidelines for offshore development.

The SUT provides recommendations for seafloor investigations related to renewable energy projects, including the collection of geophysical data and geotechnical-quality sediment samples (OSIG 2005). This professional society consists of scientists and engineers from more than 40 countries who specialize in the technical issues surrounding the construction and operation of offshore infrastructures usually related to energy production. We cannot stress enough that working in the Gulf of Maine poses challenges that terrestrial infrastructure development does not. We, therefore, advise that SUT's recommendations be followed and augmented by local expertise.

The Future of Maine's Coastal and Submarine Resources

Maine's leadership role in renewable ocean energy depends upon the safe and efficient development of its offshore resources. Compared to other nations that already produce offshore renewable power, the U.S. allows states to play a more central role in the management of their coasts and adjacent seafloor (three nautical miles from shore). Maine has the opportunity to be proactive in the delineation of its coastal resources and demarcation of its potential seafloor hazards.

Seafloor mapping is a cost-effective, nonintrusive, and environmentally sound method for identifying (a) areas where potential hazards of seafloor gas, pockmarks, and other features may exist; (b) seabed habitat critical to fisheries; (c) sediment types (i.e., rock, gravel, sand, fine-grained sediments) useful in siting offshore infrastructure; and (d) offshore cultural resources. As federal ocean management policy is being reviewed (Turnipseed et al. 2009) and national and state ocean energy potential is being evaluated (Ferland 2008; OETF 2009), initiation of a comprehensive mapping plan for Maine state waters is timely. Therefore, we recommend that Maine geophysically map its seafloor.

With a comprehensive management plan based on marine science, Maine will be well positioned to take advantage of federal and private investment in ocean resource management and renewable energy development within the approximate 3,000 square miles of ocean under Maine's jurisdiction.

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Already, other states, nations, and the European Union are meeting the needs of marine-spatial planning with seafloor mapping as their cornerstone. Nations leading in wind energy production have already mapped their seafloors (Marine Spatial Planning Initiative 2010). Maine's neighboring states have undertaken serious efforts to manage their seafloor for multiple uses. Massachusetts and Rhode Island each have their own ocean management plans, the Massachusetts Ocean Management Plan and the Rhode Island Ocean Special Area Management Plan (Ocean SAMP), respectively. Although there are key differences between these two models, both feature applied scientific research as the basis for policy planning that is also informed by stakeholder input. Seafloor mapping is a key component in both models. We recommend that Maine move toward a similar multi-user seafloor plan.¹

What Are Maine's Mapping Options?

In Maine, current offshore mapping and exploration practices are variable and not always coordinated. Multiple government agencies with marine jurisdictions use some aspect of seafloor mapping (Turnipseed et al. 2009). Individual development projects also incorporate seafloor mapping. In the former case, seafloor information becomes available in the context of agency oversight (e.g., ocean bathymetry from the National Oceanic and Atmospheric Administration [NOAA]), but may not extend, or easily relate, to local management

objectives. In the latter case, much of the information collected is privately owned and not disseminated. A comprehensive mission with clear standards for data acquisition, formatting, processing, interpretation, archiving, and distribution would reduce incompatible and inaccessible data sets. In our opinion, systematic mapping, using proven technology, driven by a governmental agency such as NOAA or the U.S. Geological Survey (USGS) or a strong partnership of agencies, will be far more advantageous to creating a common archive of information for planning and managing of the public trust than privately held piecemeal programs. Such a partnership occurs in Massachusetts where the USGS collects the data while the state uses the data for planning purposes in the Massachusetts Office of Coastal Zone Management (Massachusetts OCM 2009).

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The U.S. and Canada already collaborate on seafloor mapping for of the Gulf of Maine Mapping Initiative (Gulf of Maine Council on the Marine Environment 2009). This collaboration developed because of diverse user groups' need for seafloor information. Although the Canadian portion of the Gulf of Maine is almost entirely mapped, the U. S. portion remains unfinished. The Gulf of Maine Mapping Initiative already has contact with much of the scientific and management community for the Gulf of Maine, and this group is already a "clearinghouse" for swath-bathymetry data. The mapping data just need to be collected in an accessible way. We strongly advocate the collection and archival of subsurface data in conjunction with bathymetry data for the identification of potential geohazards such as natural gas and pockmark areas. We recommend that Maine actively pursue a partnership between a federal entity and a state office, such as the State Planning Office.

CONCLUSION

Maine is establishing itself as a leader in tidal and offshore wind power development. The day is rapidly approaching when demonstration projects and more permanent offshore energy facilities, along with transmission corridors and infrastructure, may cross through the state's submerged lands to tie into the electrical grid on the mainland. To maintain this momentum, development of renewable ocean energy needs to be placed within a larger management plan. Just as previous mapping efforts discovered pockmarks and natural gas in Maine's seafloor, better seafloor mapping will identify geohazards, areas of marine habitat, and potential offshore cultural resources. This information will be critical for additional site assessments and feasibility studies. Seafloor mapping will aid in the comparison of potential corridors, encourage private investment in offshore energy, and guide public decisions on areas of preference for energy infrastructure along with fishing, recreation, and marine conservation. Global competitiveness and energy independence and security for the state of Maine compel us to capitalize on our seafaring skills, marine sciences, and intergovernmental partnerships to more fully map the coastal waters of the Gulf of Maine. 🌊

ENDNOTE

1. For descriptions of some marine-spatial planning efforts and ocean management plans, readers may wish to visit the following Web sites:

For Canada: www.dfo-mpo.gc.ca/oceans-habitat/oceans/oap-pao/page01_e.asp

For Europe: www.balance-eu.org/ or www.infomar.ie/

For Massachusetts: www.mass.gov/czm/oceanmanagement/index.htm

For Rhode Island: seagrant.gso.uri.edu/oceansamp/

REFERENCES

- Andrews, Brian A., Laura L. Brothers and Walter A. Barnhardt. In review. "Morphologic Feature Extraction and Spatial Characterization of Seafloor Pockmarks in Belfast Bay, ME."
- Baldacci, John E. 2008. An Executive Order Establishing the Ocean Energy Task Force, No. 20 FY08/09, November 7, 2008. Office of the Governor, Augusta, ME. http://www.maine.gov/spo/special-projects/OETF/Documents/OETF_eo20fy0809.pdf [Accessed December 1, 2009]
- Barnhardt, Walter, Daniel F. Belknap, Alice R. Kelley, Joseph T. Kelley and Stephen M. Dickson. 1996. Surficial Geology of the Maine Inner Continental Shelf, 1:100,000 scale 7-map series, Open-File Nos. 96-7 through 96-13. Maine Geological Survey, Augusta. <http://www.maine.gov/doc/nrimc/mgs/pubs/online/ics/ics.htm> [Accessed December 1, 2009]
- Barnhardt, W.A., Daniel F. Belknap and Joseph T. Kelley. 1997. "Stratigraphic Evolution of the Inner Continental Shelf in Response to Late Quaternary Relative Sea-Level Change, Northwestern Gulf of Maine." *Geological Society of America Bulletin* 109:612-630.
- Barnhardt, Walter A., Roland Gehrels, Daniel F. Belknap and Joseph T. Kelley. 1995. "Late Quaternary Relative Sea-Level Change in the Western Gulf of Maine: Evidence for a Migrating Glacial Forebulge." *Geology* 23:317-320.
- Barnhardt, Walter, Joseph T. Kelley, Stephen M. Dickson and Daniel F. Belknap. 1998. "Mapping the Gulf of Maine with Side-Scan Sonar: A New Bottom-Type Classification for Complex Seafloors." *Journal of Coastal Research* 14:646-659.
- Belknap, Daniel F., Joseph T. Kelley and Allen Gontz. 2002. "Evolution of the Glaciated Shelf and Coastline of the Northern Gulf of Maine." *Journal Coastal Research, Special Issue* 36:37-55.
- Christian, Harold A. 2000. Gas Sampling and Seepage Liquefaction Assessment in Penobscot Bay, Maine, December 1999. Unpublished Report to the Department of Geological Sciences, University of Maine.
- Cousins, Christopher. 2009. "Winds of Change: Three Offshore Wind-Power Test Sites Unveiled as Maine Positions Itself to Become a Leader in Renewable Energy Production." *Bangor Daily News* (December 16).
- Ferland, John. 2008. "Tidal Energy Development." *Maine Policy Review* 17:111-113.
- Gontz, Allen M. 2005. Sources and Implications of Shallow Subsurface Methane in Estuarine Environments. Ph.D. dissertation, University of Maine, Orono.
- Gulf of Maine Council on the Marine Environment. 2009. Gulf of Maine Mapping Initiative: A Framework for Ocean Management. <http://www.gulfofmaine.org/gommi> [Accessed December 1, 2009]
- Judd, Alan and Martin Hovland. 2007. *Seabed Fluid Flow: The Impact on Geology, Biology, and the Marine Environment*. Cambridge University Press, Cambridge.
- Kelley, Joseph T., Walter A. Barnhardt, Daniel F. Belknap, Stephen M. Dickson and Alice R. Kelley. 1998. *The Seafloor Revealed: The Geology of the Northwestern Gulf of Maine Inner Continental Shelf*, Open-File 96-6. Maine Geological Survey, Augusta. <http://www.maine.gov/doc/nrimc/mgs/explore/marine/seafloor/contents.htm> [Accessed December 1, 2009]
- Kelley, Joseph T., Stephen M. Dickson, Daniel F. Belknap, Walter A. Barnhardt and M. Henderson. 1994. "Giant Sea-Bed Pockmarks: Evidence for Gas Escape from Belfast Bay, Maine." *Geology* 22:59-62.
- Marine Spatial Planning Initiative. 2010. MSP around the World. UNESCO, Paris. http://www.unesco-ioc-marinesp.be/msp_around_the_world [Accessed March 24, 2010]
- Ocean Energy Task Force (OETF). 2009. Final Report of the Ocean Energy Task Force to Governor John E. Baldacci. OETF, Augusta, ME. http://www.maine.gov/spo/specialprojects/OETF/Documents/finalreport_123109.pdf [Accessed March 28, 2010]


 Please turn the page for more references and author bios.

Offshore Site Investigation and Geotechnics Group (OSIG). 2005. Guidance Notes on Site Investigations for Offshore Renewable Energy Projects. Society for Underwater Technology, London. <http://sig.sut.org.uk/pdf/OSIG%20Renewables%20Guidance%20Notes.pdf> [Accessed December 1, 2009]

Pushing Offshore Wind Energy Regions (POWER). 2007. Case Study: European Offshore Wind Farms—A Survey for the Analysis of the Experiences and Lessons Learnt by Developers of Offshore Wind Farms—Final Report. The North Sea Region Programme, Viborg, Denmark.

Rogers, Jeff, Joseph T. Kelley, Daniel F. Belknap, Allen Gontz and Walter A. Barnhardt. 2006. "Shallow-Water Pockmark Formation in Temperate Estuaries: A Consideration of Origins in the Western Gulf of Maine with Special Focus on Belfast Bay." *Marine Geology* 225(1-4): 45-62.

Schubel, J.R. and E.W. Schiemer. 1973. "The Cause of Acoustically Impenetrable or Turbid Character of Chesapeake Bay Sediments." *Marine Geophysical Researches* 2(1): 61-71.

Sills, G.C. and R. Gonzalez. 2001. "Consolidation of Naturally Gassy Soft Soil." *Geotechnique* 51(7): 629-639.

Statoil. 2010. "Hywind: Putting Wind Power to the Test." Statoil, Stavanger, Norway. <http://www.statoil.com/en/technologyinnovation/newenergy/renewablepowerproduction/onshore/pages/karmoy.aspx> [Accessed March 24, 2010]

Tjelta, T.I., G. Svano, J.M. Strout, C.F. Forsberg and H. Johansen. 2007. "Shallow Gas and Its Multiple Impact on a North Sea Production Platform." In Proceedings 6th International Conference Offshore Site Investigation and Geotechnics, Society for Underwater Technology (SUT), London.

Turnipseed, Mary, Larry B. Crowder, Rafe D. Sagarin and Stephen E. Roady. 2009. "Legal Bedrock for Rebuilding America's Ocean Ecosystems." *Science* 324(5924): 183-184.

University of Maine. 2009. "Congressional Initiative Promotes Tidal Power Research." UMaine News (April 9). <http://www.umaine.edu/news/blog/2009/04/09/congressional-initiative-promotes-tidal-power-research/> [Accessed December 1, 2009]

Ussler, William, Charles K. Paull, J. Boucher, G.E. Friederich and D.J. Thomas. 2003. "Submarine Pockmarks: A Case Study from Belfast Bay, Maine." *Marine Geology* 202:175-192.



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