Eos, Vol. 82, No. 2, January 9, 2001

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

EOS

VOLUME 82 NUMBER 2

JANUARY 9, 2001

PAGES 13–24

Cruise Reveals History of Holocene Larsen Ice Shelf

PAGES 13, 16–17

In May 2000 the U.S. Antarctic Research Vessel *Nathaniel B. Palmer* braved extensive ice and the frigid temperatures of the Northwest Weddell Sea to penetrate the coastal leads along the Nordenskӧld Coast (Figures 1–3). The scientific objective of this international endeavor was to understand the natural variability of the Larsen Ice Shelf, the largest of several ice shelves along the northern extremities of the Antarctic Peninsula to have undergone catastrophic decay over recent years (Figure 2) [*Vaughan and Doake*, 1996; *Skvarca et al.*, 1999].

The study sought to determine the history of the Larsen Ice Shelf beyond the limits of our historical observations. Such knowledge is needed in order to assess the potentially unique nature of the current disintegration pattern and to determine the role of regional versus global warming scenarios on the future of the break-up trend.

There were more than a few surprises in what was found beneath the former Larsen Ice Shelf. An extremely deep inner shelf trough strikes out toward the northeast. Water depths exceeded 1000 m. Seafloor images revealed a spatially variable benthic ecosystem with some well-established epifaunal organisms that are adapted to strong bottom currents. Some of the communities appear to pre-date the recent ice shelf break-up event. Sediment cores revealed a stratigraphy marked by glacial-to-glacial marine sedimentation. The marine section indicates that open marine conditions existed in the area well before the present ice shelf came into existence. The timing of such events awaits further chronologic studies, which will be done in cooperation with the National Oceans Accelerator Laboratory at Woods Hole Oceanographic Institution in Massachusetts, Queen's University in Kingston, Ontario, and the Accelerator Facility of the University of Arizona.

Historical Changes in the Larsen Ice Shelf

Since 1996, after decades of relative stability, the Northern Antarctic Peninsula has lost approximately 10,000 km^2 of ice shelf; most of this is associated with changes in the Larsen Ice Shelf [*Skvarca et al.*, 1999]. The phenomenon of ice shelf disintegration is distinct from that of normal large-scale calving events that typically occur on decadal time scales. The ice shelves in the Northern Antarctic Peninsula clearly have receded in response to a changing climate that has shifted the surfaces of these shelves into the ablation zone.

This warming has led to surface meltwater production with consequent crevasse expansion, weakening of ice, and break-up of the shelf. Climate warming has pushed the mean annual temperatures significantly above -5°C, which is suggested as the climate limit for ice shelf viability [*Vaughan and Doake*, 1996]. Although the break-up that now seems to be progressing southward was first recognized on the western side of the Northern Antarctic Peninsula with the retreat of the Wordie Ice Shelf [*Doake and Vaughan*, 1991], the Larsen Ice Shelf is the largest to be affected so far [*Rott et al.*, 1996].

The Larsen Ice Shelf is the third largest ice shelf system in the Antarctic; only the Ross and Ronne-Filchner systems are larger. At one time it covered an area of approximately 81,850 km^2, an area that is roughly the size of the state of Maine. Vaughan and Doake [1996] divided the Larsen Ice Shelf into distinct regions from A, the northernmost segment, to C, the southernmost; each is progressively larger from north to south. All three ice shelves have shrunk but the most dramatic decrease in size by far has been the complete disintegration of the Larsen-A, which once extended from the Sobral Peninsula to the Seal Nunataks and Robertson Island (Figure 2). At one time early in the last century, the Larsen-A was contiguous with the ice shelf that covered the southern end of the Prince Gustav Channel. That ice shelf has decayed so that the channel is completely navigable during the austral summer.

Such large and catastrophic changes in the extent of the Larsen Ice Shelf have important implications for the stability of the Antarctic

Fig. 1. Bow of the Nathaniel B. Palmer in Borkowski Bay as it faces the Nordenskӧld Coast and Drygalski Glacier. Borkowski Bay is the area formerly covered by the Larsen Ice Shelf. Photograph by Dave Tewksbury. Original color image appears at the back of this volume.

Ice Sheet as a whole. They certainly change the local, and eventually, the regional, heat exchange between the ocean and atmosphere. Marine ecosystems are also directly affected, with large shifts in the surface extent of primary production and consequent changes in pelagic and benthic marine ecosystems in the regions of ice shelf break-up. The warming trend that has induced this break-up is also of concern, as it appears to be unprecedented over the last 500 years of ice-core paleoclimate data [*Thompson et al.*, 1994]. Yet longer-term marine records suggest a paleo-environmental history for the Northern Antarctic Peninsula marked by periods that were warmer or at least more productive and less dominated by sea ice than more recent conditions [*Smith et al.*, 1999; *Domack et al.*, 2000].

Seafloor Imagery Beneath the Larsen-A Ice Shelf

Data collection included multi-beam sonar for swath mapping of the seafloor (Figure 3), hull-mounted Chirp sonar for ultra-high resolution of subsurface reflectors, Acoustic Doppler Current Profiler for measuring water column velocities, single channel GI seismic array, and a complex suite of core systems including kasten cores, mega cores, and jumbo gravity cores. Biological studies and bottom video camera surveys of the seafloor were also conducted to serve as a baseline for understanding future changes in the marine benthic ecosystem that will occur in response to the shift to seasonally open marine waters instead of permanent shelf ice. The seafloor bathymetry presented in Figure 3 reveals unprecedented detail for the region previously covered by the former Larsen-A Ice Shelf. Although an earlier study [*Del Valle*, 1998] indicated that a deep trough existed beneath the ice shelf, the extent and magnitude of the feature were unknown until the *N. B. Palmer* completed its multibeam survey off the Nordenskӧld Coast between Cape Worsley and the Larsen-B Ice Shelf. Water depths exceed 1000 m in a very narrow zone south of the coast, with many hanging submarine valleys clearly delineating drainage of glaciers that at one time fed into the Larsen Ice Shelf. The largest of these is the Drygalski Glacier, which now terminates at tidewater (Figures 2 and 3). A larger basin extends toward the northeast and ranges from 900 m to 700 m deep. To the south, the volcanic Seal Nunataks extend as an apron or shallow bank toward the deep of the central basin, which is named the Greenpeace Trough in Figure 3. These volcanic nunataks serve as pinning points for the northern fringe of the Larsen-B Ice Shelf that extends to the south. Twenty-four sample stations were occupied with the Larsen-A area.

Core Stratigraphy

A consistent litho-stratigraphy was revealed by a set of cores collected from the central basin (The Greenpeace Trough). We highlight the details of this stratigraphy with a digital color photograph of one core, along with several paleo-environmental proxies, including magnetic susceptibility, water content, shear strength, total carbon percentage, particle size, and diatom and foraminifer content (Figure 4).

In kasten core 23, we recognize three lithofacies that include an upper diatom mud (Unit–1, 0–130 cm), a transitional granulated facies (Unit–2, 130–150 cm), and a basal unit of black mud to sandy mud (Unit 3, 150–230 cm; Figure 4).

A characteristic of Unit 3 is its uniformly dark gray color, low water content, low magnetic susceptibility, high shear strength, high total carbon content, and absence of marine fossils. We interpret this unit, as others found in the deepest portions of the Greenpeace Trough, as a comminution till deposited by glacial ice that was grounded within the trough. The term comminution indicates that the till represents progressive breakdown of locally derived bedrock, which in this case is Mesozoic black shale. This is evidenced by the shift in grain size from sandy mud to mud without any change in total carbon content. In this case, the sand profile in Unit 3 reflects the mobility or deformation profile of the till beneath an ice sheet. Adjacent cores also contain this unit, but it transitions into a clast-rich till (diamicton). The sand fraction within the black mud is dominated by black shale grains that are rich in detrital kerogen, which is spores and pollen of Mesozoic age. The coarsest grains exhibit striated and faceted surfaces.

Abruptly overlying Unit 3 is a very coarse-grained, horizontally stratified unit of olive black, gravelly mud, and muddy sand. It is clearly a transitional unit between Units 3 and 1. High magnetic susceptibility, low water contents, dilatent packing, low shear strength, and a mixture of lithologic constituents characterize this lithostratigrapic unit. Grain and clast types include black shales, but also crystalline metamorphic and granitic lithologies typical of rocks of the Nordenskӧld Coast. We interpret this unit as a sub-ice shelf facies deposited beneath the basal debris zone close to the grounding line. Passive undermelt of the basal debris led to the stratified and sorted nature of Unit 2. Higher levels of debris in the ice, compared to the source of the till of Unit 3, are reflected by the increase in crystalline lithologies, as opposed to black shale. Unit 2 is similar to other granulated facies found on the continental shelves of Antarctica [*Domack et al.*, 1999].

Unit 1 is a structureless-to-thinly bedded olive gray-to-light olive grey diatomaceous mud. Based upon the variability in magnetic susceptibility, water content, diatom abundance, and to a lesser extent, fine particle size, Unit 1 is divided into -A, -B, and -C sub-units; all were deposited in subaqueous environments. Unit 1-C is uniform, as shown by the invariable magnetic susceptibility of intermediate values. It is normally consolidated, as shown by the uniform decrease in water content with depth. It is the most clay-rich interval in Unit 1 and

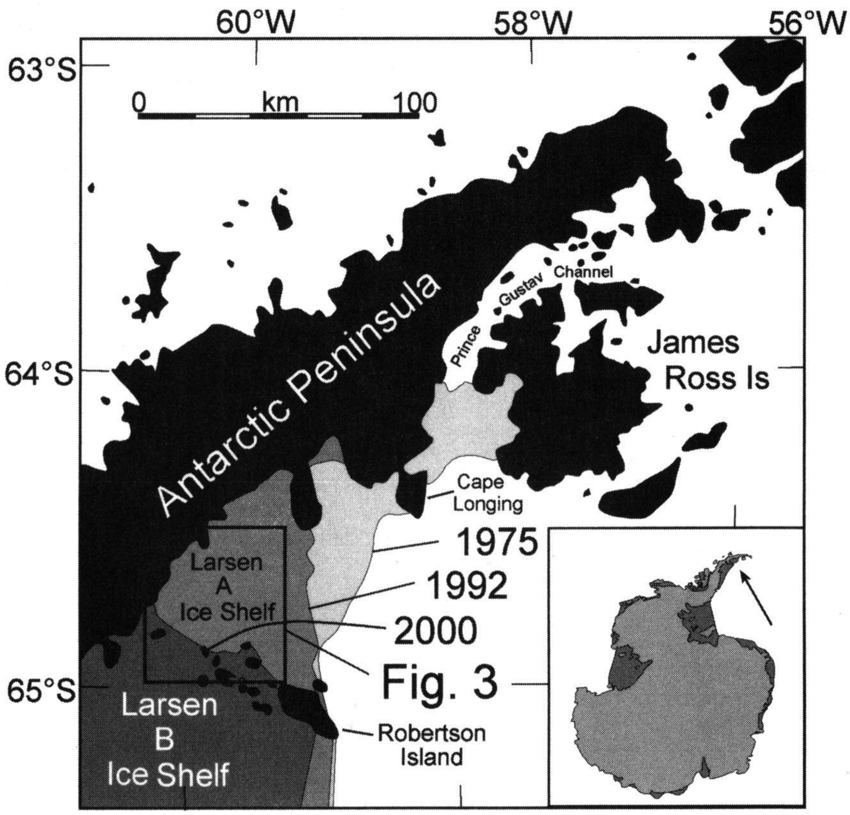

Fig. 2. Northern Antarctic Peninsula illustrating some historical positions of the terminus of the Larsen-A ice shelf. Inset shows location of Figure 3.

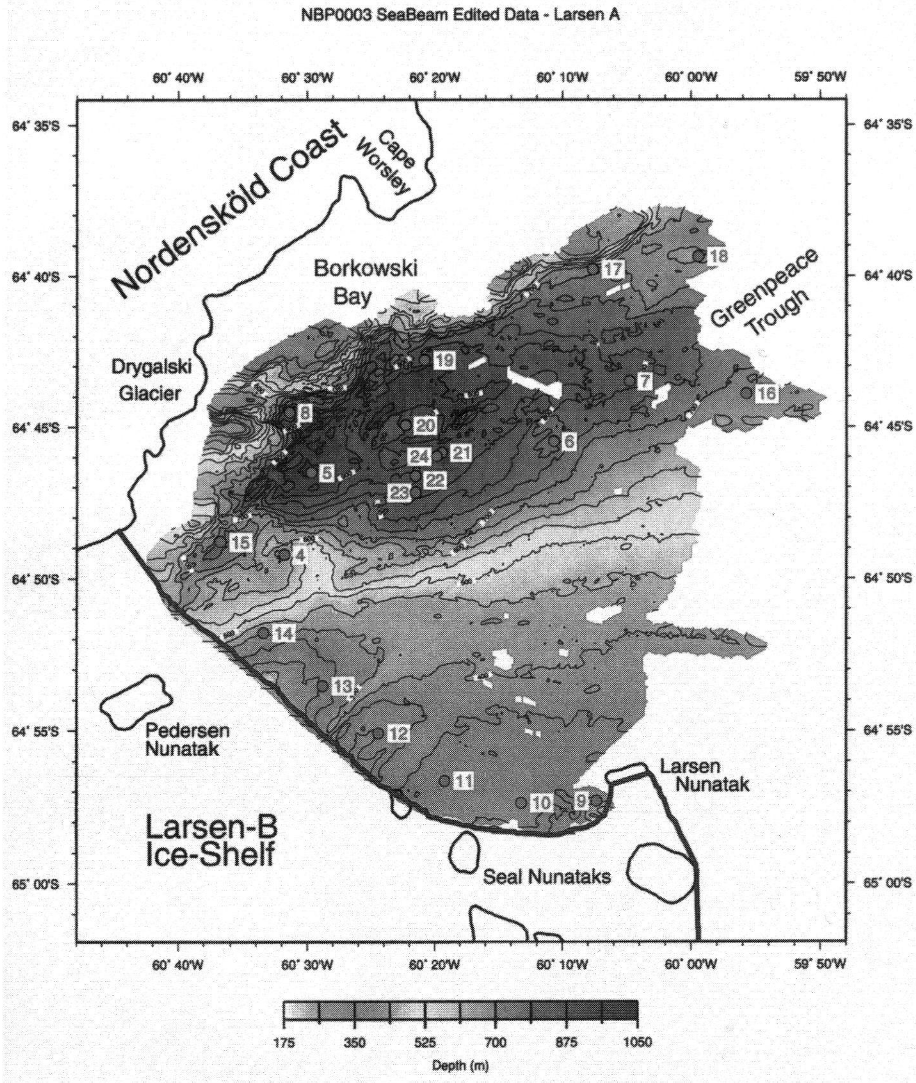

Fig. 3. Seabeam swath bathymetry of Borkowski Bay and the Greenpeace Trough. Data collected in May of 2000 during N. B. Palmer cruise 00-03. Bottom sampling stations are labeled (1-24). Note the erosional submarine landscape with hanging valleys southeast of the Drygalski Glacier, the deep northeasterly trending Greenpeace Trough, and the gentle slope ascending south toward the volcanic Seal Nunataks. The border between the deep trough and the erosional terrain likely marks a fault extrapolated from Cape Longing across and between Pederson Nunatak and the Nordensköld Coast. This structure separates crystalline rocks of the Trinity Peninsula to the north from Mesozoic sedimentary units to the south (Cretaceous shales; Map Reference BAS Series 500G, Sheet 2, Edition 1). Original color image appears at the back of this volume.

has almost no sand or gravel. The limited sand present is dominated by very fine grains and quartz-rich, crystalline lithologies. Diatoms in this unit are dominated by small (~10 microns) *Chaetoceros* spp. (~50%) with minor contributions of sea-ice related species. *Chaetoceros* are present throughout shelf waters of the Antarctic, with concentrations generally >90% in the productive waters west of the Antarctic Peninsula. The assemblage found in Unit 1-C most likely represents one transported from a low-productivity setting with high concentrations of sea ice. Foram abundances are greatest within Unit 1-C and reflect relatively low sediment accumulation rates. We tentatively interpret this unit as a sub-ice shelf facies deposited some distance from the grounding line. The occasional coarse detritus reflects englacial transport of material from the ice draining the Antarctic peninsula, most likely from the Drygalski Glacier.

Unit 1-B is clearly the most biogenic and distinctive in the occurrence of three diatom ooze layers. Olive brown in color, it consists of high concentrations of fragmented specimens of *Corethron criophilum*. This species occurs in laminated sediments from around the Antarctic margin and has been interpreted as blooming in productive waters with a shallow mixed layer, where these soda-straw shaped diatoms can float easily. The three diatom ooze layers correspond to the three peaks in water content and medium and fine silt. Due to the high percentage of fragmented valves and spines, two of the three *Corethron* layers do not stand out as peaks in absolute diatom abundance, although the layers are rich in opaline silica.

High fragmentation may be due to a combination of the light silicification of *Corethron* valves in general and grazing by zooplankton. The low carbon content of these layers as compared to higher carbon values in other *Corethron* layers from the Antarctic margin indicates a long transport path or a very efficient utilization of primary production, which may also contribute to the poor preservation of the *Corethron*. The three *Corethron* layers can be correlated throughout the deeper regions of the Greenpeace Trough, and suggest the occurrence of three large blooms of *Corethron*, and subsequent transport to the sea floor as large aggregates and mats that are concentrated in the deepest parts of the basin. The blooms are indicative of seasonally open water conditions.

This interpretation is supported by the increased relative concentration of *Chaetoceros* spp., a productivity indicator, in Unit 1-B, where it makes up as much as 80% of the diatom assemblage. Lower foram abundance in sub-unit 1-B is likely a reflection of higher accumulation rates, since the measure is a volume ratio. The detrital sand content is low in Unit 1-B and is distinctively very fine-grained and rich in heavy minerals near the base.

Unit 1-A, in the upper ~10 cm, is darker in color (dark greenish gray), has a high magnetic susceptibility, and is distinctively more compact than the underlying sub-unit. Diatom abundance is low and the assemblage is similar to that in sub-unit 1C. We interpret this sub-unit as representing a sub-ice shelf setting where detritus was deposited more slowly than in sub-unit 1-B.

Analysis of Paleoenvironmental Data

Our working hypotheses for the lithostratigraphic subdivisions in core KC-23 (Figure 4) suggest an initial recession of a large-scale glacier complex from the Greenpeace Trough that is most likely related to the transition from the Last Glacial Maximum in the Weddell Sea (Units 3 and 2). An ice shelf setting appears to have been in place for some time into the Holocene (Units 2 and sub-units 1-C). In the mid-to-late Holocene, conditions of limited seasonally open water appear to have existed after deposition of Unit 1-C, thus implying a recession of the Larsen-A ice shelf. Sub-unit 1-B, with its key horizons of diatom ooze, indicates proximity to open water blooms and enhanced primary production that is unlikely beneath the thick Larsen Ice Shelf. However, we also recognize the possibility that lateral advection of biogenic detritus may have taken place at this time under enhanced productivity in the northwestern Weddell Sea or strengthening of the western boundary current that comprises the western arc of the Weddell Gyre.

During the cruise, we did observe enhanced currents emanating from beneath the remaining front of the Larsen-B Ice Sheet, along the Seal Nunataks, and Pedersen Island. CTD

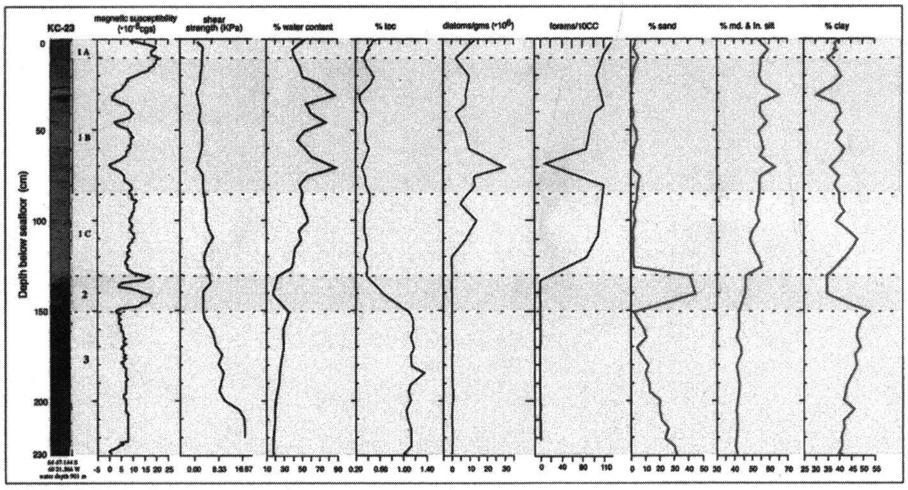

Fig. 4. Photographic log and detailed sedimentologic parameters for kasten core NBP-00-03-23. Parameters include magnetic susceptibility (CGS units), shear strength (in Pascals), water content (as percentages of wet weight), total carbon percentage, diatom valves per gram of dry sediment (measured only every 10 cm), foraminifera volume concentration, sand % (wet sieved at 63 microns), medium to fine silt %, and clay %. Note division of units into 1-3 and subdivisions 1A, 1B, and 1C. Diatom ooze bands are indicated by arrows. Original color image appears at the back of this volume.

profiles indicate a near isothermal water column with temperatures of -1.8°C. These cold currents appear to be advecting organic detritus to a rich epifaunal community of encrusting bryozoans, brachiopods, and corals observed at station 4 (Figure 3).

In our preliminary hypothesis, we suggest that the upward transition into sub-unit 1-A represents a readvance of the Larsen Ice Shelf in Late Holocene time. This scenario of ice shelf retreat and readvance most reasonably correlates with the relative timing of climatic episodes observed on James Ross Island and along the western side of the AP [*Björck et al.*, 1996; *Hjört et al.*, 1997; *Smith et al.*, 1999; *Domack et al.*, 2000]. We speculate that the timing of the ice shelf retreat corresponds to the peak of a mid-Holocene climatic optimum that is well constrained chronologically from 5000 to 3500 years before present. Furthermore, we suggest that the readvance of the Larsen Ice Shelf is a neoglacial phenomena related to enhanced cooling and more persistent sea ice in the last 2500 years.

Acknowledgments

We thank Captain Joseph Borkowski III and the crew of the *N. B. Palmer* and the staff of Raytheon Polar Services for their extraordinary effort during our cruise. We also thank Matt Curren and David Tewskbury for their enthusiastic support. The U.S. National Science Foundation Office of Polar Programs, the Environmental and Engineering Council of Canada, and the Italian Antarctic Program supported this project.

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Iridium Satellites Help Map Electrical Currents in Space

PAGE 13

The satellite constellation of Iridium LLC, which filed for Chapter 11 bankruptcy in 1999 after it failed to win enough business for its commercial satellite communications services, is still orbiting at an altitude of about 780 kilometers. Now, however, the satellites are helping to write a new chapter in understanding space weather.

Magnetometers onboard each of the system's 66 polar-orbiting satellites are working in conjunction with the high-frequency, multinational Super Dual Auroral Radar Network, or SuperDARN, to provide the first continuous measurements of electrical currents between Earth's upper atmosphere and space. These tools also are generating the first global maps of electrical power flowing into the polar upper atmosphere.

The information could help to provide advance warnings of electromagnetic storms that can present a danger to astronauts and that can also disrupt technology infrastructure, including power grids and communication systems.

With Earth's magnetosphere covering a vast region, and with solar winds approaching from the Sun at about 1.6 million kilometers per hour, this region has been difficult to monitor. In addition, the magnetosphere is so dynamic that it can sometimes change in volume by a factor of 10 in about an hour, due to changes in solar activity.

At a December 15 news briefing at the AGU 2000 Fall Meeting in San Francisco, Brian Anderson of the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland, said the Iridium constellation of satellites "provides a tremendous opportunity to monitor weather in space," and that the new measurements and maps are a major achievement in monitoring Earth's space environment.

"The Iridium orbits are ideal for monitoring this big [electromagnetic] system because the current is funneled to the polar regions where the satellites detect it," he said.

Eos, Vol. 82, No. 1, January 2, 2001

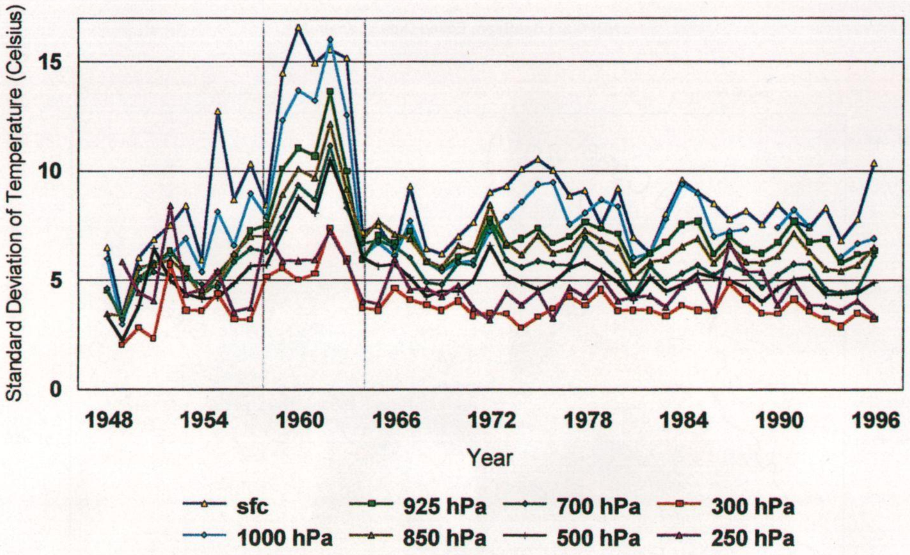

Fig. 2. Standard deviation of winter temperatures north of 80°N latitude at altitudes ranging from the surface to the lower stratosphere. The questionable quality of the 1958–1963 fixed-position radiosonde data is evident in the large temperature variability during this period.

Page 5

Eos, Vol. 82, No. 2, January 9, 2001

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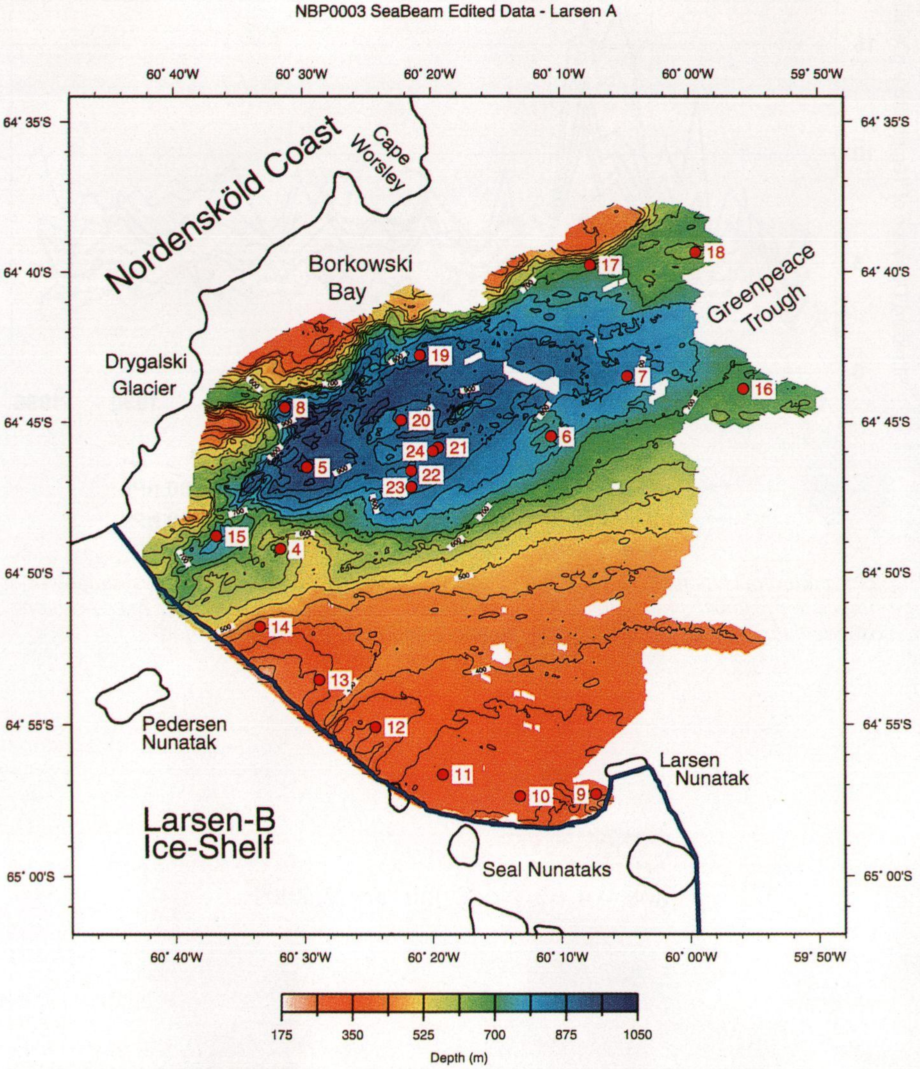
Page 13



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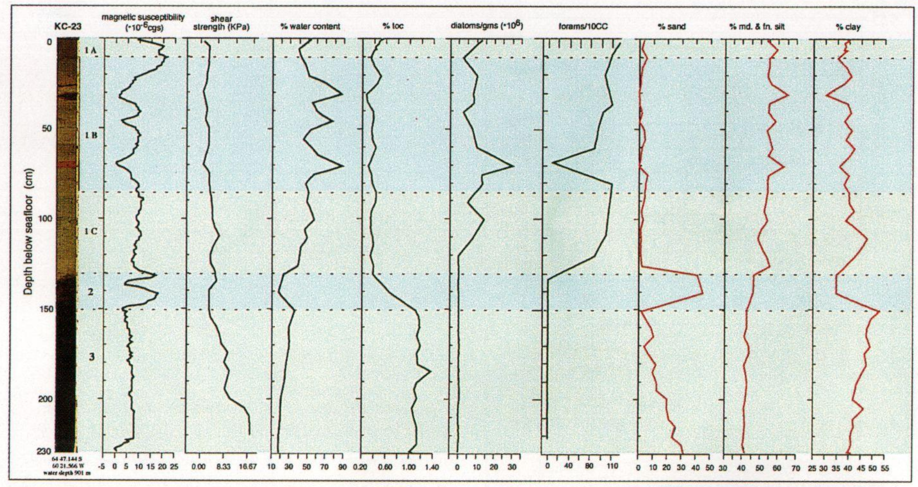

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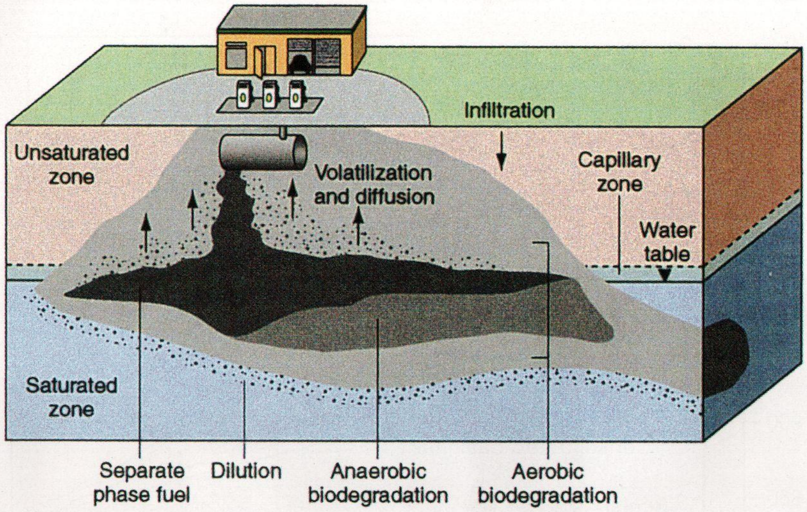

Fig. 1. Conceptual illustration of the important natural attenuation processes that affect the fate of petroleum hydrocarbons in aquifers.