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Green Icebergs Formed by Freezing of Organic-Rich Seawater to the Base of Antarctic Ice Shelves

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Although most icebergs are blue, green icebergs are seen occasionally in the Antarctic ocean. Chemical and isotopic analysis of samples from green icebergs indicate that the ice consists of desalinated frozen seawater, as does the basal ice from the Amery Ice Shelf. Spectral reflectance of a green iceberg measured near 67°S, 62°E, confirms that the color is inherent to the ice, not an artifact of the illumination. Pure ice appears blue owing to its absorption of red photons. Addition of a constituent that absorbs blue photons can shift the peak reflectance from blue to green. Such a constituent was identified by spectrophotometric analysis of core samples from this iceberg and from the Amery basal ice, and of seawater samples from Prydz Bay off the Amery Ice Shelf. Analysis of the samples by fluorescence spectroscopy indicates that the blue absorption, and hence the inherent green color, is due to the presence of marine-derived organic matter in the green iceberg, basal ice, and seawater. Thick accumulations of green ice, in icebergs and at the base of ice shelves, indicate that high concentrations of organic matter exist in seawater for centuries at the depth of basal freezing.

1. Introduction

Green icebergs are seen occasionally in the Weddell Sea, rarely in the Ross Sea, but more commonly off the Amery Ice Shelf in East Antarctica. They have been described by *Wordie and Kemp* [1933], *Binder* [1972], *Moulton and Cameron* [1976], *Amos* [1978], and *Dieckmann et al.* [1987]. Two theories have been advanced as to their origin. After analyzing color photographs of green icebergs, *Lee* [1990] concluded that inherently blue icebergs, formed from the compression of pure snow into glacial ice, can appear green under direct illumination by a near-horizon (reddened) sun. Green icebergs, however, stand out in a swarm of white and blue icebergs in all sorts of light conditions, and green icebergs have been found to contain fragments of plankton cells [*Amos*, 1978; *Dieckmann et al.*, 1987], suggesting to Dieckmann et al. that the green icebergs may have originated as seawater freezing to the base of an ice shelf ("basal ice"). Accumulations of green ice have also been reported on grounded continental ice cliffs, for example near Casey Station, Antarctica. *Goodwin* [1993] summarized these reports and concluded from oxygen isotope and solute analysis that the green ice in the base of the grounded coastal margin of Law Dome (East Antarctica) was, in fact, seawater accreted to the ice base during a late Holocene advance of the ice margin over shallow marine embayments. To evaluate these divergent viewpoints concerning the source of the color and the source of the ice, we analyzed samples of Antarctic seawater, basal ice, and green ice from ice cliffs and green icebergs.

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2. Physical Description

We examined a green iceberg, embedded in shorefast sea ice and apparently grounded on the shallow seafloor 60 km north of Mawson Station, near 67°S, 62°E, on November 19, 1988 (Figure 1). Its visible portion was approximately 160 m long by 120 m wide and 40 m tall. Like other reported green icebergs [*Wordie and Kemp*, 1933; *Binder*, 1972], this one consisted of two distinct parts, bubbly blue-white ice and clear, bubble-free green ice each about 80 m long, separated by a planar layer about 1 m thick containing clastic sediment. The surface of the green ice was textured with scallops about 5 cm wide, indicating contact with and erosion by seawater. A diagonal lattice of cracks, with 1-m spacing, penetrated the green ice normal to the surface and apparently provided the only opportunity for scattering of light. These regions were light green in color. Regions devoid of cracks were a very dark green, almost black. Chunks, tens of centimeters across, appeared colorless, as do chunks of pure blue ice, suggesting that light paths of the order of a meter or more are necessary for the green color to be visible by eye. The reflectance spectrum of the green ice portion was measured (discussed below).

A half-meter-long ice core was taken from the green portion of the iceberg about 30 m from the interface. The core cracked into numerous disks (1–3 cm thick) during drilling, suggesting residual stress. Samples of the core were taken for chemical and microscopic analysis. Similar analyses were performed on samples of ice collected from the bottom section of an ice core (basal ice) taken from the Amery Ice Shelf in 1968 [*Morgan*, 1972], from the green ice portion of a green iceberg found in 1986, and from the green ice of the Marine Ice Cliffs near Casey Station (arrow in Figure 1 inset).

Air bubbles were not visible by eye in the core section from the 1988 green iceberg. Examination of thin sections of the green iceberg and the Amery basal ice under a light microscope showed no brine pockets or air bubbles, but electron microscopy did confirm the presence of silicious frustules (cell walls) of marine phytoplankton (Table 1). The absence of air bubbles suggests that the ice originated not by the compression of snow, but rather by freezing of liquid

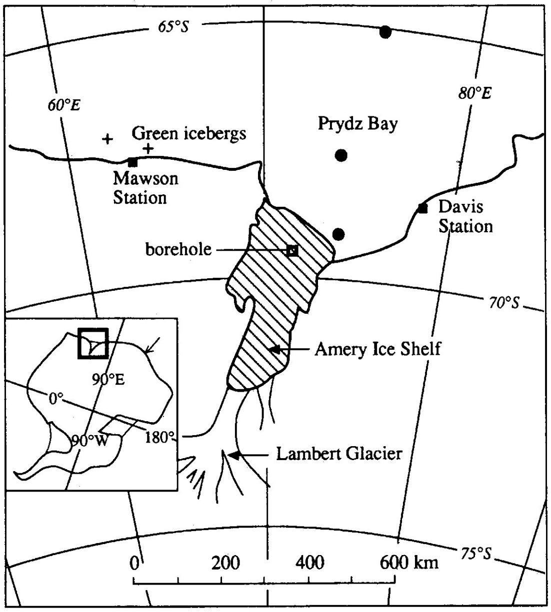

Fig. 1. Location of samples collected for the isotopic, chemical, and optical analyses: green icebergs sampled in 1986 and 1988 (pluses), seawater collected at 15 m and 400 m depth in Prydz Bay, February 1991 (solid circles), Marine Ice Cliffs near Casey Station 66°S, 111°E (arrow on inset map).

water. The lack of air bubbles could result from a freezing rate slow enough to allow the dissolved air to diffuse away into the liquid. However, the freezing rate for the Amery basal ice, the likely source of this green iceberg, was estimated at 30 cm yr^{-1} by *Morgan* [1972], i.e., about the same as that of multiyear Arctic sea ice growing at the ocean surface [*Maykut and Untersteiner*, 1971], which does contain numerous bubbles. The lack of bubbles in the basal and green ice may therefore be not indicative of slow freezing but rather a consequence of the greater solubility of air in water under pressure at 400 m depth (the base of the Amery Ice Shelf) as compared with the sea surface.

3. Oxygen Isotopes and Chemical Analyses

The near-zero values of $\delta^{18}O$ [*Craig*, 1961] of all the green ice samples indicate that they were formed by freezing of seawater, which has a $\delta^{18}O$ of approximately zero, and not by compression of Antarctic snow, which has values between −10 and −60‰. These near-zero $\delta^{18}O$ values are similar to those measured from the bottom section of an ice core taken from the Amery Ice Shelf in 1968 [*Morgan*, 1972]. A sharp transition in $\delta^{18}O$ from −40 to +2‰ at a depth of 270 m in that core was the first indication that ice shelves, and thus icebergs, could consist of ice from two sources: snow and seawater. The appearance of the ice also changed abruptly from bubbly to clear. Higher-resolution isotopic analyses of a 1-m section of this lower portion of the Amery core suggest a cycle in $\delta^{18}O$, albeit with very small amplitude of 0.1‰, and a wavelength of approximately 20 cm. This wavelength is similar to the estimated rate of annual basal accretion of 30 cm [*Morgan*, 1972], suggesting that basal ice may record seasonal variations in the composition of seawater as it freezes. Whether the apparent cycle of $\delta^{18}O$ found in this 1-m segment is a persistent cycle awaits analysis of longer sections of the Amery core. Variability in $\delta^{18}O$ along the 50-cm section of green iceberg core was about 0.2‰. The orientation of the core was not perpendicular to the direction of accumulation; thus no cycle was expected or observed. *Kipfstuhl et al.* [1992] found a near-zero value of $\delta^{18}O$ for the green iceberg they sampled, confirming a seawater origin for that iceberg as well.

The 1988 green iceberg, the Amery basal ice, and the Marine Ice Cliffs all contained sea salts at concentrations about one-thousandth that of seawater (Table 1), suggesting a seawater origin. In contrast, the 1986 green iceberg was a factor of 5 greater in salt concentration than the other green ice samples. The molar ratios of Ca^{++}, K^+, and Cl^- in all the ice samples (except glacier ice, which has almost zero ionic content), relative to Na^+ (lower part of Table 1), were similar to standard seawater ratios. However, the $SO_4^=/Na^+$ ratio was a factor of 2.5 to 6.0 lower in the ice samples than in seawater, perhaps suggesting that when seawater freezes slowly, sulfate ions are incorporated less easily than sodium into ice. Relative $SO_4^=$ exclusion has been observed in sea ice forming at the ocean surface [*Reeburgh and Springer-Young*, 1983]. The Mg^{++}/Na^+ ratio was a factor of 2.2 to 3.6 lower in the basal ice and ice cliff samples than in seawater, but the ratio in the green iceberg samples was not significantly different from seawater.

4. Optical Characteristics

Lee's [1990] hypothesis, that a reddened sun shining on blue icebergs can make them appear green, suggests that blue icebergs could appear green whenever the sky is clear at sunset or sunrise. We therefore doubt that Lee's hypothesis is the explanation for the reported observations of green icebergs, because only occasional icebergs are singled out as "green." The green color of the iceberg we observed was indeed more striking under the reddened setting sun. However, it was surrounded by many ordinary icebergs which continued to appear blue-white as the sun set. Furthermore, no sampled green iceberg has yet been found to consist of ordinary, inherently blue glacial ice.

White light transmitted through pure, bubble-free ice becomes blue because the wavelength of minimum absorption (λmin) is 470 nm [*Grenfell and Perovich*, 1981]. Snow appears white in reflection [*Liljequist*, 1956; *Warren et al.*, 1986] because successive scattering, due to refraction through small ice grains [*Bohren and Barkstrom*; 1974], allows the photons to reemerge from the snow surface after only a very short pathlength through ice, without significant absorption at any visible wavelength [*Wiscombe and Warren*, 1980; *Bohren*, 1983]. Thus the perceived color of glacially derived icebergs varies between the blue of pure ice and the white of snow, depending upon the porosity [*Bohren*, 1983].

4.1. *Spectral Reflectance of a Green Iceberg*

A portable spectrometer [*Warren et al.*, 1986] was used to measure the spectral reflectance (the ratio of reflected to incident radiation flux) of the 1988 green iceberg. The instrument consisted of a cosine collector in front of a silicon photodiode, with an intervening filter wheel containing interference filters. Bandwidth (full width at half maximum transmittance) was 10 nm for all filters.

Measurements were made in a green canyon near the top of the iceberg. The incident light was diffuse, from the near-zenith sky; the canyon wall blocked the reddened

TABLE 1. Chemical Analyses of Antarctic Ice and Standard Ocean Water

	Source*						
				Green Icebergs			
	Glacier Ice	Basal Ice	Ice Cliffs	1986	1988	1988	Seawater
			Chemical Analyses				
Plankton†	no	yes	yes	nd	yes	yes	yes
$\delta^{18}O$‡	[−20, −50]	+2	−0.2	nd	+2	+2	0
Na^+§	[0.0, 0.3]	5.84	4.33	49.5	9.57	9.46	10,543
Ca^{++}	[0.0, 0.02]	0.23	0.25	1.72	0.33	0.29	400
Mg^{++}	[0.0, 0.03]	0.32	0.13	4.5	0.96	0.97	1,272
K^+	[0.0, 0.02]	0.29	0.27	3.14	0.30	0.26	380
NH_4^+		1.34	nd	0.04	0.07	0.13	
Cl^-		11.0	6.71	73.1	18.2	17.8	18,980
$SO_4^=$		0.255	0.213	4.91	0.65	0.69	2465
PO_4^{3-}		<2.0	nd	nd	<0.2	<0.2	
NO_3^-		0.014	0.014	0.01	<0.01	0.009	
			Molar Ratios				
Ca^{++}/Na^+		0.02	0.03	0.02	0.02	0.02	0.02
Mg^{++}/Na^+		0.05	0.03	0.09	0.10	0.10	0.11
K^+/Na^+		0.03	0.04	0.04	0.02	0.02	0.02
Cl^-/Na^+		1.2	1.0	1.0	1.2	1.2	1.2
$SO_4^=/Na^+$		0.03	0.04	0.07	0.05	0.05	0.17

*Glacial ice data from Law Dome (ions [*Johnson and Chamberlain*, 1981]) and upper section of the Amery Ice Shelf borehole (isotopes [*Morgan*, 1972]). Basal ice from lower portion of Amery Ice Shelf borehole [*Morgan*, 1972]. Green ice samples from green Marine Ice Cliffs near Casey Station and two green icebergs (Figure 1) sampled in 1986 and 1988 (one and two samples, respectively). Data for standard seawater are from *Fairbridge* [1966].

†Phytoplankton were identified by electron microscopy; nd indicates no data taken.

‡Oxygen isotope analysis (per mil) was performed at the Glaciology Section, Australian Antarctic Division. Brackets indicate the range of values found.

§Ion analysis (mg-atom/L) of the green ice and Amery basal ice was performed by D. Davies at the Australian Government Analytical Laboratories (AGAL), Kingston, Tasmania.

southwestern sky. A spectral scan was taken looking at the ice, followed by a scan looking at the sky. Because of other obligations of the expedition, the only opportunity to take measurements was just after sunset, when the incident flux was decreasing with time. The solar zenith angle increased during the experiment from 91.15° to 92.00°, and the corresponding zenith sky flux dropped by 44% [*Meinel and Meinel*, 1983, Figure 4-4]. Reflected fluxes at each wavelength have been adjusted for this variation, on the basis of exact time that each filter was in use. Because of time constraints, only the green portion of the iceberg was measured, not the blue portion. The maximal reflectance was at 500–520 nm (green in color; Figure 2), as compared to 470 nm expected for pure ice, indicating that the ice contained a blue-absorbing component. We had time to measure the reflectance spectrum at only one location on the green portion of the iceberg. Optical measurements on the core samples discussed below show differences of up to a factor of 3 in absorption coefficient, implying that the reflectance spectrum must also vary with location.

4.2. *Absorption and Fluorescence Emission Spectra of Ice and Seawater Samples*

The color of natural ocean waters is shifted from the blue of pure water to green by the presence of organic material either in particulate form (phytoplankton and nonphotosynthetic particles) or in the degraded, dissolved form (gelbstoff) [*Jerlov*, 1968; *Morel and Prieur*, 1977; *Bricaud et al.*, 1981]. Most organic components found in seawater absorb strongly in the blue region of the spectrum (Figure 3), shifting λmin from 470 nm toward the longer wavelengths with increasing organic concentration.

Large phytoplankton blooms have been reported directly at ice edges in the Antarctic [*El-Sayed*, 1971], but concentrations in open water tend to be more diluted. However, in February 1991 a bloom of phytoplankton in Prydz Bay in front of the Amery Ice Shelf extended over 400 km from the ice shelf with peak chlorophyll (chl) concentrations up to 10 times those recorded in the Weddell Sea [*Smith and Nelson*, 1990] and Ross Sea [*Smith and Nelson*, 1985] and in the Bransfield Strait north of the Antarctic Peninsula [*Holm-Hansen and Mitchell*, 1991]. Fifty kilometers north of the ice shelf, the chlorophyll concentrations were greater than 70 mg chl/m^3 in the surface waters and greater than 1200 mg chl/m^2 integrated to 150 m depth (S. Wright, personal communication, 1991), indicating that seawater off the Amery Ice Shelf is rich in organic matter. We identified low concentrations of phytoplankton frustules and detrital particles by electron microscopy in the green iceberg samples, but they were rare, suggesting that some other component accounted for the strong blue absorption. High concentrations of dissolved organic matter, arising from degradation of the organic particles [*Kalle*, 1966], was therefore thought the most likely cause of the blue absorption.

Optical analyses were performed on two green ice samples of the 1988 green iceberg taken 15 and 50 cm from the core surface, two Amery basal ice samples less than 1 m apart in the 1968 borehole core, a sample collected from the Marine Ice Cliffs near Casey Station, and six seawater samples collected during the February 1991 phytoplankton bloom in

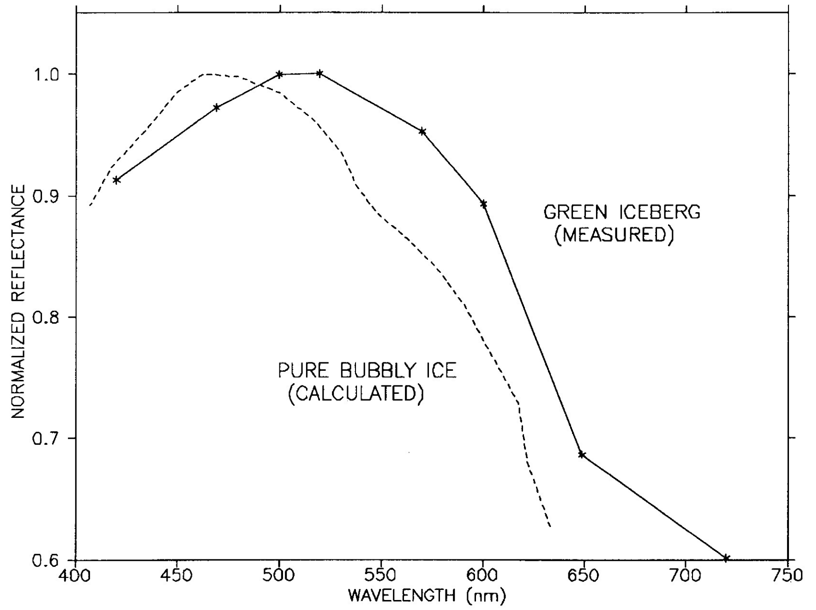

Fig. 2. Reflectance spectra (the ratio of reflected to incident radiation flux) of the green iceberg at 67°S, 62°E, on November 19, 1988 (solid), and for pure thick bubbly ice (dashed), each scaled to their respective maximum values (0.4 and 0.65). The reflectance spectrum for pure thick bubbly ice was calculated by the method of *Mullen and Warren* [1988], and is similar to Figure 11 of their paper. A lower concentration of larger sized bubbles (0.6 cm^{-3} and 2.3 mm radius, respectively) was used here to mimic the scattering coefficient due to cracks in the green iceberg. (The exact nature of the nonabsorbing scatterers used to model the visible reflectance spectrum is not important. For example, *Bohren* [1983, Figure 5] showed that the reflectance spectrum of bubbly ice could be mimicked by a model of large-grained snow.)

Prydz Bay at three stations along a transect from the ice shelf edge to more than 400 km from the ice shelf (Figure 1). Seawater samples were filtered (0.45 μm), and the filtrate was immediately frozen on the ship for transport to the University of Washington. To minimize bacterial growth, all samples were melted at 3°C rather than room temperature, taking 6–8 hours for complete thawing. Initial meltwater from the surfaces of the core samples was discarded as potentially contaminated by the coring process. Optical density was measured with a dual beam spectrophotometer (SLM-Aminco, Inc.) in 10-cm cuvettes using triple-glass-distilled water as a reference. Optical density of the liquid samples was converted to linear absorption coefficients, correcting for expansion due to freezing, then added to the

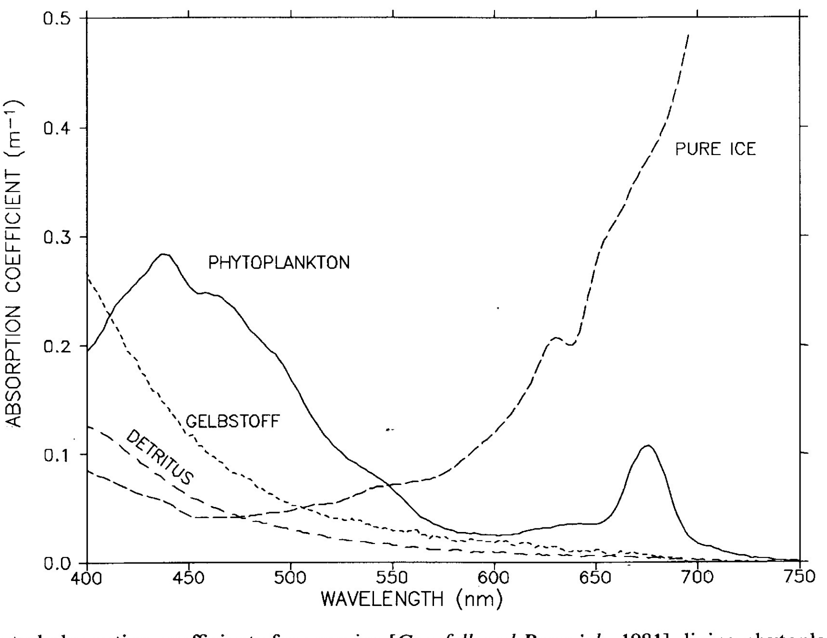

Fig. 3. Spectral absorption coefficients for pure ice [*Grenfell and Perovich*, 1981], living phytoplankton, nonphytoplankton organic particulates (detritus, including zooplankton, bacteria and nonliving cellular material), and dissolved organic matter (gelbstoff) (data from *Roesler et al.* [1989]). All of the organic components absorb strongly in the blue region of the spectrum. Addition of any one of the components in sufficient concentrations will change the color of pure ice or pure seawater from blue to green. These component absorption spectra are typical values for productive coastal waters, where chlorophyll concentrations range from 5 to 15 mg m^{-3} and riverine influx of terrestrial organics is high.

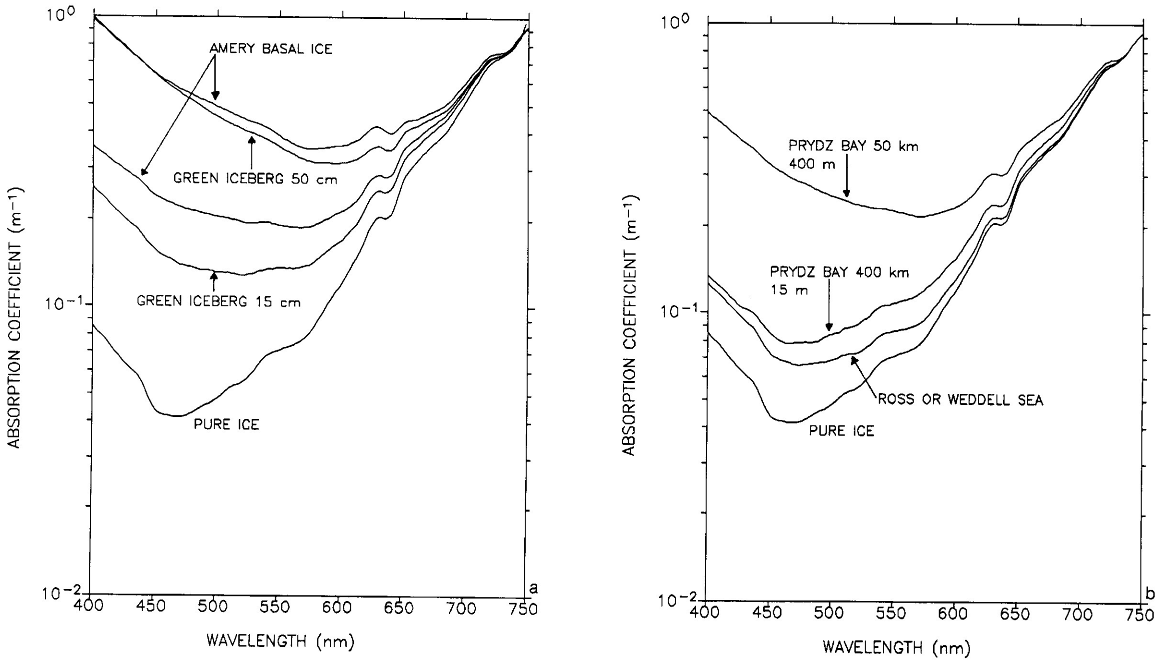

Fig. 4. (*a*) Absorption spectra for pure ice [*Grenfell and Perovich*, 1981], the Amery basal ice, and the 1988 green iceberg samples. The wavelength of minimal absorption (λmin) is shifted from 470 nm in pure ice to 570 nm for the basal ice samples and to 520 and 580 nm for the top and bottom of the green iceberg core, respectively. The variations in λmin are a direct consequence of the variations in the magnitude of absorption by gelbstoff. (*b*) Absorption spectra for the filtrate of two of the seawater samples. Seawater absorption coefficients were corrected for expansion due to freezing (multiplied by the factor 0.917) and added to pure ice absorption to show a hypothesized absorption spectrum for a basal ice that would form from these waters. These samples represent the highest and lowest values of gelbstoff absorption for the six samples measured and are located 50 km from the ice shelf edge closest to the phytoplankton bloom but at the depth of basal freezing (400 m) and about 400 km from the ice edge in the surface water (15 m) past the range of the bloom, respectively. Basal ice absorption for the Ross and Filchner-Ronne ice shelves, modeled on the basis of chlorophyll concentrations in the Ross or Weddell Seas (see text), would appear more blue and less green than that of the Amery.

absorption spectrum for pure ice [*Grenfell and Perovich*, 1981] to obtain the total absorption for each sample in situ. The uncertainty in the pure ice absorption spectrum, 8–20% over the visible spectrum, as measured by *Grenfell and Perovich* [1981] does not affect the relative variations between the samples measured here, as the mean pure ice spectrum was added to all samples.

Spectrophotometric measurements of the Amery basal ice, the green iceberg and seawater samples collected during the bloom in Prydz Bay (Figure 1) showed the enhanced blue absorption characteristic of particulate or dissolved organic matter (see Figure 3), which shifted the absorption minimum from its pure ice value (470 nm) to longer wavelengths (Figure 4). The absorption spectrum measured on the Marine Ice Cliffs sample was not significantly different from zero and thus would be indistinguishable from the pure ice absorption spectrum in Figure 4*a*. (It may be that the outer layers of the Marine Ice Cliffs, from which this sample was taken, have been bleached by long exposure to sunlight, so that the apparent color of the cliffs would be due to green ice farther back from the surface.) Comparison of Figure 4*a* with Figure 2 shows that the blue absorption of the green iceberg at 15 cm depth is sufficient to explain the shift of its reflectance spectrum relative to pure ice. The uncertainty in the absorption coefficients measured in this study was less than 5% for all samples. Thus the large variations in the absorption coefficients among the samples shown in Figure 4 must be attributed to real differences rather than experimental error. Based upon cell-specific absorption coefficients (C. S. Roesler, unpublished data, 1991), concentrations of 10^9 cells L^{-1} would be necessary to account for the observed blue absorption in the green iceberg and basal ice samples. These concentrations are equivalent to spring bloom conditions in coastal waters, and such concentrations were not confirmed by the EM analysis of the green ice samples, so the blue absorption must be due to something other than intact cells.

The absorption measurements shown in Figure 4 imply little about the nature of the absorbers. In an attempt to identify the material responsible for the absorption of blue light, the samples were also analyzed by fluorescence spectroscopy. Excitation of the samples with UV light (375 nm) resulted in the broad fluorescence peak centered at 460 nm, confirming the presence of dissolved organic matter [*Laane and Koole*, 1982] in all samples but the one from the Marine Ice Cliffs which could not be distinguished from pure water (Figure 5). The shape and magnitudes of the emission spectra of the ice and seawater samples are similar to those of highly degraded organic complexes [*Coble et al.*, 1990]. As organic particles in the surface waters sink to deeper waters or to bottom sediments, degradation of the organics from particulate to dissolved forms occurs. In sediments this process serves to concentrate the dissolved organics into the water in pore spaces in the sediment which can be recirculated into the overlying water column [*Chen and Bada*, 1989, Figure 2] by diffusion or advection by bottom currents. The isolation from significant continental organic input confirms the marine origin of these organic complexes in the samples

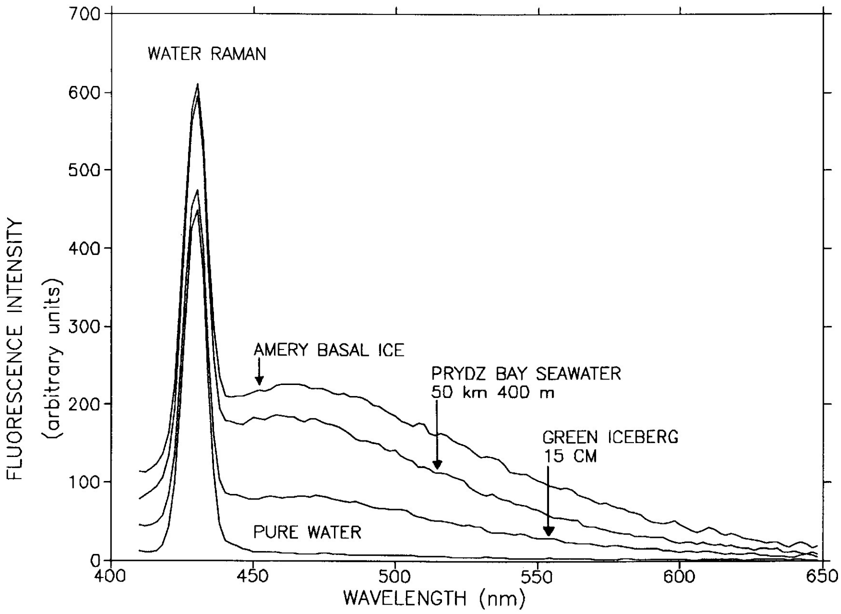

Fig. 5. An example of the fluorescence emission spectra (375 nm excitation) for one Amery basal ice sample, the green iceberg sample 15 cm from the core surface, and the 400-m Prydz Bay sample located 50 km from the ice shelf edge are shown along with pure water (MilliQ) for reference. Fluorescence emission spectra of the samples were measured in a quantum-corrected spectrofluorometer (Spex, Inc.) equipped with a single-grating excitation line and double-grating emission monochromators. Raman (inelastic) scattering by water peaks at 430 nm with this excitation. Fluorescence by dissolved organic matter (gelbstoff) is the broad peak centered at about 460 nm. A series of emission spectra were collected for each sample, with the excitation wavelengths ranging from 275 to 425 nm at 25-nm increments and the emission wavelengths ranging from 285 to 700 nm at 2-nm resolution. Red fluorescence (683 nm emission) due to phytoplankton-derived pigments was not found in any of the samples when excited with blue light (400–425 nm).

we analyzed, indicating that phytoplankton are the probable initial organic source. The organic content of the ice, if estimated by the magnitude of blue absorption, apparently varies by a factor of 2–3 over distances of tens of centimeters in both the green iceberg and the Amery basal ice (Figure 4*a*), probably owing to seasonal variations in concentrations of dissolved organic matter in seawater at the depth of freezing. Variations in organic content would also explain the lack of blue absorption and fluorescence from the single Marine Ice Cliff sample.

Sea ice also contains phytoplankton, gelbstoff, and detritus, often at such high concentrations on the underside that overturned sea ice floes appear green or even yellow [*Cota and Smith*, 1991]. These components are often hidden in undisturbed sea ice floes owing to scattering by the high bubble content of the upper sea ice layers which contain less organic matter. Higher bubble concentrations would cause the curves in Figure 2 to be raised and flattened, making the ice appear grey or white rather than blue or green [*Grenfell and Perovich*, 1984; *Allison et al.*, 1993]. Furthermore, in the Antarctic, most decaying sea ice remains snow-covered until it melts. Therefore although sea ice may sometimes appear green or yellow from above, it more often looks white or grey.

5. Origin and Implications of Green Icebergs

Our analyses support a seawater origin for the green ice of the green iceberg and show that it is similar to basally frozen ice on the Amery Ice Shelf. The Amery Ice Shelf has accreted 160 m of basal ice (as deduced from oxygen isotope measurements on the borehole core [*Morgan*, 1972]), of which probably 70–100 m remains at the calving front 120 km downstream [*Budd et al.*, 1982]. We suggest that the process of basal freezing is the origin of the green icebergs, although our results do not reveal the actual mechanism of the freezing.

Basal freeze-on also has been found in other large Antarctic ice shelves. The Filchner-Ronne Ice Shelf has accumulated up to 300 m [*Lange and MacAyeal*, 1986, 1988; *MacAyeal et al.*, 1987], but much of this is melted by a warm subshelf current before reaching the calving front [*Jenkins and Doake*, 1991]. The Ross Ice Shelf [*Zotikov et al.*, 1980] advances much faster and probably develops only 30 m of basal ice (D. MacAyeal, personal communication, 1990), and most of this melts because of a warm subice current [*Jacobs et al.*, 1979; *Thomas*, 1976]. By contrast, such a warm current is absent under the Amery Ice Shelf [*Smith et al.*, 1984].

Seawater freezes not only to ice shelves but also to thinner ice tongues and to coastal ice cliffs along ice sheet margins, where outcrops and exposures of desalinated sea ice are visible above sea level [*Goodwin*, 1993; *Gow and Epstein*, 1972; *Lorius*, 1968]. The Koettlitz Glacier tongue [*Gow and Epstein*, 1972], and the Hell's Gate Ice Shelf [*Souchez et al.*, 1991], both on the edge of the Ross Sea, undergo sufficient surface ablation to expose basal ice at their upper surfaces. This basal accretion occurs at shallow depths, probably accounting for the numerous bubbles and hence the white appearance (A. Gow, personal communication, 1991).

Why do green icebergs constitute only a small fraction of all iceberg sightings? Four conditions must be fulfilled for green ice to become exposed to view in the form of an iceberg: (1) the freezing seawater has to contain substantial concentrations of blue-absorbing components; (2) the iceberg must originate from an ice shelf with thick basal freeze-on, although in the case of certain composite icebergs the green portion is only a stripe bounded on both sides by bubbly blue-white ice [*Wordie and Kemp*, 1933] probably resulting from seawater filling a bottom crevasse [*Morgan*, 1972]; (3) the basal ice has to survive to the calving front without melting; (4) the iceberg has to capsize before the green portion melts off the bottom.

The plentiful organic matter in Prydz Bay favors green iceberg formation on the Amery. The iceberg whose reflectance spectrum we measured is a rather pale specimen by comparison with the others we have seen, so the spectra of Amery basal ice in Figure 4*a* may be more representative of the typical green icebergs calved from the Amery. The spectral absorption coefficients due to organics in the Amery basal ice appear to span the same range as those of the Prydz Bay seawater (Figure 4*b*), suggesting that unlike salts, dissolved organics are not excluded during the freezing process.

Given that phytoplankton are the likely initial source of organic matter in the Antarctic Seas, chlorophyll concentrations may provide a first proxy for ultimate dissolved organic concentrations. Thus absorption spectra for basal ice from the Filchner-Ronne and Ross ice shelves can be modeled based upon the relative reported chlorophyll concentrations in the Weddell and Ross seas with respect to Prydz Bay (approximately one-tenth the magnitude). Figure 4*b* shows the predicted absorption spectrum of basal ice from these two ice shelves, given a dissolved organic absorption spectrum one-tenth the magnitude of the maximum measured in Prydz Bay. The basal ice from these two ice shelves would appear more blue and less green than that of the Amery. However, the chlorophyll concentrations were measured at only a few locations and times in front of all three ice shelves, and the absorption by the dissolved fraction has been measured only on these samples from Prydz Bay.

The Amery also fulfills both the second and third conditions for producing green icebergs. The Ross Ice Shelf never develops a thick basal layer, and most of the thick accumulation of basal ice on the Filchner-Ronne is melted before reaching the calving front. Regarding the fourth condition, calving from all three ice shelves occurs in the form of tabular icebergs, often 100 times as wide as they are thick. Warmer waters away from the ice shelf may cause substantial melting of the iceberg bases before they break into pieces small enough to overturn. The observed green icebergs therefore may originate from the small fraction of ice which calves at the east and west margins of the ice front, where smaller icebergs are produced that can overturn sooner.

Green icebergs might be carried by the Antarctic Circumpolar Current to all areas of the Antarctic, but we would expect sightings to be more common near the source ice shelves, because most icebergs probably survive less than 2 months in the open sea [*Orheim*, 1980; *Allison and Musil*, 1989]. They therefore might be useful as tracers of ocean currents. They have been reported in the Weddell Sea, where they might come from the Filchner-Ronne Ice Shelf, but not often in the Ross Sea. Green icebergs have been seen by nearly all travelers to Mawson Station on the west side of Prydz Bay where the Amery Ice Shelf discharges, but not at Davis Station on the east side of the bay. The surface current, driven by the easterly wind, carries Amery icebergs to the west [*Smith et al.*, 1984], where many become grounded on the shallow seafloor and remain for several years. Green icebergs have not been reported in the northern hemisphere, where most of the ice shelves are short and fast-moving, allowing little time for basal accretion. The only Arctic ice shelf known to accumulate basal ice is the Ward Hunt Ice Shelf [*Lyons et al.*, 1971] north of Ellesmere Island, which calves to form the Arctic Ice Islands [*Crary*, 1956]; the basal ice has salinity 100 times that of Amery basal ice [*Jeffries*, 1991] and contains bubbles [*Nakaya et al.*, 1962], and its color is apparently unremarkable.

Basal ice varies in color depending upon the amount of organic matter in the seawater circulating under the ice shelf. We observed a range of absorption coefficients in the Marine Ice Cliff, basal ice, and green iceberg core samples, and we have seen various shades of green in different icebergs. The thick accumulations of green ice observed in green icebergs and in basal ice imply that concentrations of organic matter in seawater must remain high at the depth of freeze-on (400 m below the surface) for hundreds of years. The mechanism for sustaining the organic pool is not yet known but may be due to either recirculation patterns under the ice shelf [*Smith et al.*, 1984] or a steady input of organic-rich seawater from the surface, implying slow or rapid turnover times of the organic pool, respectively. If the second mechanism is responsible, then phytoplankton blooms, such as the one reported in Prydz Bay, should be common [*Kang and Fryxell*, 1991]. Either mechanism requires that a large portion of particulate organic matter be removed from the surface and undergo significant degradation in the water column and/or in the underlying sediments. A portion of the dissolved organic matter, recirculated in the water column or resuspended from sediment pore waters, is eventually frozen to the base of the ice shelf.

Note added in proof. The spectral albedo of cold, bubbly glacier ice was measured in November 1992 below Mount Howe, Antarctica (87°S, 150°W), where the snow is blown away by strong winds, exposing blue white ice. The albedo is higher than that of green ice, and the peak in albedo is broader than the peaks in Figure 2 because of the numerous bubbles. The albedo peaks between 470 and 500 nm, as compared with 500–520 nm for the green ice.

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Correction to "Green Icebergs Formed by Freezing of Organic-Rich Seawater to the Base of Antarctic Ice Shelves" by S. G. Warren et al.

In the paper "Green icebergs formed by freezing of organic-rich seawater to the base of Antarctic ice shelves" by S. G. Warren, C. S. Roesler, V. I. Morgan, R. E. Brandt, I. D. Goodwin, and I. Allison (*Journal of Geophysical Research*, *98*(C4), 6921–6928, 1993), there are two errors in Table. 1. In the upper part of the table, values for the sulfate concentration are in milligrams S per liter except for the standard seawater value, which is in milligrams $SO_4^=$ per liter. The molar ratio $SO_4^=/Na^+$ for seawater given in the lower part of the table should be 0.06, not 0.17; the other molar ratios are correct. The $SO_4^=/Na^+$ ratios in the green ice samples are not significantly different from the ratio in seawater. We thank John Moore of the British Antarctic Survey for pointing out this error.

It also appears that the paper would have benefited by including a diagram of the iceberg whose reflectance spectrum we measured, so we present such a diagram here (Figure 1).

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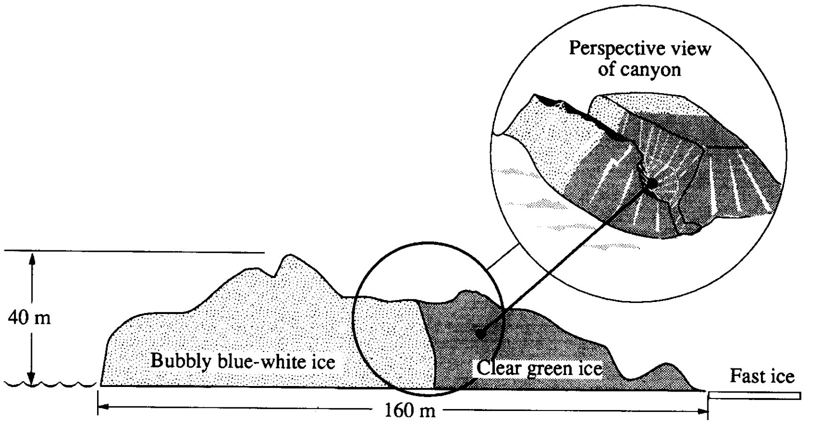

Fig. 1 Diagram of the iceberg sampled on November 19, 1988, at 67°S, 62°E (viewed toward east). Spectral measurements and core sample were taken at the location marked as a black dot in the canyon. We argue that the iceberg broke off from an ice shelf in which the boundary plane separating blue ice from green ice was originally horizontal.

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