

lakes or the open sea within 30 km of their dolines and lateral penetration of brine may be responsible for creating paths for drainage; lateral brine infiltration has been observed several kilometres from open rifts (Thomas, 1975) in the Brunt Ice Shelf, and extensive brine layers covering tens of kilometres observed in the Larsen and Wilkins Ice Shelves (Smith, 1972). Penetration of meltwater to more than 200 m depth in ice shelves has been suggested (personal communication from A. Jenkins) as the explanation for isolated spikes in the $\delta^{18}\text{O}$ profile of an ice core from the Amery Ice Shelf (presented by Robin (1983)), that are similar to near-surface $\delta^{18}\text{O}$ values. Therefore, direct meltwater penetration may account for drainage of the Amery Ice Shelf dolines.

There is no evidence of current features on George VI Ice Shelf that could be called dolines, though there are certainly many lakes. George VI Ice Shelf was rather colder in the 1940s and probably also in the earlier decades of the century than the present day (Jones, 1990). Warmer years are mainly a result of mild winters, the summer temperatures being close to 0°C. In warmer times, it is likely that much thinner surface covers of ice would form above the melt lakes, not allowing the accommodation of significant pressure from expansion of water during freezing. The water would tend to seep away gently rather than drain catastrophically, and we should expect no roof collapse or a doline feature to form.

The occurrence of dolines on ice shelves in areas where there are substantial supplies of meltwater strongly supports the theory that dolines are melt lakes that freeze over and then suffer drainage, causing the unsupported roof to collapse. Unlike ice blisters, which usually drain through cracking of the roof of the blister forming icings, dolines probably drain through fractures in their base to the sea beneath the ice shelf.

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SIR,

There is direct evidence for Pleistocene collapse of the West Antarctic ice sheet

Diatom fossils, the siliceous shells of microscopic marine planktonic algae, have been identified in glacial till recovered from beneath Ice Stream B near the Upstream B camp (UpB) in West Antarctica (Engelhardt and others, 1990; Scherer, 1991). Most of the diatoms identified in these sediments are Miocene, older than 5 Ma and represent marine conditions in the West Antarctic interior. Most of the Pliocene and Pleistocene is not represented due to glacial erosion and non-deposition during glaciated intervals. Rare post-Miocene diatoms are present in the UpB 1988–89 sediment matrix. Scherer (1991) suggested that most of these diatoms are likely to be less than ~600 000 years old and may represent remnants of the most recent deglaciation in West Antarctica.

If these findings and interpretations are correct, then they provide the first direct evidence of Pleistocene collapse of the West Antarctic ice sheet. Mercer (1978) first suggested that the West Antarctic ice sheet might have collapsed during a Pleistocene interglacial. Based on independent proxy records, including the deep-sea sediment record (e.g. Howard and Prell, 1992; Hodell, 1993), sea-level history (e.g. Cronin, 1981; Wornardt and Vail, 1991; Brigham-Grette and Carter, 1992) and

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terrestrial records of climate change (e.g. Kukla, 1989), Scherer (1991) speculated that the youngest diatoms from UpB may have been deposited in the West Antarctic interior during the unusually warm and long interglacial, oxygen-isotope stage 11, ~400 000 years ago. It should also be noted that recent studies suggest that West Antarctic ice-sheet collapse need not be in phase with climate (MacAyeal, 1992; Blankenship and others, 1993).

Do the diatoms from UpB 1988–89 indicate that there was a collapse of the West Antarctic ice sheet during the late Pleistocene? Given the potential significance of this interpretation, it is important that the data be given thorough evaluation. L. Burckle (1993) has challenged the diatom data from Upstream B (1988–89). Here I respond to Burckle's comments.

Background: Diatom biostratigraphy

Sedimentary particles, including diatoms, are mixed and transported in glacial till. Consequently, biostratigraphic analysis of diatoms in glacial sediments must be applied with unusual caution. Although Antarctic diatom biostratigraphic information is always qualitative, the age ranges of many Antarctic diatoms are well documented and biostratigraphic results are generally quite reliable. The latest composite biostratigraphic scheme for Antarctic sediments (Harwood and Maruyama, 1992) includes 184 defined diatom data ("first" and "last" stratigraphic occurrences), divided into 33 diatom zones spanning the last 36 Ma, suggesting an average zonal resolution of 1.1 Ma. Faunal turnover was unusually high during the Pliocene (5.2–1.6 Ma ago), where zonal resolution is 0.4 Ma. The use of individual diatom ranges and sub-zones can yield higher chronostratigraphic resolution. This biostratigraphic scheme was developed from more than 20 years of study of sediment records recovered by stratigraphic drilling in the Antarctic and sub-Antarctic zones by the Ocean Drilling Program (ODP) and the Deep Sea Drilling Project (DSDP).

Stratigraphic records south of about 60° S tend to be more discontinuous due to oceanographic factors and the influence of glacial activity. Due to limited high-resolution stratigraphic reference sections near the continent, the accuracy of Antarctic diatom ranges in near-shore deposits at higher latitudes has been questioned (Clapperton and Sugden, 1990; Burckle and Pokras, 1991; Burckle, 1993). These authors suggested that the stratigraphic ranges of certain diatoms may be different in the near-shore zone of Antarctica than in the Southern Ocean, where nearly continuous biostratigraphic records are preserved. This effect is called diachrony.

Limited diachrony has been documented in sediments near the Antarctic polar-front zone, the boundary between Antarctic and sub-Antarctic water masses (Burckle and Abrams, 1987; Fenner, 1991). These water masses have distinct diatom assemblages. The diachrony exhibited in this region, which is generally limited to glacial–interglacial time-scales, is due to migration of the polar front with oceanographic changes. However, significant diachrony of biostratigraphically important diatom species wholly within the Antarctic water mass

(entirely south of the polar front) has not been conclusively documented (Webb and Harwood, 1991; Scherer, 1992). In fact, the accuracy of Pliocene diatom ages in inshore waters of the Antarctic continent has recently been independently confirmed (Barrett and others, 1992).

This is not the appropriate forum for a detailed debate of this issue, so I will limit further discussion to the specific biostratigraphic issues raised by Burckle (1993). Burckle presented five specific challenges to the data and interpretations of Scherer (1991). His comments refer to possible diachrony, the apparent absence of certain taxa and the limitations of biostratigraphy in glacial sediments. I discuss each of these issues in the order presented in his paper.

The validity of *Actinocyclus ingens* as an isochronous datum

Scherer (1991) suggested that the youngest diatom assemblage identified at UpB is more similar to a late Pleistocene Antarctic assemblage than a Pliocene or early Pleistocene assemblage. In support of this interpretation, I cited the apparent absence of well-documented Pliocene species (such as those present in Sirius Group tills) and the apparent lack of the diatom *Actinocyclus ingens* (Fig. 1a), a heavily silicified form with an unusually high preservation potential in glacial sediments (Abelmann and others, 1990). I suggested that the assemblage may represent sedimentation in the West Antarctic interior, subsequent to the extinction of *A. ingens* from Antarctic waters, ~600 000 years ago (the datum is now known to be closer to 620 000 years ago (Harwood and Maruyama, 1992)).

Burckle questioned this interpretation and made the

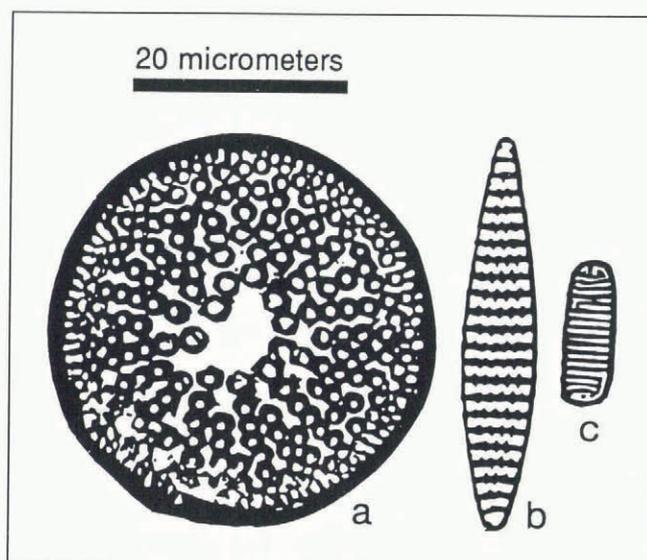


Fig. 1. Micrographs of key diatoms referred to in the text. Examples from the Southern Ocean. Magnification 1500 times. Scale bar at upper left equals 20 μm , equivalent to the smallest available sieve size. a. Centric diatom *Actinocyclus ingens*. b. Pennate diatom *Nitzschia kerguelensis*. c. Pennate diatom *Nitzschia curta*.

statement "*A. ingens* disappeared from the record during the late Quaternary in sections recovered north of about 61° S but to the south of this latitude they disappeared much earlier in time". This statement is not substantiated by available stratigraphic data. The extinction of *A. ingens* is unusually well documented. The coherence of this circum-Antarctic datum is demonstrated by the fact that the extinction of *A. ingens*, 620 000 years ago, has defined the top of the *A. ingens* zone in all of the ten high-latitude Southern Ocean diatom biostratigraphic schemes proposed since 1970 (Donahue, 1970), despite many other refinements made in Antarctic diatom biostratigraphy after nearly 25 years of study (see Gersonde and Burckle, 1990; Baldauf and Barron, 1991; Harwood and Maruyama, 1992).

The extinction of this species is known to be diachronous across the global ocean, but contrary to what Burckle reported, Antarctic waters were the last refuge of this species. The extinction of *A. ingens* was progressive, beginning in tropical latitudes 11.5 Ma ago, and 4.4 Ma ago in the mid and high latitudes of the North Pacific (Barron, 1985; Spencer-Cervato and others, 1992). However, this species persisted, indeed thrived, in the Southern Ocean until 620 000 years ago. This datum is particularly easy to identify because the heavily silicified *A. ingens* preserves particularly well and reaches an abundance acme in lower Pleistocene sediments of the Southern Ocean, prior to its final disappearance. Antarctic sediments deposited during the interval 1.6–0.7 Ma typically contain 40–60% *A. ingens* relative to other diatoms (Abelmann and others, 1990).

To support his assertion that *A. ingens* disappeared "much earlier" than 620 000 years ago south of 61° S, Burckle cited his own work, holes 690B (65° S), 695A (62° S) and 697B (62° S) of Ocean Drilling Program leg 113 in the Weddell Sea (Gersonde and Burckle, 1990). Referring to hole 690B, Burckle (1993) stated "the last occurrence of this species (*A. ingens*) is in upper Pliocene sediments". But a critical fact was not reported. This site has an hiatus spanning the interval from 2 Ma ago to about 0.75 Ma ago (see figure 7 and table 6 of Gersonde and Burckle, 1990). The entire interval characterized by unusually abundant *A. ingens* is missing from this core! The top of the *A. ingens* zone is identified at the appropriate level in hole 690B, above the unconformity, though this interval is rather diatom-poor (Gersonde and Burckle, 1990). Similarly, hole 695A, which Burckle also cited, has a highly condensed upper Pliocene and Pleistocene section, with disconformities and poor diatom preservation (see figure 10 of Gersonde and Burckle, 1990).

Referring to hole 697B, Burckle stated "*A. ingens* occurs up to the middle Quaternary, but is about 300 ka short of the 600 ka mark". He went on to state "All samples above the last occurrence of this species in this hole are barren of diatoms". It cannot be concluded that *A. ingens* became extinct 300 000 years too early at Site 697 if no diatoms are preserved in sediments that are younger than 900 000 years old! In fact, the top of the *A. ingens* zone could not be identified in this core, due to locally poor preservation and stratigraphic disturbance (see figure 11 of Gersonde and Burckle, 1990). These examples, from Burckle's own work, offer no evidence

that *Actinocyclus ingens* disappeared earlier than 620 000 years ago south of 61° S.

Contrary to what Burckle wrote, there is good evidence that this species was an important part of the plankton south of 61° S during the early to mid-Pleistocene. Few continuous stratigraphic reference sections exist south of this latitude (note problems at sites 690, 695 and 697), but the better records all show significant numbers of *A. ingens* in the Pliocene, and up to the early late Pleistocene. For example, this datum is demarcated in site 274 at 69° S at the mouth of the Ross Sea, off Cape Adare. At site 273, at 74°32' S in the Ross Sea, the top of the *A. ingens* zone may be suggested, although glacial reworking and drilling disturbance complicates the interpretation of these sites (McCollum, 1975; Savage and Ciesielski, 1983). The *A. ingens* datum may be present in the CIROS-2 drill hole, at 77°41' S, in McMurdo Sound, though stratigraphic problems are apparent in this core as well (Harwood, 1986). This datum is recognized at site 324 at 69°03' S in the Bellingshausen Sea (Schrader, 1976), as well as at virtually all Plio-Pleistocene sections in the circum-Antarctic siliceous ooze belt.

In referring to the Pleistocene record of core 1458 of Abelmann and others (1990), from the Weddell Sea at 64°59' S, Burckle stated "(this core) has few diatoms in that interval". However, in discussing core 1458, Abelmann and others (1990) stated "A distinct change in diatom assemblage occurs at about 1.6 Ma, when *Actinocyclus ingens* increases considerably in numbers (toward the top of the core)". Abelmann and others (1990) did not specifically report the level where *A. ingens* disappears, but the identification of the top of the *A. ingens* zone (620 ka) is clearly implied in the text and in their figure 5.

As outlined above, Burckle's statement that "*A. ingens* disappeared from the record during the late Quaternary in sections recovered north of about 61° S but to the south of this latitude they disappeared much earlier in time" is not only unsubstantiated, it is almost certainly incorrect. Clearly, more and better near-shore reference sections are needed, but at present there is no justification for assuming that the *A. ingens* datum is not valid for West Antarctic interior basins.

Lack of well-demarcated biostratigraphic first occurrences

Gaps in our knowledge of Neogene Antarctic diatom biostratigraphy exist; however, a great deal is well established. More than ten of the species reported from Upstream B have never been reported from Miocene sediments. Many of these have well-established first occurrences in either the early or late Pliocene and the details of first occurrences of others still need to be established. What these taxa do have in common is that they are common in Antarctic waters today. Furthermore, there is a conspicuous absence of well-established Pliocene taxa in association with the extant (living) species that have been found. This strongly implies, though does not directly indicate, a post-Pliocene assemblage. The absence of *A. ingens* provides further

suggestion of a late Pleistocene age, as discussed above. I have never suggested that these data provide “proof” of late Pleistocene collapse of the West Antarctic ice sheet, though the diatom data certainly are supportive of such an hypothesis.

A complete, undisturbed and well-preserved stratigraphic record of Pliocene and Pleistocene biosiliceous sedimentation on the Antarctic continental shelf is not yet available. Burckle used this fact to suggest that we know almost nothing of the stratigraphic ranges of common living Antarctic diatoms. For example, Burckle stated “The geologic ranges of *Thalassiosira gracilis* var. *expecta* and *T. antarctica* have never been investigated so it is not known how far back in time they ranged”. These diatoms are common and well-known in Antarctic waters today, yet they have never been reported from Miocene or Pliocene sediments from the Southern Ocean or from Antarctic continental shelf deposits. If they were a common component of sediments of these ages, then their occurrences would have been reported. The fact that their first occurrences have not been specifically documented may imply, though does not prove, a young age (i.e. post-Pliocene).

Burckle pointed out uncertainties with regard to the stratigraphic record of the small pennate diatom *Nitzschia separanda* and the rare centric diatom *Thalassiosira trifulta*. Biostratigraphic uncertainty with regard to these taxa is clearly acknowledged in figure 3 of Scherer (1991). It is unlikely that the degree of uncertainty associated with these species would alter the basic interpretation of the data in a significant way. I do not dispute that there remain ambiguities with regard to the documented ranges of individual diatom taxa. It is my belief that many of the uncertainties are due to limited reference sections and a lack of high-resolution studies, rather than problems inherent in the diatom record.

Apparent absence of *Nitzschia kerguelensis* and *Nitzschia curta*

Burckle’s third argument centered around the apparent absence of the pennate diatoms *Nitzschia kerguelensis* (Fig. 1b) and *Nitzschia curta* (Fig. 1c). Both of these taxa are abundant in Antarctic waters today. *N. curta* dominates the diatom assemblage of much of the modern Ross Sea. *N. kerguelensis* is uncommon in the Ross Sea today but it dominates sediments of the circum-Antarctic ocean. It is true that these diatoms have not been unequivocally identified at Upstream B. I must point out that lack of observation does not necessarily constitute absence, as Burckle suggested. This is particularly true with regard to these taxa, given their morphology and the laboratory methods used, as discussed below.

Micropaleontological analysis of glacial diamictos is fundamentally different from micropaleontological analysis of in-situ deep-sea sediments. In essence, analysis of diatom assemblages in subglacial till is glacial geology, not paleo-oceanography. Consequently, the methods employed are quite different. Diatoms in till are rare, mixed and often mechanically degraded, whereas Antarctic marine sediment generally includes abundant diatoms which are relatively unmixed. In order to recover

identifiable diatoms from a clay-rich till, it is necessary to use methods that are inappropriate for paleo-oceanographic studies; specifically, the use of fine sieves (20 μm mesh) and other methods to concentrate larger diatoms (Scherer, 1992). Nearly all of the diatoms I consider Pleistocene are relatively robust centric forms (large and well silicified, as is *A. ingens*). In contrast, *Nitzschia curta* and *Nitzschia kerguelensis* are pennate (long and thin) forms (Fig. 1).

There is a notable paucity of pennate diatoms of any age in data reported from Upstream B 1988–89 matrix sediments. This is due largely to the bias against pennates and diatom fragments imparted by the use of sieves, and possibly by abrasion in active till. Pennate diatoms pass through the screen, effectively eliminating them from most of the slides examined. Slides of the unsieved fraction of matrix sediments are also examined, but considerably more time has been spent on sieved preparations, due to a higher rate of data generation. The unsieved fraction examined contains diatom fragments, including small fragments of pennate diatoms, but identifiable diatom debris in these preparations of UpB 1988–89 sediment is quite rare.

Nitzschia curta (Fig. 1c) is abundant in the Ross Sea today, but it is a small and rather delicate form, and may be more susceptible to dissolution and breakage than the larger and more robust centrics. I point out that the Miocene and Pliocene ancestors of *N. curta* (including *N. praecurta*) are also apparently absent from the UpB 1988–89 matrix sediments, despite the fact that upper Miocene diatoms strongly dominate the diatom assemblage. *N. praecurta* is similar to *N. curta* in dimensions and construction, and is present (up to 5%) in upper Miocene diatomaceous sediment clasts that were recovered from Upstream B during the 1991–92 field season (Scherer, in press; see discussion below). The apparent absence of this taxon is comparable to the apparent absence of *N. curta*. Small fragments of diatoms in this lineage were encountered in examination of unsieved preparations, but tentative identification of small fragments was not reported. It would be impossible to distinguish *N. curta* from *N. praecurta* based on analysis of fragments.

Nitzschia kerguelensis (Fig. 1b) is present in low abundance in the modern Ross Sea but is present in mid-Holocene Ross Sea sediments (Kellogg and Truesdale, 1979). Why has it not been identified at Upstream B? First, I reiterate that this is a pennate diatom, thus it is not expected to be represented in sieved material. Secondly, I was reluctant to report the occurrence of fragments of diatoms that are obviously akin to *N. kerguelensis*. Some fragments are likely to be from *N. kerguelensis*, but I cannot rule out the possibility that they are from, for example, a coarse specimen of the closely related, but much older, *N. miocenica*. Positive identification of small diatom fragments is a dangerous practice.

Burckle argued that *N. curta* and *N. kerguelensis* have “dimensions similar to those pennate forms which were recovered from Ice Stream B samples”, but all pennates reported, mostly from unsieved samples, represent less than 5% of all the marine diatoms counted, whereas typical counts of in-situ marine sediment typically contain abundant pennate forms. Small clasts of upper Miocene diatom-rich sediment were recovered from the matrix

sediment from UpB 1991–92. These clasts contain more than 20% pennate diatoms when prepared without the use of sieves (Scherer, 1992). No similar diatomaceous clasts have been recovered from UpB 1988–89 matrix sediments (Scherer, 1991).

The bias toward centric diatoms in sieved preparations has always been acknowledged and discussed (Scherer, 1991, 1992). Bearing in mind that this is a till, with many natural biases already present, the methodological bias is an unfortunate but necessary evil.

Finally, there are no “mysterious absences” among the centric diatoms I report. Nearly all well-silicified centric diatoms ($>20\ \mu\text{m}$) common in modern Antarctic sediments from south of the polar front are represented in my data, in roughly appropriate proportions (Scherer, 1991, table 1).

Sediment accumulation rates during the Pliocene

Burckle abstracted the following sentence from Scherer (1991) “The apparent lack of Pliocene and early Pleistocene diatoms beneath Ice Stream B is probably a result of low net biogenic accumulation during the Plio-Pleistocene, coupled with the erosional effects of repeated grounding-line advances across the sea floor”. He then drew a comparison with high sediment-accumulation rates in the northern Weddell Sea region during the Pliocene. His argument is unclear, because the Weddell Sea and the continental shelf of the Ross Embayment sector of the West Antarctic interior are very different settings. Deposition during marine phases in the West Antarctic interior and non-deposition and erosion during glacial phases cumulatively result in low *net* accumulation, regardless of sedimentation rate at a given time. This is readily apparent in the southern Ross Sea where a major unconformity leaves middle and lower Miocene sediments exposed near the sediment surface (Savage and Ciesielski, 1983).

I suggested that the youngest diatoms from UpB may represent the most recent deglacial (Scherer, 1991). Most sedimentary evidence of earlier deglacial intervals has been removed from this region by glacial advances. The Pleistocene diatoms beneath Ice Stream B are currently being transported northward, toward the grounding line. I have not suggested that the Ross Embayment was unglaciated throughout the Pliocene and Pleistocene, nor have I suggested that West Antarctica was continuously glaciated throughout that interval. During deglacial phases, biogenic sediment-accumulation rates in the West Antarctic interior were quite high (Savage and Ciesielski, 1983; Harwood and others, 1989; Scherer, 1991, 1992). Subsequent erosion, presumably during glacial advances, removed most of this material.

The entire central Ross Embayment has been subjected to extensive glacial erosion. Massive volumes of Plio-Pleistocene sediment have been eroded from the West Antarctic interior. Glacial-bed processes carved the Ross Sea Unconformity (Savage and Ciesielski, 1983; Karl and others, 1987), transporting eroded sediments and depositing them as thick glacial sediment packets that reached up to several kilometers thick at the seaward

edge of the Ross Sea continental shelf (Bartek and others, 1991; Cooper and others, 1991). The ODP sites discussed by Burckle are from oceanic depths of the northern Weddell Sea, which experienced relatively continuous sedimentation during much of that interval, resulting in high net sediment accumulation during certain Pliocene intervals.

Interpretation of non-marine diatoms

Arguments about lakes in West Antarctica that existed more than 20 Ma ago have no bearing on the debate regarding possible Pleistocene West Antarctic ice-sheet collapse, so I will only respond to Burckle's comments in brief. In Scherer (1991), I speculated that the surprising discovery of common small sediment clasts composed of planktonic (floating) fresh-water diatoms in Upstream B sediments suggests that large lake systems may have been present in West Antarctica's past. I suggested that the lakes might have been fairly deep, based on the complete absence of benthic (bottom-dwelling) diatoms co-occurring with the planktonics in these clasts. (Diatoms need light to survive.) Burckle argued that the lakes might have been small or shallow, rather than large and deep, citing an extensive but shallow-lake system in Africa. I would expect that the African lakes discussed by Burckle contain benthic as well as planktonic diatoms, but this is an assumption on my part, based on my knowledge of diatoms. The two papers Burckle (1993) cited (Flohn, 1965 [incorrectly cited by Burckle as Flohn, 1966] and Flohn and Nicholson, 1980) contain no diatom data whatsoever!

I believe that it is reasonable to speculate that an absence of benthic diatoms in lake sediments that contain abundant planktonic diatoms may suggest deposition in relatively deep water. The relatively high abundance of these clasts in the UpB 1988–89 till and the recent discovery of the same fresh-water diatom (*Alaucosiera italica* var. A; Scherer, 1991) in sediments collected at Upstream B during the 1991–92 season (Scherer, unpublished data) can be more easily explained with large lake systems than smaller ones.

Discussion

Burckle suggested that sediments from beneath a current ice sheet “cannot be used to establish ice-sheet history”, due to re-working and sediment mixing, which he called “smearing”. He proposed instead, that deep-sea sediment cores contain the needed evidence for past ice-sheet reconstruction. I do not argue that deep-sea sediments can provide a relatively complete record and generally the best available chronology for interpreting oceanographic changes around Antarctica, and that these changes may be related to changes in the ice sheets. Analysis of deep-sea sediments provides an indispensable approach to paleoenvironmental reconstruction. However, as Burckle pointed out, proxy records such as these do not necessarily indicate linkage with any specific ice mass. This is particularly true with regard to relatively small ice sheets. Consequently, the history of the West

Antarctic ice sheet cannot be written based only on analysis of deep-sea sediments. Diatom data from beneath the ice sheet provided a valuable independent line of evidence for comparison with better-constrained time-series records from the deep sea.

There is a fundamental difference between glacial-geologic evidence, which includes diatoms in subglacial till and micro-fossil evidence from deep-sea sediment cores. Whereas marine cores may contain excellent time-series data, glacial-geologic records provide evidence of specific glacial (or deglacial) events. A complete ice-sheet history could not be written using glacial-geologic methods, because the record is, by nature, episodic. Depositional events are followed by erosional events. Glacial-geologic evidence and deep-sea proxy evidence both have specific limitations but, taken together, they can provide critical checks and balances, which may lead to consensus.

Burckle asked "Is there direct evidence for late Pleistocene collapse of the West Antarctic ice sheet?". This question contains two distinct issues: (1) Do the diatoms in question date from the late Pleistocene, and (2) Do they represent direct evidence of marine deposition in the West Antarctic interior following a collapse of the West Antarctic ice sheet?

I have interpreted the age of the youngest diatoms, based on all biostratigraphic information available, as most likely late Pleistocene. Although the data are sparse, they may, nevertheless, be very significant. Burckle challenged the age assignment, suggesting that the diatoms might be older, though he offered no specific age alternative. The broadest interpretation possible is that the diatoms could be as much as about 2 Ma older than I have suggested. However, a Pliocene age is unlikely, considering the fact that the entire (centric) diatom assemblage is indistinguishable from late-Pleistocene (centric diatom) assemblages, and that it differs greatly from well-dated mid-Pliocene assemblages of the Ross Sea continental shelf (Harwood, 1986; Barrett and others, 1992).

Regarding the mechanism of emplacement of these diatoms in UpB sediment, I have considered alternative hypotheses, including (1) possible aeolian deposition of diatoms to the surface of the ice sheet, (2) introduction by advection of diatoms by bottom currents beneath the ice shelf, or (3) as sample contamination. These hypotheses are considered less likely than the ice-sheet collapse hypothesis, as discussed elsewhere (Scherer, 1992, unpublished data). Burckle (1993) did not disagree with this interpretation. He wrote that, if the diatoms are late Quaternary, "this may be taken as direct evidence that collapse occurred sometime during this interval". Even if the diatoms reported from Upstream B are late Pliocene, rather than late Pleistocene, the significance of the observation would not be diminished. They would still seem to represent the first direct evidence of late Neogene disintegration of the West Antarctic ice sheet. In my judgement, based on a wide variety of data, the most reasonable interpretation for these diatoms is that they were deposited in the West Antarctic interior, south of Upstream B, during a marine interval (implying ice-sheet disintegration), and that the most likely time for the most recent event was within the last 620 000 years. During a

subsequent glacial advance, these diatoms were eroded and transported to the site where they were eventually recovered.

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Bering Glacier, the largest in North America with an area, including tributaries, of about 5 200 km² (Molnia, 1993) (Fig. 1a), was observed during photographic flights on 19 and 24 June 1993 during a field program near the terminus. Extensive fresh crevassing throughout regions that were unperturbed in air photographs taken on 16 March 1993 by R. Krimmel indicated an acceleration of flow characteristic of surge initiation. Historically, the surge cycle for Bering Glacier has been approximately 20 years. The last major surge occurred in 1965–67. A minor surge, similar in extent to the preliminary surge evidence described here, occurred in 1981 but did not propagate into the piedmont lobe.

Figure 1a is a full-resolution synthetic-aperture radar (SAR) image of Bering Glacier, acquired on 13 September 1992 by the European Remote Sensing satellite (ERS-1). The nominal resolution is 30 m. The terminus is at the lower left. Vitus Lake — which has been greatly enlarged by up to 10 km of retreat since the 1965–67 surge (Molnia, 1993) — is between the terminus and the coast, which appears along the bottom of the image. Figure 1b shows the flight path of 19 June and the approximate locations of the photographs in Figures 2–8. The flight of 24 June continued to upper Bagley Icefield, which did not show evidence of participating in the surge at that time.

Figure 2 shows a heavily crevassed bulge of ice at the west end of Grindle Hills; the rectangular seracs result from increasing transverse extension superimposed on longitudinal extension. Figure 3, a relatively short distance up-glacier, shows fresh crevassing in the foreground and right middle distance, indicating propagation of the surge down the tributary which flows around the north and east sides of Grindle Hills (Fig. 1b). The transient late-June snow line also appears in the middle distance. The intersecting crevasses illustrate the effect of orthogonal tensile principal stress components. Figure 4 shows fresh intersecting crevasses farther up-glacier, above the transient late-June snow line, indicating a complex surface stress field. Figure 5 shows a broad surge front with fresh rectangular seracs near Khitrov Hills. The distance along the crest, transverse to the flow direction (lower left to upper right) is on the order of 2 km. In Figure 6, which is a close-up of the surge front shown in Figure 5, a small lake is visible at bottom center. The open “holes” or fractures visible through the lake suggest subglacial water pressure locally in excess of the ice-overburden pressure at the surge front. However, the lake was clear blue rather than muddy as might be expected if it had formed as a result of direct upwelling from the bed. The vertical distance from the lake to the crest of the surge front is probably on the order of 100 m. Figure 7 shows a small lake in mid-glacier. The open crevasses clearly visible beneath the lake are probably on the order of 10–20 m apart.

The striking crevasse patterns shown in these air