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A Chemotrophic Ecosystem Found Beneath Antarctic Ice Shelf

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A new habitat for chemotrophic ecosystems has been found beneath the former extent of the Larsen Ice Shelf in Antarctica. This is the first report of such ecosystems in the Antarctic. (Chemotrophic ecosystems derive their primary metabolic energy from chemical reactions other than those of photosynthetic origin.)

An association of microbial mats and cold seep clam communities, is described, that thrived within an 850-m-deep glacial trough some 100 km, or more, from the ice shelf front. However, the continued existence of this unique ecosystem is uncertain, given the increased loading of sediment to the seafloor as a result of the ice shelf's collapse in early 2002. The vent-related ecology could have a methane source, based upon the vent's similarity with other cold seeps located along continental margins.

These results have implications for the discovery of life in extreme environments, including those found beneath the enormous extent of existing ice shelves and large lakes that lie beneath the Antarctic Ice Sheet. Because of its restricted conditions, the seafloor beneath ice shelves may provide a suitable, widespread habitat for chemotrophic systems; given this, there may be many more such habitats waiting to be discovered beneath existing ice shelves.

The seafloor beneath Antarctica's floating ice shelves covers more than 1.54 million km^2 [*Drewry*, 1983], an area of the same order of magnitude as the Amazon basin of Brazil or the Sahara desert. Yet, this expansive marine setting remains largely unexplored, even though it represents an important coupling zone among ice sheets, the seafloor, and the ocean water column [*Rignot and Jacobs,* 2002] (Figure 1).

Even more poorly understood are marine habitats beneath ice shelves where sources of primary phyto-production are severely limited, if not nonexistent [*Lipps et al.*, 1979]. The recent collapse of the Larsen Ice Shelf along the eastern coast of the Antarctic Peninsula (Figure 1) has provided an unprecedented opportunity to examine the deep confines of a sub-ice-shelf setting from a marine perspective.

This article reports on observations of a unique seafloor habitat that developed far beneath the edge of the floating Larsen B Ice Shelf, and which is now undergoing dramatic change in response to increased sediment flux to the seafloor. These observations are based upon bathymetric mapping, bottom sampling, and bottom photo/video coverage obtained during a March 2005 U.S. Antarctic Program cruise to the northwestern Weddell Sea (http://www.hamilton.edu/news/exp/antarctica/2005/).

Bathymetric Setting

The bathymetry of the Larsen B embayment is reflective of glacial erosion superimposed upon a bedrock transition from the crystalline metamorphic/igneous rocks of the Antarctic Peninsula to offshore mud rocks of Mesozoic age [*Sloan et al.*, 1995]. An over-deepened inner shelf is transected by a deep trough that is silled by a narrow bank (Figure 1c). Within the deep (850 m) axis of the trough, photo imagery was taken across approximately 5540 m^2 of the bottom via a towed video sled (Figure 1c) and small scenes were captured via a still camera.

Across the survey area, 50–70% of the bottom is draped by a white mat covering seafloor irregularities (Figure 2a). The thickness of the mat varies from a few millimeters to perhaps a centimeter or more. Across large areas (as much as several hundred square meters), the mat takes on a pustular morphology that is independent of the underlying relief. In places, gas bubbles can be seen emanating from patches of mat (Figure 2a). Also, irregular branching networks are common and appear to reflect discontinuous horizontal burrows or places where brittle stars have disrupted the sediment surface. Recent sediment can be found in most available depressions covering the mat, infilling as ponds of silt and clay and patches of diatomaceous algal "fluff" (Figure 2c). Fresh dropstones also have fallen on the mat (Figure 2b).

These stratigraphic relationships, clearly observed in the imagery, indicate that the mat was, at one time, forming across most of the bottom within the survey region but is now being covered by a fallout of ice-rafted debris and phyto-detritus, reflective of the ice shelf collapse and subsequent open marine conditions [*Gilbert and Domack*, 2003].

In addition, small mounds (1.5–2 m across and 0.75 m high) are found in places, and these are encircled by conspicuous, large bivalves (20–30 cm across) which cluster around a central orifice a few decimeters in diameter (Figure 2d). Approximately 37 individual clams can be observed around the largest of these features (Figure 2d). Radiating from such vents are clear indications of suspended particulate matter and fluidized mudflows, the latter marked by superimposed channels with levees that terminate at the base of the mound in fan-shaped mudflats. Several episodes of channel activity (eruptive events) are marked by clear patterns of cross-cutting relations between abandoned and more recently active channels.

Remnant vents are marked by less organized groupings of large mollusks that are partly buried and lack clear channel systems. Two remnant vents were observed across the survey track. Noticeably absent from the bottom images are established communities of benthic organisms typically associated with Antarctic systems.

Affinity of Vent Community

The observations support the interpretation of a chemotrophic benthic community established on the seafloor beneath the Larsen B Ice Shelf. The white mats are similar to *Begiattoa*, a genus of hydrogen sulfide (H_2S) oxidizing chemoautotrophs, common at the interface between sulfide-rich sediments and oxygen-rich waters. Chemoautotrophs are those organisms that derive their metabolic energy and fix their own carbon from the chemical transformations associated with non-photosynthetic processes.

The widespread occurrence of the mats, and their association with the observed seep communities, suggest a source of carbon fixation that is not related to phyto-primary production. Indeed, the sub-ice-shelf setting of the Larsen B trough (Figure 1) is an environment

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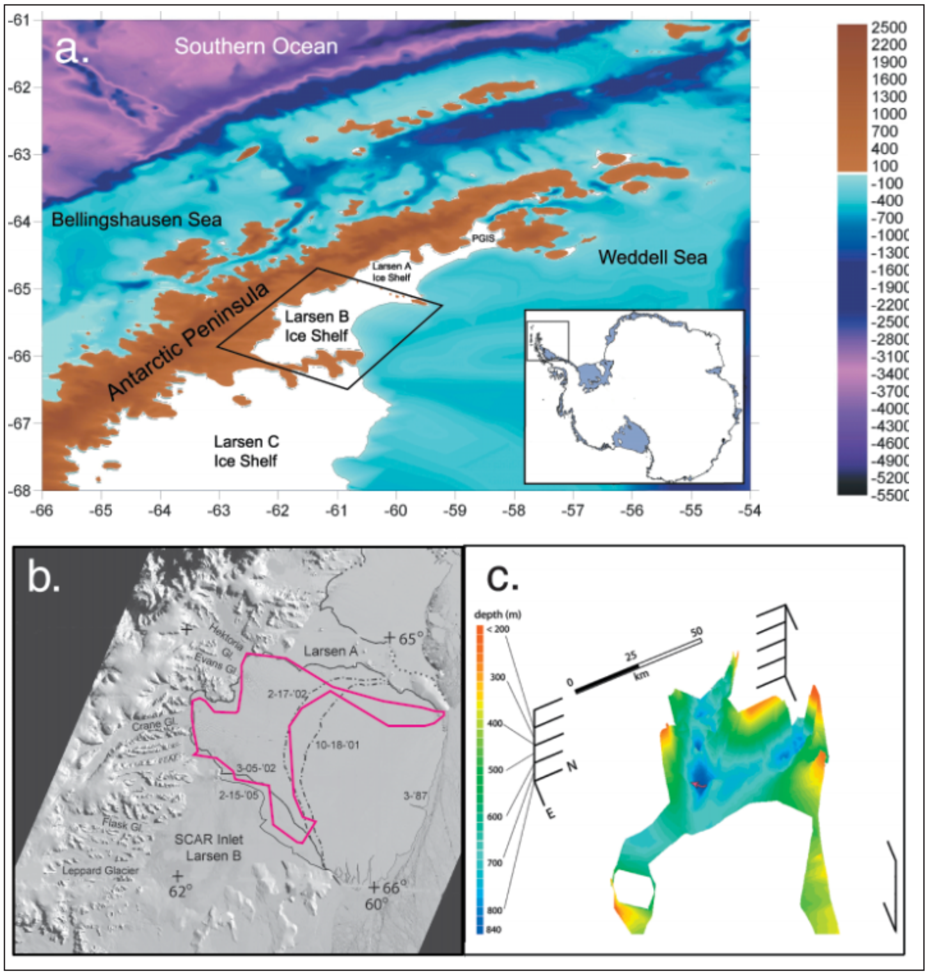

Fig. 1. (a) Area of the Larsen B Ice Shelf, northwestern Weddell Sea showing generalized bathymetry of the seafloor and the location of the study area. Inset shows the location of the study area in relation to Antarctica and large ice shelves (blue). (b) Landsat image of the Larsen Ice Shelf illustrates calving line positions since March 1986 (dates indicated; after Skvarca and DeAngelis *[2003]) and the region encompassed by the 650 nm of single-beam acoustic soundings (pink polygon). (c) Oblique view of the seafloor morphology within the survey region depicting deep glacial troughs that emanate from the Crane and Hektoria/Evans glaciers. Contour intervals are 20 m, and the location and direction of the bottom video survey are indicated by the pink arrow. Color code is depth in meters with an interval of 20 m.*

that has been restricted, if not isolated, from sources of phytoplankton detritus for more than 10,000 years [*Domack et al*., 2005]. In this case, chemoautotrophy might be expected to dominate a benthic habitat, if appropriate elemental sources are present. They apparently are in the case of the Larsen B system, but the exact chemical pathway of the system is presently unknown.

The nature of the venting fluid and/or gas is uncertain. However, it is presumed that the fluid or gas is methane with consequent hydrogen sulfide, based upon the similarity in community structure (microbial mats and clam beds) with cold seeps reported from offshore California and the Gulf of Mexico [*Sibuet and Olu*, 1998].

What remains problematic is the ultimate source of methanogenesis (i.e., a process that generates methane). Quaternary marine sediments within the basin are exceedingly lean in organic carbon, and for the most part comprise a highly condensed stratigraphy of about 1 m resting above glacial till [*Domack et al.,* 2005]. Hence, unlike cold seep systems reported from other regions, the methane may not be derived from methanogenesis within the near-surface sedimentary section via microbial activity.

Rather, it is probable that the methane derives from deeper-seated, thermogenic (i.e., a process related to thermal action and heat flow in the Earth's crust) hydrocarbons, as the bedrock beneath the trough consists of Mesozoic marine shale, known to be a prolific hydrocarbon source rock in correlative basins of Patagonia, South America. Glacial excavation deep into the bedrock may have facilitated connectivity to deep migration paths for thermogenic hydrocarbon sources, thus focusing the location of the unique habitat in the main axis of the trough. Still-camera images from 15 other sites within the survey area (Figure 1) did not demonstrate features indicative of more widespread chemotrophism.

The extremely limited availability of phytodetritus that may have been transported laterally by currents into the trough (prior to ice shelf breakup) may have allowed a methanotrophic ecosystem to have flourished, despite moderate-to-low levels of methane seepage to the surface. Under normal marine conditions, such levels may be insufficient to maintain a chemotrophic ecology. This is because the metabolic pathway would need to compete with benthic systems that are maintained by a fallout of phyto-detritus and macroalgal particulate matter derived from the surface layer and littoral zone, respectively. Therefore, ice shelves may play a critical role in allowing chemotrophism across the seafloor, when normally it might not establish itself.

These hypotheses remain to be tested by a more focused program of benthic study across the Larsen B embayment. Existing ice shelves should also receive renewed scrutiny in regard to their potential for such unusual benthic ecology. Further, these results demonstrate that chemoautotrophy can exist in extreme settings beneath ice shelves, and suggest that given sufficient chemical pathways such systems are quite possible beneath even more restricted environments, such as beneath Antarctica's subglacial Lake Vostok [*Priscu et al.,* 1999].

Ecosystem Changes

The profound changes now affecting the benthic habitat are equally intriguing. As shown by the observations, the microbial mats are rapidly (within three years) being reduced in extent by either burial from ice-rafted sediment or phytoplankton detritus. The latter product alters the ecosystem in fundamental ways by shifting the carbon source to material more readily available to "normal" benthic grazers and consequent higher-level predators; colonization is already taking place.

The impact of glacial detritus, including large dropstones found displacing microbial lamination, also has intriguing analogies with ancient glacial/carbonate (microbialaminite) associations of the Neoproterozoic "snowball Earth" [*Hoffman and Schrag,* 2002]. These ancient rocks are believed to have been deposited during periods of global ice cover and widespread ice shelf extent and are interstratified with microbialaminated intervals with glacially rafted dropstones.

Much remains to be resolved by the study of undisturbed sub-ice-shelf ecosystems. However, the window of opportunity may be closing for such research if Antarctica's ice shelves continue their pattern of collapse in response to regional warming of the atmosphere [*Vaughan et al.*, 2001].

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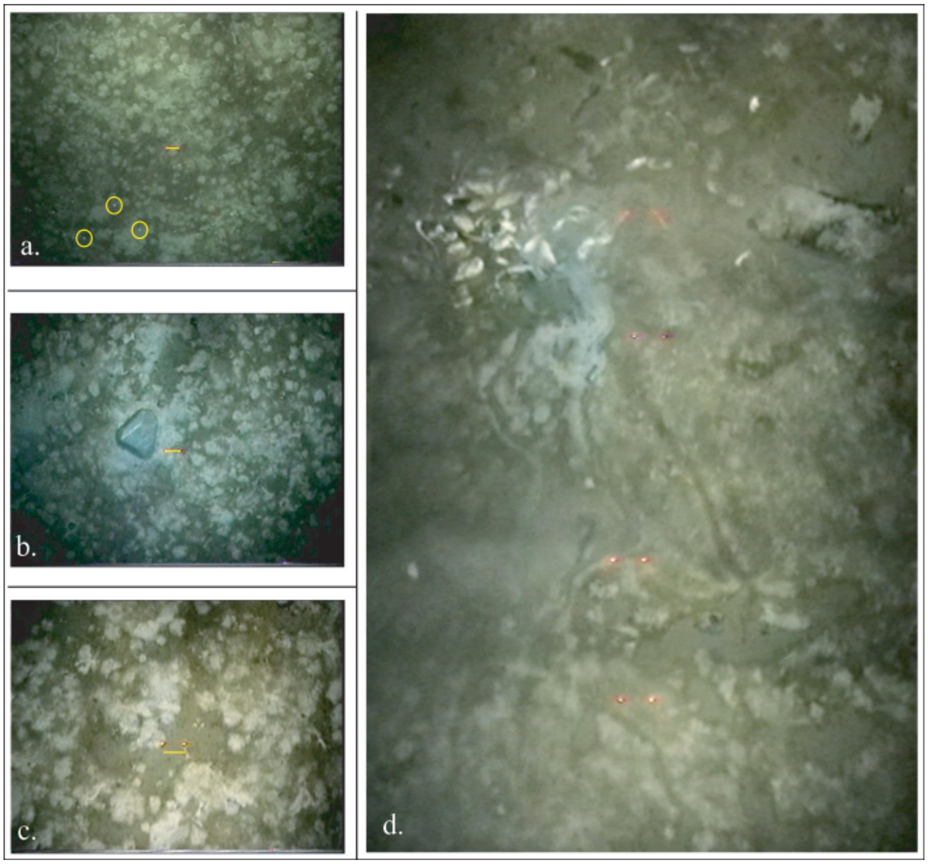

Fig. 2. (a) View of the pustular white mat covering approximately 75% of the seafloor. Scale bar is 20 cm across on the bottom, and yellow circles indicate ascending gas bubbles of unknown composition. Water depth is 840 m. (b) View of a small boulder dropstone resting on the white mat in 850 m of water. Note the clean and faceted surface of the boulder and the bottom scale (a reference scale for size placed upon the bottom) of 20 cm (yellow bar). (c) Close-up view of the seafloor at 840 m of water showing infilling of depressions across the white mat with recent, gray-colored silt and clay. Greenish fringe between the mat edge and mud infill is diatomaceous fluff. Scale bar is 20 cm across bottom. (d) View of a seep mound with a surrounding bivalve community. Note radiating mudflow channels of various ages along with suspended particulate near the vent opening (as shown by the scattering of laser pointers). This scene is a composite of four images from video with the bottom scale of 20 cm (yellow bar).

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