THE ABSOLUTE AND RELATIVE MOVEMENT, AND REGIME OF THE BRUNT ICE SHELF NEAR HALLEY BAY

By D. W. S. Limbert

Abstract. Absolute movement of the Brunt Ice Shelf was determined by means of triangulation using a number of icebergs grounded offshore. The velocity was found to be 375 m. yr^{-1} in a westerly direction. A kilometre stake pattern was used to determine strain-rates in the surface of the ice shelf, which were of the order of 5×10^{-4} $yr.^{-1}$. Vertical strains were also deduced. The probable regime of the Brunt Ice Shelf is considered in relation to its environment (Limbert, 1963, p. 73–75).

In the vicinity of Halley Bay there are no surface rock features that can be used as fixed reference points for absolute movement measurements on the Brunt Ice Shelf. Consequently, it was necessary to use other methods for the determination of absolute velocity.

By comparing sun sights taken in the years 1957–59, Blackwell (1960, p. 982–84) gave a provisional estimate of 550 ± 150 m. $yr.^{-1}$ in a west-north-west direction for the movement of the ice shelf. Bearing in mind the inaccuracies involved in astronomical fixes made in polar regions, where the necessary precision of one second of arc is rarely achieved (Swithinbank, 1958, p. 81), Blackwell's error could be much greater than given above. Indeed, there were several anomalous results not adequately accounted for.

Towards the end of 1958, MacDowall and Blackie (1960, p. 63–64) made a local magnetic survey to determine whether there were any magnetic anomalies in the immediate vicinity of the Halley Bay station. Following MacDowall's recommendation, the survey was repeated one year later to determine the velocity of the ice shelf. The movement reported by Blackwell (1960) was 460 ± 200 m. $yr.^{-1}$, in a west-north-west direction. The large error was due primarily to the use of a too widely spread grid of stations for the survey.

The presence of a number of distinctive grounded icebergs offshore from Halley Bay offered the attractive possibility that they could be used as suitable reference points for a conventional survey which would give greater accuracy than previously achieved. The methods used are described below.

Practical Details

All survey measurements are given in feet, the unit in which the surveyor's tape was calibrated. A pattern of nine stakes was laid out over an area of about 4 $km.^2$ immediately east of the station hut (Fig. 1) as part of a combined absolute movement and strain-rate investigation. For a variety of reasons this was not completed until the beginning of March 1959. The stake pattern was orientated with the sides very nearly north–south and east–west as shown in Fig. 1. Three major base lines were measured, using a 300 ft. (98·5 m.) steel surveyor's tape, to an accuracy of $\pm 0{\cdot}06$ ft. (0·002 m.) (Table Ia). Due allowance was made for temperature by applying the quoted coefficient of linear expansion, $11{\cdot}20 \times 10^{-6}$ in. $°C^{-1}$ which was confirmed by standardization in the field against an Invar tape. All measured lengths were reduced to 0° C. It was an advantage to know the length of the field tape at 0° C, because in summer, although it is in contact with the snow surface, the tape was warmed by strong insolation which raised the temperature to freezing point.

During April 1959 three theodolite stations were established but they had to be offset 18 in. (0·49 m.) from positions A_1, B_1 and A_2 (Fig. 1), because of the type of marker stake used. The offset was fixed by using a "Dexion" T-piece with the head of the T touching the stake and the legs of the theodolite tripod supported by the end of each arm of the T-piece. The error in siting this T-piece framework was approximately 1 in. (2·5 cm.), which is equivalent to about 4 sec. of arc over 1,000 m., but it was negligible compared with the range of the grounded icebergs, a distance of 9 to 18 km. The stability of the tripod and theodolite set up on the "Dexion" T-piece and well stamped into the surface was good. By standing clear of the framework it was stable enough to complete a round of angles without relevelling, even when the surface was soft in mid-summer.

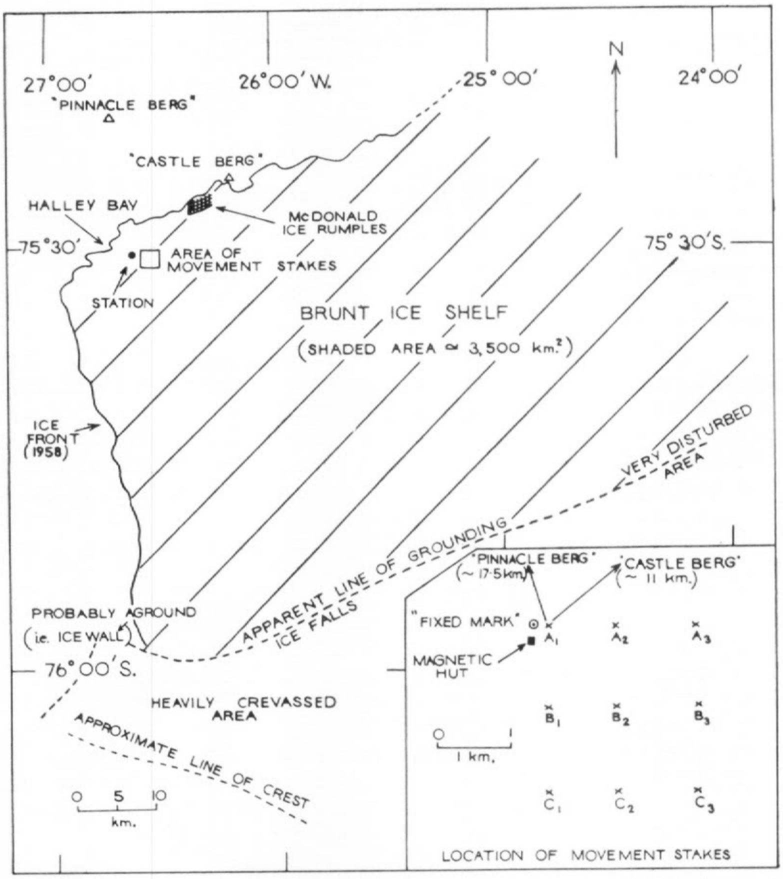

Fig. 1. Map of the Brunt Ice Shelf. The inset shows the trigonometrical points in relation to the icebergs and the "fixed mark". The coastline is based on a map prepared by L. W. Barclay in December 1959.

TABLE I. MEASURED AND CORRECTED BASE LINES

a. *As measured.*

Base Line	*Date* (1959)	*Length* (ft.)	*Change* (ft.)	*Period* (days)
A_1 to B_1	15 March	3561·73	+1·27	296
B_1 to A_2	15 March	4667·57	+2·24	298
A_2 to A_1	15 March	3016·74	+1·55	298
		(±0·06)	(±0·12)	

b. *Base lines corrected for triangulation "offset" and reduced to a 262-day period.*

Base Line	*Date* (1959)	*Length* (ft.)	*Date* (1960)	*Length* (ft.)
A_1* to B_1*	16 April	3560·25	3 January	3561·41
B_1* to A_2*	16 April	4663·25	3 January	4665·35
A_2* to A_1*	16 April	3016·91	3 January	3018·27

The distances between the offset theodolite stations, A_1*, B_1* and A_2*, were calculated from the measured base lines (Table Ib).

The first triangulation was made during the period 16–19 April 1959. Arbitrary bearings were taken to four prominent grounded bergs from each of the three triangulation points, to the other stakes in the pattern and to the "declination fixed mark". The latter point was also observed at regular intervals from the geomagnetic hut using the suspended magnetic declinometer. Reciprocal bearings of the magnetic declinometer were taken from the "fixed mark" in conjunction with a series of sun fixes. Bearings to Stake A_1 were also taken. In this way the geographical orientation of a line of longitude through the geomagnetic hut and the "fixed mark" was known at any time and, because the position of the stake pattern relative to the "fixed mark" was known, the geographical orientation, i.e. true bearings, of the stake pattern was known.

TABLE II. PRINCIPAL BEARINGS AND ANGULAR CHANGE OF BEARINGS

Ray	*Date* (1959)	*True Bearing*	*Period* (days)	*Angular Change* (sec. of arc)	*Rate of Change* (sec. day^{-1})
A_1*–PB	16 April	342°49′58″	262	+2,574	9·83
A_1*–CB	16 April	54°11′13″	262	+2,484	9·50
A_2*–PB	18 April	339°53′03″	260	+2,511	9·66
A_2*–CB	18 April	51°27′46″	260	+2,876	11·05
B_1*–PB	19 April	343°47′54″	256	+2,335	9·12
B_1*–CB	19 April	50°04′02″	256	+2,529	9·89
Probable error		±17″		±24	

PB. "Pinnacle berg". CB. "Castle berg".

Owing to the lateness of the season, with the "winter night" less than two weeks ahead, the triangulation observations were restricted to a few hours on either side of local noon, frequently in unfavourable conditions. Weather conditions varied from a temperature of −35° C and 3 m./sec. wind to −17° C and 10 m./sec. The difficulties involved in survey at low temperatures are graphically described by Swithinbank (1958, p. 84–85), and in such conditions a round of angles took well over an hour to complete. It was noticeable that the quality of the measurements dropped the longer the observations were in progress.

Subsequent to the initial survey, one of the so-called "fixed bergs" disappeared during a storm in May 1959 and another was "hull down" on the horizon by the end of the winter when the survey was repeated.

From October onwards the positions of the two remaining bergs were resurveyed at about monthly intervals with a final survey at the beginning of January 1960. Temperatures were much higher at this time, and the quality of the observations was better than that of the previous April.

TRUE BEARINGS AND APPARENT MOVEMENT OF ICEBERGS

Between 1 May and 31 December 1959 the known azimuth through the "declination fixed mark" and the magnetic declinometer changed by 10′30″ in an anti-clockwise direction. This was also true for the north–south line of the stake pattern, the bearing of which was 359°00′14″ east of true north on 16 April 1959, decreasing at a rate of 2·44 sec. day^{-1}.

Meanwhile, the two surviving bergs had apparently moved, also in a clockwise direction, relative to each of the triangulation points. The magnitude of this movement was of the order of 40 min. of arc during the eight-month period, or about 10 sec. day^{-1} (Table II).

Fig. 2 shows the apparent behaviour of the two surviving bergs. At Halley Bay floating bergs move steadily south-westwards in the ocean current, at the rate of 2–3 km. day^{-1}, which soon takes them out of visible range. Similarly, one of the grounded bergs, if temporarily freed, would be expected to move south-westwards, giving an anti-clockwise angular movement relative to the triangulation points. However, neither the "Pinnacle berg" (PB) nor the "Castle berg" (CB) behaved in this way.

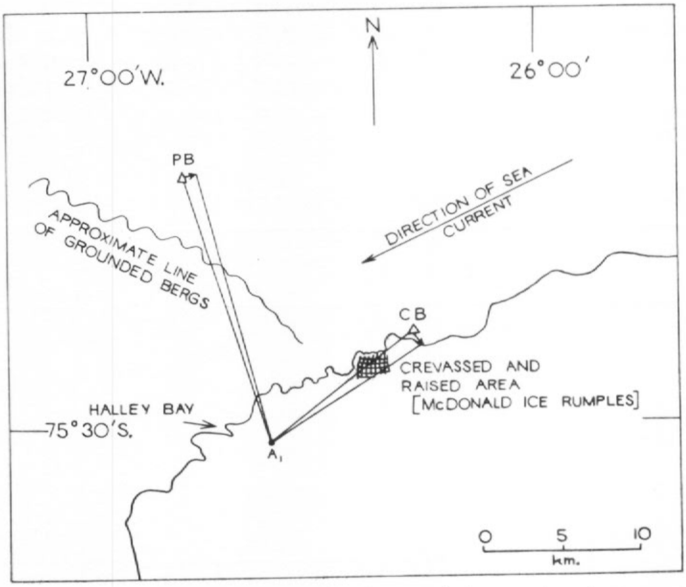

Fig. 2. Sketch showing the apparent movement of icebergs relative to the observer at A_1. The apparent angular movement of the icebergs is not to scale.
PB "Pinnacle berg".
CB "Castle berg".

Calculation of Movement

In principle, the absolute movement may be found from a single base-line sighting to a single fixed reference point such as a grounded iceberg. In practice, it is necessary to have at least two bergs in case there has been a slight drift by one of the bergs. More than one base line is also an advantage, because it will give a scatter in position of the observed point relative to a grid reference, and hence the overall error can be obtained.

The data given in Tables I and II were reduced to a common epoch, 16 April 1959 to 3 January 1960, assuming a uniform change with time. The ranges and the position coordinates of the bergs relative to the triangulation points were calculated. If both bergs remain fixed, then the north (N) and east (E) components will change by the same amount, dN and dE (Fig. 3), but from Table III it can be seen they are not the same. The discrepancy amounted to a movement of 271 ft. (83 m.) of PB relative to CB.

It seemed unlikely that, if both bergs had moved, the relative change would be as small as 271 ft. (83 m.). If PB had remained stationary, then CB must have moved south and east, directly towards the coast about 800 m. distant at the only point where the ice front is clearly grounded (the McDonald Ice Rumples). In addition, the motion would be contrary to the prevailing current. On the other hand, if CB had remained fixed, then PB must have moved north and west. This, too, is not in the direction of the current (Fig. 2) which is south-west. However, the sea is somewhat deeper than in the vicinity of CB, because this is the edge of the underwater shelf. PB was a large berg and its rotation or slight tilt would have been sufficient to account for the change. This is considered to be the most likely explanation, which is supported by a qualitative observation that the "Pinnacle berg" did not look quite the same after a storm in May. The same storm was also responsible for the disappearance of one of the original four "grounded" bergs.

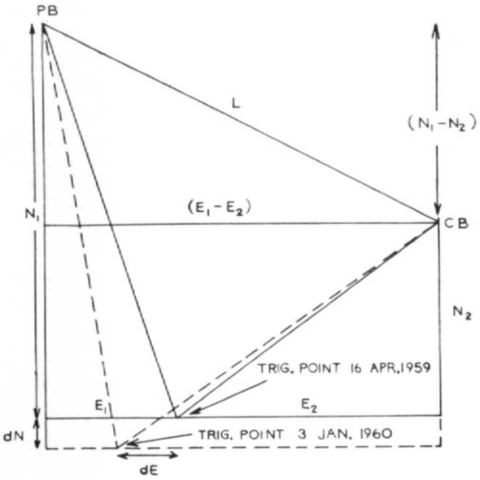

Fig. 3. Calculation of the coordinates of PB and CB.

TABLE III. CHANGES IN POSITION COORDINATES OF THE TWO BERGS

Coordinate	*Change* (ft.)	*Vector Change* (ft.)
dN_1 (PB)	$+231 \pm 230$	690 ± 240
dE_1	-650 ± 70	
dN_2 (CB)	$+60 \pm 45$	862 ± 92
dE_2	-860 ± 80	
$d(N_1 - N_2)$	$+171 \pm 235$	Movement of PB relative to CB is 271 ft. towards the north-west.
$d(E_1 - E_2)$	$+210 \pm 76$	

Positive dN indicates southward movement of the ice shelf and negative dE is westward movement.

ERRORS

The accuracy in measuring the horizontal angle between two fixed points was not better than 3 or 4 sec. of arc. A fair estimate of the accuracy, considering the snow surface and a rather worn theodolite, would be 0·2 min. of arc. In the calculation of a single range, the angle subtended at the distant "fixed" point, i.e. the berg, is derived from two bearings each of which is the result of two single measurements with an error of 0·2 min. of arc. The uncertainty of the subtended angle is then $2^{\frac{1}{2}} \times 2^{\frac{1}{2}} \times 12$ sec. (24 sec. of arc). At PB the average angle is 2·5°. Therefore, the uncertainty in calculating the range will be $\frac{24 \times 5{,}600}{2 \cdot 5 \times 3{,}600} = \pm 150$ ft. ($\pm 45 \cdot 7$ m.). A similar calculation for CB gives the uncertainty in range as ± 100 ft. ($\pm 30 \cdot 5$ m.). The actual errors in the vector change (Table III), i.e. the change in range, are of this order. In terms of the error in measuring horizontal angles this gives an accuracy of 4 sec. of arc. It is significant that CB, which is the only berg assumed to have remained fixed, has the smaller position error.

Absolute Movement of the Ice Shelf

Taking CB as fixed, the absolute motion of the Brunt Ice Shelf at Halley Bay was 862±92 ft. in 262 days of 1959, or 366±40 *m. yr.⁻¹ in a direction* 266°±5° *east of true north*. The trend slightly south of west in the movement was confirmed by the behaviour of a large berg that grounded in October 1959 about 11 miles (17·7 km.) west of Halley Bay. This berg appeared during an early break-up of the sea ice, moving from the north-east under the influence of the strong winds and the normal surface current. Bearings from triangulation stations A_1* and B_1* showed that after grounding it had an apparent tangential movement northwards, i.e. the ice shelf had a southward motion. Based on observation periods of 16 and 53 days, this movement was about 25 m. $yr.^{-1}$ which is approximately the same magnitude given by CB (25–26 m. $yr.^{-1}$).

The answer determined by the method described above is somewhat less than the values given by Blackwell (1960) and the direction is also different. These differences may well be accounted for by the magnitude of the errors of the other methods, but the possibility of seasonal changes in velocity should not be excluded, because the result given here is based on observations during the period April 1959 to January 1960. During the earlier months of the year when there is open water there could possibly be a freer and accelerated movement, which without current-borne sea ice to bar the way could be towards the north-west. More detailed work on the seaward variation of the ice-shelf movement is undoubtedly required.

Other Evidence of Movement

There is some historical evidence for the westward movement of the ice shelf. A map made by F. A. Worsley during the British Imperial Trans-Antarctic Expedition, 1914–17 (Shackleton, 1919), when superimposed on the present-day map, indicates that there was at that time a tongue of ice shelf extending westwards of the present position at Halley Bay. This is only true if it is assumed that the "Allan McDonald Glacier" (of Worsley) is the present McDonald Ice Rumples, and that the coastline southwards from the headland 9 km. south-west of Halley Bay is identical with the present one. Between these identified points on the two maps there is apparently an active ice front 25–30 km. long.

The south-west ice front is considerably lower than that at Halley Bay and it falls to 10 to 20 m. in height, indicative of the ice shelf thinning from considerable bottom melting. It is conceivable that this bottom melting exactly compensates for the ice supply from inland so that along this ice front there is no forward movement. There is little evidence from soundings made by R.R.S. *John Biscoe* in 1960 that this part of the ice shelf is grounded.

Relative Movement and Horizontal Strain-rates

It was noted by Burton (1960, p. 198) that the north–south strain-rate in the region of the Halley Bay observatory during 1957–58 was $11{\cdot}4\times10^{-4}$ $yr.^{-1}$.

The pattern of nine stakes was laid out in March 1959 for the purpose of obtaining strain-rates over a larger area. The rectangle nearest the Halley Bay station was trilaterated and the remaining three rectangles were triangulated from the three triangulation points. The triangulation was not particularly successful. The angular change during the eight-month period was generally less than 30 sec. of arc. Complete consistency was not obtained because the uncertainty between any two bearings was of the order of 24 sec. of arc and the probable errors in measuring the change in range to any distant stake was very near to the amount of movement it was hoped to detect. A longer period of observation would have overcome this difficulty.

The results of the trilateration are given in Table IV. The notable feature is that the strain-rates have fallen to between 4·0 and $6{\cdot}5\times10^{-4}$ $yr.^{-1}$ from $11{\cdot}4\times10^{-4}$ $yr.^{-1}$ of the previous year. The principal strain-rates were calculated by the method outlined by Nye (1959) and are illustrated in Fig. 4A. Strain-rates of $4{\cdot}3\times10^{-4}$ $yr.^{-1}$ in a direction 10° west of north and $5{\cdot}6\times10^{-4}$ $yr.^{-1}$ in a direction 70° east of north for a point midway between the four stakes were found. The standard error for the square was $0{\cdot}4\times10^{-4}$ $yr.^{-1}$. The rectangle $A_1B_1B_2A_2$ will deform after a period of 50 yr. in the manner shown in Fig. 4B, assuming the north–south line through A_1B_1 remains in the same position.

TABLE IV. TRILATERATED BASE LINES AND STRAIN-RATES

Base Line	*Initial Length* (ft.)	*Date* (1959)	*dl* (ft.)	*Period* (days)	$\varepsilon = \frac{dl}{l}$ yr.$^{-1}$
A_1A_2	3016·74	15 March	+1·55	299	$6{\cdot}28 \times 10^{-4}$
A_1B_1	3561·73	15 March	+1·27	297	$4{\cdot}37 \times 10^{-4}$
B_1A_2	4667·57	15 March	+2·14	299	$5{\cdot}59 \times 10^{-4}$
A_2B_2	3562·12	31 March	+1·20	286	$4{\cdot}30 \times 10^{-4}$
B_2A_1	4667·57	15 March	+1·80	299	$4{\cdot}70 \times 10^{-4}$
B_1B_2	3016·30	31 March	+0·97	286	$4{\cdot}10 \times 10^{-4}$

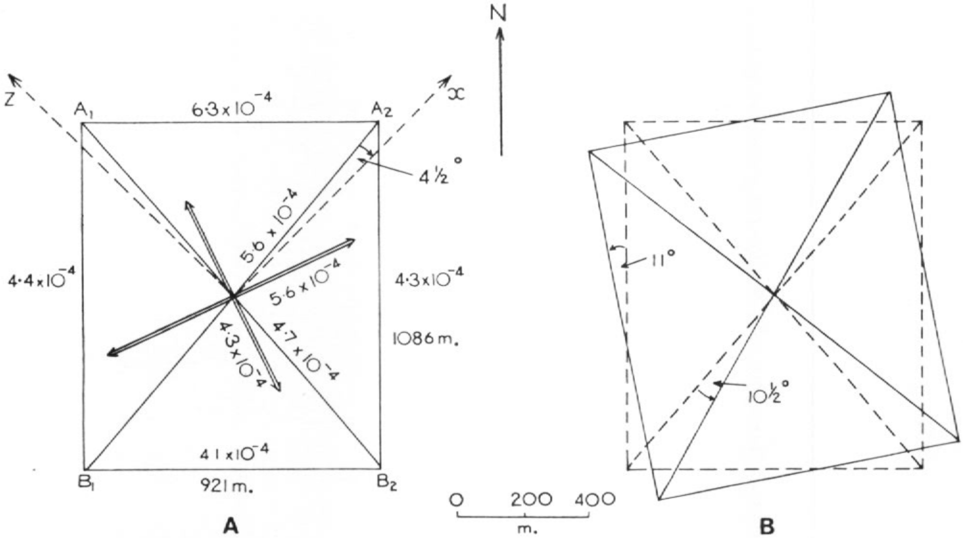

Fig. 4. A. Diagram showing the strain-rates (yr.$^{-1}$). The principal strain-rates are denoted by double line arrows.
B. Diagram showing the deformation after 50 years at the present rate.

The interpretation of these strain-rates is that there is a flow of ice away from the McDonald Ice Rumples, i.e. the ice shelf is being diverted west by south by the underwater ridge north-east of Halley Bay. The distortion produced in the surface by the different stresses is negligible compared with the twisting of the ice shelf (Fig. 4B). Nearly all of this angular change is a result of the bulk ice-shelf motion. The annual absolute twist was found to be 13·1 min. of arc, and together with the velocity of 366 m. yr.$^{-1}$ it should result in a southward motion of approximately 1·40 m. yr.$^{-1}$. The contribution to the southward movement by the surface strain-rates, acting away from the grounded parts of the ice shelf to the north and north-east of the station, is not in excess of 2 m. yr.$^{-1}$. Thus the total expected southward movement would be about 3–4 m. yr.$^{-1}$. This is almost one-sixth of the actual estimate for the movement which was about 25 m. yr.$^{-1}$. The discrepancy may be due to the effect of the drag of the sea current acting on the ice front and the presence of pack ice on the northerly coastline.

VERTICAL STRAIN

An attempt was made to level accurately to several stakes with a view to determining changes of level and the resulting changes in vertical strain as indications of bottom melting.

TABLE V. LEVELS BETWEEN POINTS ON THE ICE SHELF

Line of Level	*Elevations of One Stake from Another for Different Dates*								*Angular Change* $d\theta$
	16–19 April 1959	*4 May 1959*	*24 October 1959*	*14 November 1959*	*18 November 1959*	*18 December 1959*	*31 December 1959*	*3 January 1960*	
A_1 to A_2	{ 04′48″ 04′52″ } { 04′49″* 04′22″* (refraction) }		04′22″		04′05″			04′18″ 04′17″*	−32″
A_1 to B_1	02′14″*		01′47″	02′14″* ←—	01′36″ Rate of change consistent with other observations		—→ 02′08″*	01′32″	−42″
B_1 to A_2	01′00″			{ 01′29″ 01′26″ }		01′40″*	01′54″	01′23″*	+41″
B_1 to A_3	00′12″			01′51″			02′01″		+49″
B_1 to C_1		00′50″*		01′33″			01′57″		+62″
A_1 to C_1		(00′01″*) doubtful value	(01′42″) inconsistent		01′00″			01′12″	—

* Reverse elevation.

Five stakes, A_1, A_2, A_3, B_1 and C_1, were fitted with cross-pieces at heights of about 2 m. above the snow level for the period 16–19 April 1959.

Each of the stakes had been well "bedded down" to the same depth, so that little relative settling was to be expected between stakes. Differences in height (above the snow surface) between the cross-pieces and the theodolite telescope were allowed for and levels were reduced to that between respective cross-pieces. The angular elevations are given in Table V. The various sets of levels observed were restricted to those recorded in April or May, thus giving a reasonable period between observations. The levelling was done on days when the meteorological conditions tended to inhibit refraction. There are certain inconsistencies, notably in the elevations of B_1 relative to A_1 for 14 November and 31 December 1959. The change per day given by these two observations is, however, at the same rate as given by all the other values. In the levelling from A_1 to C_1 the observation of 24 October is inconsistent with the apparent trend of the other observations, and that of 4 May is also open to doubt. Apart from these inconsistencies, a pattern of changes in the ice-shelf level emerges and, although it is not necessarily consistent in magnitude, there is consistency in the way that parts of the stake pattern are sinking relative to one another. The approximate magnitudes of these vertical movements have been calculated (Table VI) by using changes in elevation ($d\theta$)

Table VI. Calculation of Vertical Strain

	Change of Slope		*Distance between Stakes*	*Relative Change of Level in 260 Days*	*Vertical Strain*	
	(sec.)	$d\theta$ (radians)	l (ft.)	dh (ft.)	$\frac{dh}{dl}$ (ft./ft./yr.)	
A_1-A_2	−32	−0·0001551	3,015	−0·47 ± 0·25	$2\cdot19\times10^{-4}$	
A_1-B_1	−42	−0·0002036	3,559	−0·72 ± 0·29	$2\cdot84\times10^{-4}$	
B_1-A_2	+41	+0·0001988	4,663	+0·93 ± 0·38	$2\cdot79\times10^{-4}$	Mean = $3\cdot07\times10^{-4}$
B_1-A_3	+49	+0·0002376	7,500	+1·78 ± 0·62	$3\cdot33\times10^{-4}$	
B_1-C_1	+62	+0·0003542	3,950	+1·19 ± ·032	$4\cdot22\times10^{-4}$	

Probable instrumental error of ±17 sec. is also given as ft. in the column for *dh*.

determined graphically. It can be seen that B_1 is sinking relative to A_2, i.e. the elevation of A_2 from B_1 has increased, and that A_2 and B_1 are sinking relative to A_1 ($d\theta$ is negative). For these changes to be completely consistent in magnitude, $d\theta$ for A_1 to A_2 should either be closer to zero or $d\theta$ for A_1 to B_1 should have a larger negative value, or $d\theta$ (B_1-A_2) should be smaller. Nevertheless, the indicated trends are consistent and indicate melting seawards.

Regime of the Brunt Ice Shelf

The mean vertical strain-rate is approximately 3×10^{-4} yr.$^{-1}$ and, since all other strain-rates and the absolute movement are known, it is possible to make a calculation to determine the regime of the ice shelf near the huts at Halley Bay (Crary and others, 1962, p. 2798–806).

The change in height of the ice shelf above sea-level is given by $\frac{dh}{dt} = A^{\cdot} - H\varepsilon^{\cdot} - M^{\cdot}$,

where $A^{\cdot}$ = Net annual accumulation in ice equivalent (= 41·5 cm.);
H = Total thickness of the ice shelf ($\simeq$ 150 m. (Robin, 1958, p. 113));
V = Velocity (= 366 m. yr.$^{-1}$);
$M^{\cdot}$ = Melting;
$\varepsilon^{\cdot}$ = Sum of the principal strain-rates (= $9\cdot9\times10^{-4}$ yr.$^{-1}$).

Since $$\frac{dh}{dt} = \frac{dh}{dl}\cdot\frac{dl}{dt} = V\frac{dh}{dl},$$

$$\frac{dh}{dt} = 366\times10^2\times3\times10^{-4} = 10\cdot9 \text{ cm. yr.}^{-1}.$$

Thus $M^{\cdot} = A^{\cdot} + H\varepsilon^{\cdot} - dl/dt$

$= 41 \cdot 5 - 14 \cdot 8 + 10 \cdot 9 = 37 \cdot 6$ cm. yr.$^{-1}$.

Hence, the loss by bottom melting is 37·6 cm. yr.$^{-1}$, which leaves a net gain of 3·9 cm. ice (3·5 g.) each year. For equilibrium to be maintained, this mass gain must be accounted for by an increase in the area of the ice shelf.

If A is the ice shelf area, H the thickness, ρ_m the mean density of the ice shelf and dm the net mass gain,

$$\frac{dA}{A} = \frac{dm}{H\rho_m} = \frac{3 \cdot 5}{150 \times 10^2 \times 0 \cdot 88} = 2 \cdot 6 \times 10^{-4},$$

and $A \simeq 3{,}500$ km.^{2}.

Hence, the increase in area $dA = 0 \cdot 91$ km.^{2}. The annual movement rate has been shown to be 366 m. yr.$^{-1}$, which gives an advance over a front of only 2·5 km. It therefore follows that either the annual advance of the ice shelf at Halley Bay is restricted to a very narrow front or the major contribution to the ice-shelf movement is the supply from the inland ice. It appears that the latter explanation is the more probable. The apparent active ice front, marked by fissures and inlets and formed by spreading of the ice shelf, is about 25–30 km. long and all but 2·5 km. of this must be kept moving by the supply from the inland ice.

If there is no bottom melting so that the vertical strains are nil, then the whole of the active ice front could be kept moving solely by the annual accumulation acting over the area of the ice shelf, and the contribution from the inland ice would be nil. The calving of inland ice to form the basis of the ice shelf is a specific feature of the Brunt Ice Shelf, and accordingly nullifies any argument on these lines. It must therefore be concluded that the greater part

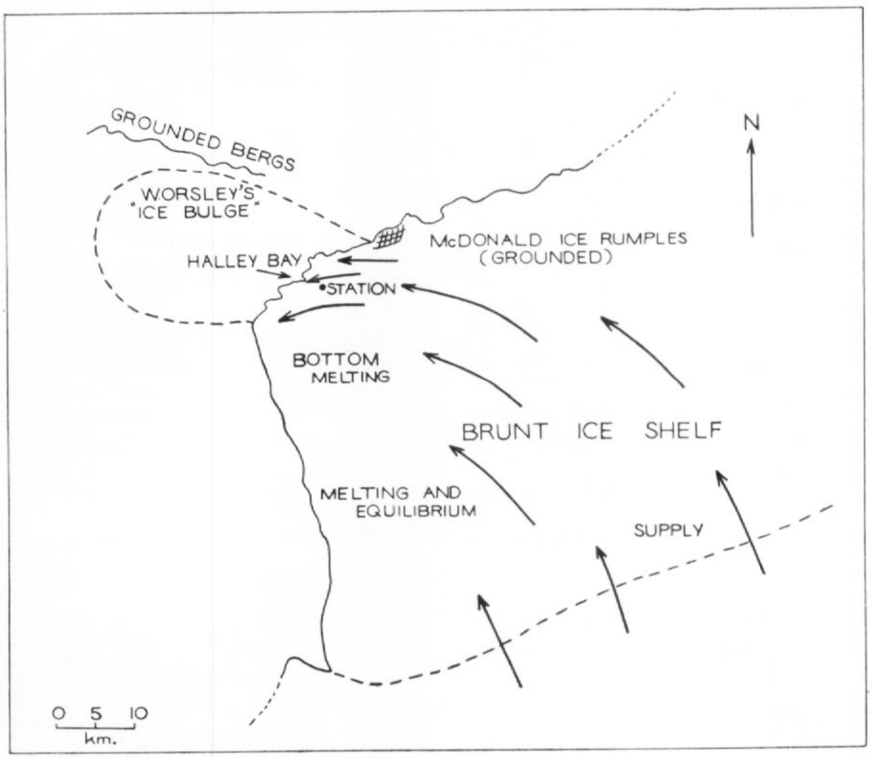

Fig. 5. Sketch map of the probable ice flow of the Brunt Ice Shelf. The given limits of Worsley's "ice bulge" are only to indicate a trend and are not meant to be definitive.

of the annual movement of the ice shelf is a direct result of flow from the inland ice, and that Halley Bay is situated in an area where the ice shelf is thinning and in near-equilibrium with bottom melting.

Summary

By using grounded icebergs as sighting points, the annual velocity of the ice shelf has been determined as 366 ± 40 m. yr.$^{-1}$ in a direction $266^\circ \pm 5^\circ$ east of true north for 1959. It is possible that this may be an underestimate, because calculations were based on an eight-month period and there is the possibility that the velocity may have been greater in the months of January and February which were not included in the period of observation.

Horizontal strain-rates in the ice shelf during 1959 were found to be less than for the previous year; again, this was possibly the result of considering a short period which did not include part of the summer. The principal strain was in a direction away from the McDonald Ice Rumples which divert the flow of ice from west-north-west to west or even west-south-west.

An estimate of the vertical strains obtained by levelling methods, together with the horizontal strains, leads to the conclusion that bottom melting in the vicinity of Halley Bay is in near balance with the annual accumulation, so that the absolute velocity of the ice shelf is almost completely maintained by supply from the inland ice moving westward over an active 25–30 km. front between the McDonald Ice Rumples and the south-west headland. The south-west ice front is possibly in equilibrium with the supply of ice and thus remains almost stationary. Fig. 5 illustrates the probable flow pattern of the Brunt Ice Shelf.

Acknowledgements

I wish to thank M. J. Blackwell, G. M. Artz, M. A. Sheret and G. R. Lush for help during the field surveying. I am also indebted to B. Chapman, who checked much of the original survey data and calculations, and to Dr. S. Evans for helpful suggestions regarding the estimation of errors and for showing me F. A. Worsley's map superimposed on later maps.

MS. received 19 April 1963

REFERENCES

Blackwell, M. J. 1960. Recent Scientific Activities at Halley Bay: International Geophysical Co-operation 1959. *Nature, Lond.*, **187**, No. 4742, 982–84.

Burton, J. M. C. 1960. The Ice-shelf in the Neighbourhood of Halley Bay. *Proc. roy. Soc.*, Ser. A, **256**, No. 1285, 197–200.

Crary, A. P., Robinson, E. S., Bennett, H. F. *and* W. W. Boyd. 1962. Glaciological Regime of the Ross Ice Shelf. *J. geophys. Res.*, **67**, No. 7, 2791–807.

Limbert, D. W. S. 1963. The Snow Accumulation Budget at Halley Bay in 1959, and Associated Meteorological Factors. *British Antarctic Survey Bulletin*, No. 2, 73–92.

MacDowall, J. *and* A. Blackie. 1960. Geomagnetic Observations. (*In* Brunt, D., *ed. The Royal Society International Geophysical Year Antarctic Expedition, Halley Bay, Coats Land, Falkland Islands Dependencies, 1955–59. I. Introduction, Aurora and Airglow, Geomagnetism.* London, Royal Society, 61–221.)

Nye, J. F. 1959. A Method of Determining the Strain-rate Tensor at the Surface of a Glacier. *J. Glaciol.*, **3**, No. 25, 409–19.

Robin, G. de Q. 1958. Glaciology. III. Seismic Shooting and Related Investigations. *Norwegian-British-Swedish Antarctic Expedition, 1949–52. Scientific Results*, **5**, 3–134.

Shackleton, E. H. 1919. *South: the Story of Shackleton's Last Expedition 1914–1917.* London, William Heinemann.

Swithinbank, C. W. M. 1958. Glaciology. I. The Movement of the Ice Shelf at Maudheim. *Norwegian-British-Swedish Antarctic Expedition, 1949–52. Scientific Results*, **3**, C, 77–96.