Considerable work remains to be done before we will truly understand the role of spontaneous activity in the nervous system and whether it is instructive or permissive in the development of neuronal connections and the maintenance or modulation of these connections in the adult. The analysis of knockout mice that lack particular patterns of activity owing to the loss or disruption of a particular ion channel, receptor, or protein involved in synaptic transmission seems to be a particularly promising avenue for future research (*13*, *18*).

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PERSPECTIVES: NATURAL GAS DEPOSITS

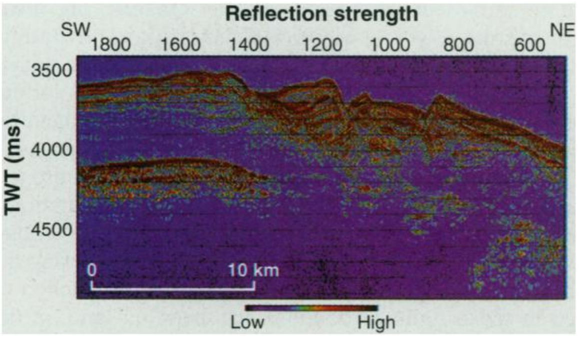
Methane in the Deep Blue Sea

Bilal U. Haq

Natural gas hydrates have been known to exist in marine sediments since the 1970s, but the pace of research into their nature has only recently picked up. Research efforts have been focused on investigating their efficacy as an alternative energy resource and on their potentially important roles in global climate change and the stability of the continental slope. Gas hydrates are considered to represent an immense, although as yet largely uncharted, source of fuel for future consumption (*1*). Indeed, hearings have been held in the U.S. House and Senate on a revived bill to inject as much as $42.5 million into hydrate research over the next 5 years.

Gas hydrates consist largely of a mixture of methane and water frozen into a solid crystalline state. At moderately high pressure and low temperature, the methane molecule is captured inside a cage of water molecules and chilled into a solid hydrate, while expelling salt. Methane hydrates exist at water depths greater than ~500 meters in the pore spaces of marine sediments on the continental slope and rise and on the sea floor where gas escapes from fault conduits (especially in the Gulf of Mexico). Because of the very low temperatures in the Arctic, hydrates also occur on land in association with permafrost. Hydrate methane is largely of biogenic origin, derived from the decay of organic material trapped in the sediments. Initial results of a field investigation (*2*) show that methanogenic microorganisms can produce methane at substantial depths in the sediment, at pressures of about 400 atmospheres.

In marine sediments, hydrates are commonly characterized by the presence of acoustic reflectors known as bottom simulating reflectors (BSRs) that are caused by the acoustic velocity contrast between a solid hydrate layer and the free gas below. BSRs mimic the sea floor (see the figure). They have been observed on many continental margins of the world (*3*), but hydrates have only rarely been sampled through drilling or brought to the laboratory in their natural state. Because of this paucity of direct sampling and analysis, estimates of the volumes of methane trapped in hydrates, or the associated free gas beneath the hydrate stability zone, remain speculative (*1*). However, even relatively conservative estimates indicate that on the order of 10,000 gigatons of carbon, or double the amount of all known fossil fuel sources, may be stored in gas hydrates (*3*).



When a gas hydrate collapses. Seismic profile of a collapse structure on the crest of the Blake Ridge, off the coast of the Carolinas. The vertical scale shows two-way travel time (TWT) in milliseconds, or depth. The prominent BSR (just below 4000 milliseconds) is intact on the left but is disrupted below the collapse structure. The collapse is confined to the hydrate depths and was most likely caused by overpressure below the hydrate stability zone. It may have been accompanied by substantial injection of methane into the seawater and atmosphere.

Thus far, the petroleum industry has not been interested in methane hydrates as a resource, because they may not be easy to recover or cost-effective to exploit, particularly if most marine hydrate is thinly dispersed in the sediment. Drilling on the Blake Ridge off the East Coast of the United States (*4*) indicates that they are very rarely locally concentrated in the otherwise widespread field of thinly dispersed hydrate.

Gas hydrates have been implicated in massive slumps and slides on the continental slopes, when hydrates break down as a result of structural changes, increased bottom temperature, or reduced hydrostatic pressure (see the figure). Ongoing experiments show that methane hydrate has a markedly higher mechanical strength than water ice (it is 10 times stronger than ice at 260 K) (*5*). The sediment thus gains considerable strength when the hydrate forms but then loses it near the base of the hydrate stability zone during dissociation. When a hydrate dissociates, it changes from a solid to a mixture of sediment, water, and gas.

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The author is in the Division of Ocean Sciences, National Science Foundation, Arlington, VA 22230, USA, E-mail: bhaq@nst.gov

The resulting change in the physical properties and shear strength of the hydrate-bearing sediment may encourage massive slope failure along low-angle detachment faults (*6*). Such slumping can pose a considerable hazard to petroleum drilling rigs and to undersea cables. In addition, extensive slope failures can conceivably release large amounts of methane gas into the seawater and atmosphere that could enhance greenhouse warming over the longer term.

Gas hydrate dissociation near the end of the last glacial period (about 18,000 years ago) may have been responsible for the rapid termination of the glacial episode (*7*). During the glacial period, the sea level fell by ~120 m, which lowered the hydrostatic pressure, leading to massive slumping that may have liberated substantial amounts of methane. This may in turn have triggered greenhouse warming and, possibly, a rapid deglaciation. Ice core records of glacial-interglacial periods from Greenland and Antarctica (*8*, *9*) show parallel temperature increases and rising concentrations of atmospheric methane and carbon dioxide. However, the temporal resolution of the records is not refined enough to determine whether the temperature rise caused hydrate dissociation and methane increase or vice versa (*9*). A decadal resolution (~50 years) will be necessary to understand the leads and lags.

The occurrence and stability of gas hydrates at oceanic depths of the continental slope and rise have led to the notion that we may be able to dispose of excess greenhouse gases, especially carbon dioxide, in the deep ocean as synthetic hydrates. Such sequestration of carbon dioxide would not be permanent because the hydrate on the sea floor would eventually be dissolved and dispersed in seawater. However, given the long time scales of ocean circulation, the large size of the oceanic reservoir, and the buffering effect of carbonate sediments, carbon dioxide in the form of solid hydrate may remain stable for hundreds to thousands of years (*10*).

Substantial uncertainty remains regarding the nature, formation, and location of the gas hydrate reservoirs—both in the sea and on land—and their energy and climate change potentials. To make meaningful estimates of their total volume on continental margins and in the permafrost, we need to know whether they are thinly dispersed in sediments or occur in substantial local concentrations. Seismic data from the Hydrate Ridge off the coast of Oregon suggest intricate plumbing systems and methane migration pathways within the hydrate stability zone and below (*11*). Disruptions in the BSR that correlate with the sea-floor morphology imply dissolution of hydrate in response to slumping and folding along this active margin. Modeling efforts suggest that advective processes and high methane flux through fault zones may be important for concentrating hydrate (*12*). Understanding of all these processes is still limited. We also need a better understanding of biological methane-forming activity under high pressure and the subsequent organic-matter decomposition associated with methanogenesis, which have to be factored into dynamic hydrate models. Finally, to appreciate the role of gas hydrates in global climate change, we need to have a better grasp of how much of the hydrate in the continental margins and the permafrost responds to oceanic and atmospheric temperature fluctuations. More importantly, we must understand the fate of the methane released from a hydrate source into the water column and the atmosphere. Studies of the geological records of past hydrate fields can also provide clues to their behavior and role in climate change.

Revival of interest in gas hydrates has opened a new frontier in ocean and Earth sciences that crosses many disciplinary boundaries. The next decade promises to be a challenging period to resolve the riddle of gas hydrates, their role in environmental change, and their potential as an energy resource.

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PERSPECTIVES: BIOGEOCHEMICAL CYCLES

The Not-So-Big U.S. Carbon Sink

Christopher B. Field and Inez Y. Fung

Less than half of the carbon emitted to the atmosphere through deforestation, fossil fuel combustion, and cement manufacture remains in the atmosphere. The remainder of the carbon emitted through these human activities is stored, at least temporarily, in carbon sinks in the oceans and in terrestrial ecosystems. Quantifying these sinks and understanding the underlying mechanisms are top priorities for understanding Earth's major biogeochemical cycles and for establishing how changes in their magnitude could affect the future trajectory of atmospheric CO_2 concentrations.

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Measured atmospheric CO_2, ^{13}C, and O_2/N_2 distributions indicate that during the past two decades, a substantial fraction of the carbon sink has been on land, in the temperate and boreal latitudes of the Northern Hemisphere (*1*). However, the mechanisms and the detailed spatial pattern of this Northern Hemisphere terrestrial sink remain elusive. On page 574 of this issue, Houghton *et al.* (*2*) synthesize the information on a leading candidate—historical changes in land use—for the United States. They conclude that during the 1980s, U.S. ecosystems accumulated carbon at a rate of 0.15 to 0.35 Pg/year [petagrams (10^{15} grams) per year], equivalent to about 10 to 30% of U.S. fossil fuel emissions. This conclusion is consistent with atmospheric analyses (*1*), which indicate that there is a sink for carbon of about 2 Pg/year north of approximately 30°N (*3*), although these analyses were unable to constrain the longitudinal distribution of the sink. However, it contrasts sharply with the result of Fan *et al.* (*4*), who suggest on the basis of atmospheric and oceanic data and modeling that the Northern Hemisphere carbon sink is predominantly North American, south of 51°N, with a magnitude about that of U.S. fossil fuel emissions. The apparent contrast between the conclusions of these two studies highlights the differences between and uncertainties asssociated with atmospheric "top-down" and terrestrial ecosystem "bottom-up" approaches.

From the perspective of terrestrial processes, the list of candidate mechanisms for

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C. B. Field is in the Department of Plant Biology, Carnegie Institution of Washington, Stanford, CA 94305, USA. E-mail: chris@jasper.stanford.edu. I. Y. Fung is at the Center for Atmospheric Sciences, University of California, Berkeley, CA 94720, USA.