Giant undersea craters were blown out by decomposing methane hydrates

Although the craters likely formed about 12 000 years ago, methane is still leaking profusely around and between them.

When hydrocarbon gas meets water at low temperature and high pressure, the hydrocarbons can become trapped inside ice-like cages. Not surprisingly, Earth's uppermost layers of sediment and rock are loaded with such gas hydrates, the vast majority of which host methane and formed in marine environments on continental margins. (See the article by Wendy Mao, Carolyn Koh, and Dendy Sloan, PHYSICS TODAY, October 2007, page 42.) A recent estimate puts the amount of sequestered methane at some 2400 gigatons, roughly a third of the mass of all other fossil-fuel reserves on Earth.[1] One concern driving gas-hydrate research is that our warming planet may destabilize those reservoirs and trigger catastrophic releases of methane from the seafloor into the ocean and ultimately the atmosphere. As a greenhouse gas, methane is 25 times as potent per unit mass as carbon dioxide over a 100-year time scale.

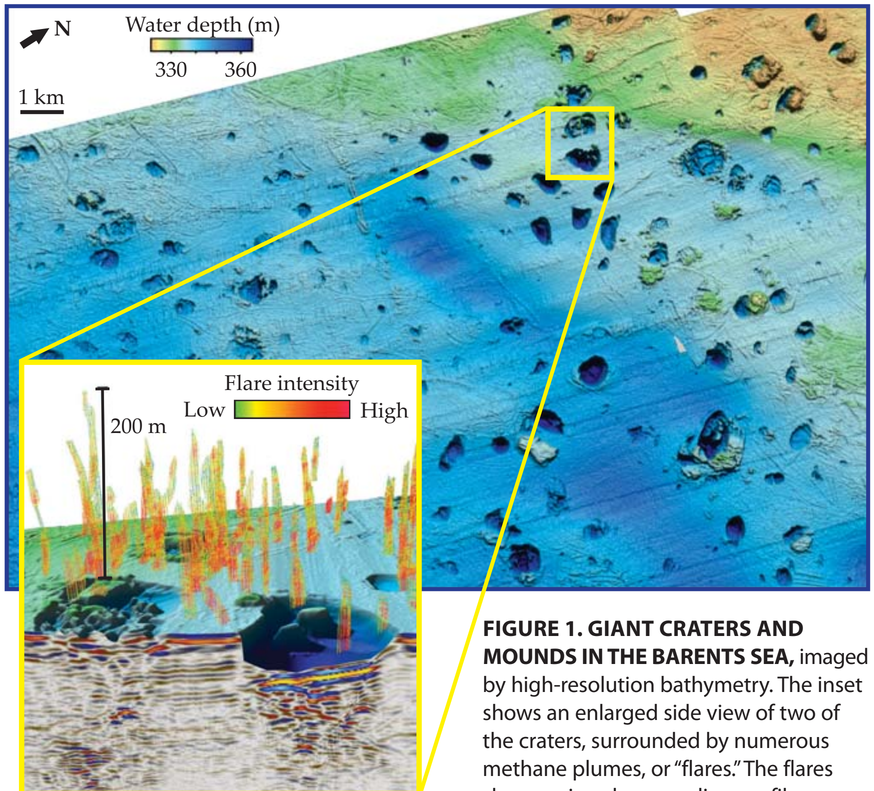

FIGURE 1. GIANT CRATERS AND MOUNDS IN THE BARENTS SEA, imaged by high-resolution bathymetry. The inset shows an enlarged side view of two of the craters, surrounded by numerous methane plumes, or "flares." The flares show up in echo-sounding profiles as acoustic anomalies because of the large density contrasts between chains of bubbles and the water column. Seismic reflections reveal layers of broken sandstone, primarily under the craters. The discontinuities are signatures of faults and fissures through which free gas can migrate from deep underground. (Adapted from ref. 3.)

In 1993 geoscientists Anders Solheim and Anders Elverhøi (both at the University of Oslo) discovered a handful of giant underwater craters, some as wide as a kilometer, that they suspected might have been formed by methane release.[2] Located on the sloping shelf of the Barents Sea north of Norway, the craters have steep walls, some as high as 30 m, made of hard, Triassic bedrock. Pockmarks from gas seepage are common in the Barents Sea, which sits atop vast oil and gas fields, but they rarely develop into such huge craters. The research pair speculated that the giant craters formed after deglaciation of the area 15 000 years ago, most likely from the dissociation of gas hydrates.

When marine scientist Karin Andreassen of the Centre for Arctic Gas Hydrate, Environment and Climate (CAGE) revisited the Barents Sea in the summers of 2013 and 2015 with a team of researchers, she expected to see only a few giant craters amid the seeps. To her surprise, she found more than a hundred of them pitting the seafloor—some with equally large mounds next to them. Solheim and Elverhøi had explored a far more localized region, and no one imagined how pervasive the giants would be. Figure 1 shows part of the 440 km^2 area that was surveyed during the recent cruises. Andreassen and her colleagues acquired high-resolution bathymetry data to map the seafloor, used sonar to image methane plumes rising from it, and deployed seismic methods to image bedrock below it. The researchers have now published an account of that survey, which bears out the earlier speculation with a unified theory of how the craters formed.[3]

Megaburps

To investigate the craters' origins, the researchers developed a numerical model of the evolution of the methane-hydrate stability zone, a region under the seafloor that maintains a high enough pressure and low enough temperature for the hydrates to remain stable. Using a simple heat-conduction equation, they essentially calculated the time required for heat to diffuse through underlying sediment and overlying ice or seawater and decompose the hydrates into water and gas. Figure 2 sketches what the model revealed: progressive thinning of the stability zone over the past 30 000 years as the Arctic moved into an interglacial period after the last ice age.

Under the crushing pressure and icy temperatures of the glacial era, free methane migrated upward from deep underground through a system of cracks and fissures, only to freeze in place as gas hydrates below the seafloor. The hydrates remained stable for millennia, sequestered within permeable bedrock. As the ice sheet retreated, the

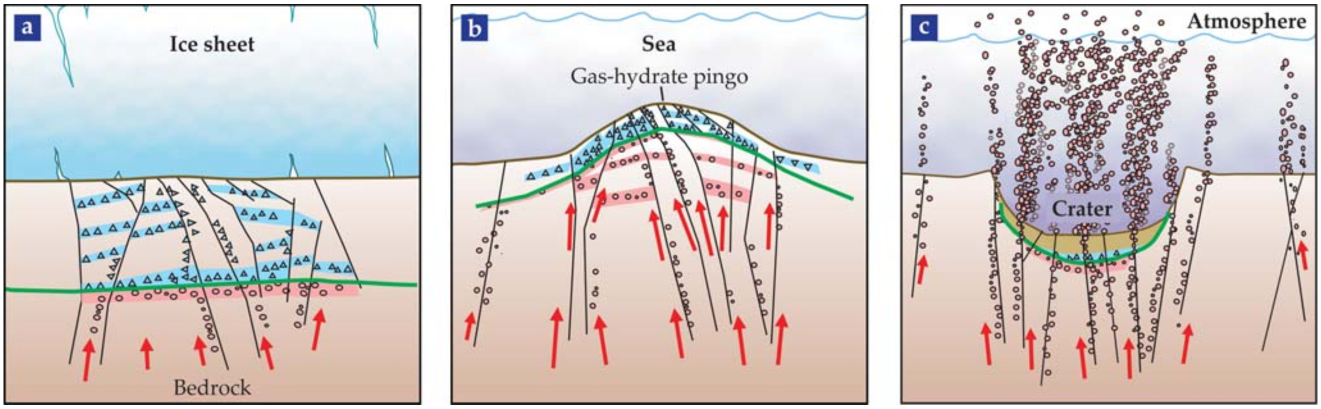

FIGURE 2. THE EVOLUTION OF A CRATER, in snapshots. **(a)** By 20 000 years ago, the Barents seafloor had been crushed for millennia under a nearly 2-km-deep ice sheet that stabilized a thick layer of methane gas hydrates (triangles). Free methane (circles) deeper underground migrated upward toward the stability zone through a network of faults (black lines). **(b)** By about 15 000 years ago, the ice sheet had melted, as had some of the hydrates, and the stability-zone boundary (green) moved closer to the seafloor. With the accumulation (pink regions) of free methane under the remaining hydrates, mounting pressure inflated the seafloor into a mound known as a gas-hydrate pingo. **(c)** A few millennia later (roughly 12 000 years ago), the pressure broke through the seafloor and pingo debris (tan) settled into a resulting crater. (Adapted from ref. 3.)

seafloor's slow rebound began a long period of depressurization and warming. Methane bubbles continued to rise and accumulate under a stability zone that thinned as the deepest hydrates decomposed. The frozen lid of hydrates nearest the cold seafloor blocked the escape of most gas, and within a couple of millennia the mounting pressure had thrust the seafloor upward into so-called gas-hydrate pingos. Eventually, the hydrate lid blew its top and liberated its massive cargo of methane into the ocean.

Although the evolution of thermodynamic conditions required for each stage took millennia, Andreassen and company conclude that the liberation of methane was "abrupt." It's plausible, they argue, that a series of localized blowouts drove hydrofractures through hard bedrock and seafloor sediment until they gave way in a single methane megaburp. What's more, the researchers' imaging of some craters revealed what look like large chunks of bedrock debris that settled back into the crater interior or onto its flanks. Despite the suggestive evidence, they haven't yet estimated the volume of methane that was released into the ocean nor the release's duration.

The crater field is probably no longer forming pingos; the hydrates that capped gas while the seafloor inflated have not been stable ever since the craters formed. And concretions of debris from the gas expulsion are thought to have partially clogged the network of underground fissures below the craters. Such concretions, says Andreassen, may explain why most of the current methane seeps are found between craters rather than in them.

But pingos appear to be growing elsewhere under the Arctic Ocean. Around 500 km northwest of the surveyed crater field, in slightly deeper water, the researchers found a cluster that may yet produce blowouts. "The pingos are younger by virtue of being deeper," says Pavel Serov, one of Andreassen's PhD students and a lead author on a paper just published about the pingo cluster.[4] "Even a 20-meter deeper seafloor makes a difference to the thickness of the stability zone" and forestalls the seafloor's local rise. No one knows how pervasive such undersea pingos and their craters are globally. But they may have formed over vast parts of the Arctic or Antarctica. An area of hydrocarbon reserves at least twice the size of Russia is thought to have been covered by glacial ice sheets (excluding Antarctica and Greenland). Today, those ice sheets are largely absent.

An atmospheric link?

Could huge blowouts affect global warming? Although the connection is outwardly possible, the University of Rochester's John Kessler is quick to point out that the release of a seemingly catastrophic amount of methane from the seafloor doesn't necessarily imply a release to the atmosphere. Rather, very little, if any, of the methane bubbling from under 200 m of water is likely to reach the surface. For one thing, the natural levels of dissolved hydrocarbons in most ocean waters are extremely low, on the scale of a few nanomoles per liter. As methane bubbles rise from the seafloor, the gas quickly diffuses from them in a "bubble-stripping" process that replaces the methane with oxygen and nitrogen.[1] And even with methane's low solubility, seawater has the capacity to dissolve the gas in concentrations approximately a million times higher before the oceans become saturated.

When the Deepwater Horizon oil rig exploded in 2010, at least 200 000 tons of natural gas spewed into the Gulf of Mexico, and the geyser-like emissions produced methane concentrations in the water up to 75 000 times their natural levels within a few kilometers of the well. But when Kessler and colleagues tracked the fate of the gas, they were astonished to find that it all dissolved in distinct layers far below the surface.[5] A second surprise was how quickly the dissolved methane was oxidized by bacteria and other microbes that use it as fuel. Indeed, the oxidation rate skyrocketed after the spill was under way; bacterial colonies bloomed to feast on the unnatural bounty. Most of the gas was gone within four months.[6]

A growing body of evidence from ice-core data also fails to support spikes in atmospheric methane from ancient hydrate blowouts. Methane is formed by both biological and thermogenic processes, each having a distinct fingerprint of carbon isotopes. Although studies have not yet placed quantitative constraints on the emissions of hydrate methane, carbon-14 analyses suggest that the release of geologically young methane from wetlands around 12 000 years ago was the main cause of an increase in atmospheric methane at the time. The contribution from hydrates was small by comparison.[7]

Nonetheless, massive amounts of hydrocarbons released into the oceans may still affect their carbon cycle and have ecological consequences. Because of the size of the newly discovered craters and the global magnitude of the climate-sensitive reservoirs they tap, any potential effects remain a topic of active research.

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References

1. C. Ruppel, J. D. Kessler, *Rev. Geophys.* **55**, 126 (2017).
2. A. Solheim, A. Elverhøi, *Geo-Mar. Lett.* **13**, 235 (1993).
3. K. Andreassen et al., *Science* **356**, 948 (2017).
4. P. Serov et al., *Proc. Natl. Acad. Sci. USA* **114**, 6215 (2017).
5. S. A. Yvon-Lewis, L. Hu, J. D. Kessler, *Geophys. Res. Lett.* **38**, L01602 (2011).
6. J. D. Kessler et al., *Science* **331** 312 (2011); M. Du, J. D. Kessler, *Environ. Sci. Technol.* **46**, 10499 (2012).
7. See, for example, V. V. Petrenko et al., *Science* **324**, 506 (2009).

PHYSICS UPDATE

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SPIDER DRAGLINE SILK'S SURPRISING TWIST

Among its many remarkable mechanical properties, spider silk is most often touted for tensile strength that rivals steel but at a fraction of the density. Its torsional strength—as evidenced by how spiders like the golden orb-weaver in the photo manage to hang from draglines without spinning out of control—has more recently caught researchers' attention. To test how spider silk responds to torsional strain, Yuming He of Huazhong University of Science and Technology in Wuhan, China, and his collaborators mounted threads drawn from golden orb-weavers in a torsion pendulum. When Kevlar thread, metal wires, and other conventional fibers are given a twist and released, they undergo damped oscillations around the initial resting point. In contrast, the spider-silk threads oscillated around an angular position that's displaced from the original resting point. That indicates that some type of plastic deformation dissipates much of the energy of the twist and reduces the subsequent oscillation amplitude. A spider-silk thread is composed of a bundle of fibrils, and each fibril contains proteins strung in a combination of amorphous chains and crystalline sheets. The researchers speculate that the amorphous chains, which are loosely linked by hydrogen bonds, can easily separate and deform. That deformation, together with friction between fibrils, can quickly dissipate applied energy. Meanwhile, the crystalline sheets act to maintain the shape of the silk. (D. Liu et al., *Appl. Phys. Lett.* **111**, 013701, 2017; photo by C. Frank Starmer.) —SC

COLLISIONS OF VISCOUS DROPLETS

From industrial food and drug processing to car and jet engines, the interactions between small liquid droplets have a surprisingly large effect on our lives. Wherever they occur, the interactions are complex—involving multiple phases and multiple time and length scales. And as shown in the figure, collisions can have different outcomes, including reflexive separation (left), stretching separation (right), and coalescence (center). Although numerical, theoretical, and experimental efforts over the past few decades have explored the underlying fluid dynamics, a detailed understanding, especially concerning the role of viscous forces, has yet to emerge. For water droplets, viscous forces are usually much less relevant than surface tension, but in spray drying and other industrial applications they can be substantial and lead to significant energy loss as the droplets merge and deform. To better understand the effect of droplet viscosity, a team of Dutch researchers led by Hans Kuipers (Eindhoven University of Technology) has analyzed the influence of viscous energy dissipation on the outcomes of 116 simulated droplet collisions. Based on their results, the researchers derive a phenomenological model that captures the dependence of the collision outcome on the droplets' viscosity, impact parameter, and ratio of kinetic energy to surface tension. The model may help improve the production of milk powder, infant formula, and many other goods. (G. Finotello et al., *Phys. Fluids* **29**, 067102, 2017.) —RJF