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The calving and drift of iceberg B-9 in the Ross Sea, Antarctica

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Abstract: Major rifts in the Ross Ice Shelf controlled the October 1987 calving of the 154 x 35 km "B-9" iceberg, one of the longest on record. The 2000 km, 22 month drift of this iceberg and the quite different tracks of smaller bergs that calved with it have extended our understanding of the ocean circulation in the Ross Sea. B-9 initially moved north-west for seven months until deflected southward by a subsurface current which caused it to collide with the ice shelf in August 1988. It then completed a 100 km-radius gyre on the east-central shelf before resuming its north-westerly drift. Based upon weekly locations, derived from NOAA-10 and DMSP satellite and more frequent ARGOS data buoy positions, B-9 moved at an average speed of 2.4 km day^{-1} over the continental shelf. It was not grounded there at any time, but cast a large shadow of open water or reduced ice thickness during the austral winters. B-9 was captured by the continental slope current in May 1989, and attained a maximum velocity of 13 km day^{-1} before breaking into three pieces north of Cape Adare in early August 1989.

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Introduction

A very long tabular iceberg, 154 km x 35 km, calved from the eastern Ross Ice Shelf between Roosevelt Island and Edward VII Peninsula in late 1987 (Fig. 1). This was not the longest iceberg on record, as the whale catcher *Odd 1* reported a 170–180 km specimen in 1927 (Wordie & Kemp 1933). The British ship *Balaena* encountered a 145 km x 40 km iceberg near 65°S, 150°W in February 1953 (Neumann & Pierson 1966, p 74). The similarity of these dimensions to other reports (e.g., McIntyre & Cudlip 1987) suggests that large aspect ratios (length/width) may be common to big icebergs. The largest iceberg in recent times (~95 km x 95 km) calved from the Larsen Ice Shelf in early 1986 (Ferrigno & Gould 1987). Even larger calving events have produced an assortment of large and small bergs, but different accounts of such events and individual iceberg sizes can vary widely (Swithinbank *et al.* 1977, Jacobs & Barnett 1987).

The main aim of this report is to describe and interpret the calving and drift of iceberg B-9. This iceberg was labelled for its quadrant of origin (90°–180°W) and sequence since iceberg monitoring began in 1974 by the Naval Polar Oceanography Center. This Suitland MD facility, also referred to as the Navy/NOAA (National Oceanic and Atmospheric Administration) Joint Ice Center, records iceberg positions and dimensions on its weekly northern ice limit charts (e.g., Navy/NOAA 1987–88). The popular interest in large icebergs was abetted in this case by the availability and wide dissemination of a LANDSAT 4 image (Fig. 2) shortly after the calving event. The tracking of large bergs by satellite (e.g., Swithinbank *et al.* 1977) can provide useful information about ocean currents, thickness of the ice, and its interactions with the sea ice and sea floor. Iceberg formation provides an opportunity to study calving mechanisms, and is a major factor in the Antarctic ice sheet mass balance. We consider these topics in the context of relevant ocean and ice shelf measurements.

The calving event and size of B-9

Iceberg B-9 calved from the eastern Ross Ice Shelf between the former Bay of Whales and Edward VII Peninsula on the Shirase Coast, i.e. from ~ 158°W–164°W (Figs. 1 & 3). According to NOAA-10 satellite imagery, separation occurred between 25 September and 13 October 1987. B-9 was estimated from the 28 November 1987 LANDSAT image (Fig.2) to have maximum dimensions of 154 x 35 km shortly after calving, and an area of ~ 4540 km^2 (J. Zwally, personal communication 1989). A larger estimate of 4750 km^2 (Eustis 1987) may have included several of the smaller bergs near B-9 in Fig. 2. In December 1987, B-9's length was shortened to 141 km by the loss of ice from its eastern end. The LANDSAT image shows the sawtooth outline of an apparent ice cliff rising above lower-lying ice to the north-east. This feature is similar to the eastern ice front mapped in Fig. 3, and inferred from a 1961 oblique aerial photograph (Swithinbank 1988, fig. 3, p. B5) to separate shelf ice from fast sea ice. This thinner, multi-year sea ice formed most of the fragment which broke away in December 1987 (Fig. 4a, b). No additional disintegration of any consequence occurred until 3–12 August 1989 when B-9 split into three pieces off Cape Adare.

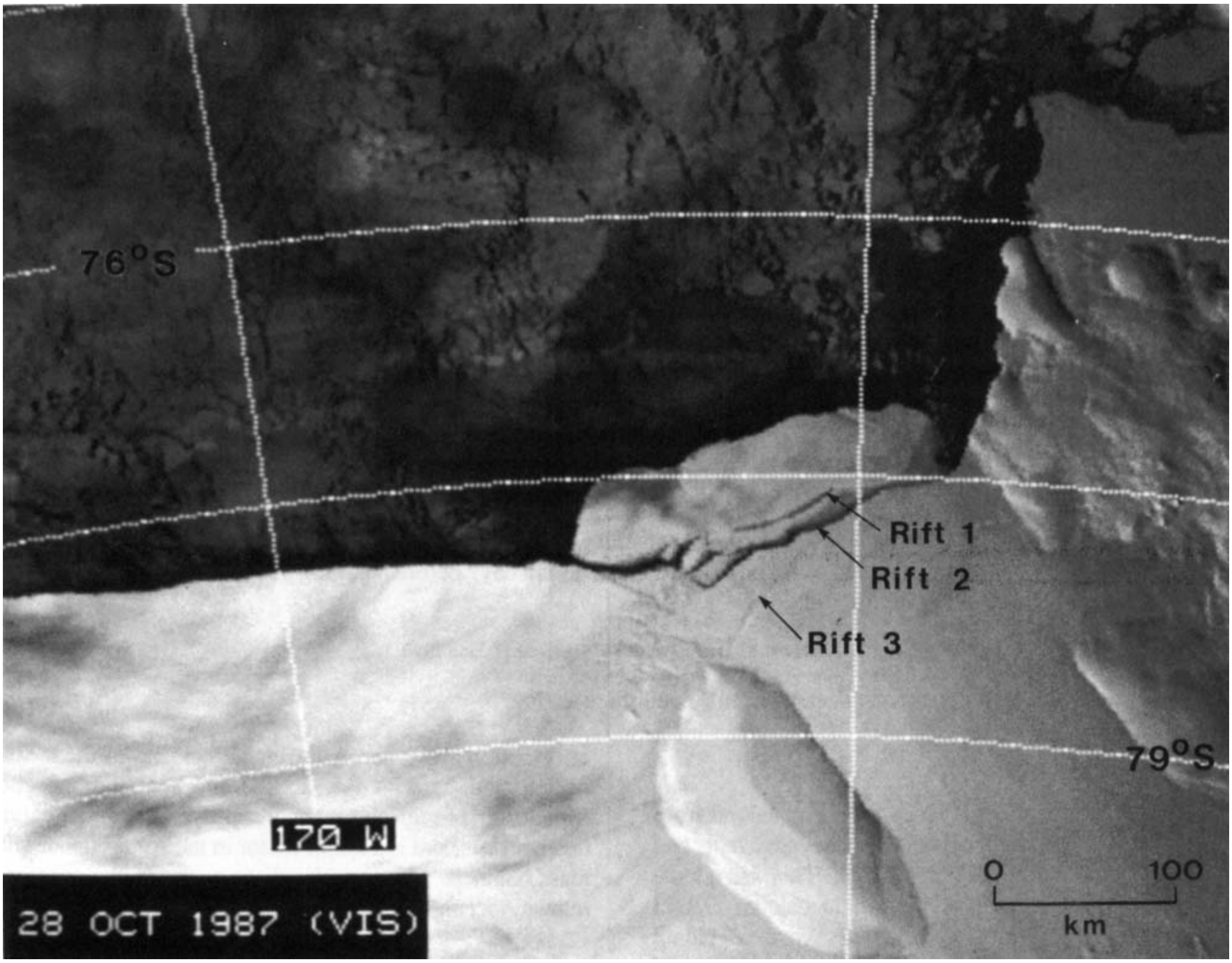

Fig. 1. NOAA AVHRR visible channel satellite image of B-9 on 28 October 1987, shortly after calving from the Ross Ice Shelf. The latitude x longitude grid is 1° (112 km) x 10°. The oblate area of higher relief to the south of B-9 is Roosevelt Island. Edward VII Peninsula lies directly east of B-9. The northernmost linear opening in the ice is labelled Rift 1 on Fig. 3. The larger opening about 20 km south of Rift 1 will form the new ice front and is labelled Rift 2 on Fig. 3. A third rift noted on Fig. 3 is just visible extending north-east from Roosevelt Island in this image. Picture courtesy of the Antarctic Research Center, Scripps Institute of Oceanography, San Diego.

Before the B-9 calving event the eastern Ross Ice Shelf front was farther north than it had been since 1954–55, and possibly at its greatest extension this century (Jacobs *et al.* 1986). The perimeter of the future B-9 had mostly formed by 1971, and well before 1962 its ends were delineated by the Bay of Whales on the west and Okuma Bay on the east (Fig.3). The width of B-9 and the shape of its initial southern side indicate that the iceberg calved along a large rift about 35 km south of the ice front (Rift 1 on Fig. 3). This feature resembled the former Grand Chasm in the Filchner Ice Shelf (C. Swithinbank, personal communication 1988), which was another site of major calving into the Weddell Sea in 1986 (Ferrigno & Gould 1987). When mapped between 1965 and 1971, Rift 1 extended ~100 km east-north-east from the crevassed area between the Bay of Whales and Roosevelt Island. Its 4 km-wide floor was 45 m below the surface of the ice shelf in 1973–78 (Shabtaie & Bentley 1982, fig. 8a). Between early 1983 and early 1985 the Bay of Whales extended eastward toward this rift, as illustrated by the January 1987 profile in Fig. 3.

We do not know what triggered the actual calving of B-9. Estimates of ice front advance suggest a recent rate increase in this sector (0.31–0.38 km a^{-1} on the SPRI/NSF 1972 map; >0.5 km a^{-1} in Thomas *et al.* 1984; >0.8 km a^{-1} in Jacobs *et al.* 1986). The last value may have been an artifact of measuring the northward effect of a north-westerly advance, but the ice front movement could have accelerated if shearing or opening occurred along existing rifts or if new rifts were created. A third linear feature (Rift 3 in Fig. 1) can be detected on NOAA-10 AVHRR (Advanced Very High Resolution Radiometer) visible channel imagery, about 20 km south of Rift 2. Rifting there (up to 50 km south of the

Fig. 2. LANDSAT 4 image on 28 November 1987 showing B-9, smaller icebergs that originated in the same calving event, and floes of sea ice which have lower brightness. Landsat data courtesy of Earth Observation Satellite Company, Lanham, Maryland.

ice front) may be associated with compression of ice flowing between Roosevelt Island and Shirase Coast and with further shearing due to different flow directions downstream of Roosevelt Island (Fig. 4a). Shabtaie & Bentley (1982) argued that rifts and bottom crevasses near Roosevelt Island are potential calving sites since they are generated close to the ice front and probably contain mostly unfrozen seawater. Rift 1 had opened along much of the distance between the Bay of Whales and Edward VII Peninsula by early 1987 (Fig. 3) when calving could have been regarded as imminent. During October 1987 the mean wind speed at Automatic Weather Station 8900, 200 km west of the Bay of Whales, was only 4.6 m s^{-1} (Sievers *et al.* 1988, p. 201). No unusual storms were recorded during that month or the latter part of September. Prevailing ocean currents beneath this section of the ice shelf are from the south-east (see below), but likely drag forces are much lower than typical bulk ice shear strengths. No record of wave or swell energy is available.

At least 25 smaller icebergs were formed during the B-9 calving event, the largest ~14 x 7 km and 11 others over 5 km in length (Figs. 1 and 4). Some of these and a number of sea ice floes are visible in the LANDSAT image (Fig. 2). The pre-calving disposition of these icebergs can be reconstructed (Fig. 4b, c) from the shapes and fracture patterns visible on this image and from NOAA-10 AVHRR (visible channel) data. These smaller bergs originated from an area of about 750 km^2 between Rifts 1 and 2 in Fig. 3. A NOAA image on 16 October 1987 suggests that initial separation may have

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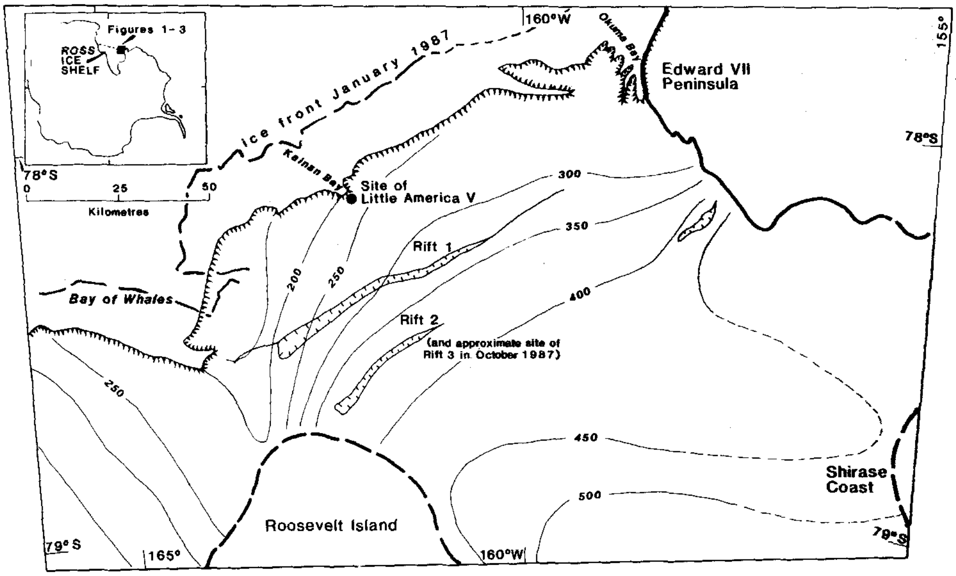

Fig. 3. Map of the north-eastern corner of Ross Ice Shelf showing the position of the ice front, ice thickness isopachs (m) and Rifts 1 & 2 in 1969–70 (after USGS/NSF, 1972). B-9 calved from Rift 1 but smaller bergs originated from between Rifts 1 & 2 (see Figs 1 & 4a–c). The approximate January 1987 position of the ice front was obtained by radar ranging from the USCG. icebreaker *Polar Sea*.

been greater along Rift 2.

The Bay of Whales, named by Ernest Shackleton in the Nimrod in January 1908, was largely eliminated by the B-9 calving event. It had persisted at longitudes 163–66°W at least since the beginning of the century, but had undergone large changes in configuration during this period. An excerpt from *Heart of the Antarctic* (Shackleton 1909 p.75) is of interest in this regard: "We were steaming along westward close to the Barrier, and according to the chart we were due to be abreast of the inlet about 6 A.M., but not a sign was there of the opening. We had passed Borchgrevink's Bight at 1 A.M., and at 8 A.M. were well past the place where Barrier Inlet ought to have been. The Inlet had disappeared, owing to miles of the Barrier having calved away, leaving a long wide bay joining up with Borchgrevink's Inlet, and the whole was now merged into what we had called the Bay of Whales. This was a great disappointment to us, but we were thankful that the Barrier had broken away before we had made our camp on it. It was bad enough to try and make for a port that had been wiped off the face of the earth, when all the intended inhabitants were safe aboard ship, but it would have been infinitely worse if we had landed there whilst the place was still in existence, and that when the ship returned to take us off she would find the place gone." The Bay has been utilized as the base for several expeditions since 1911. A new indentation, formed during the calving event at the south-west end of former Rift 2 (Figs 3 & 4) may mark the initial redevelopment of the Bay, as ice deformation and minor calving continue downstream from Roosevelt Island. In the longer term, the continued existence of the Bay of Whales may depend upon a mean ice front location within several tens of km north of Roosevelt Island.

Thickness, volume and draft of B-9

B-9 calved from an area of the ice shelf that was up to 340m thick in the early 1970's (Fig. 3). Ice thicknesses were derived from radio echo soundings obtained by the Scott Polar Research Institute and the U.S. National Science Foundation between 1967 and 1972 (Robin 1975, Shabtaie & Bentley 1982). A thickness of about 220 m is indicated for the vicinity of Little America V station, consistent with that given by Bentley *et al.* (1979). A thickness of 257 m was measured by drilling at that site in 1958–59, at which time there was no evidence of basal accretion of saline ice (Crary *et al.* 1962). If the drilled and radio echo sounding thicknesses were representative of the area, that would indicate a thinning rate of 3–4 m a^{-1} near the ice front. The mass balance equation

$$dH/dT = A - M - H\dot{\varepsilon}$$

from Crary *et al.* (1962), gives a bottom melting rate M of 3.1–4.9 m a^{-1}, where H is taken as the ice thickness in 1958–59, A is the accumulation rate (0.27 m a^{-1} from Clausen *et al.* 1979) and $\dot{\varepsilon}$ is the vertical strain rate (-210×10^{-5} from Crary 1961). The melt rate could be expected to decrease rapidly south of the ice front. From Fig. 3, thinning rates of 2–4 m a^{-1} suggest that when B-9 calved it ranged in thickness from less than 100 m at its western end to about 300 m midway along its southern side.

An average thickness of 230 m and an adjusted area of 4450 km^2, to allow for the fast sea ice that broke away in December 1987, gives a volume of >1000 km^3 for B-9. The entire calving event, including the smaller but potentially thicker bergs (see Fig. 3), would then have involved ~1200 km^3 or about 0.5% of the Ross Ice Shelf volume given in Drewry (1983). The maximum freeboard of B-9 was about 50 m (Eustis 1987). From freeboard-thickness relationships for the Ross Ice Shelf (Shabtaie & Bentley 1982), this would indicate a maximum draught around 250 m in an untilted state. That is consistent with average densities of ~850 kg m^{-3} for tabular icebergs derived from the Ross Ice Shelf and

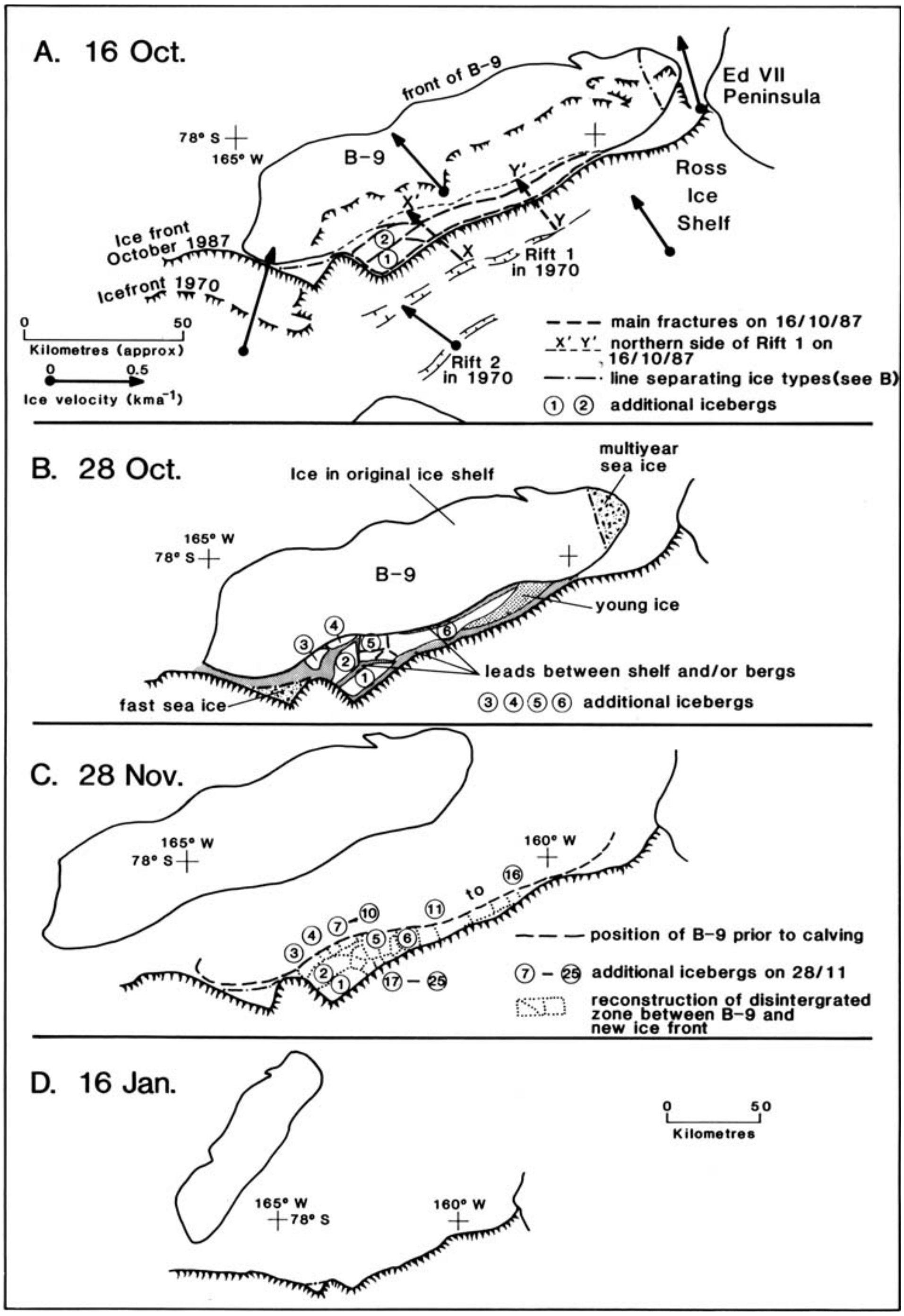

Fig. 4. Sequence of calving of B-9, and disintegration of the area between Rifts 1 and 2 into smaller icebergs. The sketches are not exactly to scale because of rectification errors and non-vertical look angles.
(a) 16 October 1987 when B-9 was 0–10 km from the calving site. The movement of points X and Y on the north side of Rift 1 to points X' and Y' on B-9 relate the B-9 calving to the rift zone. Ice velocities are after Robin (1975) and Thomas *et al.* (1984). The closest correspondence between ice velocity and ice front advance is near the east end of B-9 where the flow and advance directions were similar and rifting was least. Here the ice front moved ~ 10 km between 1969–70 and 1987, or 0.5–0.6 km a^{-1} (see text).
(b) 28 October when B-9 was 10–50 km west-north-west of the calving site. The area between Rifts 1 and 2 had then broken into several moderate-sized icebergs.
(c) 28 November (Fig. 2) when B-9 was 50–100 km west-north-west of the calving site. From this reconstruction, the area between Rifts 1 and 2 fragmented into 25 icebergs longer than about 2.5 km. These could be distinguished from sea ice floes by shading and relationship to the larger bergs in 4b.
(d) 16 January 1989 when B-9 was 100–180 km west-north-west of the calving site. By this time an area of multiyear sea ice had calved off the original east-north-east end.

grounded along the Victoria Land coast of the western Ross Sea (Keys & Fowler 1989).

Drift patterns

After calving, B-9 drifted in a complex manner over the continental shelf in the eastern Ross Sea for about 19 months (Fig. 5). The co-ordinates of its approximate centre point have been taken from the weekly Northern Ice Limit Charts (e.g., Navy/NOAA 1987–88), edited and summarized in Table I. Up to 20 July 1988 the weekly positions were determined from NOAA or DMSP satellite imagery to an accuracy of 10–15 km. During this period distances between successive fixes were often smaller than the measurement error, but useful data can be obtained from running averages and the changing long axis orientation (Table I, Figs 6, 7 & 8). Accuracy was improved to 0.3 km in late June 1988 when an ARGOS buoy was dropped on B-9, about 4 km from its centre point, during a winter re-supply flight to McMurdo Station (Moritz 1988). From 29 October 1987 until 11 May

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Table I. The positions and drift of iceberg B-9 in the Ross Sea. Data from NOAA (N-9 and N-10) and DMSP satellite imagery and ARGOS telemetry. Edited from Navy-NOAA (1987–89) weekly ice charts and status reports. The DMSP data have a resolution of ~4 km, the NOAA data ~1 km, and the ARGOS positions ~0.3 km. Early data are rounded to reflect lower accuracy.

Date	Latitude	Longitude	Data Source	Elapsed Days	Distance km	Speed km/day	Days Since Calving	Long Axis Orientn.
13-Oct-87	78 10S	161 25W	N-10	0-18	0-10	-	0	70/250
21-Oct-87	78 10S	161 25W	N-10	8	0- 3	0	8	
29-Oct-87	78 06S	162 50W	DMSP	8	37	5	16	
05-Nov-87	77 50S	163 15W	N-10	7	30	4	23	
11-Nov-87	77 55S	164 10W	N-10	6	25	4	29	
19-Nov-87	78-00S	164 20W	DMSP	8	10	1	37	ca 50/230
25-Nov-87	77 55S	164 55W	DMSP	6	17	3	43	
03-Dec-87	77 55S	165 05W	DMSP	8	4	1	51	
10-Dec-87	77 55S	165 15W	DMSP	7	4	1	58	
17-Dec-87	77 50S	165 30W	DMSP	7	10	1	65	
22-Dec-87	77 35S	166 00W	N-10	5	31	6	70	
29-Dec-87	77 35S	166 00W	DMSP	7	0	0	77	
06-Jan-88	77 35S	166 05W	N-10	8	2	0	85	
13-Jan-88	77 45S	166 40W	DMSP	7	23	3	92	
21-Jan-88	77 45S	167 00W	N-10	8	8	1	100	
28-Jan-88	77 40S	166 10W	DMSP	7	23	3	107	
08-Feb-88	77 30S	166 55W	N-10	11	20	2	118	
17-Feb-88	77 35S	166 55W	N-9	9	26	3	127	65/245
23-Feb-88	77 40S	168 10W	DMSP	6	31	5	133	
03-Mar-88	77 35S	167 15W	DMSP	9	22	2	142	60/240
09-Mar-88	77 35S	167 20W	DMSP	6	2	0	148	
16-Mar-88	77 30S	167 35W	DMSP	7	13	2	155	63/243
23-Mar-88	77 25S	167 50W	DMSP	7	10	1	162	
07-Apr-88	77 20S	168 50W	DMSP	15	27	2	177	57/237
13-Apr-88	77 10S	169 20W	DMSP	6	5	1	183	
19-Apr-88	77 10S	169 35W	DMSP	6	28	5	189	
28-Apr-88	76 55S	169 40W	N-10/DMSP	9	28	3	198	49/229
06-May-88	76 40S	169 10W	N-10	8	31	4	206	
18-May-88	76 40S	169 50W	DMSP	12	17	1	218	
25-May-88	76 35S	169 50W	DMSP	7	9	1	225	
29-May-88	76 30S	169 50W	N-10	4	9	2	229	83/263
03-Jun-88	76 35S	169 50W	N-10	5	9	2	234	
14-Jun-88	76 35S	171 00W	N-10	11	30	3	245	
22-Jun-88	76 35S	170 55W	DMSP	8	2	0	253	57/237
27-Jun-88	76 45S	172 00W	DMSP	5	33	7	258	
05-Jul-88	76 50S	172 30W	DMSP	8	15	2	266	
15-Jul-88	77 01S	172 37W	ARGOS	10	21	2	276	27/207
20-Jul-88	77 10S	173 00W	N-10	5	20	4	281	
28-Jul-88	77 20S	172 11W	ARGOS	8	27	3	289	0/180
04-Aug-88	77 30S	172 43W	ARGOS	7	22.3	3.2	296	0/180
11-Aug-88	77 42S	173 14W	ARGOS	7	30.1	4.3	303	
18-Aug-88	77 43S	173 46W	ARGOS	7	14.0	2.0	310	
25-Aug-88	77 39S	174 29W	ARGOS	7	18.4	2.6	317	20/200

1989, B-9 traversed about 1350 km of the eastern Ross Sea continental shelf at an average speed of 2.4 km day^{-1}. From then until 3 August 1989 it moved another 658 km over the western Ross Sea continental slope at 7.8 km day^{-1}.

Subsurface currents have a relatively greater effect on large icebergs than do wind-driven currents, pack ice or related wind stress. As icebergs increase in size, surface (frictional) drag increases faster than form (profile) drag. However, icebergs tend to be smoother than sea ice, thus experiencing less wind stress, and have proportionately larger keels than sails, particularly in the Antarctic. Although deep (50–250 m) wind-driven mixed layers are common in the Southern Ocean, iceberg draughts are often deeper and summer surface water layers on the continental shelf can be shallower than 25 m. Cre'pon *et al.* (1988) found that low or moderate winds (<10 m s^{-1}) have a limited effect on the motion of deep Antarctic icebergs, the trajectories of which are representative of geostrophic currents. Subsurface currents moving at different velocities and directions relative to surface currents can thus exert the main drag on large, deep-draft icebergs (Robe 1980). Although there is a major difference in surface friction between the sides and base of

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Date	Latitude	Longitude	Data Source	Elapsed Days	Distance km	Speed km/day	Days Since Calving	Long Axis Orientn.
01-Sep-88	77 38S	175 21W	ARGOS	7	19.0	2.7	324	
08-Sep-88	77 35S	176 16W	ARGOS	7	22.3	3.2	331	30/210
15-Sep-88	77 09S	176 11W	ARGOS	7	46.9	6.7	338	
22-Sep-88	76 56S	175 51W	ARGOS	7	25.7	3.7	345	30/210
29-Sep-88	76 40S	175 28W	ARGOS	7	32.4	4.6	352	
05-Oct-88	76 40S	175 11W	ARGOS	6	7.3	1.2	358	
13-Oct-88	76 31S	174 40W	ARGOS	8	20.7	2.6	366	
20-Oct-88	76 32S	174 16W	ARGOS	7	11.9	1.7	373	27/207
27-Oct-88	76 31S	173 25W	ARGOS	7	21.8	3.1	380	
03-Nov-88	76 25S	173 16W	ARGOS	7	10.0	1.4	387	
09-Nov-88	76 20S	173 15W	ARGOS	6	9.3	1.6	393	
17-Nov-88	76 20S	173 09W	ARGOS	8	2.6	0.3	401	324/144
23-Nov-88	76 25S	172 51W	ARGOS	6	10.6	1.8	407	
01-Dec-88	76 32S	172 57W	ARGOS	8	15.3	1.9	415	
08-Dec-88	76 43S	172 14W	ARGOS	7	26.8	3.8	422	
15-Dec-88	76 57S	172 04W	ARGOS	7	26.2	3.7	429	
22-Dec-88	77 08S	171 40W	ARGOS	7	22.9	3.3	436	
29-Dec-88	77 09S	171 41W	ARGOS	7	1.9	0.3	443	ca 270/90
05-Jan-89	77 10S	171 46W	ARGOS	7	2.8	0.4	450	
12-Jan-89	77 08S	171 39W	ARGOS	7	4.7	0.7	457	
19-Jan-89	77 11S	171 49W	ARGOS	7	6.9	1.0	464	
26-Jan-89	77 10S	172 06W	ARGOS	7	7.2	1.0	471	ca 200/20
02-Feb-89	77 13S	172 14W	ARGOS	7	6.5	0.9	478	
09-Feb-89	77 10S	172 16W	ARGOS	7	5.6	0.8	485	200/20
16-Feb-89	77 12S	172 27W	ARGOS	7	5.8	0.8	492	
23-Feb-89	77 09S	172 51W	ARGOS	7	11.2	1.6	499	200/20
02-Mar-89	77 04S	172 56W	ARGOS	7	9.5	1.4	506	
09-Mar-89	77 03S	173 28W	ARGOS	7	14.0	2.0	513	183/3
16-Mar-89	76 55S	173 52W	ARGOS	7	15.1	2.2	520	
23-Mar-89	76 44S	174 35W	ARGOS	7	30.1	4.3	527	
30-Mar-89	76 27S	175 09W	ARGOS	7	35.1	5.0	534	
06-Apr-89	76 09S	175 37W	ARGOS	7	35.2	5.0	541	
20-Apr-89	75 58S	176 29W	ARGOS	14	31.8	2.3	555	160/340
27-Apr-89	75 49S	176 45W	ARGOS	7	17.9	2.6	562	
04-May-89	75 39S	176 45W	ARGOS	7	18.4	2.6	569	
11-May-89	75 26S	176 44W	ARGOS	7	24.3	3.5	576	
18-May-89	74 55S	177 13W	ARGOS	7	59.2	8.5	583	
24-May-89	74 27S	177 31W	ARGOS	6	52.5	8.8	589	
01-Jun-89	74 02S	178 01W	ARGOS	8	48.6	6.1	597	150/330
08-Jun-89	73 48S	178 30W	ARGOS	7	29.5	4.2	604	140/320
15-Jun-89	73 39S	179 24W	ARGOS	7	32.7	4.7	611	
22-Jun-89	73 27S	179 11E	ARGOS	7	51.2	7.3	618	
29-Jun-89	73 15S	177 43E	ARGOS	7	52.8	7.5	625	105/285
06-Jul-89	72 52S	176 28E	ARGOS	7	59.7	8.5	632	
13-Jul-89	72 25S	175 15E	ARGOS	7	64.8	9.3	639	150/330
20-Jul-89	72 17S	174 11E	ARGOS	7	39.3	5.6	646	
27-Jul-89	71 55S	172 17E	ARGOS	7	76.3	10.9	653	118/298
03-Aug-89	71 15S	170 52E	ARGOS	7	90.8	13.0	660	

an iceberg, the ratio of the area of the base to that of the sides for B-9 is around ten times larger than that of the largest small bergs. Therefore deep currents would have influenced B-9's drift more than the smaller icebergs which calved with it (G. Robin, personal communication 1990). Wind-driven pack ice, coriolis forces, eddies and tidal currents (Yeskin 1980) will also effect iceberg drift. Tidal motions have been documented by the frequent ARGOS buoy positions available for B-9 (R. Moritz, personal communication 1989).

B-9 initially moved 40–50 km westward under the influence of two currents. At the sea surface, a coastal boundary current associated with the larger-scale East Wind Drift sets westward along the front of the Ross Ice Shelf (U.S. Naval Oceanographic Office 1960, Keys 1984). Near the depth of B-9's keel and the pre-calving ice front, an outflow from beneath the ice shelf has been identified from current meters moored during 1984 at 255 m and 540 m at location I in Fig.5 (Jacobs 1988). At that site current vectors averaged about 320°T, with the strongest north-westerly flows during November and December (Fig. 9). Similar current directions at 250–300 m were measured by Crary (1961) through the sea ice of Kainan Bay for brief periods during April and June

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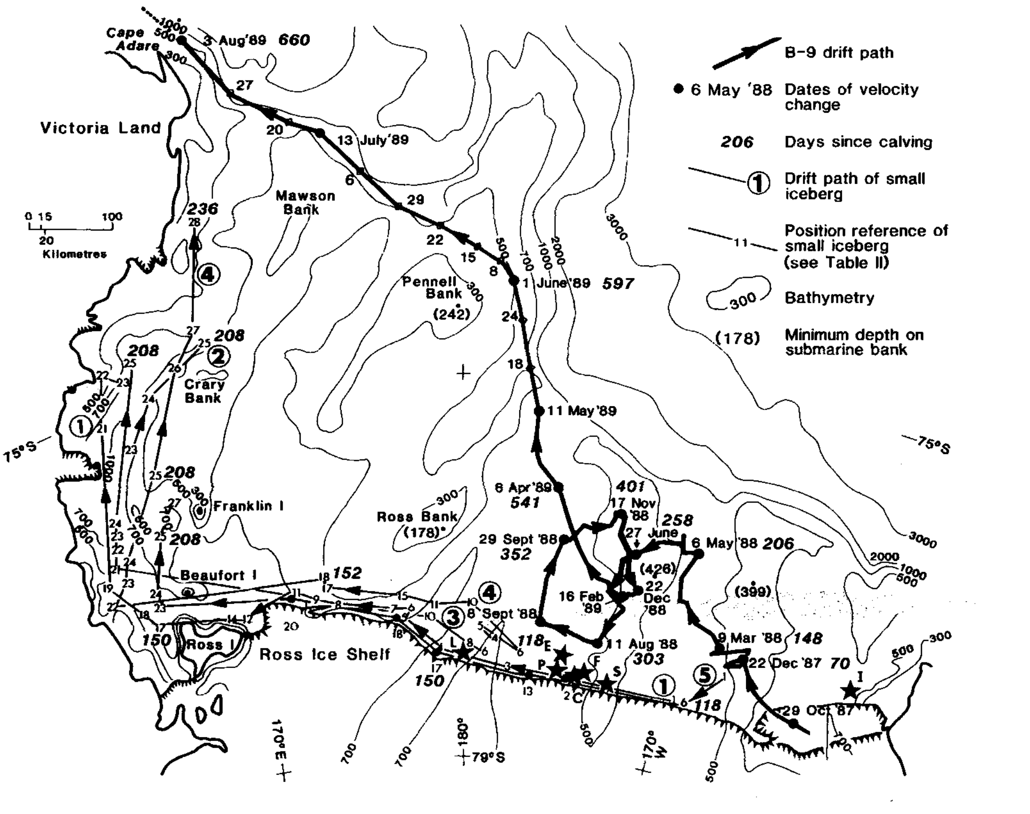

Fig. 5. The drift of B-9 (heavy solid line) constructed from the co-ordinates of the centre points in Table I, showing dates of major changes in speed or direction of drift (cf. Fig. 6). The drifts of five smaller icebergs which originated during the same calving event (circled numbers 1–5, not related to the berg numbers in Fig. 4) are shown as thinner lines between position points (see Table II). The stars labelled I, S, etc. refer to the positions of current meter moorings. Bathymetry simplified from Davey & Cooper (1987).

Table II. Drift of five smaller icebergs that calved with B-9. The columns labelled "Position No." refer to positions of the icebergs 1–5 shown on Fig. 5.

Position No.	Date (1988)	Days since calving
1	12 Jan	91
2	18 Jan	97
3	21 Jan	100
4	31 Jan	110
5	2 Feb	112
6	8 Feb	118
7	11 Feb	121
8	15 Feb	125
9	17 Feb	127
10	21 Feb	131
11	22 Feb	132
12	28 Feb	138
13	29 Feb	139
14	1 Mar	140
15	2 Mar	141
16	3 Mar	142
17	11 Mar	150
18	13 Mar	152
19	17 Mar	156
20	20 Mar	159
21	7 Apr	177
22	13 Apr	183
23	17 Apr	187
24	22 Apr	192
25	8 May	208
26	25 May	225
27	29 May	229
28	5 Jun	236

1957 and July 1958. The mean current vector at 255 m during October 1984 was 305°T at 4.3 cm s^{-1} (3.7 km day^{-1}), with an average magnitude of 6.5 cm s^{-1} and a maximum of 19.7 cm s^{-1}. Although the ocean current and iceberg drift observations are not simultaneous, the persistent north-west current directions measured for a full year at and below B-9's keel depth suggest that these earlier measurements are applicable to the first stages of the iceberg drift. The iceberg had rotated about 20° counter-clockwise (CCW) by 19 November 1987 (Fig. 8, Table I), perhaps due to contact with the ice shelf west of the former Bay of Whales (NOAA–9 IR images on 20 October 1987 and 09 November 1987; WWM 1987, p. 1625).

Net movement was north-west during the first 7 months of B-9's life as an iceberg, an indication that the current measured at I extends at least 300 km across the shelf. However, during the period from 22 December 1987–9 March 1988 there was often little movement and the drift was characterized by erratic direction changes or north-east–south-west motions. B-9's location over a submarine bank and a slight CCW rotation during this time (Figs. 5 & 8, Table I) led to speculation that the iceberg was in contact with the sea floor. That hypothesis seems untenable to us because the best available bathymetric data show water depths in the vicinity to be no less than 400 m (Fig. 5), considerably below the probable 250 m maximum draught of B-9.

From 27 June–5 July 1988, B-9 moved west-south-west and then turned south (Figs 5 & 7), eventually colliding with the ice shelf front near 173°W. Analysis of successive (4 hr) ARGOS fixes gave velocities of 5.6 km day^{-1} toward 184°T on 9 August and 5.4 km day^{-1} toward 290°T on 10 August. The southward drift for more than a month up to 10 August 1988 was apparently caused by the intermediate-depth 'warm' inflow to the sub-ice shelf cavity (Jacobs *et al*. 1985). This subsurface current, initially identified from austral summer temperature sections, has repeatedly been encountered in about the same location on the eastern shelf (Fig. 10). As B-9 drifted south, its long axis became aligned parallel with the axis of the current. A year-long record at 211 m depth in this flow (location S on Fig. 5) revealed a mean velocity of 6.5 km day^{-1} toward 176°T (Pillsbury & Jacobs 1985). B-9 was travelling at about 85% of that speed when it hit the ice shelf.

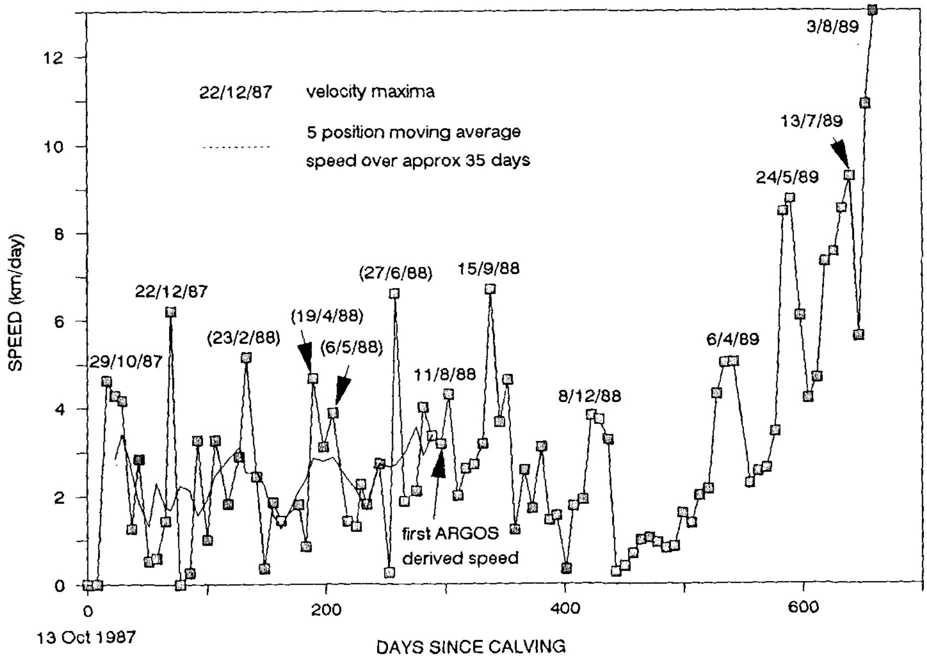

Fig. 6. Speed of iceberg B-9 from the time it calved until early August 1989, based upon non-rounded data used for Table I. Running means of five consecutive speeds are shown for the period prior to the determination of speeds based on continuous ARGOS positioning. Velocity maxima generally reflect significant changes in iceberg's speed and direction (see Fig. 5). Parentheses indicate velocity maxima defined by few data or small distances between fixes. The reason for the apparent periodicity of ~2 months in the speed maxima is unknown, but see Fig 7.

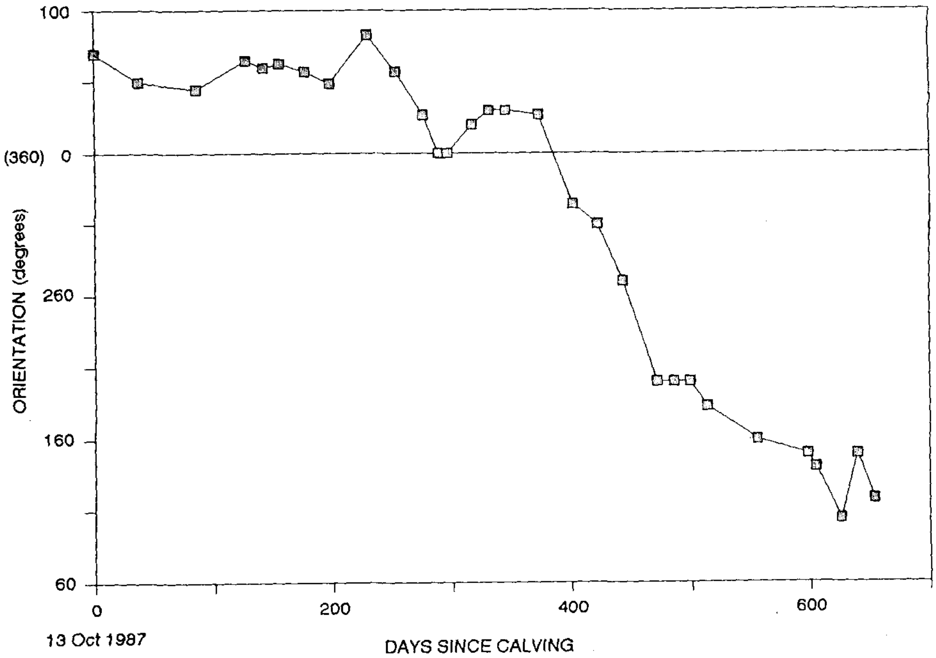

Fig. 7 Rotation of iceberg B-9 as a plot of the bearing (°True) of the long axis of the iceberg from its original south-west end. (0 shows when the iceberg was oriented north–south). Orientation changes often coincided with velocity maxima (Fig. 6) as B-9 tended to rotate parallel to current forcing and drift direction ("vaning").

Within the 1 km resolution of the NOAA satellite imagery, the impact of the collision had little observable effect on either the ice shelf or B-9. The force of impact, in Newtons, $F_I = 0.5\ m\ v^2\ d^{-1}$, would have been on the order of 5×10^{12} d^{-1}, where d is the horizontal distance over which the energy of impact is absorbed. With ice yield stresses, S, of 10^5-10^7 N m^{-2} and an impact area, A, of ~5 km x 100 m, the crushing force, $F_C = S\ A$ would be less than F_I for $d > 1$ m. Thus, in spite of the large size and momentum of B-9 when it collided with the ice shelf, no secondary calving events resulted. Swithinbank *et al.* (1977) reported indications that at least two giant icebergs had originated from the impact of other icebergs, and suggested that might be one of the major causes of calving. In the B-9 case, we have no evidence that such an impact mechanism was operative at its birth or subsequent collision with the ice shelf.

From 10 August–8 September 1988, B-9 drifted west along the ice shelf front. The southern tip rotated westward during this time, effectively moving the centre point in a west-north-west direction. This behaviour can be attributed to a coastal current that is significantly narrower than the iceberg length. The subsurface flow is also persistently westward in this region, as illustrated by the 285 m record from mooring F (Fig. 11). Site F was 10 km north of the January 1984 ice front, but a much different record was obtained at the same depth from mooring E, 20 km north of the ice front. There,

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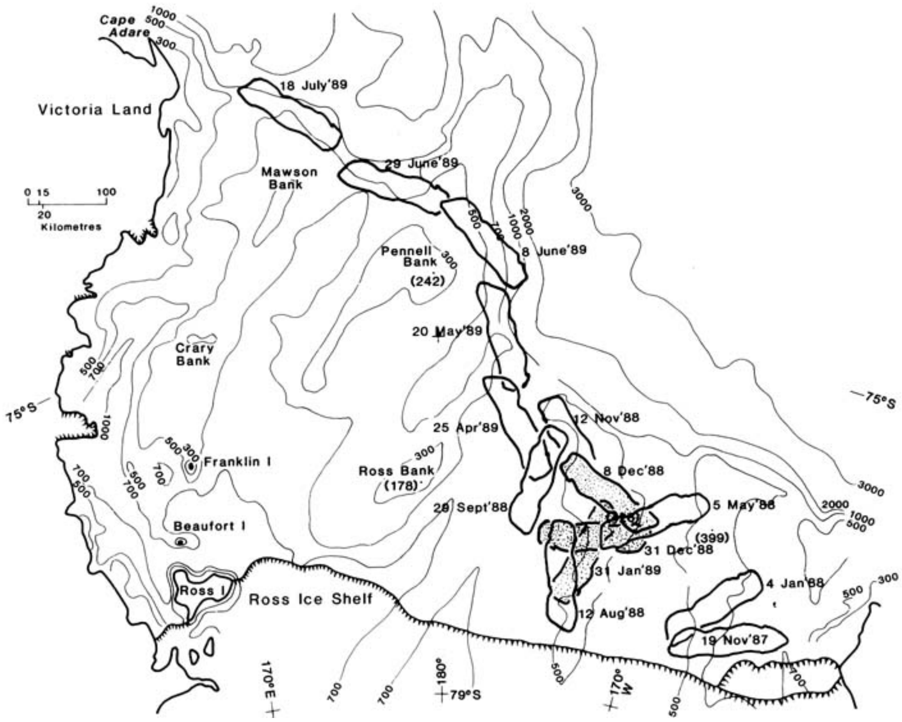


Fig. 8. Outlines of B-9 from selected cloud-free satellite images, complementing the orientation data in Table I. The diagram illustrates B-9's main drift track and varying observed orientation. By the time the iceberg reached the north-western Ross Sea it had made nearly one complete CCW revolution.

a generally north-westerly flow was measured from April through September 1984, with weaker and more meandering currents than at F. Salinity and temperature profiles perpendicular to the ice front also suggest a coastal current less than 20 km wide (Jacobs 1989, figs. 9 & 10). That flow would have been acting on less than 15% of B-9's length, consistent with the 30° CW rotation during this period (Table I). Current meters moored for a year between 237 and 327 m near 78°S, 175°W (positions P and C on Fig. 5) showed an average current velocity of 8.5 km day^{-1} toward the west. Ship drifts indicate much faster surface currents along the ice front (U.S. Naval Oceanographic Office, 1960). However, most of B-9 was north of the main coastal flow during this period, and it realized a maximum speed of only 3.2 km day^{-1}.

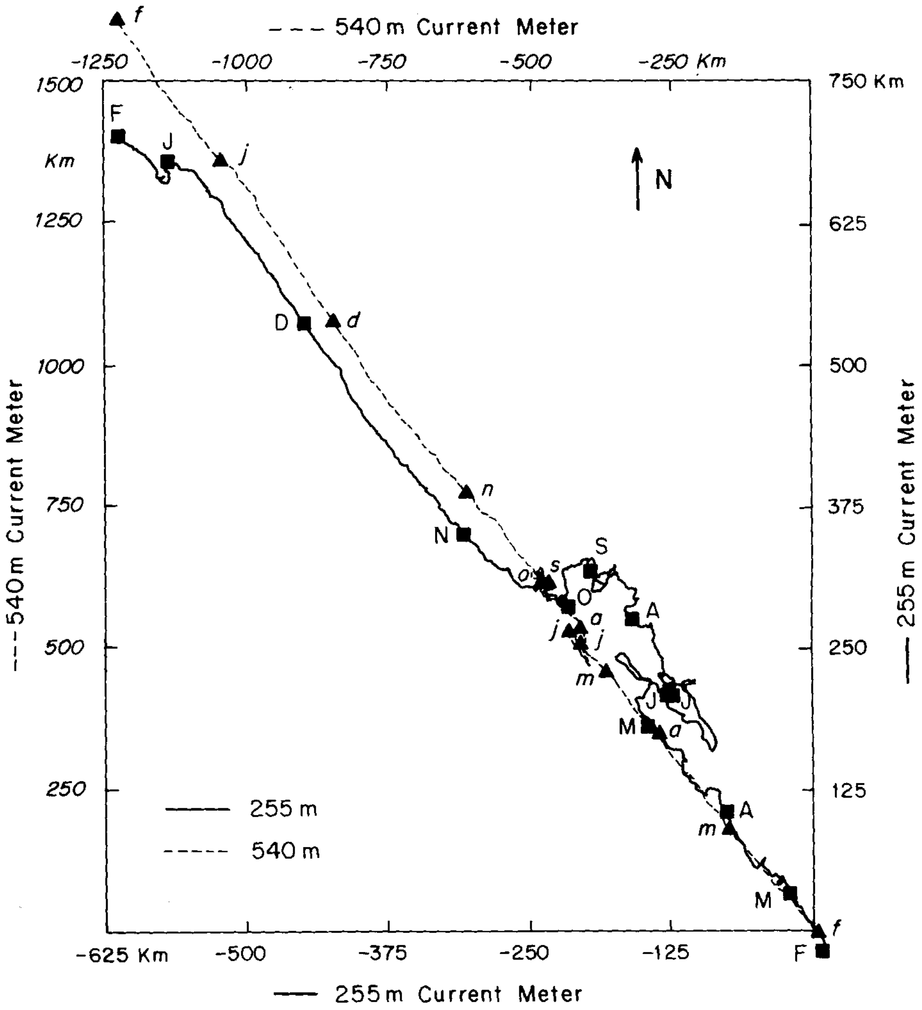
A short distance west of 176°W, B-9 abruptly changed direction towards the north, reaching a maximum weekly-average speed of 6.7 km day^{-1} in mid September (Fig. 5). Ice Shelf Water (ISW), characterized by temperatures below the sea-surface freezing temperature (<-1.95°C in Fig. 10) is known to flow northward at depth during summer in longitudes 178°E–174°W. A 444 m deep current meter at site L in Fig. 5 showed a mean flow of 5.4 km day^{-1} towards 030°T during the first half of 1978 (Pillsbury & Jacobs 1985). If ISW outflow continues during late winter-early spring and extends to relatively shallow levels (~200 m) in the water column, it could account for B-9's turn to the north. Another possibility is that the iceberg encountered a recirculation of the 'warm' core back into the open Ross Sea, e.g., near the discrete feature >-1.0°C at station 59 in Fig. 10, and as documented by closely spaced current meter moorings along the ice shelf (Jacobs 1989). This could also account for the northerly drifts recorded from May through August 1984 at mooring E in Fig. 11. In either case, the iceberg's drift during this winter period would also have been assisted by the off-shore motion of sea ice and surface water. The track became more north-easterly during October, with significant CCW rotation by 17 November. Ainley & Jacobs (1981) found evidence for eastward flow south of the shelf break in this vicinity and postulated a CW gyre encompassing the entire shelf region.

From 17 November 1988–12 January 1989, B-9 moved south-east and south, apparently again under the influence of the south-flowing 'warm' current described above. Motion was slow and erratic from ~ 12 January through 16 February, during which time it was over water less than 450 m deep (Fig. 5). The iceberg's lethargy and rotation in this period again indicated to some observers that it was in contact with the sea floor (G. Prodanchek, personal communication 1989). More likely, B-9 had over 150 m of water beneath its keel at the time, unless there are significant errors in the ice thickness calculations or in the maps of sea floor topography. Its CCW rotation during this period (Fig. 8) probably resulted from the documented northerly and southerly flows acting on its eastern and western ends.

From 16 February–11 May 1989, B-9 resumed a generally north-westerly drift, with minor CCW rotation (Table I). Maximum speeds were reached in late March and early April, with the northern end of the iceberg 20 km from the edge of the continental shelf by 11 May.

The centre of B-9 had reached the continental slope for the first time by 18 May, and its long dimension and drift direction were then aligned with the shelf break (Fig. 8).

Fig. 9. Progressive vector diagrams of ocean currents at mooring I (77°40.8' S, 160°24.2' W in Fig. 5) at depths of 255 m (solid line, bottom and right scales) and 540 m (dashed line, top and left scales). The 371 day records started on 28 January 1984, and are low-pass filtered (tides removed) with lettered squares or triangles at the beginning of each month.



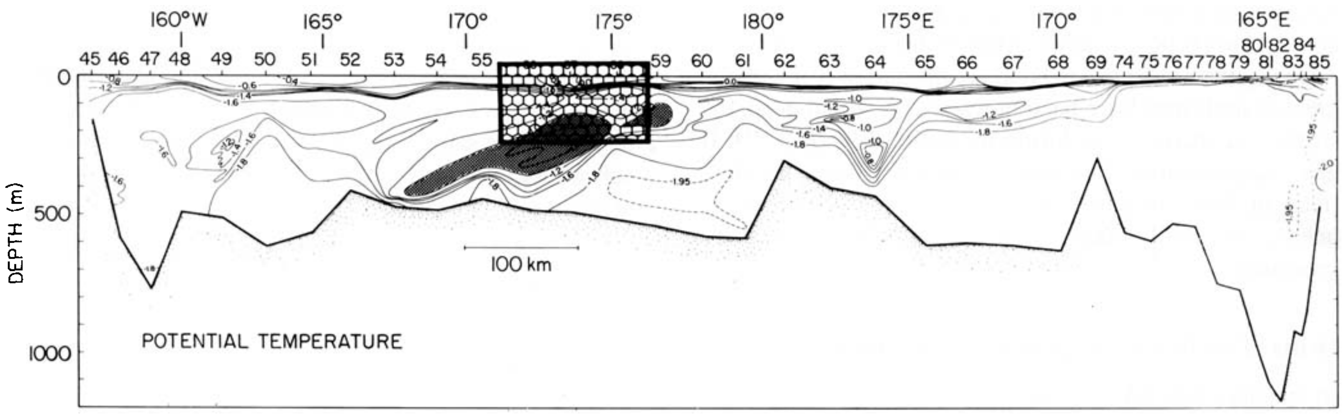


Fig. 10. An east-west section of temperature across the Ross Sea continental shelf, from the vicinity of Cape Colbeck on Edward VII Peninsula to Franklin Island to Terra Nova Bay. Data from conductivity-temperature-depth measurements made in January–February 1984 (Jacobs *et al.* 1989). An approximate long-axis cross-section of B-9 is superimposed on the 'warm' subsurface inflow to the shelf region (shading >-1.0°C). The ice shelf water (<-1.95°C) between 174°W and 180° is formed by melting beneath the Ross Ice Shelf. This water is more extensive near the ice front where it also appears at shallower depths.

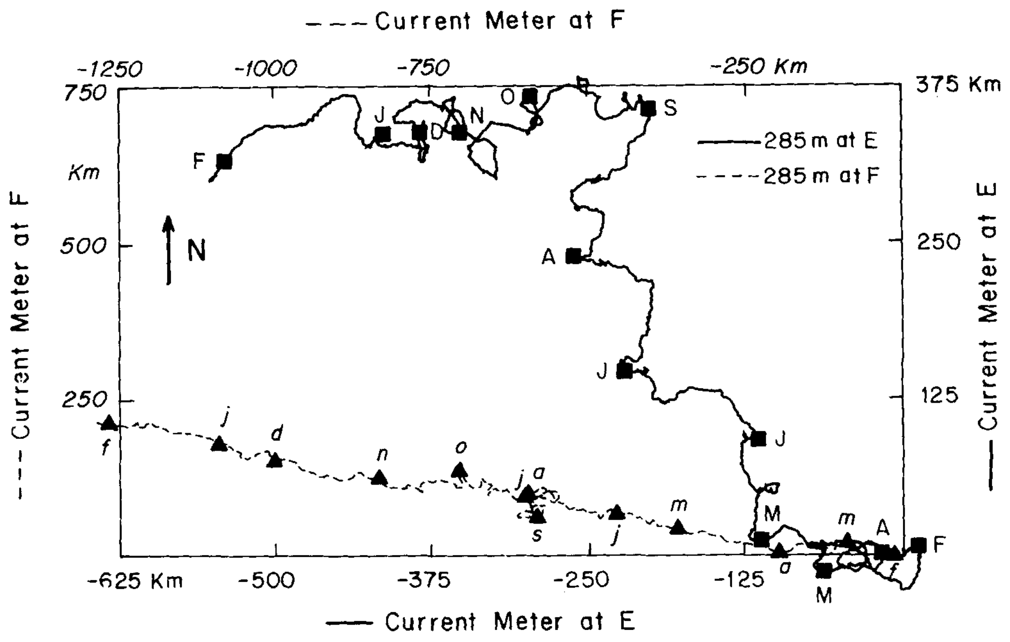


Fig. 11. Ocean current progressive vector diagrams for mooring F (78°06.5' S, 174°30.8' W) and E (77°58.3' S, 175°27.2' W) in Fig. 5, each at depths of 285 m. Record E (solid line, bottom and right scales) is for 377 days starting 25 January 1984 and F (dashed line, top and left scales) is for 375 days starting on 26 January 1984. See Fig. 9 caption.

Speeds generally increased during its subsequent north-westerly drift in the current that tracks the upper continental slope, reaching a weekly-average maximum of 13.0 km day^{-1} on 3 August. A period of lower speeds occurred in early June when B-9 crossed the outer continental shelf (<500 m) while rounding Pennell Bank. The average speed of B-9 while in the slope current was 7.8 km day^{-1}, similar to the velocities of Tchernia & Jeannin's (1983) icebergs (7.6–10.4 km day^{-1}, average 9.0 km day^{-1}). However, most of those smaller iceberg tracks were north of the continental slope and speeds were averaged over longer periods. In a two-step process, B-9 split into three irregular pieces near Cape Adare between 3 and 12 August 1989. These had dimensions of 56 x 35 km (B-9A), 100 x 35 km (B-9B), and 28 x 13 km (B-9C), with the ARGOS buoy on B-9A.

During the week prior to breakup, the part of B-9 with the greatest draft may have been in water 200–400m deep, the shallowest encountered during the entire drift (Fig. 5). If grounding occurred that may be apparent from the more frequent ARGOS data, but B-9A could be expected to behave differently after the breakup whether or not B-9 grounded.

Drifts of smaller icebergs that calved with B-9

In January 1988, AVHRR imagery showed several icebergs over 5 km long moving away from the B-9 calving site, and westwards along the ice shelf front. These icebergs originated from the collection of smaller ice shelf pieces that broke off with B-9 (Figs. 4a, b, c), and are clearly visible on its south-east side in the 28 November LANDSAT image (Fig. 2). Their dimensions were less than desirable for satellite tracking, but their shapes and common origin enabled five to be followed along the southern and western coastlines of the Ross Sea from January through May 1988 (Fig. 5).

During that time they moved at average speeds of 6–12 km day^{-1}, fastest along the central portion of the ice front. Variability in calculated speed was high (2–25 km day^{-1}), with some reversals in direction, perhaps due to tidal motions and relative positioning and rounding errors over the shorter time intervals. Tentative identification of two of the icebergs near 69°45'S, 165°E off the Pennell Coast in early July 1988 implies speeds of 10–17 km day^{-1}. That is not unreasonable, since iceberg No. 4 was moving at 16 km day^{-1} in early June 1988 (Fig. 5). The Aurora drift through the north-west Ross Sea in early August 1915 exceeded 40 km day^{-1} (Wordie, 1921). The trajectories of these bergs differed from that of B-9 because they were small enough to be carried along in the narrow coastal current. That current also increased their speeds relative to B-9, which was moving only 2.3 km day^{-1} over the same time interval. Direct measurements of subsurface currents (>125 m) along the ice front have shown major westerly components at most sites (e.g., Fig. 11).

Discussion

The drifts of B-9 and five contemporaneous smaller icebergs have extended our knowledge of how the surface and subsurface currents interact with freely-floating glacial ice on the Ross Sea continental shelf. The southern and western boundary currents are important paths for small icebergs, as previously suspected (Keys & Fowler 1989). The slope current which tracks the continental shelf edge also appears to be a preferred iceberg route in the Ross Sea. Temperature-salinity characteristics of the deep, energetic slope currents have previously been interpreted as influenced by glacial ice

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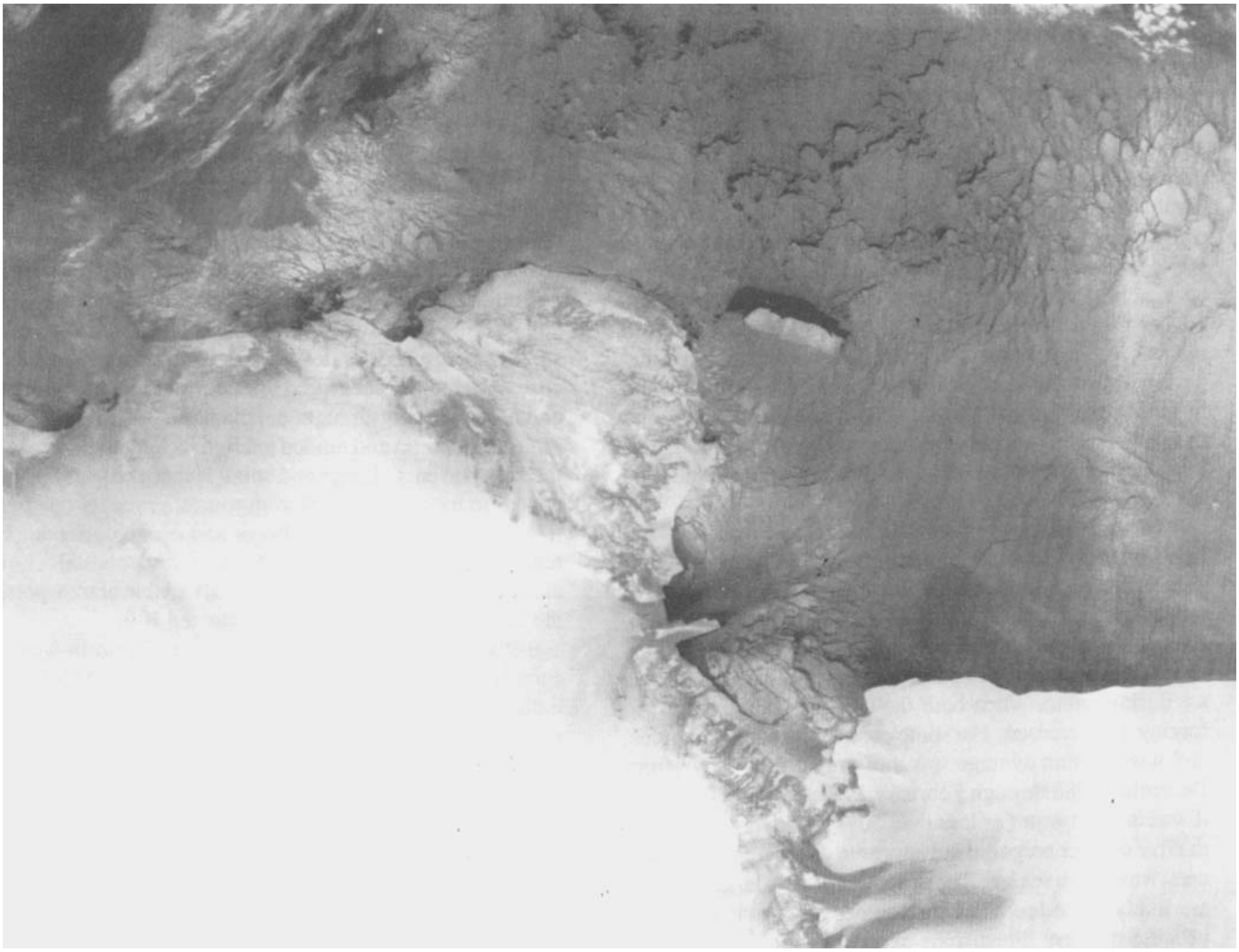

Fig. 12. NOAA AVHRR IR channel satellite image of the Ross Sea and adjacent regions on 18 July 1989. B-9 appears in the north-western Ross Sea with a large region of open water, thinner ice or lower sea ice concentration to its north. Areas of open water or thin ice can also be seen near the Ross Ice Shelf, the Victoria Land coastline around the Drygalski Ice Tongue and along the coastline of East Antarctica.

(Jacobs 1986). The tendency for icebergs to travel in the coastal and slope currents indicates that ice-rafted debris (B-9 probably contained little), bottom scour and meltwater should also be concentrated there (Jacobs 1989). The B-9 drift suggests that the slope current crosses the outer shelf where Pennell Bank deepens northward toward Iselin Bank. By contrast, two of the smaller icebergs (380–780 m) tracked by Tchernia & Jeannin (1983, plates 14 & 15) approached this current from the north-east during the summer of 1980–81, meandered over the continental rise and turned north in May near the northern end of Iselin Bank.

One of the more remarkable aspects of B-9's movement on the shelf was its southerly drift from 29 May–11 August 1988, and again from 17 November 1988–12 January 1989. Contrary to prevailing winds and the mean drift of sea ice, these sustained southward tracks must have resulted from the inflowing 'warm' water from the continental slope region. This sub-surface current had been documented previously from summer vertical temperature sections across the Ross Sea (Fig. 10) and from current meter moorings near the ice front. B-9's drift confirmed the continuity of this flow during midwinter on the central shelf (June–August 1988 in Table I), and its association with the submarine rise near 173°W. Whether B-9's escape from this current in February 1989 was due to seasonal weakening of the flow or to meandering or some other phenomena cannot be surmised from the available data. The iceberg's long dimension was similar to the current's cross section as inferred from temperature data (Fig. 10) and might thus have caused some transient course changes in the current. Temporal fluctuations

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in the northward recirculation of the warm inflow, as recorded at mooring E (Fig. 11), could also have reset B-9's trajectory.

Sea ice floes generally move between west-north-west to north- north-west across the Ross Sea continental shelf, with average velocities that increase from about 4 km day^{-1} in the south-east to about 16 km day^{-1} in the north-west (Moritz 1988). This pack ice movement is similar to B-9's drift during a major portion of its residence time on the shelf, and would have enhanced B-9's north-west drift and retarded its southward motions. Even when coherent in direction, however, the sea ice was typically moving faster than B-9, resulting in an area of open water, reduced ice thickness or lower ice concentration on its northern side (Fig. 12). B-9's shadow on the sea ice field often exceeded its own dimensions, and presumably resulted in locally greater sea ice formation and in higher sea-air heat fluxes. The combined iceberg and open water area probably introduced significant anomalies into satellite microwave data sets that are used to study the sea ice fields.

In contrast to icebergs in semi-enclosed Arctic seas, Antarctic bergs over the deep ocean are not blocked by pack ice in winter, at which time some of the most rapid and extensive movements have been noted (Tchernia & Jeannin 1984). Except for grounded bergs or small ones trapped in fast ice near the coastline, drift continues with and through the sea ice during winter when both the oceanic and atmospheric forcing are increased. For some continental shelf examples, B-9 moved at an average speed of only 1.5 km day^{-1} from December 1988 through February 1989, during which time it was in open water or less than 50% ice cover. Speeds of the five smaller bergs did not appear to differ significantly in open water or in sea ice. The drift rates of very large icebergs are likely to be less than surface ocean current velocities because the berg dimensions exceed the current widths or extend to the depth of subsurface currents travelling at different speeds or directions.

We estimated above that the original calving event involved ~1200 km^3 of glacial ice, some 15% of which was contained in the smaller icebergs. That is equivalent to roughly half of the net annual accumulation on the Antarctic ice sheet (Giovinetto & Bentley 1985). However, if the average ice-front velocity between Roosevelt Island and the Shirase Coast is 0.5 km a^{-1} (Thomas *et al*. 1984), then the mean annual outflow for that sector is <1% of the ice sheet accumulation, and the 1987 breakout would account for ~70 years of advance. This is consistent with ideas regarding major calving of large floating ice shelves on time scales of several decades (Zakharov & Kotlyakov 1980, Jacobs *et al.* 1986). In the hierarchy of icebergs, B-9 was one of the giants, but it also constituted less than 1% of the Ross Ice Shelf area of 525 840 km^2 given by Drewry (1983).

Conclusions

The simultaneous calving of B-9 and numerous smaller icebergs was controlled by major rifts in the Ross Ice Shelf. The periodicity of major calving events in that area of the eastern ice shelf is dependent upon spacing of the larger crevasses, which are generated as ice flows between Roosevelt Island and the Shirase Coast. After initial loss of some attached fast ice, B-9 retained dimensions of 141 x 35 km for ~ 22 months while drifting on or adjacent to the continental shelf. B-9 was not grounded during this period, and survived a collision with the ice shelf in spite of several possible buried rifts (Shabtaie & Bentley 1982, Fig. 9c, d).

The drift of these icebergs followed previously measured and inferred directions of surface and subsurface currents on and near the Ross Sea continental shelf. B-9 and one of the smaller bergs accelerated to speeds approximating mean current velocities measured with current meters moored at and below iceberg-draught depths (200–300 m). B-9 had a large aspect ratio and tended to align its long axis parallel to the host currents. Large and small icebergs of similar draft appear to follow quite different routes, probably due to the relative dimensions of the bergs and ocean currents. The high-velocity, 10–15 km-wide westward coastal current along the Ross Ice Shelf front proved capable of transporting the smaller icebergs, but only deflected B-9.

B-9's drift confirmed the persistence of a north-westerly current from beneath the ice shelf east of 165°W and indicated that this outflow extends at least 300 km across the shelf. It showed that the warm inflow to the shelf region in longitudes 172–174°W is present in winter and spring, as are subsurface outflows extending to the shelf break in the central Ross Sea. The strong westward continental slope current appears to override the outer shelf while rounding Pennell Bank, and thus may not track the contours of the deeper, more north-easterly Iselin Bank. From July–December 1988, B-9 completed an orbit of ~120 x 80 km on the east-central shelf. From salinity and temperature measurements, Treshnikov (1964), Klepikov & Grigor'yev (1966) and others have inferred the presence of clockwise gyres in the surface circulation on the continental shelf. South-easterly flow in the northern and eastern limbs of such gyres would be contrary to the observed drift of sea ice. However, the B-9 track showed that such current patterns exist at depth, and may be composed of discrete elements of the larger-scale circulation.

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