length. Indeed a step that crossed the whole surface of a three-dimensional crystal would have a huge energy and is forbidden. In a two-dimensional crystal, however, the surface is one-dimensional, a step on this surface is 'zero-dimensional', has a finite energy and is always allowed except at zero temperature. Thus a two-dimensional crystal cannot be facetted. In the pictures of Berge *et al.*, there are no really straight parts, and the impression of facets arises from the sharp corners. Sharp corners *are* allowed in two as in three dimensions.

The mathematics of crystal growth is a source of beautiful geometrical exercises. One approach is a transcription of the classical Wulff construction which gives the equilibrium shape. The surface free energy $\sigma(\mathbf{n})$ should merely be replaced by the growth rate $v(\mathbf{n})$. However, this yields only the limiting shape at large times. More general theorems have been derived by Frank[4].

After a talk delivered by Frank, Cabrera expressed his admiration as well as some disappointment because there was nothing left in the field. Since the work of Mullins and Sekerka we know that Frank only exhausted the simplest possible description of growth phenomena, and the experiments of Berge *et al.* illustrate the fact that this too simple picture breaks down after a finite time, when instabilities come into play, bringing dendrites and occasionally chaos. And that is a very modern field of investigation[6]. □

J. Villain is at the Centre d'Etudes Nucleaires de Grenoble, F-38041 Grenoble Cedex, France.

GLOBAL WARMING

Breakup of Antarctic ice

H. Jay Zwally

WORDIE Ice Shelf, floating on the coast of the Antarctic Peninsula, has been slowly breaking up over the past few decades, according to Doake and Vaughan on page 328 of this issue[1]. The observation, obtained from detailed analyses of satellite images, is of particular interest because the disintegration has occurred during a period of warming in the vicinity of the ice shelf, and because of growing concern about the fate of the entire Greenland and Antarctic Ice Sheets (grounded on the land masses) in a warmer climate. Because the ice shelves are important in restraining and, perhaps, stabilizing ice discharge from the continents, it is tempting[2] to see their breakup as a sign of impending doom.

How should we view the new result in the context of public concern about greenhouse warming, the potential melting of the polar ice caps, and estimates of rising sea level? Is it an indication of a serious trend or a solely regional phenomena? In particular, is the rapid change in area of the Wordie Ice Shelf relevant to the question of stability of the grounded West Antarctic Ice Sheet, described[3] as "glaciology's grand unsolved problem"? Should this melt, the global sea level could rise by 5 metres.

Doake and Vaughan correctly note that although nearby ice shelves in the Antarctic Peninsula may be at risk if the warming continues, substantial additional warming would be required to affect the more-southerly major ice shelves that help stabilize[4] the West Antarctic Ice Sheet. The breakup of the Wordie Ice Shelf (2,000 km^2 in area) is probably part of a regional phenomenon that is consistent with the regional warming in the Antarctic Peninsula, but it should not be extrapolated to other parts of Antarctica. In the vicinity, summer and autumn temperatures have been rising at about 0.05 and 0.1 K a year, respectively, since 1958 although there has been no significant trend in winter and spring temperatures[5,6]. Recent temperature trends in most regions of the Antarctic are not significant, however, and sea-ice extent, which regionally follows temperature changes, has shown no significant overall trend[5]. And although large tabular icebergs (covering about 30,000 km^2 in total) have calved from the Ross and Filchner–Ronne Ice Shelves (which cover 1,000,000 km^2) in recent years, such events are likely to be episodic and unrelated to the Wordie Ice Shelf breakup. Furthermore, ice shelves float in sea water, so that their breaking up into icebergs has no direct effect on sea level. In general, breakup of the Wordie Ice Shelf may be viewed as one of the many regional and global-scale changes that must be observed to discern the overall pattern of climate change, its causes and significance.

IMAGE UNAVAILABLE FOR COPYRIGHT REASONS

US Navy

Wordie Ice Shelf in 1966: waiting to distintegrate

But the breakup of the Wordie Ice Shelf does reveal something about the ice dynamics and the interactions between ice, atmosphere and ocean that determine the volume of polar ice and how it changes. Ice shelves are formed on the ocean as ice discharged from the continent coalesces, snow accumulates or ablates on the top surface of the shelf and ice melts or freezes to the bottom. They are especially vulnerable to climatic change because of their exposure to both oceanic and atmospheric warming. Observation of the breakup of an ice shelf provides vital information on the way the thickness of the ice shelf decreases and the way it fractures and disintegrates. Most of the ice discharging from the West Antarctic Ice Sheet does so in fast-moving ice streams that are at least partially restrained by the ice shelves. Therefore, the new result is directly relevant to the question of the future stability of the West Antarctic Ice Sheet.

The West Antarctic ice streams appear[7,8] to be undergoing significant changes unrelated to any current climatic trends. But the enhanced melting of the restraining ice shelf and its consequent breakup provides an important mechanism for the irreversible unpinning of the West Antarctic Ice Sheet to proceed relatively quickly — over timescales of centuries[4]. Ice-shelf thinning and breakup could markedly accelerate the discharge of grounded ice. However, it should be noted that the current climate of the major ice shelves is more than 10 K cooler than Wordie. Less consequential, but of more immediate concern, is the question of Antarctic mass balance (currently uncertain by around 30 per cent, equivalent to a change in global sea level of 2 mm a year). In contrast to the floating ice, the mass balance of the grounded ice responds very slowly to changes in temperature, but instantaneously to changes in precipitation that may accompany changes in temperature[9]. Continued observation of changes in the area of the Antarctic ice shelves and grounded ice sheet (with high-resolution satellite imagery) and the initiation of measurements of their volume change (by satellite laser altimetry) are urgently needed to determine the future growth or breakup of the Antarctic ice. □

H. Jay Zwally is in the Laboratory for Hydrospheric Processes, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA.

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