# ICE FLOW IN ANTARCTICA

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Abstract. A number of measurements of ice flow in the coastal regions of Antarctica are given. Observations show that the general outward movement of the continental ice, termed "sheet flow", is locally accelerated where "ice streams" are formed. Estimates indicate that ice streams, which only occupy a small fraction of the total length of coast, are responsible for the removal of more ice from the continent than the "sheet flow" over the remaining length of coast. Further estimates suggest that the great bulk of Antarctic icebergs are produced by ice shelves, but that data on ice shelf movement are inadequate at the time of writing.

Zusammenfassung. Es werden eine Anzahl Messungen der Eisbewegung in den Küstenbereichen der Antarktis wiedergegeben. Durch Beobachtungen wird erwiesen, dass die im allgemeinen nach aussen gerichtete Bewegung des kontinentalen Eises, die „sheet flow" genannt wird, dort wo sich Gletscherzungen bilden, lokal beschleunigt wird. Es wird durch Auswertungen gezeigt, dass von den Gletscherzungen, die nur einen kleinen Teil der gesamten Küste einnehmen, mehr Eis in das Meer abgeführt wird als vom ganzen übrigen Eisrand durch den „sheet flow". Weitere Auswertungen lassen vermuten, dass die Eisberge in der Antarktis grösstenteils durch Schelfeismassen hervorgerufen werden, aber Angaben über die Bewegung des Schelfeises sind zur Zeit dieser Niederschrift unzureichend.

## Introduction

The observations and measurements given in this paper were made during 1957-58 as part of the glaciological programme of the Australian National Antarctic Research Expeditions (A.N.A.R.E.). The results permit reasonable estimates of the mass flow of continental ice to be made and also tend to confirm the view that the calving of ice shelves, for which data are scant, is the most important source of icebergs. Seismic work indicates that the ice moving from the centre of Antarctica into the coastal regions of Mac-Robertson Land has a thickness of the order of 2000 m. At a distance of about 700 km. from the coast, major features of the terrain beneath the ice begin to influence the speed and direction of flow, and numerous large ice streams may be directed to one short length of coast. The enormous Lambert Glacier system, for instance, drains ice from a wide area and channels it into the constricted head of Mackenzie Bay—Prydz Bay, where the Amery Ice Shelf is located. Along the greater length of the coastline, however, the ice moves north as a sheet and terminates in coastal ice cliffs which vary in height from a few metres to about 45 m. In a coastal belt about 70 km. wide smaller features of the underlying topography affect the thinner ice and rapid moving ice streams may result. These faster streams, often referred to simply as "glaciers", may thrust a floating tongue a considerable distance out into the sea, or may terminate at the head of a bay. They range in size from about 2 to 15 km. across. The length of coastline affected by this enhanced flow would be about 10 per cent of the total.

It was not possible to measure the movement of ice shelves in 1957-58, but observations from the air show that they lose very large volumes of ice by calving each year. There is ample evidence of great inflows of ice from the continent, considerable surface nourishment and a high calving frequency.

## Measuring Methods

Measurements were made by two general methods; conventional ground survey and aerial photogrammetry. The first method was used in places which were accessible to survey parties and the second technique was evolved in order to measure the flow of certain inaccessible coastal glaciers.[1] The only method which can be used for determining the movement of the inland ice is one entailing repeated astronomical fixes over a number of years. To this end, the co-ordinates of a large fuel dump, 400 km. inland along the main tractor trail, were accurately determined in February 1958.



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The locations of measured sections and the methods used are listed below.

(*a*) *Mawson.* Immediately after arrival at Mawson stakes were established along lines running $1\frac{1}{4}$ km. east and west of the rock outcrop on which the base is situated, and approximately 200 m. from the edge of the ice cliffs (Fig. 1, p. 385). Fixed angles were swung from a reference object by a theodolite set up on the Mawson terminal moraine, and offsets from the fixed lines to the stakes were measured directly. The movement was measured three times in ten months. Three stakes were lost by calving.

(*b*) *Henderson–Casey Line.* An east-west line of stakes was laid between a nunatak south of Mt. Henderson and Casey Range, the distance from the coast being about 12 km. The line was ranged by theodolite between fixed reference points and 23 stakes were placed in a distance of 26 km. The line was run again after 230 days had elapsed and offsets to the stakes were measured directly.

(*c*) *Taylor Glacier.* Four stakes were planted on the crevassed tongue of this small glacier along a line defined by theodolite from a neighbouring hill. A triangle was observed on the hills flanking the glacier and one side was measured as a baseline. Angles to the stakes were read from two of the vertices to fix their positions and the movement of the ice was computed by observing the angular displacements of the stakes from a single point. Light aircraft were able to land alongside the glacier so that repeat measurements could be made in 20 minutes.

(*d*) *Jelbart, Dovers, and Hoseason Glaciers.* The measurement of these glaciers presented certain problems; their surfaces were dangerous and difficult to attain, and in some cases the rocks constituting the fixed points were neither intervisible nor visible from the glacier surface. The difficulty was overcome by mapping the glacier tongues with overlapping vertical aerial photographs and repeating the survey at a later date to permit flow measurement to be made on the photographs. The photographic runs were made by De Havilland Beavers at an altitude of 3100 m., and the runs were planned to include rock outcrops and skerries. Identifiable points on persistent crevasses were used as ground marks. Measurements of movement were made from prints of the photographs at the National Mapping Office, Canberra, where the marker points were plotted by the radial line method, using rocks as fixed control points.

## Results

(*a*) *Mawson.* The surface movement of the ice is given below; mean flow rates of stakes are plotted on map (Fig. 2).

(i) *West Line.*

| Period | | *Stake No. and distance from theodolite* 1 (335 m.) | 2 (503 m.) | 3 (670 m.) | 4 (837 m.) | 5 (1005 m.) | 6 (1170 m.) |
|---|---|---|---|---|---|---|---|
| 17 Feb. 57–11 June 57 (114 days) | Movement (m.) | 0 | 2·41 | 3·56 | 3·53 | 3·02 | 2·78 |
| | Rate (cm./day) | 0 | 2·1 | 3·1 | 3·1 | 2·6 | 2·4 |
| 11 June 57–16 Sept. 57 (97 days) | Movement (m.) | 0 | 1·62 | 1·77 | 1·83 | 1·74 | 0·94 |
| | Rate (cm./day) | 0 | 1·7 | 1·8 | 1·9 | 1·8 | 1·0 |
| 16 Sept. 57–10 Dec. 57 (85 days) | Movement (m.) | 0 | 2·26 | 3·72 | 4·48 | 4·24 | 4·88 |
| | Rate (cm./day) | 0 | 2·7 | 4·4 | 5·3 | 5·0 | 5·7 |
| Total (296 days) | Movement (m.) | 0 | 6·27 | 9·05 | 9·84 | 8·98 | 8·60 |
| | Rate (cm./day) | 0 | 2·1 | 3·1 | 3·3 | 3·0 | 2·9 |

(ii) *East Line.* Three stakes from the east line were lost when the ice cliffs calved on 3 April 1957. Overall movements of the remaining two stakes are given.

| Period | | *Stake No. and distance from theodolite* 1 (292 m.) | 2 (655 m.) |
|---|---|---|---|
| 18 Feb. 57–10 Dec. 57 (295 days) | Movement (m.) | 1·59 | 13·60 |
| | Rate (cm./day) | 0·5 | 4·6 |

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The depth of ice along the measured sections is about 120 m., a value which would be fairly typical for this length of coast. The higher ice velocities would probably be representative for the coast.

(*b*) *Henderson—Casey.* The stakes were placed in May 1957 and re-surveyed in January 1958. A further survey will be made late in 1958. The movements and flow rates are given below, and surface velocities are plotted against ice depths, measured by seismic methods, on map (Fig. 3).

| *Stake No.* | *Movement* (m.) | *Rate of Flow* (cm./day) |
|---|---|---|
| 0 | — | — |
| 1 | 8·4 | 3·7 |
| 2 | 9·0 | 3·9 |
| 3 | 11·6 | 5·0 |
| 4 | 14·5 | 6·3 |
| 5 | 14·0 | 6·1 |
| 6 | 9·9 | 4·3 |
| 7 | 6·4 | 2·8 |
| 8 | 7·3 | 3·2 |
| 9 | 8·5 | 3·7 |
| 10 | 9·6 | 4·2 |
| 11 | 10·1 | 4·4 |
| 12 | 10·5 | 4·6 |
| 13 | 10·7 | 4·7 |
| 14 | 13·7 | 6·0 |
| 15 | 15·6 | 6·7 |
| 16 | 17·1 | 7·4 |
| 17 | 20·0 | 8·7 |
| 18 | 25·9 | 11·3 |
| 19 | 23·8 | 10·4 |
| 20 | 22·7 | 9·9 |
| 21 | — | — |
| 22 | — | — |

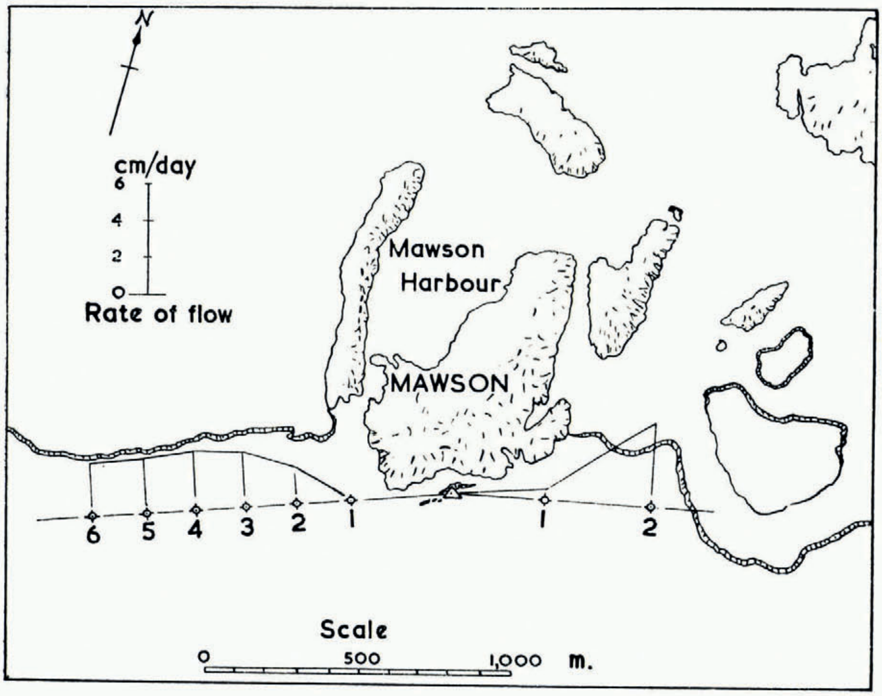


*Fig. 2. Movement of the ice adjacent to Mawson*

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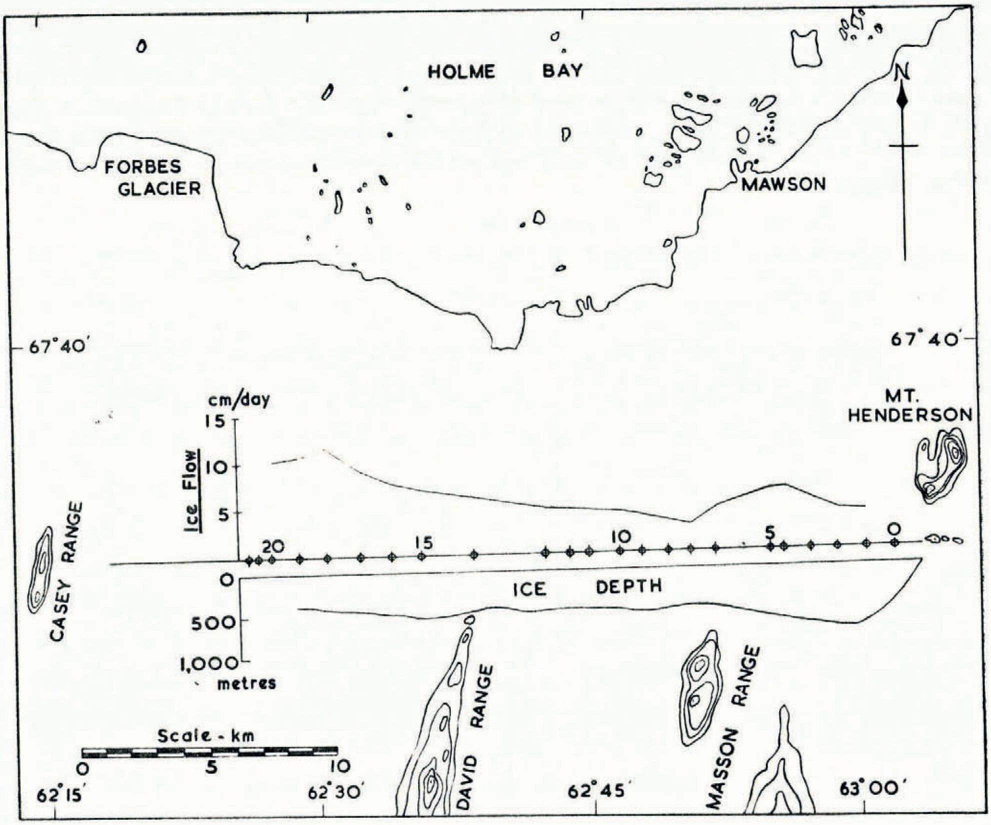


*Fig. 3. Ice flow between Mt. Henderson and the Casey Range, MacRobertson Land. The ice depths along the stake line are shown diagrammatically*

Crevasse hazards prevented re-survey of certain stakes in January 1958.

(*c*) *Taylor Glacier*. The placing of stakes on this glacier tongue was limited by adverse weather conditions and crevasses. Variations in the rates of movement are shown on map (Fig. 4).

| *Period* | | *Stake No.* 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| 6 July 57–30 Aug. 57 | Movement (m.) | 17·2 | 17·8 | 18·4 | 19·0 |
| (55 days) | Rate (cm./day) | 31·3 | 32·4 | 33·4 | 34·6 |
| 30 Aug. 57–27 Oct. 57 | Movement (m.) | 15·6 | 15·7 | 19·4 | 19·6 |
| (58 days) | Rate (cm./day) | 26·9 | 27·1 | 33·5 | 33·8 |
| 27 Oct. 57–30 Nov. 57 | Movement (m.) | 13·3 | 14·6 | 11·8 | 11·9 |
| (34 days) | Rate (cm./day) | 39·2 | 43·0 | 34·8 | 35·1 |
| Total | Movement (m.) | 46·1 | 48·1 | 49·6 | 50·5 |
| (147 days) | Rate (cm./day) | 31·4 | 32·8 | 33·8 | 34·4 |

(*d*) *Jelbart Glacier*. The readings given below are of limited value without a photographic mosaic or detailed glacier map and so the estimated mean surface velocities for each of the streams that were measured photogrammetrically are given.

*East Tongue* (period of 118 days).

| *Point* | *Movement* (m.) | *Rate of Flow* (cm./day) |
|---|---|---|
| 1 | 97 | 82 |
| 2 | 107 | 91 |
| 3 | 112 | 95 |
| 4 | 101 | 86 |
| 5 | 96 | 81 |

Mean surface velocity 88 cm./day.

*West Tongue* (period of 118 days).

| *Point* | *Movement* (m.) | *Rate of Flow* (cm./day) |
|---|---|---|
| 1 | 16 | 14 |
| 2 | 33 | 28 |
| 3 | 25 | 21 |

Mean surface velocity 23 cm./day.

*Dovers Glacier*. The points listed lie on a line crossing a portion of the glacier which is due to produce a large berg. The mean surface velocity is corrected for the widening of the crack seen in Fig. 5 (p. 385).

Period—121 days.

| *Point* | *Movement* (m.) | *Rate of Flow* (cm./day) |
|---|---|---|
| 1 | 26 | 21 |
| 2 | 94 | 78 |
| 3 | 172 | 142 |
| 4 | 214 | 177 |
| 5 | 229 | 190 |
| 6 | 261 | 216 |
| 7 | 308 | 255 |
| 8 | 323 | 267 |
| 9 | 355 | 294 |
| 10 | 104 | 86 |

The mean velocity for the central section of the stream was 215 cm./day and the mean surface velocity across the full width of the stream 200 cm./day.

*Hoseason Glacier*. This glacier is quite a small one and the measurements were made across a land-based section of the ice stream.

Period—125 days.

| *Point* | *Movement* (m.) | *Rate of Flow* (cm./day) |
|---|---|---|
| 1 | 104 | 83 |
| 2 | 109 | 87 |
| 3 | 130 | 104 |
| 4 | 130 | 104 |

Mean surface velocity 95 cm./day.

## Comments

Some idea of the rate of movement of the coastal ice cliffs can be gained from the Mawson measurements. The higher velocities are more likely to be representative, as the lower speeds were measured close to exposed rock.

There is a temptation to see indications of seasonal fluctuation in the flow rates given for the Mawson west line. Such a variation in the surface velocity might be possible, but the evidence is too scant to permit more than speculation.

The movement of the Henderson–Casey line 12 km. inland gives a mean surface velocity of 6 cm./day, a figure which is surprisingly high compared with the movement of the coastal ice cliffs. The west end of the line extended into the Forbes Glacier, however, and measurements made on this length raise the mean value for the line by about 10 per cent. If a mean

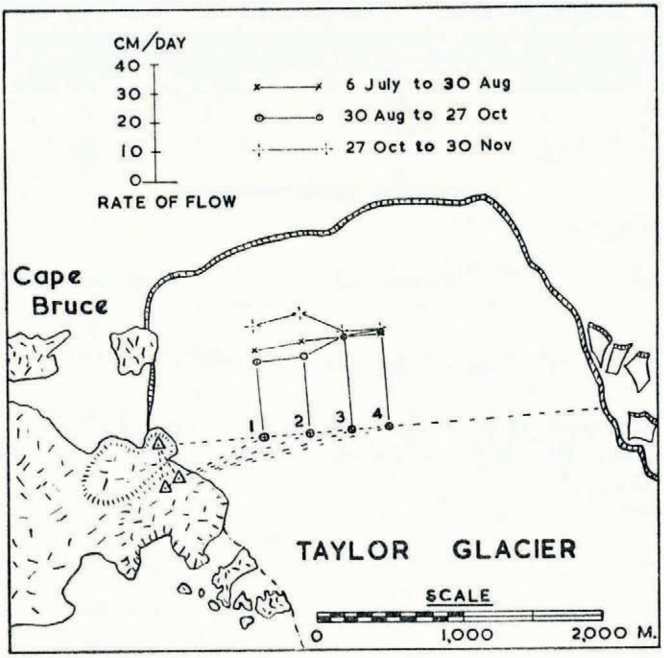


*Fig. 4. Movement of Taylor Glacier*

velocity of 5 cm./day is taken for the general sheet flow, the ice will suffer a thinning of about 200 m. on its passage down to the coast from ablation at the prevailing rate. The mean ice thickness along the line is 550 m.; if the full thickness of the ice is in motion there should be a depth of 350 m. at the coast according to the measured values of velocity and ablation. The actual depth at the coast does not exceed 200 m., so that if continuity is to be satisfied we must either postulate the existence of basal depressions containing ice which is virtually stagnant or assume a progressive change in the vertical distribution of velocity. The data are again too slight for anything beyond speculation.

The measurements discussed above suggest that the average movement of the ice cliffs along this coast is approximately 4 cm./day.

The Taylor Glacier stakes show that even a small coastal glacier moves much faster than the ice sheet generally, the velocities being almost an order of magnitude higher. The irregular way in which the stakes moved indicates that the rock constraints at the tongue tend to produce intermittent motion.

The measurements on the Jelbart, Dovers and Hoseason Glaciers bring out the significance of the work done by ice streams in removing ice from the continent. The Jelbart and Hoseason Glaciers have velocities over 20 times as great as the general ice sheet; the Dovers Glacier moves at 50 times the speed of the ice cliffs to east and west. Although ice streams take up no more than about 10 per cent of the total length of coastline, it is evident that they remove at least as much ice and probably considerably more, than the sheet flow over the remaining length of coast.

## Comparisons with Other Regions

Loewe [2] quotes the measurements of Perroud and Mawson, which give flow rates for the coastal ice of Terre Adélie of a few metres a year and 30 m. a year respectively. Loewe doubts the validity of these figures as characteristic velocities for the ice sheet, but measurements in the Mawson region give similar low speeds of ice flow. The mean velocities which Loewe quotes as necessary to maintain constant ice volume are an order of magnitude higher than the measured ones, and are based on the mass flow necessary to remove an assumed accumulation. The accumulation figure of 10 cm. of water taken by Loewe seems reasonable when compared with measurements in Mac-Robertson Land [3] and at the South Pole,[4] but the effect of ice streams is not considered (a surface velocity of 82 cm./day is quoted for the Glacier de Zélée in another chapter—p. 105). If we assume that sheet flow takes place over 90 per cent of the coastline at a speed of 4 cm./day, and that "glacier" or ice stream flow at 100 cm./day takes up 10 per cent of the coastline, then we can see that ice streams are about three times as effective as sheet flow in removing ice from the continent. Whilst this does not raise the berg formation rate to anything like that considered necessary for equilibrium by Loewe, it does improve the agreement somewhat.

Wright and Priestley [5] quote a number of measurements and estimates of ice velocities, chiefly in the McMurdo Sound area. These range from 0·3 to 85 cm./day, but it is difficult to assess the significance of the figures without further information. Measurements of Drygalski at Gaussberg are also quoted by Wright and Priestley, the movement of the continental ice there being from 33 to 44 cm./day. The continental ice immediately to east and west of Gaussberg, however, is of the stream type [6] and these velocities are similar to the ones measured on the Taylor Glacier in Mac-Robertson Land.

More recently, U.S. glaciologists of Wilkes base made measurements on the Vanderford Glacier (long. 111° E.) during 1957 and established a velocity of 211 cm./day (private communication). The Vanderford is a good example of a medium sized ice stream and is moving at roughly the same speed as the Dovers Glacier in Kemp Land. This confirmation of high velocities indicates that 100 cm./day is not likely to be an overestimate for the average velocity of ice streams overall.

## Conclusions

The measurements show that continental ice reaches the sea or ice shelf by two types of movement: sheet flow and stream flow. The rate of sheet flow must vary to some extent with ice depth and the nature of the subglacial topography, but a figure of 4 cm./day as the mean velocity is likely to be of the right order. Ice stream velocities are determined mainly by their dimensions, but most streams would have mean velocities lying in the range 30 to 300 cm./day. An overall average figure of 100 cm./day would be of the right order and would probably not be high.

Vertical velocity profiles are not considered here, but the export estimates have been roughly compensated by accepting rather low surface velocities.

The calving rate of ice shelves is difficult to estimate from pre-I.G.Y. data, but a rough calculation can be made. Shackleton [5] measured the movement of the Ross Ice Shelf as 450 m./yr., and Gould [7] gives an estimate of 530 m./yr. for the same shelf. Swithinbank [8] gives a figure of 300 m./yr. for the movement of the ice shelf at Maudheim, and also proves an equilibrium thickness of about 190 m. for the shelf ice. 400 m./yr. might be used as a working estimate of movement.

Rough export estimates for the whole of Antarctica are given below, assuming 140 m. as the coastal thickness of the continental ice, 0·87 gm./cm.$^3$ as its density, and 0·84 gm./cm.$^3$ as the mean density of shelf ice.

| | |
|---|---|
| Ice shelf (7,500 km.) | $0{\cdot}48\times10^{18}$ gm./yr. |
| Sheet flow (11,000 km.) | $0{\cdot}02\times10^{18}$ gm./yr. |
| Stream flow (1,500 km.) | $0{\cdot}07\times10^{18}$ gm./yr. |

These figures bring out the great importance of ice shelves in iceberg production. The export quantities for sheet flow and stream flow may be taken as reasonable estimates, but it is apparent that the calving rate for ice shelves is calculated from very slight data. Nevertheless, these quantities can be used until further glaciological and cartographic information becomes available.

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*Fig. 1. The location of the flow stakes in the Mawson area. The photograph also shows the nature of the ablation zone*

*Fig. 5. Dovers Glacier, Kemp Land. The fissure across the glacier is gradually widening and a large berg will eventually be produced*


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