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Coastal-Change and Glaciological Map of the Amery Ice Shelf Area, Antarctica: 1961–2004

By Kevin M. Foley, Jane G. Ferrigno, Charles Swithinbank,
Richard S. Williams, Jr., and Audrey L. Orndorff

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Conversion Factors

Multiply	**By**	**To obtain**
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)

Coastal-Change and Glaciological Map of the Amery Ice Shelf Area, Antarctica: 1961–2004

By Kevin M. Foley,[1] Jane G. Ferrigno,[1] Charles Swithinbank,[2] Richard S. Williams, Jr.,[3] and Audrey L. Orndorff[1]

Introduction

Measurement of change in area and mass balance of the Antarctic ice sheet is critically important during an interval of global warming, because of implications to rise in global sea level (Oerlemans, 1993; De Angelis and Skvarca, 2003; Zwally and others, 2005; Alley, 2007). For this reason, the U.S. Geological Survey (USGS) has utilized its extensive archive of satellite images to document changes in the cryospheric coastline of Antarctica (Ferrigno and Gould, 1987). Although changes in the areal extent of the Antarctic ice sheet are not directly related to changes in mass balance, the two are related, and the analysis of the changing coastline can yield important data (Williams and others, 2005; Cook and Vaughan, 2010). The results of the analysis are being used to produce a digital database and a number of Geologic Investigations Series Maps (I–2600), which are listed in table 1 and shown in figure 1.

This map portrays coastal change and glaciological features in the Amery Ice Shelf region. The 69 glaciological features shown on the map have all been named and authorized for use on U.S. Government publications, and they are listed in table 2. Ice fronts and coastal change have been delineated from (1) 1961 and 1984 maps from the U.S. Navy Topographic Office and the Defense Mapping Agency (DMA); (2) 1972 to 2003 Landsat imagery; (3) 1997 RADARSAT imagery; (4) the 1999–2004 Landsat Image Mosaic of Antarctica (LIMA); and (5) the 2005 Moderate Resolution Imaging Spectroradiometer (MODIS) Mosaic of Antarctica (MOA). The coastline from the DMA maps was scanned and digitized. The 1970s, 1980s, and 1990s Landsat imagery ice fronts and grounding lines were identified by Charles Swithinbank using 1:500,000-scale black and white photographic prints, then scanned and digitized. The RADARSAT, LIMA, and MOA coastlines were incorporated digitally. It is possible to see some coastal change on the outlet glaciers along the coast, but most of the noticeable change occurs on the Amery Ice Shelf front.

Geographic Description

Amery Ice Shelf, lying between 67.5° and 75° East longitude and 68.5° and 73.3° South latitude, is the largest ice shelf in East Antarctica. The latest measurements of the area of the ice shelf are 71,260 square kilometers (km^2) (Fricker, Allison, and others, 2002) and 62, 620 km^2 (Scambos and others, 2007). The ice shelf is fed primarily by Lambert, Mellor, and Fisher Glaciers; its thickness ranges from 3,000 meters (m) in the center of the grounding line (Rignot, 2002) to less than 300 m at the ice front. Lambert Glacier is considered to be the largest glacier in the world (Allison, 1979), and streaming flow

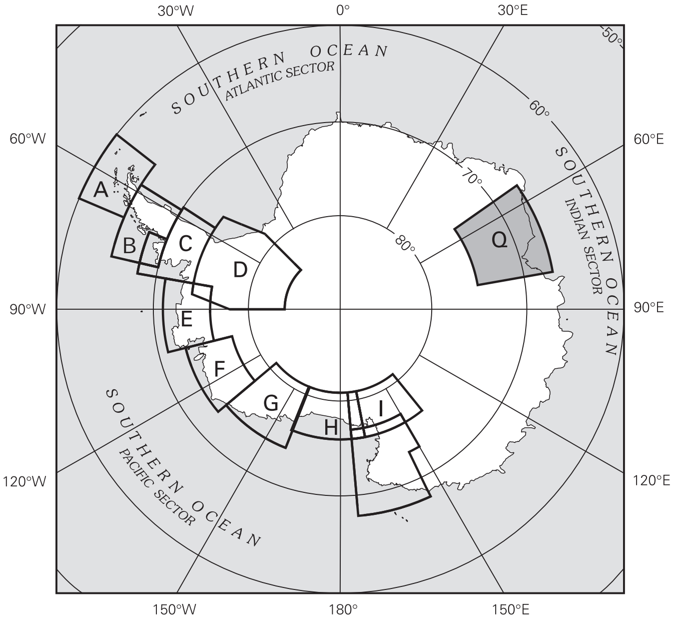

Figure 1. Index map of the planned and published 1:1,000,000-scale coastal-change and glaciological maps of Antarctica. Amery Ice Shelf area map is shaded. Maps published to date are indicated by letter and described in table 1. They are available printed and online; see table 1 for more information.

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Table 1. Coastal-change and glaciological maps of Antarctica at 1:1,000,000 scale, published to date.

[Information on ordering published maps can be obtained by calling the U.S. Geological Survey at 1–888–ASK–USGS or by visiting the USGS online at http://www.usgs.gov/pubprod]

As shown on index map	Map number	Map name	Reference (see References Cited)	URL for online access
A	I–2600–A	Trinity Peninsula and South Shetland Islands	Ferrigno and others (2006)	http://pubs.usgs.gov/imap/2600/A
B	I–2600–B	Larsen Ice Shelf	Ferrigno and others (2008)	http://pubs.usgs.gov/imap/2600/B
C	I–2600–C	Palmer Land	Ferrigno and others (2009)	http://pubs.usgs.gov/imap/2600/C
D	I–2600–D	Ronne Ice Shelf	Ferrigno and others (2005)	http://pubs.usgs.gov/imap/2600/D
E	I–2600–E	Eights Coast	Swithinbank and others (2004)	http://pubs.usgs.gov/imap/2600/E
F	I–2600–F (2d ed.)	Bakutis Coast	Swithinbank and others (2003b)	http://pubs.usgs.gov/imap/2600/F
G	I–2600–G	Saunders Coast	Swithinbank and others (2003a)	http://pubs.usgs.gov/imap/2600/G
H	I–2600–H	Northern Ross Ice Shelf	Ferrigno and others (2007)	http://pubs.usgs.gov/imap/i-2600-h
I	I–2600–I	Ross Island	Ferrigno and others (2010)	http://pubs.usgs.gov/imap/2600/I
Q	I–2600–Q	Amery Ice Shelf	This report	http://pubs.usgs.gov/imap/2600/Q

can be detected for about 1,000 km upglacier using satellite data (Bamber and others, 2000; Fricker, Warner, and Allison, 2000). The Lambert Glacier drainage system drains ice from more than 1 x 10^6 km^2 of the Antarctic interior (Allison, 1991).

Amery Ice Shelf is named after William B. Amery, who represented the Government of the United Kingdom in Australia from 1925 to 1928. The name Cape Amery was originally applied to a coastal feature mapped in 1931 by the British-Australian-New Zealand Antarctic Research Expedition (BANZARE) under the Australian geologist and explorer Douglas Mawson. By 1947, the feature was recognized to be part of an ice shelf and the name was applied to the entire shelf (Alberts, 1995).

History of Discovery and Scientific Research

The following discussion is a brief overview of the history of discovery and scientific research in the Amery Ice Shelf area. For more details, please refer to publications listed in the References Cited.

Early Expeditions

The area was sighted by expeditions of a Norwegian whaling fleet owned by Lars Christensen that sailed along the coast beginning in 1926 (Stonehouse, 2002). In 1936 and 1937, the fleet acquired aerial photographs of the ice front (Law, 1967). Lincoln Ellsworth, an American explorer, flew over the area and discovered and named the American Highland on 11 January 1939 (Alberts, 1995). In February and March 1947, the U.S. Navy took aerial photographs of the eastern ice-front margins as part of Operation Highjump (Robert Allen, USGS, oral commun., 2009). John Roscoe (1952) used these reconnaissance aerial photographs to do the first photogeographical study of the Ingrid Christensen Coast.

Soviet scientists carried out investigations in the Antarctic from whaling fleets beginning in 1947 (Nudel'man, 1968). Regular scientific work was begun in 1956 as part of the International Geophysical Year (IGY). Shipboard observations were made of the Amery ice front, and a landing was made in February 1957 as part of the Second Soviet Antarctic Expedition (Nudel'man, 1966a). During the Fifth Soviet Antarctic Expedition (1959–61), Amery Ice Shelf was observed extensively from the air (Nudel'man, 1966b). Flights in the area of the ice front continued in the 1960s and helped pinpoint the date of the last major calving event between late 1963 and early 1964.

In 1955, the Australian National Antarctic Research Expedition (ANARE) first charted the ice front from a ship (Law, 1967). Aerial photographs and astrofixes determined the eastern, southern, and western margins of the ice front in 1956, 1957, and 1958, respectively (Law, 1967). Surface observations were started in 1962 (Budd and others, 1967).

Major Field Programs

In 1963, the first major field program on Amery Ice Shelf was begun to collect data on elevation, slope, strain rate, surface temperature, snow accumulation, and ice velocity (Budd, 1966). Detailed measurements were continued in 1964. In order to obtain more complete data, a year-long field program was planned by ANARE to start in 1968; it included ice-core drilling, ice-thickness sounding, and snow-accumulation measurements, in addition to oversnow traverses. Among the results was the discovery of the presence of a large amount of

Table 2. Inventory of named glaciological features on the coastal-change and glaciological map of the Amery Ice Shelf area.

Glaciological feature	Coordinates
Allison Dome	73° 33′ S. 70° 36′ E.
Amery Ice Shelf	69° 45′ S. 71° 00′ E.
Arriens Glacier	73° 28′ S. 68° 24′ E.
Battye Glacier	70° 52′ S. 67° 46′ E.
Browns Glacier	68° 56′ S. 78° 00′ E.
Brunvoll Glacier	67° 48′ S. 66° 48′ E.
Budd Ice Rumples	71° 29′ S. 68° 46′ E.
Chaos Glacier	69° 01′ S. 78° 00′ E.
Charybdis Glacier	70° 25′ S. 67° 30′ E.
Collins Glacier	73° 40′ S. 65° 40′ E.
Cosgrove Glacier	67° 29′ S. 59° 10′ E.
Dålk Glacier	69° 26′ S. 76° 27′ E.
Dingsør Dome	68° 01′ S. 67° 43′ E.
Dolinnyy Glacier	73° 01′ S. 68° 14′ E.
England Glacier	73° 30′ S. 68° 23′ E.
Fisher Glacier	73° 15′ S. 66° 00′ E.
Flatnes Ice Tongue	69° 16′ S. 76° 44′ E.
Forbes Glacier	67° 39′ S. 62° 22′ E.
Frustration Dome	68° 00′ S. 64° 33′ E.
Geysen Glacier	73° 28′ S. 64° 33′ E.
Glukhoy Glacier	70° 48′ S. 67° 46′ E.
Greenall Glacier	73° 13′ S. 68° 18′ E.
Hargreaves Glacier	69° 48′ S. 74° 20′ E.
Helmore Glacier	73° 04′ S. 68° 19′ E.
Hoseason Glacier	67° 12′ S. 58° 07′ E.
Hovde Glacier	69° 15′ S. 76° 55′ E.
Il Polo Glacier	69° 53′ S. 74° 45′ E.
Korotkiy Glacier	72° 51′ S. 68° 09′ E.
Kreitzer Glacier	70° 22′ S. 72° 36′ E.
Kronshtadtskiy Glacier	71° 43′ S. 71° 35′ E.
Lambert Glacier	73° 30′ S. 67° 35′ E.
Lepekhin Glacier	72° 27′ S. 69° 40′ E.
Manning Glacier	73° 10′ S. 68° 14′ E.
McKinnon Glacier	70° 38′ S. 67° 45′ E.
Mellor Glacier	73° 30′ S. 66° 30′ E.

Table 2. Inventory of named glaciological features on the coastal-change and glaciological map of the Amery Ice Shelf area.—Continued

Glaciological feature	Coordinates
Morgan Glacier	73° 17′ S. 68° 17′ E.
Mulebreen	67° 25′ S. 59° 21′ E.
Nemesis Glacier	70° 32′ S. 67° 30′ E.
Peterson Icefalls	70° 05′ S. 72° 44′ E.
Petkovic Glacier	72° 58′ S. 68° 14′ E.
Pionerskiy Dome	73° 59′ S. 73° 08′ E.
Polarårboken Glacier	69° 35′ S. 75° 50′ E.
Polarforschung Glacier	69° 53′ S. 75° 07′ E.
Polar Record Glacier	69° 48′ S. 75° 35′ E.
Polar Times Glacier	69° 53′ S. 74° 35′ E.
Publications Ice Shelf	69° 38′ S. 75° 20′ E.
Ranvik Glacier	69° 10′ S. 77° 40′ E.
Razdelyayushchiy Glacier	73° 32′ S. 66° 47′ E.
Robert Glacier	67° 14′ S. 56° 18′ E.
Rofe Glacier	72° 52′ S. 68° 19′ E.
Rogers Glacier	69° 55′ S. 73° 07′ E.
Scoble Glacier	67° 23′ S. 60° 22′ E.
Scylla Glacier	70° 20′ S. 67° 00′ E.
Shennong Glacier	69° 30′ S. 76° 02′ E.
Sheraton Glacier	73° 27′ S. 68° 24′ E.
Sørsdal Glacier	68° 41′ S. 78° 25′ E.
Sørsdal Glacier Tongue	68° 42′ S. 78° 00′ E.
Stevenson Glacier	70° 06′ S. 72° 48′ E.
Strahan Glacier	67° 38′ S. 64° 37′ E.
Styles Glacier	72° 38′ S. 68° 19′ E.
Tekuchiy Glacier	69° 52′ S. 68° 12′ E.
Tingey Glacier	73° 34′ S. 68° 25′ E.
Trail Glacier	73° 28′ S. 61° 54′ E.
Turk Glacier	73° 21′ S. 68° 24′ E.
Utstikkar Glacier	67° 33′ S. 61° 20′ E.
Utstikkar Glacier Tongue	67° 30′ S. 61° 22′ E.
Venture Dome	68° 36′ S. 62° 13′ E.
Vrana Dome	69° 53′ S. 73° 28′ E.
Wilma Glacier	67° 12′ S. 55° 52′ E.

basal ice under the ice shelf and the location of the grounding line at about lat 71.2° S., based on changes in the surficial ice slope (Budd and others, 1982).

From 1988 to 1995, the Australian Antarctic Division carried out an extensive glaciology program on the ice shelf and in the vast interior of the Amery Ice Shelf drainage basin, using both ground and aerial surveys to provide data on all parts of the drainage system, with emphasis on determining the mass balance of the system and the long-term response of the basin to global climate change. Measurements showed no change in the long-term average velocity of the ice shelf or in its surface elevation. Gravity measurements revealed a uniform depth to bedrock of 1,000 m beneath the centerline of the ice shelf, which is consistent with bathymetric and ice-thickness observations (Kiernan, 2001). An excellent overview of Australian scientific activities on Amery Ice Shelf during the last 50 years is given by Janssen and Hurd (2008).

Early Studies Using Satellite Data

An early use of Landsat to study the Amery Ice Shelf area was the combination of Seasat radar altimetry data with an uncontrolled Landsat Multispectral Scanner (MSS) mosaic (Brooks and others, 1983). The result showed contoured topography, flow lines of glaciers feeding the ice shelf, and transverse fractures caused by the obstruction of ice flow. It was the first presentation of surface elevations and topographic detail that covered most of Amery Ice Shelf.

Hambrey and Dowdeswell (1994) used digital MSS Landsat imagery to analyze ice structure on Lambert Glacier and Amery Ice Shelf to determine flow patterns and flow regime. They concluded that (1) the absence of surge-type patterns indicates the system has had a constant flow regime, even though the ice thickness and mass balance may have changed, and that (2) constant flow has been maintained throughout the thousand-year history suggested by velocity data for ice along the centerline of the drainage basin.

AMISOR Project

Recognizing the importance of the interaction between Amery Ice Shelf and the adjacent and sub-ice-shelf ocean waters, as well as the effect on both the Antarctic ice-sheet mass budget and the ocean circulation as a result of changes in either the ice or the ocean, the Australian Antarctic Division in 2000 started a multidisciplinary project to study these topics—AMISOR, the Amery Ice Shelf Ocean Research Project (Allison, 2006). Among the studies undertaken, hot-water drilling through the ice enabled scientists to measure the cavity (the area between the bottom of the ice shelf and the sea-floor sediments) and to estimate the amount of melting and refreezing occurring at the bottom of the ice shelf, in order to validate ocean-circulation models. Seismic surveys also were conducted to define the shape of the cavity. Other studies included investigations of sub-ice-shelf sediments and sediment dynamics; oceanographic measurements in Prydz Bay; glaciological measurements of ice-shelf velocity, strain, and thickness; remote sensing; and numerical modeling of ice-shelf dynamics and ice-shelf and ocean interaction.

Other Studies

In the 1990s, a digital elevation model (DEM) of the Amery Ice Shelf and Lambert Glacier basin was derived using satellite radar altimetry data from the European Space Agency Remote Sensing Satellite ERS–1 (Fricker, Hyland, and others, 2000). Fricker and others (2001) were able to map the marine ice accreted to the base of Amery Ice Shelf by subtracting a radio-echo-sounding (RES) ice-thickness map that mapped only the freshwater ice, from a total ice-thickness map obtained by converting their DEM of the ice shelf. The marine ice ranged in thickness from a maximum of 190 m in the northwestern part of the ice shelf to 0 m in the southeastern part. Further detailed study of the marine ice was reported by Craven and others (2009).

King and others (2009) looked at long-term surface elevation changes of the central part of the ice shelf by comparing records from 1968 to 2007 that had been acquired by optical leveling, ERS radar altimetry, global positioning system (GPS), and Ice, Cloud, and land Elevation Satellite (ICESat) laser altimetry. They emphasized the importance of multidecadal observations and cautioned that emphasis on short-term changes can be misleading.

Fricker, Allison, and others (2002) used many data sources to redefine the location of the grounding zone of Amery Ice Shelf. They combined a DEM created from ERS–1 satellite radar altimetry with measured ice thicknesses and a simple density model in a buoyancy calculation to determine the extent of the floating ice. The calculation showed that the ice is floating as far south as lat 73.2° S., about 240 km farther south than originally thought. The result was confirmed by static GPS height measurements, analysis of Landsat imagery, mass-flux calculations, and ice-radar data. Fricker and others (2009) remapped the grounding zone using interferometric synthetic aperture radar (InSAR), MOA, and ICESat data. The new mapping reveals several ice rises and other areas of grounding that had been undocumented, and it will increase the accuracy of models of the ice shelf and models of ice-ocean interactions.

Studies relating to potential melting in the Amery Ice Shelf area include those by Rignot and Jacobs (2002) and Williams and others (2002). Rignot and Jacobs (2002) calculated the bottom melt rate of large ice streams just seaward of their grounding lines, where melting is correlated with thermal forcing of the ocean water, and determined that melt rates are far higher than generally assumed. The melt rate at the Lambert Glacier grounding line was the third highest calculated for Antarctica—31±5 meters per year (m a^{-1}), exceeded only by Pine Island and Thwaites Glaciers. These results may have major ramifications because of the potential impact on ice-sheet stability. Williams and others (2002) showed with modeling that ocean warming would increase ice-shelf melting and significantly impact the dynamics of the Antarctic ice sheet.

Velocity Estimates

Budd and others (1967) calculated ice velocities of 400 m a^{-1} at the southern end of Amery Ice Shelf and 800 m a^{-1} at a point 66 km from the ice front. By comparing an astrofix at the front of the ice shelf taken by the Soviet expedition in 1957 with one taken by ANARE in 1963, they estimated the velocity at the front to be 1,500±300 m a^{-1}.

Manson and others (2000) collected five seasons of GPS data between 1988 and 1995 to provide ice-surface velocity information at the 2,500-m topographic contour around the Amery Ice Shelf basin. The velocities varied between 0.5 m a^{-1} and 63 m a^{-1}, with the higher values on outlet glaciers and at locations near the coast.

Since 2002, the Chinese National Antarctica Research Expedition (CHINARE) has been working on Amery Ice Shelf. In the 2002–03 and 2003–04 seasons, they used static GPS to determine ice velocities at five sites near the front of the ice shelf (Zhang and others, 2006). The velocity values ranged from 900 m a^{-1} to more than 1,500 m a^{-1}, with the higher values in the center of the ice shelf, increasing toward the ice front, as would be expected. Some of the CHINARE field measurements, in addition to remote sensing data, were used by Wen and others (2007) in their calculation that the mass budgets of the Lambert, Mellor, and Fisher Glaciers are overall close to balance.

Young and Hyland (2002) used two sets of RADARSAT synthetic aperture radar (SAR) data acquired 24 days apart in September and October 1997 to generate ice-velocity estimates, using interferometric analysis (InSAR) of most of Amery Ice Shelf and adjoining grounded ice. Their results showed maximum values of 1,300 to 1,350 m a^{-1} at the center of the ice front. Inland, the velocity decreased toward the central area of the ice shelf, where it was 300 to 350 m a^{-1}; but continuing south the velocity increased, reaching a maximum about 550 km from the ice front. Here the velocity was about 800 m a^{-1} on Mellor Glacier and 930 m a^{-1} on Lambert Glacier. Young and Hyland (2002) concluded the transit time of ice from the grounding zone to the ice front was 1,100 years. The strain-rate field derived from the velocity estimates delineated the shear margins along the boundaries between the flow bands of the different ice streams that converge to form Amery Ice Shelf. Joughin (2002) used a combined InSAR and speckle-tracking method to analyze the same RADARSAT data to produce a velocity mosaic of Amery Ice Shelf. His results showed a similar pattern but somewhat slower velocities.

King and others (2007) compared geodetic-quality ice-velocity measurements in the northern part of Amery Ice Shelf made in the 1960s with GPS studies made during the 1990s to determine if there had been any multidecadal change. They found general agreement at similar geographic locations, but with the possibility of a small (~2.2 m a^{-1}) slowdown in overall velocity of the ice shelf.

The vectors representing ice velocity on this map are a subset of the velocity data compiled from various sources by the National Snow and Ice Data Center (NSIDC) VELMAP project (see the Information Sources section on the map). These data were acquired in the field by repeat geodetic surveys using a combination of standard surveying techniques, electronic distance measurement, and GPS and, in the laboratory, by analysis of satellite-acquired remote sensing data. The data were collected between 1968 and 1995. The velocity vectors represent data collected from a traverse of the drainage basin perimeter at approximately the 2,500-m elevation level. The data were collected between 1989 and 1995 by the Australian Antarctic Division, and they were combined with ice-thickness data to estimate the ice flow across the line defined by the traverse. Approximately 47 gigatonnes per year (Gt a^{-1}) of ice flows across the traverse line, of which approximately 44 Gt a^{-1} discharges through Amery Ice Shelf (Kiernan, 2001).

Coastal Change

Between the Lars Christenson Expedition of 1936 and an ANARE astrofix made in 1963, the Amery Ice Shelf front advanced steadily at a rate of approximately 1,500 m a^{-1}. However, between late 1963 and early 1964, a large piece of the ice shelf, about 9,600 km^2, calved and floated to the west. This iceberg represented about 40 years' worth of ice advance and approximately 20 percent of the ice shelf area (Budd and others, 1967). From 1965 to 2004, the ice front advanced with minimal calving, reflected in the ice-front observations shown on the map for 1969, 1974, 1988, 1997, 2003, and 2004. However, a rift noticeable in 1997 expanded in 2003 and 2004; typically an expanding rift signals the location of the next calving event. A cooperative U.S.-Australian project to monitor the propagating rift and the potential iceberg (30 km by 30 km, colloquially called the "loose tooth") was carried out during three field seasons from 2002 to 2006, examining seven episodes of rift propagation. The purpose was to determine if rift propagation and calving occur in response to short-term climate forcing through changes in winds, tides, and swell or changes in air or water temperature (Bassis and others, 2005, 2007, 2008; Fricker and others, 2005). Bassis and others (2008) concluded that the rifting process is insensitive to short-term climatic events and is driven primarily by internal glaciological stress. As of March 2010, the "loose tooth" was still attached. Fricker, Young, and others (2002) investigated the iceberg-calving cycle of Amery Ice Shelf from 1963 to the 2000s and concluded that the calving behavior follows a regular pattern in which ice-shelf advance is punctuated by calving every 60 to 70 years.

In order to help understand the mechanism of calving from ice shelves, Alley and others (2008) proposed a simple law for ice-shelf calving. They hypothesized that along-flow ice-shelf spreading is the dominant control on calving. Preliminary comparisons of various ice shelves using their hypothesis are supportive of the concept.

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