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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

BULLETIN 157

STUDIES OF A SOUTHERN FIORD

Edited by

T. M. SKERMAN

New Zealand Oceanographic Institute
Memoir No. 17

1964

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FOREWORD

THE results reported in this Memoir have come from studies, carried out by workers in a number of different disciplines, on various aspects of the one problem—the nature of the marine environment in a south-west coast fiord.

A number of the influences that complicate the open water marine environment are absent in Milford Sound, other influences are diminished or increased. With these differences from the usual marine situation, the influence of one or other variable on the organic régime can be more readily determined.

The cruise was organised and led by Mr T. M. Skerman and the present volume results from his further work in bringing the results together. The cruise was made possible by the assistance of the New Zealand Naval Board in providing the use of RNZFA *Tui* and thanks are due to her master and officers for their cooperation during the investigation. The figures illustrating this Memoir have been drawn under the supervision of Mr C. T. T. Webb, Chief Cartographer, Department of Scientific and Industrial Research.

The material has been finally edited for publication by Mr M. O'Connor, Information Bureau, D.S.I.R.

J. W. BRODIE, Director,
New Zealand Oceanographic Institute.

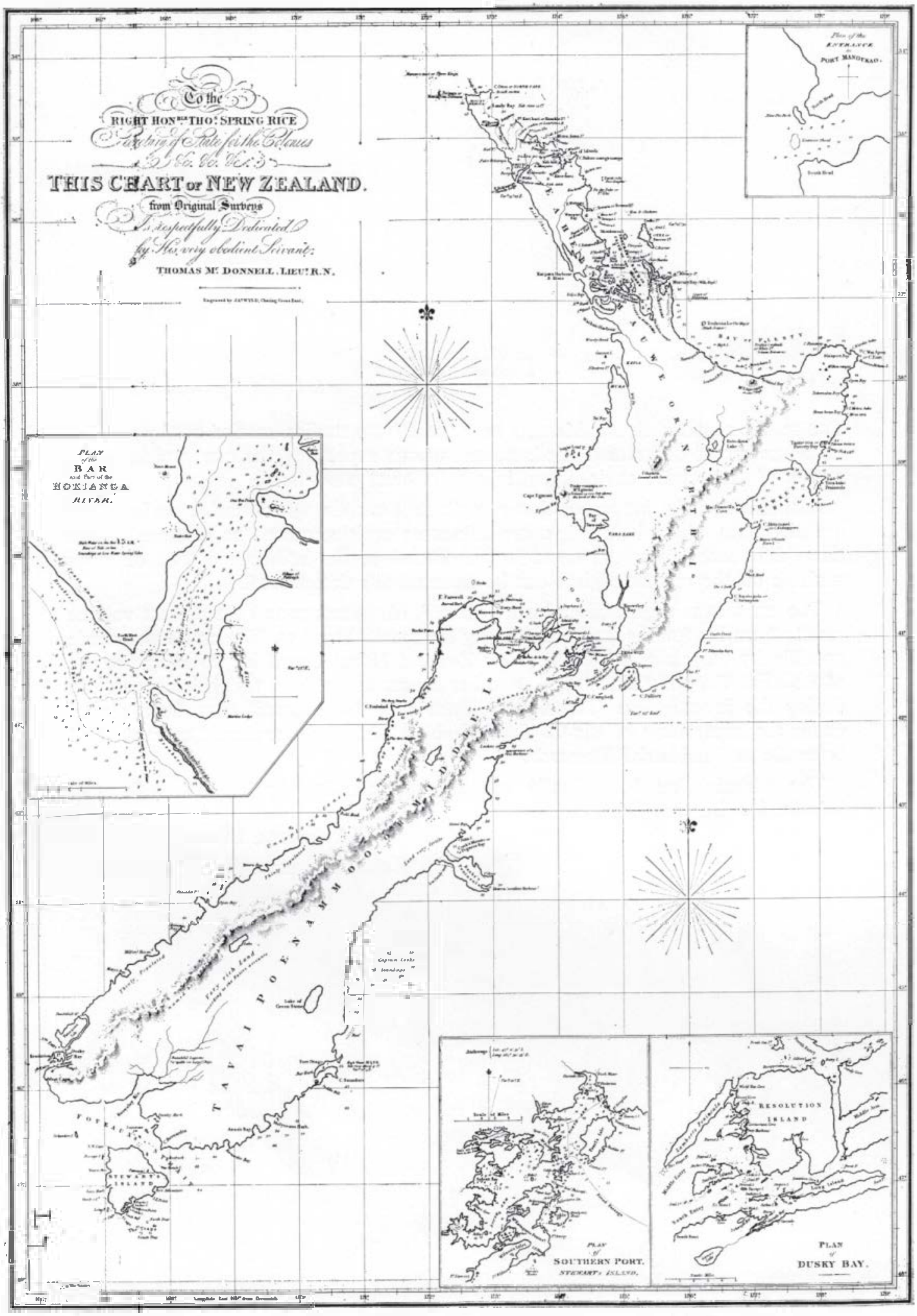

Chart of New Zealand, prepared by Lieutenant Thomas McDonnell and published in 1834 by James Wyld, Geographer to the King. (Milford Haven is the inlet on the south-western coast of the South Island at latitude 44° 30′.)

Reproduced by courtesy of the Alexander Turnbull Library.

HISTORICAL NOTE ON MILFORD SOUND

THE earliest printed chart identifying Milford is one published in 1834 by Wyld and attributed to Lieut. Thomas McDonnell, RN, "from original survey". On this, which is reproduced here by permission of the Turnbull Library, appears the name Milford Haven. Though currently listed among archives as an Admiralty document, publication of McDonnell's chart does not appear to have been authorised by the Admiralty as an Admiralty chart. As it reflects much of the maps by certain of the early explorers in New Zealand, its authority has frequently been questioned. An early critic was Peter Dillon[1], who had seen a great deal of the South Seas in the early part of the nineteenth century, and who asserted that McDonnell, an assistant to the official British Resident at Hokianga, had procured his material from the charts of Cook and d'Urville and from Duperry's Hydrographic Atlas, and had promoted it as his own. Certainly the inset of Dusky Bay (Dusky Sound) bears a striking resemblance to Cook's chart prepared during *Resolution's* visit there in 1772 and published in 1777. It seems likely then that McDonnell's contribution was substantially a compilation of other surveys, acknowledgment of which he chose to avoid, and which doubtless may have been broadened by the descriptions and sketches obtained from seamen familiar with less frequented sectors of New Zealand's coast. A senior midshipman on Duperry's ship *Coquille*, M. Jules de Blosseville, of whose own map of the Chalky Bay area incidentally McDonnell appears to have been unaware, wrote in 1823[2] of the recent discovery of "Milford Sound" (sic)[3] then known to only a few sea captains. One of these sea captains who has been given[4] as a possible person to have conferred the name is Captain Peter Williams, whose birthplace was in Milford Haven in Wales and who was known to have been whaling round the west coast of Otago in the twenties of last century. Recent historical researches* indicate, however, that another likely discoverer of Milford could have been John Grono, a sealer who was born in Wales, and who is known to have worked in these waters prior to 1823. Other names of geographic features of the region, Mt. Pembroke, Llawrenny Peaks, Cleddau Valley, are also suggestive of a Welsh association.

Some of these and other locality names may have followed the hydrographic survey by Captain Stokes of HMS *Acheron* which resulted in 1851 in the first detailed chart of the whole fiord therein called Milford Sound. Stokes comments in his diary[5] "The helmsman who first penetrated into this deep water seems to have retained but an imperfect recollection of the celebrated haven of his native land after which he thought proper to name it". It is a tribute to the skill of Stokes and his companions in their execution of the commission entrusted them by the Admiralty that this chart (Admiralty Chart 615), with only minor amendments, is in use today after the passing of over a century.

BETTY N. KREBS,
N.Z. Oceanographic Institute.

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[1] N.Z. JOURNAL. 5 Dec 1840. p. 294.

[2] BLOSSEVILLE, JULES ALPHONSE RENE PORET, 1823: Essai sur les moeurs et les coutumes des habitants de la partie meridionale de Tavai-Poenamou. In *Nouvelles Annales des voyages, de la géographie et de l'histoire, Paris 29.*

[3] MCNAB, ROBERT, 1909: "Murihuku", new ed. Wellington, Whitcombe and Tombs, pp. 330–5.

[4] BEATTIE, JAMES HERRIES, 1950: "Far Famed Fiordland". Dunedin. *Otago Daily Times*, p. 7.

[5] STOKES, J. L., Diary. MS. microfilm copy deposited in Alexander Turnbull Library, Wellington.

*Carried out by Mr F. Hall-Jones, of Invercargill, who has kindly supplied the information.

CONTENTS

FIGURES AND PLATES

INTRODUCTION

THE FIORDLAND SHELF AND MILFORD SOUND, by J. W. Brodie

THE HYDROLOGY OF MILFORD SOUND, by D. M. Garner

SEDIMENTATION IN MILFORD SOUND, by H. M. Pantin

Figure

FORAMINIFERA OF MILFORD SOUND, by S. Kustanowich

BENTHIC ECOLOGY OF MILFORD SOUND, by D. E. Hurley

CHART

Bathymetry of Milford Sound. New Zealand Oceanographic Institute Chart, Miscellaneous Series No. 5 (in pocket).

INTRODUCTION

OCEANOGRAPHERS have long been interested in the hydrological, biological, and geological properties peculiar to marine fiords. In many regions of the world these partly land-locked arms of water have been found to overlie deep basins that are almost walled in from the open sea by shallow bars – a characteristic topography in whose origin a variety of geological processes may have taken part. As a consequence of this relief, the free interchange of water between a basin and the ocean can only take place above the intervening bar or sill, and temperature and salinity below this depth tend to be uniform, approaching the properties of the water at the threshold level. Under these conditions, the deep saline basin waters can be renewed only by a turbulent or convective mixing with the surface layers, or by their displacement by more dense off-shore water being caused to flow in over the threshold and then sinking. Any effective suppression of these renewal processes, such as may arise through intense density stratification above sill depth when large quantities of fresh water enter the basin, will result in the heavier bottom waters being statically isolated until one or other of the governing conditions alter to an extent that permits dilution of the deep waters to take place. Processes of continual or intermittent replenishment of these deeper waters are thus dependent on local topographic, climatic, and hydrological factors, variation in which has led to the recognition of a wide range of marine basin types.

The primary effect of stagnation in fiord basins in which the deep water is only periodically renewed is a gradual depletion of the oxygen content of the water due to both the respiration of benthic animals and the bacterial oxidation of organic matter. Bottom muds rich in organic material deposited as debris borne into the fiord by streams become anaerobic, and hydrogen sulphide formed predominantly by bacterial sulphate reduction, as well as blackening the sediments by the precipitation of iron sulphide minerals, may diffuse upwards into the bottom basin waters rendering them uninhabitable to animal life. If renewal of these sulphuretted waters is complete, they will be displaced and lifted to the surface – an event that may be followed by a catastrophic devastation of the flora and fauna normally dwelling in the upper waters and shallow bottom areas.

The south-western coastline of the South Island of New Zealand is deeply incised by a number of large fiords, from Dusky Sound in the south to Milford Sound some 90 miles further north. The fiords are the drowned lower reaches of valleys formerly occupied by glaciers of the Last Glaciation and the sea now penetrates an average of 10 miles inland between the sheer sides of mountains rising to heights of 6,000 ft or more.

At Milford, the sea has entered the dominant lower valley of a former glacier to form a narrow arm of water nearly 9 miles long. Within two major tributary glacial valleys, meeting at the headwaters of the Sound, flow the Cleddau and Arthur Rivers over gravels of the Cleddau Delta which fans out almost to the full width of the Sound. Smaller volumes of fresh water enter the inner part of the fiord from streams of the Sinbad and Pembroke Valleys, and from the Bowen and Stirling Falls which cascade some 500 ft over near-vertical cliffs.

In the course of a hydrological survey of New Zealand coastal waters by the New Zealand Oceanographic Institute on the research vessel *Tui*, an opportunity arose in January 1957 to make a brief oceanographic expedition on the vessel to Milford Sound and examine some of its hydrological, geological, bathymetric, and biological features. As this cruise followed the thirty-second (Dunedin) meeting of the Australian and New Zealand Association for the Advancement of Science, the Institute was fortunate in being able to include a number of visiting overseas scientists among the expedition personnel. They were Professor C. E. ZoBell, Scripps Institution of Oceanography; Messrs E. J. Ferguson Wood and I. R. Kaplan of the Australian C.S.I.R.O., Division of Fisheries and Oceanography, Cronulla; and Dr V. B. D. Skerman, University of Queensland, Australia. In addition to Mr I. D. Dick of the Department of Scientific and Industrial Research, members of the Institute's staff participating were J. W.

Brodie, D. E. Hurley, H. M. Pantin, T. M. Skerman, and P. C. Spence.

Four days were spent in the Sound dredging, coring, plankton and bacteriological sampling and sounding, and in making hydrological observations, and the results of these separate investigations have been collated in the present memoir. Station positions are shown on the accompanying chart (fig. 1) and station details are given in the list which follows.

The assembly and checking of manuscripts, together with the supervision of all draughting, have each been undertaken by Mrs P. M. Cullen, New Zealand Oceanographic Institute; her achievements in these tasks are warmly acknowledged.

T. M. Skerman,
New Zealand Oceanographic Institute.

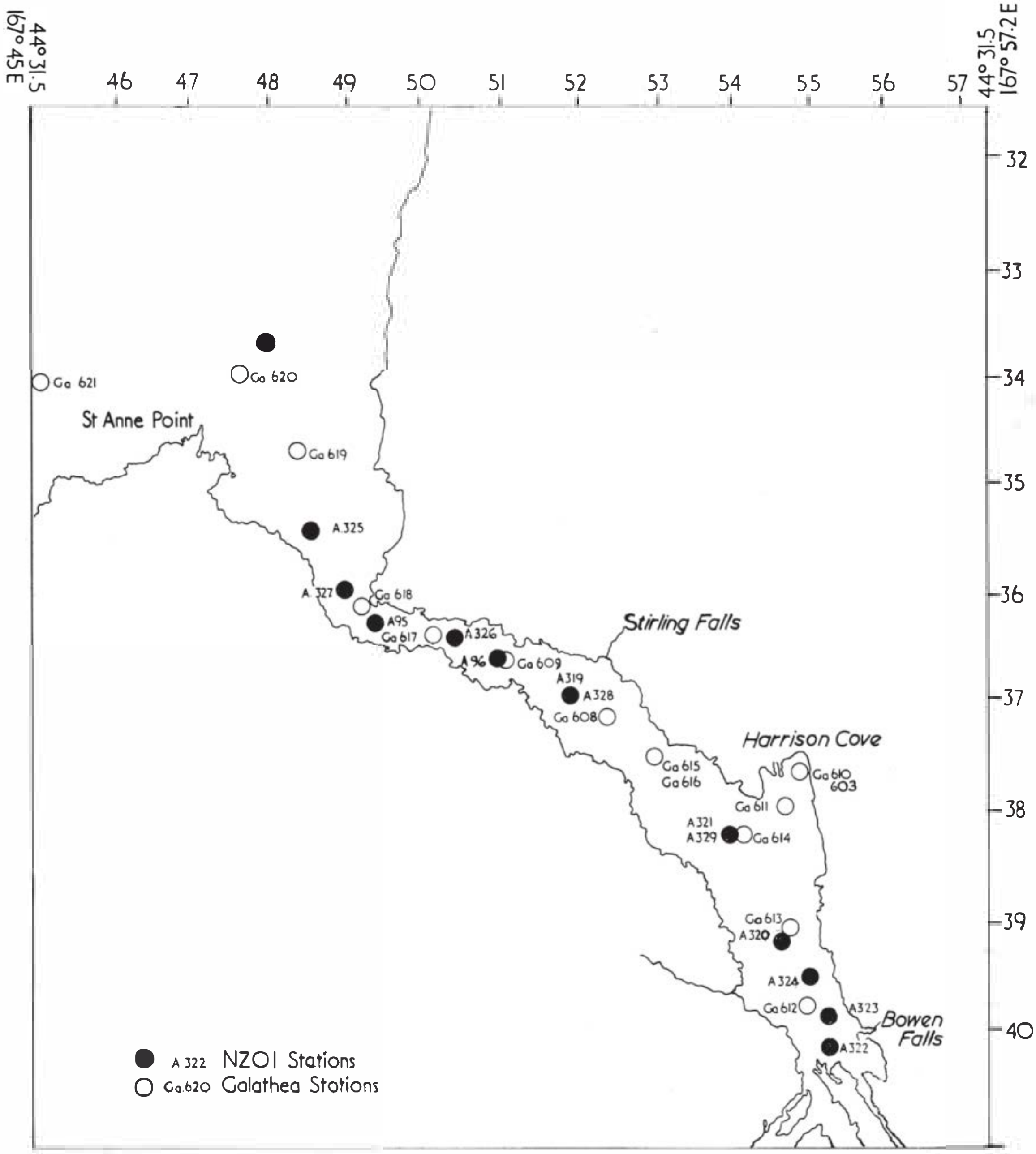

Fig. 1: Station positions.

STATION LIST

Station No.	Date	Latitude S			Longitude E			Locality	Time		Depth		Hydrology		O_2	Surface Sediment	Core Length (ft)	Bacteriology Sample		Phyto Plankton
		°	′	″	°	′	″		Start	Finish	(fm)	(m)	T/S	BT				Sediment Core (ft)	Water Depth (m)	
		(from Admiralty chart) 615											Depths (m)							
A 319	26/1/57	44	37	00	167	51	54	Outer end of Stirling Basin	1636		147	269				GP, DC		1·15	..	
A 320	27/1/57	44	39	15	167	54	40	Upper end of Stirling Basin, between Sinbad Gulley and Bridget Pt.	0630		116	212				DC			50 150 200	
A 321	28/1/57	44	38	15	167	53	58	Centre Stirling Basin opposite Williamston Pt.	0915		142	260				DC	9·75	8·50		N50 and Sample from sediment.
A 322	28/1/57	44	40	12	167	55	20	Upper Stirling Basin on delta slope	1400		10	18				DC				
A 323	28/1/57	44	39	54	167	55	12	Upper Stirling Basin	1430	1510	60	110				DC	8·25			
A 324	28/1/57	44	39	36	167	54	57	Head of Milford Sound ..	1500	1600	94	172	0 25 50 100 150	150	0 25 50 100 150	GD				
A 325	28/1/57	44	35	27	167	48	36	Seaward of Dale Pt.	1641	1705	61	112	0 25 50 100	100	0 25 50 100	GD				
A 326	28/1/57	44	36	25	167	50	28	Entrance sill	1745	1830	64	117	0 25 50 80	80	0 25 50 80	DC GD				
A 327	28/1/57	44	36	00	167	49	00	Dale Point ..	1856		62	113				DC				
A 328	28/1/57	44	37	00	167	51	54	Stirling Basin, off falls	1930		147	269	0 25 50 100 200	200	0 25 50 100 200	GD	6·00		50 150 200 250	
A 329	28/1/57	44	38	15	167	53	58	Off Williamston Pt	2048		142	260	0 25 50 100 200	200	0 25 50 100 200	GD				

THE FIORDLAND SHELF AND MILFORD SOUND

By J. W. Brodie
New Zealand Oceanographic Institute
Department of Scientific and Industrial Research, Wellington

(Received for publication, April 1962)

Summary

The relation of slope canyons, cross-shelf furrows and the submarine and subaerial morphology of Milford Sound allow recognition of three stadials of the Last Glaciation of successively decreasing intensity.

Comparison of depth recordings indicates the likelihood that slumping and redeposition of sediment from the Cleddau delta has produced a depth decrease of about 60 ft at the delta foot.

INTRODUCTION

Reports of earlier investigations from HDMS *Galathea*, of the submarine geology of Milford Sound and the adjacent shelf by Bruun, Brodie, and Fleming (1955), have described the shelf morphology off the Sound entrance and given a general indication of the configuration of the bottom of the Sound itself. From these measurements an interpretation of the late-glacial chronology was made.

Indentations of the shelf edge were suspected to be the heads of submarine canyons.

MATERIALS

Since the *Galathea's* visit in 1952 additional echo soundings have been obtained in and adjacent to Milford Sound by HMAS *Australia* and HMNZS *Black Prince*.

In the course of the present investigations a passage close inshore was followed by RNZFA *Tui* from Puysegur Point north along the coast to the entrance to Milford Sound.

As a preliminary to sampling work an extensive net of echo-sounding traverses was made in the Sound from which the bathymetric chart (chart 1) has been compiled. Soundings were carried as close as practicable to the shore line: at 1 to 2 cables off shore, side echoes from the fiord walls generally obscured the echo-sounding record.

A generalised bathymetry of the continental shelf from Preservation Inlet to Breaksea Sound is shown in fig. 1 and detail of the shelf and slope off Milford Sound entrance is shown in fig. 2.

BATHYMETRY OF MILFORD SOUND

The general nature of the morphology of Milford Sound has been apparent from the Admiralty chart (615) and the centre-line sounding traverses previously obtained (Bruun *et al.*, 1955). The present survey clarifies the nature of the bottom features.

The Cleddau delta at the head of the Sound drops steeply from its underwater margin in 2 or 3 fm, to 50 fm at a slope of 1 in 2. From this depth to the floor of the Stirling Basin in 140 fm the slope is 1 in 4. Stirling Basin extends from the delta foot to the foot of the sill just seaward of Stirling Falls. It is flat-floored in 140–147 fm, the greatest depth being opposite Stirling Falls. The early chart soundings of "212 fm" and "more that 186 fm" could not be reproduced. The basin is steep-sided, and the flat floor extends on the average to within 300 yd of the shore line. Opposite Bridget Point, a bastion-like constriction of the contours is apparent.

The shallowest sounding along the centre line of Entrance Sill is 53 fm. The steep underwater gradient at the sides is maintained along the sill and into Entrance Basin but lessens rapidly seaward.

SOUTHERN FIORDLAND SHELF AND SLOPE

The marked re-entrants on the continental shelf edge and the basins on the shelf off Milford Sound revealed by the *Galathea's* 1952 echo-sounding traverses, led to subsequent soundings

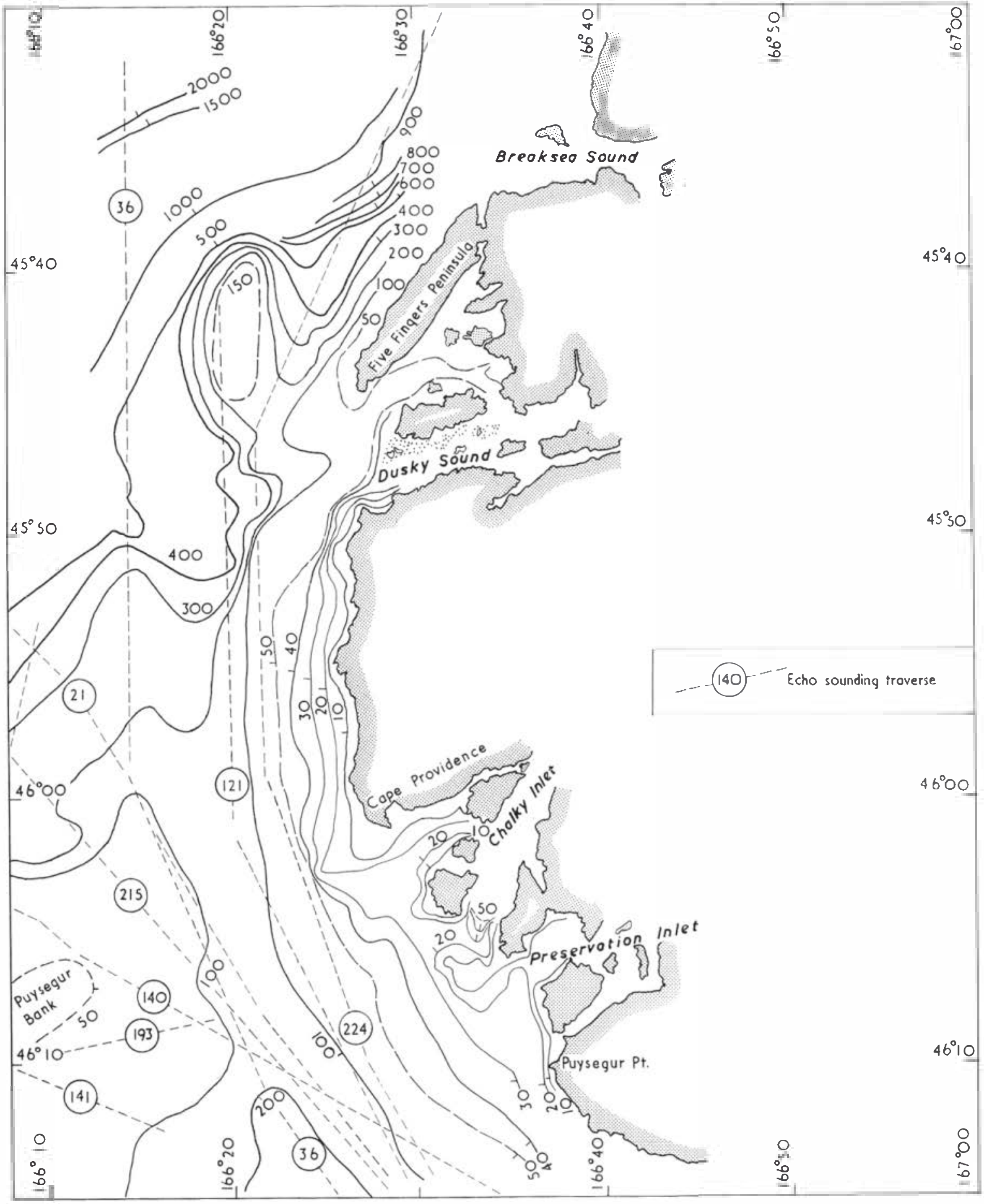

Fig. 1: The continental shelf and slope from Preservation Inlet to Breaksea Sound. Depths are in fathoms.

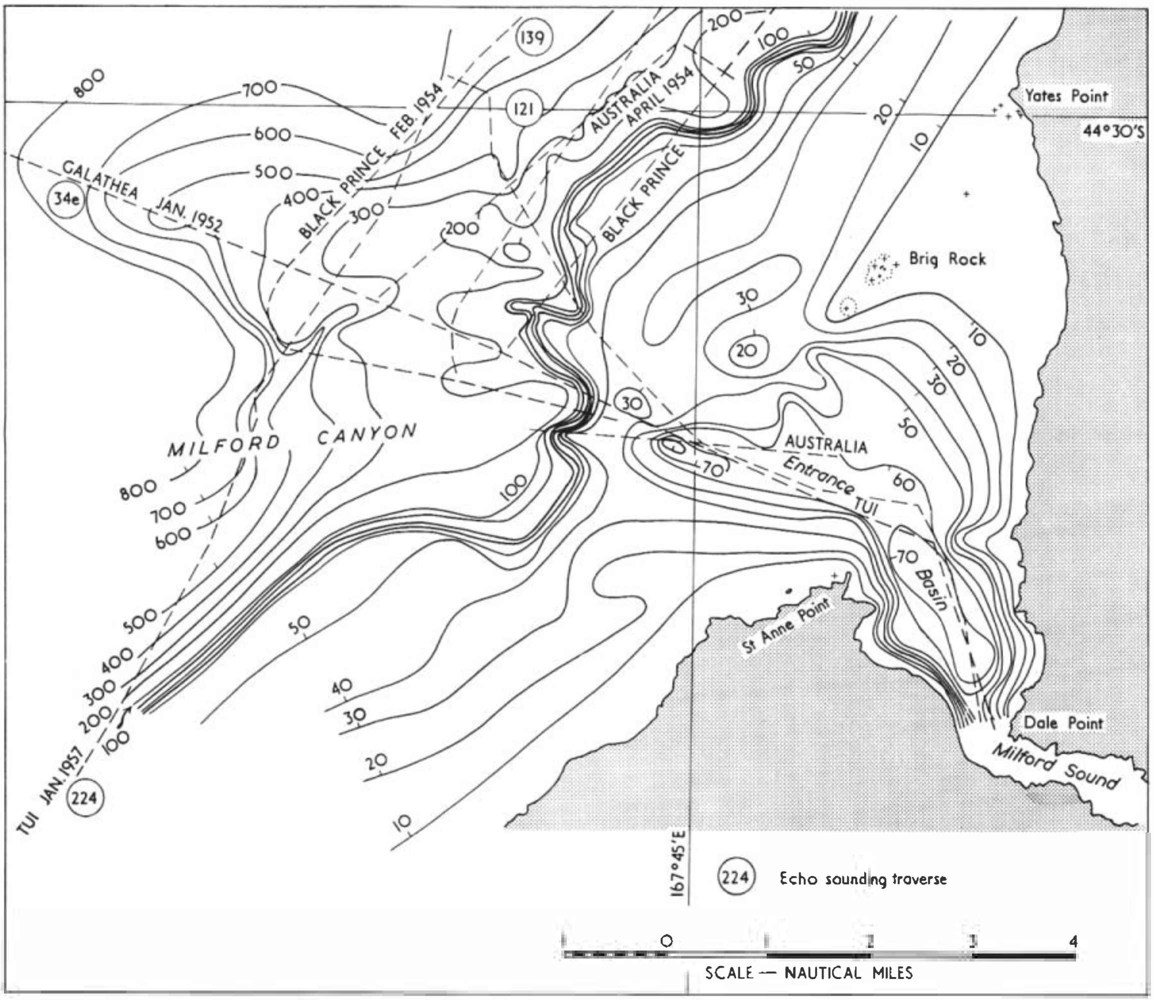

Fig. 2: Continental shelf and slope off Milford Sound. Depths are in fathoms.

to determine the presence or absence of similar features off other western Southland fiords. The results are given in fig. 1. The coastal sounding traverse taken during the present cruise has shown that the continental shelf edge is on the average less than 4 miles off shore in this region.

Off Breaksea Sound the 100-fm isobath is less than 1 mile off shore, the slope drops to 1,000 fm in 6 miles and to 2,000 fm in 11 miles. Development of a continental shelf here has been minimal.

Off Five Fingers Peninsula a level terrace with an edge in 150 fm and minimum recorded depth of 125 fm extends 7 miles off shore. North and south of this terrace are indentations of the shelf edge extending down to at least 500 fm. The southernmost of these canyons, off Dusky Sound, is steep-walled, broadly U-shaped, and more than 3 miles wide. From Dusky Sound south past Chalky and Preservation Inlets a shelf exists, generally 5 miles wide and with a well defined edge in 65–70 fm. This shelf is bordered on the south by a shallow north-west trending furrow. To the south-west the sea floor rises again to the Puysegur Bank with minimum recorded depths of 35 fm, with again a well defined break in slope at 70 fm.

Cross-shelf depressions are found here only off Dusky Sound and have not been demonstrated to occur off Chalky and Preservation Inlets.

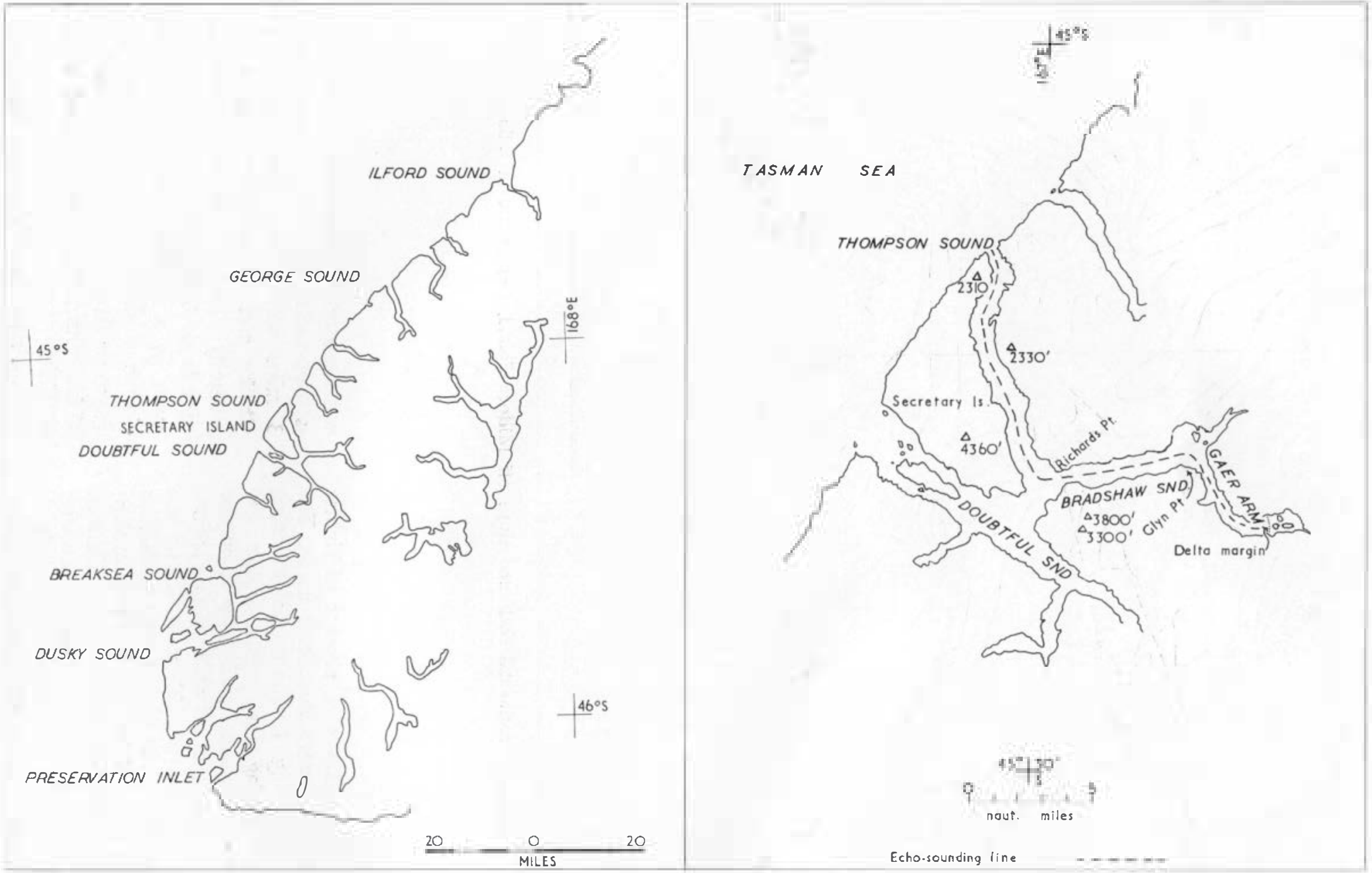

Fig. 3: Locality map of Fiordland and Thompson Sound area.

Shelf and Slope off Milford Sound

The shelf and slope off the entrance to Milford Sound are shown in fig. 2. The shelf topography is little different from that shown by Bruun *et al.* (1955). Soundings by HMAS *Australia* north of Entrance Basin show that the shelf edge lies in approximately 60 fm as it does south of the entrance to the Sound. Slope soundings by *Australia, Black Prince,* and *Tui* have confirmed the existence of the re-entrants on the shelf edge described by Bruun *et al.* (1955) and reveal that these extend seaward to form a broad ill-defined canyon over a mile wide descending to approximately 800 fm. Its northern side is a prominent salient of the continental slope.

Echo soundings between Dusky and Milford Sounds have not demonstrated the occurrence of indentations of the shelf edge or cross-shelf furrows off the fiords between. Such soundings have of necessity been made some miles off shore. The narrow shelf and steep slope down to 1,000 fm extending along the whole of this coastline makes detection of shelf edge features uncertain without precise survey.

The Slope Valleys

The slope canyons, from their cross section and location, can be ascribed at least in part to glacial action. Shelf formation is older than the stadial before last of the Last Glaciation and postdates the Penultimate Glaciation (Bruun *et al.*, 1955). Stepped spurs in Milford Sound suggest three stadials during the Last Glaciation. Stirling Basin is ascribed to the last stadial and Entrance Basin to the second. The width and depth of the glacial canyon suggest that it carried a much larger volume of ice than that responsible for the excavation of either Stirling or Entrance Basins. From the existence of features tentatively ascribed to the Penultimate Glaciation, several hundreds of feet above sea level at the coastline, both the shelf and the glacial canyon must postdate the Penultimate Glaciation as defined by Wellman (1951). The canyon predates the Entrance stadial, and may be the correlative of the broad glacial valley features at an altitude of 1,000 ft above sea level in the Sound at Stirling Basin.

Glaciation in three stadials of the Last Glaciation here recognised – Canyon, Entrance, and Stirling stadials – was thus of successively decreased intensity.

The occurrence of three discrete major lows in the floor of a glacial valley does not of itself necessarily involve occurrence at three separated times. However, the Stirling and Entrance stadials have been separated by Bruun *et al.* (1955) principally on morphological grounds, and the greater width of the Canyon glacial valley suggests a separation from the succeeding two phases. Correlation of the glacial canyon with the 1,000 ft broad valley floor remnant at Stirling Basin implies that a large amount of valley deepening, though within successively narrower confines, has taken place in the interval since its formation.

Morphological Features of Milford Sound

From the similar origins of both sets of features and the availability of published descriptions, it is customary to think of the northern European, and in particular the Norwegian fiords, when comparisons are sought for the Milford region. The morphological analogues of Milford Sound are found in the fiords of central western Norway. It is these fiords, together with those of southern and south-eastern Norway, which have provided Strom (1936) with his classic material on the peculiar hydrological conditions arising in "land-locked waters". Many of the fiords have internal sills which rise near to and above sea level. The fiords of western Norway, like those of the Milford Sound area, are carved in uplifted blocks now forming terrain of high relief and steep slopes. Strom (1948) remarks on the high relief resulting from glacial erosion and instances Sognefjord where there has been a maximum vertical excavation of 2,500 m. At Milford, Mitre Peak rises sheer from the water to a height of 5,500 ft, while the bottom of the Sound is 900 ft below sea level, giving a total relief of 6,400 ft or roughly 2,000 m. (Plates I and II.)

Echo soundings along the centre line of Entrance Basin reveal the presence of a reflecting horizon buried beneath the surface sediments (fig. 4). The basin floor is 60–70 fm deep and the reflector lies an average of 3 fm below the sediment surface. The reflector is found along a distance of roughly a mile at the seaward end of the basin, is not recorded for the central portion, and is found over the last mile, outcropping on the surface of the sediment a little seaward of Dale Point. The absence of the reflector in the central section of the basin can in part be due to the location of the sounding line here, away from the centre line of the basin. The depth of the reflector below the sediment surface may, however, increase and reach depths beyond the range of the echo sounder. A sediment sample of sandy silt was secured from Station A 325 in the Sound entrance over the reflector. From both

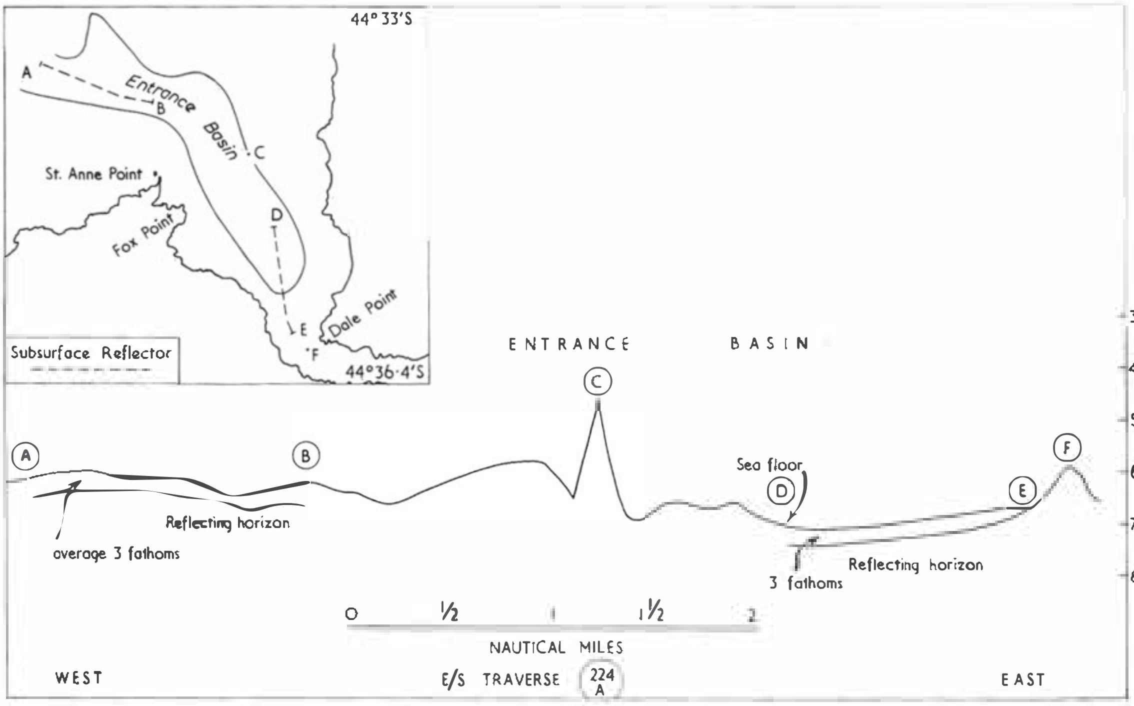

Fig. 4: Reflecting horizon at the shoreward end of Entrance Basin.
(a) Echo-sounding by HMNZS *Black Prince.*
(b) Profile from soundings by *Tui.*

Station A 327 (approximately at the outcrop of the reflector) and A 326 over Entrance Sill. sandy silt was also secured. However, patches of hard bottom are also present on the sill, as evidenced by the rocky botom fauna, also taken at Station A 326 on the centre line of the Sound. There is thus no direct evidence for the nature of the reflecting surface. At the inner end, the reflector appears to outcrop abruptly at the seaward end of Entrance Sill. Both the sediment surface in the Basin and the reflecting surface are far from regular.

It is assumed that the mixed sediments on Entrance Sill include morainic debris, but no evidence is available to determine whether the bulk of the sill is composed of moraine or is unexcavated bedrock veneered with morainic debris and later sediments. From the steep slopes at its inner termination that forms the western wall of Stirling Basin, it is more likely to be bedrock. The subsurface reflector might equally be a morainic surface or a bedrock surface beneath the superficial sediment.

Entrance Sill lay seaward of the ice termination during the Stirling phase of glacial advance. Its surface and perhaps that of the Entrance Basin reflector were developed during this phase. This assertion implies that a thickness of at least 20 ft of sediment has been deposited in Entrance Basin in post-Stirling time. Such an accumulation through the agencies of outwash, local erosion, and longshore drift could well be anticipated.

The steep western termination to Stirling Basin and the shallowing towards the entrance across Entrance Sill is paralleled in the profile of soundings in Thompson Sound and Bradshaw Sound (fig. 5). The seaward termination of the main basin in Bradshaw Sound does, however, coincide with the junction with Smith Sound, a connecting channel to Doubtful Sound, and the seaward decrease in depth of excavation here could be explained by former spillover of part of the ice load through this channel.

A generalised profile of the delta from the present survey is compared in fig. 6 with a similar profile from HMS *Acheron's* survey of 1851.

Plate 1: Aerial view of Milford Sound looking east from entrance, at lower right, across Stirling Basin.

Whites Aviation Ltd. photograph.

While detailed comparison is not possible the similarity of the upper portions, and the lesser gradient and depth now obtaining over the lower fore-slope suggest that slumping and redeposition have taken place. For this area, the curves indicate that a thickness of more than 60 ft of sediment could have been deposited in 100 years.

AGE OF SHELF FORMATION

The formation of the Continental Shelf off Milford certainly postdates the Penultimate Glaciation. A very large volume of rock has been removed in forming the present submarine and sub-aerial land margin from the margin as it must have existed at the end of Penultimate Glaciation

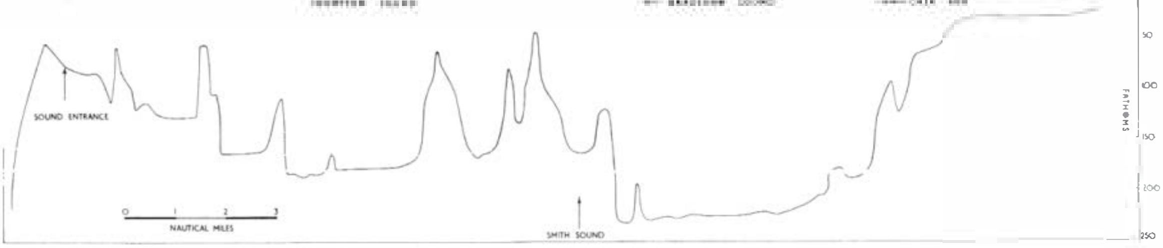

Fig. 5: Longitudinal profile in Thompson and Bradshaw Sounds.

Plate II: General view of Dusky Sound from the southern entrance. The lower relief, as compared with Milford Sound, is evident.

Whites Aviation Ltd. photograph.

time. A correspondingly long period of time must be allowed for this change. At the close of the Penultimate Glaciation, sea level rose during the last interglacial to a position above present sea level. During the rise of sea level and the time of high sea level, active coastal erosion could proceed. In the now stable North Auckland area, Brothers (1954) has correlated two Last Interglacial high stands of sea level 45–75 ft and 15–25 ft above present sea level, with the main and Late Monastirian levels of Europe. The amount of movement of land relative to sea level, caused by movement on the Alpine Fault is unknown; nevertheless, this and isostatic considerations apart, erosion at the Last Interglacial sea levels could have removed a large proportion of the difference between the present shelf and slope, and the conjectured Penultimate Glaciation land margins.

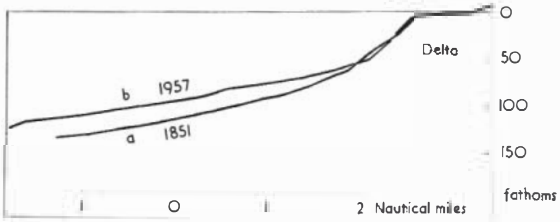

Fig. 6: Comparison of longitudinal profiles of the head of Milford Sound and Cleddau delta from:
(a) Soundings by HMS *Acheron*, 1851.
(b) Soundings from RNZFA *Tui*, 1957.

The onset of glacial conditions at the commencement of the Last Glaciation would then provide the first subsequent opportunity for marine erosion to reduce the higher Last Interglacial slope as sea level fell, and ultimately to cut a shelf at a level similar to that of the present shelf.

ACKNOWLEDGMENTS

Thanks are due to the Royal Australian Naval Authorities and the Commanding Officer HMAS *Australia* for carrying out echo soundings off Milford Sound, and to the New Zealand Naval Board and the Commanding Officer HMNZS *Black Prince* for additional soundings.

Mr P. C. Spence carried out the reduction of soundings and construction of the bathymetric chart of Milford Sound. Mr A. G. York has assisted with the reduction and plotting of additional soundings.

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THE HYDROLOGY OF MILFORD SOUND

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(Received for publication, April 1962)

Summary

Observations of temperature, salinity, and dissolved oxygen are used to derive a generalised picture of the circulation of water in Milford Sound. The high runoff of fresh water into the Sound leads to the formation of an upper layer of low salinity moving seawards. The deeper waters in Stirling Basin have properties which suggest a source from adjacent near-surface shelf waters. Possibly renewal of Basin water by inflow over the Entrance Sill occurs annually around the period of sea surface minimum temperature and maximum density. At other times of the year density relationships are such that Basin waters are probably isolated and may become anaerobic in character.

Introduction

In this section a study is made of the properties and circulation of the water of Milford Sound. Hydrological data relevant to this investigation were available as follows:

(a) The Danish Deep Sea Expedition Round the World, 1950–52, occupied three stations from HDMS *Galathea* – 603, 608, and 615 (fig. 1) – at which observations of temperature, salinity, and dissolved oxygen were made. The figures given in table 1 were provided through the courtesy of Mr A. Killerich, of Copenhagen, who is preparing the expedition's hydrographic material for publication.

(b) Observations of the vertical distribution of water temperature and salinity near the entrance to the Sound were made by the writer from m.v. *Alert* (Master, Mr A. J. Black, Dunedin) on 27 February 1955, at three points – N.Z. Oceanographic Institute Stations A 94, A 95, and A 96 – the data from which are given in table 2 and positions plotted in fig. 1. Sections of temperature and salinity across the Entrance Sill using these figures are shown in fig. 2 and 3.

(c) The Milford cruise of RNZFA *Tui* in January 1957 made the following hydrological observations.

While entering the Sound on 26 January 1957 a series of bathythermograph soundings and surface water samples were taken from about 2 miles off St. Anne Point to the head of the Sound. The results are shown in fig. 4.

On 28 January 1957 five stations – N.Z.O.I. A 324, A 326, A 328, and A 329 – were worked in the Sound, giving measurements of temperature, salinity, and dissolved oxygen. Station positions are plotted in fig. 1, and station data are listed in table 3. A vertical temperature section constructed from these data is reproduced in fig. 5.

(d) General precipitation and run-off figures for the Milford Sound Catchment are given in table 4 and were provided through the courtesy of the Chief Engineer of the Soil Conservation and Rivers Control Council, Wellington.

(e) The Director of Meteorological Services, Wellington, kindly provided the Milford Sound rainfall data covering the periods of the *Alert* and *Tui* investigations described above (table 5).

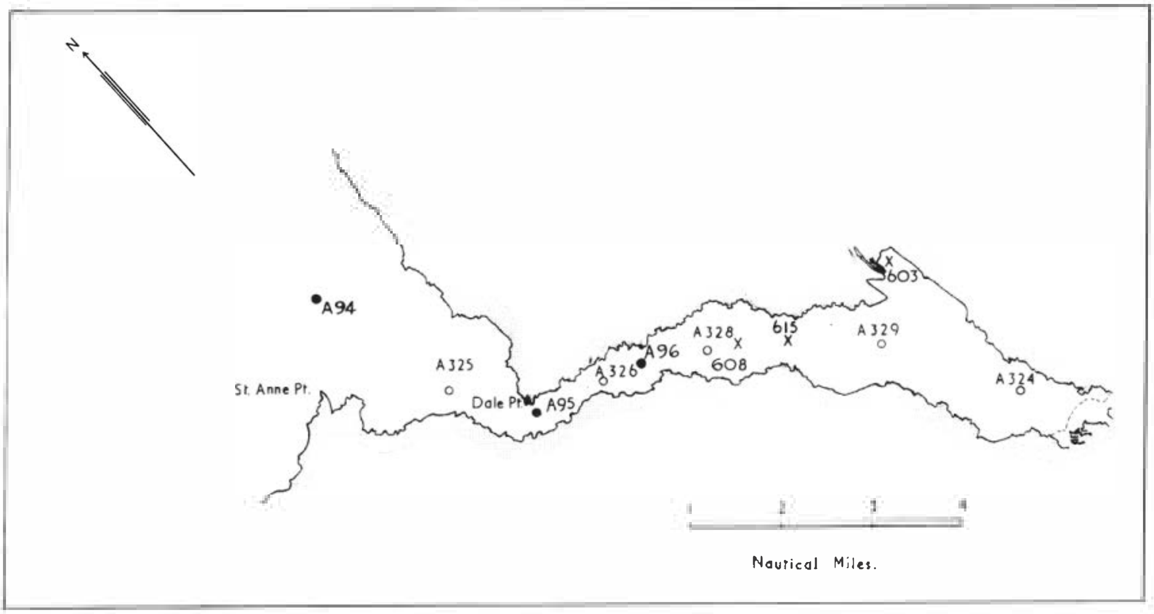

Fig. 1: Milford Sound showing the positions of hydrological stations described in the text.

TABLE 1. HYDROLOGICAL DATA FROM *Galathea* STATIONS IN MILFORD SOUND, JANUARY 1952 (data provided by A. Killerich, Copenhagen, December 1957; for positions see fig. 1)

Sta. 603 16/1/52 – Depth 30 m.

Depth (m)	*Temp.* (°c)	*Salinity* (‰)
0	14·84	20·81
15	12·45	33·62

Sta. 608 18/1/52 – Depth 290 m.

Depth (m)	*Temp.* (°c)	*Salinity* (‰)	*Dissolved Oxygen* (ml/1)
0	13·31	21·69	
24	12·66	34·34	5·90
47	12·33	34·83	5·31
71	11·73	35·01	4·97
95	11·70	35·05	4·77
142	11·59	35·04	4·83
189	11·58	35·04	4·88
242	11·58	35·05	4·84
285	11·53	35·04	

Sta. 615 19/1/52 – Depth 293 m.

Depth (m)	*Temp.* (°c)	*Salinity* (‰)
0	13·34	16·65
1	13·38	28·78
2·5	13·31	32·05
3	13·28	32·10
4	13·18	32·61
5	13·02	32·88
10	12·92	33·26
15	12·72	33·73
20	12·68	33·93

TABLE 2. HYDROLOGICAL DATA FROM NEW ZEALAND OCEANOGRAPHIC INSTITUTE STATIONS (*Alert*) WORKED IN MILFORD SOUND ON 27 FEBRUARY 1955 (for positions see fig. 1)

	Depth (m)	*Temp.* (°c)	*Salinity* (‰)
Sta. A 94			
	0	16·56	30·24
	10	15·78	34·31
	22	15·26	34·68
	48	14·34	34·92
	70	13·68	35·02
	112	12·40	35·20
Sta. A 95			
	0	15·57	30·34
	10	15·34	34·50
	20	15·18	34·81
	31	14·98	34·85
	45	14·69	34·89
	72	13·87	35·06
	98	12·72	35·17
Sta. A 96			
	0	16·16	27·83
	8	15·49	27·92
	20	14·50	28·12
	30	14·10	28·28
	48	13·71	28·51
	74	13·52	33·50
	100	13·19	25·02
	153	11·39	25·11
	198	11·36	35·12

TABLE 3. HYDROLOGICAL DATA FROM NEW ZEALAND OCEANOGRAPHIC INSTITUTE STATIONS (*Tui*) WORKED IN MILFORD SOUND ON 28 JANUARY 1957 (for positions see fig. 1). (Temperatures were measured by bathythermograph, salinities by: (a) electrical conductivity; and (b) density; and dissolved oxygen by the standard Winkler method.)

Depth (m)	*Temp.* (°c)	*Salinity* (°/₀₀) (a)	(b)	*Dissolved Oxygen* (ml/l)	(% Saturation)
Sta. A 324					
0	13·4	4·00	4·00	9·46	137
25	13·6	18·66	18·02	6·01	95
50	12·7	18·97	18·97	6·96	108
100	11·7	34·81	34·87	6·39	108
150	11·4	35·05	35·01	6·37	107
Sta. A 325					
0	13·8	30·73	30·72	8·25	141
25	13·6	34·18	34·16	6·75	118
50	12·0	34·37	34·37	7·06	102
100	11·4	35·12	35·12	6·78	114
Sta. A 326					
0	14·4	6·80	6·80	..	..
25	14·0	33·93	34·02	7·23	127
50	12·5	34·72	34·65	5·84	100
80	11·5	35·05	35·10	6·51	110
Sta. A 328					
0	12·9	8·51	8·51	..	..
25	13·5	33·87	33·87	6·70	117
50	12·4	34·61	34·56	5·78	99
100	11·7	34·33	34·36	6·31	106
200	10·9	35·10	35·12	5·32	89
Sta. A 329					
0	12·9	5·63	5·54	..	..
25	13·6	33·87	33·86	6·23	109
50	12·4	34·78	34·79	6·00	103
100	11·6	35·10	35·11	..	..
200	11·1	35·12	35·12	4·98	83

TABLE 4. GENERAL PRECIPITATION AND RUN-OFF DATA FOR THE MILFORD SOUND CATCHMENT (information supplied February 1959 by the Soil Conservation and Rivers Control Council, Wellington)

1. Catchment area: 198 square miles.
2. Rainfall:
   (a) *Milford Sound Gauge:*
   Average annual rainfall, 253 in.
   Maximum recorded annual rainfall, 329 in. (1958).
   Maximum recorded six-hour rainfall, 12 in. (2/2/58).
   Monthly average rainfalls (in.)—

January ..	25·3	July ..	14·7
February ..	23·1	August ..	17·3
March ..	22·3	September	19·8
April ..	21·8	October ..	26·8
May ..	21·6	November .	23·1
June ..	14·7	December ..	23·4

   (b) *Homer Tunnel Gauge:*
   Average annual rainfall, 280 in.
   Maximum recorded annual rainfall, 380 in. (1940)
3. Run-off (estimated):
   Average annual run-off, $2{\cdot}55 \times 10^6$ acre ft.
   Mean inflow to Sound, 3,530 cusecs.
4. Floods:
   Recorded details for a flood on the Cleddau River are:
   Catchment area, 50 square miles.
   Peak discharge, 30,630 cusecs.
   Peak run-off, 0·96 in./h.
   or 616 cusecs/square mile.

TABLE 5. REGISTER OF RAINFALL, MILFORD SOUND GAUGE, FOR FEBRUARY 1955 AND JANUARY 1957 (information supplied by the Director, New Zealand Meteorological Service, Wellington)

Day	*February 1955* *in.*	*January 1957* *in.*
1	4·47	2·43
2	0·25	..
3	..	0·11
4	..	0·67
5	..	0·48
6	..	..
7	..	..
8	0·06	0·05
9	..	0·65
10	..	trace
11	..	0·76
12	..	..
13	0·12	..
14	4·82	0·57
15	0·01	2·46
16	0·49	0·63
17	0·36	0·03
18	0·06	0·27
19	3·06	0·04
20	2·93	1·66
21	0·18	0·28
22	0·13	0·03
23	3·09	..
24	0·07	1·95
25	..	1·84
26	..	10·15
27	2·42	1·13
28	0·01	..
29	..	..
30	..	..
31	..	0·61

FACTORS DETERMINING WATER PROPERTIES

The general factors which will determine the properties of water in Milford Sound are: freshwater inflow, tides, and the bottom topography.

The geographical situation of Milford Sound is generally similar to that of the Norwegian fiords, the hydrography of which, particularly the problem of stagnation of inner basin waters, has been described by Strom (1936). Many differences are found in the New Zealand counterpart, particularly in the greater rainfall of the New Zealand Fiordland area, and the very shallow thresholds separating the inner basins of the Norwegian fiords from the open sea.

Freshwater Inflow

Coastal Fiordland is an area of hydrologically extreme characteristics. Quoting from Poole's (1951, p. 13) account of the New Zealand-American Fiordland Expedition of 1949, ". . . valleys lie close together, making the dividing ridges narrow, though they are much less steep than the valley walls . . . the prevailing, moisture-laden westerly winds which, at sea level, drop over 250 inches of rain making it one of the wettest temperate zone areas in the world . . .

The weight of saturated vegetation on steep country composed of hard, basic rock eventually becomes too great and gigantic landslips are common . . . these prevent the formation of true soil and vegetation is perched precariously in peat and litter on unweathered rock . . . In such a wet climate the vegetation is usually saturated and has little effect in controlling run-off so that rivers and lakes rise and fall with great rapidity."

Milford Sound is subject to a considerable influx of fresh water from the Cleddau and Arthur Rivers and Bowen Falls, near the head of the Sound, and the Stirling Falls, Sinbad River, and the Pembroke Stream further seawards. In addition to these permanent sources the steep walls of the Sound literally run with water during periods of heavy rain. Because of this run-off, water of low salinity, and therefore low density, appears in surface layers. According to the extent of vertical mixing between the introduced fresh water and saline ocean water, the movement seawards of the surface water will induce a deeper inflow of ocean water into the Sound to maintain the salt balance. Suggestions on the probable salinity structure of the New Zealand fiords have been proposed from molluscan evidence by Fleming (1950).

Bottom Topography

The extent to which this simple estuarine circulation can develop will depend greatly on the shape of the bottom of the Sound. The bathymetry of the region is described in detail elsewhere in this study; the important point in the present discussion is that Sound waters are in restricted communication with the open sea so far as horizontal water movement or mixing is concerned. The Entrance Sill, over which lie 80–100 m of water, separates the deeper parts of the inner Stirling Basin (about 290 m) from the relatively shallow Entrance Basin (about 120 m deep). The Entrance Basin is in turn separated from deeper waters over the slope by a sill in about 70 m of depth. The shelf edge lies about 5 sea miles off shore from Dale Point, a pronounced re-entrant bringing slope waters within some 3 miles from the coast just south of the entrance to the Sound.

In general, the density of the water column outside the Sound will increase with depth fairly rapidly in the main thermocline, the stability of which will allow free horizontal exchange between water in the Stirling Basin and that of the open sea between the surface and sill depth, only. Thus Stirling Basin is likely to be filled with water fairly uniform in temperature and salinity, having approximately the properties of the water at sill depth off the open coast. Apart from the effect of a very slow increase of temperature and decrease of salinity (giving a decrease of density) of these deep basin waters due to vertical mixing, flow from outside into the basin will occur only if shelf or slope waters at sill depth increase in density. If this does not occur, basin water below sill depth becomes isolated, leading to the eventual consumption of all dissolved oxygen through the oxidation of organic matter which may be followed by the reduction of sulphates and the liberation of hydrogen sulphide, with consequent profound biochemical effects on the basin water and sediments.

Tides

No detailed tidal information is available for Milford Sound. Admiralty Chart 615 shows spring tides rising 9 ft and neaps, 8 ft. In deep, relatively short inlets, the tide usually rises and falls nearly simultaneously over the whole of the area. Tidal streams are usually small and most pronounced near the mouth of the inlet. The volume of water required to raise the level of Milford Sound (area approximately $18{\cdot}3 \times 10^7$ sq. ft. inwards from Dale Point) by 9 ft is about $16{\cdot}5 \times 10^8$ cu. ft. This volume of water entering the Sound over the Entrance Sill to a mean depth of, say, 30 ft, would move a surface particle about $2{\cdot}6 \times 10^4$ ft into the Sound past Dale Point. This corresponds to a mean flood stream of about 0·7 knots, or a maximum rate (assuming a sinusoidal oscillation) of about 1 knot. If the tidal flow reaches to the full depth of water over the Entrance Sill, these estimates will be reduced by a factor of nearly 10. Rates will decrease rapidly inward from Dale Point.

Tidal streams in Milford Sound may thus be expected to be small, but may be important in promoting the mixture of fresh and salt water in the Sound. The actual movement of the flood stream will, of course, be balanced to some extent at the surface by the constant seaward flow of low salinity water.

DISCUSSION

Alert Stations

The *Alert* stations, worked late in February 1955, showed that water inside and below the Entrance Sill was practically isothermal (11·3°c; fig. 2) and isohaline (35·2‰; fig. 3), and smelt strongly of hydrogen sulphide when taken from

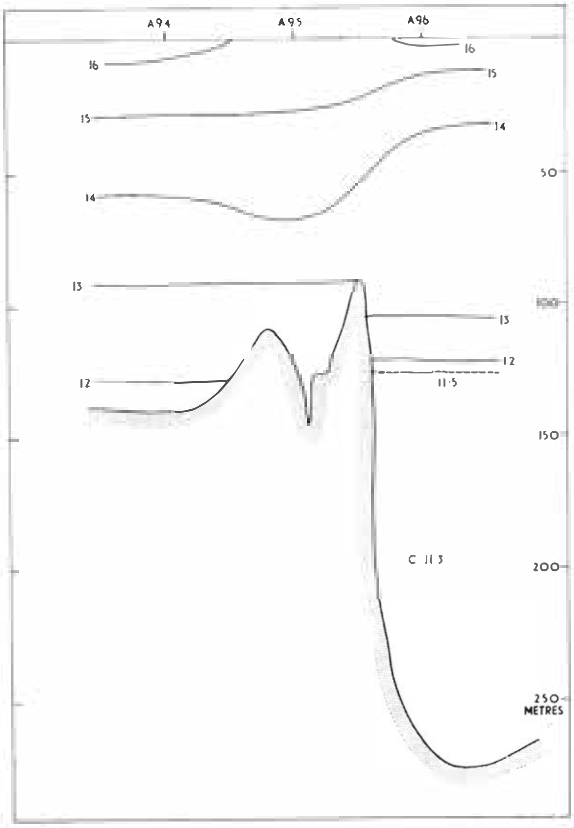

Fig. 2: Vertical cross section of sea temperature (°C) across the Entrance Sill of Milford Sound constructed from bathythermograph and reversing thermometer observations made on 27 February 1955 (see table 3).

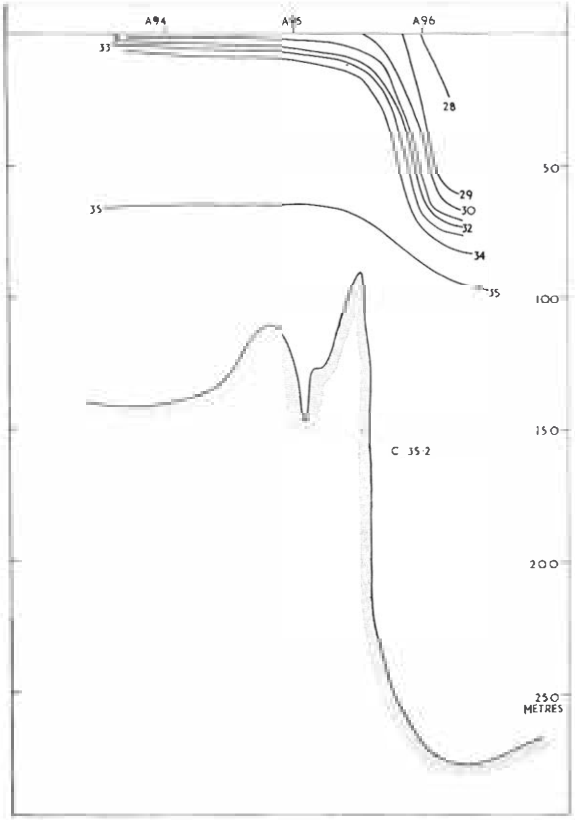

Fig. 3: Vertical cross section of sea-water salinity (‰) across the Entrance Sill of Milford Sound on 27 February 1955 (see fig. 1).

the reversing bottles. A pronounced thermocline at the top of the deep isothermal basin water and just below sill depth separated the deep water from upper layers in direct contact with shelf waters. This boundary, and the relatively low density of water over the sill indicates that basin water was isolated at the time of sampling, and probably had been for some time judging by the presence of hydrogen sulphide. Over the basin just inside the sill, surface salinity fell to a very low value (28‰), and highly diluted water appeared to be "piling up" here to a depth of about 70–80 m: above the sill this fresher water was moving seawards in a shallow layer 10–15 m deep. The movement up sound of oceanic water to balance the seaward flow of brackish water was probably taking place between the isohalines of 34 and 35‰ (fig. 3).

Tui Investigations

During the passage into the Sound on 26 January 1957 two distinct lines of demarcation between zones of discoloured water were observed, as shown in fig. 4 (a). Inside Dale Point surface water was bluish in colour up to a line off the Stirling Falls. Beyond this, a green colour was dominant up to a line off Harrison Cove which marked the limit of a dark brown surface water at the head of the Sound. The variation of surface salinity along the track shows that this brown (sediment-laden) water was practically fresh and represented the extent to which fresh water flowing into the head of the Sound remained unmixed with oceanic water. The green zone was the main area of mixing between fresh and salt water, salinity rising steadily from less than 5‰ to about 22‰. Seawards from the green/blue

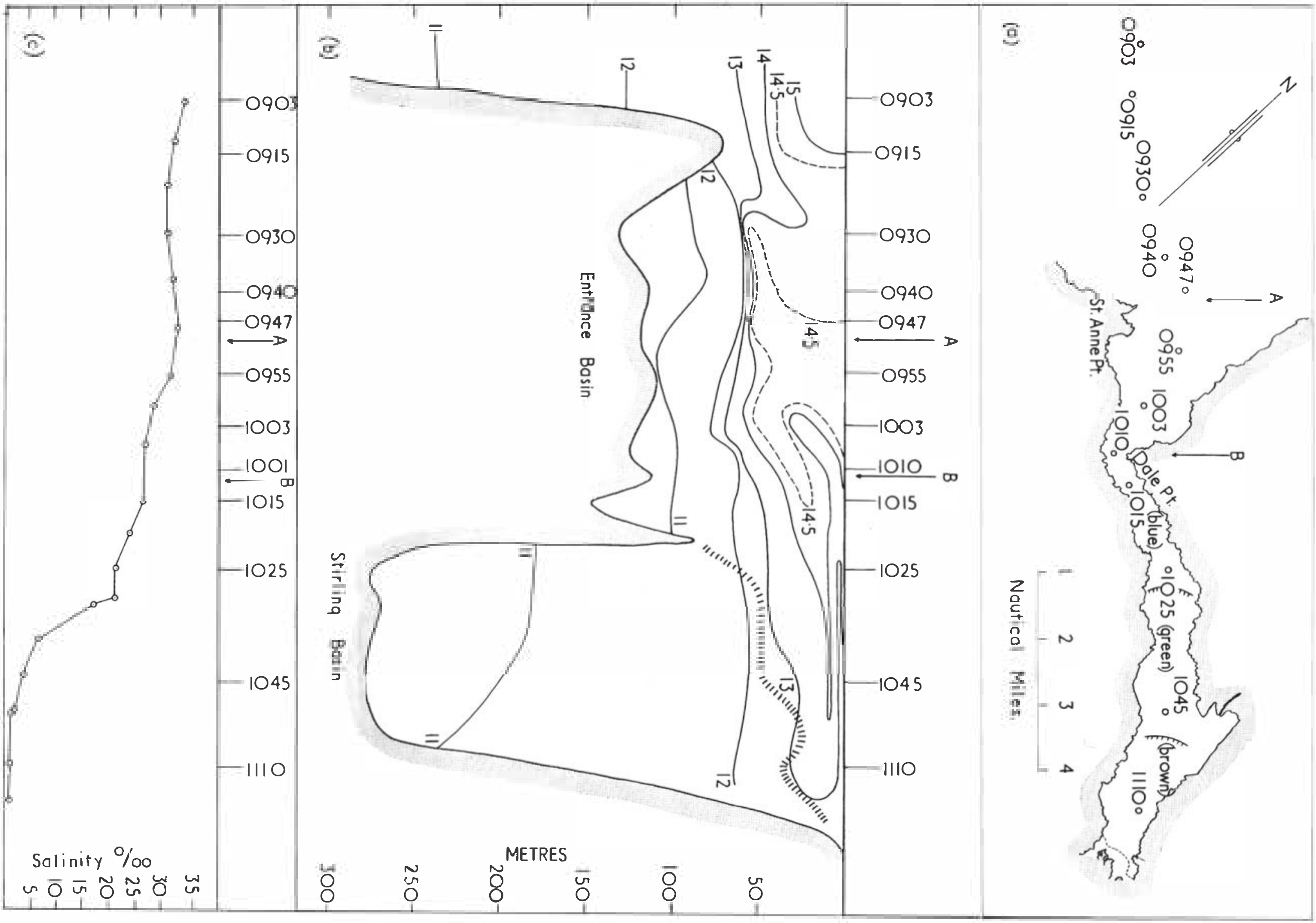

Fig. 4: (a) The position of bathythermograph soundings and surface water samples collected along Milford Sound on 26 January 1957. Positions are labelled in terms of the time (m) of observation. Lines of demarcation of water of different colours, and the position of an intermediate reflector shown by echo sounder are indicated.
(b) Vertical cross section of sea temperature (c) along this track constructed from the bathythermograms. The shading in upper layers over the Stirling Basin represents a secondary reflector recorded by echo sounder.
(c) Variation of surface salinity (‰) along the track.

line, salinity rose only slowly into the partly diluted coastal water off shore. The salinity of oceanic surface water away from this coastal influence is about 35·0‰ off this coast. From the *N.Z. Nautical Almanac and Tide Tables*, high water at Milford Sound was around 1116 hr on 26 January 1957. The passage up-sound described here was thus made during the early stages of the ebb stream. The vertical temperature section from the shelf edge to the head of the Sound in fig. 4 (b) illustrates the general circulation pattern well because of the small differences in temperature between oceanic, shelf, and upper Sound waters. The warmest water in the section (15°c) lay over and off shore from the edge of the shelf and represents the boundary between oceanic water and a cooler (partly diluted) shelf water. Water confined in the bottom of the Entrance Basin was nearly 2°c cooler than slope water at the same depth and thus no free communication was likely between the open sea and the Entrance Basin, at least along this section. The relatively warm shelf water was entering the Sound at a depth of 15–20 m over which lay the cooler, diluted water making its way seawards in the upper 10 m of depth. Water in the Entrance Basin at Sill depth was slightly denser than water in Stirling Basin to a depth of about 200 m and free flow over the sill between shelf water and water at moderate depths inside the Sound was likely.

The secondary reflector at intermediate depth recorded on the ship's fathogram for the passage fig. 4 (b) appeared near the bottom at the inside end of the Entrance Sill and came progressively nearer the surface towards the head of the Sound. Clearly this was not coincident with any density discontinuity and it is suggested that sound reflection may have been due to a mass of sinking organic material, which became progressively more waterlogged as it was carried seawards in the surface layer. Beech leaves, for instance, were present in very large quantities at the surface during the period of observation.

The series of measurements made on 28 January 1957 show substantially the same temperature pattern (fig. 5) as that measured two days earlier (fig. 4 (b)). The warm core (14°c) representing shelf water moving up-sound has become broken in fig. 5 but the relatively simple situation shown in fig. 4 (b) may still be recognised in fig. 5.

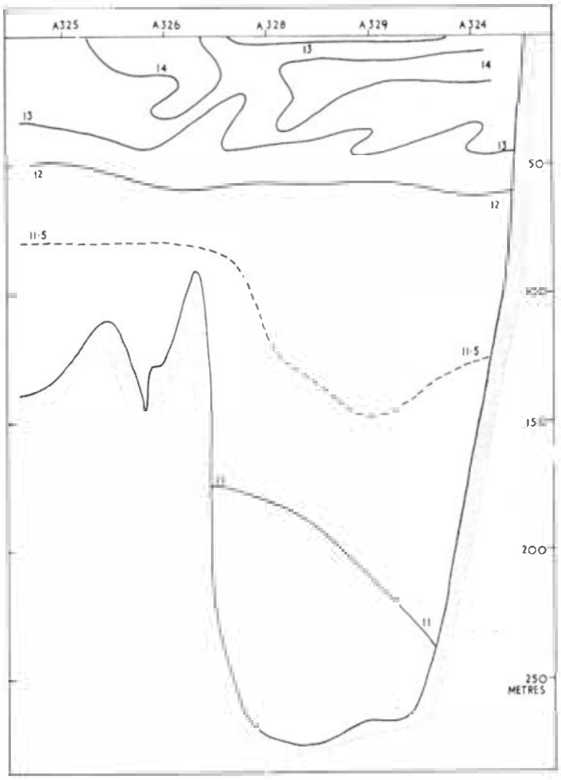

Fig. 5: Vertical section of sea temperature (°c) along Milford Sound on 28 January 1957 constructed from bathythermograph soundings at the stations shown whose positions are plotted in fig. 1.

The vertical section of salinity will presumably be comparable in structure with the temperature pattern; low values at the surface, higher values corresponding to the temperature inversion at intermediate depths showing the up-sound movement of shelf water, and still higher values in the near isohaline deep basin water (table 3). While the distribution of salinity in upper layers of Milford Sound was not measured in sufficient detail to permit a detailed evaluation of the dynamics of the estuarine system, an estimate can be made of the magnitude of water exchange in the Sound based on simple principles. If the average volume of water in the Sound is constant, the amount of water coming over the sill from the open sea plus the run-off of fresh water into the Sound must equal the volume of water flowing seawards at the surface:

i.e., $T_{out} - T_{in} = D$

where T is the total transport (*in*flow or *out*flow) over the sill and D is the discharge from the surrounding catchment.

To maintain the salt balance in the estuarine system:

$T_{in} S_{in} = T_{out} S_{out}$

where S is the mean salinity of the *in*-flowing and *out*-flowing water, over the sill.

The inward and outward transports may thus be expressed as:

$$T_{in} = D \quad \frac{S_{out}}{S_{in} - S_{out}}$$

$$T_{out} = D \quad \frac{S_{in}}{S_{in} - S_{out}}$$

From table 1 an average discharge is around 4×10^3 cusecs, and from fig. 4 (c) and table 4. S_{in} 35‰; S_{out} 30‰. These values give T_{in} approx. 24×10^3 cusecs and T_{out} approx. 28×10^3 cusecs. Thus the effect of mixing between fresh and salt water in the Sound for a situation described by the *Tui* investigations would result in a flow of about 24×10^3 cusecs through an area off Dale Point of about $6{\cdot}9 \times 10^5$ sq. ft. This gives a mean velocity of about 2½ knots to a depth of about 10 m. For an estimate of extreme conditions, the run-off quoted in table 1 for the Cleddau River in flood, 616 cusecs/square mile is taken as representative of the whole Milford Catchment, 198 square miles, i.e., a total run-off of $12{\cdot}2 \times 10^4$ cusecs. Assuming the salinity of out-flowing water is reduced to 20‰ in this case, T_{out} = approx. 4×10^4 cusecs. A closer examination of this matter will require more detailed measurements of salinity structure.

The vertical water sampling interval of the *Tui* stations was sufficient to permit a general description of the distribution of dissolved oxygen in Sound waters. Analysis for oxygen was made using standard Winkler methods which would not have been appropriate in the presence of hydrogen sulphide. The probability that deep water in the Stirling Basin was quite highly aerated during this investigation, however, was indicated from microbiological work described elsewhere in this study. A generally high concentration of dissolved oxygen was recorded at the surface, involving a relative saturation of 130–140 per cent. At sill depth the concentration was about 6 ml/l, slightly higher over the sill than over Stirling Basin, while a concentration around 5 ml/l was measured in the deeper water of the Basin. Relative saturations were still very high in the deep basin water, the lowest value measured being 83 per cent at 200 m (A 329).

Flushing of Stirling Basin

It has been noted that the density of shelf waters must be increased above that of the deeper water in Stirling Basin for the latter to be renewed from outside. A combination of the effects of freshwater inflow and bottom topography may also be responsible for "blocking" the deeper waters of Stirling Basin from renewal from the seaward side of the sill. The more intense the vertical gradient of density over the Entrance Sill becomes, the more difficult it will be for denser water to be carried over the sill into the Basin. Thus the deeper the surface layer that has been significantly diluted with fresh water discharging seawards over the sill, the more likely is the isolation of deep basin waters, cut-off being virtually complete if this diluted layer reaches to the bottom over the Entrance Sill. Comparing the *Alert* and *Tui* observations in Stirling Basin, it seems likely that Basin waters were renewed at some time between February 1955 and January 1957.

Skerman (1964, pp. 65–71) gives an estimate for the rate of bacterial oxygen uptake in the Stirling Basin as about 10^{-3} mg/l/hr. From the measured oxygen values, a difference of nearly 3 mg/l is found between the deep water of Stirling Basin and that near sill depth outside. To the extent that microbial action may be regarded as constant over the period, this suggests that complete flushing of the basin water would have occurred at least four months previously. An estimate of the intake of other oxygen consumers in the Sound is required to complete this estimate. At this rate it is interesting to see that complete stagnation, i.e., the consumption of about 10 mg/l (7 ml/l) of dissolved oxygen would take just over a year.

Conditions leading to the renewal of basin water in the region of Milford Sound may be due to: (a) An intrusion of cold, Subantarctic Water from the West Wind Drift into the predominantly subtropical environment off the South Westland coast; (b) upwelling of subsurface water due either to winds with a significant component from the south-west or a divergence of flow against the coast of an onshore water movement; or (c) the winter cooling of shelf waters.

Measurements available have indicated a mainly subtropical salinity level in the south-east Tasman Sea, although the Subtropical Convergence will not be far to the south-west of South Island. If Milford Sound were flushed through the flow of Subantarctic Water off the coast, the salinity of the deep water in Stirling Basin would be around 34·8‰, or less (with temperatures of 8–9°C). Since deeper salinities in the present work are around 35·1–35·2‰ it seems that renewal has taken place from upper layers north of the Subtropical Convergence. Wind-induced upwelling could be a controlling factor at times especially during the winter months, when Robertson (in Poole, 1951, p. 42) records that southerly winds reached a maximum frequency (of about 22 per cent) at Milford Sound. A divergence of flow of the east-flowing south Tasman branch of the Tasman Current is thought to occur off the South Westland coast; one branch flowing towards Foveaux Strait, the other northwards along the West Coast of the South Island. Mean winter minimum sea surface temperatures of about 11°C have been recorded off the coast of South Westland and the temperature of deep Stirling Basin water reported in the present work, covering observations made between 1952 and 1957, is around this value. This suggests that renewal may normally occur annually at the time of coldest winter temperatures in shelf waters, probably in August. In winter, too, the salinity of shelf waters is probably highest due to the decrease in frequency of the rain-bearing north-westerly winds, and this would tend to increase further the density of shelf waters. The "age" of Stirling Basin water derived from oxygen concentration in the previous section lends further support to this idea of an annual winter renewal of deeper water in the Stirling Basin of Milford Sound.

ACKNOWLEDGMENTS

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SEDIMENTATION IN MILFORD SOUND

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Summary

The sediments of Stirling Basin consist of sandy silt interspersed with layers of coarse sand. Most of these layers are not more than 1–2 in. thick, but one core penetrated a much thicker sand layer, nearly 5 ft thick. The sediments consist principally of hornblende, plagioclase, and mica (derived from the gneissic country rocks), together with numerous plant fragments. The sandy silt contains multigranular aggregates of two types, one type being smooth ellipsoidal faecal pellets and the other irregular masses cemented with gypsum. This gypsum probably arose as a result of alternating reduction and oxidation of sulphur within the sediment.

The silt fraction of the sandy silt is transported principally by stream outflow, while the sand fraction is supplied by wind transport from the cliffs bordering the Sound and by the rafting effect of plant fragments. The coarse sand layers are evidently due to the periodic slumping of submarine deltas and alluvial cones flanking Stirling Basin.

The thick sand layer in the lower part of Core A 321 is provisionally correlated with a period of heavy seismic activity in the years 1826–27. On this basis, the rate of accumulation of sandy silt would be about ½ in. per year.

The sediments of Entrance Sill and Entrance Basin are briefly described and discussed.

INTRODUCTION

The visit of HDMS *Galathea* to Milford Sound in January 1952 (Bruun, *et al.*, 1955) provided much new information on the form and nature of the sea bed in the Sound, and later work from RNZFA *Tui* (January 1957) has provided further data which confirm and extend the results obtained from *Galathea*. The bathymetry of the Sound has been described by Brodie (1964, pp. 15–23): the present section gives a brief account of the nature of the sediments, and discusses the various processes which have affected their development.

DESCRIPTION OF SEDIMENTS

Stirling Basin

(a) *General Nature of Sediment:* Samples taken by *Galathea* indicated that the sediments of the Stirling Basin consisted of "dark grey silt and silty sand containing much organic matter" (Bruun, *et al.*, 1955, p. 403). A number of dredge, grab, and core samples were taken during the *Tui* cruise, and these substantially confirm the results obtained by *Galathea*. It was not possible to collect samples very near the walls of the Sound, but there can be little doubt that dark sandy silt covers the floor of the Basin, at least in the flat central part. Sediment of this type was found in all the surface samples and in the uppermost parts of the cores. It is black to dark grey in colour when fresh, due to the presence of iron sulphide minerals, and contains innumerable lignitised twigs and leaves up to several millimetres in length; these are evidently derived from the thick bush which covers the sides of the mountains bordering the Sound and extends up to a level of about 3,000 ft.

The four longest cores collected by *Tui* were taken with a 12-ft piston corer, with an internal diameter of 2 in. One of these cores, 8 ft in length, was used for microbiological investigation. The other three cores (A 321, A 323, and A 328), were respectively 9 ft 9 in., 8 ft 3 in., and 6 ft 0 in. long* and were reserved for sedimentary investigation. A 323 was taken at the head of the Basin, below the Cleddau delta, A 321 in the centre of the Basin, and A 328 at its north-western end. These cores show that sandy silt with abun-

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*Core A 321 was measured while it was still moist; A 323 and A 328, when dry, but the contraction on drying was very small – not more than 2 %.

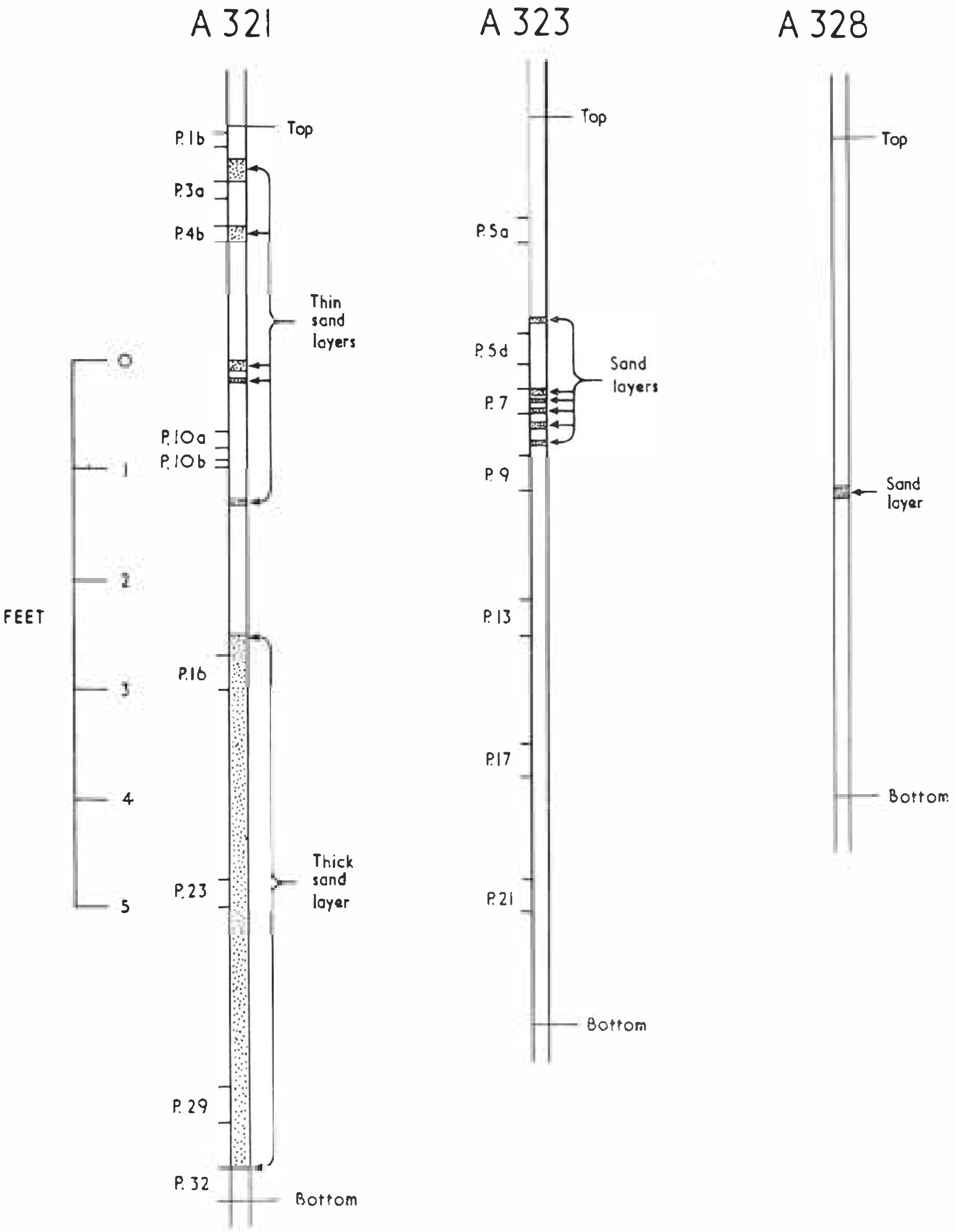


Fig. 1: Diagrams of cores A 321, A 323, and A 328, showing the position of the various sand layers (stippled), the intervening sandy silt (plain), and the location of those portions of cores used for mechanical analysis (fig. 1) and for dye-staining (plate II, B, and C).

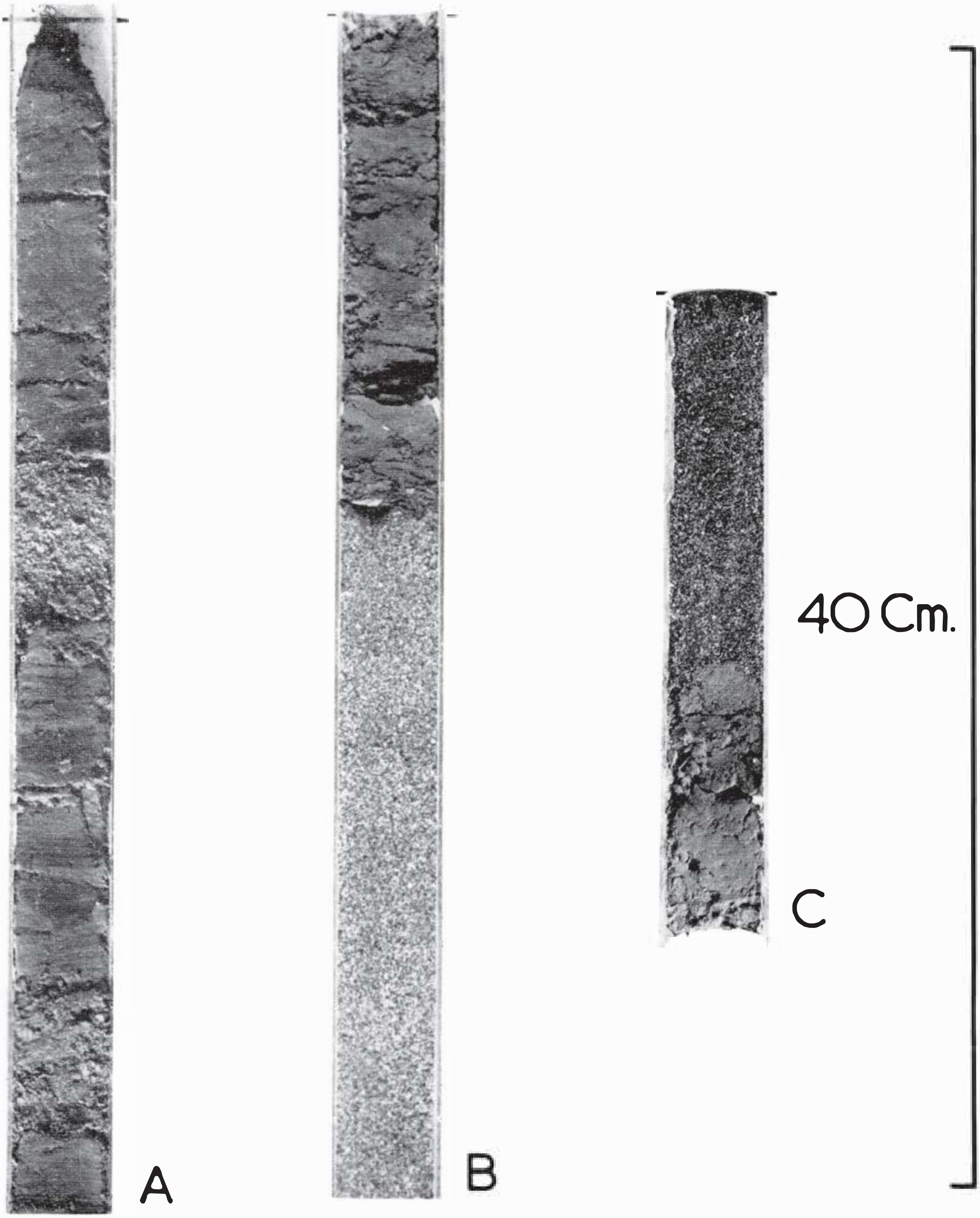


Plate I: Three portions of core A 321. A: the uppermost part of the core, showing two thin sand layers. B: the top of the thick sand layer. C: the bottom of the thick sand layer.

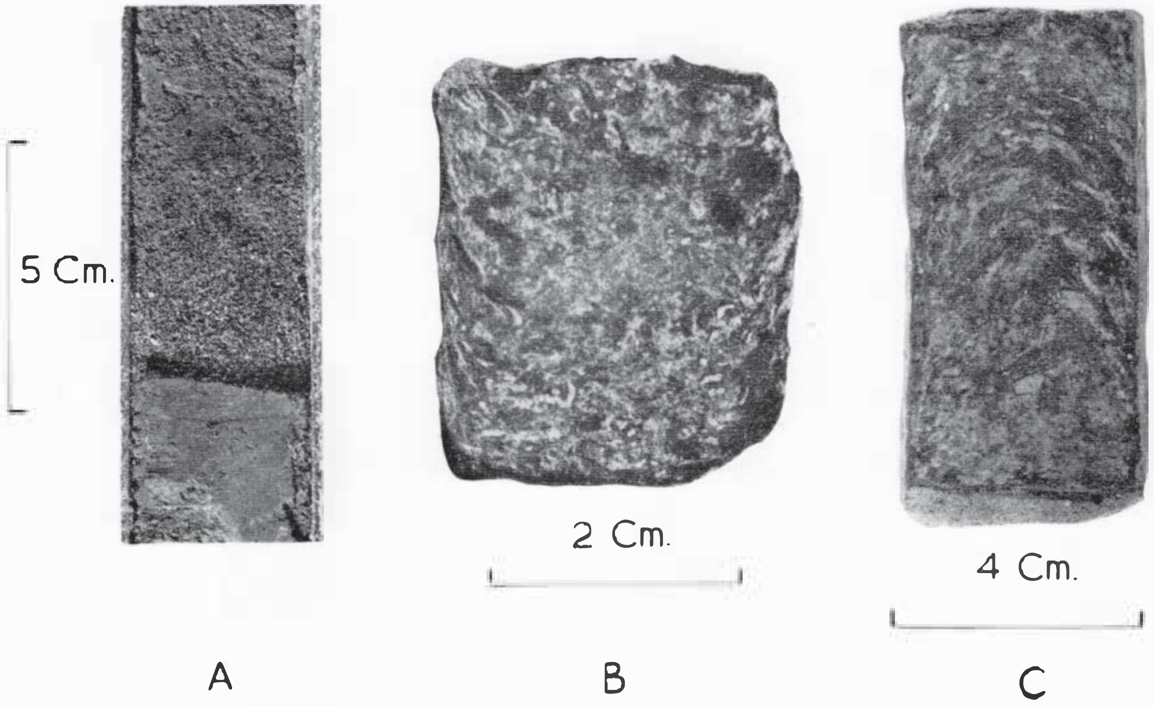


Plate II: A: The thin sand layer in core A 328, showing the sharp lower boundary (partly in shadow) and the gradational upper boundary. B: core A 321, P. 10b, stained with crystal violet. C: core A 323, P. 5d, stained with crystal violet. The internal structures in B and C show distortion at the sides, due to the processes of coring and extrusion.

dant plant fragments persists in depth, but is interspersed with layers of coarse sand with little or no silty component. Most of these layers are thin, with a thickness of only 1–2 in. (see fig. 1 and pl. I and II), but the lower part of core A 321 contains a much larger sand layer, nearly 5 ft in thickness.

The ratio of core length to thickness of sediment penetrated (compression ratio) is difficult to estimate accurately in the case of A 321 and A 323, as the corresponding smears on the outside of the corer barrel were somewhat indefinite. In both cases, however, there were no smears visible on the weight assembly above the barrel, and so it is fairly certain that the sediment was not penetrated to a depth greater than 12 ft. The minimum compression ratio is thus about 5/6 in the case of A 321 and about 2/3 in the case of A 323. A well defined smear 8 ft long was seen in the case of A 328, giving a compression ratio of 3/4.

(b) *Constitution of the Sandy Silt:* (see fig. 2) Mechanical analyses of selected portions of A 321 and A 323 show that the sand fraction of the sandy silt is mostly fine-grained (0·062–0·125 mm), but a small proportion of coarser material is always present, and the largest grains frequently exceed 1 mm in diameter. Angular mineral grains form an important part of the sand fraction, and consist mainly of plagioclase, hornblende, and mica, together with smaller quantities of epidote and minor amounts of quartz, pyroxenes, and garnet (see table 1). Some of the larger grains are composite, containing more than one mineral, and these usually consist of plagioclase and hornblende in roughly equal proportions. The various minerals are presumably derived from the gneisses which form the surrounding mountains, and the composite grains are evidently fragments of a moderately coarse hornblende-plagioclase rock. In addition to mineral grains, the sand fraction also contains numerous plant fragments, occasional tests of small molluscs and foraminifera, and numerous discrete aggregates of sand and silt grains which are not broken up by normal mechanical analysis procedure (compare Shepard, 1956, p. 2567). These aggregates are of two types, some being comparatively fine-grained with a smooth ellipsoidal shape, and others coarser in

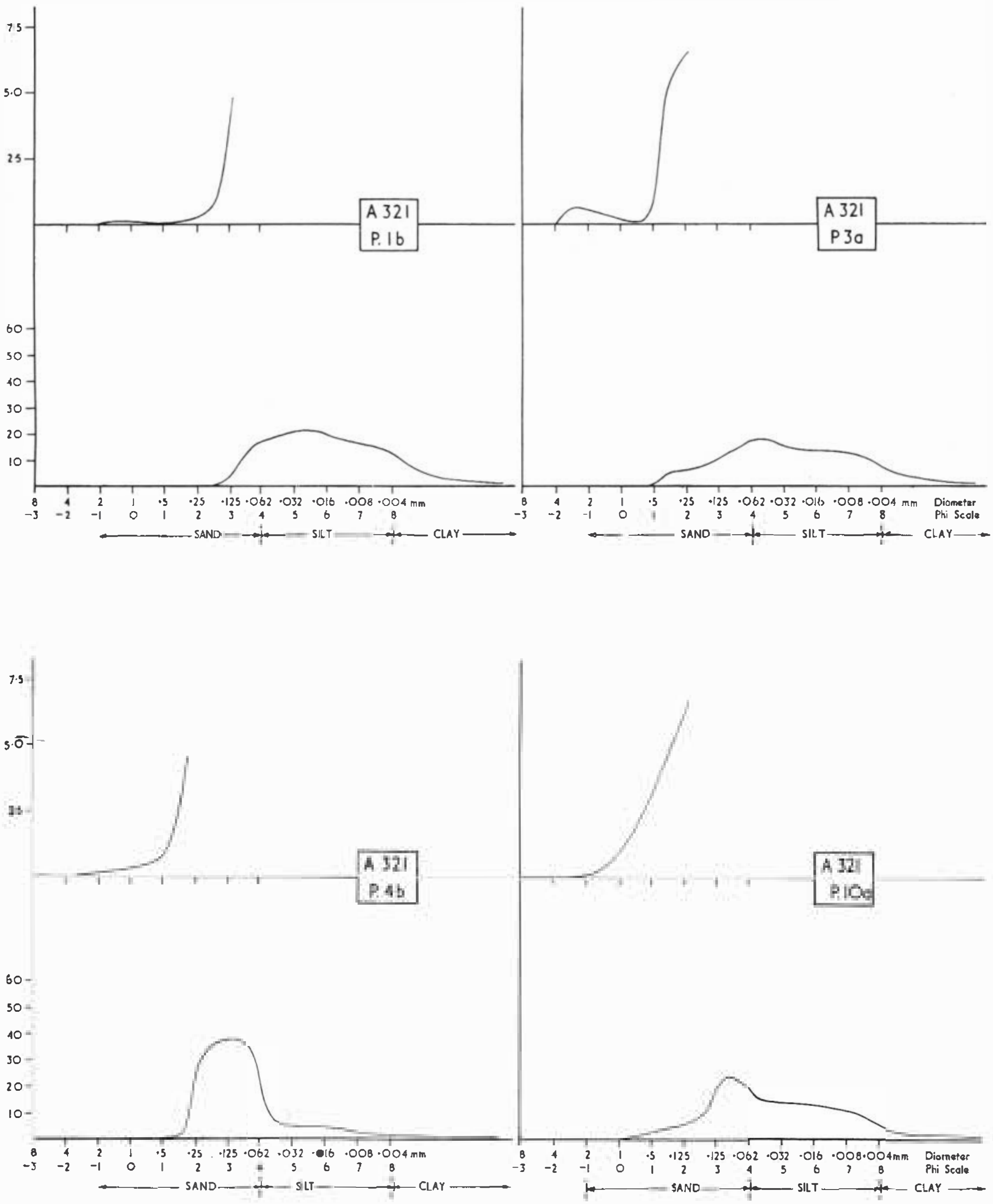


Fig. 2: Size frequency distribution curves for portions of A 321 and A 323. Weight percentage per phi unit is plotted against grain diameter. The general size distribution is shown in the lower diagram of each pair, while the upper diagram shows the coarser material in the sample plotted on an expanded scale.

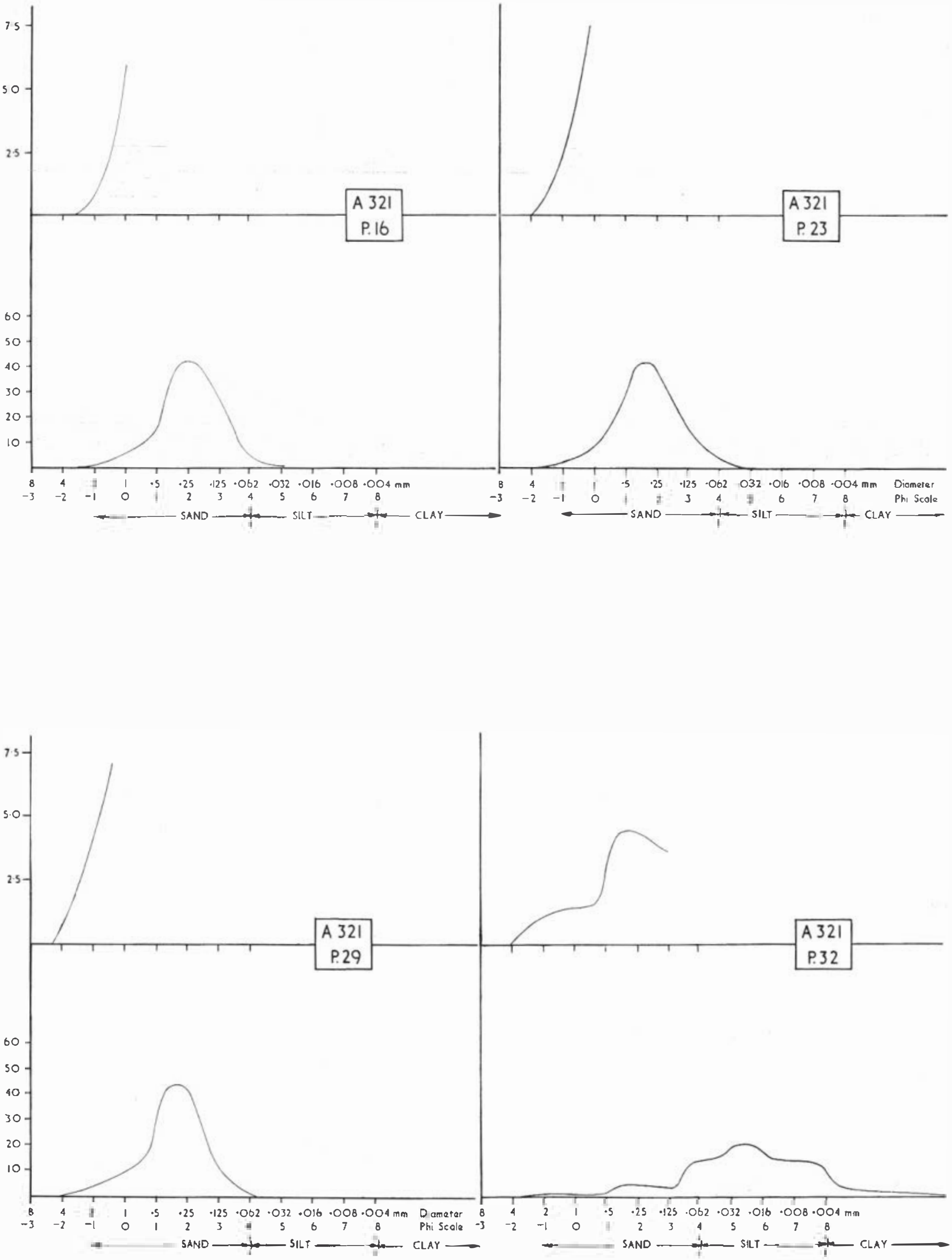
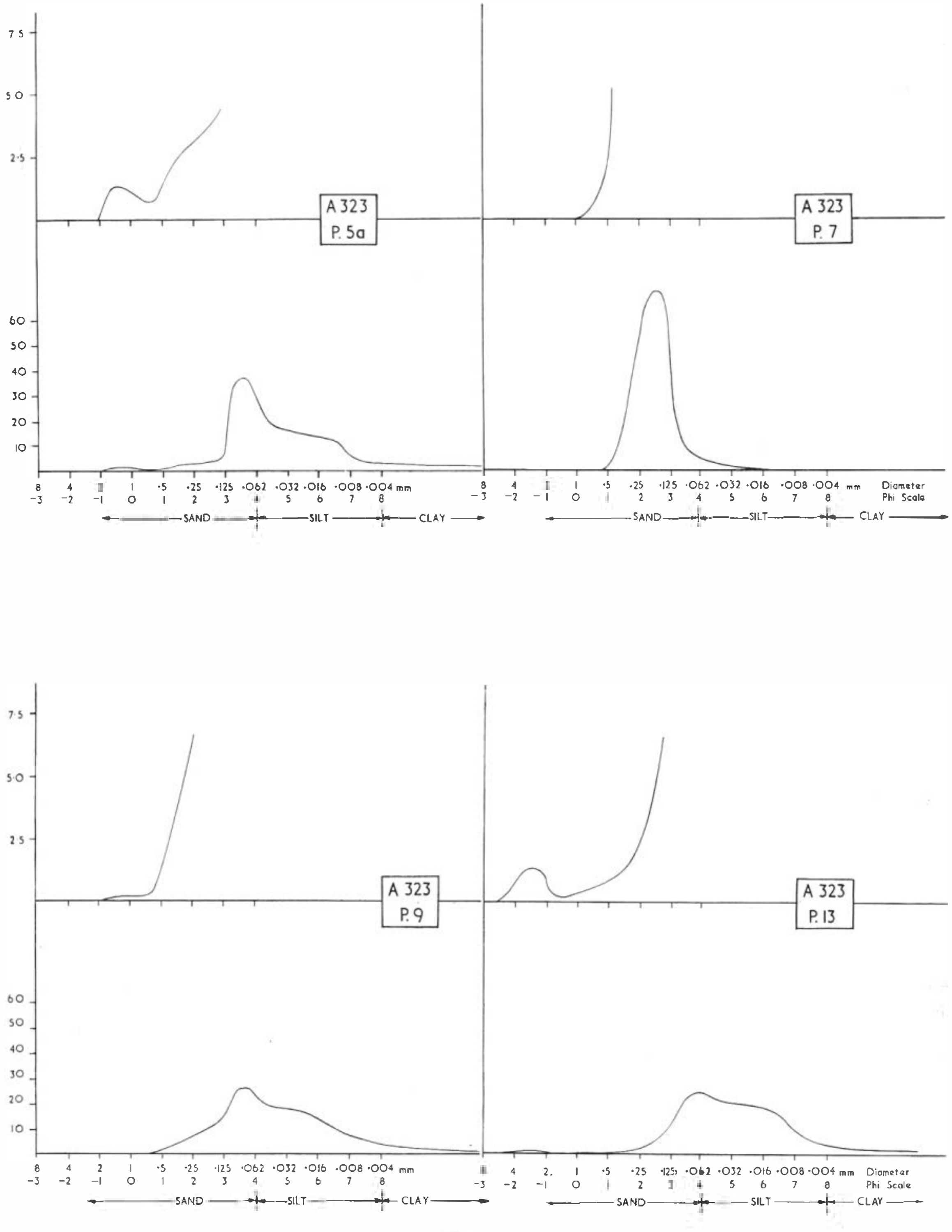


Fig. 2—continued.



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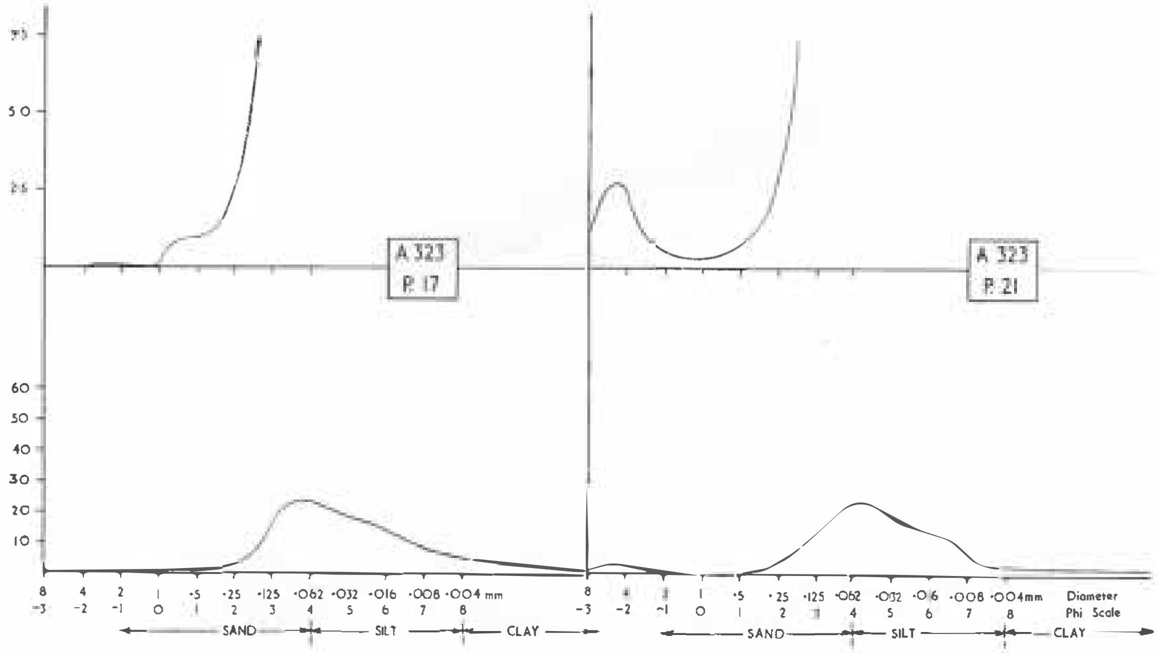

Fig. 2—continued.

TABLE 1. COUNTS OF SAND GRAIN TYPES AND MINERAL SPECIES

	A 321 + 120 Sieve Fraction								A 323 + 120 Sieve Fraction					
	P. 1b	P. 3a	P. 4b	P. 10a	P. 16	P. 23	P. 29	P. 32	P. 5a	P. 7	P. 9	P. 13	P. 17	P. 21
Hornblende.. ..	14	99	121	26	410	445	428	58	35	92	71	31	52	52
Plagioclase ..	37	191	257	55	405	395	391	67	175	249	188	142	204	166
Epidote	3	23	18	4	90	88	109	12	4	11	6	6	4	7
Biotite	64	36	46	28	39	22	25	44	77	65	103	99	118	103
Muscovite	34	9	8	7	14	14	13	9	9	15	12	10	12	8
Chlorite	55	21	22	24	12	5	8	20	16	23	6	17	9	15
Augite	..	1	9	..	2	3	1	2	1	2	5	6	10	9
Hypersthene ..	1	2	4	..	3	5	1	1	3	1	..	..	2	1
Garnet	..	5	..	1	5	7	7	4	..	..	1	..	..	..
Iron ore	..	7	2	..	..	..	..	..	..	..	..	..	..	1
Quartz	2	1	4	..	17	9	11	2	6	5	5	1	1	2
Plant fragments ..	205	69	9	117	2	7	5	137	161	29	84	180	87	125
Shells and shell fragments	5	2	..	2	..	..	..	5	..	..	..	..	..	..
Smooth aggregates ..	45	1	..	2	..	..	..	..	4	1	3	..	..	4
Irregular aggregates ..	35	33	..	234	1	..	1	139	9	7	16	8	1	7
	500	500	500	500	1,000	1,000	1,000	500	500	500	500	500	500	500

grain with a much more irregular shape (see table 2). The smooth ellipsoidal aggregates appear to have no distinctive cement phase, whereas the more irregular aggregates have a gypsum cement. The mineralogy of both types appears to be similar to that of the containing sediment, and they were apparently formed in place, as some contain foraminifera or small molluscan fragments.

The characteristics of the two types of aggregate vary somewhat between core A 321 and core A 323, and within the cores themselves. In core

Table 2. Counts of Sand Grain Types

A 321. Sieve Fractions Other Than + 120

—		Mineral Grains	Plant Fragments	Shells and Shell Fragments	Smooth Aggregates	Irregular Aggregates	Total
P. 1b	+ 16	1	2	1	. .	1	5
	+ 30	3	22	7	. .	13	45
	+ 60	30	113	7	20	30	200
	+ 240	132	49	1	. .	18	200
P. 3a	+ 8	. .	. .	. .	. .	6	6
	+ 16	. .	3	1	. .	16	20
	+ 30	64	28	. .	. .	108	200
	+ 60	97	48	1	6	48	200
P. 4b	+ 8	. .	2	. .	. .	. .	2
	+ 16	3	101	. .	. .	25	129
	+ 30	45	114	. .	5	36	200
	+ 60	169	21	. .	4	6	200
	+ 240	197	2	1	. .	. .	200
P. 10a	+ 8	. .	3	2	. .	. .	5
	+ 16	. .	46	6	. .	40	92
	+ 30	. .	44	4	. .	152	200
	+ 60	4	85	1	2	108	200
	+ 240	128	14	. .	. .	58	200
P. 32	+ 8	5	6	3	. .	4	18
	+ 16	81	43	13	. .	51	188
	+ 30	94	36	3	. .	67	200
	+ 60	60	53	1	1	85	200
	+ 240	153	15	1	. .	31	200

A 323. Sieve Fractions Other Than + 120

P. 5a	+ 16	1	36	1	. .	73	111
	+ 30	17	99	. .	41	43	200
	+ 60	54	71	1	55	19	200
	+ 240	167	31	. .	. .	2	200
P. 7	+ 35	112	38	1	7	42	200
	+ 60	169	6	. .	13	12	200
	+ 230	180	13	. .	. .	7	200
P. 9	+ 18	. .	39	. .	. .	1	40
	+ 35	29	113	. .	6	52	200
	+ 60	26	52	. .	81	41	200
	+ 230	180	16	. .	. .	4	200
P. 13	+ 10	. .	12	. .	. .	. .	12
	+ 18	. .	66	. .	. .	4	70
	+ 35	2	133	1	. .	63	200
	+ 60	65	101	. .	14	20	200
	+ 230	172	28	. .	. .	. .	200
P. 17	+ 10	. .	8	. .	. .	. .	8
	+ 18	. .	12	. .	. .	8	20
	+ 35	12	105	. .	. .	83	200
	+ 60	75	95	. .	5	25	200
	+ 230	175	25	. .	. .	. .	200
P. 21	+ 10	. .	27	. .	. .	1	28
	+ 18	. .	77	. .	. .	8	85
	+ 35	7	151	. .	. .	42	200
	+ 60	65	86	. .	27	22	200
	+ 230	179	21	. .	. .	. .	200

A 321, the ratio of smooth to irregular aggregates falls rapidly with increasing depth in the core. Near the top of the same core, the gypsum cement in the irregular aggregates is whitish in colour with a fibrous or columnar habit, but further down the gypsum is more compact, with a resinous lustre. In core A 323, the ratio of smooth to irregular aggregates tends to fall with increasing depth, but this tendency is locally reversed, even near the base of the core. The gypsum cement in the irregular aggregates is the white fibrous variety near the top of A 323, this being replaced lower down by the resinous variety, but the white variety makes a limited reappearance near the base of the core.

Dye-staining of selected portions of the cores (see Pantin, 1960) shows that the sandy silt has been considerably disturbed by benthic organisms; stratification on a scale of 3–4 mm is sometimes visible, but the layers are very irregular and indistinct (see plate II, B and C).

(c) *Constitution of the Coarse Sand Layers:* The mineralogy of the coarse sand layers is somewhat different from that of the prevailing sandy silt (see table 1). All size fractions consist dominantly of mineral grains, the largest of which may reach 4 mm or more in diameter. A pebble of hornblendic gneiss with a maximum diameter of 22 mm was found in A 321 near the base of the thick sand layer (P. 29), but this was exceptional,* the next largest grains in the same sample being only 5–6 mm in diameter. Plant fragments and multigranular aggregates occur in the thin sand layers, but are virtually absent from the thick layer in A 321. In this case, however, there is a very thin zone rich in plant fragments at the top of the layer (see plate IB). There is also a concentration of plant fragments towards the top of the thin sand layer in A 328 (see plate IIA).

The sand layers all have a sharp lower boundary, and the majority have also a sharp upper boundary, but the upper part of the sand layer in core A 328 does grade into the overlying sandy silt, although the transition is rapid (see plates I and II). Otherwise there is little sign of grading in the thin sand layers. The thick sand layer in Core A 321 is fairly uniform, but shows a slight tendency towards oscillatory grading; the grain-size decreases to a local minimum about 1½ ft above the base of the layer, increases to a local maximum 3 ft above the base, and finally decreases continuously towards the top.

Entrance Sill and Entrance Basin

The samples taken by *Galathea* and *Tui* in these portions of the Sound indicate that the sediments in both areas are decidedly variable. Sandy silt and sand occur in the Entrance Basin, while sandy silt, pebbly silt, and silt mixed with gravel and angular cobbles have all been found on the Entrance Sill. Hurley (1964, pp. 79–89) found a mixture of hard-bottom and soft-bottom animals in the fauna from the *Tui* station on the Sill (A 326). The finer-grained sediments of the Sill and Entrance Basin are very similar in general constitution to those of the Stirling Basin, although plant material is less abundant.

SEDIMENTATION

Stirling Basin

(a) *Sandy Silt:* It is evident that sandy silt is the type of sediment deposited under normal conditions in this part of the Sound. The silt fraction is presumably derived mainly from glacial rock-flour, and the sand from glacial debris and from subaerial weathering of the country-rock. These materials are removed from the mountains and brought into the Basin by the inflowing rivers and streams. The silt fraction must remain in suspension long enough to be transported all over the Basin before settling out and falling to the bottom; this is clearly shown by the ubiquitous distribution of the silt, and by the characteristic turbidity of the superficial water in the Sound. When *Tui* entered the Sound after several hours of very heavy rain, an almost fresh and highly turbid surface layer was encountered in the Stirling Basin, and even on the third day of the visit, when no rain fell, the surface water was greenish and the ship left a clear blue wake.

The coarser sand fractions, however, cannot be carried far in suspension, as they would tend to settle out as soon as the transporting streams and rivers entered the Basin. Sandy deltas and alluvial cones formed in this way are visible at the mouths of the rivers and larger streams, and it is probable that the angle between the sheer walls and the flat bottom of the Sound is partially filled by alluvial cones deposited by the cascading streams which descend the precipitous cliffs. While grains of sand and grit might reach the edge of the Stirling Basin by rolling down the foresets of these deltas and cones (cf. core A 323), no such material could travel across the flat floor of the Basin under conditions of steady deposition. The presence of sand in the silty sedi-

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*This fragment was omitted from the size frequency curve for p. 29.

ments on the floor of the Stirling Basin cannot, therefore, be explained in terms of transport by inflowing rivers and streams.

Even under the extreme conditions of 26 January 1957, the turbid fresh water entering the Basin was less dense than sea water, and spread out over the surface of the Sound. This is the condition known as hypopycnal flow (Bates, 1953, p. 2125). It is thus highly unlikely that a turbidity current (hyperpycnal flow, see Bates, loc. cit.) is ever set up by waters flowing into the Sound. This is supported by the normal salinity of samples taken from near the bottom of the Stirling Basin on 28 January 1957, only two days after the flood. If any significant hyperpycnal flow had occurred on 26 January 1957, the salinity of the bottom waters would almost certainly have been considerably less than was actually observed. The sand fraction of the typical Basin sediment cannot therefore have been transported by turbidity flow along the bottom.

Wave action in a sheltered inlet such as Milford Sound must be quite inadequate to transport sand at a depth of 150 fm, and tidal streams in the Sound are apparently small, even over the Entrance Sill (Garner, 1964, p. 28). The steep slope leading from the Basin to the Sill shows no evidence of modification due to an influx of sediment over the Sill, the area where the effect of waves and tidal currents on the sea bed would be strongest, and this supports the conclusion that no significant quantities of sand can be transported into the Stirling Basin by waves and tidal currents.

There are, however, two processes by which sand could be transported all over the Basin. Strong winds are very common around Milford Sound, as in the whole of Fiordland, particularly around the higher parts of the mountains. These winds must be capable of removing loose sand from the cliffs and carrying it for a considerable distance before it falls to earth or into the Sound. The winds are often so strong that the cascades descending the cliffs are blown into spray long before they reach the Sound, and under these conditions any sand carried downwards by the descending water would be blown well out over the Sound. This process must contribute at least some of the coarser fractions of the sandy silt. It is also highly probable that a certain amount of sediment, including sand, is rafted into the Sound by the enormous quantities of plant fragments that are swept in with every flood. The presence of sand in the silty sediments of the Basin thus appears to be due to the high topographical relief, high winds, and high rainfall: these conditions in combination are found in relatively few marine environments.

(b) *Coarse Sand Layers:* The presence of the various layers of coarse sand cannot be accounted for in terms of wind transport or rafting. They have clearly been deposited as the result of a sporadic process that plays no significant part in the deposition of the more normal sandy silt. Several lines of evidence lead to the conclusion that slumping has been responsible for the deposition of these sand layers. The outer slopes (foresets) of the deltas and alluvial cones flanking Stirling Basin will in most cases be at the angle of repose. Foresets advance not only by virtue of individual grains rolling down from the top, but also by the periodical accumulation and slumping of layers of sand on the upper part of the slope. Accumulative slumps of this type usually involve only small masses of sediment, but this process is probably adequate to account for the thin sand layers, on the assumption that the slumps have enough potential energy to carry the sand out into the centre of the Basin. The sharp contacts of the sand layers are in favour of the slumping hypothesis.

The thick sand layer in core A 321 requires a somewhat different explanation. It is of a different order of thickness from the thin sand layers, and while it is probably the result of an exceptionally heavy slump, the simple accumulation-slump process does not seem to be adequate to account for the large quantity of sand involved. Slumping on a much greater scale could undoubtedly occur during an earthquake, and the layer may well have resulted from such an event, as the area is seismically active (Henderson, 1932; Eiby, 1958).

(c) *Rate of Sedimentation:* No regular varve-type layering has been found in the sediments of the Basin. The varves of glacial lakes owe their layering to variation in the discharge of inflowing glacial streams, which are controlled mainly by the seasonal (and fairly regular) variation in the available volume of melt water. The stream discharge into Stirling Basin, on the other hand, is controlled dominantly by local variations in rainfall, and any sedimentary layering would thus be far less regular than that of typical varves. In addition, any small-scale layering in the Basin sediments would be obscured to a greater or less extent by the activities of benthic organisms. Varves or their equivalent do not, therefore, provide a time scale for sedimentation in the Basin.

An estimate of the rate of sedimentation can be made, however, on the assumption that the thick sand layer in A 321 is the result of slumping caused by a historically recent earthquake of exceptional severity. There are no datable earthquake records from the period before the beginning of European settlement in New Zealand, and systematic records have only been kept since the days of seismographs, but diaries, historical accounts, and press reports provide a good deal of information regarding the more intense earthquakes of the nineteenth century. Some of these records are recounted by Henderson (1932), and it appears from the accounts of sealers operating in the Dusky Sound area that "from 1826 to 1827 there was an almost constant succession of earthquakes, some of which were sufficiently violent to throw men down" (op. cit., p. 130). This implies an intensity of about 8 on the modified Mercalli scale. No other series of earthquakes of comparable intensity has been recorded from the area since that time. The thick sand layer in A 321 may thus have been produced by an earthquake (or a series of earthquakes) in 1826–7. There is about 4 ft 1½ in. of sandy silt above the thick sand layer, which would give a sedimentation rate of about 49½ in. in 130 years, or about 0·38 in. per year, assuming no shortening in the core (compression ratio 1/1). With a compression ratio of 5/6, this figure would rise to about 0·46 in. per year.

(d) *Aggregates:* The smooth ellipsoidal aggregates which occur in the sandy silt are undoubtedly faecal pellets. Their shape and smooth outline correspond to one of the commonest types observed by Moore (1939, fig. 1, d-g) and by many other workers. Their preservation in the upper layers of sediment is evidently due to a degree of compaction greater than that of the surrounding material, while their tendency to disappear with increasing depth of sediment can be explained by compaction of the sediment as a whole due to loading, with the mechanical distinction between pellets and matrix being gradually reduced.

The irregular gypsiferous aggregates do not appear to be faecal pellets. They are rather similar in form to the aggregates described by Shepard (1956, p. 2567) from the marginal sediments of the Mississippi delta and by the same author (1958, p. 154) from the Laguna Madre. The Mississippi delta aggregates, however, have either a calcareous or a ferruginous cement, and the Laguna Madre aggregates a calcareous cement: gypsum-cemented aggregates were not recorded from either locality. Shepard concluded that the Laguna Madre aggregates are related to the high evaporation in that area, which presumably causes the physico-chemical precipitation of $CaCO_3$. A similar explanation cannot apply to the gypsiferous Milford Sound aggregates, as evaporation at the bottom of Stirling Basin is out of the question, and in any case the sea water near the bottom of the Basin is fairly normal in composition and would not be saturated with gypsum.

A certain amount of the gypsum may have resulted from the oxidation of sulphide by the air after the cores were taken. The presence of sulphides in these sediments has been demonstrated by Kaplan and Rafter (1964, pp. 73–6), and a reactive sulphide phase would be readily oxidised by the air with the formation of sulphate. However, the chemical analyses (Kaplan and Rafter, 1964, tables 2 and 3, p. 75) indicate that sulphate is present in the sediments of the Sound under natural conditions. The recorded percentages of sulphate are too great to represent merely the sulphate content of interstitial sea water; the additional sulphate in the sediments presumably takes the form of gypsum, and this must account for at least some of the gypsum in the aggregates.

The presence of gypsum in the sediments of Milford Sound can be explained in terms of the unusual hydrological conditions which occur there. The precipitation of this mineral in contact with sea water that is undersaturated with $CaSO_4.2H_2O$ implies a mechanism by which sulphur is removed from the sea water and concentrated in some compound which is later converted to gypsum. The reduction of $SO_4^=$ to $S^=$ in the interstitial water, and the consequent precipitation of sulphides within the sediment, would be an available mechanism for concentrating the sulphur. Skerman (p. 68) has shown that sulphate-reducing bacteria are abundant in the Stirling Basin sediments, and that the Eh of the sediments is consistently low, except in the superficial layer. The presence of H_2S in the bottom waters in February 1955 (m.v. *Alert,* Station A 94 – A 96) shows that under some conditions the whole bottom environment is strongly reducing. On the other hand, the bottom water was found to be slightly oxygenated in January 1952 (HDMS *Galathea,* Station 608) and more strongly so in January 1957 (at N.Z.O.I. Stations A 324–9), showing that there must be considerable variations in Eh from time to time in the bottom water. These variations would be communicated to the interstitial water in the superficial sediment, and $S^=$ formed during a reducing phase might well be re-oxidised to $SO_4^=$, particularly if sulphur-oxidising bacteria were present. Skerman (1964, p. 69) has shown the presence of such bacteria in the superficial sediment. With a sufficient initial sulphide content, the concentration of $SO_4^=$ in the interstitial sea water would rise to a point at which $CaSO_4.2H_2O$ (gypsum) would precipitate. This precipitation would cease if the sulphides were exhausted or if sulphur-oxidising conditions were discontinued, but complete re-solution might be prevented by detrital grains packing into cavities left by dissolving gypsum. It is therefore suggested here that the gypsum-cemented aggregates represent centres of oxidation of sulphides or other reduced sulphur compounds. This hypothesis is supported by the available data on sulphur isotope distribution in the sediments. Kaplan and Rafter (1964, pp. 73-6), consider that the concentration of ^{32}S in the sediments can best be explained on the assumption that $SO_4^=$ in the interstitial water is first reduced to $S^=$, which is then oxidised again to $SO_4^=$ at a later stage.

Entrance Sill and Entrance Basin.

The samples from the Entrance Sill support the views of Bruun *et al.*: "The irregular topography of Entrance Sill suggests that moraines were dumped on the valley floor near the terminal face of the glacier that excavated Stirling Basin." (op. cit., p. 406). After the retreat of the glacier, the moraines would have been subjected firstly to subaerial erosion, and then to marine erosion, due to the Flandrian eustatic rise in sea level. Continuing submergence would progressively reduce the effect of marine erosion, and the Sill is probably an area of limited sedimentation at the present day, except possibly around the rock step. Only the streams flowing into the Sound directly opposite the Sill can contribute significantly to sedimentation in this area, since the rock step must almost entirely prevent sediment from migrating out of the Stirling Basin and over the Entrance Sill. The low rate of sedimentation on the Sill has not been sufficient to obliterate the glacial topography.

Bruun, *et. al.* (op. cit., p. 406) suggests further that ". . . Stirling Basin was excavated during the last stadial of the last glaciation, and Entrance Basin no earlier than the previous (?maximum) stadial of the same glaciation. Entrance Basin has been modified, subaerially during the Stirling Basin phase, and subsequently by marine processes during the Flandrian". These processes have not succeeded in obliterating Entrance Basin, and although the Basin is probably an area of slow sedimentation at the present day, relict sediments corresponding to earlier phases of development may also be exposed. The samples so far obtained from the Entrance Basin are in favour of this view; sand is found on the south side of the Basin at about the same depth as sandy mud further north, a feature which cannot be readily explained in terms of present-day sedimentation. Many more samples, however, are required to give an adequate picture of sediment distribution in the Entrance Basin and on the Entrance Sill.

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FORAMINIFERA OF MILFORD SOUND

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Summary

Foraminifera from seven sediment samples along the length of Milford Sound were examined and the distributional trend noted. Three faunal zones are recognised on the basis of the frequency distribution of the common benthic foraminifera and the restricted occurrences of other less abundant yet diagnostic forms. These zones correspond with the three geographic regions of the area: Entrance Basin and Sill, Stirling Basin proper, and the delta at the head of the Stirling Basin. Some 117 species of foraminifera are provisionally recognised, including 12 planktonic forms.

INTRODUCTION

Though our knowledge of the distribution of Recent foraminifera in shallow-water coastal environments such as bays, deltas, estuaries, and lagoons has advanced considerably during the past decade, only a few studies have been made of deeper-water inland environments such as fiords. An outstanding contribution, however, in this field was made by Höglund (1947) in his studies of the foraminifera from Gullmar Fiord and the Skagerrak of Norway.

Milford Sound, New Zealand, is another example of a fiord environment. In January 1957, members of the New Zealand Oceanographic Institute, in the course of an oceanographic investigation of Milford Sound from RNZFA *Tui*, collected sediment samples from this area. A preliminary analysis of the material obtained provided the basis for the present study.

PREVIOUS WORK

Little detailed work on the distribution of Recent foraminifera in the New Zealand region has been carried out. The systematic study by Vella (1957) of the foraminifera from Cook Strait sediments was the first major contribution to an understanding of their present-day distribution.

Finlay (in Wellman, 1955) listed a foraminiferal fauna "no older than Pliocene" in age and deposited between 75 and 100 fm, from a marine silt of the Paringa Formation in the Bruce Bay - Haast River area, South Westland. The fauna listed is very similar to the Recent fauna from Milford Sound and from the present known distribution of foraminifera there, the assemblage from the Paringa Formation can be correlated with the fauna characteristic of the Entrance Basin and Sill.

The bathymetry and geological features of Milford Sound have been previously described by Bruun, Brodie, and Fleming (1955) and by Brodie (1964, pp. 15–23).

LOCATION AND DESCRIPTION OF AREA

Milford Sound is one of a group of drowned glacial valleys, which characterise the south-western coast of the South Island. Its morphology is that of a typical fiord, consisting of the shallow Entrance Basin with a Sill (minimum depth, 53 fm) and the deeper Stirling Basin (depth, 147 fm) at the head of which is the delta of the Cleddau and Arthur Rivers. The fiord extends for approximately 9 miles from the delta to the open sea, the minimum width (½ mile) being in the region of the Entrance Sill. The average width of Stirling Basin is about 1 mile.

Milford Sound differs from many Norwegian fiords (Strom, 1936) by having a lower threshold allowing more frequent horizontal mixing between

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the waters of the basin and open sea, thus preventing stagnation of the bottom basin waters.

STATIONS

Sediment samples were obtained at seven stations distributed along the length of Milford Sound (table 1).

METHOD OF STUDY

On shipboard, part of each haul was placed in an oyster pot and retained as a dry sample for geological analysis. This material became available for the present study. All the foraminifera, therefore, have been considered as dead and recently dead, since no reliable distinction could be made between the dead foraminifera and those alive at the time of collection.

A uniform mass of sediment (10 g) was taken from each sample, washed through a 200-mesh sieve (having openings 0·074 mm in diameter), dried and examined. For each station the number of specimens in the 10-g subsample was counted with the help of a Swift 14-point counter. A faunal analysis has been made by plotting the cumulative percentages of benthic foraminifera at each station (fig. 2) showing only the dominant species or groups of species of the population.

TABLE 1. LOCATION OF STATIONS

Stations	Depth Fathoms	Location	Sampling Gear
A 325	61	Seaward of Dale Pt.	Dietz grab.
A 327	62	Off Dale Pt.	Cone dredge.
A 326	64	Entrance Sill	Cone dredge.
A 328	147	Stirling Basin, off Falls	Dietz grab.
A 321	142	Centre Stirling Basin	Piston corer.
A 320	116	Upper Stirling Basin (delta foot) ..	Cone dredge.
A 324	94	Head of Stirling Basin (delta slope)	Dietz grab.

HYDROLOGICAL CONDITIONS

Garner (1964, pp. 26–7) has shown that at the time of sampling the bottom temperature and salinity were nearly uniform in both basins, and that the bottom waters in Stirling Basin were well aerated. The salinity of the bottom waters ranged between 35·05 and 35·12 parts per thousand (‰) in both Entrance Basin and Stirling Basin. The surface salinities showed a marked decline from 30·13‰ at the seaward end of Entrance Basin to 6·80‰ at the Sill end. The Stirling Basin surface salinities were consistently low (4·00–8·51‰).

Bottom temperatures in the Entrance Basin were 11·4–11·5°C with a slightly colder temperature of 10·9–11·4°C in Stirling Basin. The surface temperatures show a range 13·8–14·4°C in the Entrance Basin, and a 12·9–13·4°C range in Stirling Basin.

The dissolved oxygen content of the surface waters is available only from two stations. The bottom waters of Entrance Basin were better oxygenated (6·51–6·78 millilitres per litre) compared with those of Stirling Basin (4·98–6·37 ml/l).

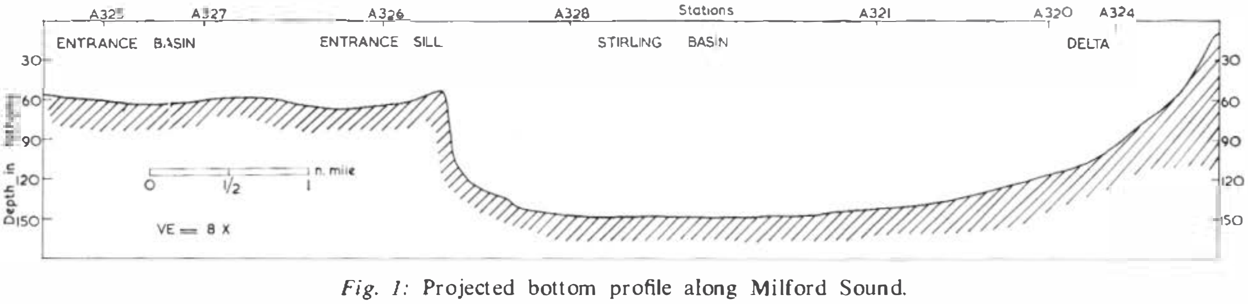

Fig. 1: Projected bottom profile along Milford Sound.

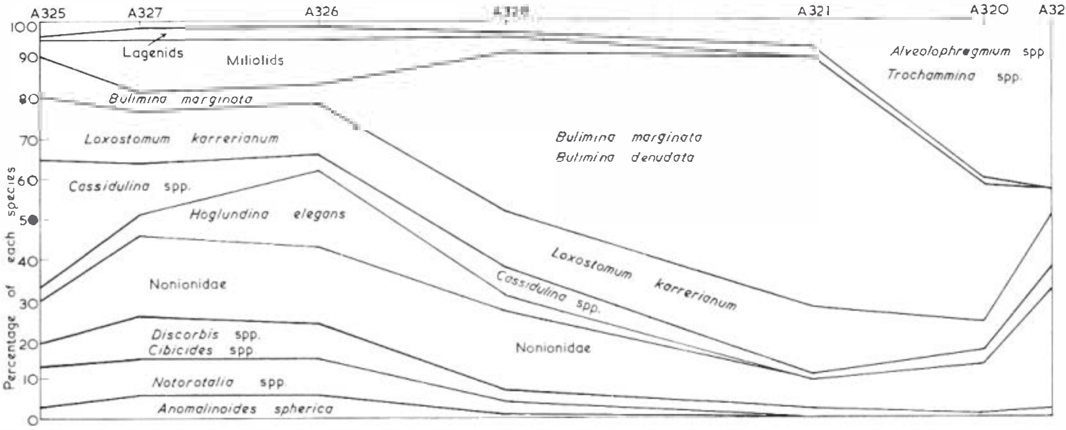

Fig. 2: Frequency distribution of Benthic foraminifera.

SEDIMENTS

The sediments of Milford Sound fall largely into two categories: (1) the coarser-grained sandy silts and sands of Entrance Basin, with pebbly silts occurring on the Sill; (2) and the finer-grained silts and muds of Stirling Basin, characterised by the abundance of aggregations and faecal pellets. The delta and basin sediments contain in addition a large proportion of organic materials in the form of plant debris.

FORAMINIFERAL STUDIES

Distribution

The composition of the foraminiferal faunas from each of the seven stations considered in this study is presented in table 3. These extend from the entrance to the Sound to the delta end of Stirling Basin, and are treated here in this order, and comments on the composition and variation of the fauna from each station are noted.

From these stations, 117 species, including 12 planktonic forms, are provisionally recorded.

Station A 325 (Entrance Basin): The benthic fauna is dominated by several species of *Cassidulina* making up about 30 per cent of the benthic foraminifera in the sample. Other abundant species include *Loxostomum karrerianum, Bulimina marginata, Notorotalia zelandica, Astrononion novo-zealandicum,* and *Nonion flemingi.* These all together make up approximately another 45 per cent of the fauna and are considered here as the subdominant species. Other common species are *Höglundina elegans, Anomalinoides spherica, Nonionella turgida.*

TABLE 2. SEDIMENTS AND SOME HYDROLOGICAL DATA. (Hydrological data are taken from figures prepared by Garner (1964, pp. 25–33), and sediment determinations from Pantin (1964, pp. 35–47))

N.Z.O.I. Station Number	Depth (m)	Sediment Type	Depths of Hydrological Measurements (m)	Temp. (°c)	Salinity (°/cc)	Dissolved Oxygen (ml/l)
A 325	119	Silt	Surface	13·8	30·73	8·25
			100	11·4	35·12	6·78
A 327	113	Silty sand ..	..	..	..	..
A 326	91	Silty sand ..	0	14·4	6·80	..
			80	11·5	35·05	6·51
A 328	269	Mud	0	12·9	8·51	..
			200	10·9	35·10	5·32
A 321	260	Sandy silt ..	0	12·9	5·63	..
			200	11·1	35·12	4·98
A 320	212	Silt	..	..	..	..
A 324	172	Silt	0	13·4	4·00	9·46
			150	11·4	35·05	6·37

TABLE 3. DISTRIBUTION OF FORAMINIFERA IN MILFORD SOUND

Faunal List		Entrance Basin		Sill	Stirling Basin		Delta	
	BENTHIC SPECIES	Station A 325	Station A 327	Station A 326	Station A 328	Station A 321	Station A 320	Station A 324
1.	*Rhabdammina* sp.							X
2.	*Proteonina* cf. *difflugiformis* (Brady)		X	X			X	
3.	*Reophax scorpiurus* Montfort	X						
4.	*Reophax subfusiformis* Earland ..	X	X	X				
5.	*Alveolophragmium* cf. *jeffreysi* (Williamson)	X				X	X	XX
6.	*Alveolophragmium* cf. *crassimargo* (Norman)	X			X	X		
7.	*Alveolophragmium* sp. B.						X	XX
8.	*Trochammina* cf. *squamata* (Jones and Parker)	X	X	X	X	X	XXX	XX
9.	*Trochammina* sp.				X	X	X	
10.	*Trochammina* cf. *astrifica* Rhumbler	X						
11.	*Cyclammina* sp.						X	X
12.	*Textularia proxispira* Vella		X	X				
13.	*Textularia ensis* Vella		X	X				
14.	*Textularia conica* d'Orbigny	X	X	X				
15.	*Textularia* sp.		X					
16.	*Textularia* cf. *tenuissima* Earland	X					X	
17.	*Siphotextularia* aff. *mestayerae* Vella		X		X			
18.	*Siphotextularia fretensis* Vella		X	X				
19.	*Spiroloculina elevata* Weisner	X						
20.	*Siphonaperta* sp. A.			X				
21.	*Siphonaperta* sp. B.							X
22.	*Quinqueloculina lamarckiana* d'Orbigny	X	X	X	X			
23.	*Quinqueloculina suborbicularis* d'Orbigny	X	X	X				
24.	*Quinqueloculina kapitiensis* Vella	X						
25.	*Quinqueloculina delicatula* Vella ..	X	X	X				
26.	*Quinquinella hornibrooki* Vella ..	X	X					
27.	*Miliolinella vigilax* Vella		X					
28.	*Pateoris* cf. *hauerinoides* (Rhumbler)			X				
29.	*Hauerinella* aff. *inconstans* (Brady)	X						
30.	*Pyrgo* aff. *ezo* Asano	X						
31.	*Cornuspira* cf. *involvens* (Reuss) ..	X	X	X				
32.	*Robulus limbosus* (Reuss)					X		
33.	*Robulus orbicularis* (d'Orb.)	X						
34.	*Robulus suborbicularis* Parr				X			
35.	*Robulus* cf. *rotulatus* (Lamarck) ..		X	X				
36.	*Astacolus reniformis* (d'Orb.)		X					
37.	*Lenticulina gibba* (d'Orb.)	X	X					
38.	*Lenticulina peregrina* (Schwager)	X	X					
39.	*Frondicularia* cf. *californica* Cush. and McCulloch ..	X						
40.	*Saracenaria latifrons* (Brady)			X				
41.	*Vaginulinopsis tasmanica* Parr	X		X				
42.	*Marginulina glabra* d'Orb.			X				
43.	*Dentalina subsoluta* (Cush.)	X						
44.	*Dentalina emaciata* (Reuss)			X				
45.	*Lagena striata* (d'Orb.)	X		X		X		X
46.	*Lagena costata* (Williamson)			X	X			
47.	*Lagena laevis* (Montagu)					X		
48.	*Oolina* sp.	X						
49.	*Fissurina marginata* (Montagu) ..	X				X		
50.	*Bolivina cacozela* Vella		X	X	X	X		
51.	*Bolivina malovensis* Heron-Allen and Earland	X						
52.	*Bolivina pseudo-plicata* Heron-Allen and Earland ..	X	X		X	X		
53.	*Bolivina pygmaea* Brady	X			X	X	X	X
54.	*Bolivina seminuda* Cush.		X					X
55.	*Virgulina rotundata* Parr	X						
56.	*Virgulina spinosa* Heron-Allen and Earland	X						XX
57.	*Loxostomum karrerianum* Brady	XX	XX	XX	XX	XX	X	X
58.	*Bulimina marginata* d'Orb.	X	X	X	XXX	XXX	XX	X
59.	*Bulimina denudata* Cushman and Parker			X	XXX	XXX	XX	
60.	*Bulimina aculeata* d'Orb.					X		X
61.	*Globobulimina turgida* (Bailey) ..	X	X	X	X	X	X	
62.	*Ceratobulimina* sp.							
63.	*Robertinoides* cf. *pumilum* Höglund	X						
64.	*Uvigerina* cf. *peregrina* Cush. ..		X	X				
65.	*Angulogerina angulosa* (Williamson)	X						
66.	*Chilostomella ovoidea* Reuss		X	X				
67.	*Seabrookia* cf. *earlandi* Wright	X						
68.	*Pullenia bulloides* (d'Orb.)					X		

TABLE 3. DISTRIBUTION OF FORAMINIFERA IN MILFORD SOUND—*continued*

Faunal List	Entrance Basin		Sill	Stirling Basin		Delta	
BENTHIC SPECIES	Station A 325	Station A 327	Station A 326	Station A 328	Station A 321	Station A 320	Station A 324
69. *Pullenia quinqueloba* (Reuss)			X				
70. *Cassidulinoides orientalis* (Cush.)	XXX	XX	X	X	X	X	X
71. *Cassidulina islandica* Norvang	X						
72. *Cassidulina* aff. *laevigata* d'Orb.	X						
73. *Cassidulina* sp.	X						
74. *Ehrenbergina* sp.					X		
75. *Astrononion novo-zealandicum* Cushman and Edwards	X	XX	XX	X			
76. *Nonion flemingi* Vella	X	X	X	X	X	X	X
77. *Nonion subturgidum* (Cush.)	X	X	X	X	X	X	X
78. *Nonionella turgida* (Williamson)	X	X	X	X	X	XX	XXX
79. *Elphidium novo-zealandicum* Cush.	X	X	X	X			
80. *Elphidium* aff. *advenum* (Cush.)	X	X		X	X		X
81. *Elphidiononion simplex* (Cush.)		X		X		X	
82. *Elphidiononion charlottensis* Vella	X	X	X	X			
83. *Elphidiononion* sp.	X						
84. *Notorotalia* cf. *clathrata* (Brady)				X	X		
85. *Notorotalia zelandica* Finlay	X	X	X	X			
86. *Notorotalia inornata* Vella	X	X	X				
87. *Spirillina* cf. *vivipara* Ehrenberg	X						
88. *Spirillina* aff. *tuberculata* Brady	X						
89. *Patellina corrugata* Williamson	X	X	X		X		
90. *Patellinella inconspicua* (Brady)	X	X		X			
91. *Gyroidina* sp.				X			
92. *Höglundina elegans* (d'Orb.)	X	X	XXX				
93. *Eponides umbonatus* (Reuss)		X	X	X			
94. *Gavelinopsis* aff. *lobatulus* Parr.				X			
95. *Discopulvinulina* cf. *bertheloti* (d'Orb.)	X	X	X	X			
96. *Discorbis* spp. (— *Gavelinopsis*)	X						
97. *Rosalina* sp.	X	X					
98. *Rosalina* cf. *bradyi*		X	X				
99. *Pileolina* cf. *radiata* Vella	X	X					
100. *Anomalinoides spherica* (Finlay)	X	X	X				
101. *Cibicides marlboroughensis* Vella	X	X	X	X	X		X
102. *Cibicides* sp. aff. "*marlboroughensis*"							X
103. *Cibicides* large sp.				X			
104. *Dyocibicides* sp. A	X	X	X				
105. *Dyocibicides* sp. B	X	X	X				
PLANKTONIC SPECIES							
106. *Sphaeroidina bulloides* d'Orb.	X	X	X	X	X	X	X
107. *Globigerinella aequilaterelis* (Brady)	X	X					X
108. *Globigerina* cf. *subcretacea* Lomnicki				X			
109. *Globigerina bulloides* d'Orb.	X	X	X	XX	X	X	X
110. *Globigerina quinqueloba* Natland	X			X	X	X	X
111. *Globigerina pachyderma* (Ehrenberg)					X	X	X
112. *Globigerina* sp. A.	X					X	X
113. *Globigerina* sp. B.						X	
114. *Globigerina inflata* d'Orb.	X	X	X	X			
115. *Globorotalia truncatulinoides* (d'Orb.)		X	X				
116. *Globigerinoides ruber* (d'Orb.)		X				X	X
117. *Orbulina universa* d'Orb.		X	X	X			X

XXX dominant XX subdominant X present

Rare forms restricted to this station include *Trochammina* cf. *astrifica* Rhumbler, *Robertinoides* cf. *pumilum* Höglund and *Angulogerina angulosa*.

Although the *Cassidulina* species make up such a high numerical proportion of the fauna, such genera as *Notorotalia*, *Loxostomum*, *Astrononion*, because of their larger size, appear at first sight to be the dominant species.

The planktonic foraminifera make up over 6 per cent of the total fauna, *Sphaeroidina bulloides* being the most abundant species and together with *Globigerina bulloides* comprising most of the fauna.

Station A 327 (Entrance Basin): On the whole the fauna is very similar to that of the most seaward station (A 325) with all the common species persisting but in somewhat changed frequencies. *Cassidulina* sp. no longer remains the sole dominant species in the assemblage but is joined by *Loxostomum karrerianum*, with *Notorotalia* spp. *Astrononion novo-zealandicum* and *Elphidium* aff. *advenum* which are also very abundant. *Anomalinoides spherica*, *Höglundina elegans*, *Bulimina* spp., *Cibicides* and *Discorbis* spp. are common.

The most interesting feature of the benthic fauna at this station is the major rise in the Miliolid percentage (12 per cent) and the incoming of *Astrononion novo-zealandicum* and *Elphidium* aff. *advenum* into the subdominant range of species with the reduction in the number of *Cassidulina*.

Some of the benthic species not present in the previous sample include: *Siphotextularia* sp., *Uvigerina* sp., *Chilostomella* sp., *Rosalina* cf. *bradyi*.

Planktonic foraminifera comprise 8 per cent of the total fauna. Five species were recognised, *Globigerina bulloides* being the most common.

Station A 326 (Entrance Sill): The foraminiferal fauna is again similar to that from the other two stations in Entrance Basin. The foraminiferal abundance in the sediment shows a marked increase although the number of species has not increased proportionately. The frequency occurrence of species shows a slight change, *Höglundina elegans* and *Astrononion novo-zealandicum* become the dominant element in the fauna. *Loxostomum karrerianum* and *Notorotalia* spp. become the subdominant species, with *Bulimina* spp. and *Cassidulina* spp. becoming less abundant, but still common. *Eponides umbonatus* is also common in this assemblage. *Globobulimina turgida* still persists.

The arenaceous fauna is similar in composition to that trend as from previous stations, comprising about 2 per cent of the benthic fauna, the Lagenids, 3·5 per cent; and the Miliolids again show a high percentage, viz. 11 per cent. *Siphonaperta* sp. appears to be restricted to this station.

The main feature of the benthic fauna at this station is the sudden rise of the *Höglundina elegans* percentage at the expense of *Cassidulina* spp. and the increase of *Astrononion novo-zealandicum* with a reduction in *Elphidium* aff. *advenum* numbers, *H. elegans* and *A. novo-zealandicum* being here dominant in the assemblage.

The planktonic foraminifera make up approximately 12 per cent of the total fauna, with *Sphaeroidina bulloides* again the dominant species. The other planktonic species include *Globigerina bulloides*, *Globigerina inflata*, *Globorotalia truncatulinoides*, and *Orbulina universa*.

Station A 328 (Stirling Basin): The foraminiferal fauna at this station is neither as rich nor as abundant as at the previous stations. There is a sharp change in the composition of the fauna: some of the species become drastically reduced in numbers and others disappear completely.

Bulimina marginata with *Bulimina denudata* become the dominant element (45 per cent), with *Loxostomum karrerianum* next in abundance. The arenaceous foraminifera still occur in small frequencies but the Miliolids, with only 2·5 per cent, become quite insignificant. *Astrononion novo-zealandicum*, *Nonion flemingi*, *Nonionella turgida*, are common, while *Cibicides marlboroughensis* and *Rosalina* cf. *bradyi* still persist. *Notorotalia* and *Anomalinoides spherica* are no longer a common constituent in the assemblage.

The striking feature of the whole fauna is the high proportion of planktonic foraminifera, amounting to some 22 per cent of the total fauna. *Globigerina bulloides* is the most abundant species. *Sphaeroidina bulloides* and *Globigerina quinqueloba* are also common. Other species present include *Globigerina subcretacea*, *Globigerina inflata*, and *Orbulina universa*.

The foraminifera from this station are in a good state of preservation, appearing much fresher (seldom filled, hardly worn or broken) than those in the three stations from Entrance Basin and Sill.

Station A 321 (Stirling Basin): The fauna of this station is poorer both in the number of species (31) and the abundance of individuals

(230) than the preceding station, yet in the frequency occurrence of the common species it is very similar.

The assemblage is dominated by *Bulimina marginata* and *B. denudata*, with *Loxostomum karrerianum* also being abundant. Miliolids are no longer present, *Anomalinoides spherica* is represented only by a single immature specimen and *Notorotalia clathrata* makes its last appearance.

Station A 320 (Delta): The fauna at this station is an extremely poor one; only 95 foraminifera belonging to 11 species were encountered.

The arenaceous foraminifera begin to make up a considerable proportion of the fauna. Thirty individuals were present, belonging mainly to *Trochammina* cf. *squamata*. The two *Bulimina* species are still relatively common as is *Loxostomum karrerianum*. *Globigerina bulloides* and *G. quinqueloba* comprise the bulk of the planktonic fauna (23 per cent).

Station A 324 (Delta): A slightly richer fauna (16 species, with 150 foraminifera in the sample is dominated by the arenaceous forms *Alveolophragmium* cf. *jeffreysi*, *Alveolophragmium* sp. and *Trochammina* cf. *squamata*, although individually *Nonionella turgida* is the most common benthic species. *Globigerina bulloides* and *G. quinqueloba* make up the bulk of the planktonic population which reaches 25 per cent of the total fauna.

Distributional Trends

Faunal analyses have been made from each station and the results are presented in fig. 1–7. These show the relationship of the following variables with respect to the geographic position of the station along the length of the Sound: abundance of foraminifera; concentration of species; occurrence of test types; number of arenaceous and planktonic individuals; and the percentage of planktonic forms in the fauna. The graphs illustrate several significant features in the distribution and variation of the fauna along the profile and some general trends are noted.

1. *Frequency Distribution of Benthic Foraminifera:* The frequency distribution (fig. 2) illustrates the occurrence of the common species or groups of species along the traverse. Many of the rare species and those occurring in smaller frequencies have been combined with the dominant forms of the same family or related group of species for statistical purposes. For example, all the *Nonion*, *Elphidium* and related genera have been grouped in *Nonionidae*, *Globobulimina* with *Bulimina* spp., and *Textularia* spp. with the arenaceous forms.

The dominant species fall into two faunal types (table 3).

(a) A persistent fauna, in which species or groups of species show either minor fluctuations in their frequencies along the length of the Sound, such as *Loxostomum karrerianum* and the Nonionidae group; or those which show major fluctuations, such as the *Cassidulina* and Bulimina groups. Some of the less common species not shown in fig. 2, yet having a widespread distribution, include *Nonion flemingi*, *Nonion subturgidum*, *Nonionella turgida*, *Globobulimina turgida*, and *Cibicides marlboroughensis*.

(b) A restricted fauna, consisting of those species which are abundant in part of the Sound only; these are *Astrononion novozealandicum*, *Höglundina elegans*, *Anomalinoides spherica;* the *Notorotalia* group, and the *Miliolids*.

2. *Abundance of Foraminifera:* The number of foraminifera (i.e., total number of foraminifera present in 10 g of dry sediment) is high and

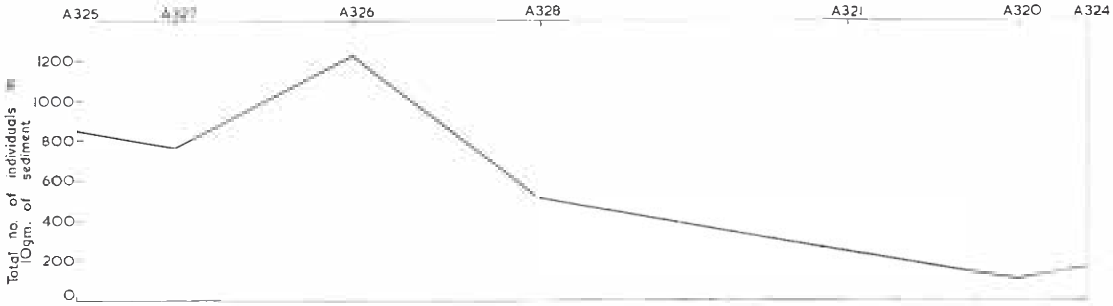

Fig. 3: Abundance of foraminifera.

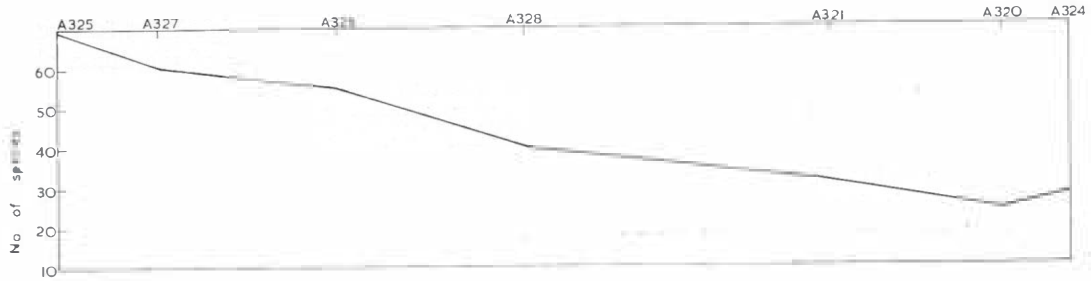

Fig. 4: Number of species.

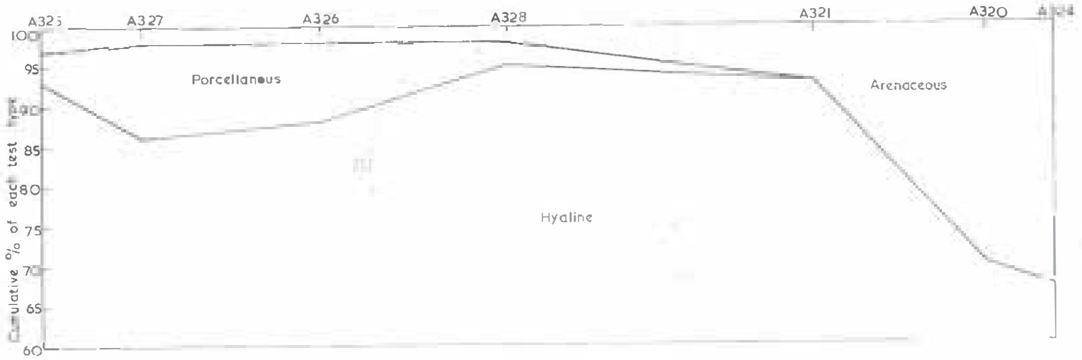

Fig. 5: Occurrence of test types.

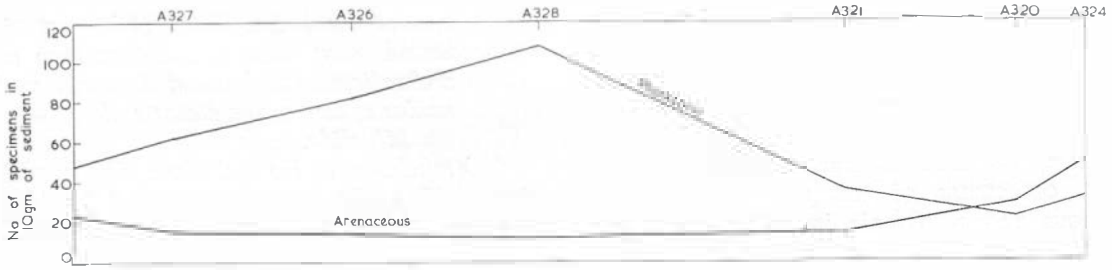

Fig. 6: Number of Arenaceous and Planktonic foraminifera.

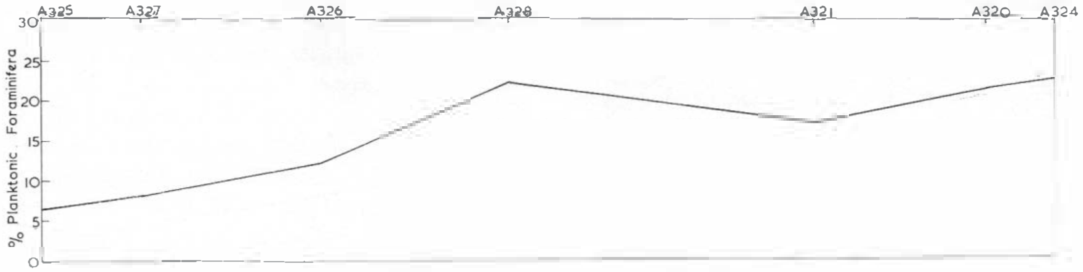

Fig. 7: Percentage of Planktonic foraminifera.

fluctuates in the Entrance Basin, reaching a peak in the Sill region, followed by a continuous decrease towards the delta end of Stirling Basin (see fig. 3).

3. *Number of Species:* The species number is here defined as the total number of species in a sediment sample. The number decreased progressively landward from a maximum of some 70 species at the seaward end of Milford Sound to some 55 species at the Entrance Sill, between 30 and 40 species in Stirling Basin and some 20–30 species at the delta end of the Basin (see fig. 4).

4. *Occurrence of Test Types:* The foraminifera were subdivided into three groups based on the nature of the test. The arenaceous forms comprise all those species with an agglutinated test; porcellaneous forms include species mainly belonging to the Miliolidae; and all other benthic and planktonic forms fall into the hyaline group.

The percentage of arenaceous forms is low (3 per cent) in the Entrance Basin region but increases in Stirling Basin, reaching over 30 per cent in the delta region. Conversely the porcellaneous forms are abundant (10 per cent) only in the Entrance Basin and Sill areas, whereas foraminifera with hyaline tests are the most common forms at all stations (see fig. 5).

5. *Planktonic Foraminifera:* The number of planktonic foraminifera in the sediment increases inland away from the seaward end of Milford Sound, rises to a maximum at the Sill end of Stirling Basin, and then falls off landwards. The numbers at the delta end are only slightly less than those at the entrance to the Sound (fig. 6).

Although there is only a minor difference in the number of planktonic foraminifera between the sediments of Entrance Basin and those of the delta end of Stirling Basin, the plankton in the former region makes up a smaller proportion (3 per cent) of the total fauna than in the Stirling Basin, where it constitutes a major element of the fauna (over 20 per cent) (see fig. 7).

Faunal Zones

Three faunal zones can be established, characteristic of the three regions: Entrance Basin and Sill, Stirling Basin, and the lower delta region of the Stirling Basin, each having a distinct assemblage.

Fauna I: Typical mainly of the Entrance Basin and Sill region (depth, 50–65 fm; silty sand to sandy bottom; temperature, 11·4–11·5°c; salinity, 35·05–35·12‰). The fauna is characterised by the restricted occurrence of such species as *Textularia proxispira, T. ensis, Chilostomella ovoidea,* high frequency occurrences of Miliolids, *Astrononion novo-zealandicum, Notorotalia zelandica, N. inornata, Anomalinoides spherica, Höglundina elegans, Cassidulina* spp., *Discorbis* spp., and *Cibicides* spp.

Fauna II: Stirling Basin (depth, 140–147 fm; sandy silt bottom with plant debris; bottom temperature, 10·9–11·4°c; salinity, 35·05–35·12‰). The fauna has few restricted species and is mainly characterised by the rarity or absence of the many common species from Zone I, and the predominance of *Bulimina marginata, B. denudata,* and *Loxostomum karrerianum* in the benthic assemblage. *B. aculeata* and *Notorotalia* cf. *clathrata* (Brady) are diagnostic of this assemblage.

Fauna III: Confined to the lower delta region of Stirling Basin (depth, 115–95 fm; sandy silt bottom with much plant debris, general hydrologic conditions similar to the remainder of Stirling Basin – locally the bottom waters here, as in Stirling Basin, might become depleted in oxygen with the liberation of H_2S due to the decomposition of organic material in the sediment). The fauna shows a reduced frequency occurrence of the common species in Fauna II, high frequencies of arenaceous forms, especially *Trochammina* cf. *squamata, Alveolophragmium* cf. *jeffreysi,* and the restricted occurrence of *Alveolophragmium* sp. B., *Trochammina* sp., *Cyclammina* sp. Among the non-arenaceous forms *Bulimina marginata, B. denudata, Loxostomum karrerianum,* and *Nonionella turgida* are the most common species.

The variation in percentage distribution of shell types (fig. 5) also supports the threefold faunal zonation of the area.

1. The Sill region is characterised by the presence of about 10 per cent of porcellaneous forms with some 85 per cent hyaline types.
2. Porcellaneous forms are rare in Stirling Basin, the bulk of the tests being hyaline with a slight increase in the percentage of arenaceous forms.
3. In the lower delta environment, porcellaneous forms are completely absent and arenaceous forms are dominant.

Distribution of Individual Species

There is no problem with derived foraminifera in an area of gneissic terrain, but the possibility of a reworked origin for several common species of the Sill fauna present in the Stirling Basin sediments cannot be overlooked.

Although Miliolidae are typically shallow-water inhabitants, they range into a variety of environments and certain species prefer a deep-water habitat (Green, 1960). In the area investigated the *Quinqueloculina* assemblage is mainly restricted to the Sill region (Fauna I).

Bulimina marginata and *B. denudata* are persistent throughout the Sound, but appear in greater numbers in the Stirling Basin sediments where the finer substratum or the greater depth could favour their abundance.

High percentages of *Cassidulina* species are reported from the outer part of the continental shelf both on the east coast (Parker, 1948) and west coast of North America (Bandy, 1953). In Santa Monica Bay, California, Zalesny (1959) found that the "bottom sediments seem to be the influencing factor affecting the abundance of several species of Cassidulina". They showed a definite preference for rock and gravel areas. This was not the case in Milford Sound, however, where the *Cassidulina* spp. occurs in maximum concentration near the entrance to the Sound on a silty substratum, rather than on the coarser floor of the Sill.

Höglundina elegans which has been reported from depths greater than 490 fm (Walton, 1955) and greater than 1,000 fm by Bandy (1953), off California, is a common constituent of the Sill fauna, reaching its greatest concentration on the shallowest part of the Sill (50 fm). Its rarity in the sediments of Stirling Basin, therefore, is difficult to explain.

The widely distributed forms show great tolerance to large variations in the physical conditions, and the nature of the substratum.

Significance of Variation in Concentration of Foraminifera

The higher concentration of foraminifera in the sediments of Entrance Basin can be explained in terms either of a greater number of species, a lower rate of sedimentation, or possibly a local enrichment of the fauna from the effects of bottom currents in the Sill region. Many of the foraminifera here appear worn and often broken, pointing to their exposed state on the sea floor and the possibility of bottom transport. The coarser nature of the sediments also points to stronger current action coupled with a slower rate of deposition, allowing the tests to accumulate in larger numbers and for longer periods on the sea floor before being buried. In Stirling Basin, however, the greater influx of sediments coupled with a reduction in the number of species may account for the lower concentration of the foraminifera. The predominance of well preserved specimens in the samples indicates a fast burial rate of dead tests, and the fresh looking individuals could have been alive or only recently dead at the time of collection. There is no evidence for bottom transport of sediments in Stirling Basin.

A correlation, based on the rate of sedimentation and the ratio of live to dead foraminifera was made by Walton (1955) in Todos Santos Bay, California. High live-to-dead (L/D) ratio indicated rapid burial of tests, whereas low L/D ratio meant slow deposition. In the Santa Cruz Basin, California, Resig (1958) found that the number of foraminifera per gram of sediment decreased with depth; the number on the rim of the basin (78–80 fm) was up to 70 times the number below sill depth, i.e., in the basin proper at depths of 800–1,000 fm. Polski (1959), in his studies of the foraminifera from the north Asiatic Coast found that the foraminiferal number increased both with depth and distance from shore, planktonic species contributing to the great abundance in the offshore areas.

The Planktonic Foraminifera

For an inland water environment, such as Milford Sound, a fauna comprising 12 planktonic species (table 3) in relative abundance is an interesting feature.

In Entrance Basin the plankton makes up between 7 and 12 per cent of the total fauna in the sediment, but in the Stirling Basin it reaches over 20 per cent. Not all species, however, were found together in any one sample, but showed a random distribution. *Sphaeroidina bulloides* was more abundant in the Entrance Basin sediments, the cosmopolitan *Globigerina bulloides* being the dominant form in the Stirling Basin sediments. *G. quinqueloba* was commonly found only in Stirling Basin and *G. pachyderma* was recorded from the latter region only.

The fauna is a mixed one comprising both warm-temperate and cold water elements.

1. The representatives of the warm-temperate fauna, characteristic of the mid-latitudes are:

Globigerinella aequilateralis *Globigerina subcretacea* *Globigerinoides ruber*	Rare – represented by several individuals only.

G. subcretacea Lomnicki is presently considered as a distinct species, although it could be taken for a variety of *Globigerinella aequilateralis*, or *G. bulloides*.

2. Representatives of a cold-water fauna restricted to the higher latitudes and to the cold water currents of the mid-latitudes include:

   Globigerina pachyderma – rare.
   Globigerina quinqueloba – common in Stirling Basin.

3. Species showing widespread occurrence, due to wide degree of temperature tolerance:

   Globigerina bulloides – abundant.
   Globigerina inflata – rare.
   Globorotalia truncatulinoides – rare.
   Orbulina universa – rare.
   Sphaeroidina bulloides – common in Entrance Basin.

There is some doubt about the planktonic habitat of *Sphaeroidina bulloides;* Phleger and Parker (1951) consider it a planktonic species, yet Bradshaw (1959) does not record it in plankton tows.

The above relationship reflects the hydrologic conditions in Milford Sound. Garner (1964, p. 32) states that the "conditions leading to the renewal of basin water in the region of Milford Sound may be due to: (a) an intrusion of cold, Subantarctic Water from the West Wind Drift into the predominantly Subtropical environment off the South Westland coast; (b) upwelling of subsurface water due either to winds with a significant component from the south-west or a divergence of flow against the coast of an onshore water movement; (c) the winter cooling of shelf waters".

The number of planktonic foraminifera in sediments decreased slightly landward from the open end of the Sound with maximum numbers occurring in the region of the Sill; however, considering the higher rate of deposition in the Stirling Basin, this decrease might not be significant.

Although Reiter (1959) found that *Globigerina* species can be swept into enclosed areas, such as bays, during periods of storm activity and become buried in a well-preserved state in beach sediments, it is not likely that such a mechanism would account for the distribution of the plankton in the sediments of Milford Sound, as it would not explain the high concentration of them near the Sill, nor the significant decrease in numbers away from the open coast. This is only acceptable as a partial explanation, particularly with species represented by few individuals, as storms could bring in oceanic surface waters abundant in planktonic foraminifera. Those in greater abundance and in a good state of preservation could have lived inside Milford Sound.

Bradshaw (1959) found that the greatest number of living planktonic foraminifera occurred between 6 and 30 m, and Bé has concluded that the upper 200 m of water which is approximately equivalent to the euphotic zone corresponds with the maximum concentration of planktonic foraminifera, the numbers becoming insignificant below that depth.

Garner (1964, pp. 31–2) has shown that the circulation pattern in Milford Sound is determined mainly by the freshwater inflow and the bottom topography of the region. He points out that horizontal mixing does take place between the oceanic waters from the open shelf and both the upper layers of low salinity and lower waters of normal salinities of the Stirling Basin. The oceanic waters with normal salinities (34–36‰) can be found throughout the Sound below 10 m (temperature 12–16°C) in Entrance Basin and below 70 m (temperature 11·3–14°C) in Stirling Basin.

In the absence of information on the occurrence of living planktonic foraminifera in the waters of Milford Sound, only tentative suggestions can be advanced of the possible factors affecting their distribution, as evidenced by their occurrence in the sediments.

If it is assumed that the distribution of the planktonic foraminifera is in part controlled by salinity, then, despite the lowered salinity at the surface in Stirling Basin the planktonic foraminifera might be expected to occur at deeper levels where the appropriate salinity is found. This would permit the occurrence of planktonic forms in relatively high numbers at the three landward stations in Stirling Basin.

On the other hand, the zone of great abundance of plankton in the sediments of the Stirling Basin near the Sill (Station A 328) corresponds with a boundary of horizontal water mixing between surface waters of low and normal salinity (Garner, 1964, p. 32). The freshwater stream from the delta coming into contact with the more saline oceanic waters could well be responsible for the sudden dying off of many planktonic foraminifera.

There is some evidence to suggest that the higher concentration of individuals recorded from Station A 328 could be due to the greater number living in this part of Stirling Basin.

The presence of low salinity water at the surface, from the head of the Sound to the vicinity of Station A 328, could also inhibit the production of phytoplankton on which the planktonic foraminifera depend mainly for food.

SUMMARY

The results of the study can be summarised:

1. The number of species decreases landward away from the seaward end of the Sound.
2. The area of greatest foraminiferal abundance is Entrance Basin with a maximum occurring on the Sill.
3. The number of arenaceous foraminifera is greatest at the delta end of Stirling Basin.
4. The planktonic fauna is relatively rich, considering the inland nature of the environment.
5. Planktonic foraminifera occur throughout the Sound, the greatest number being present at the Sill end of Stirling Basin.
6. Two faunal types exist in the area: the cosmopolitan group, and those with restricted occurrences.
7. Three foraminiferal biofacies are recognised, characteristic of the three geographic regions of the area.
8. Foraminifera with porcellaneous tests are most abundant in the Sill sediments and are characteristic of that assemblage.
9. Common species in Entrance Basin and Sill, such as large *Notorotalia* spp., *Textularia* spp., *Höglundina elegans*, *Anomalinoides spherica* are almost restricted to this zone.
10. *Bulimina marginata* and *B. denudata* occur commonly in Stirling Basin, and are the dominant species of that assemblage.
11. High proportions of arenaceous foraminifera characterise the assemblage of the lower delta of Stirling Basin.
12. On the basis of foraminiferal abundance in the sediments of Milford Sound, it can be shown that the rate of sedimentation is considerably greater in Stirling Basin than in the Entrance Sill region.
13. Foraminifera in the sediments of Stirling Basin are in a better state of preservation than those from the Sill.
14. No glauconite-filled foraminiferal tests were encountered in the sediments.

ACKNOWLEDGMENTS

The author is indebted to Dr Paul Vella, Geology Department, Victoria University of Wellington, for introducing him to the field of foraminifera and for subsequent discussions. Sincere thanks go to Mr N. de B. Hornibrook, N.Z. Geological Survey, for provision of facilities and for willing assistance generally. The author is particularly grateful to Mr D. J. Cullen and Dr R. H. Hedley for reading the manuscript and making useful suggestions.

FAUNAL REFERENCE LIST

No detailed systematic treatment is presented in this study. Identification of the previously described species was aided by such monumental work as Brady's (1884), referred to below as the "Challenger Foraminifera", which was recently supplemented with a taxonomic revision of the plates by Barker (1960), referred to below as the "Taxonomic Notes". References to systematic work by Asano, Cushman, Finlay, Höglund, Loeblich and Tappan and others will also be found. The systematic study by Vella (1957) of some Recent New Zealand foraminifera was of immense value to the present investigation. He described 40 new species from the Recent fauna.

Listed below are the names of the species discussed in the text with the reference on which the identification was based. The reference to the original description and the full synonymy is available in the reference quoted and is not restated here.

Alveolophragmium cf. *crassimargo* (Norman), Loeblich and Tappan, 1953, Smithson. Misc. Coll. 1217:28–31, pl. 3. figs. 1–3.

Alveolophragmium cf. *jeffreysi* (Williamson), Loeblich and Tappan, 1953, Smithson. Misc. Coll. 121 (7) :31–2, pl. 3, figs. 4–7.

Angulogerina angulosa (Williamson), Cushman and McCulloch, 1948, Allan Hancock Pac. Exped. 6 (5) :279–80. pl. 35, fig. 6.

Anomalinoides spherica (Finlay) = *Anomalina spherica* Finlay, 1940, Roy. Soc. Trans, N.Z., 69:460, pl. 66, figs. 166–71; *Anomalinoides spherica frigindex* Vella, 1957, N.Z. Geol. Surv. Pal. Bull. 28: 39, pl. 9, figs. 192–4.

Astacolus reniformis (d'Orbigny) – Brady, 1884, *Challenger* Foraminifera and Barker, 1960, Taxonomic Notes, pl. 70, fig. 3.

Astrononion novo-zealandicum Cushman and Edwards, in Cushman, 1939, U.S. Geol. Surv. Prof. Pap. 191:37, pl. 10, fig. 12.

Bolivina cacozela Vella, 1957, N.Z. Geol. Surv. Pal. Bull. 28:33, pl. 8, figs. 162. 163.

Bolivina malovensis Heron – Allen and Earland, 1932, *Discovery* Rep. 4, :355, pl. 9, figs. 12–5.

Bolivina pseudo – plicata Heron – Allen and Earland, 1932, *Discovery* Rep. 4, :355, pl. 9, figs. 9–11.

Bolivina pygmaea Brady, in Brady, 1884, *Challenger* Foraminifera, p. 421, pl. 53, figs. 5, 6: Cushman and McCulloch, 1942, Allan Hancock Pac. Exped. 6 (4) :204–5, pl. 25, figs. 8–12.

Bolivina seminuda Cushman, in Parr, 1950, B.A.N.Z. Ant. Res. Exped. Rep. 5, (6) :339, pl. 12, fig. 17.

Bulimina aculeata d'Orbigny, in Cushman and Parker, 1947, U.S. Geol. Surv. Prof. Pap. 210-D:120–1, pl. 28, figs. 8–11.

Bulimina denudata Cushman and Parker, 1938, Contr. Cush. Lab. Foram. Res., 14:15, pl. 10, figs. 1, 2, also 1947, U.S. Geol. Surv. Prof. Pap. 210-D:117–8, pl. 27, figs. 13, 14.

Bulimina marginata d'Orbigny, in Cushman and Parker, 1947, U.S. Geol. Surv. Prof. Pap. 210-D: 119–20, pl. 28, figs. 5–6.

Cassidulina islandica, Norvang, Loeblich and Tappan, 1953, Smithson, Misc. Coll. 121 (7) :118–20, pl. 24, figs. 1a, b.

Cassidulinoides orientalis (Cushman), in Brady, 1884. *Challenger* Foraminifera, pl. 54, figs. 10a, b: see Barker, 1960. Taxonomic Notes.

Chilostomella ovoidea Reuss, Brady, 1884, *Challenger* Foraminifera, p. 436, pl. 55, figs. 12–23: Cushman. 1924, U.S. Nat. Mus. Bull. 104 (5) :2–3, pl. 1. figs. 1–10. Barker, 1960, in his Taxonomic Notes follows Thalmann in breaking up Brady's species into *C. oolina* Schwager and *C. ovoidea* Reuss. The Milford Sound specimens more closely resemble *C. oolina* Schwager of Barker, but because of the uncertainty which exists at present over the identification of the *Chilostomella* species, the local specimens are compared with *C. ovoidea* Reuss of Cushman.

Cibicides marlboroughensis Vella. 1957, N.Z. Geol. Surv. Pal. Bull. 28:40, pl. 9, figs. 189–91.

Cornuspira cf. *involvens* (Reuss) Brady, 1884, *Challenger* Foraminifera p. 200. pl. 11, figs. 1–3: Graham and Militante, 1959, Stanford Uni. Publ. 6 (2) :58, pl. 9, figs. 5, 6a. b.

Dentalina emaciata Reuss, Asano, 1956, Sci. Rep. Tohoku Univ. 27:17–18, pl. 4, figs. 18–24.

Dentalina subsoluta (Cushman) in Brady, 1884, *Challenger* Foraminifera, p. 503, pl. 62, figs. 13–16: pl. 64, fig. 28, see Barker. 1960, Taxonomic Notes.

Discopulvinulina cf. *bertheloti* (d'Orbigny), in Brady. 1884. *Challenger* Foraminifera. pl. 89. figs. 11, 12: see Barker, 1960, Taxonomic Notes.

Elphidium aff. *advenum* (Cushman) in Cushman. 1939, U.S. Geol. Surv. Prof. Pap. 191:60–1, pl. 16. figs. 31–5: pl. 17, figs. 1, 2.

Elphidium novo-zealandicum Cushman. in Cushman, 1939. U.S. Geol. Surv. Prof. Pap. 191:63, pl. 17. fig. 18.

Eponides umbonatus (Reuss) Phleger and Parker, 1951. Geol. Soc. Am. Mem. 46 (2) :22, pl. 11, figs. 10a. b, 13a, b, 14a, b: *Eponides tenera* (Brady) in Vella, 1957, N.Z. Geol. Surv. Pal. Bull. 28, p. 10.

Frondicularia cf. *californica* Cushman and McCulloch, 1950, Allen Hancock, Pac. Exped. 6 (6), p. 328, pl. 43, figs. 5–8.

Gavelinopsis aff. *lobatulus* (Parr) in Brady. 1884. *Challenger* Foraminifera pl. 88, fig. 1: see Barker. 1960, Taxonomic Notes.

Globigerina bulloides d'Orbigny. Phleger and Parker. 1951, Geol. Soc. Am. Mem., 46 (2), pl. 19. figs. 6. 7.

Globigerina inflata d'Orbigny. Phleger and Parker, 1951, ibid, pl. 19, figs. 10. 11.

Globigerina pachyderma (Ehrenberg), Phleger and Parker. 1951, ibid, pl. 19. figs. 12, 13.

Globigerina quinqueloba Natland. Bradshaw, 1959. Bush. Found. Foram. Res. Contr. 10 (2) :38, pl. 6. figs. 24, 25.

Globigerina subcretacea Lomnicki = *Globigerina subcretacea* (Lomnicki) in Graham and Militante. 1959, Stanford Univ. Publ. 6 (2):111, pl. 18, figs. 10a–c.

Globigerinella aequilateralis (Brady), Phleger and Parker, 1951. Geol. Soc. Am. Mem. 46 (2) :35, pl. 19, fig. 14.

Globigerinoides ruber (d'Orbigny). Phleger and Parker, 1951, ibid. pl. 19, fig. 16.

Globorotalia truncatulinoides (d'Orbigny), Phleger and Parker, 1951, ibid. pl. 20. figs. 10–13.

Globobulimina turgida (Bailey), in Höglund, 1947, Zool. Bidrag. Uppsala, 26:248–50, pl. 20, fig. 5: pl. 21, figs. 4, 8; pl. 22, fig. 5; text-figs. 247–57, 271.

Hauerinella aff. *inconstans* (Brady) = *Opthalmidium inconstans* Brady, 1884, *Challenger* Foraminifera, pl. 189, pl. 12, figs. 5, 7, 8: see Barker, 1960, Taxonomic Notes.

Höglundina elegans (d'Orbigny), in Phleger and Parker, 1951, Geol. Soc. Am. Mem. 46 (2) :22, pl. 12, figs. 1a, b.

Lagena striata (d'Orbigny), Asano, 1956, Sci. Rep. Tohoku Univ. 27:32–4. pl. 5, figs. 28, 29.

Lenticulina peregrina (Schwager) in Cushman and McCulloch, 1950, Allan Hancock Pac. Exped. 6 (6) : 302. pl. 39. fig. 5.

Loxostomum karrerianum (Brady), in Brady, 1884. *Challenger* Foraminifera, p. 424, pl. 53, figs. 19–21: Asano, 1958, Sci. Rep. Tohoku Univ. 29:25–6, pl. 5. figs. 8, 9. (Two varieties were noted.)

Marginulina glabra d'Orbigny, Asano, 1956, Sci. Rep. Tohoku Univ. 27:13–4, figs. 11, 13, pl. 4.

Miliolinella vigilax Vella, 1957. N.Z. Geol. Surv. Pal. Bull. 28:37–8, pl. 9, fig. 183–4.

Nonion flemingi Vella, 1957, N.Z. Geol. Surv. Pal. Bull. 28:37–8, pl. 9, fig. 183–4.

Nonion subturgidum (Cushman), in Cushman, 1939, U.S. Geol. Surv. Prof. Pap. 191:25, pl. 6, fig. 29.

Nonionella turgida (Williamson) in Cushman, 1939. U.S. Geol. Surv. Prof. Pap. 191:32–3, pl. 9, figs. 2, 3.

Notorotalia cf. *clathrata* (Brady) in *Challenger* Foraminifera, p. 709, pl. 107, figs. 8a-c; see also Barker. 1960, Taxonomic Notes.

Notorotalia inornata Vella, 1957, N.Z. Geol. Surv. Pal. Bull. 28:54, pl. 2, fig. 29; pl. 3, figs. 36, 38.

Notorotalia zelandica Finlay, 1939, Trans. Roy. Soc. N.Z. 68:518–9; *Notorotalia zelandica zelandica,* Vella, 1957, N.Z. Geol. Surv. Pal. Bull. 28:55, pl. 2, figs. 31, 33, 34.

Orbulina universa d'Orbigny, Bradshaw, 1959, Cush. Found. Foram. Res. Contr. 10 (2) :49, pl. 8, figs. 17, 18.

Patellina corrugata Williamson, in Brady, 1884, *Challenger* Foraminifera p. 634, pl. 86, figs. 1–7.

Patellinella inconspicua (Brady), in Brady, 1884. *Challenger* Foraminifera p. 357–8, pl. 42, figs. 6a, b, c; see Barker. 1960. Taxonomic Notes.

Pateoris cf. *hauerinoides* (Rhumbler). Loeblich and Tappan, 1953. Smithson. Misc. Coll. 121 (7) :42–5, pl. 6, figs. 8–12.

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MICROBIOLOGICAL STUDIES IN STIRLING BASIN, MILFORD SOUND

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Summary

The waters of Stirling Basin, Milford Sound, support an abundant heterotrophic bacterial population that is indicative of their high content of organic matter, most of which is probably terrigenous in origin. Aerobes outnumbered anaerobes throughout the water column, whereas in the sediments, the converse situation was apparent. Sulphate-reducing bacteria were observed at all sampled depths of sediments, which were generally of –ve Eh, but only in the bottommost Basin waters. All attempts to isolate photosynthetic purple or green sulphur bacteria (Thiorhodaceae) from Basin waters failed. Thiobacilli were isolated only from surface sediments where oxygenated waters overlay muds in which hydrogen sulphide was being liberated. On the whole, the microbiological data is consistent with the hydrological findings that at the time of sampling, the Basin waters were oxygenated throughout.

Based on published figures on oxygen uptake by multiplying marine bacteria and a mean aerobic bacterial density in the water, a figure for the overall bacterial oxygen uptake has been estimated at 13·1 ml oxygen per litre per year. This uptake due to bacterial oxidative processes in the water would require to be balanced by replenishment processes in order to prevent complete oxygen depletion below sill depth. The above figure includes neither the oxygen consumption by bacteria in the sediments, nor the respiratory activities of the benthic and pelagic fauna. On the other hand, if the organic material undergoing decomposition in Stirling Basin is of a refractory nature, it would contribute to a lower biochemical oxygen demand than the figure indicates.

INTRODUCTION

The activities of micro-organisms within the sediments and overlying waters of fiords and marine basins have been the object of many studies since Zelinski (1893) first demonstrated sulphate-reducing bacteria from bottom muds in the Black Sea. More recent investigations such as those of Norwegian fiords (Strom, 1936), the Black Sea (Kriss, 1959), and marine basins off the coast of southern California (Emery and Rittenberg, 1952) have considered the morphological and hydrological factors leading to the stagnation or ventilation of waters within such areas and the influence of these factors upon the type and extent of bacterial activity, which itself has an important bearing upon the diagenesis of sediments and the characteristics of the overlying water.

The chief features of a marine basin with a restricted intake of dissolved oxygen and an abundant supply of terrestrial organic material have already been outlined in the Introduction (Skerman, 1964, pp. 11–12). Bacterial oxidation of this organic matter by aerobic and facultative heterotrophs as it sinks to the bottom is primarily responsible for a loss of oxygen from the water. Similar oxidation processes in the sediments further deplete the oxygen in the interstitial and overlying water with concomitant lowering of oxidation-reduction potentials which may eventually fall to a level at which sulphate-reducing bacteria become active. Hydrogen sulphide so formed in the sediments may diffuse upwards into the water where its abiogenic oxidation causes even further depletion of dissolved oxygen and conditions may become anaerobic.

A great many secondary reactions, catalysed by bacteria, are largely dependent upon these initial changes (involving Eh, pH, total organic content) which themselves are brought about by organic activity. As pointed out by Emery and Rittenberg (1952), the various microbial groups responsible for many such biochemical processes are almost universally distributed in most types of sediment and unfortunately their isolation and enumeration may contribute little to an understanding of the particular environment. However, due to the unique characteristics of some marine fiords, certain microbial groups may flourish as a consequence of the introduction of large quantities of organic material and the presence of hydrogen sulphide.

The anaerobic depths of the Black Sea, which contains no free oxygen at depths below some 200 m, have attracted the attention of many microbiologists. Issatchenko (1924) found numerous sulphate-reducing bacteria in the deeper waters and particularly in the sediments, while photoautotrophic purple sulphur bacteria have been observed by Kriss and Rukina (1953). Recently, Kriss (1959) has discussed the presence of certain filamentous bacteria, whose abundance is so great that their total biomass throughout the hydrogen sulphide zone of the Black Sea exceeds that of the phyto- and zooplankton in the oxygenated upper zone. Kriss considers these to be autotrophic purple sulphur bacteria.

Chemosynthetic autotrophs of the *Thiobacillus* group have also been reported from the Black Sea. ZoBell (1946) recorded that Ravich-Sherbo (1930) found large numbers of *Thiobacillus thioparus* in the zone where oxygenated surface water merged with deeper layers containing H_2S. Issatchenko and Egorova, (1939), however, were unable to demonstrate such bacteria in samples they took from these boundary layers.

The limited time on *Tui* cruise to Milford Sound precluded any exhaustive survey of microbial populations present, or the physico-chemical properties of water and sediments influenced by their activity. The opportunity was therefore taken to assess the abundance of general heterotrophic bacteria throughout the water and sediments, to determine the organic content, Eh and pH of sediments, and to search for the presence of several groups of micro-organisms whose activity may be expected to be manifested under anaerobic conditions of a poorly ventilated fiord. Upon the consideration of the results so obtained, it is hoped that further investigations might be planned.

METHODS

Sampling

Water samples were collected from various depths using a "J—Z" apparatus (ZoBell, 1941) with rubber bulb aspirators. Sediment samples were taken from cores obtained by piston (2 in. diameter) and gravity ($1\frac{3}{8}$ in. diameter) corers.

Samples were processed in the ship's laboratory immediately after collection. After measuring the lengths of cores, the plastic liners were cut at 1 ft intervals from the uppermost mud layers and from each section so exposed 1 g quantities of sediment were isolated aseptically from radially central positions and transferred to plugged tubes containing 9 ml of sterile sea water. These sediment suspensions and the water samples from the Sound were used at once for inoculating selective media and dilution series.

From each of the 1 ft sections of one 8 ft core (Station A 321) two sediment subsamples were taken, one for subsequent analyses of organic carbon and nitrogen, and the second for measurements of pH and Eh. The latter determinations were made with a PYE "Universal" pH and millivoltmeter (using glass and platinum electrodes with a calomel reference electrode) as soon as the temperature of the freshly collected mud samples had reached equilibrium with the air in the laboratory.

For rough estimations of the abundance of general aerobic and anaerobic heterotrophic bacteria and of sulphate-reducing bacteria in waters and sediments, serial dilution methods in appropriate media were used. For autotrophic forms (thiobacilli, photosynthetic purple and green sulphur bacteria), 0·1 g and 1 g quantities of sediment and 1 ml volumes of water were inoculated directly into screw-capped bottles containing appropriate enrichment media.

Media

The following media were used:

(a) For general aerobes: ZoBell's Medium 2216 E (Morita and ZoBell, 1955).
(b) For general anaerobes: Above medium with 1 g sodium formaldehydesulphoxylate per L.
(c) Sulphate reducers: ZoBell's Medium M 10 E (Morita and ZoBell, 1955).

The above media were previously dispensed and sterilized at 120°c for 30 min in 1 oz screw-capped tubes. After their inoculation in decimal dilution series, tubes for the culture of anaerobes and sulphate reducers were filled to capacity with sterile medium and tightly sealed.

(d) Thiobacilli:

(i)	g
$(NH_4)_2SO_4$	0·1
K_2HPO_4	2·0
$MgSO_4 \cdot 7H_2O$	0·1
$CaCl_2$	0·1
$FeCl_3 \cdot 6H_2O$	0·002
$MnSO_4 \cdot 4H_2O$	0·02
NaCl	24·0
$Na_2S_2O_3 \cdot 5H_2O$	10·0

Distilled H_2O to 1 litre
pH 6·8

(ii)	g
NH_4Cl	0·1
KH_2PO_4	3·0
$MgCl_2 \cdot 6H_2O$	0·1
$CaCl_2$	0·1
$Na_2S_2O_3 \cdot 5H_2O$	5·0
NaCl	24·0

Distilled H_2O to 1 litre
pH 3·5

These media were dispensed in 1 oz screw-capped tubes and sterilized by steaming for 1 h on three successive days. After inoculation either with 0·1 g or 1 g quantities of mud samples, or with 1 ml water samples, caps were lightly replaced and tubes incubated in the dark.

(e) Photosynthetic sulphur bacteria:

(i) Green sulphur bacteria:

Larsen's medium (Larsen, 1952) with 3 per cent NaCl and 1 g/L $Na_2S{\cdot}9H_2O$. pH7·3

(ii) Purple sulphur bacteria:

Above medium with 0·3 g/L $Na_2S{\cdot}9H_2O$. pH7·5

After inoculation with either water or mud, the 1 oz tubes were completely filled with sterile medium, sealed, and on return to the laboratory incubated before three 30-watt fluorescent lights at 18–20°C.

All inoculated tubes were stored on board the ship for one week during the remainder of the cruise. Incubation was continued at 20°C ashore for a further two weeks, when tubes were examined for growth on the basis of increased turbidity in comparison with uninoculated controls. As there is evidence that the time lapse between inoculation and the first sign of development in media may be extremely protracted in some groups of bacteria (Emery and Rittenberg, 1952; Kriss, 1959) incubation of negative tubes was continued for six months after the first inspection. Loopfuls of the well shaken contents of all tubes were examined under a phase contrast microscope to check positive cultures for the presence of living bacteria.

RESULTS

Basin Waters

The abundance of aerobic and anaerobic heterotrophic bacteria, and of sulphate-reducing bacteria from the water profiles at Stations A 320 and A 328 is summarised in table 1. Estimates of numbers of bacteria per ml are expressed as logarithms of the reciprocals of the highest dilutions showing growth (after ZoBell, 1955): Thus the index

1 = at least 10, but less than 100 bacteria/ml.

2 = at least 100, but less than 1,000 bacteria/ml.

TABLE 1. ABUNDANCE OF AEROBIC, ANAEROBIC, AND SULPHATE-REDUCING BACTERIA PER ML AT DIFFERENT DEPTHS OF WATER AT STATIONS A 320 AND A 328. (Expressed as log. nos. of the reciprocals of the highest dilution showing evidence of growth)

	Sta. A 328: Water Depth 270 m.			Sta. A 320: Water Depth 216 m.		
Depth (m)	Aerobes	Anaerobes	Sulphate Reducers	Aerobes	Anaerobes	Sulphate Reducers
50	6	3	0	5	4	0
150	5	4	0	7	6	0
200	..	..	..	4	6	0
250	6	3	2	..	..	..

In general terms, the indicated numbers of heterotrophic bacteria ranged from 1,000 to 10^7 per ml of water, there being a greater quantitative response to aerobic than to anaerobic culture. It is probable, that many bacteria present in the water were facultative forms capable of growth under either set of conditions. The demonstration of sulphate reducers in waters close to the bottom of the basin at Station A 328 in numbers ranging between 100 and 1,000 per ml is in conflict with data on the dissolved oxygen content of waters at these depths (5 ml/l, Garner, 1964, pp. 25–33). These obligatory anaerobic forms may have been carried upwards from bottom sediments disturbed by currents or, alternatively, they may have been distributed in the water strictly locally in association with particles of decaying organic material where the immediate environment was of such a reducing nature that sulphate reduction could take place. There was no detectable odour of H_2S in water samples taken from these depths at this station.

Basin Sediments

Tables 2 and 3 summarise the quantitative data obtained on the occurrence of bacteria in sediments throughout the cores from Stations A 319 and A 321.

TABLE 2. ABUNDANCE OF AEROBIC, ANAEROBIC, AND SULPHATE-REDUCING BACTERIA PER GRAMME (WET WEIGHT) OF SEDIMENT THROUGHOUT THE CORE FROM STATION A 319. (Log. reciprocals of highest + ve dilutions)

Sta. A 319: Water Depth 270 m

Core Depth cm (Total length = 35 cm)	Aerobes	Anaerobes	Sulphate Reducers
2	6	7	5
10	5	6	3
20	3	7	3
30	0	5	2

Contrasting the situation in the overlying waters, anaerobes generally exceeded aerobes in abundance throughout sediments of both cores, in which highest numbers of bacteria were found in the topmost 2–3 cm of sediment. Sulphate reducers were commonest in the uppermost layers of mud, occurring only sporadically below a core depth of 3 ft. It may be seen from the Eh data (table 3) that sediments of this core were of a markedly reducing nature only below the surface layers.

Cultures of water and sediment samples set up for photosynthetic purple and green sulphur bacteria failed to give any positive response even after prolonging incubation for six months. Good growth of thiobacilli developed in liquid cultures, with strong pellicle formation, after two to three weeks incubation of all samples inoculated with surface muds. No such growth appeared in tubes inoculated with water samples, or with sediments from deeper sections of the cores. As a check on methods for the photosynthetic forms, the same media were inoculated with samples of reducing black sulphide muds from shallow areas of Wellington Harbour, with positive results for both groups.

Microscopic examinations of wet mounts of sediments by phase contrast showed that morphologically, rod-shaped forms were the most abundant. Spirilli were common, but coccal forms were few. Fungi commonly appeared in cultured dilutions of mud samples. Their absence from control tubes inoculated with sterile sea water suggests that they may have developed from spores associated with deposited plant material rather than as laboratory contaminants.

TABLE 3. pH AND Eh CHARACTERISTICS, ORGANIC CONTENT PER GRAMME DRY WEIGHT AND ABUNDANCE OF AEROBIC, ANAEROBIC, AND SULPHATE-REDUCING BACTERIA PER GRAMME (WET WEIGHT) OF SEDIMENT THROUGHOUT THE CORE FROM STATION A 321. (Log. reciprocals of highest + ve dilutions)

Sta. A 321: Depth 274 m.

Core Depth (total length 8·5 ft)	Aerobes	Anaerobes	Sulphate Reducers	Eh (mv)	pH	Org. C. (%)	Org. N. (%)
1 in.	6	6	5	000	7·2	3·7	..
1 ft	3	5	3	−100	7·4	1·7	0·11
2 ft	2	5	0	−100	7·3	1·9	0·11
3 ft	2	5	3	..	..	0·7	0·07
5 ft	3	3	2	−120	7·3	1·6	0·11
6 ft	3	4	0	−100	7·3	1·8	0·12
7 ft	2	3	2	−190	7·5	1·7	0·12
8 ft	0	1	0	−180	7·4	1·9	0·12

DISCUSSION

From consideration of the data a number of points may be established as a basis for discussion.

1. It is evident that the waters of Stirling Basin support an abundant heterotrophic bacterial flora. Despite the well known limitations of the dilution method of quantitative estimations and other difficulties of cultural technique in providing general purpose media, it may be assumed that the estimates given represent minimal numbers of bacteria present in the samples. In comparison with the incidence of bacteria in oceanic and most off-shore waters (see, for instance, ZoBell, 1946), these are greater by several orders of magnitude, and infer the presence of a relatively high content of organic matter in Basin waters.

2. No discernable evidence of free hydrogen sulphide in Basin waters was found. Sulphate-reducing bacteria, though abundant in samples of surface sediment, were demonstrated in the water only at depth close to the bottom; even then the extent of their activity *in situ* must remain in doubt. Under the oxygenated conditions that prevailed in Basin waters at the time, it is likely that any H_2S liberated either as a result of localised

bacterial sulphate reduction, or from the proteolytic degradation of plant debris, would be abiogenically oxidised almost as fast as it formed.

3. Photosynthetic sulphur bacteria, which might be expected to thrive in an anaerobic environment in the presence of H_2S and adequate illumination, could not be demonstrated from Basin water samples. Aerobic thiobacilli, some species of which oxidise H_2S to sulphur and sulphuric acid, could be demonstrated only in samples of surface sediments. This finding is interpreted as a reflection of the oxygenated state of bottom Basin waters overlying the predominantly reducing muds.

The dissolved oxygen status of Stirling Basin subsurface waters will represent the net balance between the supply (by all circulatory processes) and the overall consumption in the respiration of animals and in the bacterial oxidation of organic material. Two major factors influencing the rate and kind of bacterial activities in Basin waters will be the supply and nature of organic material, and the existing oxygen content. It may be assumed that the greater proportion of organic matter of these waters is of terrigenous origin, having been carried in by the rivers and waterfalls discharging into the upper regions of the Sound. Deposition of organic material derived from phytoplankton – the ultimate source of organic matter within sediments of the open oceans – is unlikely to be great in the Sound because the turbidity of surface waters probably imposes a heavy restriction on the penetration of light, a condition that may persist throughout much of the year. Some marine organic material would, of course, be introduced into Basin waters during the occasions when the latter are renewed from the open sea. Of the plant fragments, litter, and soil organic matter composing the bulk of the organic material entering the Basin, some will be borne directly seawards within the surface low density waters, while the heavier fractions will sink to deeper regions below sill depth. Microbial decomposition of this sinking material will be enhanced in the presence of free oxygen which will favour the growth and rapid reproduction of heterotrophic aerobes. The greater the depth of water through which the organic debris has to sink, the longer will it take to reach the bottom and generally, the more advanced will be its oxidation. On reaching the Basin floor, the decomposition and transformation of organic matter will again be favoured in the presence of oxygen in the overlying waters. Some oxygen may pass into the sediments by diffusion, and the benthic organisms present (Hurley, 1964, pp. 79–89), apart from their capacity to ingest and break down organic detritus, may in the course of their scavenging activities turn over and mix surface sediments, thereby bringing buried organic material in contact with the oxygenated waters above.

In laboratory experiments, ZoBell (1940) showed the rate of oxygen consumption of active bacteria in sea water to be independent of the oxygen tension within the range between 0·31 and 12·74 ml/l, but that the oxygen consumption decreased when the amount of oxidisable organic matter present became a limiting factor. It was shown in his experiments that the bacterial oxidation of complex organic substances such as lignoproteins proceeded only slowly, the oxygen consumption being much slower than when asparagine or glucose were being utilised, but the rate of oxygen uptake was again found to be independent of observed oxygen tensions in excess of 0·4 ml/l.

In view of the possibility of the waters of Stirling Basin below sill depth periodically becoming isolated from off-shore circulation, information on the rate of oxygen uptake by bacteria is desirable. ZoBell (1940) estimated that marine bacteria multiplying in sea water consumed an average of 15×10^{-12} ml oxygen per cell per hour at 22°c. This consumption was found to be increased nearly four times when the sea water was enriched with 0·05 per cent glucose or asparagine. Taking 10^6 as the mean number of aerobes per ml of water in Stirling Basin and by assuming a metabolic activity at 5°c 1/10 of that at 22°c, the daily oxygen consumption would be (15×10^{-12}) $(10^5) \times 24$, or approximately $3{\cdot}6 \times 10^{-2}$ ml per litre of water. Assuming that the active bacterial population in Basin waters remains constant throughout the year, this would amount to an uptake of 13·1 ml oxygen per litre per year, which would have to be replenished either continually or periodically by diffusion, convection, or exchange processes in order to prevent oxygen depletion below sill depth. The above estimate includes neither the oxygen consumption by bacteria in the bottom sediments nor the respiratory activities of the benthic and pelagic fauna, but ZoBell (1940) concluded that the oxygen uptake of marine animals is probably much less than that of an equivalent mass of bacterial cells. It is further probable that the organic material undergoing decomposition in Stirling Basin has a high proportion of less readily oxidisable constituents, and this would contribute to a lower biochemical oxygen demand than that indicated by the above figures.

The surface, and other finer textured layers of sediment from the core examined, were darkish-grey in colour. This suggested the presence of iron sulphide minerals, formed as a result of sulphate reduction in zones of negative Eh where organic material was being rapidly deposited. The organic analyses (table 3) show the greatest organic carbon content was in surface sediments, viz, 3·7 per cent, while values were considerably lower in the deeper sections, viz, 0·7 to 1·9 per cent. These figures roughly correspond to an organic matter content of 6·6 per cent for the surface sediment and an average of 3·4 per cent between core depths of 1 and 8 ft, using a conversion factor of 1·8 (Trask, 1955). These quantities of organic matter are much lower than the majority of those given by Strom (1936) for sediments of the poorly ventilated Norwegian fiords he examined, where in some cases of extreme stagnation of the deeper waters, sediments were found to have an organic carbon content of up to 23·4 per cent. The relatively low figures for the percentage organic content of the single core examined from the Stirling Basin are at variance with the observations of other authors (Bruun *et al.*, 1955, Pantin, 1964, pp. 35–47, and Hurley, 1964, pp. 79–89) all of which describe numerous plant fragments as being conspicuous features of dredge and grab samples.

In view of this, the analyses of the organic carbon content of the single core examined appear anomalously low; some consideration should be given to the possibility of this being an atypical sample. Pantin (1964, p. 44) notes that sediments of Stirling Basin varied from coarse sand to fine sandy mud with plant fragments being almost exclusively associated with the latter. He suggests that the presence of sand lenses in the sediments may have arisen from rapid sedimentation following the periodic slumping of material accumulated in the vicinity of the mouths of inflowing rivers and streams bordering the Basin. In general, due to their relatively high permeability, coarse sediments tend to have a low content of organic matter; further, their rapid deposition, as in the case of typical nearshore sediments, would lead to a high clastic dilution of settling organic material with the result that percentage carbon contents may be low. Irregular patterns of various sedimentation processes throughout the Basin could, therefore, contribute to wide differences in certain properties between core samples.

At the time of the *Tui* cruise the waters of Stirling Basin were oxygenated throughout its depth, the least dissolved oxygen content being 5 ml/l, representing a difference from saturation value of 83 per cent (Garner, 1964, p. 27). The abundance of benthic metazoans (Hurley, 1964, pp. 79–89) further suggests that a state of complete oxygen depletion in bottom waters does not occur frequently. Although the observations of Emery and Rittenberg (1952) show that some bottom-living scavengers within marine basins may continue to exist at very low oxygen tensions, the low redox potentials of Stirling Basin sediments close to the surface (just how close was often difficult to measure due to the semifluid nature of the uppermost material of core samples) suggests that the benthic fauna may be living a precarious existence almost in contact with muds in which H_2S is being liberated. The evidence implies, therefore, that either the total oxygen uptake is never great enough to exhaust all oxygen in Basin waters during the interval between occasions of renewal with off-shore water, or, if no renewal occurs, other processes of diffusion, lateral water movement and mixing are sufficiently active to maintain an oxygenated status in waters below sill depth.

It is self evident that many more data than at present available are necessary for a full appraisal of those processes, in which microbial activities are concerned, that have a direct bearing on the physico-chemical characteristics of Milford Sound waters and sediments. It would, for instance, be especially desirable to have details on both the amount and chemical nature of organic material entering the Sound and being deposited in the sediments, and on any seasonal or short-term fluctuations involved. Seasonal variation in rainfall may have far-reaching effects in that any periodic reduction of inflowing fresh turbid waters may permit increased light penetration and consequently photosynthetic activity which would serve to augment the dissolved oxygen content of Basin waters.

Of further importance to phytoplankton populations within the Sound are the nutrient cycles in which the bacteria are intimately concerned. The liberation of ammonia by micro-organisms in the breakdown of nitrogenous organic matter must take place in both the waters and sediments of Stirling Basin. Assuming that reducing conditions are characteristic of all the sediments, oxidation of this ammonia to nitrite and ultimately nitrate by obligatory aerobic *Nitrobacteriaceae* will, however, be possible only in the waters. As the liberation of ammonia from organic matter may be expected to be greatest in the bottom sediments, microbial nitrification is probably most active in the immediately overlying water. If deep-water circulation in the Basin is suppressed under conditions of stable density stratification, the replenishment of nitrate and other nutrients in the euphotic zone from these deep regions thus enriched would be inhibited: and in addition to the effects of low surface salinities and high turbidities, phytoplankton populations may become relatively impoverished also as a result of a depletion of available nutrients. On the other hand, any convective or turbulent process leading to a vertical mixing of Basin waters would supply the upper layers with these substances, which then may or may not accumulate according to the density and activity of phytoplankton. Analyses for nitrate nitrogen to determine any gradient throughout water profiles in the Basin may therefore be of considerable value in indicating the rate of mixing between deep and overlying waters.

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TRANSFORMATIONS OF SULPHUR COMPOUNDS IN THE SEDIMENTS OF MILFORD SOUND

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Summary

As part of a wider investigation of the variations in the ratios of the stable isotopes of sulphur in nature, analyses have been made of sulphur compounds present in samples originating from the waters and sediments of Milford Sound. In the sediments, three types of sulphur compounds were evident: sulphate, acid volatile sulphide, and a fixed sulphide. The results indicate that sedimentary sulphate shows a consistently higher ^{32}S content than does sea water sulphate. This is interpreted as being a consequence of a re-oxidation, in surface sediments, of ^{32}S-enriched sulphate. This sulphate then serves to dilute any ^{34}S-enriched sulphate to yield finally a sulphate that is slight enriched with ^{32}S with respect to that of sea water. Supporting evidence for this explanation from pH, redox and microbiological data is discussed.

INTRODUCTION

Since the classical review by Strom (1936), on the characteristics of the Norwegian fiords, it has often been considered that such environments are highly euxinic. However, Fleming and Revelle (1939) in summarising the work on Norwegian fiords, estimated that of the total studied, 44 were stagnant while 41 were not. Little extensive work has been done on such environments from other localities, although the work on the Canadian fiords by Tully (1949) does not indicate highly reducing conditions in the bottom waters.

The results obtained from Milford Sound further show that stagnation is not a phenomenon common to the bottom water of all fiords. It can be seen from the data presented by Garner (1964, pp. 25–33) that the surface water was saturated while the bottom water was only slightly depleted in oxygen. The bacteriological studies of Skerman (1964, pp. 65–71) further suggest that anaerobic conditions do not exist in the water, because of the scarcity of sulphate-reducing bacteria, which are obligate anaerobes. No sulphide could be detected by smell during the course of collecting water samples.

The sediments on the other hand were dark or black, and on the whole reducing. Free hydrogen sulphide could be detected in some core samples and could be liberated in others by the addition of dilute hydrochloric acid. We therefore have the conditions of an oxidising environment in the water, overlying a reducing environment in the sediment.

This is important from a paleo-ecological point of view, since the sediment would probably be converted into a black shale or mudstone and might be thought to indicate stagnation. However, the sediment would also contain many highly aerobic organisms formerly living at the oxygenated mud-water interface.

Because of the high rainfall in this region – more than 250 in./annum – erosion is a dominant process. The high relief aids in the rapid transport of rock debris to the fiord, and sediments are thus brought into the basin in large quantities, where they are rapidly deposited. The abundant bush cover on the lower mountain slopes, in combination with the high rainfall and rapid erosion, give rise to large quantities of organic matter which are deposited with the sediments in the basin. The relatively low organic content of the mud, as indicated by Skerman's results, suggests that a rapid decomposition occurs.

The anomalous condition of an oxidising surface water and a reduced mud indicates that a rapid renewal of water across the sill introduces

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oxygen into the basin; while a rapid biological decomposition of the organic matter results in a depletion of oxygen and production of reducing conditions in the sediment. These conditions are preserved by a continual inflow of detrital material which bury the older sediments.

RESULTS AND DISCUSSION

Although the oxygen analyses represented in Garner's data show saturation at the surface and only relatively small decreases with depth, the oxidation reduction potentials given in table 1 for the water samples are not high. By comparison with the results given by Baas Becking, Kaplan and Moore (1960) it can be seen that the redox potentials are somewhat lower than the average for sea water. This appears to confirm the contention of the above-named authors that the oxygen content *per se* does not control the E_h of sea water. It is possible that the terrigenous organic matter and the relatively unweathered detrital material supplied in large quantities have the effect of poising the water at a lower potential. The pH was slightly lower than in normal sea water, but this is not unexpected in view of the large quantities of fresh water continuously brought in.

TABLE 1. pH AND OXIDATION-REDUCTION POTENTIALS (EH) OF WATER SAMPLES

Station No.	Depth in Metres	Eh	pH
A 324	0	−240	6·8
	25	+210	7·8
	50	+130	8·0
	100	+150	7·8
	150	+255	7·8
A 325	0	+240	8·0
	25	−240	8·0
	50	+230	8·0
	100	+270	7·9
A 326	0	+280	8·0
	25	+300	8·0
	50	+190	7·9
	80	+180	8·2
A 328	0	+180	8·0
	25	+250	7·7
	50	+240	8·1
	100	+230	7·8
	200	+240	8·0
A 329	0	+210	7·9
	25	+240	8·0
	50	+230	7·9
	100	+200	7·7
	200	+220	7·7

The results in table 2 show that the sediments were moderately reducing. Since the sediments were coarser than in most basins, as can be judged by their low water content, there is probably a continuous exchange between the interstitial water and the overlying water. This would prevent the formation of highly reducing conditions. The dried sediment is dark grey in colour due to a high proportion of black hornblende grains, but is almost black when freshly collected, probably due to the presence of hydrotroilite. The low pH value relative to the overlying water may indicate biological activity resulting in the release of CO_2 and organic acids, as well as cation exchange (cf. Baas Becking *et al.* 1960). The unweathered detritus may undergo rapid diagenesis leading to the release of Mg or Ca and the uptake of the more alkaline K during clay mineral formation.

The analyses of sulphur compounds in the sediment, though incomplete, serve to demonstrate that essentially three types of sulphur compounds are present – sulphate, acid volatile sulphide, and a fixed sulphide. Elementary sulphur could not be detected. On the whole the finer sediments contained the most volatile sulphide.

Four samples were used for isotope analyses. These represent surface sediments from Stations A 319 and A 329 and the water overlying them.

The results given in table 3 show that the isotope ratios for the sea-water sulphate fall very close to the average of 21·76 given by Ault (1959). The slightly higher ratio for sample R240/1, Station A321, may in part be due to experimental error in the measurement and partly to the influence of intermixing with fresh water, since the area in which this restricted basin lies has an annual rainfall of 270 in. and a very high run-off rate into the fiord. The influence of fresh water may also be reflected in the somewhat lower sulphate content for this sample.

The sulphate in the sediments shows a consistently higher S^{32} content than that in the sea water. This cannot be explained on the basis of sulphate reduction, since in that case there would be an enrichment of S^{34}. Here again, as in other natural environments described by Kaplan, Rafter and Hulston (1960), it would appear that a reoxidisation of sulphide is occurring with the formation of a sulphate enriched in S^{32}. This sulphate dilutes the S^{34} rich sulphate. This process should occur only at the surface, where a sufficiently high oxygen tension is present. On this assumption, an increase with depth down a sediment profile should produce sulphate correspondingly increasing in S^{34} content. This suggestion of sulphate formation by hydrogen sulphide oxidation is also reflected in both a higher oxidation reduction potential as well as a higher isotope ratio in sample R240/5, Station A 329. The presence of *Thiobacillus* demonstrated by Skerman (1964, pp. 65–71) in surface muds support these conclusions.

TABLE 2. SOME CHEMICAL CHARACTERISTICS OF THE SEDIMENTS OF MILFORD SOUND

Station No.	Depth below Surface cm	Eh (mu)	pH	H_2O Content (Wet Weight of Sediment)	Total S (Percentage Dry Weight of Sediment)	$SO_4^=$ (Percentage Dry Weight of Sediment)	Volatile $S^=$ total (Percentage Dry Weight of Sediment)	Combustible $S^=$ (Percentage Dry Weight of Sediment)	Description
A 319 ..	0-10	−100	7·20	45·0	..	..	..	..	..
	10–20	000	7·20	41·7	..	..	..	..	..
	20–30	−130	7·30	42·0	..	..	..	..	Slight smell H_2S.
	dredge	−100	7·20	49·8	·218	·280	·080	·041	
A 319 ..	0–10	−200	7·20	37·8	..	..	·012	..	Slight smell H_2S coarse sediment.
A 319 ..	0–20	−070	7·40	47·1	..	..	·031	..	
A 324 ..	grab	−040	7·20	43·4	·152	·245	·014	·025	..
A 328 ..	106·7–137·2	−120	7·30	36·7	..	..	tr.	..	..
	137·2–152·4	−140	7·30	37·0	..	..	tr.	..	..
	152·4	−120	7·30	35·4	..	..	tr.	..	..
A 328 ..	dredge	000	7·15	..	..	..	..	..	..
A 329 ..	grab	015	7·10	44·25	·219	·262	·061	·069	Slight smell H_2S.
A 321 ..	0–30·5	000	7·20	39·0	..	..	·018	..	..
A 321 ..	0–2·5	000	7·20	37·2	..	..	·005	..	..
	30·5–61·0	−100	7·40	36·6	..	..	·006	..	Slight smell H_2S.
	61·0–91·4	−100	7·30	..	..	..	..	..	..
	132·1–152·4	−120	7·30	31·4	..	..	tr.	..	..
	152·4–184·9	−100	7·30	34·6	..	..	·003	..	..
	184·9–213·4	−190	7·50	34·6	..	..	·002	..	..
	213·4–243·8	−180	7·40	39·4	..	..	·003	..	..

TABLE 3. SULPHUR ISOTOPE FRACTIONATION IN THE BOTTOM WATER AND SURFACE SEDIMENTS

Station No.	Lab. No.	Sample Description	$SO_4^=$		Acid Volatile $S^=$		Combustible $S^=$	
			Per Cent*	S^{32}/S^{34}†	Per Cent	S^{32}/S^{34}†	Per Cent	S^{32}/S^{34}†
A 321 ..	R 240/1	Bottom sea water .. .. $SO_4^=$ only form of sulphur	·234	21·80	..	..	..	..
A 319 ..	R 240/2	Bottom sea water .. .. $SO_4^=$ only form of sulphur	·268	21·75	..	..	..	..
A 319 ..	R 240/3	Surface sediment .. .. $\Sigma S^= \; 0{\cdot}218\%$ $S^{32}/S^{34} = 22{\cdot}47$	·280	21·86	·080	22·92 % enrich 4·62 (wrt $SO_4^=$)	·041	22·78 % enrich 4·04 (wrt $SO_4^=$)
A 329 ..	R 240/5	Surface sediment .. .. $\Sigma S^= \; 0{\cdot}219\%$ $S^{32}/S^{34} = 22{\cdot}39$	·262	21·99	·061	22·83 % enrich 3·68 (wrt $SO_4^=$)	·069	22·86 % enrich 3·80 (wrt $SO_4^=$)

* Sulphur contents calculated as weight/volume in water and weight/weight of dry sediment.

† All isotope ratios are calculated from the New Zealand standard which has an S^{32}/S^{34} ratio of 22·10.

The isotope ratios for both the acid volatile and combustible sulphides (probably of the pyrite type as well as perhaps some other base metal sulphides) show an expected enrichment in S^{32}. The highest enrichment shown in table 3 is 4·62 per cent for the acid volatile sulphide of sample R240/3, Station A 319, with respect to the sulphate in this sample. This enrichment falls close to the value of 4·6 per cent found by Feely and Kulp (1957) for samples of sulphides and sulphates from the salt domes of Louisiana and Texas. Since bacterial sulphate reduction in this fiord is still active (Skerman, *op. cit.*), and no other reasonable explanation can be offered for the formation of such high concentrations of sulphides, we must conclude that fractionations of 4·6 per cent (or somewhat higher if based on the S^{32}/S^{34} ratio of $SO_4^=$ in sea water) can be attained by such biological systems, under suitable conditions. Such information will eventually be of use in calculating the number of sulphate-reducing bacteria in the sediment and the rate of water renewal in the basin, once reliable results become available from laboratory experiments on isotope fractionation during bacterial sulphate reduction. (cf. Kaplan, Emery, and Rittenberg, 1963.)

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A NOTE ON POLLEN DISTRIBUTION IN A CORE FROM MILFORD SOUND

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An examination has been made of the pollens in a core (A 321), taken in 142 fm in Stirling Basin, Milford Sound. The enclosing sediment is a sandy silt, containing abundant plant fragments.

Preparation of Pollen Samples

To dissolve out the mineral matter the samples were digested overnight in hydrofluoric acid and then boiled in hydrochloric acid. To reduce the organic debris they were then macerated with Schultz's solution followed by heating to boiling point in an acetolysis mixture (nine parts acetic anhydride to one part conc. sulphuric acid). After centrifuging in distilled water the sediment was mounted in glycerine jelly. Counting of pollen was continued until 100 specimens of the dominant tree pollen type had been noted.

Results

Pollen preparations from the samples were satisfactory only for the top part of the core, down to a depth of 132 cm. Below this the microfossil content was poor, consisting mainly of fern spores, a result which suggests differential preservation through oxidational decomposition of the pollen. In the part of the column which it was possible to examine, there was no significant difference in the proportions of the pollen types such as would suggest a change in the surrounding vegetation during the period of decomposition. This is shown by the proportions of the main pollen types in the following samples:

Table I

Lab. Number	L1335	L1340
Sample Number	3a	13b
Depth	20–25 cm	130–132 cm
Nothofagus menziesii	54%	47%
N. spp. (*N. cliffortioides?*)	25%	26%
Dacrydium cupressinum	6%	7%
Phyllocladus sp. (*P. alpinus?*)	5%	8%
Other conifers	10%	12%

Under these circumstances a detailed investigation was not attempted. The pollen and spore flora was not rich but included a slightly higher than average representation of ferns and monocotyledons.

Table 2 lists the pollen types noted in the present instance and by Dr R. A. Couper (manuscript report in N.Z. Geological Survey records) in samples from a 30 cm core at a depth of 290 m, taken by the *Galathea* expedition in 1951. (*Galathea* Station 608.)

Discussion

Of 54 pollen/spore types, 21 (39 per cent) represented endemic species and a high proportion (72 per cent), whatever be the reason, represent species of the bog and swamp flora, nearly half of them bog-forest types presumably from vegetation higher up. A few represent species not reported in a botanical survey of the Caswell and George Sounds District (Poole, 1951) and represent either local occurrences in the Milford Sound area or wind transport. There is a general similarity in the pollen flora from this locality and the locality of Dr Couper's samples except that in all but two of his samples, pollen of mountain beech predominated over that of silver beech.

Sedimentation in this area is presumably fairly rapid. Samples over a longer time range might have afforded interesting comparisons with pollen results from the Cameron Mountains area.

TABLE 2. LIST OF POLLEN AND SPORE TYPES IDENTIFIED IN SAMPLES FROM MILFORD SOUND

	RAC	WFH
Sphagnaceac		
Sphagnum sp.	*	*
Psilotaceae		
†*Tmesipteris tannensis* Bernh	*	
Lycopodiaceae		
Lycopodium billardieri Spring		*
L. fastigiatum group	*	
L. scariosum Forst. f.		*
Hymenophyllaceae		
Hymenophyllum sp.	*	*
Hymenophyllum scabrum A. Rich	*	
Dicksoniaceae		
†*Dicksonia fibrosa* Col.	*	
D. squarrosa Sw.	*	*
Cyathcaceae		
Cyathea colensoi (Hook.) Domin.	*}	
C. dealbata (Forst.) Swartz	*}	*
C. smithii Hook. f.	*}	
C. medullaris Forst. (Sw.)		*
Polypodiaceae		
Microsorium diversifolium (Wild.) Copel.	*	*
Dennstaedtiaceae		
Hypolepis sp.		*
Pteridaceae		
Histiopteris incisa (Thunb.) Smith	*	*
Paesia scaberula (Rich.) Kuhn	*	*
Pteridium aquilinum (L.) Kuhn var *esculentum* (Forst.) Kuhn	*	
Blechnaceae		
Blechnum sp.	*	*
Adiantaceae		
Adiantum sp.	*	
Pinaceae		
†*Cupressus* sp. (introduced)	*	
Taxaceae		
†*Dacrydium bidwillii* type	*	*
D. cupressinum Sol. ex Forst.	*	*
Phyllocladus sp.	*	*
Podocarpus dacrydioides Rich.	*	*
P. ferrugineus type	*}	*
P. totara type	*}	
Winteraceae		
Pseudowintera sp.		*
Chloranthaceae		
Ascarina lucida Hook.	*	*
Cruciferae	*	
†Chenopodiaceae	*	*
Polygonaceae		
Muehlenbeckia sp.	*	
Geraniaceae		*
Onagraceae		
Fuchsia sp.	*	*
Haloragidaceae		
Myriophyllum sp.	*	*
Myrtaceae		
Leptospermum sp.	*	*
Metrosideros sp.	*	*
Tiliaceae		
Aristotelia sp.	*	
Cunoniaceae		
Weinmannia racemosa Linn. f.	*	
Malvaceae		
Hoheria sp.	*	*
Fagaceae		
Nothofagus menziesii (Hook.) Oerst.	*	*
N. spp. (fusca group)	*	*
Araliaceae		
Nothopanax sp.	*	*
Umbelliferae	*	
Epacridaceae		
Dracophyllum sp.	*	*
Myrsinaceae		
Suttonia sp.	*	*
Rubiaceae		
Coprosma sp.	*	*
Compositae (Tubuliflorae)	*	*
Liliaceae		
†*Dianella intermedia* Endl.	*	
†Typhaceae		
Typha muelleri Rhorb.	*	
Smilacaceae		
Rhipogonum scandens Forst.	*	
Agavaceae		
Phormium sp.	*	*
Restionaceae	*	
Cyperaceae	*	*
Gramineae	*	*

†Not recorded in a botanical survey of the flora and vegetation of the Caswell and George Sounds District (Poole, A. L. 1951: Trans. roy. Soc. N.Z. 79 (1):62–83) and representing either a local occurrence or wind transport.

BENTHIC ECOLOGY OF MILFORD SOUND

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Summary

The benthic fauna of Milford Sound, New Zealand, is composed of two major communities, which differ according to the nature of the bottom and the topography of the Sound. At the entrance sill, there is a rocky bottom fauna, comparable with entrance still faunas found elsewhere in Fiordland, and in the main basin there is a muddy bottom *Echinocardium* community comparable with other New Zealand soft-mud communities, and similar, in depleted form, to that found at the Entrance Basin. There are also similarities to a Japanese *Lucinoma-Prionospio* occurrence. The biological evidence is not inconsistent with the possibility that an almost complete dying off of the fauna may occasionally occur in the inner basin with subsequent replenishment by pelagic larvae from outside. The fauna is generally similar to that recorded for other Western Southland fiords.

INTRODUCTION

During the New Zealand Oceanographic Institute investigations in Milford Sound, New Zealand, in January 1957, cone dredgings were taken at several stations along the length of the fiord to provide information on the benthic fauna (fig. 1, table 1).

Milford Sound has been shown by Bruun *et al.* (1955) to consist of an entrance basin mainly deeper than 60 fm extending from the fiord entrance as far as 2 miles out on to the continental shelf; an entrance sill 40–80 fm deep from the fiord entrance 1½ miles up towards its head; "a steep-walled, flat-floored depression occupying the midle third of the fiord" (Stirling Basin); and, at the head of the fiord, the Arthur-Cleddau Delta.

The biological dredgings were made at all except the outermost station in the Entrance Basin (Sta. A 325) where the first dredging was unsuccessful and time did not allow further attempts.

In this paper, discussion of the fauna has been mostly confined to the Mollusca, Brachiopoda, Polychaeta, and Echinodermata. It has not been possible to obtain identifications of all groups and although information on some groups of minor significance is available, lack of systematic revision in the groups concerned has prevented definite identifications for several species. Use has been made of some data from the Danish *Galathea* Expedition dredgings in Milford Sound, recorded in Dell (1956).

I am greatly indebted to the following for identification of material: Dr R. K. Dell, Dominion Museum, Wellington, (Mollusca and Brachiopoda), Professor H. B. Fell, Victoria

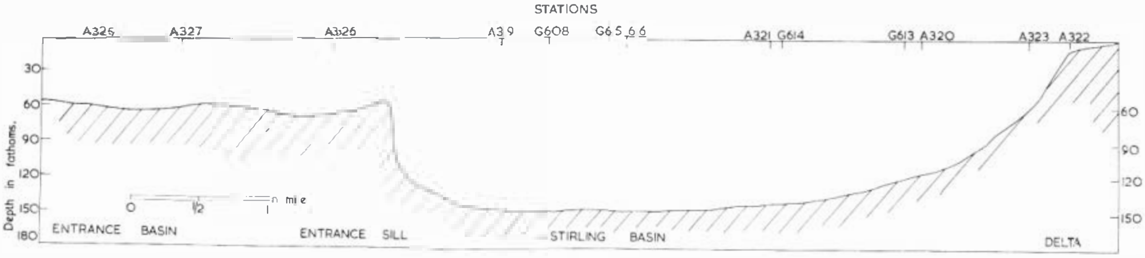

Fig. 1: Projected bottom profile along Milford Sound.

TABLE 1

Station	Date	Locality	Time		Depth (fm)	Samples Taken
			Start	Finish		
A 319	26/1/57	Outer end of Stirling Basin	1636		147	Peterson grab, cone dredge
A 320	27/1/57	Upper end of Stirling Basin centre between Sinbad Gulley and Bridget Pt. "near hostel" (DEH)	0630		116	Cone dredge
A 321	28/1/57	Centre Stirling Basin opposite Williamston Pt. "a little seaward of W'son Pt" (DEH)	0915		142	Cone dredge
A 322	28/1/57	Upper Stirling Basin on delta slope "farthest landward" (DEH)	1400		12–8	Cone dredge
A 323	28/1/57	Upper Stirling Basin	1430	1510	60	Cone dredge
A 325	28/1/57	Seaward of Dale Point	1641	1105	61	Cone dredge unsuccessful at position
A 326	28/1/57	Entrance Sill	1745	1830	64	Cone dredge
A 327	28/1/57	Dale Point. Position	1856		62	Cone dredge

University of Wellington (Echinodermata), Professor George A. Knox, University of Canterbury, Christchurch (Polychaeta), Dr J. C. Yaldwyn, Victoria University of Wellington (Decapoda), and Dr N. S. Jones, Port Erin Marine Biological Station, U.K. (Cumacea).

STATION OBSERVATIONS

N.Z.O.I. Station A 327 (62 fm).

At this station, between the Entrance Sill and the Entrance Basin, the bottom sediment was sandy mud, with numerous glass worm tubes (*Hyalinoecia* sp.), dead shells, a few sipunculids and a high proportion of twigs and wood, blackened after burial in the sediment. The ophiuroid, *Amphiura norae** Benham, was common and the echinoid, *Pseudechinus* sp., was noted. There were also fragments of the heart-urchin, *Echinocardium cordatum* (Pennant).

Dredging in the Entrance Basin itself (N.Z.O.I. Station A 325) proved unsuccessful.

N.Z.O.I. Station A 326 (64 fm).

On the Sill, at Station A 326, there was a marked change to muddy sand with much shell gravel, coral, and stones. Eighteen species of polychaetes were collected at Station A 327, and 11 at A 326, but only five were common to both stations. Of the polychaetes at A 326, only *Aglaophamus verilli*, *Glycera americana*, and a Maldanid species ocurred at any of the inner stations. The ophiuroid, *Amphiura norae*, was present with fragments of the hard-bottom inhabitant, *Evechinus chloroticus* (Val.), and of *Echinocardium cordatum*.

The live molluscs, *Nemocardium pulchellum*, *Cadulus delicatulus*, and *Divaricella huttoni* were important at Station A 327; at A 326 they were among the most common Mollusca, but all of the shells were empty. *Dentalium nanum*, present alive at A 327, was absent elsewhere although dead shells of *Dentalium suteri* were found at A 326. Live *Chlamys* sp. juveniles at A 327 were probably of the same species as an empty *Chlamys suprasilis crepusculi* from A 326.

N.Z.O.I. Station A 319 (147 fm).

There was a marked change in fauna from Station A 326 on the Sill to the deep Station A 319 in the middle of Stirling Basin. At A 319 *Echinocardium cordatum* was common and *Amphiura norae* was present. The sediment was sandy mud and contained many twigs and large brown leaves. Only two species of molluscs, *Uberella denticulifera* and *Cadulus delicatulus* were found alive, and both occurred at other basin stations farther up the fiord. The polychaetes at Station A 319 also showed affinities with the other basin stations, *Ninoe* sp., *Notomastus* sp., *Euclymene* sp., and *Terebellides stroemi* being present at one or other of the Stirling Basin stations while *Notomastus* sp., *Ninoe* sp., and *Melinna* sp. occurred at the Entrance Basin Station A 327. However, *Aglaophamus verrilli*, contrary to the general trend, occurred at both Stations A 319 and A 326 on Entrance Sill.

Dead *Nemocardium pulchellum* occurred at all of the Stirling Basin stations, except Delta Station A 322, whereas live *Cadulus delicatulus* were found at A 319, 320, and 323. This was the only

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*Now *Hemilepis norae* (Benham). See Fell, H. B. 1962: A Revision of the Major Genera of Amphiurid Ophiuroidea. *Trans. roy. Soc. N.Z. Zool. 2 (1)*: 1–26.

species found living at A 327 which was also found alive further inside the fiord. *Uberella denticulifera* was living at Stations A 319 and A 320, and dead shells were present at the intervening Station A 321, but the species was absent elsewhere.

N.Z.O.I. Station A 321 (142 fm)

The faunas at Stations A 321, 320, 323, and 322 were not dissimilar although A 321 was generally depleted compared with the other inner Basin stations. The soft-bottom dwelling *Echinocardium cordatum* was found at all stations except A 321, but while numerous individuals were taken at the inner stations, only fragments were found at A 326 and A 327. *Amphiura norae,* an ophiuroid which is also considered to be an indicator of soft bottom, was present at A 319, 326, and 327. The more important polychaetes, e.g., *Terebellides stroemi, Aglaophamus verrilli, Glycera americana,* also tended to appear at most of the inner Basin stations.

The quantity of sediment taken at Station A 321 was very small and had a predominant twig and leaf component. Two shrimps of a species new to New Zealand (Family Axiidae) were taken at A 321, and a further specimen at A 319.

All shells at A 321 were dead. The most predominant polychaete was *Cirratulus* sp., found in greater numbers at neighbouring Station, A 320.

N.Z.O.I. Station A 320 (116 fm)

Station A 320 yielded a larger quantity of sediment of slightly sandy mud with a fine twig and foliage component, but the faunal element was generally poor. *Echinocardium cordatum* was important (Fell, 1958), but the six species of live molluscs present were represented by only seven specimens. The most common polychaetes were *Cirratulus* sp., *Ninoe* sp., and *Scalibregma inflatum.*

Amongst the Mollusca, *Nucula hartvigiana* and *Solemya parkinsoni* occurred alive at inner Basin Stations A 320 but were missing from A 326 and A 327; *Tecticrater ("Cocculina") cervae,* which was found alive at A 320, was taken dead in quantity at A 326; *Cuspidaria fairchildi,* alive at A 320, was dead at A 327.

N.Z.O.I. Station A 323 (60 fm)

The sediment here was sandy mud with a high percentage of wood, twig, and leaf. The leaves were a green or brown colour, obviously of more recent origin than those found at deeper stations. *Echinocardium cordatum* was again present, and flatworms made an appearance. Only four species of polychaetes and three of molluscs were found, but two of the latter, *Cadulus delicatulus* and *Solemya parkinsoni,* were living.

N.Z.O.I. Station A 322 (8–12 fm)

The shallow Station A 322 was characterised by numerous small heart urchins (*E. cordatum*), an absence of molluscs, and nine species of polychaetes. Four species of polychaetes did not occur elsewhere, and seven were present only inside the Entrance Sill. The sediment was sandy mud, with a high proportion of twigs and green leaves. The absence of molluscs may have been due to the small size of the sample, but Fleming (1950) noted that "the littoral faunas of the inner sounds (where the profile allows of their development) are poor in species". Amphipods, one or two species of which occurred at all other stations, were also missing, but two ovigerous specimens of the Cumacean, *Diastylis insularum* Calman, were present. The predominant polychaetes were *Dorvillea* sp. and *Terebellides stroemi.*

COMMENTARY

There are distinct differences between the sill Station, A 326, the Entrance Basin Station A 327, and the inner Stirling Basin Stations A 319, 321, 320, 323, and 322, with lesser differences between the Entrance and Stirling Basin stations.

The echinoderm and ophiuroid *Echinocardium cordatum* and *Amphiura norae,* which are indicators of soft bottom, occur at most inner basin stations. It is possible that the unusual depths of some of these *Echinocardium* records, e.g., 147 fm at Station A 319, are due to animals actively or passively penetrating into the deep basin where conditions cannot be drastically unsuitable. Fleming (1950) has noted that "in the steep-sided fiords, gravitation of the dead shells of shallow-water molluscs into the over-deepened basins seems to be a regular process". It is probable that this process also applies to at least some extensions of echinoderm depth ranges in the Southern Fiords. However, it is also possible that the *Echinocardium* have settled out in the basin directly from pelagic larval stages brought in from Entrance Basin populations by surface-water movement or by deep high-density water from off shore, since the specimens at Station A 319 (147 fm) are consistently smaller (20–25 mm total length) than those at the shallower and closer inshore Station A 320 (116 fm, length 30–36 mm). This suggests the existence of two different age-populations.

Evechinus chloroticus occurs as a "single water-worn fragment" at Station A 326. This species is "characteristically a hard bottom indicator" (Fell, pers. comm.) but Fell (1952) has elsewhere described anomalous occurrences of this species in apparently soft bottom in other southern fiords. While his explanation, that there are possibly rapid transitions from hard to soft bottom in the Fiords and that mud frequently overwhelms the hard-bottom communities, is generally both credible and likely, here it is even more likely that the dredge at A 326 passed through both a representative sample of hard-bottom community and a soft-bottom pocket. This would explain the presence of other hard-bottom indicators, such as coral, and such soft-bottom indicators as the three juvenile *Amphiura norae*. Fragments of *E. cordatum* can be similarly explained, although they could also be due to transport from the Entrance Basin. The general appearance of the material from A 326 is that of a hard-bottom fauna.

The polychaete picture is simpler (table 2). Six species occur only at the sill station, A 326; 10 species occur only at A 327; 16 species are restricted to the Stirling Basin stations and, of these, four are present only at the innermost station. A few species overlap these boundaries.

Most molluscs found alive at Station A 327 were represented only by dead shells at A 326. Several occurring live or dead at A 327 occurred as dead shell within Stirling Basin, e.g., *Nemocardium pulchellum*. A number of species occurred as dead shell at both A 326 and A 327, presumably carried in from slightly further out, or from pockets of different, unsampled bottom within the general areas of these two stations. Three species, *Linucula gallinacea*, *Austroneaera wellmani*, and *Fax mirabilis powelli*, occurred alive on the sill at A 326 but were found nowhere else. None of the live molluscs from the inner Basin stations were found alive on the Sill, but at least one, *Cadulus delicatulus*, was also taken alive at the Entrance Basin Station, A 327.

This distribution pattern agrees with that shown by those *Galathea* dredgings for which information is available – Stations 608, 613, 614, 615, and 616. Differences from the pattern established by the N.Z.O.I. investigations are slight. Three species taken by *Galathea*, *Nucinella maoriana*, *Genaximus otagoensis*, and *Cadulus tetiger*, did not appear in the present material. The remaining 10 *Galathea* stations extend the distributional pattern already described for the inner basin (table 3) but it is not known whether the *Galathea* specimens were alive or dead.

Thus, although sampling was limited and results presented here might be modified by a more intensive programme, the N.Z.O.I. investigations reveal an inner, Stirling Basin fauna which is different from the fauna of the Entrance Sill, but not greatly different from that of the outer Entrance Basin. The differences between the Sill fauna and that of the basins are obviously related to the contrast between the muddy bottoms at the basin stations and the rocky bottom sampled on the sill. Additionally, the sill is located in the narrow neck of the Sound where water passage is constricted and where the flow of water is likely to be much stronger than elsewhere in the fiord.

TABLE 2. DISTRIBUTION OF POLYCHAETES IN MILFORD SOUND

—	327	326	319	321	320	323	322
Aglaophamus verrilli	+	+	+	..	..	+	..
Notomastus sp.	+	..	+	..	+	..	+
Ninoe sp.	+	..	+	+	+	..	..
Melinna sp.	+	..	..	..	..	..	..
Onuphis sp.	+	..	..	..	..	..	..
Orbinia papillosa	+	..	..	..	..	..	..
Platynereis	+	..	..	..	..	..	..
Pygospio sp.	+	..	..	..	..	..	..
Lysilla sp.	+	..	..	..	..	..	..
Maldanid n.g.	+	..	..	..	..	..	..
Glycera lamelliformis	+	..	..	..	..	..	..
Goniada maorica	+	..	..	..	..	..	..
Eupanthalis sp.	+	..	..	..	..	..	..
Hyalinoecia sp.	+	..	..	..	..	..	..
Aphrodita talpa	+	..	..	..	..	..	..
Spionid sp.	+	..	..	..	..	..	..
Myriochele sp.	+	..	..	..	..	..	..
Glycera americana	..	+	+	+	+	+	..
Maldanid sp.	..	+	+	..	+	..	..
Hyalinoecia tubicola	..	+	..	..	..	..	..
Leanira laevis	..	+	..	..	..	..	..
Aglaophamus maoriana	..	+	..	..	..	..	..
Eunice australis	..	+	..	..	..	..	..
Prionospio malmgreni	..	+	..	..	..	..	..
Chloeia inermis	..	+	..	..	..	..	..
Lumbrinereis sp.	..	+	..	..	..	..	..
Ancistrosyllis sp.	..	..	+	..	..	..	..
Euclymene sp.	..	..	+	..	..	+	..
Nicolea sp.	..	..	+	..	..	..	..
Terebellid	..	..	+	..	..	..	..
Cirratulus sp.	..	..	..	+	+	..	..
Polydora sp.	..	..	..	+	..	..	..
Terebellides stroemi	..	..	..	..	+	+	+
Dorvillea loveni	..	..	..	..	+	..	+
Brada (?) sp.	..	..	..	..	+	..	+
Harmothoe praeclara	..	..	..	..	+	..	..
Scalibregma inflatum	..	..	..	..	+	..	..
Pectinaria sp.	..	..	..	..	+	..	..
Podarke angustifrons	..	..	..	..	..	..	+
Phyllodocid sp.	..	..	..	..	..	..	+
Armandia maculata	..	..	..	..	..	..	+
Haploscoloplos kerguelenensis	..	..	..	..	..	..	+

TABLE 3. DISTRIBUTION OF SOME MOLLUSCA FOUND IN MILFORD SOUND
(Arranged by Station in Order of Position from Entrance of Sound to Delta Region)
+ = living d = dead g = *Galathea* material, condition not stated

Species	*Tui* Stations Only						*Tui* and *Galathea* Stations									
	327	326	319	321	320	323	327	326	319	608	615–6	321	614	613	320	323
Fissidentalium zelandicum							+									
Chlamys sp.		d						d								
Poroleda lanceolata		d						d								
Nemocardium pulchellum	+	d	d	d	d	d		d	d	g	g	d	g	g	d	d
Cadulus delicatulus	+	d						d		g	g			g		
Linucula gallinacea	d		d				d		d							
Austroneaera wellmani	d						d	+								
Fax mirabilis powelli																
Uberella denticulifera				d								d				
Tecticrater cervae		d						d							+	
Solemya parkinsoni						+									+	
Nucula hartvigiana										g	g		g		+	
Cuspidaria fairchildi	d						d							g	+	
Nucinella maoriana											g		g			
Neilo australis	d	d	d				d	d	d	g	g			g		
Lucinoma galathea	d	d					d	d		g	g					
Thyasira peroniana	d		d	d			d		d	g	g	d	g	g		
Maorithyas marama	d						d			g			g			
Leptomya retiaria		d						d			g					
Dentalium nanum											g					

BOTTOM COMMUNITIES

Consideration of the faunal lists for each station indicates, as suggested above, that two distinct communities can be recognised which are comparable to communities already recognised elsewhere in New Zealand waters.

The Echinocardium *Community*

The fauna from the Stirling Basin Stations, A 319, 320, 323, and 322, is characterised by *Echinocardium cordatum* and *Amphiura norae*, and is thus directly comparable with Powell's *Echinocardium* formation (Powell, 1937) from Auckland Harbour, with Fleming's "Soft Mud Substratum Community" from the Western Southland Fiords (Fleming, 1950), and with Dell's *Echinocardium* community from Queen Charlotte Sound (Dell, 1951). These two species were not taken at Station A 321, but there are no grounds for considering this station essentially different from those listed above.

Dosinia lambata, the third dominant of Powell's typical formation, is absent, but many of the "subdominants" and "secondary species" are present. The absence of *Dosinia* is probably explained by a statement in Powell (1937): "The *Dosinia* is also affected bathymetrically, for it is shown to be absent in dredgings taken in less than two fathoms as well as from those exceeding eleven fathoms." *Dosinia greyi*, which Fleming (1950) mentions as being locally important in other southern fiords, is not present, nor are *Tawera spissa*, "*Tellina*" *huttoni* or *Melliteryx*. *Cadulus delicatulus* is important, but *Neilo australis* was found only as dead shells at one basin station and the two outer stations, and *Leptomya retiaria* was found only as dead shell at the sill station.

The subdominant polychaete, *Glycera americana*, of Powell's Auckland *Echinocardium* formation was present in the Stirling Basin stations, and *Terebellides stroemi* is also common to both localities.

Dell's Queen Charlotte Sound *Echinocardium* formation has affinities with Milford in non-dominant species as shown by the presence of *Nucula hartvigiana* and *Thyasira peroniana*, although the latter is considered subspecifically different in the two localities.

Elements in the Milford Community not mentioned by Powell, Dell, or Fleming as being found elsewhere, are the molluscs *Uberella denticulifera* and *Solemya parkinsoni*, and the polychaetes *Ninoe* sp., *Cirratulus* sp., *Scalibregma inflatum*, *Notomastus* sp., *Aglaophamus verrilli* and *Dorvillea loveni*.

Basically, therefore, the Stirling Basin stations indicate an *Echinocardium* community, showing both obvious affinities with, and some minor differences from, similar communities reported from Auckland by Powell (1937), Queen Charlotte Sound by Dell (1951), and the Western Southland Fiords by Fleming (1950).

Although Fleming characterised the *Echinocardium* community from the Western Southland Fiords as a soft mud community, the Milford sediments have a definite sandy component (Pantin, pp. 35-47), Powell (1937) noted that "a predominance of the fine-sand grade over the silt which takes place in certain of the soft-bottom dredgings is the most favourable to *Echinocardium*, and on this type of bottom . . . the more sandy nature of the mud is responsible for the elimination of the bivalve *Dosinia lambata*". Jones (1950) characterised a similar Northern Hemisphere *Echinocardium* association as an offshore muddy sand association. I have therefore followed Thorson (1957) in designating this community by one of its most important species, but have preferred to follow Powell and Dell in accepting *Echinocardium cordatum** as the distinguishing species in preference to Thorson's suggested *Amphiura*, particularly since *Amphiura rosea* in the north is replaced by *A. norae* in the south.

*The Brachiopod-*Chlamys *Community*

The fauna of Station A 326, on the Entrance Sill, is reminiscent of Powell's *Tawera* + *Glycymeris* formation, although neither of these species is present, but is far better treated as a "Brachiopod-*Chlamys*" community as recorded by Fleming (1950) from the more southern fiords, and by Dell (1951) from Queen Charlotte Sound in the north.

Dead brachiopods, *Tegulorhynchia nigricans*, and a dead Chlamys, *C. suprasilis crepusculi*, are present, as in Fleming's Southern Fiord "Brachiopod-*Chlamys*" association.

Found in both Milford and in Dell's Queen Charlotte Sound "Brachiopod-*Chlamys*" formation, which was described in more detail, are *Tegulorhynchia nigricans*, *Nuculana bellula*, *Cardita aoteana*, *Nemocardium pulchellum*, *Cosa costata*, *Rochefortula reniformis*, *Chlamys* sp., *Modiolus aerolatus*, *Leptomya retiaria*, *Emarginula striatula*, *Micrelenchus* sp., *Sigapatella novaezealandiae*, *Zegalurus tenuis*, and *Cadulus delicatulus*. Dell considers this "a Brachiopod-*Chlamys* formation superimposed upon a somewhat modified *Venericardia-Tawera* association". In spite of the representation in Milford of the two dominants of the Brachiopod-*Chlamys* community by dead shells only, the author believes this is an accurate description of the community, and the apparent absence of other members of the typical Brachiopod-*Chlamys* community is probably the result of limited dredging.

This interpretation is in keeping with the nature of the bottom and of the general environmental situation. Fleming (1950) regarded the association as one which occurs in "areas of strong currents where the sediment is bypassed" and noted that in fiord samples "the texture of the bottom is generally coarse, with pebbles and dead molluscan shells and lesser amounts of fine sediment". Dell (1951) considered the situation in Queen Charlotte Sound "exactly analogous", and Hurley (1959) has published photographs of a similar Brachiopod-*Chlamys* locality in Cook Strait.

Fleming's two stations are both in the entrance channels of fiords – the channel of the Narrows (Long Sound), and the channel inside Oke Island, Wet Jacket Arm of Breaksea Sound. These localities are similar to that of Station A 326, and his descriptions of environment and sediments also apply to the Milford Sound Entrance Sill.

The Mixed Community of Station A 327.

This station does not readily fit into any one of the acknowledged communities, but is recognisable as a mixture of Brachiopod-*Chlamys* and *Echinocardium* community. Had Station A 325 yielded a satisfactory dredge sample, it would probably have indicated that A 327 lay between the Entrance Sill Brachiopod-*Chlamys* community and an Entrance Basin *Echinocardium* community.

The movement of dead shells by bottom currents could account for the presence of some of the Brachiopod-*Chlamys* associants, e.g., the dead *Tegulorhynchia nigricans* but not for the live juvenile *Chlamys*.

These two species are the dominants of Fleming's Brachiopod-*Chlamys* association from the Southern Fiords. The following molluscs from A 327 occur also in Dell's Queen Charlotte Sound Brachiopod-*Chlamys* association: *Nuculana bellula*, *Limatula maoria*, *Nemocardium pulchellum*, *Emarginula striatula*, and *Cadulus delicatulus*. *Myadora antipoda* and *Nucula strangei* replace Dell's *Myadora novaezealandiae* and

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*Fell (1952) considers *Echinocardium australe* (Gray) a synonym of *Echinocardium cordatum* (Pennant).

Nucula hartvigiana. Of these, only *Cadulus delicatulus* appears in Powell's list of *Echinocardium* associants as a "species found in the typical formation". It is therefore reasonable to recognise a Brachiopod-*Chlamys* element at this station, although, as shown by comparison with A 326, it is not a full representation of this community.

Of the other species, most of the important ones appear in Powell's *Echinocardium* community. *Cadulus delicatulus, Amphiura norae, Echinocardium cordatum, Lumbrinereis* sp., *Onuphis* sp., *Glycera tesselata* and *Hyalonoecia tubicola* or related species of these genus are starred as typical species by Powell, leaving little doubt of the presence of elements of an *Echinocardium* community.

Thus, the fauna of both Entrance and Stirling Basins would appear to be basically that of an *Echinocardium* community. There are, however, a number of species occurring at A 327 which do not appear at the inner basin stations. These include the polychaetes *Orbinia papillosa, Onuphis* sp., *Platynereis* sp.,? *Pygospio* sp., *Lysilla* sp., *Goniada maorica, Eupanthalis* sp., *Aphrodita talpa,* Spionid sp.,? *Myriochele* sp., and the molluscs *Maorithyas marama, Tellinella charlottae, Tellinella huttoni huttoni, Dentalium nanum, Fissidentalium zelandicum,* and *Poroleda lanceolata.* While some of these may properly belong to a Brachiopod-*Chlamys* community, others undoubtedly belong to the *Echinocardium* community. It would seem, therefore, that the Stirling Basin *Echinocardium* community is depleted in comparison with similar communities outside the fiord. The reasons for this depletion are probably to be found in the physical and hydrological barrier presented by the Entrance Sill, the depth of most of the Stirling Basin stations, the shallow water effect of the lowered surface salinities after heavy rain, and the possibility of occasional stagnation of the Stirling Basin (Garner, 1964, p. 32).

AFFINITIES OF THE MILFORD FAUNA

Fleming (1950) considered the Fiordland fauna contained four distinct elements: (1) a nucleus of endemic New Zealand elements; (2) a smaller but important element having affinities with northern New Zealand or Australia, or both; (3) a small subantarctic element; and (4) a small endemic element.

Among species found in Milford with northern New Zealand and Australian affinities, as listed by Fleming, are *Haliris setosa* and the genera *Fax, Poroleda,* and *Austroneaera,* while *Tugali suteri* and *Micrelenchus micans* are species he considered endemic to Fiordland.

SIMILARITIES TO WESTERN SOUTHLAND FIORDS

The benthic fauna of Milford Sound shows close affinities with the faunas of the fiords which Fleming studied: Preservation Inlet, Chalky Sound, Dusky Sound, Breaksea Sound, Daggs Sound, Doubtful Sound, and George Sound.

Apart from Mollusca, Fleming mentioned the presence of *Echinocardium* and brachiopods. The *Echinocardium* community in Milford is similar to those in Preservation Inlet, Dusky Sound, and Doubtful Sound.

The Brachiopod-*Chlamys* community also occurs in Long Sound (Preservation Inlet) and Breaksea Sound, in similar relation to the bottom morphology of the fiord.

The Milford stations add 11 new species of Mollusca to the Fiordland fauna, but all are known from elsewhere in New Zealand, and almost certainly will be found later in other southern fiords.

Such elements of Fleming's Fiordland faunule as *Fax, Austroneaera, Poroleda, Chlamys suprasilis crepusculi, Haliris setosa, Tugali suteri, Micrelenchus micans,* and *Tecticrater (Cocculina) cervae,* appear in the Milford dredgings, indicating the similarity to other southern fiords. Thus, Fleming's general comments on affinities apply also to Milford.

EFFECTS OF CIRCULATION ON BENTHIC ANIMALS OF THE FIORD

The nature of the circulation in Milford Sound is discussed by Garner (1964, pp. 25–33) who shows that, at the time of the N.Z.O.I. investigations in 1957, the bottom water was of comparatively high salinity (35·01–35·12‰) with a dissolved oxygen content of 5·32–4·98 ml/l. The existing type of circulation suggested by the 1957 investigations, where there is a surface outflow of relatively fresh water across the sill and a bottom inflow of saline water from outside, would be sufficient to account for the species of benthic organisms found in the Sound, if the inner basin were to be flushed at least once a year. This is so particularly for *Echinocardium cordatum* which Powell (1937) found intolerant of salinities below 34‰, "a further indication of the relatively euryhaline benthic conditions in land-locked fiords" (Fleming, 1950). Fleming had also noted that benthic molluscs in other southern fiords showed little sign of reduced salinity, being species which "elsewhere in New Zealand are found chiefly in the open sea bottom or at least in non-estuarine bays".

If the situation outlined above were consistent from year to year, the bottom of the inner basin could at all times be associated with water of relatively high salinity, receiving the full benefit of any inflowing sea water. The surface waters would, however, be considerably diluted to a depth of several feet by the frequent torrential rains* and heavy river inflow. This would explain the general lack of littoral Mollusca, considered by Fleming "poor in species" – as also indicated by the present investigations – and the presence "of euryhaline forms tolerant of low salinity" (Fleming, 1950).

There is, however, a possibility that some degree of stagnation occurs in Stirling Basin, and its effects on the benthos should be considered. *Alert* stations, in 1955, indicated that the basin water had been isolated for some time and it was noticed to smell "strongly of hydrogen sulphide" (Garner, 1964, p. 28).

In this situation, which Garner considers could arise if the surface waters in Stirling Basin were diluted by fresh water as deep as the bottom of the Entrance Sill, the consequent lack of flushing by water from the open sea would give rise to both lowered salinity and lowered oxygen in Stirling Basin. These two variables would thus be correlated unless the situation arose where river water entering the Sound was so heavily laden with sediment that it sank immediately below the salt water in a hyperpycnal flow or "turbidity current" (Pantin, 1964, p. 45). If this happened, highly oxygenated and low salinity conditions would temporarily result in the Basin; however, Pantin considers turbidity currents of this type highly unlikely.

The effects of lowered oxygen tension on the bottom fauna are not likely to be as drastic as those of lowered salinity until a state of almost complete stagnation is reached. For most marine animals, according to Richards (1957, pp. 212, 213): "Respiratory consumption of oxygen is essentially independent of the oxygen tension down to some lower limit of the latter . . . it appears that . . . the oxygen content is not a primary factor in limiting life and growth except where sulfides develop under completely anaerobic conditions."

The *Alert* stations indicate that this latter possibility should be considered. If a catastrophic degree of stagnation or disastrously low salinity occasionally took place, say once in several years, it would not be inconsistent with the biological evidence as it was found in 1957.

It was noticeable that relatively few Mollusca, alive or dead, were taken in the inner (Stirling) Basin as compared with the outer (Entrance) Basin and Sill communities (table 4).

While the figures given in table 4 are quantitatively only very grossly comparable, because of the method of sampling used and the differences in size of sample obtained, the figures indicate a distinct falling off in numbers of species and animals per unit area within the inner basin.

The animals recorded in the inner part of the fiord in 1957 are typically those with pelagic larvae – polychaetes, molluscs, and echinoderms.

TABLE 4. OCCURRENCE OF MOLLUSCA AT MILFORD STATIONS

Station	327	326	319	321	320	323	322
Live specimens	125	10	7	..	7	5	..
Live species	9	3	2	..	6	2	..
Dead specimens	130	167	29	19	2	4	..
Dead species	17	33	4	3	1	1	..
Total number of species ..	26	36	6	3	7	3	..

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*During the N.Z.O.I. visit, over 10 in. of rain fell on one day, mostly in the morning. Very similar conditions were recorded by Commander G. H. Richards, HMS *Acheron*, 1851, in his remark book, during the *Acheron's* survey of Daggs Sound. "A remarkable scene occurred during our stay in this sound. Our anchorage was at the head of the northern arm, a cable's length from the shore, in 12 fm: the change of the moon brought a N.W. gale, with heavy rain, and in the course of a few hours no less than fourteen magnificent cascades were pouring down the steep sides of the mountains (upward of 3,000 ft high), by which we were surrounded, bringing with them trees of considerable size, and all other obstructions met with in their passage. The effect was as if a heavy surf were breaking round the vessel: the mist, floating as low as our mast-heads, occasionally obscured everything but the summit of the mountains and the foam below, and produced altogether a scene as grand as it is possible to conceive, which lasted without abating in any degree for two days, when the water alongside, which had been as salt as the ocean, was for a considerable depth below the surface perfectly fresh." (Quoted in Tilly, 1886).

The situation can therefore be conceived where an occasional catastrophic destruction of the benthic fauna is followed by repopulation by pelagic larvae brought in on the tide from the Entrance Basin. This is consistent with the depleted *Echinocardium* type community and with the sizes of the animals collected.

None of the *Echinocardium* specimens taken is larger than 36 mm in length (table 5). Fell (1952) quotes the occurrence of a 69 mm specimen from Stewart Island in connection with Clark's statement that specimens from the Southern Hemisphere rarely exceed 45 mm in length (Clark, 1946). There appears to be little information available about size ranges and adult ages of *Echinocardium cordatum*, but Thorson (1957) considers this species as having a three-year life expectancy and Jensen (1919) states that "even rather great [specimens of *Echinocardium cordatum*] weighing 10–12 g, are not more than 3 years old". This would suggest that the specimens taken in Milford fall into two immature age groups (possibly two separate "year-classes"), the specimens from A 320 being all between 30 and 36 mm, those from other stations between 12 and 25 mm.

On this evidence there may have been completely stagnant conditions as recently as 1955, provided there was immediate repopulation from outside the Sound after complete overturn and replenishment of the sea water in the basin.

The similarities of Milford to other Southland fiords would indicate that the Milford circulation pattern is likely to obtain in them also.

TABLE 5. SIZE RANGES OF *Echinocardium cordatum* TAKEN IN MILFORD SOUND

Station	A 319	A 320	A 323	A 322
Depth ..	147 fm	116 fm	60 fm	12–8 fm
Size ..	20–25 mm	30–36 mm	15–18 mm	12–25 mm
Number of specimens	5	6	6	64

THE OCCURRENCE OF *Lucinoma* AND *Prionospio* AND THEIR SIGNIFICANCE

Although only taken dead on the *Tui* Cruise – at outer Stations A 326 and 327 – living *Lucinoma galathea* were a significant discovery during the *Galathea* investigations of Milford. Until found by the *Galathea* at Station 614 in 268 m ("mid-channel, between Pater Point and Williamston Point, opposite entrance to Harrison Cove, January 19, 1952"), this species was known only as a Pliocene fossil from the North Island, New Zealand (Marwick, 1953). Dell (1956) records it from two further *Galathea* stations in Milford Sound, Station 608 (44°37′S, 167°52′E, 305 m, 18/1/1952) and Station 615 (44°37′S, 167°53′E, 293 m, 19/1/1952); also from 300 fm off the East Otago Coast, and from various stations on the Chatham Rise and around the Chatham Islands.

There is an intriguing similarity between Milford Sound and a Japanese bay, Beppu-wan, described by Miyadi (1941). Beppu-wan is a steep-walled basin with a sill depth of 59 m and an inner basin of 74 m, and there is an unconfirmed suggestion that hot water springs in the basin may be the cause of peculiar temperature distribution in the basin deep-water. In this inner basin, Miyadi recognised two communities, a *Lucinoma acutilineata* (Conrad) community restricted to the 61–68 m zone, and an overlapping *Prionospio pinnata* Ehlers community between 45 and 68 m. He noted that "the distribution of type animals within their grounds was surprisingly regular, and the steep side-wall of the basin seemed to contribute to the sharp differentiation of these ecological areas", although "where the slope of the basin was steepest, both boundary lines of *Lucinoma* and *Prionospio* associations were coincident".

Significantly, live *Prionospio malmgreni*, were taken at Station A 326 in Milford where dead *Lucinoma galathea* shells were also present, although this sill station was typified by a Brachiopod-*Chlamys* association. Probably, the *Prionospio* and *Lucinoma* came from mud pockets within the latter association.

Describing the characteristics of the Japanese *Lucinoma* community, Miyadi says: "The clam never occurred on shallower bottom than 60 m, and the depth may be one of the principal environmental factors controlling its distribution. *Lucinoma* is a clam of the northern system, and the low temperature at depth may be another important factor. The temperature of *Lucinoma* ground ranged between 10·6°C and 13·5°C by my measurement, and it is supposed to remain always below 18°C . . . The bottom consisted of soft blackish mud. It is expected that the sediments in this depression are rich in organic matter . . . and their black colour is a proof for it. The severe submarine micro-climate especially the microstratification of low oxidation-reduction potential prevailing . . . may prevent the settlement of many animals which demand high oxygen tension and thus serve to keep away predatory animals and offer a safe ground of rich nutriment for a few which can tolerate it. *Lucinoma acutilineata* is one of such animals."

Parallels with the Milford situation appear to be rather more than coincidence, especially the possibility that *Lucinoma* may through wide tolerance of such conditions be associated with lowered oxygen tension, mud rich in organic matter, and general sulphuretted stagnant conditions. According to Miyadi, oxygen content of deep water in Beppu-wan does not fall below 80 per cent saturation in winter; summer values are unknown but salinities in the *Lucinoma-Prionospio* zones are as follows:

45 m: 33·24–29·15‰
60 m: 33·95–28·98‰
70 m: 33·44–29·79‰

Compare this with the situation in Milford where bottom temperatures measured by *Galathea* at *Lucinoma* stations (608 and 615) were 11·53°–12·68°C; salinity, 35·04–33·93‰; and dissolved oxygen, 4·84 ml/l. Comparable N.Z.O.I. Stations A 328 and A 329 (28 Jan 1957) at 200 m depth revealed temperatures of 10·9°–11·1°C; salinities of 35·10–35·12‰: and dissolved oxygen of 5·32–4·98 ml/l or 89–83 per cent saturation (Garner, 1964, pp. 25–33).

Miyadi's *Lucinoma* and *Prionospio* communities are recorded by Thorson (1957) in a list of those "insufficiently known and without known parallels". Whether or not separate communities or subcommunities corresponding in every respect to Miyadi's would be revealed by closer examination in Milford, it would seem that *Lucinoma*, at least, is a genus which may be associated with reducing basin or fiord conditions sufficient to deter other species.

Feeding of Ophiuroids

Fell (1952) noted that the ophiuroid *Pectinura maculata* in Dusky Sound, a neighbouring fiord, had been "selectively feeding" on anthers and pollen of Southern Beech (*Nothofagus* sp.). This is not surprising when the bottom sediments of these fiords are examined. The proportion of vegetable matter is so high that it would be difficult for the animals not to ingest pollen when feeding. Because of the extremely heavy, sudden and frequent rainfall, and the presence everywhere of vegetation on vertical cliffs overhanging the water, there must be a constant rain of pollen to the bottom of the fiord basins. Leaves and debris are frequently seen floating on the surface, especially after rain, and analysis of pollen and spore content in cores from Stirling Basin shows a preponderance of pollen of *Nothofagus* sp. Harris (1964, pp. 77–8) records the *Nothofagus* content at a depth of 20–25 cm as 79 per cent and at 130–132 cm as 73 per cent, indicating that this situation has not changed appreciably for several decades.

Additions to Molluscan Checklist

The following species of Mollusca are additions to Fleming's checklist of Fiordland Mollusca:

Uberella denticulifera (Marwick).
Nucula (Ennucula) strangei Adams.
Divaricella huttoniana Vanatta.
Lucinoma galathea Marwick. See Marwick, 1953; Dell, 1956.
Tellinella charlottae (Smith).
Barbatia novaezealandiae Smith.
Escalima regularis Powell.
Tahunanuia alata Powell.
Maoricrater explorata Dell.
Zeacolpus (Stiracolpus) delli Marwick.
Cadulus tetiger Finlay. See Dell, 1956.
Dentalium suteri Emerson.

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A LIST OF MOLLUSCA AND BRACHIOPODA COLLECTED BY N.Z.O.I. FROM MILFORD SOUND

By R. K. Dell
Dominion Museum, Wellington

(Received for publication, April 1962)

The following is a list of Mollusca taken during the N.Z. Oceanographic Institute investigations in Milford Sound, in January 1957.

Station A 319

- *Neilo australis* (Q. and G.) (4d (= dead))
- *Nemocardium pulchellum* (Gray) (11d)
- *Linucula gallinacea* (Finlay) (1d)
- *Thyasira peroniana peregrina* Iredale (13d)
- *Uberella denticulifera* (Marwick) (5)
- *Cadulus delicatulus* Suter (2)

Station A 320

- *Nucula hartvigiana* (Pfeffer) (1)
- *Solemya parkinsoni* (E. A. Smith) (1 juv.)
- *Nemocardium pulchellum* (Gray) (2d)
- *Cuspidaria fairchildi* Suter (1)
- *Tecticrater cervae* (Fleming) (1)
- *Uberella denticulifera* (Marwick) (2)
- *Cadulus delicatulus* Suter (1)

Station A 321

- *Thyasira perioniana peregrina* Iredale (9d)
- *Nemocardium pulchellum* (Gray) (1d)
- *Uberella denticulifera* (Marwick) (9d)

Station A 323

- *Solemya parkinsoni* Smith (1)
- *Nemocardium pulchellum* (Gray) (4d)
- *Cadulus delicatulus* Suter (4)

Station A 326

Brachiopoda

- *Tegulorhynchia nigricans* (Sowerby) (dead valves)

Mollusca

- *Linucula gallinacea* (Finlay) (6)
- *Nuculana bellula* (Adams) (6d)
- *Poroleda lanceolata* (Hutton) (1d)
- *Neilo australis* (Q. and G.) (1d)
- *Bathyarca cybaea* (Hedley) (4d)
- *Barbatia novaezelandiae* Smith (2d)
- *Chlamys suprasilis crepusculi* Fleming (1d)
- *Aulacomya maoriana* Iredale (5 small d)
- *Modiolus aerolatus* (Gould) (1 small d)
- *Cosa costata* (Bernard) (6d)
- *Escalima regularis* Powell (2d)
- *Divaricella huttoniana* Vanatta (6d)
- *Lucinoma galatheae* Marwick (3 juv. d)
- *Rochefortula reniformis* (Suter) (3d)
- *Tahuanuia alata* Powell (1d)
- *Cardita aoteana* Finlay (2d)
- *Leptomya retiaria* Hutton (3d)
- *Nemocardium pulchellum* (Gray) (c. 20d)
- *Austroneaera wellmani* Fleming (1)
- *Haliris (Setaliris) setosa* (Hedley) (5d)
- *Myadora antipoda* Smith (4d)
- *Parvithracia suteri* Finlay (10d)
- *Emarginula striatula* ([illegible]. and G.) (1d)
- *Micrelenchus micans* (Suter) (4d)
- *Notoacmea parviconoidea* (Suter) (10d)
- *Maoricrater explorata* (Dell) (6d)
- *Tecticrater cervae* (Fleming) (10d)
- *Zegalurus tenuis* (Gray) (7d)
- *Sigapatella novaezealandiae Lesson* (2d)
- *Uberella vitrea* (Hutton) (8d)
- *Zeacolpus (Stiracolpus) delli* Marwick (4d)
- *Fax mirabilis powelli* Fleming (3)
- *Microvoluta biconica* (Murdoch and Suter) (2d)
- *Siphonaria zelandica* (Q. and G.) (3d)
- *Cadulus delicatulus* Suter (11d)
- *Dentalium suteri* Emerson (13d)

Station A 327

BRACHIOPODA

Tegulorhynchia nigricans (Sowerby) (1d)

MOLLUSCA

Linucula gallinacea Finlay (2d)
Nucula (Ennucula) strangei Adams (6d)
Nuculana bellula Adams (2d)
Poroleda lanceolata Hutton (7 (6d))
Neilo australis (Q. and G.) (9d)
Bathyarca cybaea Hedley (4d)
Chlamys sp. (15 juv.)
Aulacomya maoriana Iredale (5 small d)
Divaricella huttoniana Vanatta (15 small)
Lucinoma galathea Marwick (c. 30 d)
Thyasira peroniana peregrina Iredale (5d)
Maorithyas marama Fleming (2d)
Limatula maoria Finlay (6 small)
Nemocardium pulchellum (Gray) (c. 40)
Myadora antipoda Smith (6d)
Haliris (Setaliris) setosa (Hedley) (c. 20 d.)
Cuspidaria fairchildi Suter (1d)
Austroneaera wellmani Fleming (2d)
Tellinella charlottae (Smith) (25d)
Tellinella huttoni huttoni (Smith) (4d)
Emarginula striatula (Q. and G.) (1 juv.)
Fissidentalium zelandicum (Sowerby) (1)
Cadulus delicatulus Suter (c. 20)
Dentalium nanum Hutton (c. 20)

A LIST OF POLYCHAETA COLLECTED BY N.Z.O.I. FROM MILFORD SOUND

By G. A. Knox

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(Received for publication, April 1962)

The following is a list of Polychaeta taken during the N.Z. Oceanographic Institute investigations in Milford Sound, in January 1957.

Station A 319

Aglaophamus verrilli (McIntosh) (1)
Terebellid (1 posterior end)
Ninoe sp. (8)
Glycera americana Leidy (2)
Ancistrosyllis n. sp. (1)
Notomastus ? sp. (2)
Euclymene sp. (1)
Nicolea sp. (fragment)
Maldanid sp. (1)

Station A 320

Dorvillea loveni (Kinberg) (3)
Terebellides stroemi Sars. (5)
Brada ? sp. (1)
Harmothoe praeclara (Haswell) (1)
Scalibregma inflatum Rathke (36)
Cirratulus sp. (57)
Ninoe sp. (25)
Notomastus sp. (5)
Maldanid sp. (fragments)
Ancistrosyllis n. sp. (4)
Glycera americana Leidy (1)
Pectinaria sp. (1 and fragments)

Station A 321

Glycera americana Leidy (2)
Ninoe sp. (2)
Cirratulus sp. (5)
Polydora sp. (fragment)

Station A 322

Dorvillea loveni (Kinberg) (12)
Terebellides stroemi Sars (11)
Haploscoloplos kerguelensis (McIntosh) (3)
Lumbrinereis sp. (2)
Podarke angustifrons (Grube) (4)
Brada sp. (3)
Phyllodocid sp. (fragment)
Armandia maculata (Webster) (1)
Notomastus sp. (4)

Station A 323

Aglaophamus verrilli (McIntosh) (5)
Terebellides stroemi Sars (4)
Euclymene sp. (2)
Glycera americana Leidy (1)

Station A 326

Melinna sp. (2)
Aglaophamus maoriana Knox (1)
Eunice australis Quatrefages (2)
Prionospio malmgreni Claparède (6)
Hyalinoecia tubicola (Müller) (1)
Chloeia inermis Quatrefages (1)
Leanira laevis McIntosh (1)
Lumbrinereis sp. (6)
Maldanid sp. (fragment)
Glycera americana Leidy (1)
Aglaophamus verrilli (McIntosh) (1)

Station A 327

Notomastus sp. (1 and fragments)
Lumbrinereis sp. (3 and fragments)
Ninoe sp. (3)
Aglaophamus verrilli (McIntosh) (1)
Onuphis sp. (1)
Orbinia papillosa (Ehlers) (2)
Platynereis sp. (2)
? *Pygospio* sp. (2)
Melinna sp. (1)
Lysilla sp. (1)

Maldanid n. gen (1 and fragment)
Glycera lamelliformis McIntosh (7)
Goniada maorica Benham (1)
Eupanthalis n. sp. (1 fragment)
? *Myriochele* sp. (1)
? *Hyalinoecia* (tubes only)
Aphrodita talpa Quatrefages (2)
Spionid sp. (fragment)

SYSTEMATIC LIST

- Family Aphroditidae Malmgren
  - *Aphrodita talpa* Quatrefages
- Family Polynoidae Malmgren
  - *Harmothoe praeclara* (Haswell)
- Family Polyodontidae Pfugfelder
  - *Eupanthalis* n. sp.
- Family Signalionidae Malmgren
  - *Leanira laevis* McIntosh
- Family Amphinomidae Savigny
  - *Chloeia inermis* Quatrefages
- Family Phyllodocidae Williams
  - Phyllodocid sp. indet.
- Family Hesionidae Malmgren
  - *Podarke angustifrons* (Grube)
- Family Pilargidae Saint-Joseph
  - *Ancistrosyllis* n. sp.
- Family Nereidae Johnston
  - *Platynereis* sp.
- Family Nephthyidae Grube
  - *Aglaophamus maoriana* Knox
  - *Aglaophamus verrilli* (McIntosh)
- Family Glyceridae Grube
  - *Glycera americana* Leidy
  - *Glycera lamelliformis* McIntosh
- Family Goniadidae Kinberg
  - *Goniada maorica* Benham
- Family Eunicidae
  - *Eunice australis* Quatrefages
  - *Hyalinoecia tubicola* (Müller)
  - *Lumbrinereis* sp.
  - *Ninoe* sp.
  - *Onuphis* sp.
- Family Dorvilleidae Chamberlain
  - *Dorvillea loveni* (Kinberg)
- Family Orbiniidae Hartman
  - *Orbinia papillosa* (Ehlers)
  - *Haploscoloplos kerguelensis* (McIntosh)
- Family Spiionidae
  - *Polydora* sp.
  - *Pygospio* sp. ?
  - *Prionospio malmgreni* Claparède
- Family Cirratulidae Carus
  - *Cirratulus* sp.
- Family Flabelligeridae Saint-Joseph
  - *Brada* sp.
- Family Scalibregmidae Malmgren
  - *Scalibregma inflatum* Rathke
- Family Opheliidae Malmgren
  - *Armandia maculata* Webster
- Family Capitellidae Grube
  - *Notomastus* sp.
- Family Oweniidae Rioja
  - ? *Myriochele* sp.
- Family Maldanidae Malmgren
  - *Euclymene* sp.
  - Maldanid sp. indet.
  - Maldanid n. gen.
- Family Pectinariidae Quatrefages
  - *Pectinaria* sp.
- Family Ampharetidae Malmgren
  - *Melinna* sp.
- Family Terebellidae Malmgren
  - *Lysilla* sp.
  - *Nicolea* sp.
  - Terebellid sp. indet.
- Family Trichobranchidae Malmgren
  - *Terebellides stroemi* Sars

A LIST OF ECHINODERMATA COLLECTED BY N.Z.O.I. FROM MILFORD SOUND

By *H. Barraclough Fell
Zoology Department, Victoria University of Wellington

(Received for publication, April 1962)

The following is a list of Echinodermata taken during the N.Z. Oceanographic Institute investigations in Milford Sound, January 1957.

Station A 319
- *Echinocardium cordatum* (Pennant) (5 small)
- †*Amphiura norae* Benham (5)

Station A 320
- *Echinocardium cordatum* (Pennant) (6)

Station A 322
- *Echinocardium cordatum* (Pennant) (numerous small individuals)

Station A 323
- *Echinocardium cordatum* (Pennant) (6 small)

Station A 326
- *Echinocardium cordatum* (Pennant) (fragments)
- *Evechinus chloroticus* (Val.) (single water-borne fragment)
- *Amphiura norae* Benham (3)

Station A 327
- *Pseudechinus* sp. (2 juv.)
- *Amphiura norae* Benham (10)
- *Echinocardium cordatum* (Pennant) (fragment)

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*Now at Museum of Comparative Zoology, Harvard University, Cambridge, U.S.A.

†Now *Hemilepis norae* (Benham). See Fell, H. B. 1962: A Revision of the Major Genera of Amphiurid Ophiuroidea. *Trans. roy. Soc. N.Z. Zool. 2 (1)*:1–26.

A NOTE ON DIATOMS OCCURRING IN MILFORD SOUND

By *E. J. Ferguson Wood

C.S.I.R.O., Division of Fisheries and Oceanography, Cronulla, Australia

(Received for publication, April 1962)

The opportunity was taken during the sampling operations carried out from RNZFA *Tui* in Milford Sound to secure some of the sediment for a preliminary analysis of the diatom population. The sediment sample examined (a sandy silt) came from Sta. A 321 in the middle of Stirling Basin and in 142 fm.

Subsequently, but over the same position, a vertical net haul was taken through the surface water layers.

Diatom occurrences in the samples were as follows:

Station A 321, surface sediment:

Live forms—

- *Coscinodiscus marginatus*
- *Navicula* spp.
- *Goniaulax polyedra*
- A flagellate

Dead forms—

- *Amphora* sp. prob. *javanica*
- *Diploneis crabro*
- *Navicula* spp.

Station A 321, vertical phytoplankton net haul:

- *Nitzschia seriata*
- *Thalassiothrix nitzschioides*
- *Streptotheca thamesis*
- *Chaetoceros teres*
- *Chaetoceros danicus*
- *Striatella interrupta*
- *Schroederella delicatula*
- *Chaetoceros vanheurcki*
- *Leptocylindrus danicus*
- *Asterionella japonica*
- *Dinophysis forti*
- *Ceratium buceros*
- *C. lineatum*
- *Peridinium divergens*
- *Goniaulax polygramma*

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*Now at University of Miami, U.S.A.

INDEX

MILFORD SOUND

BATHYMETRY

SCALE 1 : 32,750 AT LAT. 44° 36′

TO ACCOMPANY N.Z. OCEANOGRAPHIC
INSTITUTE MEMOIR NO. 17

NOT TO BE USED FOR NAVIGATIONAL PURPOSES
MISCELLANEOUS SERIES NO. 5

C. T. T. Webb, Chief Cartographer

Isobaths drawn from soundings on Admiralty Chart 615 (H.M.S. Acheron 1851, H.M.S. [illegible] 1935) and additional echo-soundings by H.D.M.S. Galathea 1952, H.M.N.Z.S. [illegible] 1954 and H.M.A.S. Australia 1954 in the records of the N.Z. Oceanographic Institute, and for the area east of Dale Point, detailed N.Z.O.I. echo-soundings taken [illegible] 1957.

Bathymetry by J. W. Brodie. Compilation by [illegible]
[illegible]

[illegible]

Fathoms

Fathoms	
0—50	
50—100	
100—150	

References

Isobaths — 80 —
Isobaths drawn thus — 88, 89, 90, 91
Down-slope direction
Formlines
[illegible]
[illegible]

Topographic detail from plan "Topographical Survey of Milford Sound" by T. W. Preston, May 1927 (Records of the Survey of New Zealand, Vol. LVI) with additions from photographs.

Note: The topographic [illegible] is no more than a general [illegible] of the land form.

This chart is not to be used for navigational purposes.

Refer to this chart as N.Z. Oceanographic Institute Chart, Miscellaneous Series No. 5, Milford Bathymetry 1963.

NEW ZEALAND OCEANOGRAPHIC INSTITUTE
WELLINGTON

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