

ICE-SHELF STABILITY

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Introduction

Ice shelves are floating ice sheets and are found mainly around the Antarctic continent (Figure 1). They can range in size up to 500 000 km² and in thickness up to 2000 m. Most are fed by ice streams and outlet glaciers, but some are formed by icebergs welded together by sea ice and surface accumulation. They exist in embayments where the shape of the bay and the presence of ice rises, or pinning points, plays an important role in their stability. Ice shelves lose mass by basal melting, which modifies the properties of the underlying water mass and eventually influences the circulation of the global ocean, and by calving. Icebergs, sometimes more than 100 km in length, break off intermittently from the continent and drift to lower latitudes, usually breaking up and melting by the time they reach the Antarctic Convergence. The lowest latitude that ice shelves can exist is determined by the mean annual air temperature. In the Antarctic Peninsula a critical isotherm of about -5°C seems to represent the limit of viability. In the last 40 years or so, several ice shelves have disintegrated in response to a measured atmospheric warming trend in the western and northern part of the Antarctic Peninsula. However, this warming trend is not expected to affect the stability of the larger ice shelves further south such as Filchner–Ronne or Ross, in the near future.

What are Ice Shelves?

Physical and geographical setting

An ice shelf is a floating ice sheet, attached to land where ice is grounded along the coastline. Nourished mainly by glaciers and ice streams flowing off the land, ice shelves are distinct from sea ice, which is formed by freezing of sea water. Most ice shelves are found in Antarctica where the largest can cover areas of 500 000 km² (e.g. Ross Ice Shelf and Filchner–Ronne Ice Shelf). Thicknesses vary from nearly 2000 m, around for example parts of the grounding line of Ronne Ice Shelf, to about 100 m at the seaward edge known as the ice front.

Typically, ice shelves exist in embayments, constrained by side walls until they diverge too much for the ice to remain in contact. Thus the geometry of the coastline is important for determining both where an ice shelf will exist and the position of the ice front. There are often localized grounding points on sea bed shoals, forming ice rises and ice rumpled, both in the interior of the ice shelf and along the ice front. These pinning points provide restraint and cause the ice shelf to be thicker than if it were not pinned. Ice flows from the land to the ice front. Input velocities range from near zero at a shear margin (e.g., with a land boundary), to several hundred meters per year at the grounding line where ice streams and outlet glaciers enter. At the ice front velocities can reach up to several kilometers per year. A characteristic of ice shelves is that the (horizontal) velocity is almost the same at all depths, whereas in glaciers and grounded ice sheets the velocity decreases with depth (Figure 2).

In the Antarctic, most ice shelves have net surface accumulation although there may be intensive summer melt which floods the surface. The basal regime is controlled by the subice circulation. Basal melting is often high near both the grounding line and the ice front. Marine ice can accumulate in the intermediate areas, where water at its *in situ* freezing point upwells and produces frazil ice crystals. Surface temperatures will be near the mean annual air temperature whereas the basal temperature will be at the freezing point of the water. Therefore the coldest ice is normally in the upper layers.

Ice shelves normally form where ice flows smoothly off the land as ice streams or outlet glaciers. In some areas, however, ice breaks off at the coastline and reforms as icebergs welded together by frozen sea ice and surface accumulation. The processes of formation and decay are likely to operate under very different conditions. An ice shelf is unlikely to reform under the same climatic conditions which caused it to decay. Complete collapse is a catastrophic process and rebuilding requires a major change in the controlling parameters. However, there is evidence of cyclicity on periods of a few hundred years in some areas.

Collapse of the northernmost section of Larsen Ice Shelf within a few days in January 1995 indicates that, after retreat beyond a critical limit, ice shelves can disintegrate rapidly. The breakup history of two northern sections of Larsen Ice Shelf (Larsen A and Larsen B) between 1986 and 1997 has been

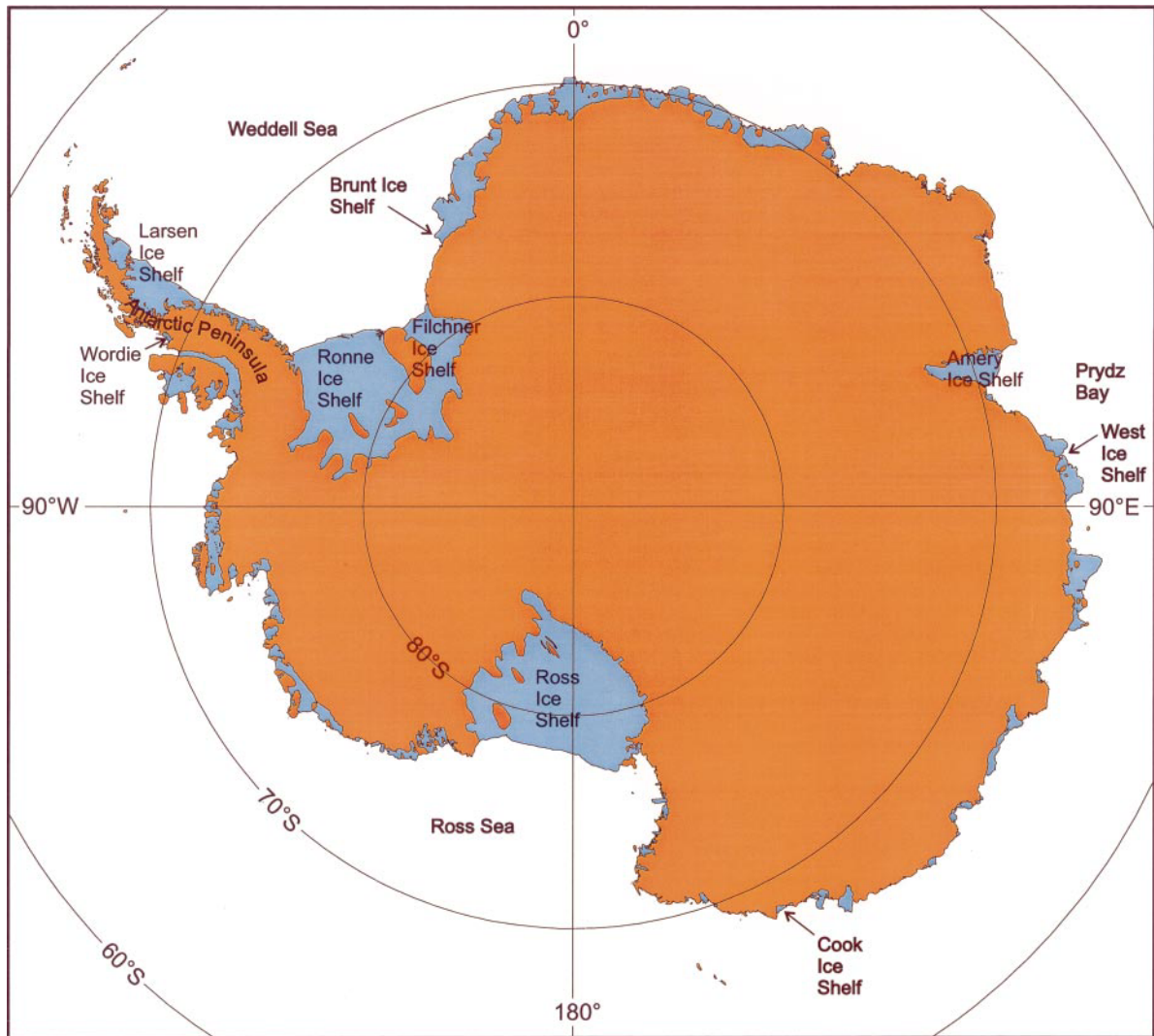


Figure 1 Distribution of ice shelves around the coast of Antarctica.

used to determine a stability criterion for ice shelves. Analysis of various ice-shelf configurations reveals characteristic patterns in the strain-rates near the ice front which have been used to describe the stability of the ice shelf.

Why Are Ice Shelves Important?

Ice shelves are one of the most active parts of the ice sheet system. They interact with the inland ice sheet, glaciers and ice streams which flow into them, and with the sea into which they eventually melt, either directly or as icebergs. A typical Antarctic ice shelf will steadily advance until its ice front undergoes periodic calving, generating icebergs. Calving can occur over a wide range of time and spatial scales. Most ice fronts will experience a quasi-continuous 'nibbling' away of the order of tens to hundreds of

meters per year, where ice cliffs collapse to form bergy bits and brash ice. The largest icebergs may be more than 100 km in size, but will calve only at intervals of 50 years or more. Thus when charting the size and behavior of an ice shelf it can be difficult to separate and identify stable changes from unstable ones.

Mass balance calculations show that calving of icebergs is the largest factor in the attrition of the Antarctic Ice Sheet. Estimates based on both ship and satellite data suggest that iceberg calving is only slightly less than the total annual accumulation. Ice shelf melting at the base is the other principal element in the attrition of the ice sheet, with approximately 80% of all ice shelf melting occurring at distances greater than 100 km from the ice front. Although most of the mass lost in Antarctica is through ice shelves, there is still uncertainty about

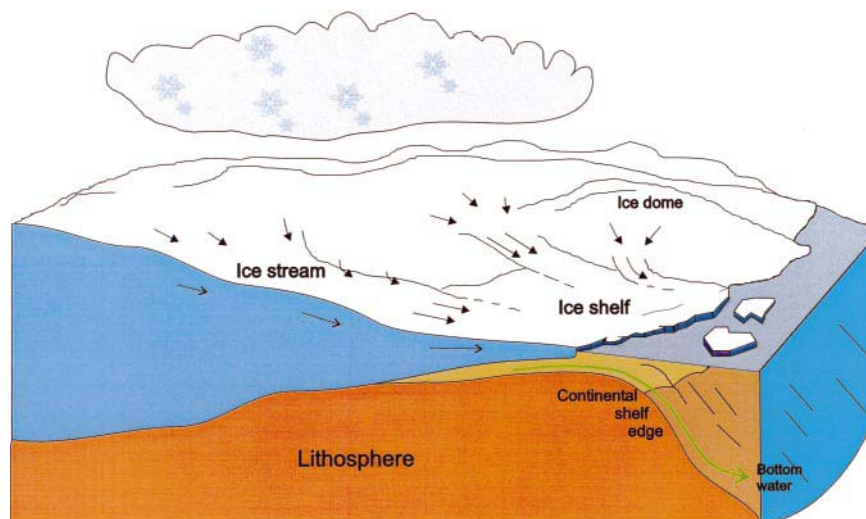


Figure 2 Cartoon of ice shelf in bay with ice streams.

the role ice shelves play in regulating flow off the land, which is the important component for sea-level changes. Because ice shelves are already floating, they do not affect sea level when they breakup.

Ice shelves are sensitive indicators of climate change. Those around the Antarctic Peninsula have shown a pattern of gradual retreat since about 1950, associated with a regional atmospheric warming and increased summer surface melt. The effects of climate change on the mass balance of the Antarctic Ice Sheet and hence global sea level are unclear.

There have been no noticeable changes in the inland ice sheet from the collapse of the Antarctic Peninsula ice shelves. This is because most of the margins with the inland ice sheet form a sharp transition zone, making the ice sheet dynamics independent of the state of the ice shelf. This is not the case with a grounding line on an ice stream where there is a smooth transition zone, but generally the importance of the local stresses there diminishes rapidly upstream.

An important role of ice shelves in the climate system is that subice-shelf freezing and melting processes influence the formation of Antarctic Bottom Water, which in part helps to drive the oceanic thermohaline circulation (*see Sub Ice-shelf Circulation and Processes*).

How Have Ice Shelves Changed in the Past?

As the polar ice sheets have waxed and waned during ice age cycles, ice shelves have also grown and retreated. During the last 20–25 million years, the Antarctic Ice Sheet has probably been grounded

out to the edge of the continental shelf many times. It is unlikely that any substantial ice shelves could have existed then, because of unsuitable coastline geometry and lack of pinning points, although the extent of the sea ice may have been double the present day area. At the last glacial maximum, about 20 000 years ago, grounded ice extended out to the edge of the continental shelf in places, for example in Prydz Bay, but not in others such as the Ross Sea. When the ice sheets began to retreat, some of the large ice shelves seen today probably formed by the thinning and eventual flotation of the formerly grounded ice sheets.

Large ice shelves also existed in the Arctic during the Pleistocene. Abundant geologic evidence shows that marine Northern Hemisphere ice sheets disappeared catastrophically during the climatic transition to the current interglacial (warm period). Only a few small ice shelves and tidewater glaciers exist there today, in places like Greenland, Svalbard, Ellesmere Island and Alaska.

There have been periodic changes in Antarctic ice-shelf grounding lines and ice fronts during the Holocene. The main deglaciation on the western side of the Antarctic Peninsula which started more than 11 000 years ago was initially very rapid across a wide continental shelf. By 6000 years ago, the ice sheet had cleared the inner shelf, whereas in the Ross Sea retreat of ice shelves ceased about the same time. Retreat after the last glacial maximum was followed by a readvance of the grounding line during the climate warming between 7000 and 4000 years ago. Open marine deposition on the continental shelf is restricted to the last 4000 years or so. Short-term cycles (every few hundred years) and

longer-term events (approximately 2500 year cycles) have been detected in marine sediment cores that are likely related to global climate fluctuations.

More recently, ice-shelf disintegration around the Antarctic Peninsula has been associated with a regional atmospheric warming which has been occurring since about 1950. Ice front retreat of marginal ice shelves elsewhere in Antarctica (e.g., Cook Ice Shelf, West Ice Shelf) is probably also related to atmospheric warming. There is little sign of any significant impact on the grounded ice.

Where Are Ice Shelves Disintegrating Now? Two Case Studies

The detailed history of the breakup of two ice shelves, Wordie and Larsen, illustrate some of the critical features of ice-shelf decay.

Wordie Ice Shelf

Retreat of Wordie Ice Shelf on the west coast of the Antarctic Peninsula has been documented using high resolution visible satellite images taken since 1974 and the position of the ice front in 1966 mapped from aerial photography. First seen in 1936, the ice

front has fluctuated in position but with a sustained retreat starting around 1966 (Figure 3). The ice shelf area has decreased from about 2000 km² in 1966 to about 700 km² in 1989. However, defining the position of the ice front can be very uncertain, with large blocks calving off to form icebergs being difficult to classify as being either attached to, or separated from, the ice shelf.

Ice front retreat until about 1979 occurred mainly by transverse rifting along the ice front, creating icebergs up to 10 km by 1 km. The western area was the first to be lost, between 1966 and 1974. Results from airborne radio-echo sounding between 1966 and 1970 suggested that the ice shelf could be divided into a crevassed eastern part and a rifted western part where brine could well-up and infiltrate the ice at sea level. By 1974 there were many transverse rifts south of Napier Ice Rise and by 1979 longitudinal rifting was predominant. Many longitudinal rifts had formed upstream of several ice rises by 1979, some following preexisting flowline features. A critical factor in the break-up was the decoupling of Buffer Ice Rise; by 1986 ice was streaming past it apparently unhindered, in contrast to the compressive upstream folding seen in earlier images. Between 1988 and 1989 the central part of

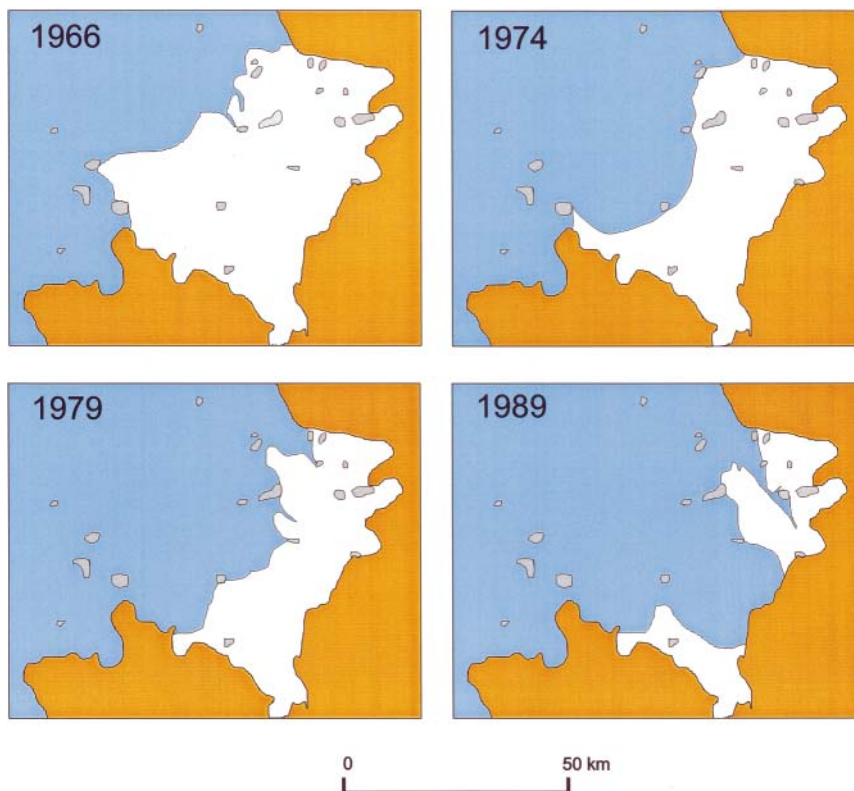


Figure 3 Cartoon showing retreat of Wordie ice front between 1966 and 1989.

the ice shelf, consisting of broken ice in the lee of Mount Balfour, was lost, exposing the coastline and effectively dividing the ice shelf in two. By 1989, longitudinal rifting has penetrated to the grounding line north of Mount Balfour. Further north, a growing shear zone marked the boundary between fast-flowing ice from the north Forster Ice Piedmont and slower moving ice from Harriot Glacier. There has been no discernible change in the grounding line position.

The major ice rises have played several roles in controlling ice-shelf behavior. When embedded in the ice shelf, they created broken wakes downstream, and zones of compression upstream which helped to stabilize the ice shelf. During ice front retreat, they temporarily pinned the local ice front position and also acted as nucleating points for rifting which quickly stretched upstream, suggesting that a critical fracture criterion had been exceeded. At this stage, an ice rise, instead of protecting the ice shelf against decay, aided its destruction by acting as an indenting wedge.

Breakup was probably triggered by a climatic warming which increased ablation and the amount of melt water. Laboratory experiments show that the fracture toughness of ice is reduced at higher temperatures and possibly by the presence of water. Instead of refreezing in the upper layers of firn, free water could percolate down into crevasses and, by increasing the pressure at the bottom, allow them to grow into rifts or possibly to join up with basal crevasses. Processes like these would increase the production rate of blocks above that required for a 'steady state' ice front position. The blocks will drift away as icebergs if conditions, such as bay geometry and lack of sea ice, are favorable. Thus, ice front retreat would be, *inter alia*, a sensitive function of mean annual air temperature.

Some ice shelves, such as Brunt, are formed from blocks that break off at the coast line and, unable to float away, are 'glued' together by sea ice and snowfall. These heterogeneous ice shelves contrast with those, such as Ronne, where glaciers or ice streams flow unbroken across the grounding line to form a more homogeneous type of ice shelf. Before 1989, Wordie Ice Shelf consisted of a mixture of both types, the main tongues being derived from glacier inputs, while the central portion was formed from blocks breaking off at the grounding line and at the sides of the main tongues. The western rifted area that broke away between 1966 and 1974 was described in early 1967 as 'snowed-under icebergs' and it was the heterogeneous central part that broke back to the coastline around Mount Balfour in 1988/89. Increased ablation would not only en-

hance rifting along lines of weakness but would also loosen the 'glue' that held the blocks together.

Larsen Ice Shelf

The most northerly ice shelf in the Antarctic, Larsen Ice Shelf, extends in a ribbon down the east coast of the Antarctic Peninsula from James Ross Island to the Ronne Ice Shelf. It consists of several distinct ice shelves, separated by headlands. The ice shelf in Prince Gustav Channel, between James Ross Island and the mainland, separated from the main part of Larsen Ice Shelf in the late 1950s and finally disappeared by 1995.

The section between Sobral Peninsula and Robertson Island, known as Larsen A, underwent a catastrophic collapse at the end of January 1995 when it disintegrated into a tongue of small icebergs, bergy bits and brash ice. Previously the ice front had been retreating for a number of years, but in a more controlled fashion by iceberg calving. Before the final breakup, the surface that had once been flat and smooth had become undulating, suggesting that rifting completely through the ice had occurred. Collapse during a period of intense north-westerly winds and high temperatures was probably aided by a lack of sea ice, allowing ocean swell to penetrate and add its power to increasing the disintegration processes. The speed of the collapse and the small size of the fragments of ice (the largest icebergs were less than 1 km in size) implicate fracture as the dominant process in the disintegration (Figure 4).

The ice front of the ice shelf known as Larsen B, between Robertson Island and Jason Peninsula, steadily advanced for about 6 km from 1975 until 1992. Small icebergs broke away from the heavily rifted zone south of Robertson Island after July 1992 and a major rift about 25 km in length had opened up by then. This rift formed the calving front when an iceberg covering 1720 km² and smaller pieces corresponding to a former ice shelf area of 550 km² broke away between 25 and 30 January 1995, coincident with the disintegration of Larsen A. The ice front has retreated continuously by a few kilometers per year since then (to 1999) and the ice shelf is considered to be under threat of disappearing completely.

Why Do Ice Shelves Break-up?

Calving and Fracture

Calving is one of the most obvious processes involved in ice shelf breakup. Although widespread, occurring on grounded and floating glaciers, including ice shelves, as well as glaciers ending in



Figure 4 Photo of the Larsen breakup. Picture taken approximately 10 km north of Robertson Island, looking west north-west. In the far background the mountains of the Antarctic Peninsula can be seen.

freshwater lakes, it is not well understood. The basic physics, tensile propagation of fractures, may be the same in all cases but the predictability of calving may be quite different, depending on the stress field, the basal boundary conditions, the amount of surface water, etc. Fracture of ice has been studied mainly in laboratories and applying these results to the conditions experienced in naturally occurring ice masses requires extrapolations which may not be valid. Questions such as how is crevasse propagation influenced by the ice shelf geometry and by the physical properties of the ice such as inhomogeneity, crystal anisotropy, temperature and presence of water, need to be answered before realistic models of the calving process can be developed. The engineering concepts of fracture mechanics and fracture toughness promise a way forward.

Fracture of ice is a critical process in ice shelf dynamics. Mathematical models of ice shelf behavior based on continuum mechanics, which treat ice as a nonlinear viscous fluid will have to incorporate fracture mechanics to describe iceberg calving and how ice rises can initiate fracture both upstream and downstream. High stresses generated at shear margins around ice rises, or at the ‘corner points’ of the ice shelf where the two ends of the ice front meet land, can exceed a critical stress and initiate crevassing. These crevasses will propagate under a favor-

able stress regime, and if there is sufficient surface water may rift through the complete thickness. Transverse crevasses parallel to the ice front act as sites for the initiation of rifting and form lines where calving may eventually occur.

Calving is a very efficient method of getting rid of ice from an ice shelf – once an iceberg has formed, it can drift away within a few days. Sometimes, however, an iceberg will ground on a sea bed shoal, perhaps for several years. Once an Antarctic iceberg has drifted north of the Antarctic Convergence, it usually breaks-up very quickly in the warmer waters.

Climate Warming

Circumstantial evidence links the retreat of ice shelves around the Antarctic Peninsula to a warming trend in atmospheric temperatures. Observations at meteorological stations in the region show a rise of about 2.5°C in 50 years. Ice shelves appear to exist up to a climatic limit, taken to be the mean annual -5°C isotherm, which represents the thermal limit of ice-shelf viability. The steady southward migration of this isotherm has coincided with the pattern of ice-shelf disintegration.

There are too few sea temperature measurements to show if the observed atmospheric warming has resulted in warmer waters, and thus increased basal

melting. Although basal melting may have increased, the indications are that it is surface processes that have played the dominant role in causing breakup. The mechanism for connecting climate warming with ice-shelf retreat is not fully understood, but increased summer melting producing substantial amounts of water obviously plays a part in enhancing fracture processes, leading to calving.

The retreat of ice shelves around the Antarctic Peninsula that has occurred in the last half of the twentieth century has raised questions about whether or not this reflects global warming or whether it is only a regional phenomenon. The warming trend seems to be localized to the Antarctic Peninsula region and there is no significant correlation with temperature changes in the rest of Antarctica.

Stress Patterns

Numerical models of ice shelves have been used to examine their behavior and stability criteria. The strain-rate field can be specified by the principal values ($\dot{\epsilon}_1$ and $\dot{\epsilon}_2$ where $\dot{\epsilon}_1 > \dot{\epsilon}_2$) and the direction of the principal axes. A simple representation is given by the trajectories, which are a set of orthogonal curves whose directions at any point are the directions of the principal axes. Analyses of the strain-rate trajectories for Filchner Ronne Ice Shelf and for different ice shelf configurations of Larsen Ice Shelf show characteristic patterns of a 'compressive arch' and of isotropic points (Figure 5). The 'compressive arch' is seen in the pattern formed by the smallest principal component ($\dot{\epsilon}_2$) of the strain-rate trajectories. Seaward of the arch both principal strain-rate components are extensive, whereas inland of the arch the $\dot{\epsilon}_2$ component is compressive. The arch extends from the two ends of the ice front across the whole width of the ice shelf. It is a generic feature of ice shelves studied so far and structurally stable to small perturbations. It is probably related to the geometry of the ice shelf bay. A critical arch, consisting entirely of compressive trajectories, appears to correspond to a criterion for stability. If the ice front breaks back through the arch then an irreversible retreat occurs, possibly catastrophically, to another stable configuration. The exact location of the critical arch cannot yet be determined *a priori*, but it is probably close to the compressive arch delineated by the transition from extension to compression for $\dot{\epsilon}_2$.

Another pattern seen in the strain-rate trajectories is that of isotropic points. They are indicators of generic features in the surface flow field which are stable to small perturbations in the flow. This means that their existence should not be sensitive either to reasonable errors in data used in the model or to

simplifications in the model itself. They act as (permanent) markers in a complicated (tensor) strain-rate field and are often located close to points where the two principal strain-rates are equal or where the velocity field is stationary (usually either a maximum or a saddle point). Isotropic points are classified by a number of properties, but only two categories can be reliably distinguished observationally, by the way the trajectory of either of the principal strain-rates varies around a path enclosing the isotropic point. In one case the trajectory varies in a prograde sense and the isotropic point is called a 'monstar', whereas in the other case the trajectory varies in a retrograde sense and the isotropic point is called a 'star' (Figure 5).

The two categories of isotropic points can be identified in the model strain-rate trajectories, 'stars' occurring near input glaciers and 'monstars' near ice fronts if they are in a stable configuration. Icebergs calving off Filchner Ice Shelf in 1986 moved the position of the 'monstar' up to the newly formed ice front, whereas on Ronne Ice Shelf the 'monstar' is about 50 km inland of the ice front. This suggests that the existence of a monstar can be used as a 'weak' indicator of a stable ice front. Calving can remove a monstar even if the subsequent ice front position is not necessarily an unstable one and may readvance.

How Vulnerable are the Large Ice Shelves and How Stable are Grounding Lines?

The two largest ice shelves (Ross and Filchner-Ronne) are too far south to be attacked by the atmospheric warming that is predicted for the twenty-first century. Basal melting will increase if warmer water intrudes onto the continental shelf, but the effects of a warming trend could be counter-intuitive. If the warming was sufficient to reduce the rate of sea ice formation in the Weddell Sea, then the production of High Salinity Shelf Water (HSSW) would reduce as well. This would affect the subice shelf circulation, replacing the relatively warm HSSW under the Filchner-Ronne Ice Shelf with a colder Ice Shelf Water which would reduce the melting and thus thicken the ice shelf. Further climate warming would restore warmer waters and eventually thin the ice shelf by increasing the melting rates, possibly to values of around 15 m year^{-1} as seen under Pine Island Glacier. The likelihood of this is discussed in **Sub Ice-shelf Circulation and Processes**.

The supplementary question is what effect, if any, would the collapse of the ice shelves have on the

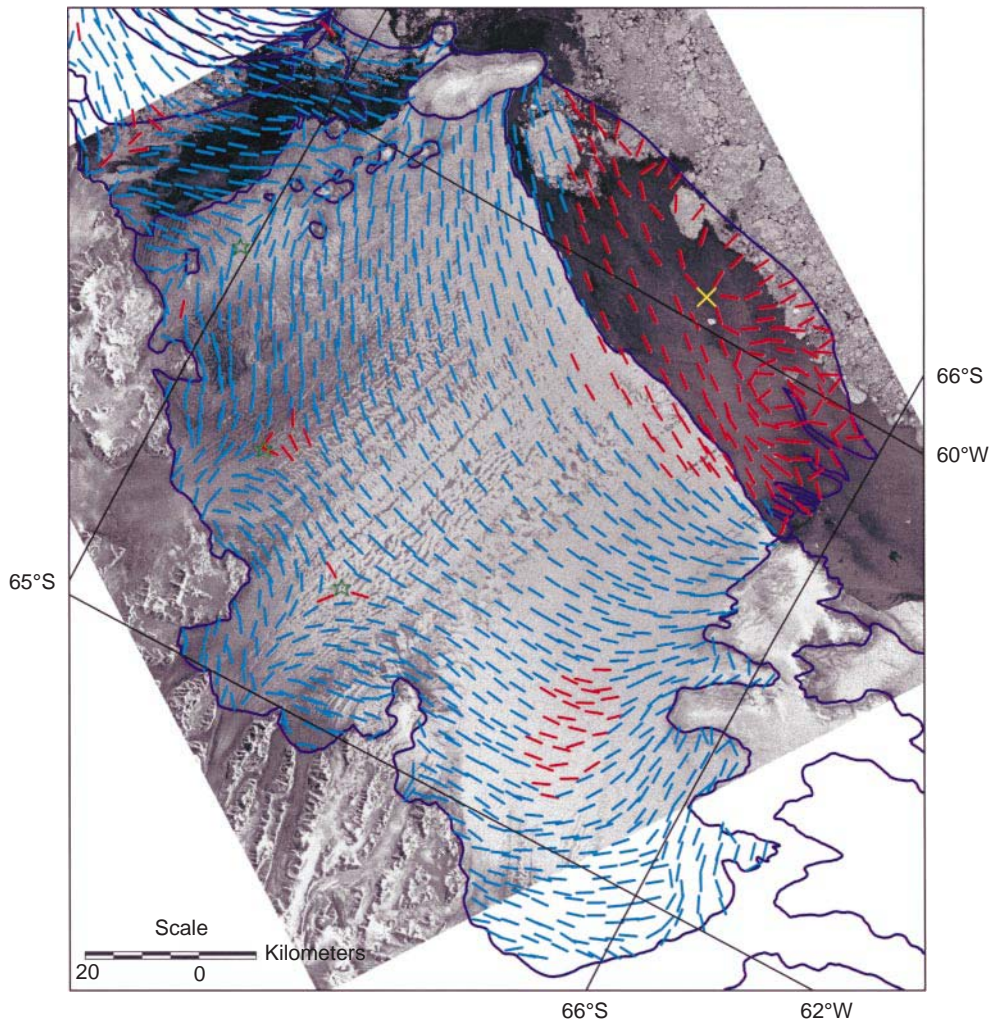


Figure 5 Modeled strain-rate trajectories on Larsen Ice Shelf superimposed on a Radarsat image taken on 21 March 1997. The trajectory of the smallest principal strain-rate (ϵ_2) is negative (compressing flow, blue) over nearly all the Larsen Ice Shelf in its post-iceberg calving configuration (January 1995) but is positive (red) in the region where the iceberg calved. The pattern shows isotropic points ('stars,' green) near where glaciers enter the ice shelf and, for the 'iceberg' area a 'monstar' (yellow cross) near the ice front. 'Stars' are seen for all the different ice front configurations, indicating that no fundamental change is occurring near the grounding line due to retreat of the ice front. A 'monstar' is only seen for Larsen B before the iceberg calved in 1995. The disappearance of the isotropic point is perhaps a 'weak' indication that the iceberg calving event was greater than expected for normal calving from a stable ice shelf and suggests further retreat may be expected.

ice sheet, especially the West Antarctic Ice Sheet (WAIS). It has been a tenet of the latter part of the twentieth century that the WAIS, known as a marine ice sheet because much of its bed is below sea level, is potentially unstable and may undergo disintegration if the fringing ice shelves were to disappear. However, the theoretical foundations of this belief are shaky and more careful consideration of the relevant dynamics suggests that the WAIS is no more vulnerable than any other part of the ice sheet.

The problem lies in how to model the transition zone between ice sheet and ice shelf. If the transition is sharp, where the basal traction varies over lengths of the order of the ice thickness, then it can be

considered as a passive boundary layer and does not affect the mechanics of the sheet or shelf to first order. Mass conservation must be respected but there is no need to impose further constraints. Requiring the ice sheet to have the same thickness as the ice shelf at the grounding line permits only two stable grounding line positions for a bed geometry which deepens inland. Depending on the depth of the bed below sea level, the ice sheet will either shrink in size until it disappears (or, if the bed shallows again, the grounding line is fixed on a bed near sea level), or grow to the edge of the continental shelf. The lack of intermediate stable grounding line positions in this kind of model has been used to

support the idea of instability of marine ice sheets. However, permitting a jump in ice thickness at the transition zone means the ice sheet system can be in neutral equilibrium, with an infinite number of steady-state profiles.

Another kind of transition zone is a smooth one, where the basal traction varies gradually, for example, along an ice stream. The equilibrium dynamics have not been worked out for a full three-dimensional flow, but it seems that the presence of ice streams destroys the neutral equilibrium and helps to stabilize marine ice sheets. This emphasizes the importance of understanding the dynamics of ice streams and their role in the marine ice sheet system.

Attempts to include moving grounding lines in whole ice sheet models suffer from incomplete specification of the problem. Assumptions built into the models predispose the results to be either too stable or too unstable. Thus there are no reliable models that can analyze the glaciological history of the Antarctic Ice Sheet. Predictive models rely on linearizations to provide acceptable accuracy for the near future but become progressively less accurate the longer the timescale.

See also

Bottom Water Formation. Icebergs. Ice–Ocean Interaction. Sub Ice-shelf Circulation and Processes.

Further Reading

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IGNEOUS PROVINCES

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Introduction

Large igneous provinces (LIPs) are massive crustal emplacements of predominantly Fe- and Mg-rich (mafic) rock that form by processes other than normal seafloor spreading. LIP rocks are readily distinguishable from the products of the two other major types of magmatism, midocean ridge and arc, on the Earth's surface on the basis of petrologic, geochemical, geochronologic, geophysical, and physical volcanological data. LIPs occur on both the continents and oceans, and include continental flood basalts, volcanic passive margins, oceanic plateaus, submarine ridges, seamounts, and ocean basin flood basalts (Figure 1, Table 1). LIPs and their small-scale

analogs, hot spots, are commonly attributed to decompression melting of hot, low density mantle material known as mantle plumes. This type of magmatism currently represent ~10% of the mass and energy flux from the Earth's deep interior to its crust. The flux may have been higher in the past, but is episodic over geological time, in contrast to the relatively steady-state activity at seafloor spreading centers. Such episodicity reveals dynamic, non-steady-state circulation within the Earth's mantle, and suggests a strong potential for LIP emplacements to contribute to, if not instigate, major environmental changes.

Composition, Physical Volcanology, Crustal Structure, and Mantle Roots

LIPs are defined by the characteristics of their dominantly Fe- and Mg-rich (mafic) extrusive rocks; these most typically consist of subhorizontal, subaerial basalt flows. Individual flows can extend