Giant sea-bed pockmarks: Evidence for gas escape from Belfast Bay, Maine

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ABSTRACT

Circular depressions, or pockmarks, cover the sea floor in many estuarine regions of the western Gulf of Maine. In Belfast Bay, Maine, they are found in densities up to 160/km^2, are up to 350 m in diameter and 35 m in relief, and are among the largest and deepest known. The pockmarks appear to form from the escape of biogenic natural gas and pore water and are far larger than features associated with thermogenic gas elsewhere. These pockmarks are thought to have formed (1) catastrophically during an earthquake, tsunami, or storm, or (2) slowly over thousands of years. Recent observations of bubble releases suggest continuing activity and a potential geologic hazard. The pockmarks involve a poorly documented coastal process of sediment redistribution and methane release, largely unrecognized in the rock record but widespread in middle- to high-latitude embayments.

INTRODUCTION

Sea-bed pockmarks have been recognized on the bottom of lakes and oceans around the world (Hovland and Judd, 1988; Fader, 1991). They are roughly conical depressions that often originate from the escape of natural gas and interstitial water from muddy, unconsolidated sediment (Hovland and Judd, 1988; Judd and Hovland, 1992), and range from a few metres to several hundred metres in diameter and up to 30 m in relief. Found in water depths down to thousands of metres, fields of pockmarks may exceed 1000/km^2 (Fader, 1991; Judd and Hovland, 1992).

Although only recently recognized, pockmarks are important as (1) indicators of subsurface petroleum deposits (Hovland and Judd, 1988), (2) offshore geologic hazards (Sills and Wheeler, 1992), (3) contributors to global warming through greenhouse gas (methane) release (Lashof and Ahuja, 1990; Judd and Hovland, 1992), and (4) sources of enhanced biological productivity (Levy and Lee, 1988). We suggest that pockmark fields also represent significant regions of sediment redistribution in temperate estuaries that may mark sites of past seismic activity.

A large, shallow-water pockmark field near Belfast, Maine, contains some of the largest pockmarks yet discovered. This field may have originated during a catastrophic event or may have evolved slowly. If the pockmarks formed catastrophically during an earthquake, they may indicate a region with heretofore unrecognized seismic hazards, analogous to sand liquefaction features on land (Tuttle and Seeber, 1991). If the pockmark field formed slowly, it represents a coastal process not fully understood. Regardless of its origin, the Belfast Bay field appears to be active today. The formation of this field, as well as other shallow-water fields nearby, has profoundly reshaped the sea floor and redistributed a vast quantity of muddy sediment.

GEOLOGIC BACKGROUND AND PREVIOUS WORK

Natural gas is recognized on seismic-reflection profiles as enhanced reflectors or acoustically obscured zones (Judd and Hovland, 1992). Regions with natural gas are common in nearshore and deep-water regions of the Gulf of Maine (Kelley et al., 1989; Fader, 1991) and throughout the world (Hovland and Judd, 1988). In the deeper Mesozoic basins of the Scotian Shelf and surrounding areas, escaping thermogenic gas derived from the high-temperature cracking of petroleum at depth has caused many small pockmarks to form (Fader, 1991).

Within shallow-water embayments of coastal Maine, natural gas commonly obscures seismic-reflection profiles across shelf valleys and nearshore basins (Shipp, 1989; Kelley et al., 1989). These valleys were cut in glacial sediment by rivers during the sea-level regression to a lowstand around 10.5 ka (Kelley et al., 1992) and were filled with muddy, organic-rich sediment during the following transgression. Because bedrock in the area is largely igneous and metamorphic, we infer that shallow-water natural gas is biogenic, or derived from the relatively recent bacterial breakdown of organic matter.

Fader (1991) described a pockmark field in eastern Canada that apparently formed from the escape of biogenic gas, possibly during earthquakes, as has been noted in California (Field and Jennings, 1987). The Canadian field is located in seismically active Oak Bay, along the Maine-Canada border. Kelley et al. (1989) found possible evidence for Quaternary faulting in the sediment of Oak Bay.

Pockmarks were first reported from Belfast Bay by Scanlon and Knebel (1989), who suggested gas escape as the proximate cause for their formation. However, no explanation was offered for the release of gas and the formation of pockmarks here, as opposed to the many other nearby embayments that contain gas but lack pockmarks. Seismicity along a nearby fault, reportedly active in the late Quaternary (Gerber and Rand, 1978), may have initiated their formation. However, no tremors coincided with a local fisherman's report of "enormous numbers of gas bubbles" erupting from the bay in 1992 (Russell Coombs, Isleboro Island, 1993, personal commun.). Recently, pockmarks and gas-charged muddy sediments were recognized in another estuary within 35 km of Belfast Bay (Barnhardt, 1992).

DESCRIPTION OF THE BELFAST BAY POCKMARK FIELD

In the summer of 1989, 140 km of side-scan sonar and fathometer records, 10 km of seismic-reflection profiles, and four piston cores up to 5 m in length were collected from Belfast Bay (Fig. 1). In 1990, the submersible *Delta* made 17 dives to study the pockmarks.

The pockmark field measures 40 km^2 and contains >2000 pockmarks, with an average density of ~50/km^2. The distribution of the pockmarks is not uniform, however; dense clusters of up to 160/km^2 exist in the southwest. The largest pockmarks are composite features (350 m diameter, 35 m relief maximum) and are in deep water (30 m depth to interpockmark sea floor). They occur above a channel that is cut into glacial marine material and is filled with thicker Holocene sediment. Fewer and smaller pockmarks are found inshore and to the northeast, occasionally in lines subparallel to north-south–trending outcrops of till (Figs. 1 and 2A). Near these are other irregularly distributed circular spots that exhibit no associated relief (Fig. 2A). They are commonly marked by an acoustically darker outer ring and a lighter central area. The pockmark diameters correlate significantly with their relief, and a regression equation, relief (m) = 0.7089 + 0.2046 (diameter [m]), allows estimation of the volume of the observed pockmarks at ~9.9 × 10^7 m^3.

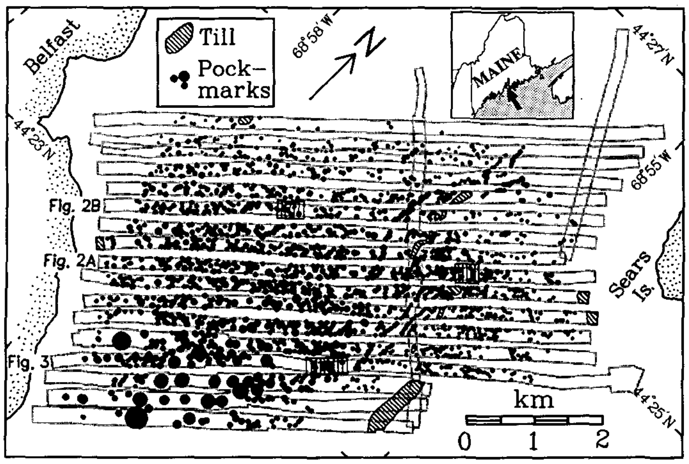

Figure 1. Map of sea-floor pockmarks in Belfast Bay, Maine. Gray boxes show extent of side-scan sonar imagery; vertical lines mark location of figures.

All pockmarks have a sharply defined morphology, steep slopes, and little secondary modification, and thus appear fresh. The slope of the upper walls of the pockmarks averages 30°, and many flatten out in the center (Fig. 2A). Equivocal vents, possibly 5-cm-diameter burrows, were observed on the walls of some pockmarks from the submersible. Acoustically reflective, dark "eyes" were present at the bottom of many pockmarks on the sonargrams (Fig. 2A). Similar features are associated with dense benthic communities elsewhere (Fader, 1991), although none were observed from the submersible in Belfast Bay.

No ejecta rims were observed around the pockmarks, and no slump deposits were detected in the depressions. However, many of the pockmarks were partly filled with a turbid layer, and one appeared to be actively venting gas (Fig. 2B). The curved arch of the fathometer trace suggests that a current was moving the gas and suspended matter to the west as it rose, analogous to a hypothesized depiction of pockmark formation (Josenhans et al., 1978). Black marks on the same sonargrams are within the water column and are probably gas bubbles. Although no other active pockmarks were recognized positively, water-column noise (black irregular marks), identical to that near the active pockmark, was frequently recorded nearby.

As noted by Scanlon and Knebel (1989), seismic-reflection records are obscured by natural gas in many places in the bay, except beneath pockmarks where underlying reflections are visible (Fig. 3). Small pockmarks exist in areas that lack seismically observed gas, but no pockmarks penetrate glacial-marine sediment. Buried pockmarks were not observed here as they have been elsewhere (Fader, 1991).

Piston cores, ranging in length from 5.1 to 2.4 m, all contained

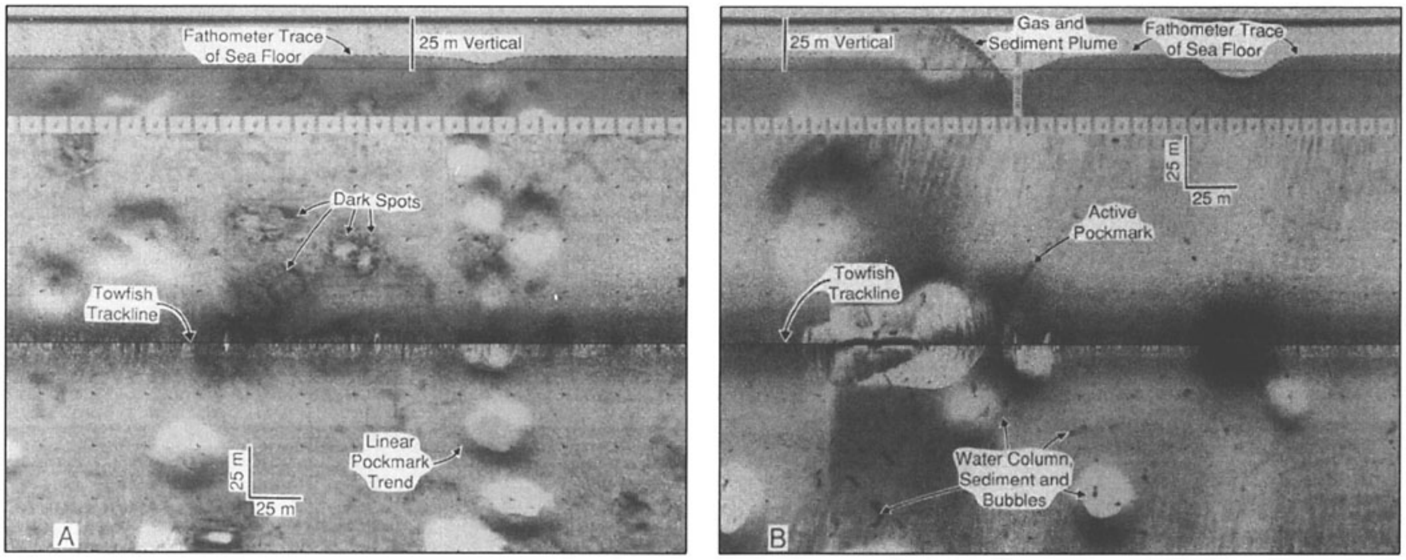

Figure 2. Side-scan sonar images (locations in Fig. 1). Upper channel is fathometer trace with no vertical exaggeration. Dark returns represent strong reflection of acoustic energy from side of pockmark away from towfish and are reversed on opposite sides of towfish trackline. A: Acoustically dark circular features along towfish trackline have no topographic expression and may represent gas pockets slightly below sea bed. As gas is released, sediment collapse may form pockmarks. B: Actively venting pockmark is obscured in side-scan sonar image as fathometer locked onto rising plume of sediment and bubbles. Irregular black marks on record and above bottom in fathometer trace probably represent suspended sediment and gas bubbles. Dashed line is automatic bottom-tracking notation. Note loss of track and disturbed image over active vent.

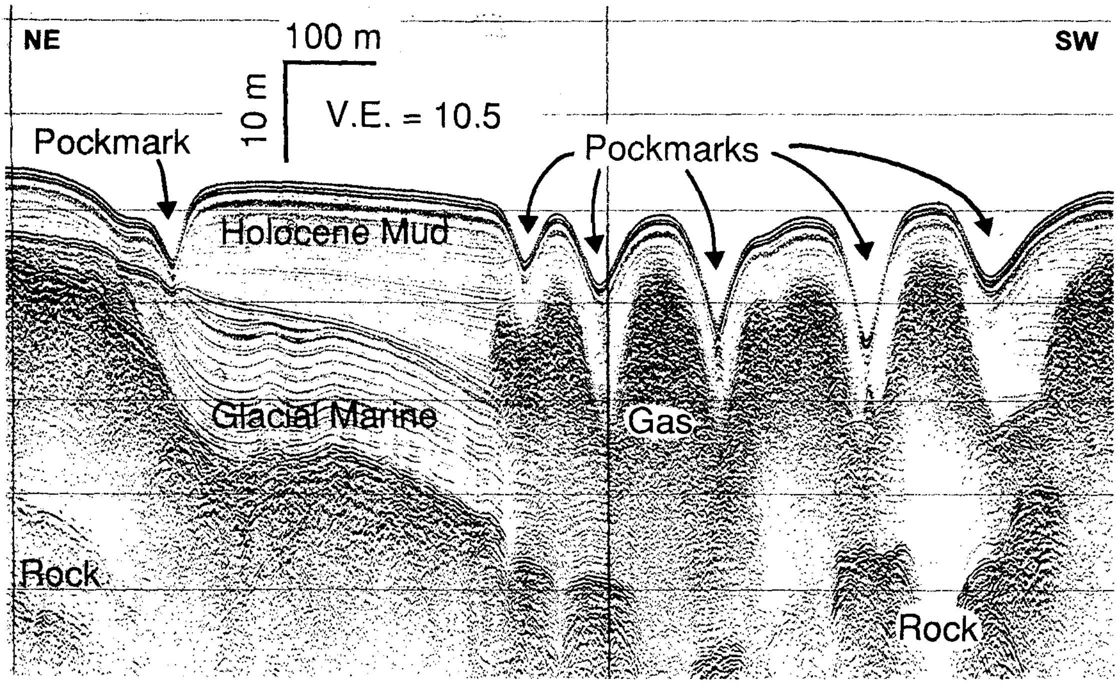

Figure 3. Interpreted seismic-reflection profile over pockmarks (arrows) (Fig. 1). Note that gas masks seismic record, except beneath large pockmarks where reflections from strata and bedrock are recorded, and that no gas is associated with pockmarks on left side of record.

relatively uniform dark brown (2.5Y 4/2) to olive-gray (5Y 4/2) clay. Occasional shell and wood-fragment horizons were the only sedimentary structures. The mean grain size of core samples ranged from 9.2ϕ to 10.8ϕ, similar to surficial sediment in the area (Ostericher, 1965). Loss-on-ignition values ranged from 5% to 9%; water contents ranged from 45% to 56%. Our cores did not reach the unconformity on the surface of the glacial-marine sediment, but Ostericher (1965) found abundant wood fragments on that contact.

DISCUSSION

It is probable that the escape of interstitial, biogenic natural gas and pore water formed the pockmarks. Thermogenic gas, which presumably forms numerous small pockmarks in the Gulf of Maine, Canada (Fader, 1991), and the North Sea (Hovland and Judd, 1988), is improbable in Maine's igneous and metamorphic rock terrane. Although ground-water escape cannot be ruled out, the glacial marine mud in the area appears, from seismic records, to be undisturbed and is relatively impermeable. Locally, there is no hydraulic head to drive ground-water flow along the unconformable contact between glacial-marine and Holocene sediment. No salinity anomalies were noted during submersible dives into the pockmarks.

We propose two models for the origin of pockmarks. The first, an equilibrium model, suggests that they are more common than previously suspected and that they are part of the ordinary evolution of a bay containing fine-grained, organic-rich sediment. In this model, coastal bluffs of fine-grained glacial-marine sediment erode as sea level rises, and mud is redeposited with organic matter on the bay floor. The organic matter may come from a river (the nearby Penobscot River has the largest watershed in Maine) or from erosion of a freshwater peat bog, a common feature along Maine's glaciated coast. Gas is produced by the microbial breakdown of the organic matter and migrates upward once interstitial bubbles are formed. The acoustically dark spots (Fig. 2A), which are concentrated in areas of small, possibly youthful, pockmarks, may represent an early stage of pockmark formation. Dark spots may be subsurface gas concentrations imaged by side-scan sonar through thin, water-rich surficial sediment. Some of the radially symmetrical spots have irregular microtopography in fathometer profiles, perhaps representing an early stage of fluid release involving progressive collapse and enlargement.

In this scenario, gas is released when interstitial pore pressure exceeds the shear strength of the muddy overburden. As gas is released, it resuspends overlying mud, which is dispersed by tidal currents. Once a pockmark is formed, nearby gas migrates toward the newly developed area of locally reduced lithostatic pressure. The pockmark is excavated until it reaches the underlying glacial-marine surface, where it expands horizontally and becomes flattened in the center. The acoustically reflective glacial-marine surface could thus represent the dark "eyes" in the center of some pockmarks. Scour from tidal currents in the field might prevent sedimentation in the pockmark and prevent a raised ejecta rim from forming (Josenhans et al., 1978). The largest pockmarks, under this hypothesis, are the oldest, and are found (as observed) in the deepest water. Pockmarks remain active as long as a supply of gas persists and erupt episodically when pressure builds up. Cyclic hydrostatic loading during major storms or reduction of overburden at extremely low tides are possible mechanisms for continuing eruptions. The unusual brownish color and structureless sediment in cores probably results from partial oxidation of that sediment in the water column during gas eruption. In contrast, cores of gas-charged, muddy sediment from other embayments in Maine are dark (Shipp, 1989).

This model explains many aspects of the pockmarks but does not explain why more pockmark fields are not known. Although recent sea-floor mapping in Maine and elsewhere (Fader, 1991; Barnhardt, 1992) has led to the discovery of additional fields, there are seemingly identical bays with gas-charged, fine-grained sediment but no observed pockmarks (Shipp, 1989). It is also unclear how the supply of gas is able to continue to excavate pockmarks for so long without being depleted. Although buried pockmarks elsewhere suggest depletion of the gas supply (Fader, 1991), none have been recognized in thousands of kilometres of seismic-reflection records from coastal Maine (Shipp, 1989).

An alternative catastrophic model invokes an instantaneous event as the origin of pockmark formation, as is also required by other models (Harrington, 1985). Earthquakes are relatively common events in formerly glaciated regions (Gregersen and Basham, 1989) and have been implicated in the formation of some pockmarks in Canada (Fader, 1991) and California (Field and Jennings, 1987). Earthquakes have also occurred in the Belfast area within historical time (Gerber and Rand, 1978; Smith et al., 1989). Alternatively, a tsunami or major storm waves could briefly reduce the confining pressure on the sea bed and release gas. More gas exists and would be released catastrophically from areas with thicker deposits of Holocene sediment. Thicker deposits are found in deeper water, and so larger pockmarks would be expected (and are observed) there.

The catastrophic model attempts to explain the local nature of pockmarks as an artifact of unusual events but leaves open the question of when the events occurred. As with the equilibrium model, the catastrophic model permits gas escape to continue after its initial release because of the reduced overburden pressure at the pockmarks. In this model the dark spots may represent shallow gas deposits not yet vented. The catastrophic model fails to explain why other muddy bays in the region, which have also undergone historical seismic events (Smith et al., 1989), apparently do not contain pockmarks (Kelley et al., 1989).

Neither proposed model explains why pockmarks exist in areas lacking appreciable natural gas (Fig. 3), although Harrington (1985) suggested that interstitial water escape alone may be sufficient for pockmark formation. Furthermore, our existing data do not permit an explanation for the linear trends of pockmarks, although they appear to be subparallel to and may be influenced by subsurface till and bedrock, which could confine lateral growth and fluid flow (Fig. 1).

SUMMARY AND CONCLUSIONS

Large quantities of muddy sediment have been transported during the formation of pockmarks in several shallow bays in the western Gulf of Maine. Pockmarks in Belfast Bay are larger than those commonly associated with thermogenic gas escape and are among the largest in the world. The escape of biogenic natural gas and associated pore water appears to be responsible for pockmark formation. The pockmark field in Belfast Bay is active today, but it is not yet possible to determine whether the field, and others like it, formed slowly or suddenly. We favor a model of an unusual triggering event or events followed by continued evolution to the present.

No similar pockmark fields associated with biogenic gas release are reported from low latitudes; they are exclusively from formerly glaciated terranes. We speculate that buried bog deposits might explain this observation, or that there may be a microbial control related to temperature. A thorough investigation of pockmarks, including measurement of discharging fluids, is required to determine their origin and understand their significance.

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