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Fiord Studies : Caswell and Nancy Sounds, New Zealand

Edited by

G.P. GLASBY

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FRONTISPIECE : Oblique aerial photograph looking along length of Caswell Sound (Whites Aviation Ltd).

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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

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INTRODUCTION

by

G.P. Glasby

Although the development of fiord-type environments is a well documented phenomenon in the Northern Hemisphere, the geological conditions controlling the development of the New Zealand fiords are complicated by the fact that the Alpine Fault intersects the coastline immediately north of Milford Sound. The Fiordland region therefore lies on the active margin of New Zealand.

For the marine scientist, the principal feature of interest in the Fiordland region lies in the development of a number of large fiords, from Dusky Sound in the south to Milford Sound some 175 km further north, which represent the drowned lower reaches of valleys formerly occupied by glaciers in the last glacial period. The characteristic features of these fiords are the incised nature of the topography, which often shows evidence of successive periods of glacial activity, and the development of shallow sills at the entrances of the fiords, which restrict the free circulation of water within the fiords. In the case of Lake McKerrow, seaward access to the fiord has become completely cut-off and the drowned valley is now landlocked. Glaciers do not now enter the fiords of New Zealand, although this phenomenon is encountered elsewhere (Pickard 1971, 1973).

Because of the characteristic relief of the fiords, free exchange of water between the ocean and the basin can take place only above the intervening sill, and the salinity and temperature 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 offshore water flowing in over the threshold and then sinking. An effective suppression of these renewal processes, such as may arise through intense density stratification above sill depth due to the influx of large quantities of fresh water into the basin, will result in the heavier bottom waters being statically isolated until conditions alter sufficiently to enable replacement of the deep waters to take place. The basins therefore become analagous to what Worthington (1971) has described as "Arctic Mediterranean Seas".

If the above conditions are extreme, stagnation of the bottom waters of fiords can take place due to depletion of oxygen in the waters by the process of biological respiration (Richards 1971). This phenomenon is, however, rare and the bottom waters of the majority of fiords in Norway, British Columbia, Alaska, and Chile are aerobic. Bottom muds rich in organic material deposited by streams as debris in the fiords may, however, still become anoxic, even in fiords where the bottom waters are significantly oxygenated, owing to biological oxygen demand in the sediments themselves. Hydrogen sulphide is then formed by bacterial sulphate reduction. This has the effect of blackening the sediment due to the formation of iron sulphide minerals and rendering the bottom sediments uninhabitable for animal life. The development of a sulphide-rich environment within the sediment column is therefore an important factor in defining both the sedimentation characteristics and the distribution of bottom fauna within fiord-type environments (*see also* Degens and Stoffers 1976). Examples of lakes and fiords in which anoxic conditions have been observed in the bottom layers are given by Strøm (1957, 1961), Williams *et al* (1961), Bøyum (1973), Barnes *et al* (1974), Bremmeng (1974), and Beyer (1976).

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In this memoir, an attempt is made to define more closely the bathymetry, sedimentology, hydrology, and biology of Caswell and Nancy Sounds in order to elucidate the principal features of the marine environment in the southern fiords of New Zealand. To facilitate interpretation, the data are compared wherever possible with previously reported findings from Milford Sound (Skerman 1964). The reader is referred to Hall-Jones (1965) for a more general description of Fiordland.

Samples were collected from MV *Taranui* during the period 26 January - 8 February 1971. Members of the N.Z.O.I. staff participating in the cruise were Drs G.P. Glasby and I.N. Estcourt, Messrs J. Irwin B.R. Stanton, D.G. McKnight and J.C. McDougall. The master, officers and crew of MV *Taranui* are thanked for their assistance in this project.

REFERENCES

BARNES, M.A.; BARNES, W.C.; MATHEWS, W.H.; MURRAY, J.W. 1974: Fatty acids in the bottom sediments of a meromictic fjord lake, British Columbia, Canada. Abstracts with Programs Annual Meeting Geological Society of America 6(5) : 424.

BEYER, F. 1976: Influence of freshwater outflow on the hydrography of the Dramsfjord in southern Norway. Pp 75-67 *in* Skreslet, S.; Lernebo, R.; Matthews, J.B.L.; Sakshaug, E. (eds) "Fresh Water on the Sea". Proceedings of a symposium on the influence of freshwater outflow biological processes in fjords and coastal waters, 22-25 April 1974, Geilo, Norway. The Association of Norwegian Oceanographers, Oslo.

BØYUM, A. 1973: Salsvatn, a lake with old seawater. *Swiss Journal of Hydrology 35* : 262-7.

BREMMENG, G.S. 1974: Strandvatn, northern Norway, a lake with old sea-water. *Swiss Journal of Hydrology 36* : 351-6.

DEGENS, E.T.; STOFFERS, P. 1976: Stratified waters as a key to the past. *Nature, London 263* : 22-7.

HALL-JONES, G. 1965: Handbook to the Fiordland National Park. Fiordland National Park Board, Invercargill. 74 p.

PICKARD, G.L. 1971: Some physical oceanographic features of inlets of Chile. *Journal of the Fisheries Research Board of Canada 28* : 1077-106.

PICKARD, G.L. 1973: Water structure in Chilean fjords. Pp 95-104 *in* Fraser, R. (comp.) "Oceanography of the South Pacific 1972". N.Z. National Commission for UNESCO, Wellington. 524p.

RICHARDS, F.A. 1971: Anoxic versus oxic environments. Pp 201-17 *in* Hood, D.W. (ed.) "Impingement of Man on the Oceans". Wiley-Interscience, New York. 738 p.

SKERMAN, T.M. (ed.) 1964: Studies of a Southern Fiord. *Memoir N.Z. Oceanographic Institute 17. (N.Z. Department of Scientific and Industrial Research Bulletin 157).* 101 p.

STRØM, K. 1957: A lake with trapped sea-water? *Nature, London 180* : 982-3.

STRØM, K. 1961: A second lake with old sea-water at its bottom. *Nature, London 189* : 913.

WILLIAMS, P.M.; MATHEWS, W.H.; PICKARD, G.L. 1961: A lake in British Columbia containing old sea-water. *Nature, London 191* : 830-2.

HISTORICAL NOTE

by

G.P. Glasby

Because much of the early European exploration of Fiordland was carried out by sealers and whalers, the historical records are incomplete and the naming of some of the less frequently visited fiords remains a matter for conjecture. Caswell Sound is such a fiord. Beattie (1950) mentions a tradition that it was named after Jim Caswell, a half-caste Maori who was in charge of a sealing gang wrecked near its mouth. More probably, however, it was named after either Commander Thomas Caswell, R.N. or Commander William Caswell, R.N. who visited it in the 1830s. Mount Tanilba, which rises above the north head of the entrance, bears the name of the Caswell family home in England. Marble occurs at Caswell Sound and was worked for a time between 1881 and 1887 by the Caswell Sound Marble Company. Samples of the stone obtained a high award at an early international exhibition in Sydney. In 1863, James McKerrow looked down on the sound from Mount Pisgah, and in 1927 a party under T.W. Preston fixed the latitude and longitude of observation spots at Caswell Sound by precise astronomical observation and mapped the area at the head of Caswell Sound. In 1949 an area at the head of the sound was explored extensively by a joint New Zealand-American expedition (Poole 1949, 1951).

Nancy Sound is most probably named after the *Nancy*, a later command of Captain John Grono, a sealer born in Wales and skipper of the schooner *Governor Bligh*, who is known to have worked in these waters prior to 1823 and who rescued a party of marooned sealers in Open (Jackson's) Bay on about 27 November 1813.

In spite of these early visits, it is clear from a map prepared by Lieut. Thomas McDonnell, R.N. (McDonnell 1834) that very little was known at that time about the area north of Doubtful Sound. The Admiralty survey of 1850-52, under Capt. John Lort Stokes in the vessel *Acheron*, was the first comprehensive survey of the coastline of Fiordland and it is a tribute to the skill of these surveyors that their chart (British Admiralty Chart 768, on which the Hydrographic Office (1959) chart is based) with only minor amendments is still in use today. The name Caswell Sound appears for the first time on the Stokes chart. Unfortunately, apart from the published charts, no record of this work is readily available.

Exploration overland did not press west of Lake Te Anau until 1877, when Q. McKinnon, more reknowned for his work in the Clinton Valley on the Milford Track, accompanied by G. Tucker, a rabbit poisoner, travelled from Lake Te Anau towards Caswell Sound and saw the lakes to which they gave the names Lake McKinnon and Lake Tucker. Doubt still exists on the whereabouts of Lake Tucker and it is not named in modern charts. According to the sketch map McKinnon produced, however, it is probable that what he thought was Caswell Sound was actually Lake Marchant (Hall-Jones 1968).

Finally, it must be remembered that the fiords have an extensive Maori history. Caswell Sound was named Tai-te-timu (ebbing tide) by the Maoris and Nancy Sound Hinenui (big woman). An excellent account of the Maori history of Fiordland is given by Beattie (1949). It is of interest that the Maoris named only six features in Caswell Sound and 12 features in Nancy Sound, amongst the lowest in all the fiords. This suggests that the two were amongst the least visited of the fiords.

REFERENCES

BEATTIE, J.H. 1949: The Maoris and Fiordland. Otago Daily Times, Dunedin. 104p.

BEATTIE, J.H. 1950: Far Famed Fiordland. Otago Daily Times, Dunedin. 141p.

HALL-JONES, J. 1968: Early Fiordland. A.H. & A.W. Reed, Wellington. 199p.

HYDROGRAPHIC OFFICE, ROYAL NEW ZEALAND NAVY, 1959: Daggs Sound to Caswell Sound 1:72,000. *Chart NZ7522.*

McDONNELL, Thomas 1834: Chart of New Zealand from Original Surveys. Wyld, Charing Cross, London.

POOLE, A.L. 1949: Brief account of the New Zealand-American Fiordland Expedition. *N.Z. Science Review 7* : 134-7.

POOLE, A.L. (comp.) 1951: Preliminary reports of the New Zealand-American Fiordland Expedition investigation in Fiordland, New Zealand, in 1949. *N.Z. Department of Scientific and Industrial Research Bulletin 103* . 99p.

BATHYMETRY OF CASWELL AND NANCY SOUNDS

by

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ABSTRACT

Caswell and Nancy Sounds are characterised by a series of basins along their lengths which become progressively deeper from the head of the sounds seaward. Maximum depths of the main basins are 416 m for Caswell Sound and 279 m for Nancy Sound and each is separated from the shelf area by a sill at the entrance. The geology and glacial history of the area are discussed.

INTRODUCTION

Caswell and Nancy Sounds lie between latitudes 45°S and 45°15'S on the south-west coast of South Island, New Zealand (Fig. 1). Both are characterised by steep-sided valleys typical of fiords. The valleys are covered by native bush extending from the snow line to the high water mark. Each sound receives water from many small steep-sided streams and large rivers flow into their heads. Nancy Sound also receives water from a river entering at Heel Cove, 3 km from its head. The main rivers entering the sounds flow across alluvial plains in their lower reaches. The bathymetry and structure of the offshore region outside the fiords has been documented elsewhere (Barker 1967; Christoffel and van der Linden 1972; van der Linden and Hayes 1972; Woodward 1972; Davey and Broadbent 1974; Davey and Williams 1975).

METHODS

An extensive network of traverses 300-400 m apart was run across the fiords at right angles to the shore line. Several longitudinal traverses were also carried out in each fiord to check the main network of soundings. Soundings were taken from a 3.7 m boat powered by outboard motor, using a Furuno F850 echo sounder operating at a frequency of 50 kHz from a 12-volt battery. This small boat enabled sounding traverses to be carried to the shore line giving detail of the steep fiord walls.

Temperature and water salinity data were collected at the time of the sounding survey from stations (8 stations Caswell Sound; 6 stations Nancy Sound) along the length of the Sounds (*see* Stanton, p.73). These data were used to correct the bathymetric data for variations in the velocity of sound in water using Matthews Tables (1939). Tidal measurements were also taken over the period of the survey, and soundings were reduced to approximately Mean Low Water Spring tidal levels.

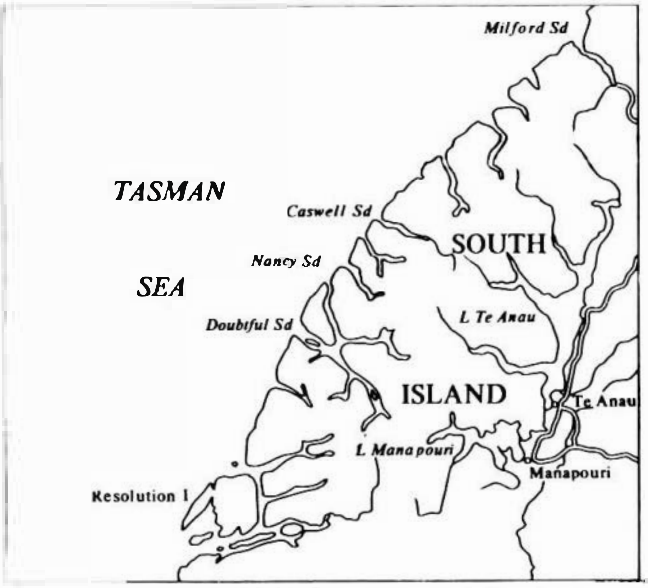

FIG. 1. Relative positions of Milford, Caswell, and Nancy Sounds.

PREVIOUS SOUNDINGS

Both Caswell and Nancy Sounds were surveyed in 1851 by HMS *Acheron* using lead line and the soundings (143 in Caswell Sound, 100 in Nancy Sound) are recorded on Hydrographic Office Chart NZ7522. In the present survey, 1,175 soundings have been used to establish the bathymetry of Caswell Sound and 1,026 soundings for Nancy Sound. The deepest *Acheron* sounding for Caswell Sound is 230 fm (421 m), which compares with the deepest recorded sounding of 416 m in this survey; Nancy Sound shows 134 fm (245 m) which compares with 279 m in this survey. The positions of the deepest recorded depths for both sounds are close to the maximum depths shown on Chart NZ7522 from HMS *Acheron*.

BATHYMETRY

The bathymetry of Caswell and Nancy Sounds is shown in Figs 2 and 3. As both sounds are narrow in relation to their lengths it is not possible to show all contours at this scale and reference may be made to the published bathymetric charts (Irwin 1973, 1974).

CASWELL SOUND

Caswell Sound lies WNW, is 15 km long and varies in width from 0.4 to 1.6 km. The bottom topography is characterised by steep sides and three main basins which lie along its length. From the head of the sound the bottom slopes gently to Stillwater Basin, 2.2 km long and up to 0.6 km wide, enclosed by the 140 m contour. At the seaward end of this basin and 4.4 km from the head of the sound, the depth increases to 163 m. Enclosed by the 160 m contour, this inner basin occupies a small area 0.6 km long and from 0.1 to 0.2 km wide, 0.8 km east of Boat Rock.

A sill 110 m deep lies off Boat Rock between Stillwater Basin and the smaller Walker Basin which is 6.0 km from the head of the sound. Enclosed by the 160 m contour and 0.7 km long and from 0.1 to 0.2 km wide, the maximum depth of Walker Basin is 167 m. A small hole of 129 m lies near the centre of the dividing sill.

West of Walker Point the bottom rises to a sill with a depth of 147 m, from this point and along the centre of the sound the bottom slopes steeply to a depth of 320 m, 1.4 km down-sound, then becomes less steep to become the third and largest basin, Marble Basin. Enclosed by the 400 m contour, Marble Basin is 2.5 km long and from 0.5 to 0.4 km wide and has a maximum depth of 416 m near its centre. From the 400 m contour the bottom at mid-sound rises gently to 320 m 1.6 km further seaward and about 1.2 km from the entrance. Across the entrance to the sound the shallowest depth recorded was 143 m in a position north of Styles Island.

The entrance may be shallower than the 143 m shown on the chart but it was not possible to sound further seaward from a small boat. The echo-sounding record (Fig. 4) taken on MV *Taranui* along the approximate centre line of the sound shows a minimum depth of 66 m at the entrance, but there is nothing to indicate that this track is along the deepest section of the entrance sill.

NANCY SOUND

Nancy Sound is leg-shaped. The "foot" of the sound is 3.6 km long and lies ENE. The main part of the sound lies in a NW direction for 10 km and W for 2 km. The width varies between 0.4 and 1.4 km. The bottom topography of Nancy Sound is similar to that of Caswell Sound in that the fiord walls are steep, but Nancy Sound has four basins along its centre.

From the head of the sound the bottom slopes to Heel Basin, off Heel Cove, centred 3.2 km down the sound. Enclosed by the 100 m contour and 1.3 km long and 0.2 km wide the maximum depth found was 111 m. A sill of 78 m, SW of Bend Point, divides Heel Basin from Richards Basin at 220 m, 0.2 km long and 0.1 km wide, 5.7 km from the head of the sound.

Further seaward the bottom rises to a sill 193 m deep and 0.4 km long, before gently sloping to Stokes Basin, maximum depth 223 m, 3.0 km further down the sound. Stokes Basin is very narrow, the sound walls show less gradient below 120 m depth with the contours bulging towards mid-sound restricting its width. Within 0.3 km of Stokes Basin the bottom rises to a sill of 204 m before sloping gently to the fourth and main basin, Acheron Basin.

Enclosed by the 260 m contour, 2.4 km long and from 0.3 to 0.4 km wide, Acheron Basin has a maximum depth of 279 m at 11.2 km from the head of the sound. From the 260 m contour the bottom at mid-sound rises gently in 2.2 km to become 77 m deep between Anxiety Island and Entrance Island. Further seaward a traverse across the sound entrance gave a maximum depth of 95 m, so the depth of 77 m would appear to be the shallowest sill sounding. An echo sounder trace (Fig. 5) taken on MV *Taranui* along the approximate centre line of the sound shows a sill depth of 33 m but the trace may not be along the deepest section of the entrance sill.

COMPARISON OF CASWELL, NANCY AND MILFORD SOUNDS

Previous studies by Bruun *et al* (1955) showed Milford Sound to have a main basin (Stirling Basin), with a maximum depth of 293 m recorded on a mid-sound traverse by HDMS *Galathea*. Subsequent studies by Brodie (1964), however, recorded a maximum depth of 269 m in Stirling Basin which is separated from an entrance basin of maximum depth of 140 m by a small basin of 128 m, 1.0 km east of Dale Point.

Table 1 shows the main morphological properties of each sound. All three sounds are characterised by

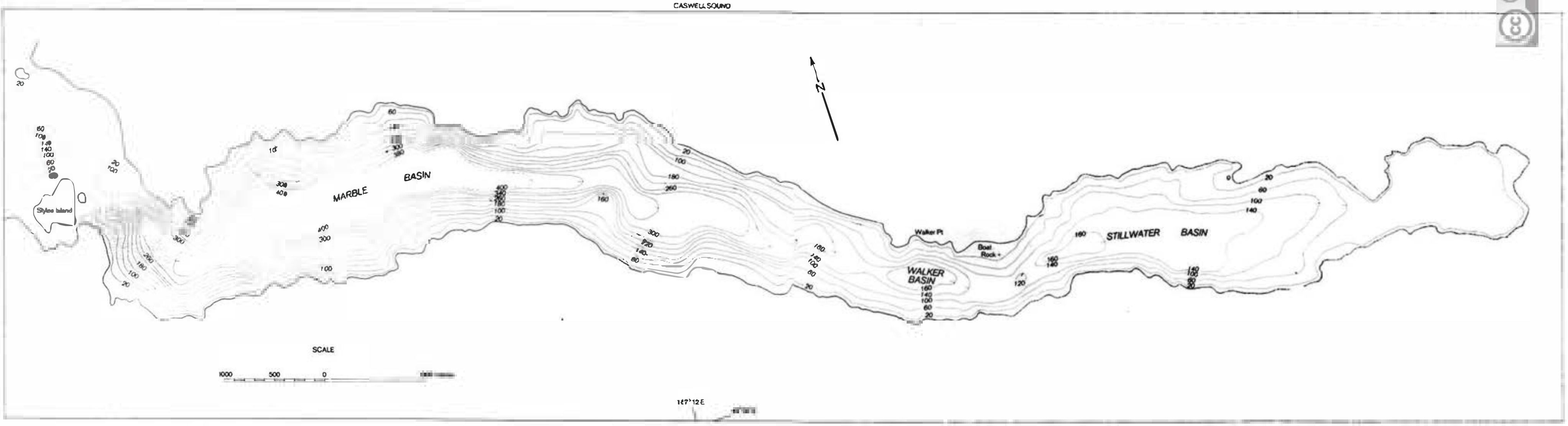

FIG. 2. Bathymetry of Caswell Sound in metres.

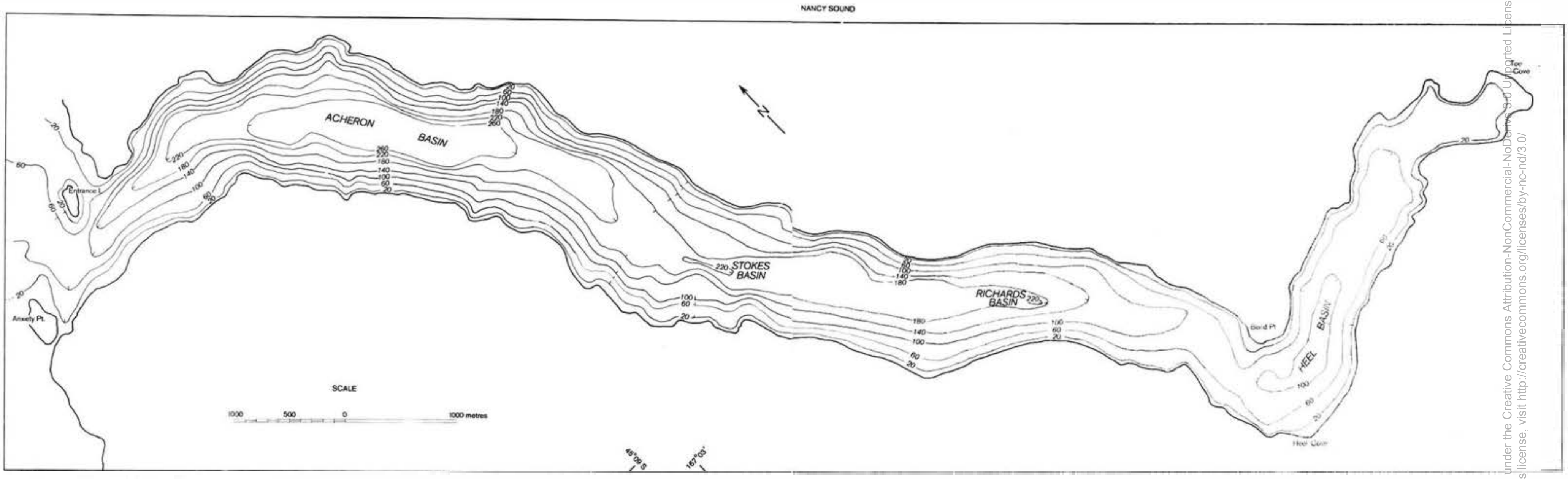

FIG. 3. Bathymetry of Nancy Sound in metres.

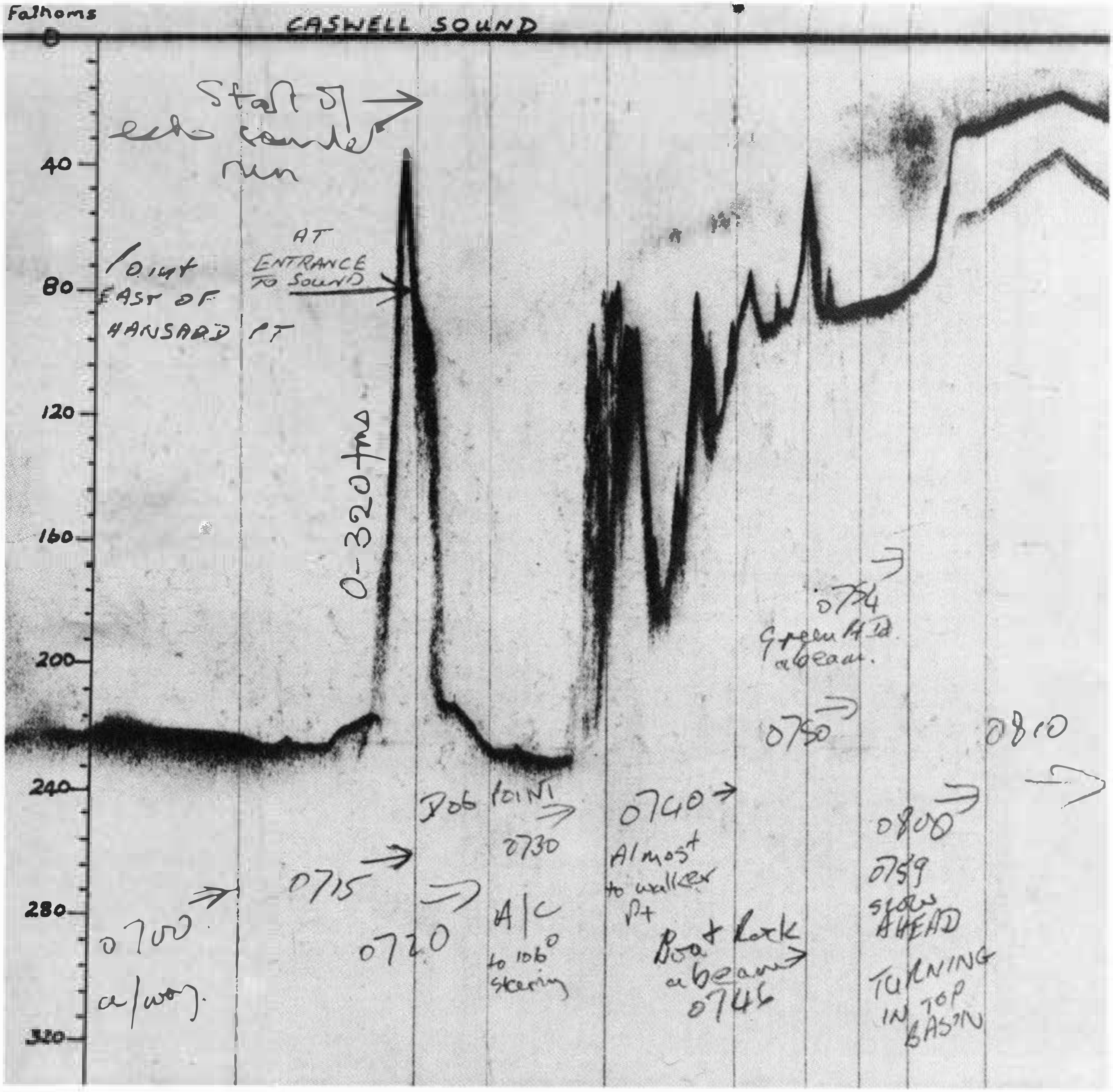

FIG. 4. Echo sounder record from MV *Taranui* along approximate centre line of Caswell Sound showing entrance sill and basins.

very steep-sided walls which become steeper adjacent to their main basins. Although of similar length (*see* Table 1), the main basin of Milford Sound (Stirling Basin) lies 6.5 km from the head of the sound while the main basins of Caswell Sound (Marble Basin) and Nancy Sound (Acheron Basin) are 11 and 12 km respectively from their heads. The basins along Caswell and Nancy Sounds become progressively deeper seaward from their heads but in Milford Sound the deepest basin is close to the head of the sound.

An entrance sill of 143 m was recorded for Caswell Sound and 77 m for Nancy Sound. Bruun *et al* (1955) recorded an entrance sill minimum centre line depth of 82 m for Milford Sound while Brodie (1964) recorded 97 m.

GLACIAL HISTORY

The drowned glacial valleys of Milford and Dusky Sounds extend across the narrow continental shelf

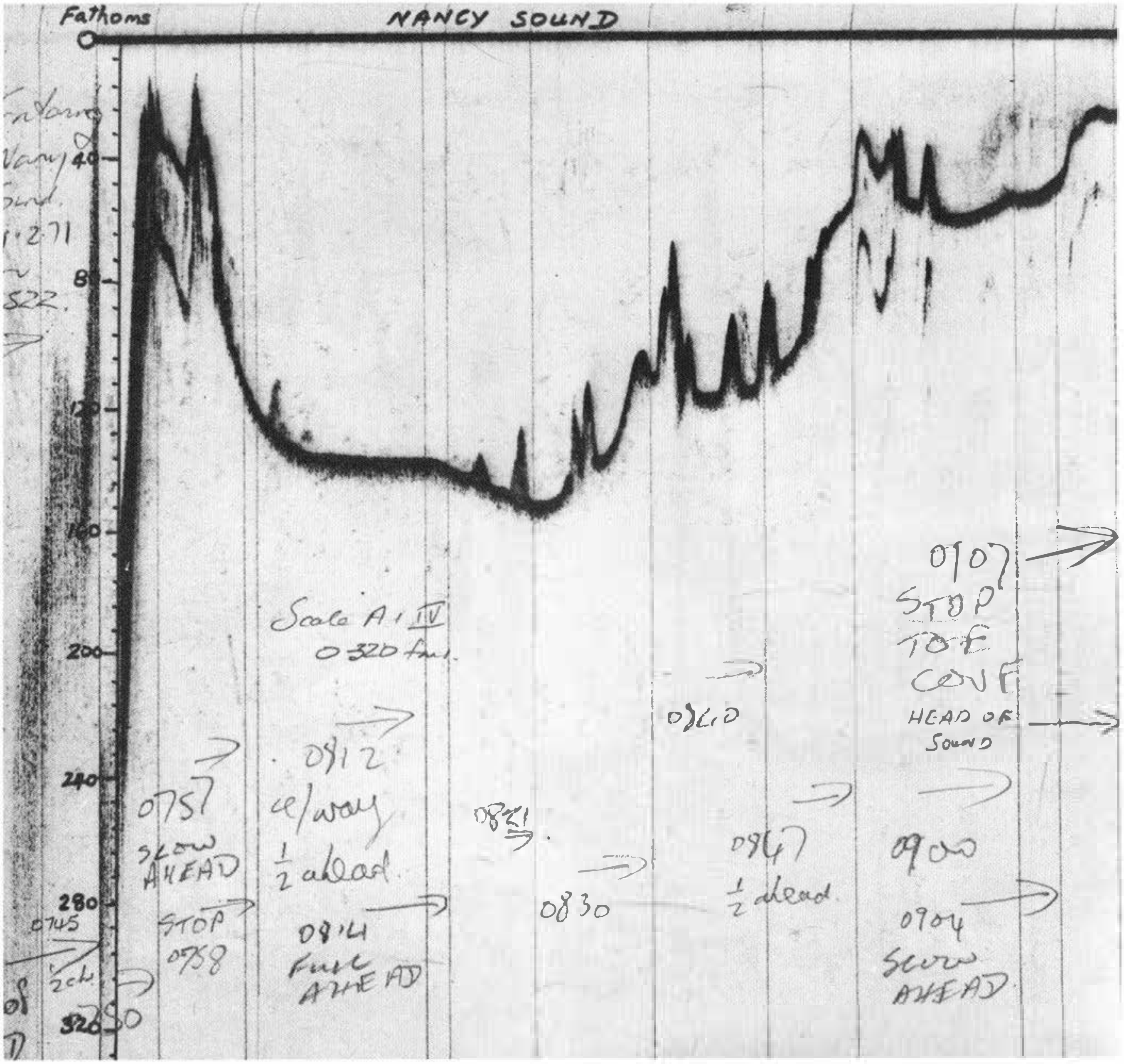

FIG. 5. Echo sounder record from MV *Taranui* along approximate centre line of Nancy Sound showing entrance sill and basins.

TABLE 1. Morphological data for Caswell, Nancy and Milford Sounds.

	Length (km)	Maximum width (km)	Minimum width (km)	Maximum depth (m)	(Number) and depth of basins (m)	(Number) and depth of sills (m)
Caswell	15.0	1.6	0.4	416	(3) 163, 167, 416	(3) 110, 147, 143
Nancy	15.6	1.4	0.4	279	(4) 111, 220, 223, 279	(4) 78, 193, 204, 77
Milford (from Brodie 1964)	14.0	2.6	0.5	269	(3) 269, 128, 140	(3) 97, 110-128, 110-128

(Brodie 1964). There are indications from the present data that the same situation exists off Nancy Sound.

The last episode of downcutting of the glacial valleys of Fiordland, as represented in Milford Sound by Stirling Basin and the steep, freshly trimmed lower fiord walls, took place in the last stadial of the last Glaciation (Bruun *et al* 1955). At Milford Sound the cross-sectional profile reveals the remains of broader, higher, glacial valley floors assigned to the penultimate Glaciation.

At the junctions with tributary ice streams, the valley floor was further excavated by the ice. In Nancy Sound such an explanation can be made for Richards Basin and Stokes Basin which are down-fiord from a large glacial tributary that entered from the south shore at Heel Cove, and again for Acheron Basin which lies down-fiord from a former major glacial tributary from the north-east shore. In Caswell Sound, the major basin (Marble Basin) follows the junction with a former glacial tributary valley from the north shore. Similarly in Milford Sound the Stirling Basin follows the junction with the Pembroke Valley (Bruun *et al* 1955). In all three fiords deepening was accompanied by widening so that each fiord is widest at the major basin.

The situation of the major deep basin in each of Milford, Nancy and Caswell Sounds in an area immediately landward of the present coast suggests that the last stadial glacier was of similar extent in each.

GEOLOGY OF THE CASWELL AND NANCY SOUNDS AREA

The Fiordland region has been described by a number of authors, notably Andrews (1906), Park (1921), Benson (1935a, b), Cotton (1948), Wood (1960, 1965, 1972) and Oliver (1975). The form of the fiords results from the action of thick glaciers that overdeepened the floors of pre-existing valleys which were formed by preglacial fluvial erosion (Lobeck 1939; Flint 1945; Wellman and Willett 1942; Cotton 1947, 1952; Willett 1950; Winslow 1966, 1968; Soons 1968; Davies 1969). Excavation of valleys under the ice proceeded far below sea level. When the glaciers disappeared, the sea was able to enter and occupy nearly vertical-walled trenches and troughs of great depth (Cotton 1948). Shore processes have not been investigated here but have been the subject of study in Fiordland lakes (Pickrill 1976).

Benson (1935a) notes that the sides of the fiords rise steeply from the shore at angles of up to about 25 to 30° when cut in schists and up to 50 to 60° or even steeper when cut in granite.

Early authors (Andrews 1906; Park 1921) infer that, because the summits and ridge crests of the Fiordland region are at very even levels, there existed at earliest Middle Tertiary times a plateau (the "Fiordland Peneplain") and that the glaciers followed the floors of river valleys cut in this plateau, the directions of which had to some extent been determined by fractures transversing the crystalline rocks of the area.

Caswell and Nancy Sounds are cut in Paleozoic schists and gneisses (Wood 1960). The rocks about the entrance to Caswell Sound consist of hornblende-plagioclase gneiss and schist, garnet-augite and garnet-hypersthene gneiss with amphibolite above 610 m, all of the Wet Jacket Formation. Within this entrance area, on the north and south sides, are hornblende-gneiss, calc-gneiss, schist and marble of the Long Sound Formation outcrop. On the southern shore, Lake Shirley is surrounded by rocks of the Long Sound Formation and this is itself surrounded by rocks of the Wet Jacket Formation. Except for a small area of outwash gravels and moraines of the last glaciation at the head of Caswell Sound, the remainder of the surrounding area is composed of weakly foliated paragneiss and orthogneiss, with and without garnet, of the Bradshaw Formation.

On the north shore of Caswell Sound nearly opposite Dog Point, which is about one-third of the length of the sound from the entrance, a deposit of blue-grey marble was discovered by Alexander Mackay in 1881. The total thickness of the outcrop was estimated at 60 m. On the south side of the sound, 1.8 km west of Dog Point, white marble from 14 to 15 m thick was found at the water's edge (Mackay 1882).

The rocks surrounding most of Nancy Sound are the weakly foliated paragneiss and orthogneiss of the Bradshaw Formation. A small area adjacent to the entrance of the sound is made up of hornblende-gneiss, calc-gneiss, schist and marble (Long Sound Formation) and on the south side of the entrance there is an area of muscovite schist and hornblende-plagioclase gneiss (Thompson Formation). Where rivers enter the sound at Toe Cove, the head of the sound, and at Heel Cove, there are small areas of alluvium, beach gravels, and estuarine and swamp deposits.

REFERENCES

ANDREWS, E.C. 1906: The ice flood hypothesis and the New Zealand Sounds. *Journal of Geology 14* : 32-54.

BARKER, P.H. 1967: Bathymetry of the Fiordland continental margin. *N.Z. Journal of Science 10* : 128-37.

BENSON, W.N. 1935a: Notes on the geographical features of southwestern New Zealand. *Geographical Journal 86*: 393-401.

BENSON, W.N. 1935b: Some land forms in southern New Zealand. *Australian Geographer 2* : 3-22.

BRODIE, J.W. 1964: The Fiordland shelf and Milford Sound. Pp 15-23 *in* Skerman, T.M. (ed.) "Studies of a Southern Fiord". *Memoir N.Z. Oceanographic Institute 17 (N.Z.*

Department of Scientific and Industrial Research Bulletin 157). 101p.

BRUUN, A.Fr.; BRODIE, J.W.; FLEMING. C.A. 1955: Submarine geology of Milford Sound, New Zealand. *N.Z. Journal of Science and Technology B36* : 397-410.

CHRISTOFFEL, D.A.; VAN DER LINDEN, W.J.M. 1972: Macquarie Ridge-New Zealand Alpine Fault transition. *Antarctic Research Series 19* : 235-42.

COTTON, C.A. 1947: "Climatic Accidents in Landscape-Making". Whitcombe & Tombs Ltd, Christchurch. 354p.

COTTON, C.A. 1948: Otago's Physiography. *In* Garnier, B.J. (ed.) "The Face of Otago". *Otago Centennial Historical Publication* : 17p.

COTTON, C.A. 1952: "Geomorphology". Whitcombe & Tombs Ltd, Christchurch. 505p.

DAVEY, F.J.; BROADBENT, M. 1974: Seismic investigations in Fiordland, New Zealand. Paper presented at NELCON 10th N.Z. National Electronics Convention, University of Auckland, 26-30 August, 1974.

DAVEY, F.J.; WILLIAMS, R.B. 1975: Seismic survey in Fiordland, March 1974. *Geophysics Division Technological Note 71* : 13p.

DAVIES, J.L. 1969: "Landforms of Cold Climates". Australian National University Press, Canberra. 200p.

FLINT, R.F. 1945: "Glacial Geology and the Pleistocene Epoch". John Wiley & Sons, New York. 589p.

HYDROGRAPHIC OFFICE, ROYAL NEW ZEALAND NAVY, 1959: Daggs Sound to Caswell Sound 1:72,000. *Chart NZ7522.*

IRWIN, J. 1973: Caswell Sound Bathymetry 1:15,840. *N.Z. Oceanographic Institute Chart, Miscellaneous Series 23.*

IRWIN, J. 1974: Nancy Sound Bathymetry 1:15,840. *N.Z. Oceanographic Institute Chart, Miscellaneous Series 24.*

LOBECK, A.K. 1939: "Geomorphology". McGraw-Hill, New York. 731p.

MACKAY, A. 1882: On the Caswell Sound marble. *N.Z. geol. Surv. Rep. geol. Explor. 1881, 14* : 115-8.

MATTHEWS, D.J. 1939: Tables of the velocity of sound in pure water and sea water for use in echo sounding and sound ranging. *Admiralty Hydrographic Department 282* : 1-51.

OLIVER, G. 1975: Geology of Doubtful-Breaksea Sounds, New Zealand. Unpublished Ph.D. thesis, University of Otago.

PARK, J. 1921: Geology and mineral resources of western Southland. *Bulletin of the N.Z. Geological Survey 23 (n.s.)* : 88p.

PICKRILL, R.A. 1976: The lacustrine geomorphology of Lakes Manapouri and Te Anau. Unpublished Ph.D. thesis, University of Canterbury. 402p.

SOONS, J.M. 1968: Raised submarine canyons : A discussion of New Zealand examples. *Annals of the Association of American Geographers 58* : 606-13.

VAN DER LINDEN, W.J.M.; HAYES, D.E. 1972: Resolution Bathymetry. *N.Z. Oceanographic Institute Chart, Oceanic Series 1:1,000,000.*

WELLMAN, H.W.; WILLETT, R.W. 1942: The geology of the west coast from Abut Head to Milford Sound. Part 2. Glaciation. *Transactions of the Royal Society of N.Z. 72* : 199-219.

WILLETT, R.W. 1950: The New Zealand Pleistocene snow line, climatic conditions and suggested biological effects. *N.Z. Journal of Science and Technology B32* : 18-48.

WINSLOW, J.H. 1966: Raised submarine canyons : An exploratory hypothesis. *Annals of the Association of American Geographers 56* : 634-72.

WINSLOW, J.H. 1968: Stopping at the water's edge : Reason or habit? A reply. *Annals of the Association of American Geographers 58* : 614-34.

WOOD, B.L. 1960: Sheet 27 Fiord 1st Edn. "Geological Map of New Zealand 1:250,000". *N.Z. Department of Scientific and Industrial Research, Wellington.*

WOOD, B.L. 1965: Geology of Fiordland. Pp 47-53 *in* Hall-Jones, G. (ed.) "Handbook to the Fiordland National Park". Fiordland National Park Board, Invercargill. 74p.

WOOD, B.L. 1972: Metamorphosed ultramafites and associated formations near Milford Sound, New Zealand. *N.Z. Journal of Geology and Geophysics 15* : 88-128.

WOODWARD, D.J. 1972: Gravity anomalies in Fiordland, south-west New Zealand. *N.Z. Journal of Geology and Geophysics 15* : 22-32.

SEDIMENTATION AND SEDIMENT GEOCHEMISTRY OF CASWELL, NANCY AND MILFORD SOUNDS

by

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ABSTRACT

Sediments from three fiords of South Island, New Zealand - Caswell, Nancy and Milford Sounds - are organic-rich sandy silts and silty sands interspersed with discrete horizons of sand and fibrous organic material. Grain size analyses show that the sediments become progressively finer towards the fiord basins. Introduction of the sandy silts into the fiords represents the normal situation of suspension load transport of material, whereas introduction of the discrete horizons of sands and fibrous organic matter is caused by periodic debris avalanches into the fiord. Trace metal contents of sediments from the three fiords are similar, although slight differences are apparent, and the fiords are characterised by high rates of sedimentation (in the range 84-430 cms/10^3yrs).

INTRODUCTION

Studies of the sedimentation characteristics of the New Zealand fiords have previously been restricted to Milford Sound (Pantin 1964) where dark grey organic-rich sandy silt interspersed with sand layers appears to form the dominant sedimentary regime. Data collected during the visit of MV *Taranui* to the fiords in 1971 enable a more detailed sedimentological survey of two other fiords, Caswell and Nancy Sounds, to be made in an attempt to deduce the principal modes of sedimentation in this environment. This paper gives a brief account of the chemical and mineralogical characteristics of the sediments and discusses the various processes which have affected their development. In order to present a more objective classification of sediment type, colours of the sediments are described by using the U.S. Geological Survey rock-color chart (Goddard *et al* 1963).

SAMPLE COLLECTION AND DESCRIPTION

Sediment samples were collected using a variety of techniques including foram corer, dredge, grab, and piston corer, the last being a modification of the Kullenberg piston corer described by Langford *et al* (1969). One of the major problems in this study was the extreme difficulty of obtaining undisturbed piston cores in the organic-rich sediments encountered. This stems mainly from the tendency of the sediment to form a slurry with any residual water in the core barrel. Unless the piston remains at the surface of the sediment throughout the entire coring operation, water is sucked into the core barrel and slurrying of the sediment results. This can be particularly pronounced when the core is brought inboard since the core must be held in a horizontal position using the winch systems available on MV *Taranui*. In this position slurrying throughout the sediment column may occur and the core is rendered useless for stratigraphic purposes. Thus great care had to be taken in the collection of piston cores and the interpretation of core stratigraphy.

CASWELL SOUND

Three piston cores, 14 foram cores, 2 dredges, and 5 grab samples were collected at regular intervals in Caswell Sound (Fig. 1; Appendix) and grain size analyses carried out on surface sediment samples (Tables 1 and 2). The surface sediments consist principally of organic-rich sandy silts and silty sands similar to those described by Pantin (1964) for Milford Sound. As shown in Fig. 2, sediments become progressively finer in texture in the major basins, and gravels and sands form the principal sediment type at the entrance to the fiord. Because of the steepness of the slopes of the fiord, no samples were collected in the vicinity of the fiord walls. No manganese deposits were encountered, although specifically looked for. In this the fiord differs from certain of the Northern Hemisphere fiords, such as the Jervis Inlet (Canada)

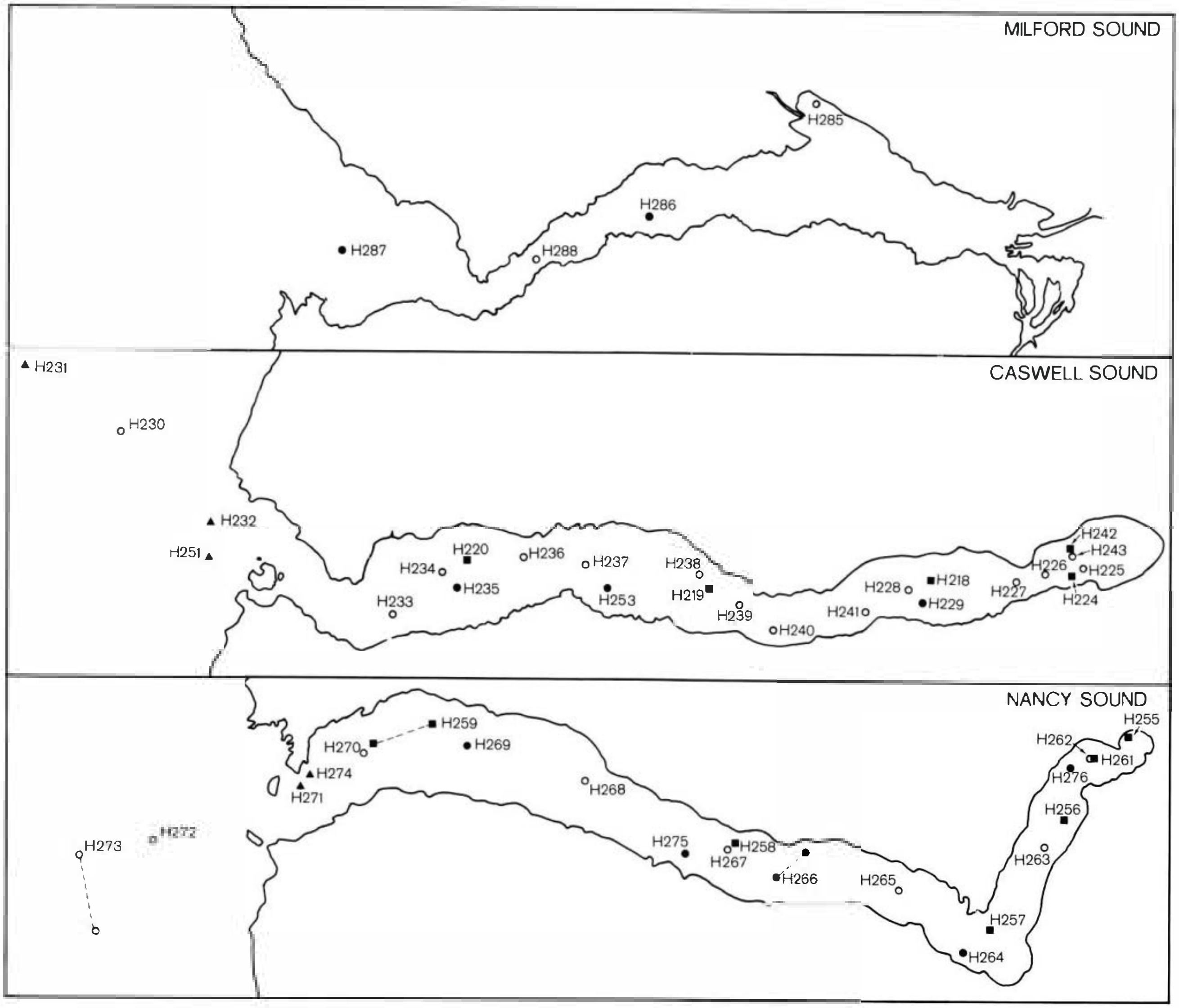

FIG. 1. Schematic diagram showing position of sediment samples in Caswell, Nancy and Milford Sounds. ● Piston core and foram core. o Foram core (H273 also dredge). ▲ Dredge. ■ Grab and underwater camera (H242 and H261 only grab).

and Loch Fyne (Scotland) (Grill *et al* 1968; Calvert and Price 1970), where such deposits are found.

The vertical distribution of material in the sedimentary column is hard to define because of difficulties in obtaining an undisturbed core, as previously discussed. Of the three piston cores taken in Caswell Sound, core H235 was very badly slurried; core H253 was slurried in two regions, leaving large air gaps; and core H229 was largely undisturbed.

Considering a traverse from the head of the fiord, core H229 consists of dusky yellowish brown mud (10 YR 3/2) to a depth of 456 cm with a well defined layer of fibrous organic matter at 176-177 cm overlying a layer of sand at 177-178 cm. Black staining, possibly due to the formation of iron sulphides, was noted in the upper 0.8 cm of the core and also occurred as diffuse horizontal markings in the range 230-250 cm. Core H253, from mid-fiord, consists principally of olive grey mud (5 Y 3/2) with a diffuse layer of sand at 31-36 cm. Core H235 is too badly slurried for detailed stratigraphic studies but consists principally of sand interspersed with layers of olive grey mud (5 Y 3/2). Since olive grey mud (5 Y 3/2) forms the dominant constituent of the foram core from this station, it may form the principal surface sediment type from this locality. The smell of H_2S was noted in cores H229 and H253. Photographs of these cores are presented in Figs 3 and 4 and schematic diagrams of core stratigraphy presented in Fig. 5.

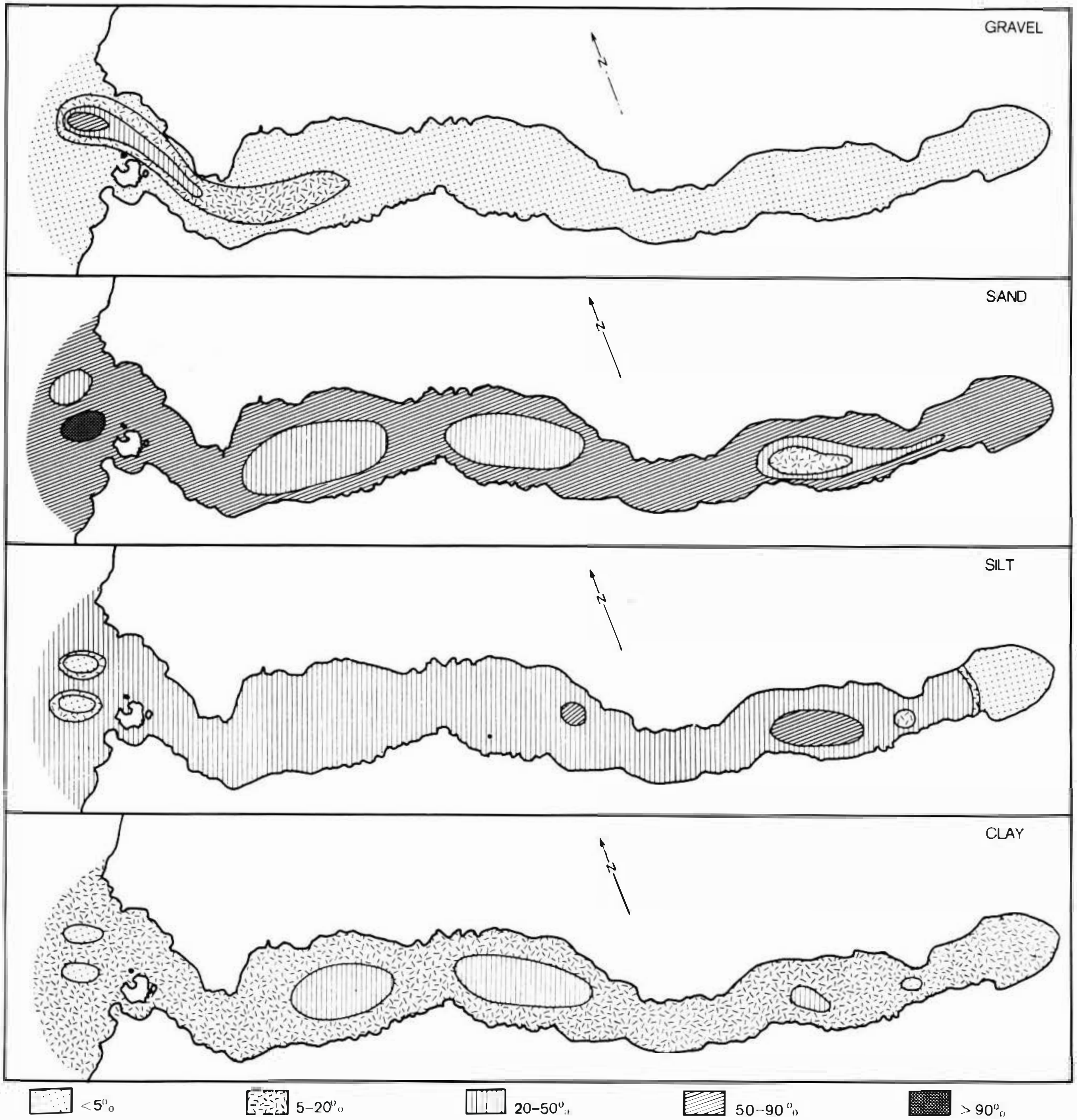

FIG. 2. Schematic diagram showing variations in sediment grain size in Caswell Sound.

NANCY SOUND

Five piston cores, 7 foram cores, 3 dredges, and 6 grab samples were collected in this fiord (Fig. 1; Appendix). The surface sediments again consisted mainly of organic-rich sandy silts and silty sands as encountered in Caswell Sound and showed the same tendency to become finer in texture in the basins (Tables 1 and 2; Fig. 6).

The stratigraphy of the piston cores was again difficult to define because of slurrying of the sediment which resulted in the development of air locks in all five cores studied. Slurrying in the upper layers of the

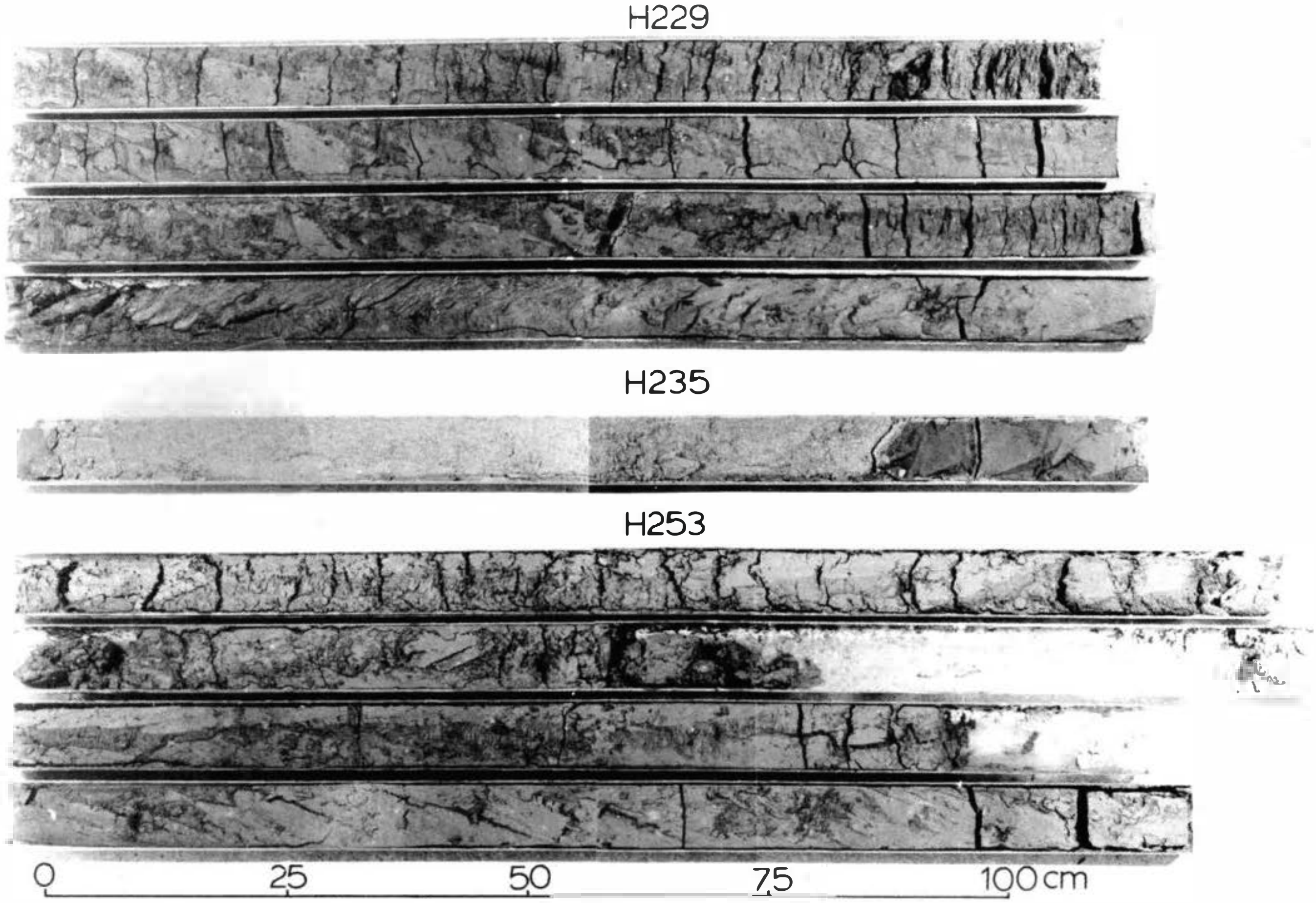

FIG. 3. Photographs of sediment cores from Caswell Sound.

sediment was so extensive in core H276 as to render it useless for stratigraphic purposes.

Considering a traverse from the head of the fiord, core H276 consists of a badly slurried zone approximately 276 cm long overlying a thick layer of sand 224 cm long interbedded with thin layers of greyish black mud (N 2) at depths of 354-355.5 cm and 363-365 cm. The slurried layer consists principally of sand, this probably resulted from the preferential loss of the organic-rich mud from the upper layers of the core due to slurrying, since mud forms the principal component of the surface sediment at this locality.

The four other cores consist of olive black mud (5 Y 2/1) interbedded with layers of sand and fibrous organic material. Of particular interest is the development of a characteristic sequence of fibrous organic matter interbedded with sand in the upper layers of cores H264, H266, and H269. Although this may serve as a useful marker bed, it cannot be traced to core H275 where an entirely different stratigraphic sequence is observed. Wood fragments appear to be well preserved in the sediment, and were encountered at different levels in cores H264 and H266. The bases of cores H266 and H275 are both characterised by a thick layer of sand. Although this may reflect the loss of the middle section of core H275, it may mark the base of the mud layers in this fiord, in which case the total thickness of organic-rich mud may not be significantly greater than 500 cm. The smell of H_2S was detected in cores H264, H269, and H275 and a diffuse black staining, possibly due to the formation of iron sulphide minerals, was observed in core H269 at a depth of 0-5 cm around the edge of the core and throughout the core at a depth 22-29 cm. Photographs of these cores are shown in Figs 4 and 7 and schematic diagrams of core stratigraphy presented in Fig. 8.

MILFORD SOUND

Two piston cores and 2 foram cores were collected in this fiord to supplement data already obtained by Pantin (1964) (Fig. 1; Appendix). Surface sediments were again sandy silts and silty sands (Tables 1 and 2; Fig. 9) as previously described for this fiord by Bruun *et al* (1955) and Pantin (1964).

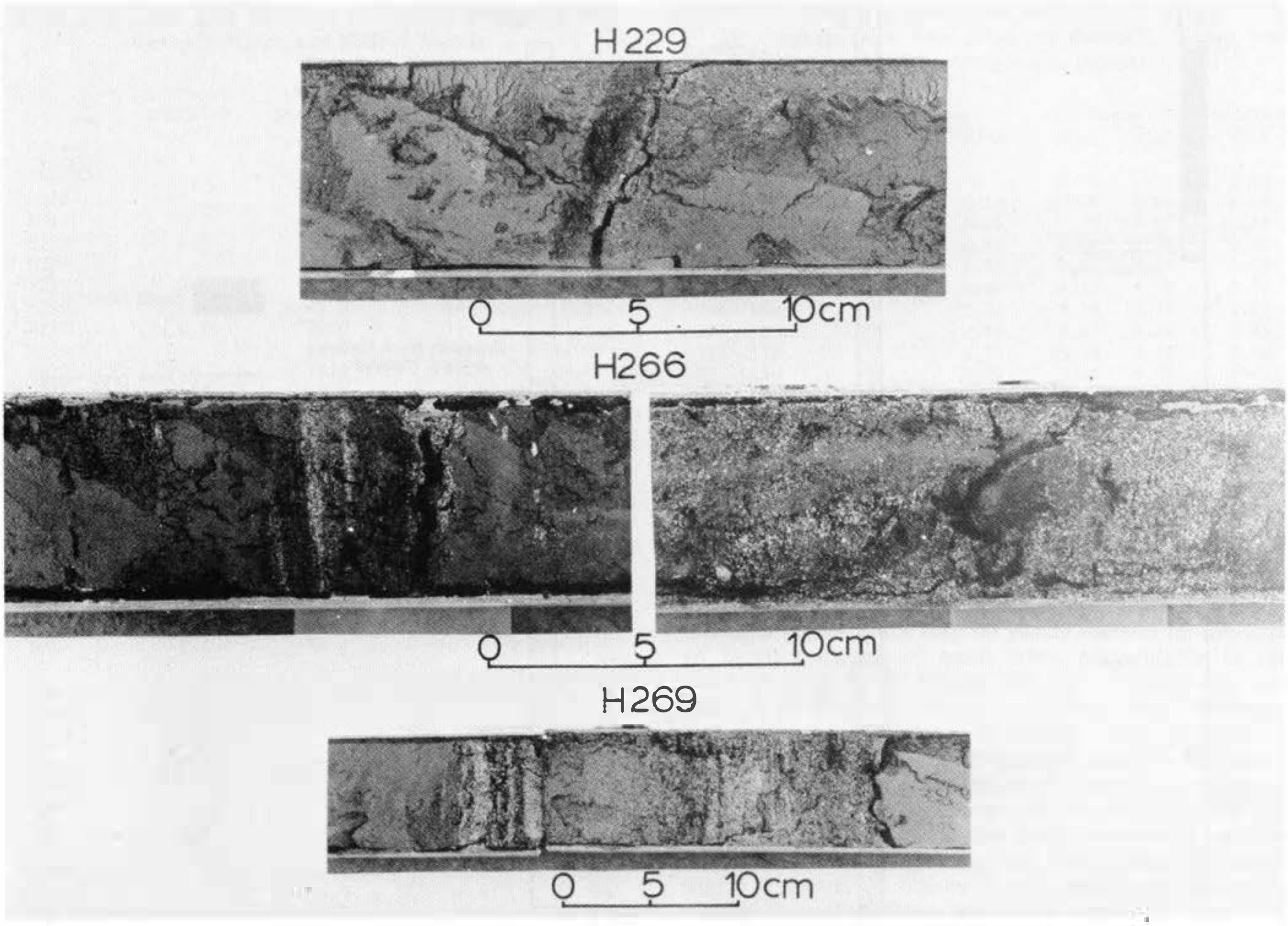

FIG. 4. Higher magnification photographs of sections of sediment cores showing interbedded horizons. Cores from Caswell, Nancy and Milford Sounds.

Core H286 consists of a dark greenish grey mud (5 GY 4/1) interbedded with thin layers of sand at intervals down the core. Blackening of the sediment was noted in the upper 5 cm of the core and also in the range 5-23 cm where horizontal black streaking occurred. This was possibly due to the formation of iron sulphide minerals. Evidence of bioturbation, shown by the recurrence of burrow markings, was noted at 36 and 70 cm. These burrow markings were surrounded by a layer of browner sediment. The core smelt of H_2S.

By contrast, the stratigraphy of core H287 was difficult to study because of the vertical disturbance of the core. Such disturbances occur where a thick layer of sand is overlain by less dense organic-rich mud. In such a case, the less dense mud rides over the sand when the core is brought inboard giving rise to a vertical streaking of both components in the core (Figs 10 and 11). In core H287 sand forms the principal sediment type in the upper 82 cm with thin layers of dark greenish grey mud (5 GY 4/1) at depths of 0-1.5 cm and 32-34 cm. Below this depth, the core is characterised by vertical streaking of the sand and the mud which becomes less significant with depth until mud becomes dominant in the deeper sections of the core. No smell of H_2S could be detected in the core. Photographs of these cores are shown in Fig. 10 and schematic diagrams of core stratigraphy presented in Fig. 11

In both cores H286 and H287, there was no evidence for the gypsum cement observed by Pantin (1964) in previous cores from Milford Sound.

SEDIMENTATION CHARACTERISTICS

Several studies have been concerned with sedimentation in fiord-type environments (e.g., Strøm 1936; Pickard 1956; Toombs 1956; Cone *et al* 1963; Gucleur and Gross 1964; Holtedahl 1965, 1967; Richards 1965; Richards *et al* 1965; Folger *et al* 1972; Hoskin and Burrell 1972; Pharo 1972; Schubel and Pritchard 1972; Carter 1973; Knox and Kilner 1973; Johnson 1974; Strömgren 1974; Flaate and Janbu 1975; Bokuniewicz *et al* 1976; Slatt and Gardiner 1976).

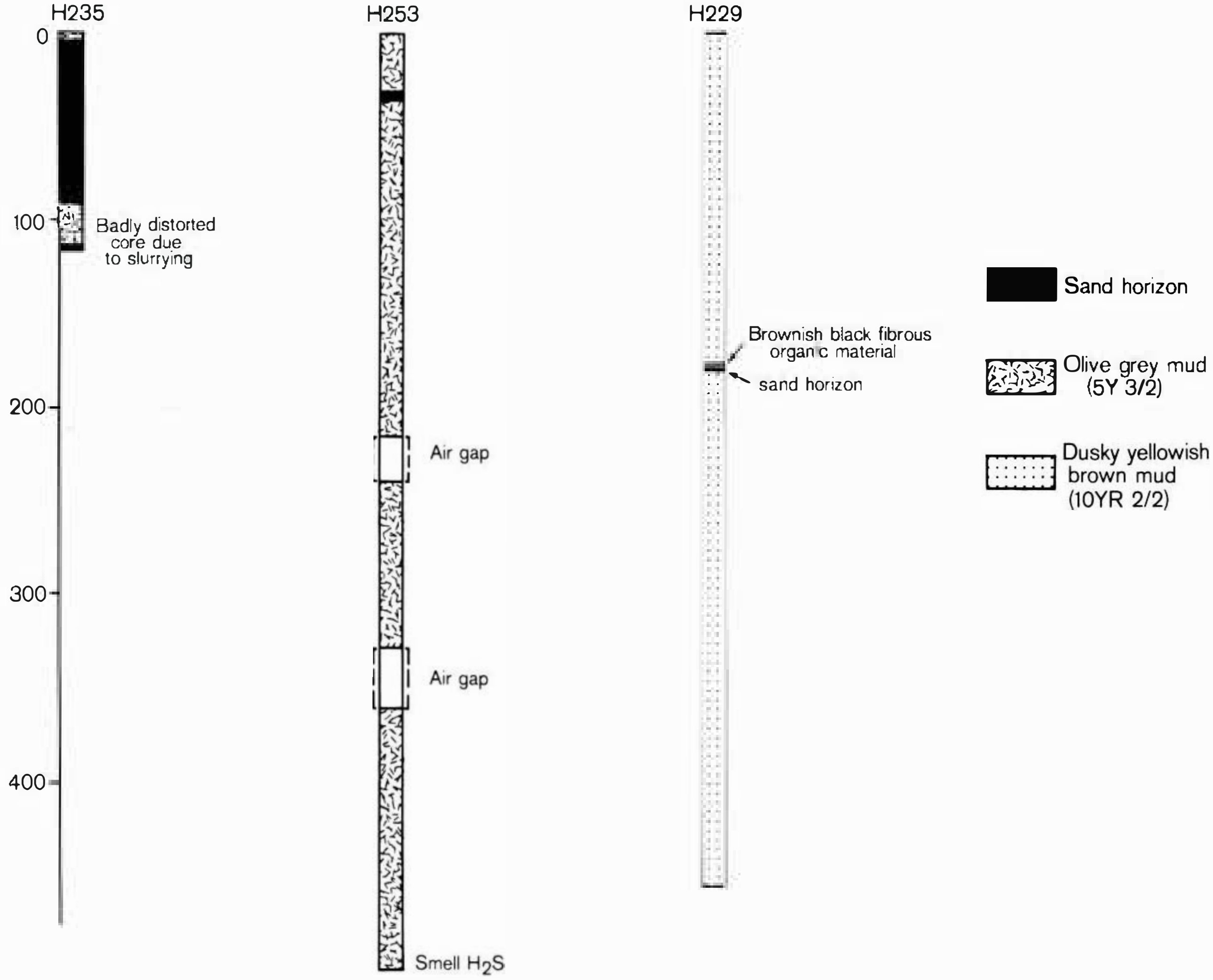

FIG. 5. Schematic diagram of core stratigraphy in Caswell Sound.

The most significant feature of the data presented here is the marked difference in sedimentation type between fiords. Whereas the principal sediment in Caswell Sound is dominantly olive grey mud (5 Y 3/2) interbedded with relatively few layers of sand, that in Nancy Sound is dominantly olive black mud (5 Y 2/1) interbedded with frequent layers of sand and fibrous organic material and that in Milford Sound is dark greenish grey mud (5 GY 4/1) interbedded with a number of sand layers.

Although no precise origin can be offered to account for these differences in sediment type, it is possible that differences in the colour and texture of the muds between the fiords reflect differences in the vegetation cover, topography, and soil profile in the surrounding region. Where the vegetation cover is dense and the topography favourable, a thick well-developed organic-rich soil horizon will develop and the soil will be transported to the fiord by normal erosional processes as a dark organic-rich mud. Where the vegetation is less dense and the topography steeper, the organic content of the soil will be lower and this will lead to the development of a lighter, less organic-rich mud. By this criterion, the darkening of the sediment in the increasing order Milford Sound → Caswell Sound → Nancy Sound indicates an increasing vegetation cover and less steep topography in Nancy Sound compared with Caswell and Milford Sounds respectively. Unfortunately, soils in Fiordland have not been mapped in sufficient detail to test this hypothesis. Soils around the three fiords are, however, all mapped as upland and high country podzolised yellow brown earths and podzols (Titiraurangi) with limited areas of Recent soils (Seaforth) at the head of each fiord. A belt of brown granular loams and clays (Olivine) also cuts across Milford Sound. The characteristics of these soils have been summarised by Wright and Miller (1952) and N.Z. Soil Bureau (1968; pp 52-4, map 10).

The development of discrete layers of sand and fibrous organic matter within the sediment column

TABLE 1. Grain size analyses of surface sediments from Caswell, Nancy and Milford Sounds.

	% Gravel (>2057μ)	% Sand (64-2057μ)	% Silt (4-64μ)	% Clay (<4μ)
Caswell Sound				
H218	-	23.6	59.2	17.2
H219	0.2	54.4	32.0	13.4
H220	0.2	33.8	42.5	23.4
H224	-	55.0	38.3	6.7
H225	0.1	52.9	37.8	9.1
H226	0.4	48.1	42.9	8.6
H227	0.9	79.0	16.5	3.6
H228	-	12.3	66.1	21.6
H229	-	15.1	64.0	20.8
H231	1.3	64.0	23.2	11.4
H232	63.6	35.1	1.3	
H233	18.0	34.1	32.4	15.6
H235	-	25.8	49.6	24.6
H236	-	52.2	40.1	7.7
H237	0.7	35.6	42.6	21.2
H238	-	26.5	51.7	21.8
H239	8.7	65.2	21.1	5.1
H241	2.2	56.6	32.2	9.0
H242	-	57.6	36.8	5.7
H243	0.3	55.8	37.1	6.7
H251	0.7	98.8	0.6	
H254	1.0	98.0	1.0	
Nancy Sound				
H255	-	67.5	28.0	4.6
H256	-	20.3	55.9	23.9
H257	-	42.8	33.0	24.2
H258	-	48.1	32.6	19.3
H259	0.4	34.7	42.8	22.1
H261	-	44.2	44.3	11.5
H262	3.1	68.4	21.5	7.1
H263	-	15.5	56.6	27.9
H264	-	55.0	28.0	17.0
H265	0.8	60.2	27.7	11.3
H266	-	27.6	46.8	25.6
H267	-	55.7	28.0	16.3
H268	-	26.9	49.7	23.4
H270	1.5	48.2	35.0	15.4
H272	0.5	58.9	30.8	9.8
H275	0.2	33.6	45.5	20.7
H276	3.6	72.6	16.9	6.8
Milford Sound				
H285	0.2	36.7	54.0	9.3
H286	0.2	44.6	61.5	33.7
H287	-	10.9	64.0	25.0
H288	1.0	29.0	47.9	22.1

which occurs in each of the fiords studied most probably reflects periods of flash flooding, when large quantities of undecomposed vegetation and alluvium are swept into the fiords. The much denser sand particles settle out first giving rise to the characteristic layers of sand overlain by discrete layers of fibrous undecomposed organic matter. This process is presumably cyclic where interbedding of discrete layers of sand and undecomposed organic material is observed.

TABLE 2. Complete grain size analyses of surface sediments from five sites in Caswell, Nancy and Milford Sounds. Analyses in percent.

	Caswell		Nancy		Milford
	H228	H236	H265	H267	H288
> 2057μ		-	0.79	-	1.05
1400 - 2057μ	{ 0.03	0.12	0.07	0.81	0.14
1000 - 1400μ		0.15	0.23	0.93	0.24
700 - 1000μ	{ 0.03	0.59	0.60	2.30	0.35
500 - 700μ		1.53	1.37	4.24	0.68
353 - 500μ	{ 1.10	3.10	4.47	7.71	0.84
250 - 353μ		5.52	8.15	10.78	1.22
178 - 250μ	{ 1.29	6.18	9.87	8.94	2.15
125 - 178μ		8.77	15.26	9.08	6.06
89 - 125μ	{ 3.95	6.78	9.54	4.91	6.45
64 - 89μ		8.30	10.64	6.03	10.88
32 - 64μ	12.88	6.70	11.81	9.94	15.28
16 - 32μ	20.61	9.38	7.70	6.78	12.90
8 - 16μ	10.31	8.71	3.08	5.87	10.52
4 - 8μ	14.60	16.75	5.13	5.42	9.17
2 - 4μ	11.16	2.01	2.57	4.52	7.47
< 2μ	24.04	15.41	8.73	11.74	14.60

Within each fiord, correlation of marker horizons is made difficult by the slurrying of cores. In Nancy Sound, for example, it proved impossible to correlate discrete horizons of sandy material stratigraphically between cores. This may be partly caused by the loss of large sections of each core, particularly in the case of core H275 where 142 cm of core were lost due to slurrying. Several factors may, however, influence the thickness of marker beds of sand. It would, for example, be anticipated that the thickness of the bed would decrease with increasing distance from the source of discharge of the sediment into the fiord. In addition, there may well be several sources of sediment discharge into the fiord. This is particularly apparent in Nancy Sound where sediment discharge from Toe Cove would be expected to give a different stratigraphic sequence in core H276 from that encountered in cores H264, H266, H275 and H261 where sediment discharge is more probably derived from the rivers draining Heel Cove. The presence of numerous rivers draining into both Caswell and Milford Sounds also suggests several source areas for sediment discharge. The data may therefore support the conclusion of Smith (1959) that correlation between cores in this type of environment may not be possible except over very short distances.

The precise mechanism of incorporation of alluvial material in the sedimentary sequence of glacial lakes has been discussed by a number of authors (Mathews 1956; Smith 1959; Pantin 1964; Brodie and Irwin 1970; Irwin 1971, 1972, 1975; Ludlam 1974; Gilbert 1975; Hampton 1975). This problem is particularly relevant in accounting for the alternating sequence of organic-rich muds and sand horizons in the sedimentary sequence. According to Brodie and Irwin (1970), sediment slumping is an important factor in controlling this distribution and three variants of density currents are postulated in lake environments where sediment is actively being contributed in river water of appropriate temperatures.

(a) Continuous underflow or inflow of relatively low density currents from the normal flow of rivers into the lake; sediment load very fine grained.

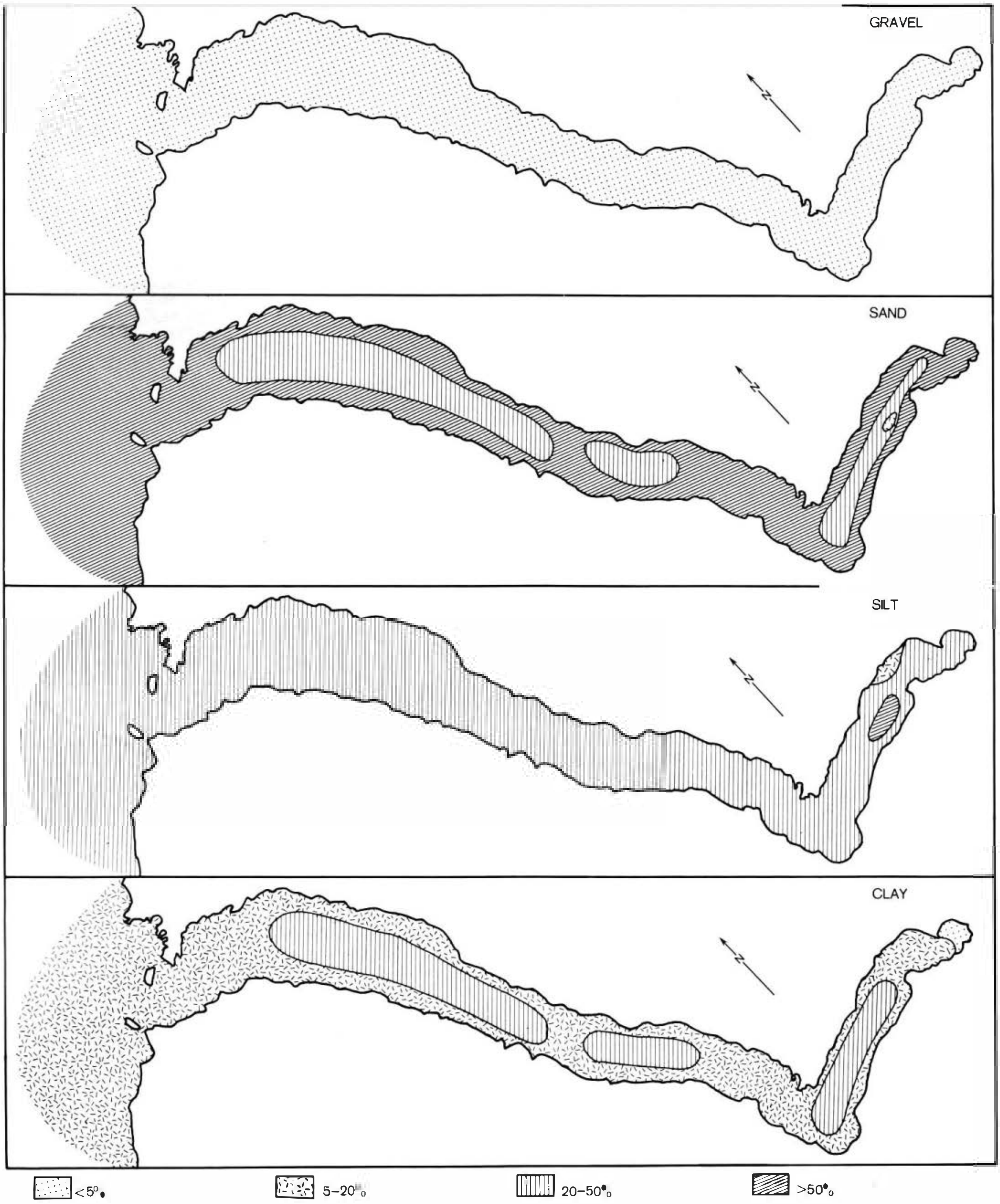

FIG. 6. Schematic diagram showing variations in grain size in Nancy Sound.

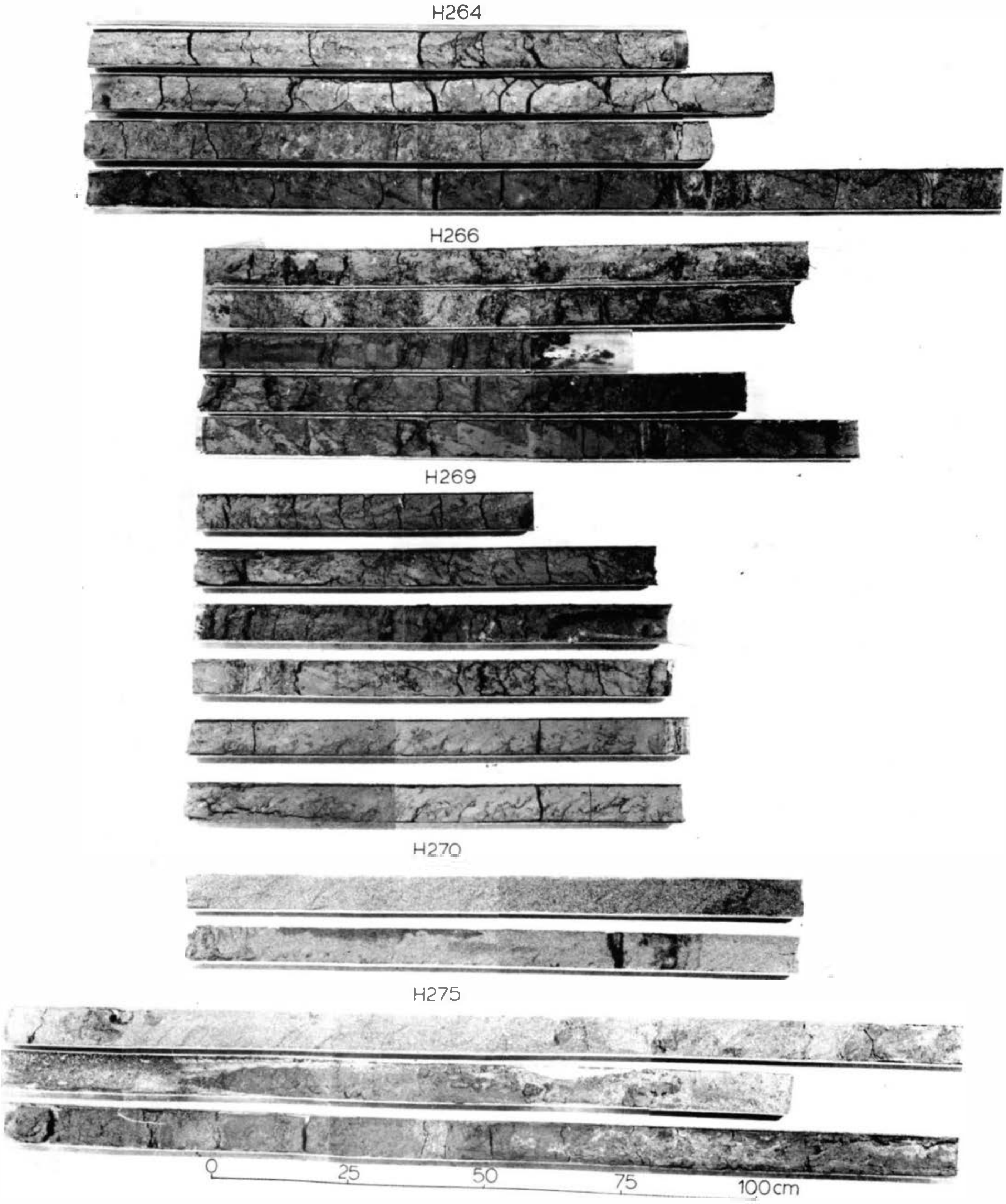

FIG. 7. Photographs of sediment cores from Nancy Sound.

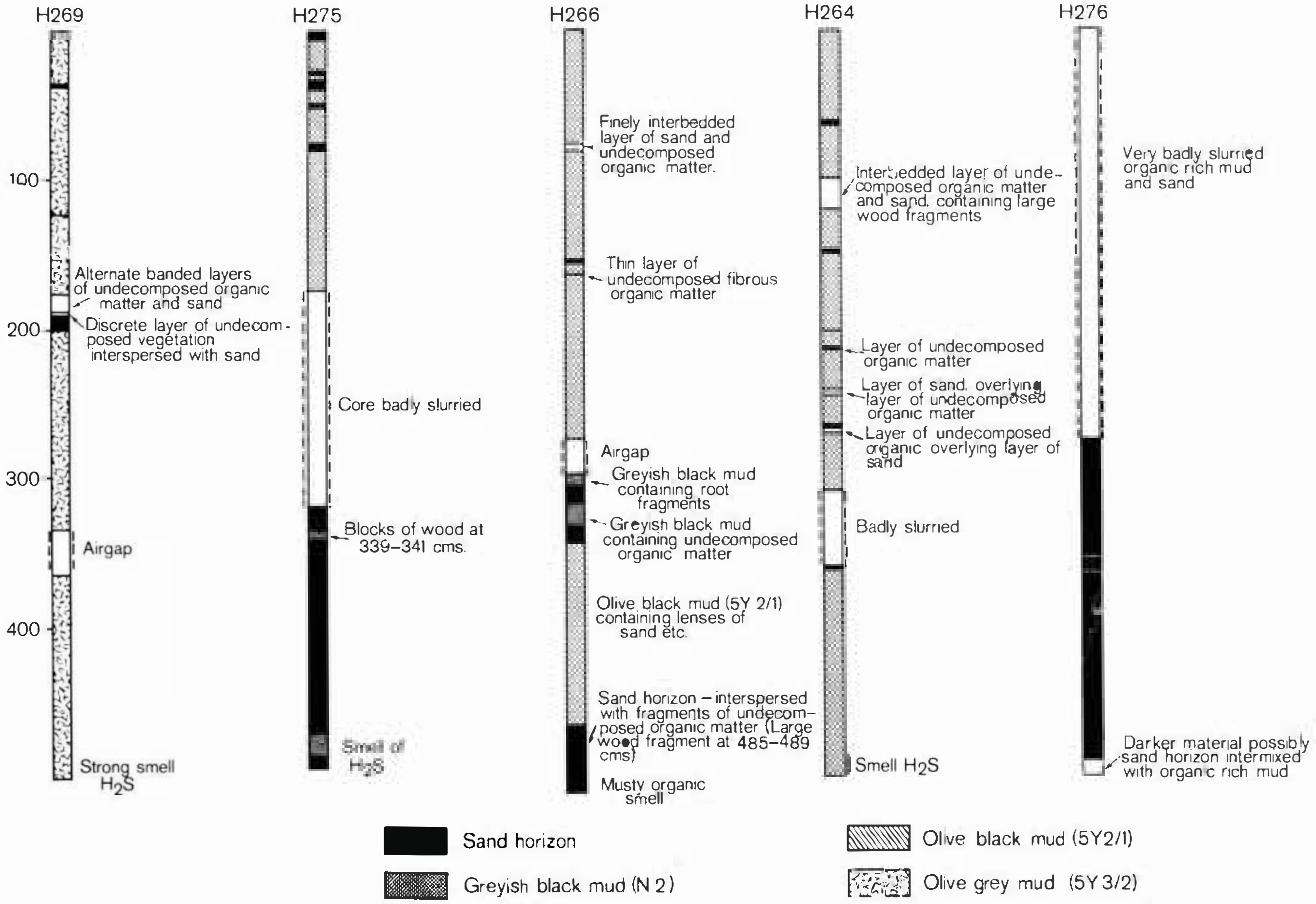

FIG. 8. Schematic diagram of core stratigraphy in Nancy Sound.

(b) High density underflows at discrete intervals related to flood discharges of rivers into the lake; sediment load includes a proportion of coarser grade sediment.

(a) and (b) are defined as *Primary* density currents, the sediment initially involved not being already deposited in the lake.

(c) High density turbulent flows (turbidity currents) generated by slumping of previously deposited slope sediments; initial sediment load may contain a high proportion of coarse grade sediment.

(c) can be classed as a *Secondary* density current.

This hypothesis is particularly attractive for New Zealand fiords. During normal river discharge, fine sediment derived principally from the erosion of organic-rich soil is brought into the fiord by mechanism (a). During extensive flooding, however, much coarser material consisting of debris derived from the river course and undecomposed vegetation is brought into the fiord by mechanism (b). In this way, alternate sequences of mud and sand can be deposited throughout the fiord.

This hypothesis is supported by the marked variations in the rate of influx of fresh water into the fiords resulting from local changes in the precipitation characteristics. From data presented by the Soil Conservation and Rivers Control Council (1965, p.108) the instantaneous discharge of the Cleddau River, the representative basin for the Fiordland region, can vary between 100 and 10,000 cusecs (3 and 300 m^3/sec) in the course of a year. Since the transporting power of a stream increases at the rate of the fifth or sixth power of its velocity (Kuenen 1950; Blyth 1960; Raudkivi 1967), this suggests that flooding may be responsible for the transport of the coarser sand sized material into the fiords whilst normal river discharge leads to the transport of fine material. This hypothesis agrees with Pantin's (1964) previously postulated mechanisms for the influx of fine and coarse sediment layers in Milford Sound in which sand layers are brought into the fiord during periods of increased river flow. Thus, the organic-rich mud horizons represent suspension load transport and the sand horizons represent bed load transport. Whereas the deposition of the suspension load is probably a continuous process, whose magnitude is dependent on seasonal fluctuations in rainfall, that of the bed load is probably a catastrophic process.

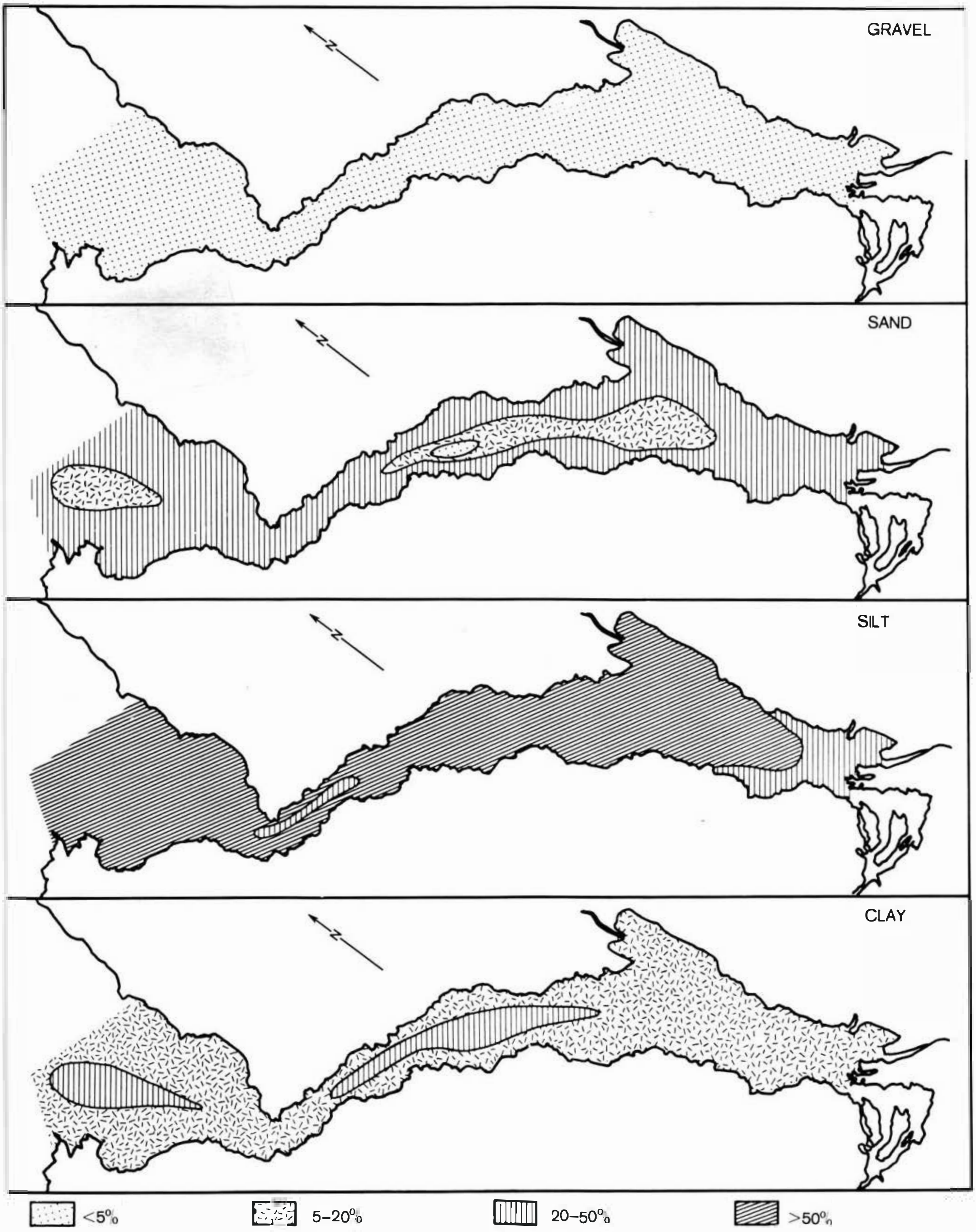

FIG. 9. Schematic diagram showing variations in grain size in Milford Sound.

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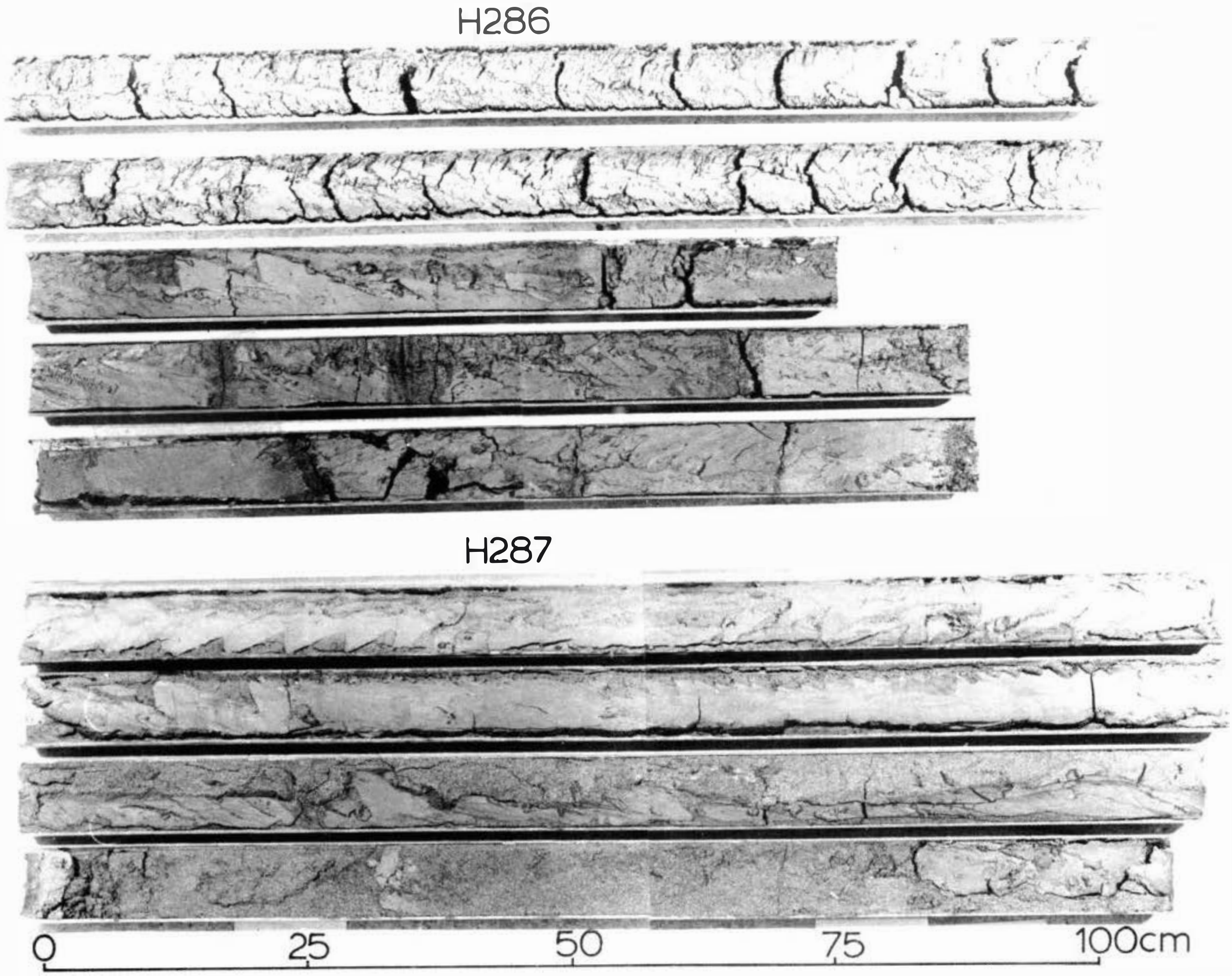

FIG. 10. Photographs of sediment cores from Milford Sound.

This view is supported by the fact that Fiordland soils are subject to periodic debris avalanches (Wright and Miller 1952; Jackson 1966; N.Z. Soil Bureau 1968, p.295; Pain and Hosking 1970; Eyles 1971; Johnson 1976). The frequency and thickness of the sand horizons therefore most probably reflects the frequency and magnitude of debris avalanches and the distance from source. The reader is referred to Pantin (1964) for a fuller discussion of fiord sedimentation.

One of the conspicuous features of the fiord sediments examined in this study is the complete absence of varves. According to Flint (1945), electrolytes present in seawater cause the rapid flocculation of suspended material in the water column. Sediment introduced into the saline waters of the fiords from the rivers is therefore precipitated as a homogeneous mass of mixed coarse and fine particles and varves cannot form. This contrasts with the situation in Lakes Pukaki and Tekapo where a varved sedimentary sequence has been observed in either the lake sediments or adjacent cliffs bounding the lakes (Irwin 1972; Brodie, pers. comm.). Varves have, however, been reported in fiord environments in Canada (*see* Gross *et al* 1963; Buddemeier 1969).

Pantin (1964) noted the occurrence of gypsum in Milford Sound. According to H.M. Pantin (pers. comm.), the gypsum occurs as a whitish material between grains in the sand fractions and is formed during periodic flushing of the fiord when sulphides within the sediment are oxidised to form the sulphate ion. The solubility product of $CaSO_4.2H_2O$ is then exceeded and gypsum precipitates. It is of interest that no evidence of gypsum occurrence was noted during a superficial examination of the cores studied here.

MINERALOGY

Mineralogical analysis of selected fine grained sediments was carried out using a combination of X-ray diffraction and infrared techniques (*see* Fieldes

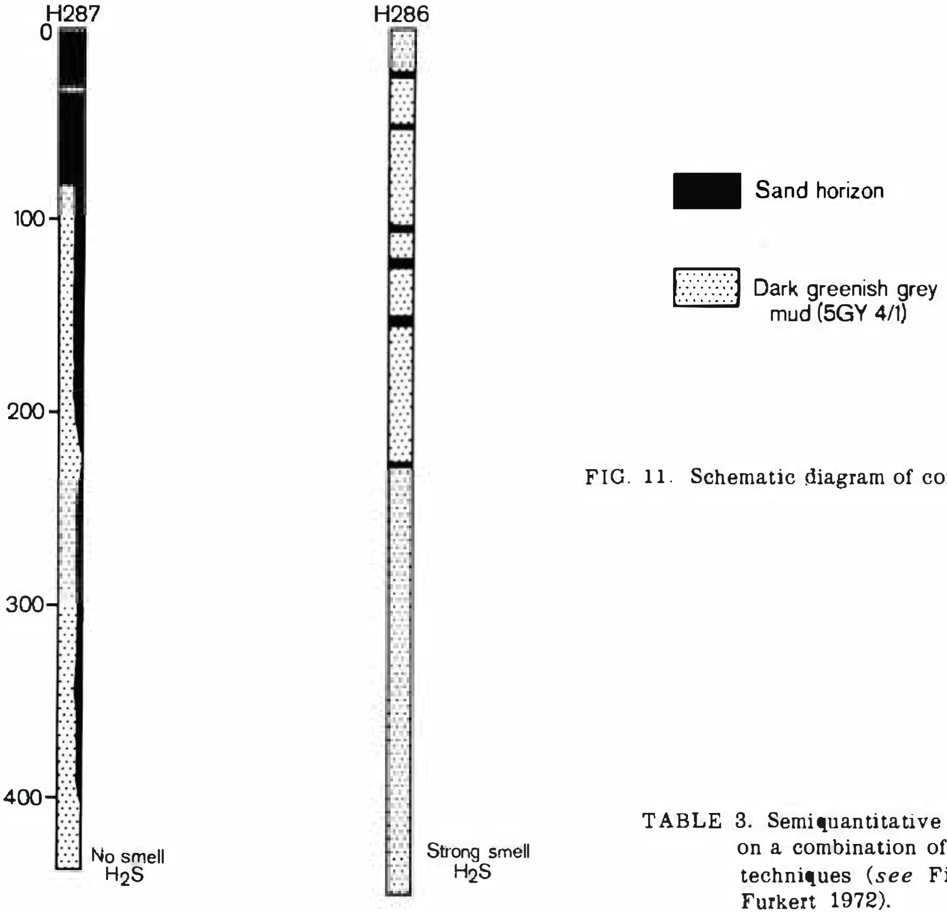

FIG. 11. Schematic diagram of core stratigraphy in Milford Sound.

et al 1972; Wells and Furkert 1972). The results presented in Table 3 indicate that the sediments contain dominantly feldspar, quartz, mica, chlorite, hornblende, amorphous material, and calcite. Differences in mineralogy are apparent both within a single fiord and between fiords. The most conspicuous trend, although not always well defined, is the higher contents of feldspar and hornblende and lower contents of quartz, mica, chlorite and calcite in sediments from Nancy Sound compared with those from Caswell and Milford Sounds. This trend is somewhat surprising since the country rock around Caswell and Nancy Sounds is similar (Bradshaw Formation), and differs from that around Milford Sound (Milford Formation). Similarly, this trend in mineralogy does not follow the trend in trace metal distribution (*see* next section). It must be noted however, that sediments from Milford Sound do appear to have higher contents of mica, chlorite and hornblende and lower contents of calcite than those from Caswell Sound. The mineralogy does not appear to vary systematically along the fiords suggesting that the influence of salinity variations on clay mineral stability is not a major factor in influencing the mineralogy in this type of environment (*see* Edzwald and O'Melia 1975).

According to Burns (pers. comm.), coccoliths are absent in sediments from core H264 from Nancy Sound.

TABLE 3. Semiquantitative mineralogical analyses based on a combination of X-ray diffraction and infra-red techniques (*see* Fieldes *et al* 1972; Wells and Furkert 1972).

Stn No.	Depth (cm)	Feldspar	Quartz	Cristobalite*	Mica	Chlorite	Hornblende	Amorphous	Calcite	Halloysite	Montmorillonite
Caswell Sound											
H229	400-405	10	10	1	3	8	5	30	3	-	2
H235	0-3	5	10	0.5	8	10	3	10	30	-	-
H253	100-105	8	10	1	12	10	3	20	10	-	-
Nancy Sound											
H264	0-15	10	5	2	<3	3	10	30	3	-	-
H264	274-290	35	5	1	<3	3	10	15	3	-	-
H266	250-255	10	15	1	15	8	7	10	10	-	-
H269	230-235	12	10	1	5	5	5	15	3	-	-
H275	50-55	25	5	2	8	5	10	10	3	-	-
Milford Sound											
H286	400-405	8	15	1	12	10	10	10	3	-	1
H287	400-405	8	10	1	18	15	7	10	3	-	-

Not detected : Amorphous silica, vermiculite, illite, kaolinite.

* Cristobalite may not be present in these samples as Dr G. Oliver (pers. comm.) was unable to identify this mineral in the coarse or fine fractions of core H264 by optical techniques.

GEOCHEMISTRY

Although a number of studies have described the trace element geochemistry of fiord sediments (Strøm 1948; Manheim 1961; Gross 1967; Veeh 1967; Crecelius 1969; Piper 1971; Sharma 1971; Brown *et al* 1972; Nissembaum *et al* 1972; Phillips 1972; Presley *et al* 1972; Skei *et al* 1972; Burrell 1973; Gadow and Schaefer 1973; Kolodny and Kaplan 1973; Erlenkeuser *et al* 1974; Hallberg 1974; Hancock 1974; Niemisto and Viopio 1974; Almgren *et al* 1975; Deuser 1975; Grasshoff 1975; Heggie and Burrell 1975; Morris and Culkin 1975; Price and Skei 1975; Reinson 1975; Lieberman and Healy 1976; Loring 1976a, b; Sholkovitz 1976; Villumsen 1976; Yeats and Bewers 1976; Grundmanis and Murray 1977), only one previous study on this subject has been carried out in the New Zealand region (Williamson 1972). For this reason, a series of samples were analysed for a range of elements. The samples were dried at 110°C for 48 hours and analysed by atomic absorption spectrophotometry following $HNO_3/HClO_4/HF$ extraction (Table 4). Semiquantitative optical emission spectrographic analyses are presented in Table 5 for comparison.

TABLE 4. Chemical analyses of sediments from Caswell, Nancy and Milford Sounds. All analyses in p.p.m., except where otherwise stated.

Deptn (cm)	Ti	V	Cr	Mn	% Fe	Co	Ni	Cu	Zn
CASWELL SOUND									
Stn H229									
30-35	6096	154	74	586	4.47	50	70	53	73
150-155	6033	155	75	498	4.42	51	61	58	74
250-255	6354	170	100	599	4.91	49	71	57	80
350-355	6139	125	85	581	4.83	51	72	73	78
400-405	5945	176	71	594	4.85	46	70	62	77
Stn H235									
0-3	3433	107	43	479	2.81	32	51	87	96
Stn H253									
0-5	5000	159	66	501	3.97	43	64	44	73
100-105	5090	125	76	529	4.04	44	62	41	75
200-205	5081	112	73	500	3.92	53	47	36	69
NANCY SOUND									
Stn H264									
0-15	6260	126	81	613	4.46	56	64	48	76
69-84	6037	107	70	647	4.60	58	64	48	70
122-137	6102	188	52	712	4.57	51	54	43	88
183-198	6392	135	100	651	4.85	55	80	45	67
274-290	6080	179	88	613	4.31	56	67	42	67
396-411	6424	144	110	684	4.85	70	73	44	71
457-472	6567	118	103	554	4.60	57	72	49	74
Stn H266									
5-10	5399	84	53	529	4.00	43	58	59	64
100-105	5509	102	60	573	4.16	27	55	60	64
200-205	6120	114	44	537	4.66	57	59	73	70
250-255	5016	93	57	532	3.99	38	53	49	61
300-305	5145	110	55	517	3.92	36	56	50	63
Stn H269									
0-5	4893	140	63	547	3.77	45	50	47	67
110-115	5123	153	89	613	4.12	56	53	47	67
230-235	5031	144	56	567	3.98	45	48	46	64
300-305	5188	96	64	558	3.97	44	60	52	63
Stn H275									
50-55	5380	163	56	610	4.28	56	56	42	66
100-105	5569	146	52	644	4.66	58	50	52	65
MILFORD SOUND									
Stn H286									
0-10	5112	198	99	1011	5.72	57	83	173	94
60-65	5016	128	86	900	5.13	31	73	85	76
200-205	5259	159	105	942	5.35	61	83	88	76
300-305	5064	171	101	961	5.30	57	72	89	73
400-405	5032	153	104	721	5.17	62	96	85	74
Stn H287									
400-405	5489	200	144	659	4.65	58	90	58	77
% Precision (1σ)	1.3	15.6	13.3	17.0	1.7	6.7	4.9	6.1	4.0

The results presented in Table 4 indicate similar levels of trace metal abundance in sediments from each of the three fiords with no well defined pattern of distribution with depth in individual sediment cores. There is some evidence that sediments from Milford Sound are slightly higher in V, Cr, Mn, Fe, and Cu compared with sediments from the other two fiords. This may reflect differences in the lithology of the surrounding rock; the dominant lithology around Milford Sound being the Milford Formation (strongly folded, well-foliated hornblende-garnet gneiss) whereas that around Caswell and Nancy Sounds is the Bradshaw Formation (weakly foliated paragneiss and orthogneiss, with and without garnet). Trace metal contents of the fiord sediments are similar to those previously reported for South Island lakes (Glasby 1975), although some differences are apparent. Trace metal contents of sediments from Milford Sound most resemble those from Lakes Wakatipu, Wanaka, and Hawea, whereas sediments from Caswell and Nancy Sounds are more similar to those from Lakes Ohau, Pukaki, and Tekapo. These similarities in composition may be fortuitous since Lakes Wakatipu, Wanaka, and Hawea are surrounded by chlorite schists and Lakes Ohau, Pukaki, and Tekapo are surrounded mainly by Pleistocene rocks in a region where greywacke and argillite predominate. Although no precise origin of trace metal variations between fiords can be given, it is significant that whereas the contents of molybdenum and, to some extent, copper are controlled by sedimentary processes in South Island fiords, the contents of other metals are controlled dominantly by provenance (Williamson 1972). In addition, Gross (1967), Piper (1971), and Presley *et al* (1972) point out the importance of the mineralogy of the lithogenic material and the abundance of organic matter in controlling the abundance of the first transition series elements in fiords elsewhere, although the concentration of zinc may be controlled by other factors (Piper 1971). It is possible, therefore, that the lithology of the sediment plays an important role in controlling compositional differences in sediments between fiords (*see also* Glasby 1975). The absence of any marked variation in trace metal contents with

TABLE 5. Semiquantitative analyses of fiord sediments by optical emission spectrography. All analyses in p.p.m.

Stn No.	Depth (cm)	B	Cr	Mn	Mo	Cu	Ni	Ba	V	Co	Sr	Be	Zr	P	Zn	Pb	Sn	Ga
CASWELL SOUND																		
H229	400-405	250	50	1000	ND	300	50	100	100	ND	25	10	50	250	25	50	1	10
H235	0-3	250	50	750	ND	500	50	100	100	ND	100	10	50	100	25	25	5	10
H233	100-105	250	100	1000	ND	250	50	250	100	ND	50	10	50	150	25	25	1	10
NANCY SOUND																		
H264	0-15	250	50	>1000	ND	250	50	100	100	ND	25	10	50	150	50	25	1	10
H266	250-255	250	50	>1000	1	250	50	100	150	ND	50	10	50	150	25	25	1	10
H269	230-235	250	50	>1000	1	250	50	250	150	ND	100	10	50	100	25	25	1	10
H275	50-55	150	25	>1000	1	250	50	100	150	5	50	10	50	100	25	10	1	10
MILFORD SOUND																		
H286	400-405	150	200	>1000	5	500	50	100	250	5	25	10	100	100	150	50	5	10
H287	400-405	150	250	>1000	ND	500	100	100	250	5	25	10	250	100	100	25	1	10

Not detected in any sample : Hg, As, Sb, Tl, Au, Ge, W, La and Ag.

Copper values possibly contaminated from Cu arcing rods.

ND = Not detected.

depth in the sediment column suggests that diagenetic processes are not important in redistributing trace metals within the sediment in this type of environment. The similarity in composition of South Island lake and fiord sediments also suggests that the salinity of the overlying waters does not have any marked influence on the trace metal contents of the sediments in this region, at least for the elements analysed.

In conclusion it must be emphasised that the observed trace element variations between the fiords, although significant, are small and may reflect, in part, variations in the lithology of the source material. Other factors may, however, be important in controlling the overall level of trace metal abundance in the sediment and further studies are needed to ascertain the effects of the sedimentary environment on the trace metal contents of the sediments.

RATES OF SEDIMENTATION

In order to compute sedimentation rates, ^{14}C dates were obtained on a series of three wood samples collected at depth in two piston cores from Nancy Sound. The results shown in Table 6 indicate a narrow range of ages between 1135 and 1260 years. In core H264, the proximity of the two ages (within the combined precision limits of the two analyses) and the fact that the samples occur in the same stratigraphic horizon suggest that the depositions of these wood samples may have been more or less contemporaneous, representing one catastrophic event c.1200 years ago. That some error, analytical or sampling, is present is indicated by the fact that the deeper sample in the core has a slightly younger age than the shallower sample. The differences are, however, small. It is probable that the sedimentation rate is slightly higher than calculated in Table 6 because no allowance has been made for the presence of the sand horizon at a depth of 61-63.5 cm. If this horizon were omitted in the calculation, the sedimentation rate would be decreased by approximately 2%. The sedimentation rate calculated for core H266 is far more speculative because the sediment overlying the wood sample contains a number of sand horizons as well as a sizable airlock. However, the computed sedimentation rate is probably of the right order of magnitude. Thus sedimentation rates are computed to be in the range 84-430 cm/10^3 years. This indicates a reasonably fast

TABLE 6. ^{14}C dates of wood samples from piston cores taken in Nancy Sound.

Stn No.	Depth in sediment (cm)	^{14}C reference No.	Wood type*	^{14}C age (yrs B.P)	Sedimentation rate (cms/10^3yrs)
H264	105.5 - 110	NZ 1354	*Nothofagus fusca* or *Nothofagus menziesii*	1260 ± 73	83.7 - 87.3
H264	116	NZ 1355	Bark sample	1135 ± 75	102.2
H266	484 - 488	NZ 1356	*Weinmannia racemosa*	1135 ± 154	426.4 - 429.9

* Identification by Dr R.N. Patel, Forest Research Institute, Rotorua, based on Poole and Adams (1964).

rate of sedimentation in this type of environment and faster than that obtained from a Norwegian fiord by Aarseth *et al* (1975). Because of the problems in obtaining undisturbed piston cores described earlier and the presence of sand horizons in the sediment, it must be emphasised that these rates are only approximate.

As a comparison, sedimentation rates were also calculated from an estimate of the total annual sediment discharge into each fiord, based on discharge data from the Cleddau River and multiplying by a factor based on the relative areas of the catchments draining into each fiord. Knowing the approximate surface area of each fiord, the mean amount of sediment deposited in the fiord per unit area per unit time (in mgm/cm^2/yr) could be calculated. From an estimate of the sediment density, approximate sedimentation rates could be calculated. These calculations (as shown in Table 7) contain a number of assumptions: no allowance is made for the effects of anomalously high run-off rates in sediment transport into the fiord or for the effects of debris avalanches; no allowance is made for the fact that sedimentation is restricted to the fiord basins and not the fiord walls (*see* Lehman 1975) (thus making the effective area of the fiord smaller than assumed); and many of the numbers used in the calculations are only approximations. Nevertheless, the sedimentation rates calculated in this way are of the same order, although lower, than the values determined by ^{14}C dating and show the value of the mass balance approach in studying sedimentation problems.

TABLE 7. Calculation of sedimentation rates based on sediment discharge data.

Catchment areas : Caswell Sound	271 km^2
Nancy Sound	231 km^2
Milford Sound	510 km^2
Cleddau River	155 km^2

Mean annual discharge from the Cleddau River

= 27.2 m^3/sec = 960 cusecs

≏ 10 tons sediment/day

(data based on Ministry of Works sediment rating curves)

Calculated sediment discharge into Caswell Sound	≏ 6400 tons/yr
Calculated sediment discharge into Nancy Sound	≏ 5500 tons/yr
Approximate area of Caswell Sound	≈ 15 km^2
Approximate area of Nancy Sound	≈ 14 km^2
Mean sedimentation rate for Caswell Sound	≏ 43.3 mg/cm^2/yr
Mean sedimentation rate for Nancy Sound	≏ 40 mg/cm^3/yr
Assuming sediment density	≏ 1.5 gm/cm^3
Approximate mean sedimentation rate for Caswell Sound	28.8 cm/1000 yr
Approximate mean sedimentation rate for Nancy Sound	26.6 cm/1000 yr

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REFERENCES

AARSETH, I.; BJERKLI, K.; BJORKLUND, K.R.; BOE, B.; HOLM, J.B.; LORENTZEN-STYR, T.J.; MYHRE, L.A.; UGLAND, E.S.; THIEDE, J. 1975: Late Quaternary sediments from Korsfjorden, western Norway. *Sarsia 58* : 43-66.

ALMGREN, T.; DANIELSSON, L.G.; DYRSSEN, D.; JOHANSSON, T.; NYQUIST, G. 1975: Release of inorganic matter from sediments in a stagnant basin. *Thalassia Jugoslavica 11(1-2)* : 19-29.

BLYTH, F.G.H. 1960: "A Geology for Engineers". Edward Arnold (Publishers) Ltd, London. 341 p.

BOKUNIEWICZ, H.J.; GEBERT, J.; GORDON, R.D. 1976: Sediment mass balance of a large estuary, Long Island Sound. *Estuarine and Coastal Marine Science 4* : 523-36.

BRODIE, J.W.; IRWIN, J. 1970: Morphology and sedimentation in Lake Wakatipu, New Zealand. *N.Z. Journal of Marine and Freshwater Research 4* : 479-96.

BROWN, F.S.; BAEDECKER, M.J.; NISSEMBAUM, A.; KAPLAN, I.R. 1972: Early diagenesis in a reducing fjord, Saanich Inlet, British Columbia - III. Changes in organic constituents of sediment. *Geochimica et Cosmochimica Acta 36* : 1185-203.

BRUUN, A.Fr.; BRODIE, J.W.; FLEMING, C.A. 1955: Submarine geology of Milford Sound, New Zealand. *N.Z. Journal of Science and Technology B36* : 397-410.

BUDDEMEIER, R.W. 1969: Radiocarbon study of varved marine sediments of Saanich Inlet, British Columbia.

Unpublished Ph.D. thesis, University of Washington, Seattle. 136 p.

BURRELL, D.C. 1973: Distribution patterns of some particulate and dissolved trace metals within an active glacial fjord. Pp 89-103 *in* "Radioactive Contamination of the Marine Environment". International Atomic Energy Agency, Vienna. 786 p.

CALVERT, S.E.; PRICE, N.B. 1970: Composition of manganese nodules and manganese carbonates from Loch Fyne, Scotland. *Contributions to Mineralogy and Petrology 29* : 215-33.

CARTER, L. 1973: Surficial sediments of Barkley Sound and the adjacent continental shelf, west coast, Vancouver Island. *Canadian Journal of Earth Sciences 10* : 441-59.

CONE, R.A.; NEIDELL, N.S.; KENYON, K.E. 1963: Studies of the deep-water sediments with the continuous seismic profiler. 5. The natural history of Hardangerfjord. *Sarsia 14* : 61-78.

CRECELIUS, E.A. 1969: Molybdenum enrichment in the sediments of an anoxic fjord. *EOS Transactions of the American Geophysical Union 50* : 208 (Abstract).

DEUSER, W.G. 1975: Reducing environments. Pp 1-37 *in* Riley, J.P. and Skirrow, G. (eds) "Chemical Oceanography". Second edition. Vol. 3. Academic Press, London. 564 p.

EDZWALD, J.K.; O'MELIA, C.R. 1975: Clay distributions in Recent estuarine sediments. *Clays and Clay Minerals 23* : 39-44.

ERLENKEUSER, H.; SUESS, H.; WILLKOMM, H. 1974: Industralization affects heavy metal and carbon isotope concentrations in Recent Baltic Sea sediments. *Geochimica et Cosmochimica Acta 38* : 823-42.

EYLES, R.J. 1971: Mass movement in Tangoio Conservation Reserve, northern Hawke Bay. *Earth Science Journal 5* : 79-91.

FIELDES, M.; FURKERT, R.J.; WELLS, N. 1972: Rapid determination of constituents of whole soils using infrared absorption. *N.Z. Journal of Science 15* : 615-27.

FLAATE, K.; JANBU, N. 1975: Soil exploration in a 500 m deep fjord, western Norway. *Geotechnology 1* : 117-39.

FLINT, R.F. 1945: "Glacial Geology and the Pleistocene Epoch". John Wiley & Sons, New York. 589 p.

FOLGER, D.W.; MEADE, R.H.; JONES, B.F.; CORY, R.L. 1972: Sediments and waters of Somes Sound, a fjordlike estuary in Maine. *Limnology and Oceanography 17* : 394-402.

GADOW, S.; SCHAEFER, A. 1973: Die Sedimente der Deutschen Bucht : Korngroessen, Tonmineralien und Schwermetalle. *Senckenbergiana Maritima 5* : 165-78. (In German; English Abstract.)

GILBERT, R. 1975: Sedimentation in Lillooet Lake, British Columbia. *Canadian Journal of Earth Sciences 12* : 1697-711.

GLASBY, G.P. 1975: Geochemistry of superficial lake sediments from the South Island, New Zealand. *NZOI Records 2* : 77-82.

GODDARD, E.N.; TRASK, P.D.; DE FORD, R.K.; ROVE, O.N.; SINGEWALD, J.T.; OVERBECK, R.M. 1963: "Rock-color Chart". U.S. Geological Survey Publication.

GRASSHOFF, K. 1975: The hydrogeochemistry of landlocked basins and fjords. Pp 455-597 *in* Riley, J.P. and Skirrow, G. (eds) "Chemical Oceanography". Second edition. Vol. 2. Academic Press, London. 647 p.

GROSS, M.G. 1967: Concentrations of minor elements in diatomaceous sediments of a stagnant fjord. Pp 273-82 *in* Lauf, G.H. (ed.) "Estuaries". *American Association for the Advancement of Science Publication 83* : 757 p.

GROSS, M.G.; GUCLEUR, S.M.; CREAGER, J.S.; DAWSON, W.A. 1963: Varved marine sediments in a stagnant fjord. *Science, New York 141* : 918-9.

GRILL, E.V.; MURRAY, J.W.; MACDONALD, R.D. 1968: Todorokite in manganese nodules from a British Columbia fjord. *Nature, London 219* : 358-9.

GRUNDMANIS, V.; MURRAY, J.W. 1977: Interstitial water chemistry in Saanich Inlet. *EOS Transactions of the American Geophysical Union 58(6)* : 421-2 (Abstract).

GUCLEUR, S.M.; GROSS, M.G. 1964: Recent marine sediments in Saanich Inlet, a stagnant marine basin. *Limnology and Oceanography 9* : 359-76.

HALLBERG, R.O. 1974: Paleoredox conditions in the Eastern Gotland Basin during recent centuries. *Merentutkimuslait Julk./Havsforskningsinst. Skr. 238* : 3-16.

HAMPTON, M.A. 1975: Competence of fine-grained debris flow. *Journal of Sedimentary Petrology 45* : 834-44.

HANCOCK, P.M. 1974: Geochemical prospecting in Fiordland - A review of the limitations and valid applications in the Fiordland environment. *N.Z. Geochemical Group Newsletter 33* : 12-3.
(*see also* Pp 399-401 *in* Williams, G.J. "Economic Geology of New Zealand". The Australasian Institute of Mining and Metallurgy, Victoria, Australia. 409p.)

HEGGIE, D.T.; BURRELL, D.C. 1975: Distributions of copper in interstitial waters and the water column of an Alaskan fjord. *EOS Transactions of the American Geophysical Union 56* : 1006.

HOLTEDAHL, H. 1965: Recent turbidities in the Hardangerfjord, Norway. *Colston Research Society Proceedings 17* : 107-40.

HOLTEDAHL, H. 1967: Notes on the formation of fjords and fjord-valleys. *Geografiska Annaler 49* : 188-203.

HOSKIN, C.M.; BURRELL, D.C. 1972: Sediment transport and accumulation in a fjord basin, Glacier Bay, Alaska. *Journal of Geology 80* : 539-51.

IRWIN, J. 1971: Exploratory limnological studies of Lake Manapouri, South Island, New Zealand. *N.Z. Journal of Marine and Freshwater Research 5* : 164-77.

IRWIN, J. 1972: Sediments of Lake Pukaki, South Island, New Zealand. *N.Z. Journal of Marine and Freshwater Research 6* : 482-91.

IRWIN, J. 1975: Morphology and classification. Pp 25-56 *in* Jolly, V.H. and Brown, J.M.A. (eds) "New Zealand Lakes". Auckland University Press/Oxford University Press, Auckland. 388 p.

JACKSON, R.J. 1966: Slips in relation to rainfall and soil characteristics. *Journal of Hydrology 5* : 45-53.

JOHNSON, P.N. 1976: Changes in landslide vegetation at Lake Thomson, Fiordland, New Zealand. *N.Z. Journal of Botany 14* : 197-8.

JOHNSON, R.D. 1974: Dispersal of Recent sediments and mine tailings in a shallow-silled fjord, Rupert Inlet, British Columbia. Unpublished Ph.D. thesis, University of British Columbia. (*Dissertation Abstracts International 35(11)* : 5491B, 1975.)

KNOX, G.A.; KILNER, A.R. 1973: The ecology of the Heathcote estuary. Unpublished report, Estuarine Research Unit, University of Canterbury, Christchurch. 358 p.

KOLODNY, Y.; KAPLAN, I.R. 1973: Deposition of uranium in the sediment and interstitial water of an anoxic fjord. *Proceedings of the Symposium on Hydrogeochemistry and Biogeochemistry, Tokyo, September 7-9, 1970, 1* : 418-42.

KUENEN, Ph.H. 1950: "Marine Geology". John Wiley & Sons, New York. 508 p.

LANGFORD, A.; McDOUGALL, J.C.; ROBERTSON, N.D. 1969: A new large-diameter piston corer and core-liner cutter. *N.Z. Journal of Marine and Freshwater Research 3* : 595-601.

LEHMAN, J.T. 1975: Reconstructing the rate of accumulation of lake sediment : the effect of sediment focusing. *Quaternary Research 5* : 541-50.

LIEBERMAN, S.H.; HEALY, M.L. 1976: Trace metal associations with humic substances in northwest fjords. *EOS Transactions of the American Geophysical Union 57* : 931.

LORING, D.H. 1976a: The distribution and partition of zinc, copper, and lead in the sediments of the Saguenay fjord. *Canadian Journal of Earth Sciences 13* : 960-71.

LORING, D.H. 1976b: Distribution and partition of cobalt, nickel, chromium, and vanadium in the sediments of the Saguenay fjord. *Canadian Journal of Earth Sciences 13* : 1706-18.

LUDLAM, S.D. 1974: Fayetteville Green Lake, New York. 6. The role of turbidity currents in lake sedimentation. *Limnology and Oceanography 19* : 656-64.

MANHEIM, F.T. 1961: A geochemical profile in the Baltic Sea. *Geochimica et Cosmochimica Acta 25* : 52-70.

MATHEWS, W.H. 1956: Physical limnology and sedimentation in a glacial lake. *Bulletin of the American Geological Society 67* : 537-52.

MORRIS, R.J.; CULKIN, F. 1975: Environmental organic chemistry of oceans, fjords, and anoxic basins. *Environmental Chemistry 1* : 81-108.

NEW ZEALAND SOIL BUREAU, 1968: General survey of the soils of South Island, New Zealand. *Soil Bureau Bulletin N.Z. 27* : 404 p, 13 maps.

NIEMISTO, L.; VIOPIO, A. 1974: Studies on the recent sediments in the Gotland Deep. *Merentutkimuslait Julk./ Havforskningsinst. Skr. 238* : 17-32.

NISSEMBAUM, A.; PRESLEY, B.J.; KAPLAN, I.R. 1972: Early diagenesis in a reducing fjord, Saanich Inlet, British Columbia - I. Chemical and isotopic changes in major components of interstitial waters. *Geochimica et Cosmochimica Acta 36* : 1007-27.

PAIN, C.F.; HOSKING, P.L. 1970: The movement of sediment in a channel in relation to magnitude and frequency concepts a New Zealand example. *Earth Science Journal 4* : 17-23.

PANTIN, H.M. 1964: Sedimentation in Milford Sound. Pp 35-47 *in* Skerman, T.M. (ed.) "Studies of a Southern Fiord". *Memoir N.Z. Oceanographic Institute 17 (N.Z. Department of Scientific and Industrial Research Bulletin 157).* 101 p.

PHARO, C.H. 1972: Sediments of the central and southern Strait of Georgia, British Columbia. Unpublished Ph.D. thesis, University of British Columbia. 290 p.

PHILLIPPS, J. 1972: Chemical processes in estuaries. Pp 33-48 *in* Barnes, R.S.K. and Green, J. (eds) "The Estuarine Environment". Applied Science Publishers Ltd, London. 133 p.

PICKARD, G.L. 1956: Physical features of British Columbia inlets. *Transactions of the Royal Society of Canada, Series III, 50* : 47-58.

PIPER, D.Z. 1971: The distribution of Co, Cr, Cu, Fe, Mn, Ni and Zn in Framvaren, a Norwegian anoxic fjord. *Geochimica et Cosmochimica Acta 35* : 531-50.

POOLE, A.L.; ADAMS, N.M. 1964: "Trees and Shrubs of New Zealand". Government Printer, Wellington. 250 p.

PRESLEY, B.J.; KOLODNY, Y.; NISSEMBAUM, A.; KAPLAN, I.R. 1972: Early diagenesis in a reducing fjord, Saanich Inlet, British Columbia II. Trace element distribution in interstitial water and sediment. *Geochimica et Cosmochimica Acta 36* : 1073-90.

PRICE, N.B.; SKEI, J.M. 1975: Areal and seasonal variations in the chemistry of suspended particulate matter in deep water fjord. *Estuarine and Coastal Marine Science 3* : 349-69.

RAUDKIVI, A.J. 1967: "Loose Boundary Hydraulics". Pergamon Press, Oxford. 331p.

RENSON, G.E. 1975: Geochemistry of muds from a shallow restricted estuary, Australia. *Marine Geology 19* : 297-314.

RICHARDS, F.A. 1965: Anoxic basins and fjords. Pp 611-45 in Riley, J.P. and Skirrow, G. (eds) "Chemical Oceanography". Vol. 1. Academic Press, London. 712 p.

RICHARDS, F.A.; CLINE, J.; BORENKOW, W.W.; ATKINSON, L.P. 1965: Some consequences of the decomposition of organic matter in Lake Nitinat, an anoxic fjord. *Limnology and Oceanography (Supplement) 10* : R155-R201.

SCHUBEL, J.R.; PRITCHARD, D.W. 1972: The estuarine environment. *Journal of Geological Education 20* : 60-8.

SHARMA, G.D. 1971: Sediments. Pp 169-88 *in* Hood, D.W. (ed.) "Impingement of Man on the Oceans". Wiley-Interscience. New York. 738p.

SHOLKOVITZ, E.R. 1976: Flocculation of dissolved organic and inorganic matter during the mixing of river water and seawater. *Geochimica et Cosmochimica Acta 40* : 831-45.

SKEI, J.M.; PRICE, N.B.; CALVERT, S.E.; HOLTENDAHL, H. 1972: The distribution of heavy metals in sediments of Sarfjord, west Norway. *Water, Air and Soil Pollution 1* : 452-61.

SLATT, R.M.; GARDINER, W.W. 1976: Comparative petrology and source of sediments in Newfoundland fiords. *Canadian Journal of Earth Sciences 13* : 1460-5.

SMITH, A.J. 1959: Structures in the stratified Late-Glacial clays of Windermere, England. *Journal of Sedimentary Petrology 29* : 447-53.

SOIL CONSERVATION AND RIVERS CONTROL COUNCIL, 1965: "Hydrology Annual No. 13". Ministry of Works, Wellington. 245 p.

STRØM, K.M. 1936: Land-locked waters. Hydrography and bottom deposits in badly-ventilated Norwegian fjords with remarks upon sedimentation under anaerobic conditions. Skrifter Ukgitt av Det Norske Videnskaps-Akademi 1 Oslo 1. Mat.-Naturv. Klasse 1936. No. 7, 85 p, 9 pls.

STRØM, K.M. 1948: A concentration of uranium in black muds. *Nature, London 162* : 922.

STRÖMGREN, T. 1974: The use of a weighted arithmetic mean for describing the sediments of a landlocked basin (Borgen fjorden, western Norway). *Deep Sea Research 21* : 155-60.

TOOMBS, R.B. 1956: Some characteristics of Bute Inlet sediments. *Transactions of the Royal Society of Canada, Series III, 50* : 59-65.

VEEH, H.H. 1967: Deposition of uranium from the ocean. *Earth and Planetary Science Letters 3* : 145-50.

VILLUMSEN, A. 1976: Recent iron-rich sediments in the Skjerma river system and in Ringkobing fjord. (Iron pollution of the river Skjerna and Ringkobing fjord, western Jutland.) *Danmarks geologiske undersogelse Arbog 1975* : 31-43.

WELLS, N.; FURKERT, R.J. 1972: Mineralogy of parent materials, topsoils, and erosion products of Taita Experimental Station. *N.Z. Journal of Science 15* : 141-55.

WILLIAMSON, G.P. 1972: Fiordland reconnaissance, New Zealand. Final Report. *Kennecott Explorations (Australia) Pty Ltd. Eastern District Technical Report 19* : 15 p.

WRIGHT, A.C.S.; MILLER, R.B. 1952: Soils of south-west Fiordland. *N.Z. Department of Scientific and Industrial Research Soil Bulletin (n.s.) 7* : 31p.

YEATS, P.A.; BEWERS, J.M. 1976: Trace metals in the waters of Saguenay fjord. *Canadian Journal of Earth Sciences 13* : 1319-27.

GAMMA-RAY STUDIES OF SEDIMENT CORES FROM CASWELL, NANCY AND MILFORD SOUNDS

by

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ABSTRACT

Gamma-ray studies of eight cores from three New Zealand fiords indicate the potential usefulness of the technique in identifying various stratigraphic horizons in the cores by their density differences.

INTRODUCTION

Eight cores from Caswell, Nancy, and Milford Sounds (2 from Caswell, 4 from Nancy and 2 from Milford) were used to assess the potential application of gamma-ray absorption in the routine description of density distribution in sediment cores (*see* Corey and Hayes 1970; Whitmarsh 1971; Bennett and Keller 1973). Differences from the visual core descriptions in the previous paper by G.P. Glasby (Pp19–23), reflect the ability of gamma-ray measurements to identify minor layering in the cores.

The apparatus used in this study (Fig. 1) consists of a carriage which holds a 100 millicurie ^{137}Cs source contained in a lead shield with a gamma-ray detector opposite (Preiss 1968). The carriage is driven along the length of the core barrel by an electric motor and chain drive, and the count rate is recorded on a strip chart. From this, a density profile along the core can be derived. The apparatus is designed to accommodate cores 7.5 cm in diameter up to 3 m long contained in PVC liner with a wall thickness of 2.4 mm.

Calibration was carried out using lead, glass and air. The lead block was 7.5 cm thick with a density of 11.3 gm/cm^3; the glass was 7 cm thick with a density of 2.47 gm/cm^3, and the air had a density of 1.23 x 10^{-6} gm/cm^3 calculated from room temperature and barometric pressure.

Following calibration, the unopened cores were positioned, the carriage driven along the core, and a density profile obtained. The gamma-ray profile from the upper section (0-170 cm) of core H275 (Nancy Sound) with the corresponding stratigraphy, and calibration control profiles of lead, glass, and air included is shown in Fig. 2.

Each core was scanned twice, being rotated 90° for the second measurement. Individual cores were then opened using a standard core splitter (Langford *et al* 1969) and sediment texture and grain size determined. In the case of the upper sections of cores H275 (Nancy Sound) and H286, H287 (Milford Sound), grain-size analyses were carried out at specific points along the cores using standard sieve techniques in order to relate the absorption profiles obtained to sediment grain size.

RESULTS

The gamma-ray absorption profiles from the eight cores are shown in diagrammatic form (Fig. 3) with the stratigraphy of each core alongside showing the relationship between variations in density and grain size discontinuities. This relationship is discussed in greater detail for individual cores.

CASWELL SOUND

Core H229 (456 cm) consists of dusky yellowish brown mud (particle size < 64 µ) throughout the length of the core, except for two horizons at 134 cm and 175 cm from the top, which contain brownish-black fibrous organic material mixed with fine sand (64-125 µ). Both horizons appear more dense than the surrounding mud.

Core H253 (498 cm) consists of olive grey mud with one noticeable fine sand horizon at 32 cm which shows greater density than the surrounding mud.

NANCY SOUND

Core H266 (531 cm) shows no profiles from the uppermost 318 cm, owing to poor compaction. From here to the bottom, the core consists of greyish black and olive-black mud with a sand layer 9 cm thick, 34 cm from the top of this section. The sand has a greater density than the mud; so has the layer (49 cm

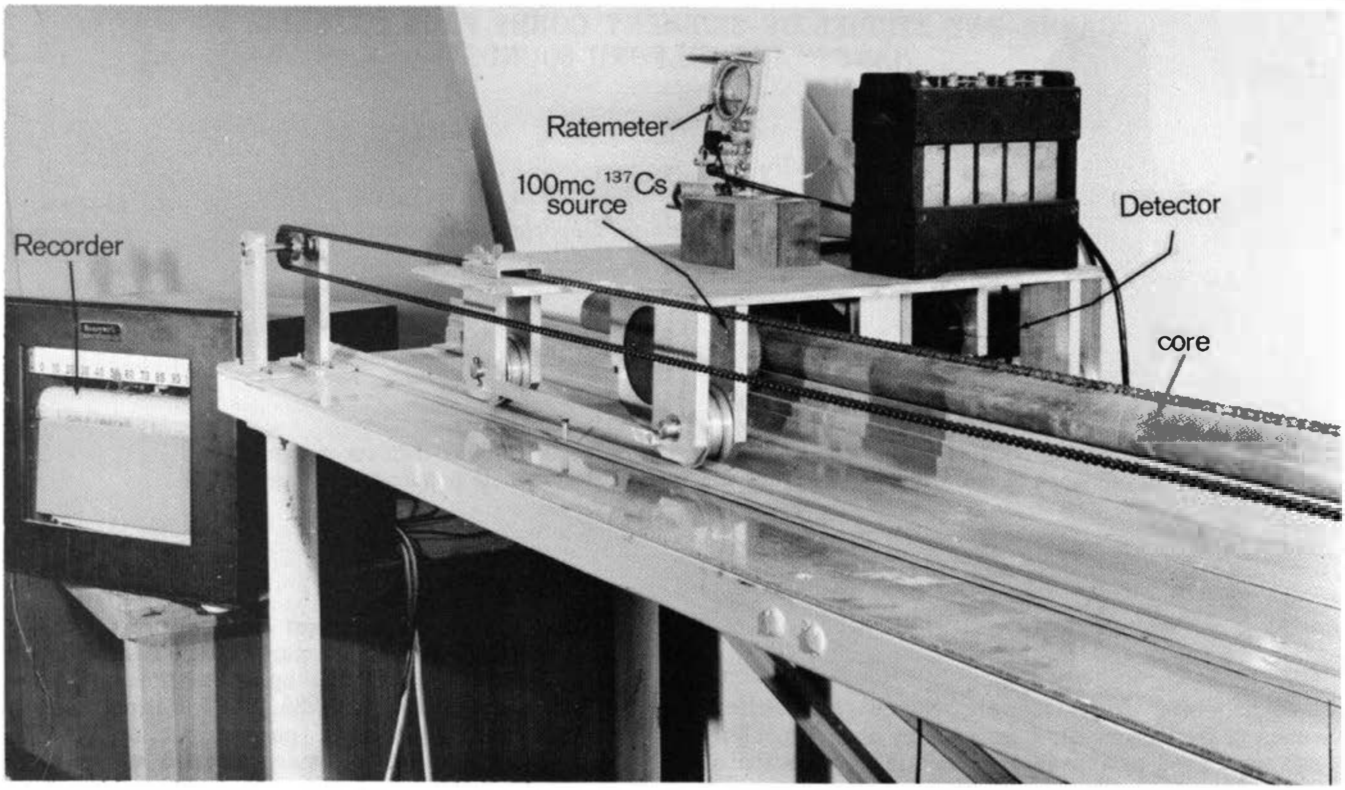


FIG. 1. Photograph showing principal features of the gamma-ray apparatus.

thick and at the base of the core) of sand interspersed with fragments of undecomposed organic matter.

Core H269 (500 cm) consists of olive grey mud along its length with two small fine sand horizons at 35 cm and 125 cm from the top. Between 175 and 200 cm lies a band of undecomposed organic matter and sand plus a band of fine sand. These four layers all have a greater density than the remainder of the core.

Core H275 (492 cm) has been cut into three sections; the mid-part (170-318 cm), being disturbed, was discarded. Ten samples (X1-X10) of the upper section (0-170 cm) have been analysed and consist of mud and fine, medium, and coarse sands in varying percentages (Fig. 4). Up to 48% coarse grey sand ($> 500\mu$) is seen in sample X7 and 38% olive-black mud ($< 64\mu$) in X9. Five layers of muddy sand to a depth of 100 cm have been analysed (X2, X4, X6, X8, X9) and show differences in gamma-ray absorption (Fig. 2), X2 and X4 show greater density and X6, X8 and X9 show lower density.

Analysis of sub-samples of sand (X1, X3, X5, X7, X10) (Fig. 4) likewise shows varying absorption profiles with X1 (fine sand) showing greater density, and X5 (coarse-medium sand) showing lower density. With X3 (coarse-medium sand), X7 (medium-coarse sand) and X10 (fine sand) there is no appreciable variation in the profiles.

The coarse sand is composed of approximately 50% quartz with the remaining fraction consisting of a variety of dark minerals including amphibole grains. The lower section (318-492 cm) consists of fine grey sand (64-125μ) with two layers of grey-black mud (3 cm and 5 cm wide respectively), both showing lower densities.

Core H276 (500 cm): the upper section of this core to 275 cm consists of organic-rich mud and sand. No profiles were taken owing to disturbance within the core.

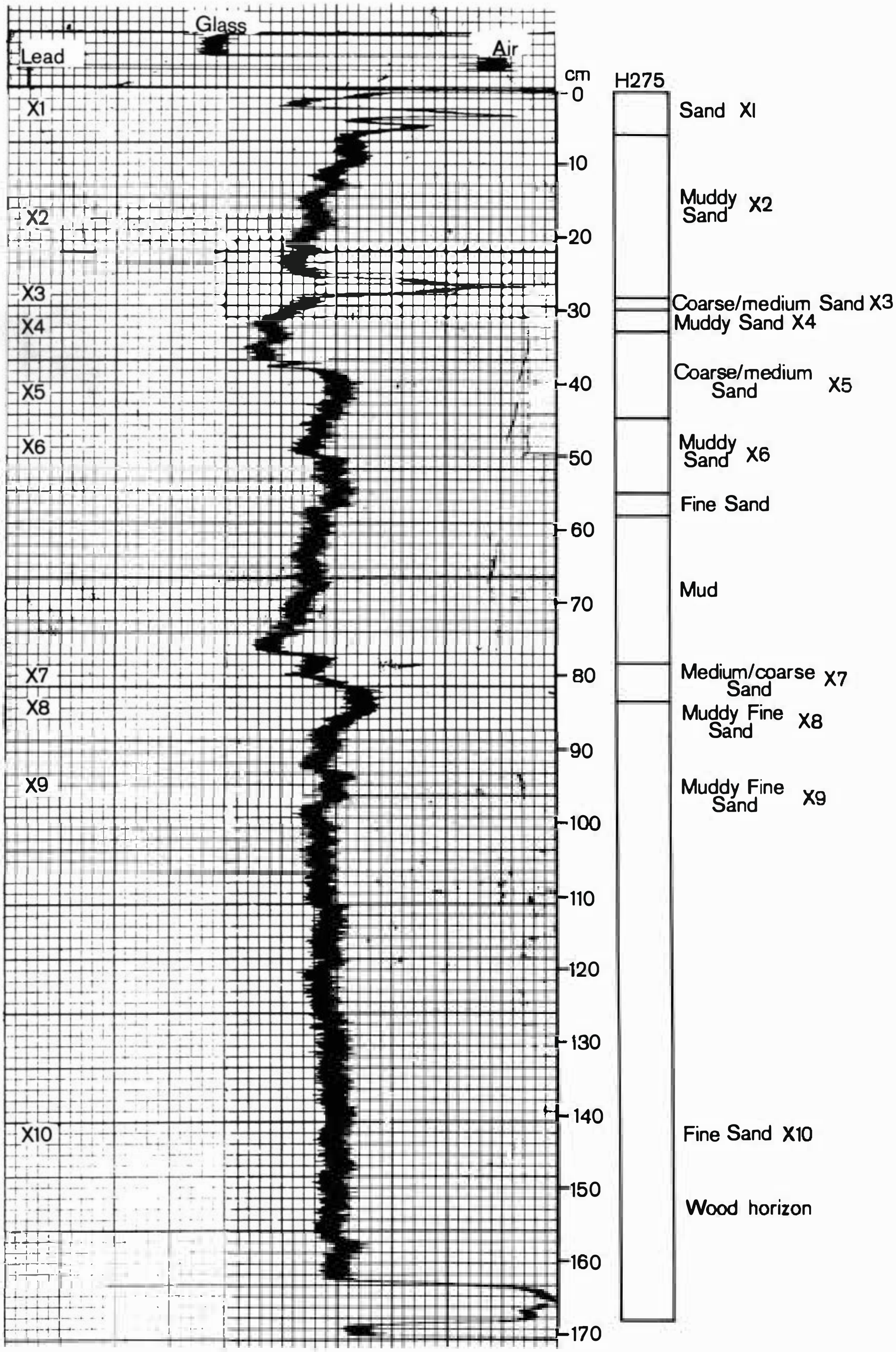
The lower section (275-500 cm) consists of fine sand with two bands of grey-black mud cementing together numerous mineral grains, with a band of fine sand separating the mud layers. The profile for both bands of mud indicates lower densities.

MILFORD SOUND

Core H286 (449 cm) is predominantly dark green-grey mud with six fine sand horizons with well-defined

FIG. 2. Print of gamma-ray absorption profile from core H275, with stratigraphy shown alongside. Calibration readings for lead, glass and air are included.

▶


Glass
Lead
Air
cm
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
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160
170
X1
X2
X3
X4
X5
X6
X7
X8
X9
X10
H275
Sand Xl
Muddy Sand X2
Coarse/medium Sand X3
Muddy Sand X4
Coarse/medium Sand X5
Muddy Sand X6
Fine Sand
Mud
Medium/coarse Sand X7
Muddy Fine Sand X8
Muddy Fine Sand X9
Fine Sand X10
Wood horizon

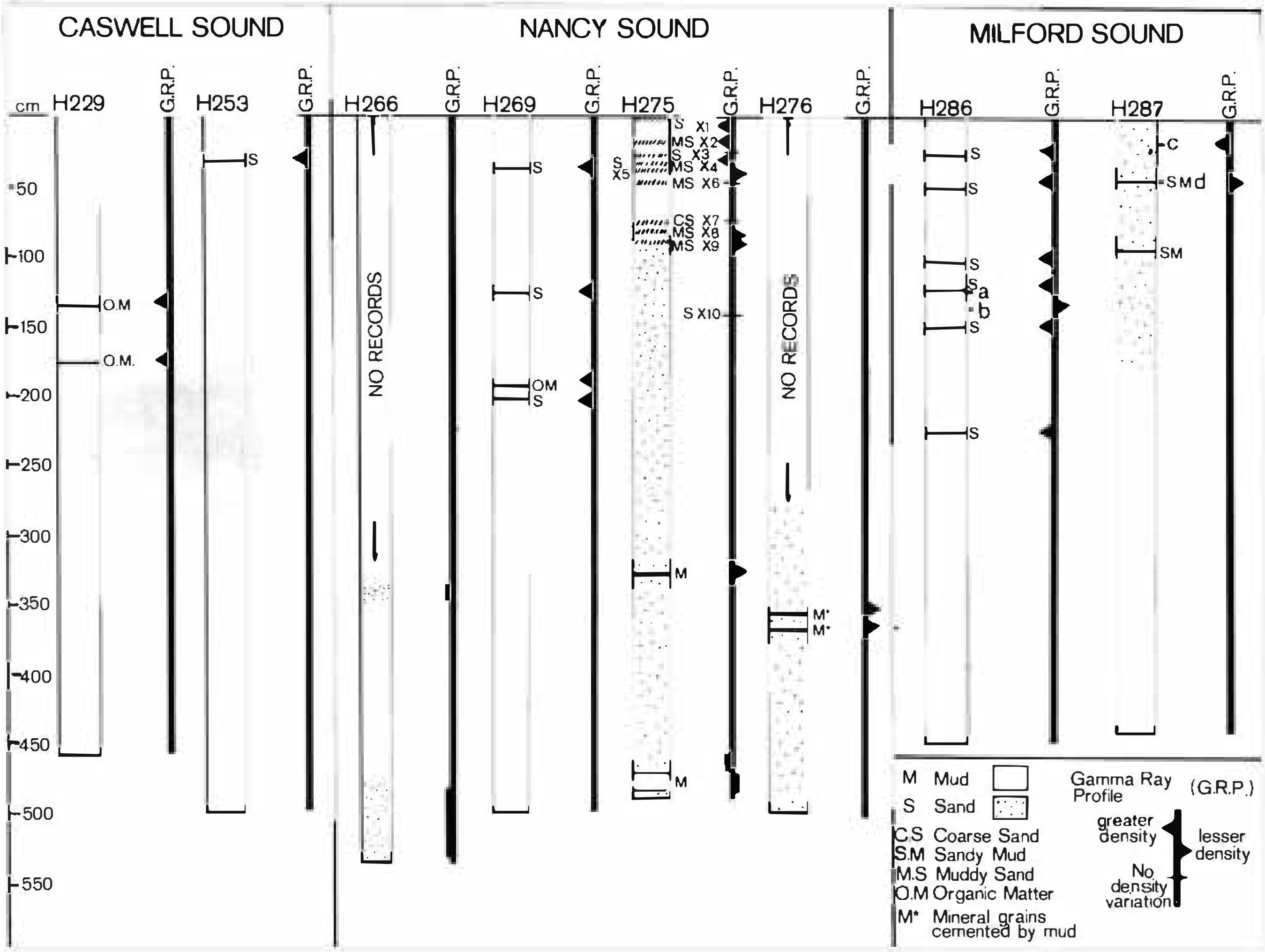

FIG. 3. Gamma-ray absorption profiles from eight cores with corresponding stratigraphy in diagrammatic form alongside.

boundaries. Grain-size analyses are shown in Table 1. The profiles relating to these analyses show greater density for the sand and lower density for the mud.

Core H287 (437 cm) shows two distinct sedimentary layers with mud ($< 64\ \mu$) from 175 cm to the bottom of the core. Analysis of sediment from the upper layer (c, Table 1) shows 88.7% fine sand, 3.6% medium sand and 7.4% mud with a reading of greater density on the profile. There are two sandy mud horizons in this upper layer, analysis of which (d, Table 1) shows 70.8% greenish-grey mud and 27.5% fine sand with a marked quantity of mica in the sand grade. This subsample was taken at a profile reading relating to lesser density.

DISCUSSION

The bulk density of a sediment depends on the densities and relative amounts of the solid constituents or mineral grains in the sediment, of the water in the pore spaces between the grains, and of the gases entrapped or formed in the sediment.

Submarine sediments have a high water content and porosity, and this makes accurate calibration of gamma-ray profiles difficult. It is uncommon to obtain a specimen of sediment with a uniform density distribution.

The results presented here therefore give an indication only of the relative densities along the core. When dealing with unopened cores, absorption profiles can, however, act as a guide for transverse cutting of the core (enclosed in liner) for the purpose of handling and storage. The possibility of interfering with horizons, layering and areas of marked density variations would be minimised by referring to the appropriate profile.

Of the cores examined, sand horizons in a muddy core show a higher density, whereas mud horizons in a sandy core show a lower density. Anomalies occur

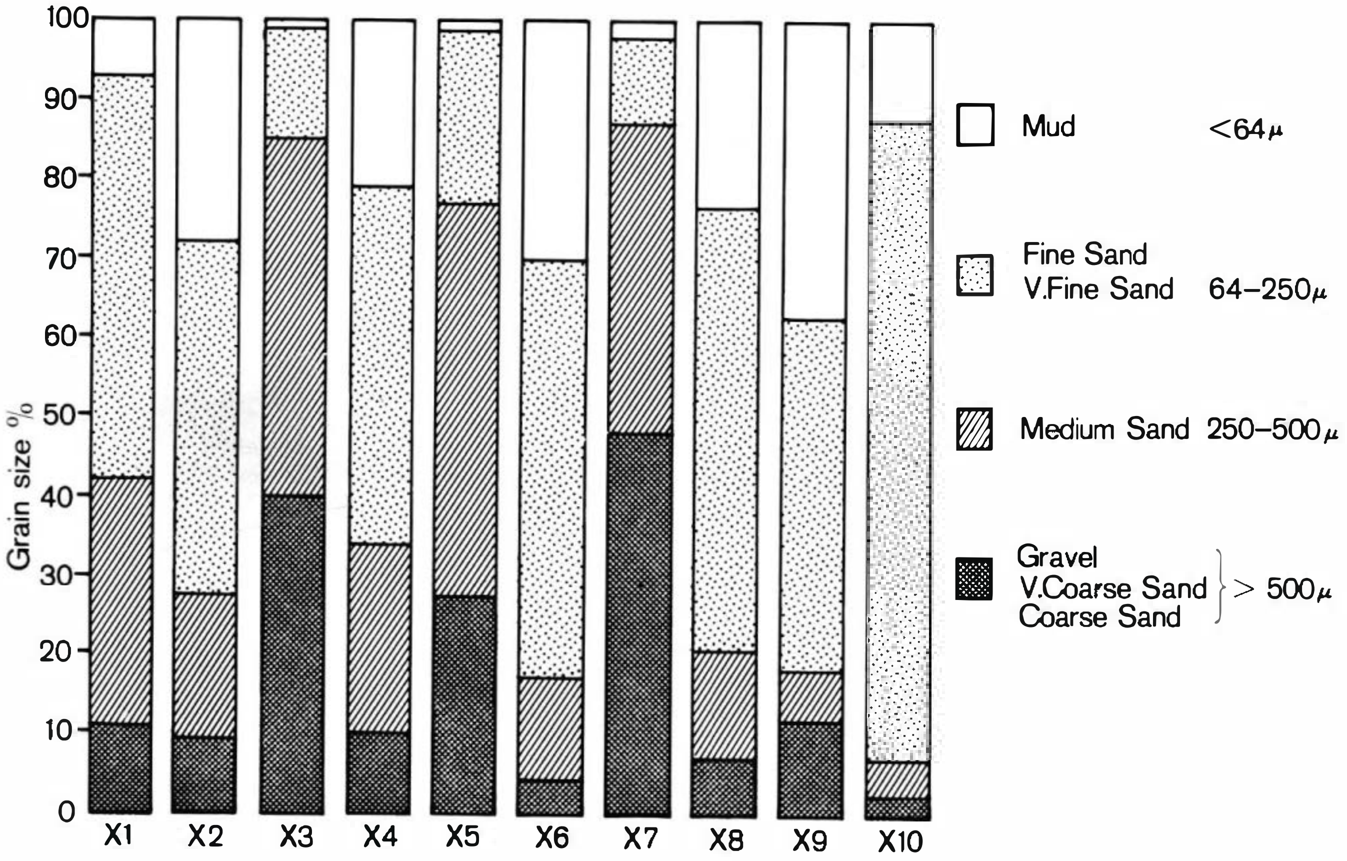

FIG. 4. Detailed plots of grain-size analyses from selected positions in core H275 (Nancy Sound). The positions in the core of the samples analysed are shown in Fig. 2. Grain-size analyses of a, b, c, and d on the Milford Sound cores are shown in Table 1.

TABLE 1. Percentage grain-size variations from Milford Sound cores.

	Gravel; Very coarse sand; Coarse sand.	Medium sand	Fine sand; Very fine sand.	Mud
	(>500 μ)	(250 - 500μ)	(64-250μ)	(<64μ)
H 286				
a. (125 cm from top of core)	2.03	26.64	66.86	4.46
b. (135 cm from top of core)	1.60	0.27	4.79	93.33
H 287				
c. (20-21 cm from top of core)	0.25	3.61	88.73	7.41
d. (33-34 cm from top of core)	0.69	0.98	27.40	70.83

in H275 where, in zones containing varying proportions of sand and mud, the densities differ from those seen in the other cores.

In the profiles obtained from H266 and H275 (Nancy Sound), there is a marked increase in density at the bottom of each core. This may be caused by either the nature of the sand and organic fragments in H266 and the sand particles in H275, or to compaction in the cores at depth (between 445 and 530 cm).

Although it is not always possible to know the nature of the sediment from the absorption profiles before opening a core, disturbance of the sediment during opening can be minimised by referring to the density changes shown on the profiles.

REFERENCES

BENNETT, R.H.; KELLER, G.H. 1973: Physical properties evaluation. *Initial Reports of Deep Sea Drilling Project Leg 16* : 513-19.

COREY, J.C.; HAYES, D.W. 1970: Determination of density and water content of marine sediment in an unextruded core using fast neutron and gamma ray attenuation. *Deep Sea Research 17* : 917-22.

LANGFORD, A.; McDOUGALL, J.C.; ROBERTSON, N.D. 1969: A new large diameter piston corer and core-liner cutter. *N.Z. Journal of Marine and Freshwater Research 3* : 595-601.

PREISS, K. 1968: Non destructive laboratory measurement of marine sediment density in a core barrel using gamma radiation. *Deep Sea Research 15* : 401-7.

WHITMARSH, R.B. 1971: Precise sediment density determination by gamma ray attenuation above. *Journal of Sedimentary Petrology 41* : 882-3.

POLLEN DISTRIBUTION IN SEDIMENTS FROM CASWELL, NANCY AND MILFORD SOUNDS

by

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ABSTRACT

Pollen diagrams are presented from three profiles, each about 5 m deep, from Caswell, Nancy and Milford Sounds. The profiles are from depths of 145 m (Caswell), 99 m (Nancy), and 297 m (Milford) below the surface of each fiord. Pollen frequencies are assumed to reflect the composition of the surrounding vegetation, despite a lack of detailed plant community studies adjacent to the coring sites. Podocarp pollen is thought to be under-represented and *Nothofagus menziesii* pollen over-represented in the profiles. A virtual lack of vegetational changes during the deposition of the sediments suggests an age of less than 600 years for each profile, giving an average rate of sedimentation in the fiords of about 8 mm per year. This varies slightly from rates of 10 mm per year for Milford Sound, and 5 mm per year for Nancy Sound, based on radiocarbon dates.

INTRODUCTION

Samples for pollen analysis were taken from three N.Z. Oceanographic Institute cores from Caswell Sound (core H229), Nancy Sound (core H264) and Milford Sound (core H286), Fiordland. The surrounding coastal vegetation is a temperate rain forest dominated by *Nothofagus menziesii*, *N. solandri* var. *cliffortioides*, *Weinmannia racemosa*, *Podocarpus hallii*, *Dacrydium biforme*, *Phyllocladus alpinus*, *Cyathea* spp., and *Metrosideros* spp. Montane, and sub-alpine vegetation occurs within a few kilometres of the coast.

Samples were taken at irregular intervals from the cores down to a maximum depth of almost 5 metres (Table 1). The sediments are sandy to muddy carbonaceous silts, rich in pollen and dinoflagellate cysts, and relatively simple to process for pollen analysis. Details of sample preparation are found in Lennie (1968).

PREVIOUS WORK

The nearest sites for which Quaternary pollen work has been published are at Lake Monk, in the Cameron Mountains, at the south end of the fiord system (Harris 1963) and Milford Sound at the north end (Harris 1964). The Lake Monk pollen results are quite different from those of the fiord cores having a much higher percentage of podocarps and a much lower percentage of *Nothofagus menziesii* pollen. Other Fiordland and Southland localities have pollen spectra similar to Lake Monk (Harris 1963, p.44; *see also* Cranwell and von Post 1936).

METHOD OF STUDY

Pollen counts were continued until 100 specimens of the dominant tree pollen (*Nothofagus menziesii*) had been counted. The total pollen counts range from 135 to 643 grains. The full pollen lists include those types found after a count of 100 specimens of the dominant tree pollen (Tables 2-4).

Counts of dinoflagellate cysts were made at the same time, and are included in the pollen lists to give a frequency index when compared with pollen and spore types.

LOCATION OF CORES

Caswell Sound (core H229) : the core was taken towards the eastern end of the sound on the southern side (*see* Table 1). Streams form waterfalls over high, steep cliffs bordering the sound. Several large streams enter the fiord close to the coring site providing a steady supply of sediment.

Nancy Sound (core H264) : the core was taken from towards the eastern end of Nancy Sound, near Heel Cove (*see* Table 1). It was sunk close to the southern

TABLE 1. Locality and sampling data on cores from Caswell, Nancy and Milford Sounds.

	Milford Sound	Caswell Sound	Nancy Sound
Core number	H286	H229	H264
Latitude	44°37.05'S	45°02.01'S	45°10.91'S
Longitude	167°51.86'E	167°17.75'E	167°06.30'E
Depth of water above top of core	297 m	145 m	99 m
Sample	Depth in sedimentary column (cm)		
1	0-10	0	0-15
2	60-65	30-35	67-83
3	130	100	120-135
4	200-205	150-155	150
5	300-305	200	180-195
6	400-405	250-255	270-285
7		300	390-405
8		350-355	460-475
9		400-405	
10		450	

wall of the fiord near several small streams which supply regular amounts of sediment across small deltas. The nearby walls of the fiord are not as steep as those near the cores from Caswell and Milford Sounds. No major rivers feed into this fiord.

Milford Sound (core H286) : this core was taken at the north-west end of the Stirling Basin (*see* Table 1). The nearest land is approximately 0.6 km to the south-west where the slopes both below and above sea-level are very steep, rising to 1700 metres within 3 km. The only major stream is the Stirling River, 1.5 km from the core site.

RESULTS AND DISCUSSION

The preservation of the pollen and spores is good in all samples. There is no indication of the differential preservation of *Cyathea* and other fern spores below 132 cm in the cores reported by Harris (1964) from core A321 in Milford Sound in the south-east corner of the Stirling Basin. A few pollen grains were found to be deeply corroded but this may have been caused by water transportation to the sites of deposition. There are no significant differences in the proportions of the main pollen types that would suggest any major change in the surrounding vegetation during the period of deposition.

Little is known about the coastal vegetation in the vicinity of the core localities and no attempt is made to correlate the pollen rain with pollen source. Over 100 pollen forms have been recognised, of which just over 50% represent bog and swamp species, a lower proportion than from core A321 in Milford Sound (Harris 1964). This portion of the pollen spectra represents pollen from upland vegetation transported either by wind or streams flowing into the fiord. A higher proportion of corroded grains occurs in species representing upland vegetational types, suggesting that the latter is more probable.

A few pollen and spores of plants not recorded during the botanical surveys of either the Caswell and George Sound areas (Poole 1951a) or Secretary Island (Wardle 1963; Mark and Baylis 1963; Baylis *et al* 1963; Murray 1963; Wardle and Mark 1970; Scott 1970) were identified. These are *Sphagnum* sp. (recorded in montane and subalpine vegetation between Caswell and Charles Sounds by Given 1971), *Dacrydium bidwillii*, *Libocedrus* sp. (possibly an introduced Cupressaceae), Lauraceae, ?*Plagianthus* type, *Geniostoma ligustrifolium*, *Arthropodium* sp. and *Myoporum laetum*. All are either wind-transported or may represent local occurrences. The presence of *Myoporum laetum* at the base of the Nancy Sound sequence is unexpected as it is rare in the south of the South Island (Allan 1961). ?*Plagianthus* type may be derived from the relatively common *Hoheria glabrata*, and *Dacrydium bidwillii* is difficult to distinguish from *D. biforme* which is known from this area (N.T. Moar, pers. comm.).

CASWELL SOUND (Figs 1, 2; Table 2)

Table 2 lists the number of pollen, spores, and dinoflagellate cysts found in Caswell Sound, including pollen of *Pinus* and *Casuarina*. *Pinus* is a widespread introduced species; and *Casuarina*, indigenous to Australia, very rarely grows outside public parks in New Zealand (Moar 1969). *Pinus* could be a contaminant (it often occurs in the chemicals used in processing palynological samples) but *Casuarina* probably arrived in the profile by long distance wind dispersal from Australia (Moar 1969). *Casuarina* occurs in three of the bottom six samples. *Sphagnum* spores are common in the top five samples and absent in the bottom five. Murray (1963) states that *Sphagnum* is rare at Secretary Island, 11 km south of the mouth of Caswell Sound, and it is not listed by Poole (1951a) in his list of the flora of Caswell and George Sounds. It probably colonised Caswell Sound quite recently and was overlooked during Poole's botanical survey.

Figure 1 is a pollen diagram of the major components of the pollen spectra. The profile shows only minor variations :

(a) Two samples are low in *Cyathea* spores.

(b) Slight increases in the percentages of Myrtaceae and *Weinmannia racemosa* pollen occur at the expense of *Nothofagus* lower in the profile. The variations are too slight to have any significance.

(c) Dinoflagellate cysts are rare in samples 2 to 10 (30-450 cm).

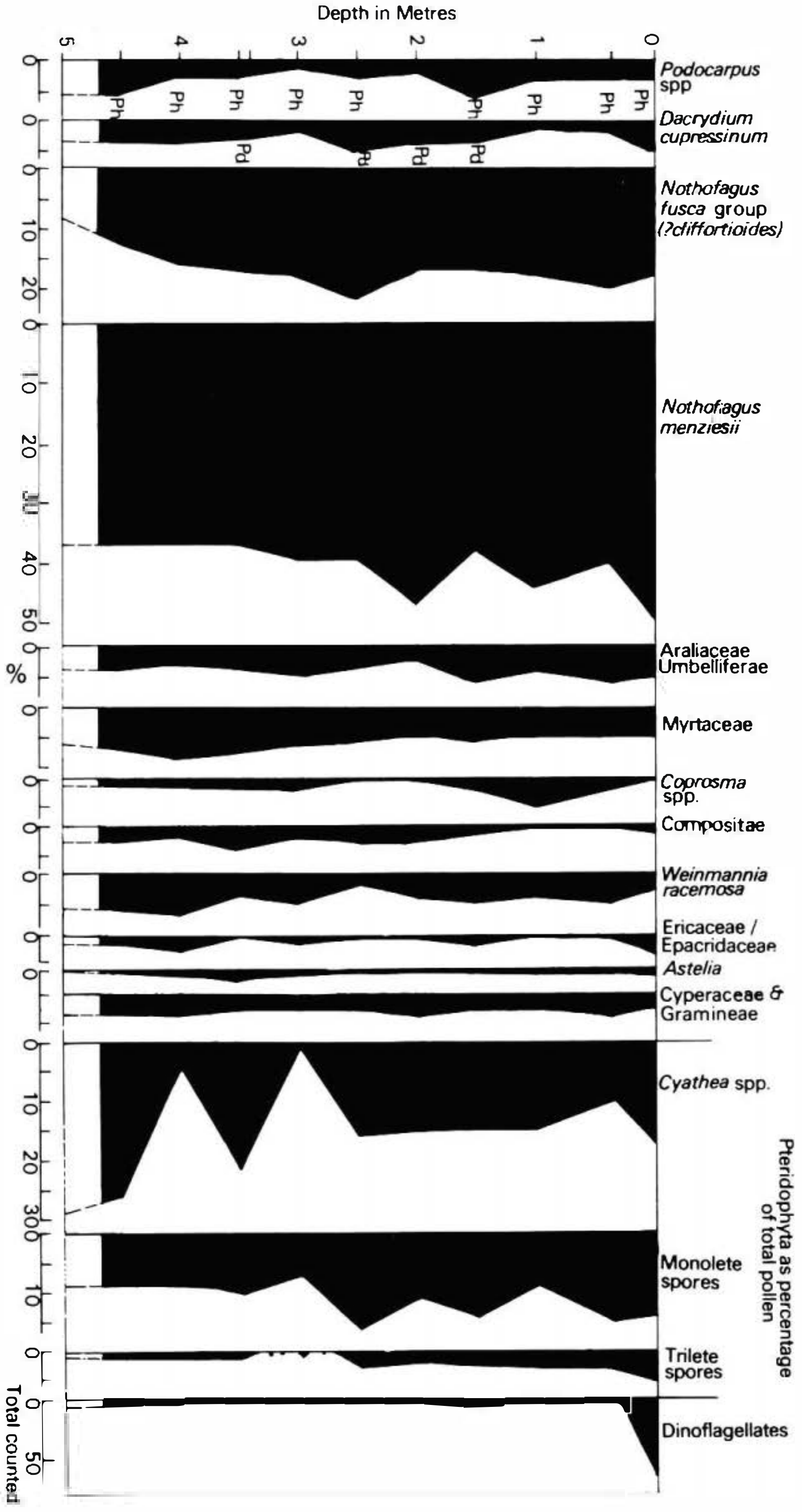

FIG. 1. Pollen diagram, Caswell Sound, Fiordland, core H229, showing pollen percentages.
Ph = *Phyllocladus* sp.;
Pd = *Podocarpus dacrydioides.*
Spores are excluded from the pollen sum.

Figure 2 shows the relative percentages of *Nothofagus* and podocarp pollen. As with Nancy Sound (*see* below) the results are uniform throughout the profile, possibly because of rapid sedimentation.

The pollen and spores identified from plants not listed by Poole (1951a) are *Sphagnum* sp., *Dacrydium bidwillii* (=? *D. biforme*), *Haloragis* sp. and *Metrosideros* (=? *M. umbellata*). The pollen assemblage does

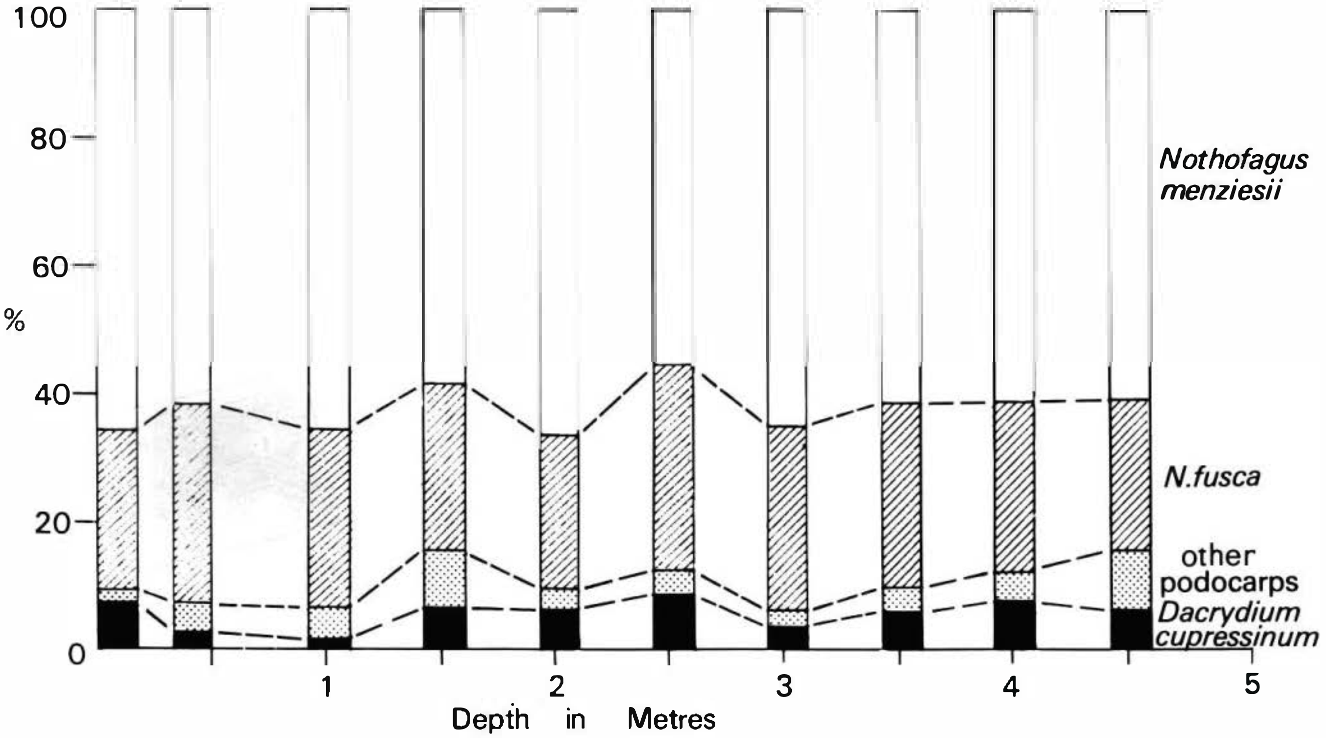

FIG. 2. Diagrammatic representation of *Nothofagus menziesii*, *N. fusca* group, *Podocarpus* spp. and *Dacrydium cupressinum* as percentages from core H229, Caswell Sound, Fiordland.

not differ significantly from that of Nancy Sound, and probably represents pollen rain from a Class III and IV or Class B plant community, of Wardle (1963) and Wardle *et al* (1970), respectively.

NANCY SOUND (Figs 3, 4; Table 3)

Table 3 lists the number of pollen, spores, and dinoflagellate cysts found in the Nancy Sound samples. The samples contain specimens of *Pinus* sp., *Casuarina* sp., and *Cupressus* sp. which represent either long distance transport or contamination. *Casuarina* occurs as isolated grains in many Quaternary profiles and is found in both Caswell and Milford Sounds.

Figure 3 is a pollen diagram of the major components of the pollen spectra. Four noticeable changes occur in the profile but the significance of these is not known :

(a) *Cyathea* spores are rare in sample 3 (120-135 cm).

(b) *Dacrydium cupressinum* (rimu) increases from less than 1% of the total pollen count (excluding spores) in the first three samples to about 5% in the lower 4 samples (180-475 cm).

(c) *Nothofagus fusca* group pollen decreases as the percentage of rimu pollen increases.

(d) Dinoflagellate cysts are rare in samples 5 to 8 (180-475 cm).

Figure 4 shows the relative percentages of *Nothofagus* and podocarp pollen. The results are uniform for almost 5 m, possibly because of rapid sedimentation. Radiocarbon dates from wood of *Nothofagus* sp. at a depth of 105.5-110.0 cm (1260 ± 73 yrs B.P.) and bark at 116.0 cm (1135 ± 75 yrs B.P.) indicate a sedimentary rate of 83.7-102.2 cm/10^3 years (*see* p.33). A further date from wood of *Weinmannia racemosa* at a depth of 484-488 cm (1135 ± 154 yrs B.P.) indicates a sedimentary rate of 426.4-429.9 cm/10^3 or 4 mm/year (*see* p.33). This is not consistent with the assumption that sedimentary rates were rapid and that the uniform pollen profile represents 600 years or less as discussed on p.59.

There appear to be no published details of the vegetation around Nancy Sound, but vegetation studies on Secretary Island, 8 km south of the mouth of Nancy Sound have been undertaken by Wardle (1963) and Mark and Baylis (1963). The pollen assemblage from the core appears to represent a pollen rain from a Class III and IV plant community (Wardle 1963) or a Class B community (Wardle *et al* 1970). The main components of the pollen assemblage are *Nothofagus menziesii*, which dominates all samples (*see* Figs 3, 4), *Nothofagus solandri* var. *cliffortioides* (*fusca* group), *Weinmannia racemosa*, *Metrosideros* spp. and *Cyathea* spp.

MILFORD SOUND (Figs 5, 6; Table 4)

Table 4 lists the number of pollen, spores, and dinoflagellate cysts found in core H286 from Milford Sound. *Pinus* pollen was not found but four out of the six samples contain *Casuarina*, and the two bottom

TABLE 2. Numbers of pollen and spore types identified in samples from Caswell Sound. tr = trace (< 1%).

SPECIES	Slide	L5988	L5989	L5990	L5991	L5992	L5993	L5994	L5995	L5996	L5997
	Sample	1	2	3	4	5	6	7	8	9	10
Dinoflagellates (several species)		62	tr	tr	7	3	tr	tr	tr	tr	5
Sphagnaceae											
Sphagnum sp.		tr	tr	tr	tr	tr	-	-	-	-	-
Lycopodiaceae											
Lycopodium billardieri		tr	tr	tr	tr	tr	tr	-	-	-	tr
L. fastigiatum group		-	-	tr	tr	tr	tr	-	tr	tr	tr
L. scariosum			-	tr	tr	-	-	-	tr	-	tr
Ophioglossaceae											
Ophioglossum sp.		-	-	tr	-	-	-	-	-	-	-
Hymenophyllaceae											
Hymenophyllum spp.		7	6	4	4	3	6	tr	4	tr	tr
H. sanguinolentum		tr	-	tr	tr	tr	tr	-	-	-	tr
Dicksoniaceae											
Dicksonia squarrosa		tr	4	tr	tr	tr	tr	-	tr	-	tr
Cyatheaceae											
?*Cyathea dealbata*)											
C. medullaris)		52	35	48	57	44	62	3	85	13	108
C. smithii)											
Polypodiaceae											
Phymatodes diversifolium		tr	4	tr	tr	3	tr	tr	5	tr	tr
P. scandens		-	tr	-	-	-	-	-	tr	tr	-
Pyrrosia serpens		-	tr	-	?tr	-	tr	?tr	tr	-	-
Dennstaedtiaceae											
Hypolepis sp.		-	tr	-	tr	tr	tr	-	-	-	-
H. tenuifolia		-	-	tr	-	-	-	-	-	-	-
Lindsaeaceae											
?*Lindsaea* sp.		-	-	tr	tr	tr	-	-	tr	-	tr
Pteridaceae											
Paesia scaberula		tr	tr	-	-	-	tr	-	tr	-	tr
Pteridium aquilinum var. *esculentum*		-	-	-	-	tr	tr	-	-	-	-
Gleicheniaceae											
Gleichenia sp.		-	-	-	-	tr	-	-	-	-	-
Osmundaceae											
Todea sp.		tr	-	-	-	-	-	-	-	-	-
Blechnaceae											
Blechnum sp.		tr	tr	tr	tr	tr	4	-	tr	tr	tr
Unidentified monolete spores		42	45	26	49	30	53	20	35	26	34
Podocarpaceae											
Dacrydium bidwillii		tr	tr	tr	tr	tr	tr	-	-	tr	tr
D. cupressinum		9	4	tr	10	8	13	4	8	12	9
Podocarpus dacrydioides		-	-	-	tr	tr	tr	-	tr	-	-
P. ferrugineus group		tr	5	6	10	4	6	tr	7	6	16
P. totara group		-	tr	tr	tr	tr	tr	tr	tr	tr	tr
Phyllocladus sp. (?*alpinus*)		tr	tr	tr	tr	-	tr	tr	tr	tr	tr
Pinaceae											
?*Pinus* sp. (introduced)		tr	tr	-	-	-	-	-	-	-	-
Winteraceae											
Pseudowintera colorata		tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
Violaceae											
Melicytus sp. (?*ramiflorus*)		-	-	tr	4	tr	tr	tr	tr	tr	tr
Caryophyllaceae		-	tr	-	-	-	-	-	tr	-	-
Meliaceae											
?*Dysoxylum spectabile*		-	-	-	-	-	-	tr	-	-	-
Chloranthaceae											
Ascarina lucida		-	tr	tr	tr	tr	tr	tr	tr	tr	tr
Polygonaceae											
?*Rumex* sp.		-	-	-	-	tr	-	-	-	-	-
Chenopodiaceae		tr	tr	tr	tr	tr	tr	-	tr	tr	tr
Haloragaceae											
Gunnera sp.		-	-	tr	tr	-	tr	-	-	tr	tr
Haloragis sp.		-	-	-	-	-	tr	-	-	-	-
Myriophyllum sp.		-	-	-	-	-	tr	tr	-	-	-
Onagraceae											
Epilobium sp.		-	-	-	-	-	-	-	-	tr	-
Fuchsia excorticata		tr	tr	tr	tr	-	-	tr	tr	tr	tr
Coriariaceae											
?*Coriaria* sp.		-	-	-	-	tr	-	-	-	-	-

TABLE 2. Continued

SPECIES Slide	L5988	L5989	L5990	L5991	L5992	L5993	L5994	L5995	L5996	L5997
Sample	1	2	3	4	5	6	7	8	9	10
Myrtaceae										
?*Eugenia maire*	-	-	-	-	-	-	-	tr	-	-
Leptospermum sp. (?*scoparium*)	tr	tr	tr	tr	tr	tr	-	tr	-	-
Lophomyrtus sp.	-	-	tr	-	-	-	-	-	-	-
Metrosideros spp.	9	12	10	14	10	15	17	21	21	18
?*M. robusta*	-	-	-	tr	tr	-	-	-	tr	tr
Malvaceae										
Hoheria sp. (?*glabrata*)	-	-	tr	-	tr	tr	-	tr	tr	tr
Cunoniaceae										
Weinmannia racemosa	7	12	10	13	9	5	13	12	19	15
Fagaceae										
Nothofagus menziesii	100	100	100	100	100	100	100	100	100	100
N. fusca group (?*cliffortioides*)	38	49	41	44	36	58	46	45	42	35
Araliaceae	6	12	7	6	4	6	6	6	tr	7
?*Pseudopanax* sp.	4	tr	tr	10	tr	tr	6	4	4	4
Rhamnaceae										
?*Pomaderris* sp.	tr	-	-	tr	-	-	-	-	tr	-
Cornaceae										
Griselinia sp.	-	-	-	-	-	-	tr	-	-	-
Umbelliferae	tr	-	tr	tr	tr	tr	tr	-	tr	2
?*Hydrocotyle* sp.	-	tr	-	tr	-	-	-	-	-	-
Ericaceae/Epacridaceae										
?*Epacris* sp.	-	-	-	-	-	-	-	-	tr	-
cf. *Gaultheria* spp.	6	tr	tr	4	3	tr	4	tr	7	5
Myrsinaceae										
Myrsine sp.	-	tr	tr	tr	3	4	6	7	tr	4
Loganiaceae										
?*Geniostoma ligustrifolium*	-	-	tr	-	-	-	-	-	-	-
Apocynaceae										
?*Parsonsia* sp.	-	-	-	-	-	tr	-	-	-	-
Rubiaceae										
Coprosma sp.	tr	6	11	5	tr	tr	4	6	4	4
Nertera sp.	-	tr	tr	tr	tr	-	tr	-	tr	tr
Compositae	tr	tr	tr	5	6	8	6	11	6	9
Scrophulariaceae										
Hebe sp.	-	tr	tr	-	-	?tr	-	tr	-	-
Casuarinaceae										
Casuarina sp. (introduced, transported)	-	-	-	-	tr	-	-	tr	-	tr
Unidentified dicotyledonous pollen grains	4	8	11	13	13	17	17	17	16	16
Potamogetonaceae										
?*Potamogeton* sp.	-	tr	-	-	-	-	-	-	-	-
Liliaceae										
Astelia sp.	tr	tr	tr	tr	tr	tr	3	5	tr	tr
Bulbinella hookeri	-	-	-	tr	-	-	tr	tr	tr	-
Agavaceae										
?*Cordyline* sp.	tr	tr	tr	-	-	tr	tr	tr	tr	-
Restionaceae	-	-	-	-	-	tr	-	tr	tr	tr
Sparganiaceae										
?*Sparganium* sp.	-	-	-	-	-	tr	tr	tr	tr	-
Orchidaceae	-	-	-	-	-	-	-	-	tr	tr
Cyperaceae	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
Gramineae	5	10	5	7	6	6	5	8	9	11
Total Count	376	348	315	392	303	395	278	403	316	425

samples contain pollen of the Australian myrtaceous genus, *Eucalyptus*, which is characterised by a noticeable thickening of the exine around the apertures.

The pollen diagram (Fig. 5), like those of Caswell and Nancy Sounds, shows few changes for the whole core. It does show, however, a slight decrease with depth in the percentage of *Nothofagus fusca* group, *Weinmannia racemosa* and *Cyathea* corresponding with an increase in podocarps and *Nothofagus menziesii*. It is unlikely that these differences result from climatic or vegetational changes but probably represent variations in the pollen rain (but see below). Figure 5 omits dinoflagellate cysts because of their consistent scarcity in the profile, always less than 1%.

Figure 6 shows the relative percentages of *Nothofagus* and podocarp pollen. There is a noticeable decrease in the ratio of *Nothofagus fusca* group pollen (thought to be *N. solandri* var. *cliffortioides*) to *N. menziesii*, and to a lesser extent the podocarps, down

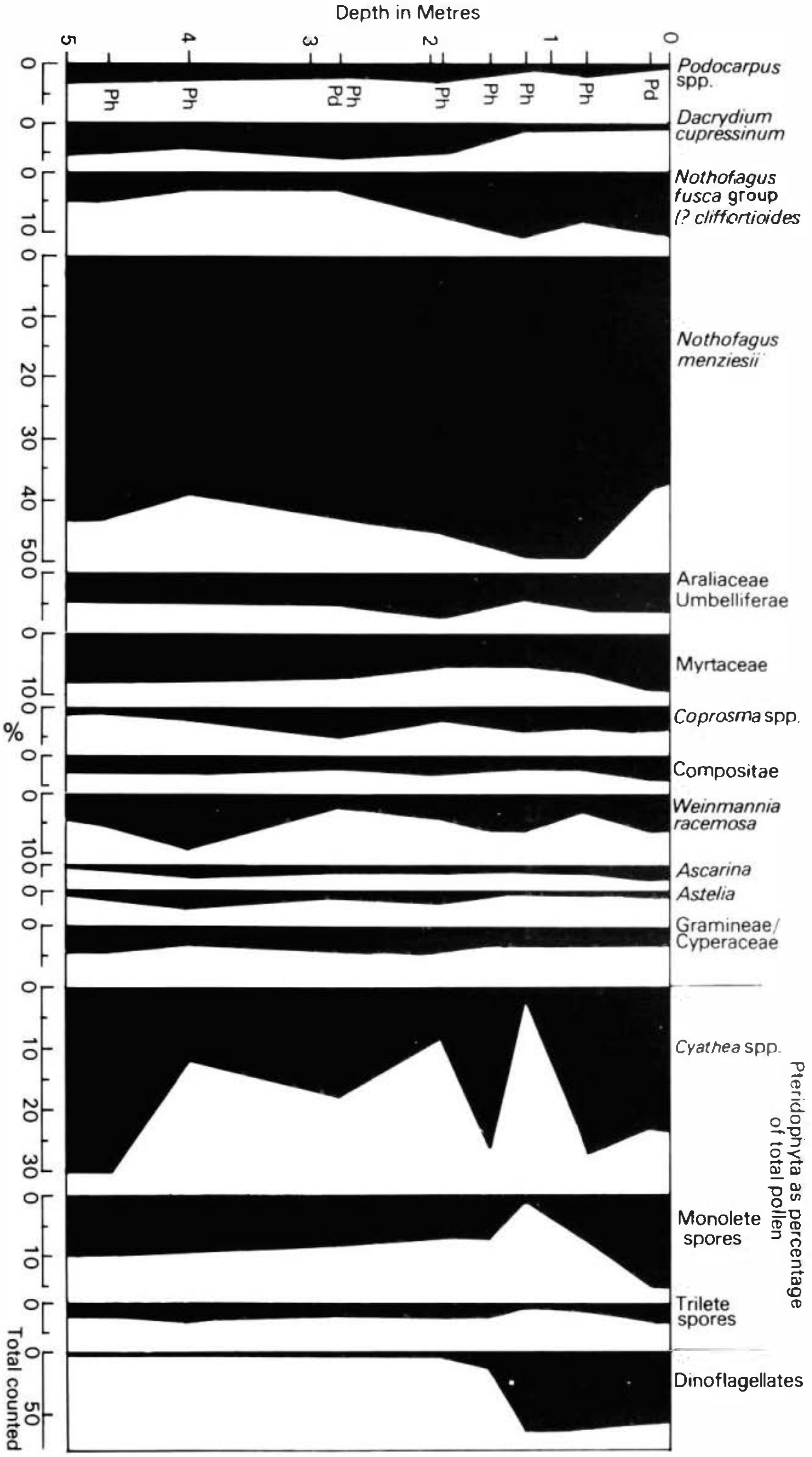

FIG. 3. Pollen diagram, Nancy Sound, Fiordland, core H264, showing pollen percentages.
Ph = ***Phyllocladus*** **sp.;**
Pd = ***Podocarpus dacrydioides.***
Spores are excluded from the pollen sum.

the profile. This could represent a gradual regeneration of *N. fusca* at the expense of *N. menziesii.*

Pollen and spores of plants not listed by Poole (1951a) include *Sphagnum* sp., *Dacrydium bidwillii* (=? *D. biforme), Haloragis* sp., *Metrosideros robusta* (=? *M. umbellata),* Compositae (*Taraxacum* type), and *Arthropodium* sp. Geraniaceae and *Phormium*, reported by Harris (1964) from Milford Sound (core A321), and *Tmesipteris tannensis, Hymenophyllum scabrum,*

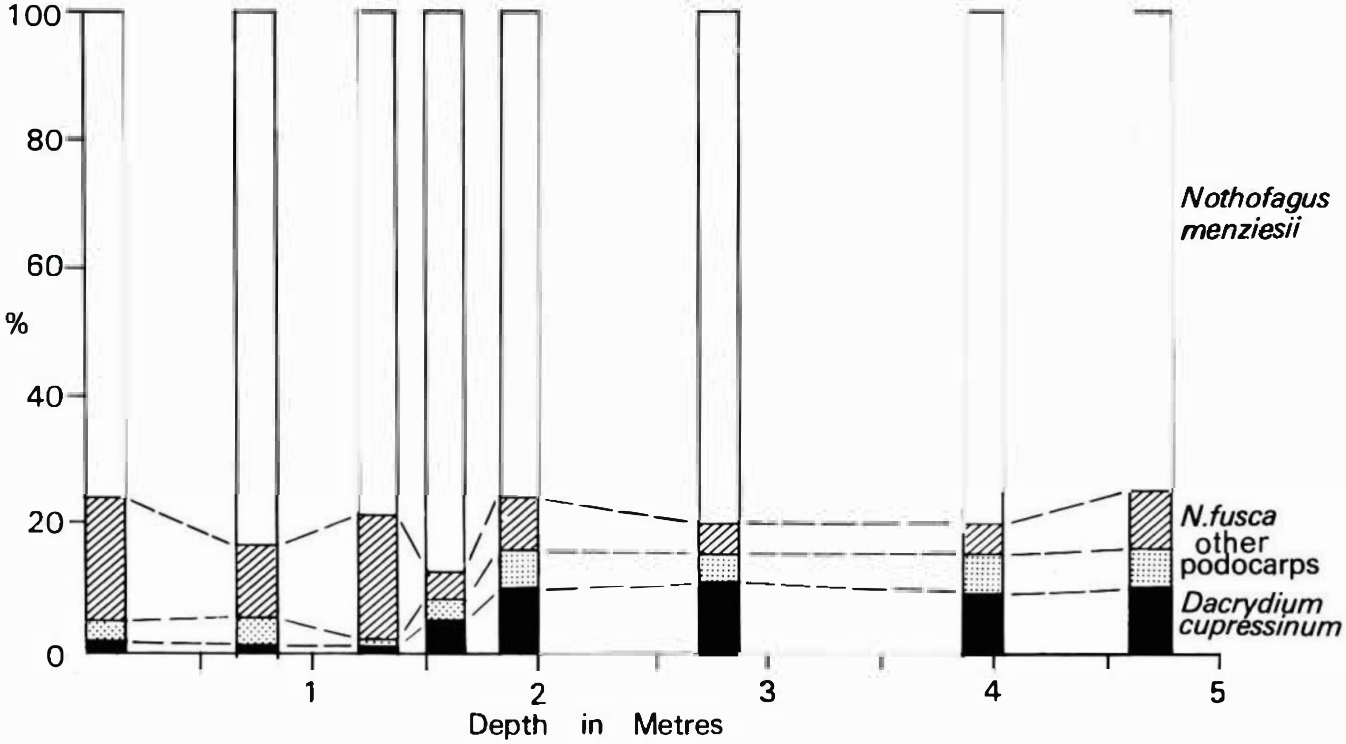

FIG. 4. Diagrammatic representation of *Nothofagus menziesii*, *N. fusca* group, *Podocarpus* spp. and *Dacrydium cupressinum* as percentages from core H284, Nancy Sound, Fiordland.

Cyathea colensoi, *Adiantum* sp., *Muehlenbeckia* sp., and *Dianella intermedia* (= *D. nigra*) reported by Couper (*in* Harris 1964), were not found in the present study.

The pollen assemblage is similar to that of both Nancy and Caswell Sounds and represents a similar pollen source.

COMPARISONS

The three pollen profiles are very similar from north to south, apart from differences in the number of dinoflagellate cysts which are not part of the pollen profile. The higher percentage of Gramineae pollen in Milford Sound suggests a more open forest vegetation. Caswell and Nancy Sounds are more enclosed and less likely to receive an influx of pollen from upland or more open vegetation.

Points of note in the pollen profiles include :

(a) Southward decrease in the percentage of monolete spores (including *Blechnum* and *Phymatodes*), *Myrsine* sp., *Nothofagus fusca* group, and podocarps (including *Phyllocladus* and *Podocarpus*).

(b) Southward increase in the percentage of *Nothofagus menziesii*, *Ascarina lucida*, *Cyathea* spp., and other trilete spores.

(c) Consistency of the percentages of Myrtaceae and *Dacrydium cupressinum* in all three cores.

The significance of changes can only be gauged by further pollen studies in the area, but they presumably reflect slight differences in the surrounding vegetation.

DINOFLAGELLATE CYSTS

For convenience, marine dinoflagellate cysts (mainly representing the genus *Spiniferites*) are included in Figs 1 and 3 and listed in Tables 2, 3, and 4, but are not included as part of the pollen sum in the main pollen diagrams. The dinoflagellate assemblage is poor in species, as is typical of a coastal environment (Williams and Sarjeant 1967).

Figure 7 shows the southward increase in the number of dinoflagellate cysts, combined with a decrease lower in the profile. This latitudinal distribution may be temperature and/or salinity controlled, and the decline lower in the profile may be caused by differential preservation or a change in the conditions influencing encystment. Factors determining the abundance of dinoflagellate cysts in marine sediments also include the rate of deposition, sediment supply, turbulence and currents in the water column, activity of benthic animals, and the settling velocities of the cysts (Wall 1970). These latter are not considered to be significant as there is no evidence of any change in the rates of activity of these factors but they should be recognised as potential causes of variation in the distribution of cysts.

TABLE 3. Numbers of pollen and spore types identified in samples from Nancy Sound. tr = trace (< 1%), present = pollen type noted during count but not recorded separately at the time.

SPECIES	Slide Sample	L5961 1	L5962 2	L5963 3	L5983 4	L5964 5	L5965 6	L5966 7	L5967 8
Dinoflagellates (several species)		54	62	64	16	3	tr	5	tr
Sphagnaceae									
Sphagnum sp.		tr	-	-	-	-	tr	-	tr
Psilotaceae ?		-	tr	-	-	-	-	-	-
Lycopodiaceae									
Lycopodium billardieri		tr	-	-	tr	tr	tr	-	tr
L. fastigiatum group		tr	-	-	tr	tr	tr	tr	tr
L. scariosum		-	-	-	-	tr	-	-	-
Schizaeaceae									
Schizaea sp. (?*fistulosa*)		tr	-	-	-	-	-	-	-
Hymenophyllaceae									
Hymenophyllum sp.		tr	-	-	tr	-	tr	tr	tr
H. sanguinolentum		tr	tr	-	-	-	-	-	-
Dicksoniaceae									
Dicksonia squarrosa		tr	tr	-	tr	tr	tr	-	tr
Cyatheaceae									
?*Cyathea dealbata*] *C. medullaris*] *C. smithii*]		104	82	tr	76	23	58	40	126
Polypodiaceae									
Phymatodes diversifolium		6	tr	tr	tr	tr	tr	tr	tr
P. scandens		tr	tr	-	tr	tr	tr	tr	tr
Pyrrosia serpens		-	-	-	-	-	tr	tr	-
Dennstaedtiaceae									
Hypolepis spp.		6	-	-	tr	tr	-	tr	tr
Lindsaeaceae									
Lindsaea sp. (?*trichomanoides*)		tr	-	-	-	tr	-	-	tr
Pteridaceae									
Histiopteris incisa		-	-	-	-	-	-	-	tr
Paesia scaberula		tr	-	-	tr	-	tr	tr	-
Pteridium aquilinium var. *esculentum*		-	tr	-	-	tr	-	-	tr
Pteris comans		tr	-	-	-	-	-	-	-
Aspleniaceae									
Asplenium sp. (?*flaccidum*)		tr	-	-	-	-	-	tr	-
Blechnaceae									
Blechnum sp.		tr	tr	-	tr	tr	tr	tr	tr
?*B. fraseri*		-	tr	-	-	-	-	-	-
Adiantaceae									
Adiantum sp.		-	tr	-	-	-	tr	tr	-
Marsileaceae									
?*Pilularia* sp.		-	-	tr	-	-	-	-	-
Unidentified monolete spores		62	13	tr	15	16	23	27	33
Unidentified spores		tr	tr	-	-	-	-	-	-
Podocarpaceae									
Dacrydium bidwillii		-	tr	-	tr	tr	-	tr	tr
D. cupressinum		tr	tr	tr	4	11	14	9	11
Podocarpus dacrydioides		tr	-	-	-	-	tr	tr	-
P. ferrugineus group		tr	4	tr	tr	6	4	7	6
P. totara group (?*P. hallii*)		tr	tr	tr	-	tr	-	tr	tr
Phyllocladus sp. (?*alpinus*)		-	tr	tr	tr	tr	tr	tr	tr
Cupressaceae									
Libocedrus sp.		-	-	-	-	-	-	-	tr
?*Cupressus* sp. (introduced)		tr	-	-	-	-	-	-	-
Pinaceae									
Pinus sp. (introduced)		tr	-	-	tr	-	tr	-	-
Winteraceae									
Pseudowintera colorata		tr	tr	tr	tr	tr	tr	tr	tr
Lauraceae									
(?*Beilschmiedia*)		-	-	-	-	-	tr	-	-
Monimiaceae									
Hedycarya arborea		tr	-	-	-	-	-	-	-
Cruciferae		-	-	tr	-	tr	-	-	tr
Violaceae									
Melicytus sp. (?*ramiflorus*)		tr	tr	tr	tr	-	tr	tr	tr
Carophyllaceae									
Colobanthus sp.		-	-	-	-	-	tr	-	-
Meliaceae									
?*Dysoxylum spectabile*		-	-	-	-	-	-	tr	tr
Chloranthaceae									
Ascarina lucida		6	tr	tr	tr	3	tr	4	tr

TABLE 3. Continued

SPECIES	Slide	L5961	L5962	L5963	L5983	L5964	L5965	L5966	L5967
	Sample	1	2	3	4	5	6	7	8
Polygonaceae									
Muehlenbeckia sp.		-	-	-	-	-	tr	-	-
Chenopodiaceae		tr	tr	tr	tr	tr	tr	tr	tr
?Geraniaceae		-	tr	tr	-	-	-	-	tr
Haloragaceae									
Gunnera sp. (?*monoica*)		-	tr	-	-	-	tr	tr	-
Haloragis sp. (?*erecta*)		-	-	-	-	-	tr	-	-
Myriophyllum		tr	-	-	tr	tr	-	-	tr
Onagraceae									
Epilobium sp.		-	-	-	-	-	-	tr	-
Fuchsia excorticata		tr	tr	tr	tr	tr	tr	tr	tr
Coriariaceae									
Coriaria sp.		-	tr	tr	-	3	tr	tr	-
Myrtaceae									
?*Eugenia maire*		-	-	-	-	tr	-	-	tr
Leptospermum spp. (?*scoparium*)		tr	tr	tr	tr	tr	tr	tr	tr
Lophomyrtus sp.		tr	tr	-	tr	-	tr	tr	-
Metrosideros spp.		21	11	9	14	7	12	18	14
?*M. robusta*		-	tr	-	-	tr	tr	present	tr
Elaeocarpaceae									
Aristotelia sp.		tr	tr	-	-	-	-	-	tr
Malvaceae									
Hoheria sp. (?*glabrata*)		tr	-	tr	tr	tr	tr	tr	-
Plagianthus sp.		-	-	-	-	-	-	tr	-
Cunoniaceae									
Weinmannia racemosa		17	7	12	14	9	4	23	10
Fagaceae									
Nothofagus menziesii		100	100	100	100	100	100	100	100
N. fusca group (?*cliffortioides*)		27	16	24	6	12	7	6	11
Thymelaeaceae									
Pimelea sp.		-	-	-	-	tr	-	-	-
Araliaceae		9	5	5	tr	5	tr	8	7
Pseudopanax sp.		8	4	3	9	10	10	6	5
Loranthaceae									
Loranthus sp.		-	-	-	-	tr	-	-	-
Rosaceae									
Rubus sp.		-	-	-	-	tr	-	-	-
Umbelliferae		tr	tr	tr	tr	tr	tr	4	tr
Hydrocotyle sp.		-	-	-	-	-	-	-	tr
Ericaceae/Epacridaceae									
?*Epacris* sp.		-	-	tr	-	-	-	-	-
cf. *Gaultheria* spp.		tr	tr	tr	tr	tr	tr	tr	tr
Myrsinaceae									
Myrsine sp.		tr	tr	tr	tr	tr	tr	tr	tr
Rubiaceae									
Coprosma sp.		11	4	7	tr	tr	12	6	tr
Nertera sp.		tr	tr	tr	tr	-	tr	tr	-
Compositae		10	4	4	tr	6	5	7	6
Gentianaceae		-	-	-	-	-	-	tr	tr
Plantaginaceae									
Plantago sp.		-	tr	-	-	-	-	-	-
Scrophulariaceae									
Hebe sp.		-	-	-	-	-	tr	tr	-
Myoporaceae									
Myoporum laetum		-	-	-	-	-	-	tr	tr
Unidentified dicotyledonous grains		8	7	6	-	10	15	11	17
Casuarinaceae									
Casuarina sp. (introduced, wind transported)		-	-	-	-	tr	-	tr	-
Potamogetonaceae									
Potamogeton sp.		-	tr	-	-	-	-	-	-
Liliaceae									
Astelia sp.		tr	tr	tr	tr	4	tr	8	tr
Bulbinella hookeri		tr	tr	-	-	-	tr	-	-
Agavaceae									
Cordyline sp.		tr	tr	tr	-	tr	tr	tr	-
Phormium sp. (?*colensoi*)		-	-	tr	tr	-	tr	tr	-
Palmae									
?*Rhopalostylis sapida*		-	tr	tr	-	tr	-	-	-
?Orchidaceae		tr	-	-	tr	-	-	tr	-
Cyperaceae		tr	tr	tr	tr	3	tr	tr	tr
Gramineae		tr	5	5	6	6	7	6	8
Total Count		460	309	209	291	270	323	338	416

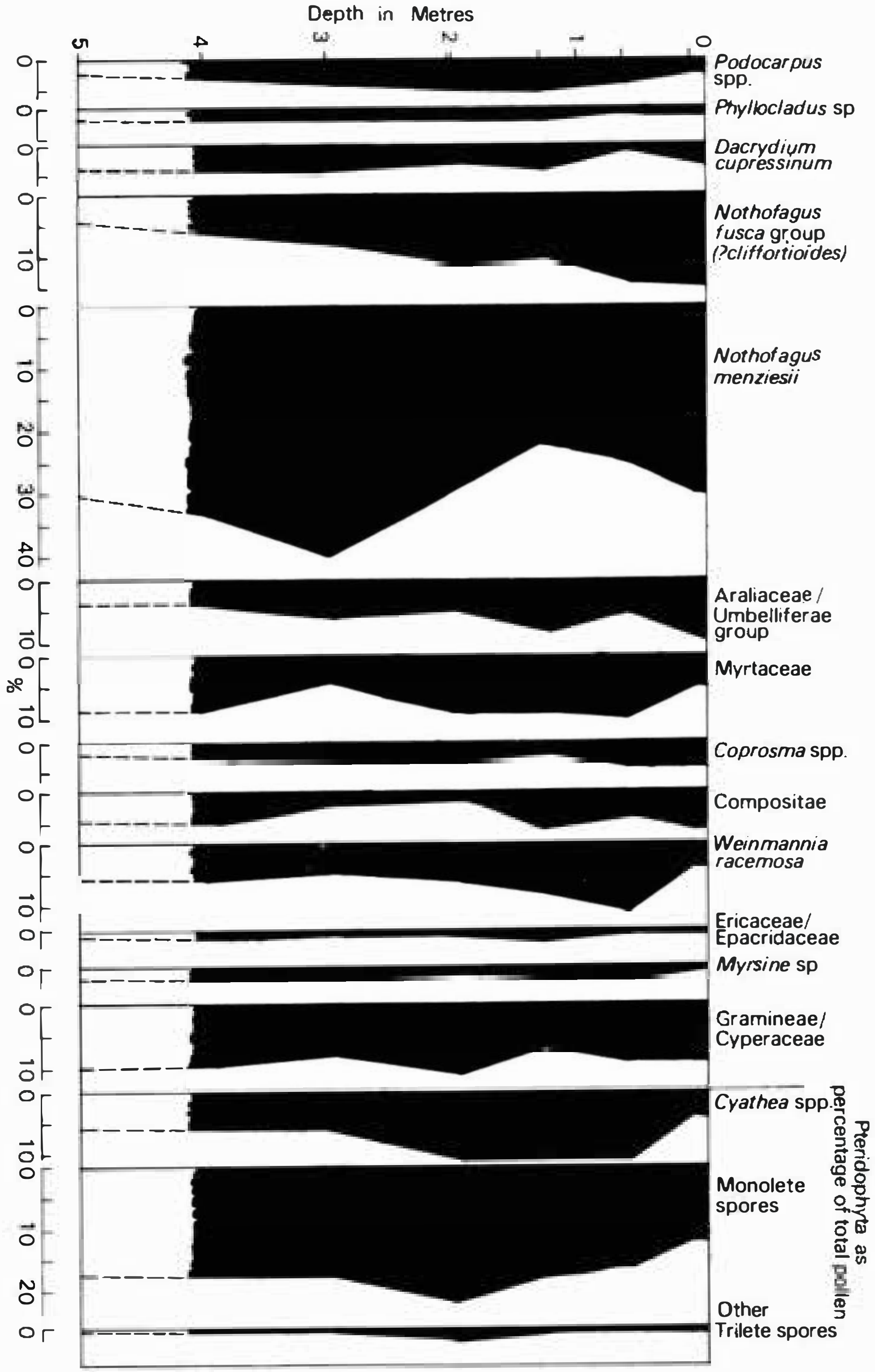

FIG. 5. Pollen diagram, Milford Sound, Fiordland, core H286, showing pollen percentages.

Spores are excluded from the pollen sum.

POLLEN REPRESENTATION

The large variation in the percentages of fern spores (particularly *Cyathea* spp., which produce large numbers of spores, and monolete spores similar to *Blechnum*) suggests that in many cases they are over-represented in the pollen spectra. Although ferns are locally prominent on the walls of the fiord, in most localities the forest vegetation comes down to sea level and should mask out ferns in the pollen profiles. *Nothofagus menziesii* forms up to 50% of the total pollen assemblages, and is probably also over-

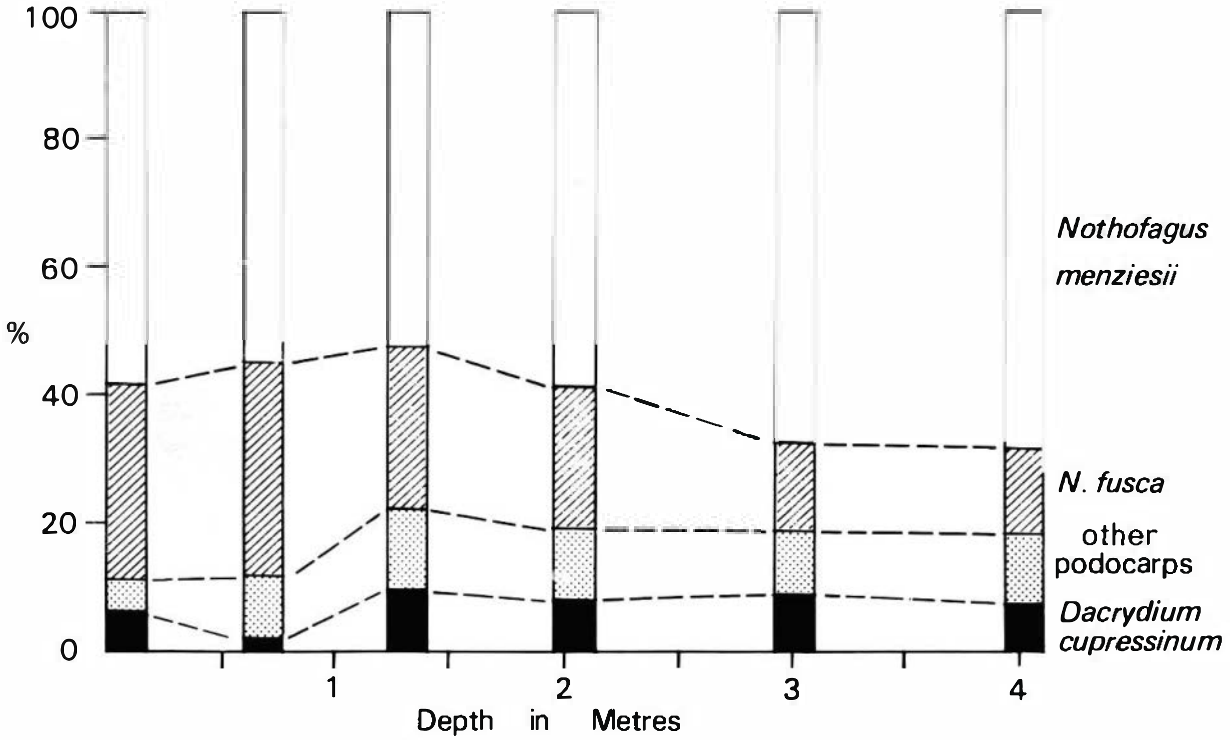

FIG. 6. Diagrammatic representation of *Nothofagus menziesii*, *N. fusca* group, *Podocarpus* spp. and *Dacrydium cupressinum* as percentages from core H286, Milford Sound, Fiordland.

represented in the fiord sediments, particularly as this pollen is considered to be under-represented in the present pollen rain (McKellar 1973).

Podocarpus spp. appear to be under-represented since they rarely form more than 4% of the total assemblages but are relatively common in the surrounding vegetation. Winged conifer grains differ from angiosperm and other non-winged grains in their flotation ability and tend to be deposited around shorelines rather than on the off-shore sea floor (Erdtman 1943). Since the flora immediately surrounding the coring sites in the three fiords is not known accurately, any conclusions on the representation of various pollen groups must be regarded as tentative.

Most ofthe vegetation types listed by Poole (1951a) and Wardle and Mark (1970) are represented in the pollen types listed from the three fiords. However, no pollen referable to *Elytranthe* (commonly found associated with groves of *Nothofagus*, as a parasite), *Euphrasia*, or *Gleichenia* (common in boggy and swampy areas) were identified.

There is a higher percentage of podocarp and beech pollen in Caswell Sound, 60-80% as opposed to 50-70% in Milford and Nancy Sounds. It is not known whether this corresponds to the pollen rain of the surrounding vegetation at the present day.

CLIMATE

The present climate of Fiordland is wet, with an annual rainfall of over 6300 mm per annum at sea-level. Rainfall further inland exceeds 7500 mm per annum. It is also windy, with the prevailing westerly winds being diverted to northerlies or north-easterlies parallel to the Southern Alps, and mild (Robertson, *in* Poole 1951b). Moar (1966) suggested that little effect would be apparent on the vegetation if a rainfall variation of some magnitude occurred in areas of heavy rainfall over 2500 mm per year. Heavy rainfall and westerly winds also have a moderating influence on the effect of temperature changes.

No attempt can be made to relate the profiles to temperature changes during the last thousand years. During this time climatic changes are reported to have occurred in Europe (e.g., Lamb 1965) and in New Zealand (e.g., Holloway 1954; reviewed in Park 1970). A change to drier, cooler conditions some 600 years ago was proposed by Raeside (1948) and confirmed by Holloway (1954) on the basis of soil disequilibrium and inland vegetational changes, but others suggested that this change may have been caused by fire (Molloy *et al* 1963). There is no evidence of vegetational change in the cores, suggesting that the time interval represented might fall within the last 600 years.

TABLE 4. Numbers of pollen and spore types identified in samples from Milford Sound. tr = trace (< 1%), present = pollen and spore types noted during count but not recorded separately at the time.

SPECIES	Slide	L5998	L5999	L6000	L6001	L6002	L6003
	Sample	1	2	3	4	5	6
Dinoflagellates (several species)		tr	tr	tr	tr	tr	tr
Bryophyta		-	-	-	-	-	tr
Sphagnaceae							
Sphagnum sp.		-	tr	tr	tr	-	tr
Lycopodiaceae							
Lycopodium billardieri		-	tr	tr	tr	-	-
L. fastigiatum group		tr	-	tr	tr	tr	-
L. scariosum group		-	-	-	-	-	tr
Hymenophyllaceae							
Hymenophyllum sp.		tr	tr	tr	tr	tr	tr
H. sanguinolentum		-	tr	-	tr	tr	-
Dicksoniaceae							
Dicksonia fibrosa		-	?tr	tr	-	-	-
D. squarrosa		tr	tr	tr	tr	tr	-
Cyatheaceae							
?Cyathea dealbata)							
C. medullaris)		16	61	71	57	19	23
C. smithii)							
Polypodiaceae							
Phymatodes diversifolium		4	6	5	6	tr	tr
P. scandens		-	tr	-	-	-	-
Pyrrosia serpens		-	-	tr	-	-	-
Dennstaedtiaceae							
?Hypolepis sp.		-	-	-	tr	-	-
Lindsaeaceae							
?Lindsaea sp.		-	-	-	tr	-	-
Pteridaceae							
Paesia scaberula		-	tr	tr	tr	tr	tr
Pteridium aquilinum var. *esculentum*		-	tr	tr	tr	-	tr
Histiopteris incisa		-	tr	tr	tr	tr	tr
Blechnaceae							
Blechnum spp.		present	present	present	present	present	present
Unidentified monolete spores		45	79	106	107	51	66
Podocarpaceae							
Dacrydium bidwillii group		-	-	tr	-	tr	-
D. cupressinum		11	tr	16	11	10	13
Podocarpus dacrydioides		-	-	tr	tr	tr	-
P. ferrugineus group		7	14	19	14	9	8
P. totara group		present	tr	tr	tr	tr	tr
Phyllocladus sp.		4	tr	9	6	4	6
Cupressaceae		-	-	-	tr	-	-
Lauraceae							
?Laurelia novaezelandiae		tr	-	-	-	-	-
Winteraceae							
Pseudowintera colorata		-	tr	tr	tr	-	-
Monimiaceae							
Hedycarya arborea		tr	-	tr	-	-	-
Violaceae							
Melicytus sp. (*?ramiflorus*)		-	tr	tr	tr	tr	-
Caryophyllaceae		-	-	-	tr	-	-
Chloranthaceae							
Ascarina lucida		tr	tr	tr	tr	tr	tr
Chenopodiaceae		tr	tr	tr	-	tr	tr
Haloragaceae							
Gunnera sp.		-	tr	-	tr	tr	-
Haloragis sp.		-	tr	tr	-	-	-
Myriophyllum sp.		tr	tr	tr	tr	-	tr
Onagraceae							
Epilobium sp.		-	-	tr	-	-	tr
Fuchsia excorticata		tr	tr	tr	tr	tr	tr
Coriariaceae							
Coriaria sp.		6	tr	tr	6	tr	tr
Myrtaceae							
Eucalyptus sp. (? introduced, ? wind transported)		-	-	-	-	tr	tr
Leptospermum sp.		-	tr	tr	tr	tr	4
Lophomyrtus sp.		-	-	-	tr	-	-
Metrosideros sp.		17	37	40	27	9	23
?M. robusta		-	tr	6	tr	-	-

TABLE 4. Continued

SPECIES — Slide	L5998	L5999	L6000	L6001	L6002	L6003
Sample	1	2	3	4	5	6
Elaeocarpaceae						
Aristotelia sp.	-	-	tr	tr	-	?tr
Malvaceae						
Hoheria sp.	tr	tr	tr	tr	tr	tr
Plagianthus sp.	tr	-	-	tr	tr	-
Cunoniaceae						
Weinmannia racemosa	13	44	34	22	12	17
Fagaceae						
Nothofagus fusca group (?*cliffortioides*)	52	56	47	37	21	20
N. menziesii	100	100	100	100	100	100
Araliaceae	17	14	25	12	12	7
Pseudopanax sp.	9	6	12	tr	tr	tr
Loranthaceae						
Loranthus sp.	-	tr	tr	-	-	-
Rhamnaceae						
?*Pomaderris* sp.	tr	tr	-	-	-	-
Cornaceae						
?*Griselinia* sp.	tr	-	-	-	-	-
Umbelliferae	tr	-	tr	tr	tr	tr
cf. *Angelica* sp.	-	-	-	-	tr	-
Hydrocotyle sp.	-	-	-	-	tr	tr
Ericaceae/Epacridaceae						
cf. *Gaultheria* sp.	tr	tr	10	5	tr	5
Myrsinaceae						
Myrsine sp.	tr	7	9	5	5	7
Loganiaceae						
?*Geniostoma ligustrifolium*	-	tr	tr	-	tr	-
Rubiaceae						
Coprosma spp.	12	16	10	11	7	6
?*Nertera* sp.	-	-	tr	tr	tr	tr
Compositae (Liguliflorae)	tr	-	-	-	-	-
Compositae (Tubuliflorae)	19	15	25	5	4	16
Scrophulariaceae						
Hebe sp.	tr	tr	-	tr	-	tr
Casuarinaceae						
Casuarina sp. (introduced, wind transported)	tr	tr	-	tr	tr	-
Unidentified dicotyledonous pollen grains	20	16	16	17	15	14
Liliaceae						
Arthropodium sp.	tr	-	-	-	tr	tr
Astelia sp.	tr	tr	tr	5	tr	tr
Bulbinella hookeri	-	-	-	tr	-	-
Agavaceae						
?*Cordyline* sp.	-	tr	tr	tr	-	-
Smilaceae						
Ripogonum scandens	-	-	-	-	-	tr
Restionaceae	-	tr	6	tr	-	tr
Sparganiaceae						
?*Sparganium* sp.	-	tr	tr	-	-	-
Orchidaceae	-	tr	-	-	?tr	-
Cyperaceae	6	tr	tr	tr	tr	tr
Gramineae	23	33	28	26	18	28
Typhaceae						
Typha orientalis	-	-	tr	-	-	-
Total Count	404	565	644	529	329	399

INTRODUCED POLLEN

Except for occasional grains of *Pinus* and possibly *Cupressus* (? *macrocarpa*) there is no evidence of pollen from introduced plants in the cores. *Pinus* is a common contaminant in chemicals and thus in many pollen samples. However, it occurs too sporadically in the top 280 cm of Caswell and Nancy Sounds to be referable to Zone 5c of Harris (1963) in which it was shown to be a valuable index in gauging the rates of sedimentation. *Casuarina* and *Eucalyptus* indicate wind transportation from Australia suggesting that the fiords trapped pollen crossing the Tasman Sea. Logging and agriculture have not, as yet, had any obvious effect on the influx of pollen.

POLLEN DISTRIBUTION

Nearly all the identified pollen types come from anemophilous plants indicating that wind plays a major part in disseminating pollen over the fiords. A small percentage of the pollen, probably including all corroded grains, is probably distributed into the centre of the fiords by currents. Some of the slight variations in the profile could be caused by sorting of pollen by currents. There was no evidence for mixing of pollen by burrowing organisms.

RATES OF SEDIMENTATION

The consistency of the pollen spectra over the full length of all cores to a depth of about 5 m may result from rapid sedimentation. If the supposed climate change some 600 years ago (Holloway 1954; Lamb 1965) were to have a recognisable effect on the vegetation, the lack of evidence of any change down to 475 cm would support a rapid sedimentation rate of approximately 8 mm/year. Again, a high sedimentary rate is to be expected from the proximity to land, together with the enclosed nature of the fiords which are supplied by relatively large quantities of detritus each year. Furthermore, Pantin (1964) estimated a sedimentation rate of approximately 10 mm/year for the south-eastern corner of the Stirling Basin in Milford Sound. His estimate, based on the presence of a thick layer of sand, was provisionally correlated with a period of strong seismicity in 1826-27. If the same rate is assumed for core H286 at the north-west corner of the Stirling Basin, then the pollen profile represents a period of approximately 400 years. As rates are unlikely to be substantially different in Caswell and Nancy Sounds, the pollen profiles likely represent approximately 450 and 475 years respectively.

The radiocarbon evidence gives a different picture. Radiocarbon dates from Nancy Sound suggest a sedimentary rate of approximately 1-5 mm per year (*see* p.33). This would mean that the pollen profile represents an interval of approximately 950-4750 years. If this rate is also assumed for both Milford and Caswell Sounds, the time interval there would be 800-4000 years and 900-4500 years respectively.

It has been shown, however, that radiocarbon dates on material from marine environments can be unreliable. For example, Emery and Bray (1962) obtained radiocarbon ages of 1230 and 2100 years B.P. from surface samples off the coast of Southern California. Later, Eade (1971) listed a combination of five factors that can contribute towards an incorrect age for surface samples. These are the age of sea water, mixing of sediments, erosion or non-deposition (unlikely in this fiord environment), introduction of older material, and fractionation of carbon isotopes. To this could be added the redeposition or transportation of the dated sample. For these reasons, the older radiocarbon dates from the Nancy core should be taken as evidence of a minimum rate of sedimentation of about 5 mm for Nancy Sound, with a maximum rate of 10 mm/year in Milford Sound, based on Pantin (1964). The rate of sedimentation calculated from pollen is between these two values, and a relatively rapid rate of sedimentation is therefore likely.

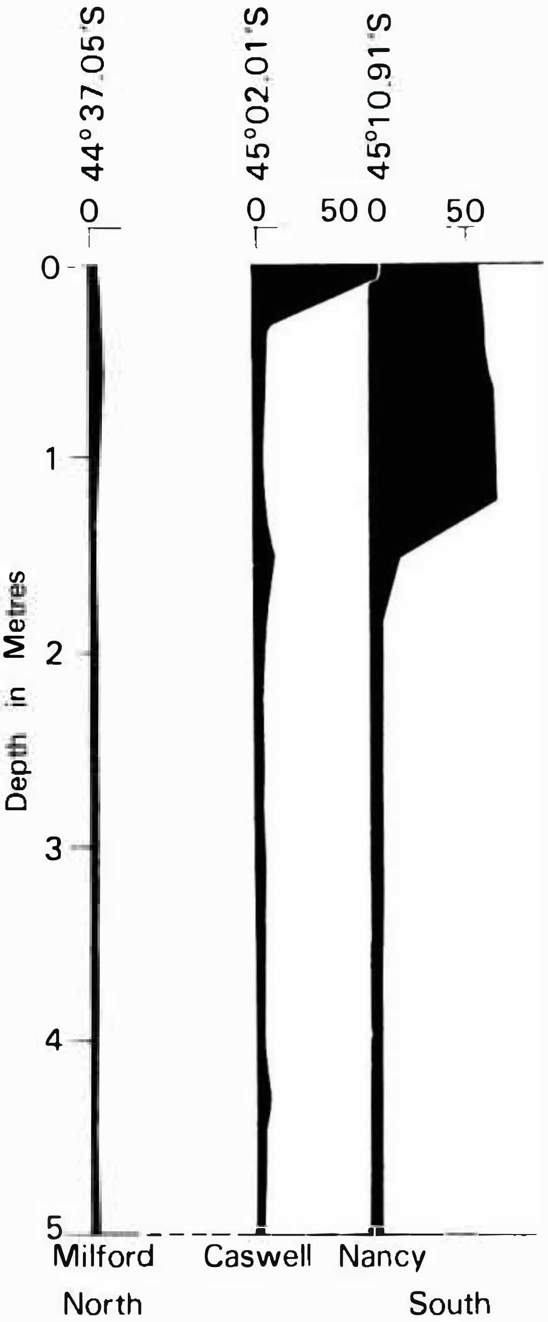

FIG. 7. Diagrammatic representation of the distribution of the total counts of dinoflagellate cysts in cores from Milford, Caswell and Nancy Sounds, Fiordland. The graph shows a southward increase in total counts combined with a decrease lower in the profile.

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REFERENCES

ALLAN, H.H. 1961: "Flora of New Zealand". Vol. 1. Government Printer, Wellington. 1085 p.

BAYLIS, G.T.S.; WARDLE, P.; MARK, A.F. 1963: Vegetation studies on Secretary Island, Fiordland. Part 8 : Vascular plants recorded from Secretary Island. *N.Z. Journal of Botany 1* : 236-42.

CRANWELL, L.M.; VON POST, L. 1936: Post-Pleistocene pollen diagrams from the Southern Hemisphere. *Geografiska Annaler, Stockholm 18* : 308-47.

EADE, J.V. 1971: The use of radiocarbon dating in marine geology. *Radiocarbon Users Conference, Wellington, 17-18th August, 1971* : 157-64.

EMERY, K.O.; BRAY, E.E. 1962: Radiocarbon dating of California Basin sediments. *Bulletin of the American Association of Petroleum Geologists 46* : 1839-56.

ERDTMAN, G. 1943: "An Introduction to Pollen Analysis". Chronica Botanica Company, Waltham, Massachusetts. 239 p.

GIVEN, D.R. 1971: Montane-alpine vegetation near Lake Shirley, Fiordland. *N.Z. Journal of Botany 9* : 3-26.

HARRIS, W.F. 1963: Palaeo-ecological evidence from pollen and spores. *Proceedings of the N.Z. Ecological Society 10* : 38-44.

HARRIS, W.F. 1964: A note on pollen distribution in a core from Milford Sound. Pp 77-8 *in* SKERMAN, T.M. (ed.) "Studies of a Southern Fiord". *Memoir N.Z. Oceanographic Institute 17. (N.Z. Department of Scientific and Industrial Research Bulletin 157).* 101 p.

HOLLOWAY, J.T. 1954: Forests and climates in the South Island of New Zealand. *Transactions of the Royal Society of N.Z. 82* : 329-410.

LAMB, H.H. 1965: The early medieval warm epoch and its sequel. *Palaeogeography, Palaeoclimatology, Palaeoecology 1* : 13-37.

LENNIE, C.R. 1968: Palynological techniques used in New Zealand. *N.Z. Journal of Geology and Geophysics 11* : 1211-21.

MARK, A.F.; BAYLIS, G.T.S. 1963: Vegetation studies on Secretary Island, Fiordland. Part 6 : The subalpine vegetation. *N.Z. Journal of Botany 1* : 215-20.

McKELLAR, M.H. 1973: Dispersal of *Nothofagus* pollen in eastern Otago, South Island, New Zealand. *N.Z. Journal of Botany 11* : 305-10.

MOAR, N.T. 1966: Post-glacial vegetation and climate in New Zealand. Royal Meteorological Society. *Proceedings of the International Symposium on World Climate from 8000 to 0 B.C.* : 155-6.

MOAR, N.T. 1969: Possible long-distance transport of pollen to New Zealand. *N.Z. Journal of Botany 7* : 424-6.

MOLLOY, B.P.J.; BURROWS, C.J.; COX, J.E.; JOHNSTON, J.A.: WARDLE, P. 1963: Distribution of sub-fossil remains, eastern South Island, New Zealand. *N.Z. Journal of Botany 1* : 68-77.

MURRAY, J. 1963: Vegetation studies on Secretary Island, Fiordland. Part 7 : Bryophytes and Lichens. *N.Z. Journal of Botany 1* : 221-35.

PANTIN, H.M. 1964: Sedimentation in Milford Sound. Pp 35-47 *in* SKERMAN, T.M. (ed.) "Studies of a Southern Fiord". *Memoir N.Z. Oceanographic Institute 17. (N.Z. Department of Scientific and Industrial Research Bulletin 157).* 101 p.

PARK, G.N. 1970: Palaeoclimatic change in the last 1,000 years. *Tuatara 18* : 114-23.

POOLE, A.L. 1951a: Flora and vegetation of the Caswell and George Sounds District. Area covered by the New Zealand-American Fiordland Expedition. *Transactions and Proceedings of the Royal Society of N.Z. 79* : 62-83.

POOLE, A.L. 1951b: Preliminary Reports of the New Zealand-American Fiordland Expedition. *N.Z. Department of Scientific and Industrial Research Bulletin 103* : 99 p.

RAESIDE, J.D. 1948: Some post-glacial climatic changes in Canterbury and their effect on soil formation. *Transactions of the Royal Society of N.Z. 77* : 153-71.

SCOTT, G.A.M. 1970: Vegetation studies on Secretary Island, Fiordland. Part 11 : Epiphytic and ground crytogamic vegetation on the northern slopes. *N.Z. Journal of Botany 8* : 30-50.

WALL, D. 1970: Quaternary dinoflagellate micropalaeontology : 1959 to 1969. *Proceedings of the North American Paleontological Convention, September 1969. Part G* : 844-66.

WARDLE, P. 1963: Vegetation studies on Secretary Island, Fiordland. Part 2 : The plant communities. *N.Z. Journal of Botany 1* : 171-87.

WARDLE, P.; MARK, A.F. 1970: Vegetation studies on Secretary Island, Fiordland. Part 10 : Vascular plants recorded from Secretary Island. *N.Z. Journal of Botany 8* : 22-9.

WARDLE, P.; MARK, A.F.; BAYLIS, G.T.S. 1970: Vegetation studies on Secretary Island, Fiordland. Part 9 : Additions to Parts 1, 2, 4 and 6. *N.Z. Journal of Botany 8* : 3-21.

WILLIAMS, D.B.; SARJEANT, W.A.S. 1967: Organic-walled microfossils as depth and shoreline indicators. *Marine Geology 5* : 389-412.

ORGANIC CONSTITUENTS OF SEDIMENTS FROM NANCY SOUND

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ABSTRACT

A sediment core from Nancy Sound contained a variety of organic compounds typically found in recent marine sediments. The organic carbon content of the sediments ranged from 3.50% to 4.36%, somewhat higher than that found in most open sea sediments but lower than in the organic-rich sediments of the Black Sea. Of the organic carbon in the sediments 23 to 39% was in the form of humic and fulvic acids. The amounts of normal alkanes (24.3 to 29.1 ppm) found in the Nancy Sound sediments were considerably greater than those found in most marine sediments and were similar to those of a reducing core from Saanich Inlet, British Columbia. The average carbon preference index, CPI, of 8.3 and the pristane to n-C_{17} ratio of 0.7 were indicative of a primarily terrestrial source of the sedimentary organic matter. An increase in the perylene content of the sediment with increasing depth of burial, from 0.054 to 0.138 ppm, and a decrease in chlorin content, from 23.5 to 7.6 ppm, is evidence of geochemical changes in the sedimentary organic matter over the short period of time represented in the Nancy Sound sediments. The presence of steranols in near surface sediments and of significant amounts of carotenoids in deeper samples is indicative of reducing conditions favourable for the preservation of many organic compounds.

A sediment sample from Bay of Plenty contrasted in several ways with the Nancy Sound sediments. The organic carbon content was lower, 0.52%, and the ratio of humic to fulvic acids was much greater, 0.23 as compared to 1.2. The amount of normal alkanes in the Bay of Plenty sample was 5.4 ppm, the carbon preference index was 1.4, and the pristane to n-C_{17} ratio was 1.5, factors which would indicate a primarily marine origin for the organic matter.

INTRODUCTION

As part of a major study of marine sediments from the Nancy Sound area in Fiordland, the organic constituents of seven sections of a 5.02 m core (H264) were investigated. A complete geological description of the core is presented on p. 22 . The study deals with the organic carbon, the humic and fulvic acids, the aliphatic and isoprenoid hydrocarbons, a single aromatic hydrocarbon perylene, the sterols, and the chlorins and related carotenoid pigments. These organic compounds were selected as those most likely to yield geochemical information for sediments from Nancy Sound. For comparison, a single sample from the 305-320 cm level of core H211 (37°18.2'S, 177°21.5'E, 1500 m) taken from Bay of Plenty was also analysed.

The purpose of this investigation was

(1) to reveal the type, identity, and quantity of indigenous organic compounds;

(2) to measure the stability of these compounds under the existing geochemical conditions, and

(3) to reveal the source of the sedimentary organic material as either terrestrial or aquatic biota.

Comparisons were made with the organic constituents of other recent marine sediments particularly those of Saanich Inlet, British Columbia (Brown *et al* 1972).

ANALYTICAL METHODS

Analytical procedures as outlined in Fig. 1 are modifications of those described previously by Peake *et al* (1974).

About 50 g of sediment was extracted successively with acetone and then a mixture of three parts benzene to one part methanol using a Polytron ultrasonic homogeniser to disaggregate the sediment and thoroughly contact the particles with the solvent.

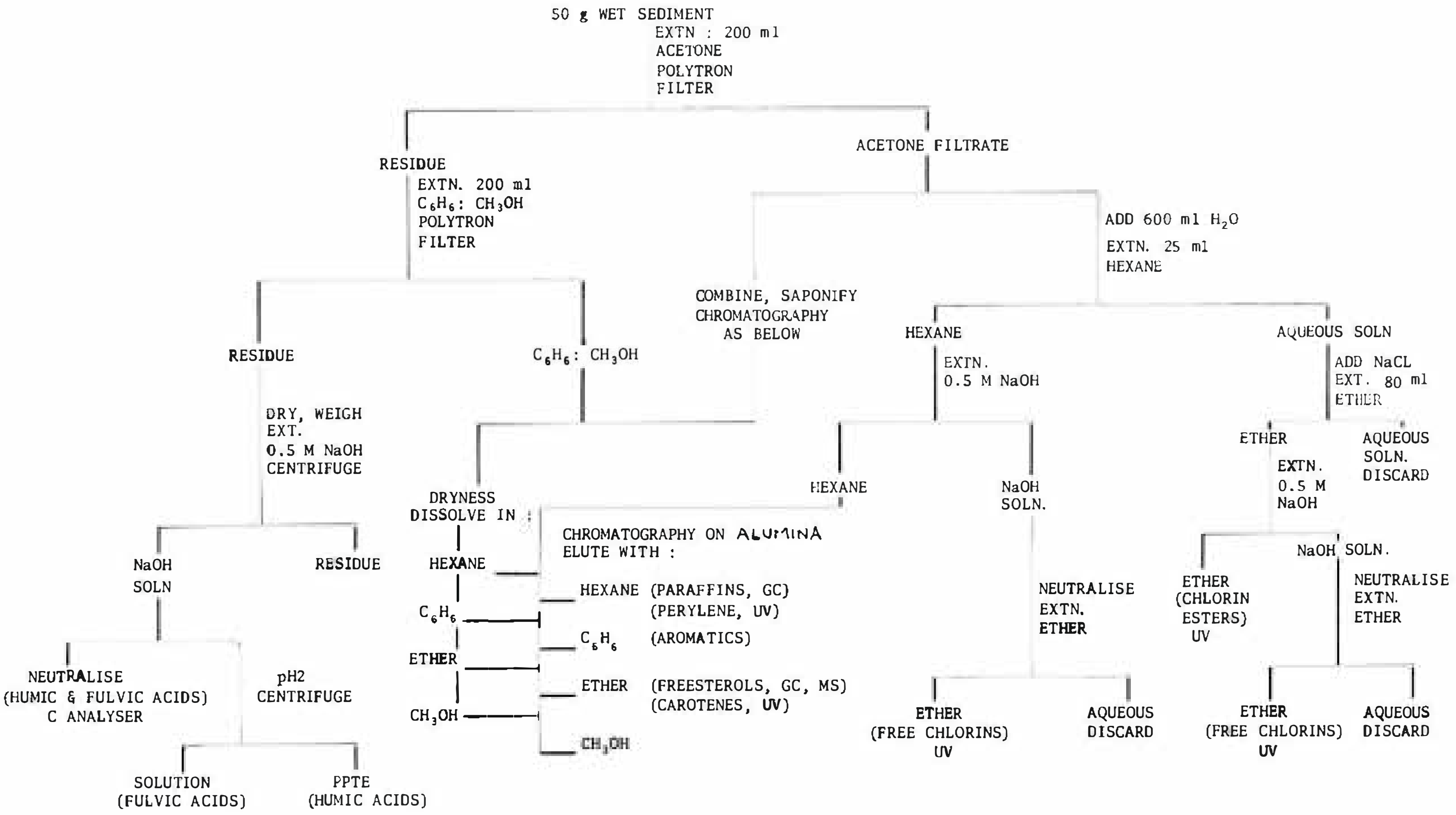

FIG. 1. Analytical procedures.

Ultrasonic techniques have been shown by McIver (1962) to be effective in the extraction of organic material from recent sediments; however, the system used in this study differs from conventional ultrasonic probes in that the sample was repeatedly cycled through a generator and subjected to high pressure mechanical shearing as well as high frequency shear-shock waves, thus improving extraction effectiveness. The resulting extracts were examined by ultraviolet spectroscopy to determine their total chlorin content. Each of the two extracts was divided into two parts, half of the acetone extract and half of the benzene-methanol extract to be analysed for free and esterified chlorins, hydrocarbons, carotenes and free sterols; the other half of each extract was to be saponified and analysed for total sterols.

In preparation for multiple component analysis half of the acetone extract was diluted with three volumes of water; neutral lipids including hydrocarbons, sterols, neutral chlorins and carotenoids were then taken into n-hexane. Free chlorins were separated from esterified chlorins by extracting both the hexane and the ether solutions with 0.5 mol sodium hydroxide. After transfer of the free chlorins back into ether the amounts of both classes of compounds were determined by ultraviolet spectroscopy.

The second half of the original extracts was saponified by refluxing with 5% potassium hydroxide in methanol for one hour. The neutral fraction containing hydrocarbons and both the original free sterols and those bound sterols released by saponification were extracted from the potassium hydroxide with n-hexane. The various components were separated by chromatography on alumina and analysed as above.

Total organic carbon in the sediments was determined by the Leco combustion method. Organic carbon occurring as humic and fulvic acids was measured in colloidal suspension in solution by a Beckman Model 915 carbon analyser. The humic and fulvic acids were extracted by repeatedly shaking the sediment for 16 hour periods with 0.5 mol sodium hydroxide under a nitrogen atmosphere. The carbon content of the resulting basic solution was determined by neutralising the solution and immediately analysing with the Beckman carbon analyser. The pH of the solution was further reduced to two and after several days the resulting precipitate of humic acids was separated by centrifugation. A colloidal suspension was made by adding water and shaking, and the amount of carbon was determined as before. Similarly, the amount of carbon remaining in the acid solution as fulvic acids was measured. The independent determination of fulvic acid, humic acids and total humic and fulvic acids provided a check of this method of analysis. Results were found to agree to ± 5%.

RESULTS AND DISCUSSION

ORGANIC CARBON

The amount and type of organic carbon in recent and ancient sediments is of fundamental interest in studies of the diagenetic history of organic accumulations such as coal and petroleum deposits. Most studies have centred on changes in the organic matter of ancient sediments with relatively few studies of organic carbon in recent sediments.

In a review of the accumulation of organic matter in bottom sediments, Bordovskiy (1965a) discussed the factors influencing the organic carbon content of recent marine sediments. Using the data of Lisitsyn (1955) and Bezrukov *et al* (1961) for the distribution of organic carbon in sediments for the western half of the Bering Sea and the northern half of the Pacific Ocean respectively, Bordovskiy (1965a) noted that the organic carbon content was greatest in a zone extending along the marginal areas of the northern Pacific coincident with the greatest rate of sediment deposition along the lower part of the continental slope, in deep water trenches, and adjacent areas of the ocean floor. In this zone the organic carbon content exceeded 2% whereas in areas closer to the shore values were generally less than 1%. Central regions of the Pacific yielded sediments with less than 0.25% organic carbon. The highest organic carbon content in smaller inland basins is found in sediments from their central portions. Bordovskiy (1965a) cited the work of Pakhomova (1961) who found organic carbon in the central and southern depressions of the Caspian Sea in excess of 3% of the sediment.

The organic carbon content of the sediments from Nancy Sound core H264 ranged from 3.50% to 4.36% whereas the sample from the Bay of Plenty core H211 contained only 0.52% as shown in Table 1. Thus, the sediments of core H264 were relatively high in organic carbon compared with those of the Bering Sea, the northern Pacific Ocean, and other areas including the Mediterranean Sea, 0.74%; Gulf of Mexico, 0.52%; Gulf of Batabano, Cuba, 1.4%; Orinoco Delta, Venezuela, 0.86%; Beaufort Sea, Canada, 1.14%; and an oxidising area of Saanich Inlet, Canada, 0.95% (Hunt 1961; Brown *et al* 1972; Peake *et al* 1972). The values were similar to those of reducing sediments from Saanich Inlet (2.4% to 5.1% organic carbon; Brown *et al* 1972) but considerably lower than organic rich areas such as the Black Sea (over 21%; Degens 1971) and a Norwegian fiord (23.4%; Strom 1955). Thus the sample from the Bay of Plenty core H211 was more typical of continental shelf sediments than were the Nancy Sound samples.

A number of investigators have found a decline in the organic carbon content of marine sediments with increasing depth of burial and have ascribed this decrease to the decomposition of organic material (Emery and Rittenburg 1952; Lisitsyn 1955; Starikova 1956; Bordovskiy 1965b). Most of this change could be caused by microbial activity within the first few centimetres of the sediment and could result not only in decreases in organic carbon by loss of carbon

TABLE 1. Organic carbon and humic and fulvic acids in Nancy Sound core H264 and Bay of Plenty core H211.

Core	Depth of burial (cm)	% Water	% Organic Carbon	Humic Acid (ppm of dry sediment)	Fulvic Acid (ppm of dry sediment)	Total humic and fulvic acid (% of organic carbon)	Ratio of humic to fulvic acids
H264	0-15	50.8	4.11	9,020	7,080	39.2	1.27
	69-84	52.5	4.47	5,390	4,980	23.2	1.08
	122-137	47.1	4.33	6,460	4,490	25.3	1.44
	183-198	48.7	4.36	5,270	5,170	23.9	1.02
	274-290	46.1	4.59	6,480	5,090	25.2	1.27
	396-411	43.3	3.66	4,480	4,080	23.4	1.10
	457-472	43.3	3.50	5,760	4,830	30.0	1.19
H211	305-320	30.0	0.516	270	1,170	28.1	0.23

dioxide but also in alteration of existing organic carbon and the generation of new compounds.

An overall decrease in the organic carbon with depth was observed in core H264. However, this decrease was not systematic; a relatively constant amount of organic carbon in sediments buried to a depth of less than 290 cm and a lesser amount in sediments from the 396-411 cm level and the 457-472 cm level. The organic carbon content did not change significantly between the 0-15 cm sample and the 69-84 cm sample, the region where oxidative decomposition by microorganisms would be expected to be greatest. Such a change would only be apparent if the amount and type of organic material remained constant during deposition and the geochemical environment had not changed.

The relationship of organic carbon content to sediment grain size was established in Bering Sea silts (Lisitsyn 1955) as summarised by Bordovskiy (1965a), Table 2. The sediments from Nancy Sound analysed in this study are mainly sandy silts and silty sands (*see* p.21).

HUMIC AND FULVIC ACIDS

Humic and fulvic acids are defined as the organic constituents of a soil or sediment which are soluble in 0.5 mol sodium hydroxide, with the fulvic acids being soluble not only in basic solutions but also in acid solutions of pH 2, whereas the humic acids are precipitated from acid solutions at this pH level. Although the chemical structures of humic and fulvic acids from marine sediments are by no means fully understood, various investigators have determined their gross composition and in some cases the range of molecular weights in each fraction (Rashid and King 1969, 1970, 1971; Bordovskiy 1965a; Brown *et al* 1972; Nissenbaum and Kaplan 1972). The compositions range from 48.9-59.8%C, 4.6-6.6%H, 1.5-6.2%N, 0.87-5.9%S and 27.2-36.7%O. Fulvic acids are commonly of lower molecular weight than humic acids, usually less than 10,000 as compared with 2,000,000 or more for humic acids.

TABLE 2. Organic carbon and grain size in Bering Sea sediments (Bordovskiy 1965a).

Type of sediment	Total organic carbon % of dry sediment
Medium-grained sands	0.32
Coarse silts	0.76
Fine silt muds	0.97
Silt-clay muds	1.38
Clay muds	0.54

The carbon contained as humic and fulvic acids in the sediments from the Nancy Sound core constituted from 23 to 39% of the total organic carbon (Table 1). The proportion of total humic and fulvic acids was 39% in the surface sample, a stable 23 to 25% in the five samples between 69 and 411 cm and 30% at a depth of burial of 457-472 cm The 305-320 cm interval from the Bay of Plenty core contained 28% of the organic carbon as humic and fulvic acids.

Data from various sources on the humic and fulvic acids as a percentage of the total organic carbon in sediments have been summarised by Nissenbaum and Kaplan (1972); the values ranged from 4 to 68%. Of particular interest were the sediments from reducing areas of Saanich Inlet which contained similar amounts of organic carbon to the Nancy Sound samples. Forty to 68% of the organic carbon in the Saanich Inlet sediments was in the form of humic and fulvic acids - a significant difference from the 23-39% of the Nancy Sound sediments. Thus there is a greater amount of insoluble carbon in the Nancy Sound sediments; carbon which may eventually become kerogen.

Bordovskiy (1965b) found a general tendency for the proportion of humic and fulvic acids to total organic carbon to decrease with depth, although there were many exceptions. A sharp difference in this proportion exists between the surface sample from Nancy Sound and the sample from the 69 - 84 cm level. Such a change could be caused by differences in the organic material at the time of deposition or more probably by microbial and chemical change in the active surface zone of the sediments.

In the Saanich Inlet sediments, Brown *et al* (1972) found fulvic acids to be dominant over humic acids in near-surface sediments, but the percentage of fulvic acids declined with depth until at 3450 cm the humic material became 3½ times more abundant. In the shorter core from Nancy Sound no such relationship existed. The humic acids were more abundant than fulvic acids in all sections of the core analysed. The situation was totally reversed in the Bay of Plenty sample where fulvic acids were over four times more abundant than the humic acids, demonstrating the fundamentally different nature of the organic matter in the two cores (Table 1).

HYDROCARBONS

The pioneering work of Trask and Wu (1930), in demonstrating the presence of hydrocarbons in recent sediments, and of Smith (1952), in determining the composition of sediment hydrocarbons, sparked interest in recent sedimentary material as the possible source of petroleum hydrocarbons. Subsequent studies have dealt with the amount and type of hydrocarbons present, including possible precursor compounds, and diagenetic processes which could create hydrocarbons. Investigations focused on the long chain aliphatic hydrocarbons which usually reflect the predominance of odd-numbered paraffinic hydrocarbons found in terrestrial higher plants.

Normal alkane hydrocarbons

The Nancy Sound core contained 27.5 ppm normal alkanes in the surface sediment, 24.3 ppm at the 274-290 cm level and 29.1 ppm at the 457- 472 cm level, (Table 3). The amounts were similar to those reported in reducing sediments from Saanich Inlet, 11.1 -32.7 ppm, but considerably higher than the 2.3 and 7.0 ppm found in oxidising sediments from the same area (Brown *et al* 1972). The 5.4 ppm normal alkanes found in the Bay of Plenty sample is within the range found in a number of recent marine sediments including the oxidising sill of Saanich Inlet; 3.9 ppm in near surface sediments from San Nicolas Basin, California; 0.61 to 2.3 ppm in Tanner Basin, California; 2.2 ppm in the Mississippi Delta (Kvenvolden 1970); and 1.23 to 9.40 ppm found in ten surface sediment samples from Beaufort Sea, Canada (Peake *et al* 1972).

The predominance of odd-numbered alkanes in plants and recent sediments is described by the carbon preference index, CPI, which expresses the relative abundance of normal alkanes having odd carbon numbers to those having even carbon numbers (Cooper and Bray 1963). Many land plants have a CPI greater than 4; for example, maize 5.1, barley 7.2, oats 9.2 (Cooper and Bray 1963), and Italian rye grass 36 (Eglinton *et al* 1962). The carbon preference indices of 16 algae analysed by Clark and Blumer (1967) fell within the range 0.4 to 1.5 with a mixed plankton sample having a CPI of 1.2. Bacteria have CPIs of about 1 (Han and Calvin 1969) and eight sponges exhibited CPIs in the range 1.0 to 1.4 (Koons *et al* 1965). Thus the CPI of normal alkane hydrocarbons in sediments may be used as an indicator of the relative amounts of hydrocarbons which are derived from land or aquatic organisms.

The CPI of the surface sample from the Nancy Sound sediment was 8.9, of the 274 - 290 cm sample 8.8, and of the 457 - 472 cm sample 7.3, indicating a strong contribution of hydrocarbons (and therefore total organic matter) from land sources. In contrast the Bay of Plenty sample had a CPI of only 1.4, indicative either of destruction of land-derived hydro-

TABLE 3. Organic constituents of Nancy Sound core H264 and Bay of Plenty core H211.
(1) ppm in dry sediment, (2) μg/g of total organic carbon.

Core	Depth of burial (cm)	Chlorins		Carotenes		Alkanes		Perylene		Sterols	
		(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
H264	0-15	15.2	370	0.13	3.2	27.5	670	0.054	1.31	2.9	71
	69-84	16.4	367	0.05	1.1			0.070	1.57	1.1	25
	122-137	8.5	196	0.10	2.3			0.082	1.89	7.8	180
	183-198	5.4	124	0.01	0.2			0.081	1.88	1.5	34
	274-290	5.6	122	0.12	2.6	24.3	529	0.138	3.01	5.5	120
	396-411	5.3	145	0.04	1.1			0.102	2.79	2.8	77
	457-472	5.2	149	0.06	1.7	29.1	831	0.114	3.26	4.1	117
H211	305-320	2.0	388	0.005	1.0	5.4	1050	0.036	6.98	0.19	37

carbons or, more likely, aquatic organisms contributing the major part of the hydrocarbons. CPIs of Nancy Sound sediments were high when compared with those of Saanich Inlet, 1.3 - 2.7, average 2.1 (Brown *et al* 1972); Beaufort Sea. 1.6 - 6.0, average 2.9 (Peake *et al* 1972); seven ocean basins offshore Southern California, 2.4 - 5.1, average 3.7 (Bray and Evans 1961); and deep-sea sediments from the Gulf of Mexico and western Atlantic, 1.8 - 4.6, average 2.7 (Aizenshtat *et al* 1973).

Isoprenoid hydrocarbons

The isoprenoid hydrocarbons, primarily phytane and pristane, are of particular geochemical interest because of their stability and their characteristic structure which is clearly derived from isoprene units of biogenic origin. If complex mixtures of hydrocarbons such as crude oils are utilised by microorganisms as a carbon source they preferentially degrade the normal paraffinic hydrocarbons over the branched and cyclic compounds (Stone *et al* 1940), thus increasing the relative proportions of isoprenoid compounds present. A convenient measure of this effect is the ratio of the isoprenoid pristane (2,6,10, 14- tetramethylpentadecane) to the normal C_{17} hydrocarbon, heptadecane. The Nancy Sound sediments exhibited a ratio of 0.7 compared with 1.5 for the Bay of Plenty sample. These ratios could be interpreted as meaning that paraffinic hydrocarbons in Bay of Plenty were degraded by microorganisms. However, planktonic algae contain large amounts of pristane and yield large pristane to C_{17} ratios (10.2 in Saanich Inlet); thus the high ratio in the Bay of Plenty sediment is probably an indication of a substantial planktonic contribution of hydrocarbons. Sediments from three cores from Saanich Inlet gave ratios from 0.3 to 0.6 and ten samples from Beaufort Sea averaged 1.0.

Perylene

Of the many aromatic hydrocarbons which occur in recent and ancient sediments, the most commonly recognised compound is perylene. Because of its intense fluorescence emission and its characteristic ultraviolet absorption spectrum, perylene can readily be detected and quantitatively measured even when accompanied by complex mixtures of other aromatic compounds. It has been suggested that the precursors of perylene arise predominantly from land organisms and that conversion of these precursors to perylene occurs when rates of deposition are fast and reducing conditions are established in the sediment (Aizenshtat 1973).

The Nancy Sound core contained from 0.054 to 0.138 ppm perylene, showing a general increase with depth. This trend is more apparent when the amount of perylene is considered as a function of the organic carbon content, with 1.3 μg/g in surface sediment and 3.3 μg/g in the sample from the 457-472 cm level (Table 3). A similar increase with depth was found by Brown *et al* (1972) in the Saanich Inlet sediments. The Bay of Plenty sample was relatively rich in perylene, containing 7.0 μg/g of organic carbon, indicating either a relatively abundant source of perylene precursors in the deposited organic matter or geochemical conditions which were more favourable for the generation of perylene. The oxidation-reduction conditions and the length of time since deposition could also be two of the factors involved. The abundance of perylene in the Bay of Plenty sample does not support the theory of a terrigenous origin of perylene precursors for it is this sample which exhibits the lowest CPI value and the greatest pristane to nC_{17} ratio implying a lesser contribution of organic material from land sources.

The amounts of perylene found in the Nancy Sound and Bay of Plenty cores are considerably less than in the Saanich Inlet samples where 2.4 ppm or 91 μg/g of organic carbon was found in the deepest sample, 34.5 m below the sediment-water interface. The amounts were of the same order of magnitude as found in sediments from Santa Barbara Basin and considerably more than found in Tanner Basin sediments and in JOIDES hole 3 from the Gulf of Mexico which contained less than 0.0001 ppm (Aizenshtat 1973).

CHLORIN PIGMENTS

Chlorophyll pigments are present in terrestrial and aquatic plants, with chlorophyll ***a*** and ***c*** and their degradation products being found in marine and fresh water sediments. Chlorophylls undergo a series of degradation reactions including

(a) loss of a magnesium ion and the addition of two hydrogen atoms to yield pheophytin,

(b) loss of the phytyl group to yield pheophorbide, and

(c) hydrolysis and decarboxylation to yield porphyrins.

Chlorophyll and pheophytin are esters and may be separated from the other chlorins which are generally free acids on the basis of solubility in basic solutions. Chlorins may be further identified and quantitatively measured by ultraviolet spectroscopy (Hodgson and Baker 1967) and may be detected in trace amounts by fluorescence spectroscopy.

Total chlorins extracted from the Nancy Sound sediments were primarily insoluble in sodium hydroxide and gave an absorption spectrum with a major peak in the region of 408-410 nm, indicative of pheophytin ***a***, the first major degradation product of chlorophyll. As chlorophyll ***a*** is easily converted to pheophytin *a* under laboratory conditions the presence of pheophytin *a* rather than chlorophyll is to be expected. As shown in Table 3, the amounts of chlorins found in the Nancy Sound sediments decreased with increasing depth indicating destruction of the chlorins with time. Similar decreases with depth have been noted by other investigators (Brown *et al* 1972). Vanadyl or nickel porphyrin complexes of the type found in petroleum and in other marine sediments (Hodgson *et al* 1963) were not detected. The proportion of esters to free acids was greatest in the surface sediment. It did not change systematically and there was no conclusive evidence of an effective degradation pathway from chlorophyll to pheophytin.

CAROTENOID COMPOUNDS

The carotenoids are a major group of compounds associated with chlorophyll in both terrestrial and aquatic plants. The basic carotenoid structure consists of 40 carbon atoms with a predominantly conjugated system and methyl substitution. The most commonly recognised carotenoids are the hydrocarbon carotenes : β carotene, α carotene, lycopene, and others of formula $C_{40}H_{56}$. These carotenes are readily soluble in petroleum ether when partitioned between petroleum ether and methanol, whereas the second major group of carotenoids, the xanthophylls, contain two hydroxyl groups in their structure and are retained by the methanol. Carotenoids are readily detected in extract from sediments by their characteristic absorption spectra in the 400 -600 nm region.

Absorption spectra of the diethyl ether -10% methanol eluate from the alumina chromatography column showed a number of peaks indicative of carotenes, the major ones being at 449, 474, and 420 nm. Calculations of the amount of carotenes present were made based on an extinction coefficient for β carotene of 1.25×10^{-5} ℓ mol^{-1} cm^{-1} for the 474 nm peak. This peak was chosen rather than the major one at 449 nm because of less contribution from interfering compounds. The amount of carotenes in samples from core H264 ranged from 0.13 μg/g to 0.01 μg/g with the sample from core H211 containing only 0.0005 μg/g. Although the 0-15 cm sample contained the greatest amount of carotene there was no systematic decrease with depth nor was there any other indication of geochemical or microbial degradation of carotenes. Carotenes are readily oxidised and are best preserved under reducing conditions. By comparison, the reducing sediments of the Black Sea contained 1-40 μg/g of material showing the characteristic carotenoid spectra. From the polarity, as shown by their retention by an alumina chromatography column, approximately half of the carotene pigments appeared to be hydrocarbons, probably largely β carotene; the other half was thought to possess one or more hydroxyl groups. In the present study carotenoids extracted from the Nancy Sound samples required a solvent consisting of 10% methanol and 80% diethyl ether to elute them from the alumina chromatography column, suggesting the presence of polar groups or possibly the binding of the hydrocarbon carotene to a larger, more polar molecule.

STEROLS

Sterols, which are derived from plant and animal matter, are found in recent sediments and persist over geologic time to become the sterane constituents of petroleum. Despite changes in the peripheral groups and saturation of double bonds the characteristic ring structure of sterols enables recognition of the corresponding steranes in petroleum as being derived from sources similar to contemporary sterols. Although few published data are available sterols are probably common constituents of recent marine sediments with β sitosterol, stigmasterol, campesterol, and brassicasterol being the most abundant compounds. In sediments, sterols occur as free compounds and as compounds bound either as fatty acid esters or as complexes in inorganic and organic matrixes.

Gas chromatographic analysis of the sterol fraction of the Nancy Sound sediments showed four prominent peaks each of which was found by mass spectral analysis to indicate a sterol and its corresponding partially reduced steranol. The sterols identified were β sitosterol (which accounted for 83-94% of the sterols present), cholesterol, campesterol, and stigmasterol totalling from 1.1-7.8 ppm (Table 3). There was no systematic change with depth in the total amount of sterols, in the relative abundances of the four sterols measured, nor in the relative proportions of the bound and free sterols. The steranols appear to have been produced from plant and animal sterols in the sediments after deposition. Terrestrial plants and algae do not commonly contain significant quantities of these compounds. In simulated maturation laboratory experiments, steranes have been produced from sterols under mild temperatures and reducing conditions with pressure (Steel *et al* 1972) and by heating in sealed tubes (Rhead *et al* (1971). Similar partially reduced sterols were found in sediments from Beaufort Sea (Peake *et al* 1972) and from Mono Lake, California, where a gradual reduction of double bonds in the sterol nucleus and side chains appears to have occurred over a 97,000 year period (Henderson *et al* 1971). The Bay of Plenty sample contained the same four sterols as detected in the Nancy Sound sediments with β sitosterol being the predominant sterol constituent; however, the amounts detected were low, totalling only 0.19 ppm.

Quantitative data for sediments from other areas are few. A surface sediment sample from San Pedro Basin offshore from Southern California contained a similar array of sterols but in much larger amounts, totalling 40 ppm; and a 3000 to 4000 year old sediment from Baffin Bay, Texas, contained 6 ppm sterols (Attaway and Parker 1970). Beaufort Sea surface sediments contained 5.2 ppm total sterols, of which β sitosterol, cholesterol, campesterol and stigmasterol totalled 2.6 ppm. Thus, the sterols of the Nancy Sound sediments appear to be typical in both the types of sterol and the amounts present with reduction processes occurring at rates similar to those in other surface marine sediments.

CONCLUSIONS

There are three major factors which govern the amount and chemical composition of organic material in recent marine sediments :

(a) the origin of the organic matter, terrestrial or marine, and the productivity of the biogenic source;

(b) the degree of oxidative degradation, both chemical and microbial, during deposition; and

(c) chemical alteration and diagenesis of the deposited material.

The amount and type of organic compounds found in the Nancy Sound sediments is indicative of a depositional environment favourable for the preservation of organic material. Although many physical and chemical parameters may contribute to such an environment, the absence of prolonged exposure of the organic matter to oxygen is the key factor. Such conditions are likely to be the result of the rapid rate of deposition in Nancy Sound (calculated by Glasby, p.33, to be from 83.7-102.2 cm/1000 yr) and in some parts of Saanich Inlet (400 cm/1000 yr., Brown *et al* 1972). Further, the sediment of Saanich Inlet is known to be reducing and the overlying water periodically becomes anoxic.

Once the organic material has been deposited under reducing conditions and is protected from degradative oxidation, geochemical alterations to the chemical structure of most compounds is likely to be very slow. As the sediments of core H264 from Nancy Sound and the recent sediments of Saanich Inlet represent only an instant of geological time (less than 6000 yr. and 8500 yr. respectively), only the most labile organic compounds are likely to have undergone significant chemical change and the organic compounds should closely reflect the composition of the indigenous biogenic source material. In Nancy Sound the aliphatic hydrocarbons in the sediment are typical of those found in terrestrial plants whereas in Saanich Inlet a significant input from marine biota is indicated. The most labile compounds examined were the chlorins which, despite a reducing environment, were rapidly degraded in both the Nancy Sound and Saanich Inlet sediments. Changes also occurred in the sterol compounds, which were partially reduced to the corresponding steranols, and in the aromatic hydrocarbons, with the formation of perylene being evidence of geochemical activity. Thus the depositional environment in the Nancy Sound sediments appeared to be similar to that of Saanich Inlet and also to that of other reducing marine basins with conditions favourable for the preservation of organic compounds. In environments of this type variations in the amount and type of organic material present are governed not so much by degradative processes as by the productivity and chemical composition of the biogenic source. In contrast the Bay of Plenty sample represented a very different type of sedimentary environment, one in which oxidative destruction of organic matter was an important process during deposition, resulting in smaller amounts of both total organic carbon and individual groups of organic compounds.

REFERENCES

AIZENSHTAT, Z. 1973: Perylene and its geochemical significance. *Geochimica et Cosmochimica Acta 37* : 559-67.

AIZENSHTAT, Z.; BAEDECKER, M.J.; KAPLAN, I.R. 1973: Distribution and diagenesis of organic compounds in JOIDES sediment from Gulf of Mexico and western Atlantic. *Geochimica et Cosmochimica Acta 37* : 1881-98.

ATTAWAY, D.; PARKER, P.L. 1970: Sterols in recent marine sediments. *Science, N.Y. 169* : 674-6.

BEZRUKOV, P.L.; LISITSYN, A.P.; ROMANKEVICH, Y.A., SKORNYAKOVA, N.S. 1961: "Contemporary sedimentation in the northern Pacific. Contemporary marine and oceanic sediments". Isdatel'stvo Akademii Nauk SSSR, Moscow.

BORDOVSKIY, O.K. 1965a: Accumulation and transformation of organic substances in marine sediments : 3 - Accumulation of organic matter in bottom sediments. *Marine Geology 3* : 33-82.

BORDOVSKIY, O.K. 1965b: Accumulation and transformation of organic substances in marine sediments : 3 - Transformation of organic matter in bottom sediments and its early diagenesis. *Marine Geology 3* : 83-114.

BRAY, E.E.; EVANS, E.D. 1961: Distribution of n-paraffins as a clue to recognition of source beds. *Geochimica et Cosmochimica Acta 22* : 2-15.

BROWN, F.S.; BAEDECKER, M.J.; NISSENBAUM, A.; KAPLAN, I.R. 1972: Early diagenesis in a reducing fiord, Saanich Inlet, British Columbia - III. Changes in organic constituents of sediment. *Geochimica et Cosmochimica Acta 36* : 1185-203.

CLARK, R.C.; BLUMER, M. 1967: Distribution of n-paraffins in marine organisms and sediment. *Limnology and Oceanography 12* : 79-87.

COOPER, J.E.; BRAY, E.E. 1963: A postulated role of fatty acids in petroleum formation. *Geochimica et Cosmochimica Acta 27* : 1113-27.

DEGENS, E.T. 1971: Sedimentological history of the Black Sea over the last 25,000 years. *In* Campbell, A.S. (ed.) "Geology and History of Turkey". Petroleum Exploration Society of Lybia.

EGLINTON, G.; GONZALES, A.G.; HAMILTON, R.J. 1962: Hydrocarbon constituents of the wax coatings of plant leaves : A taxonomic survey. *Phytochemistry 1* : 89-102.

EMERY, K.O.; RITTENBERG, S.C. 1952: Early diagenesis of California Basin sediments in relation to origin of oil. *Bulletin of the American Association of Petroleum Geologists 36* : 735-806.

HAN, J.; CALVIN, M. 1969: Hydrocarbon distribution of algae and bacteria, and microbiological activity in sediments. *Proceedings of the National Academy of Science (U.S.) 64* : 436-43.

HENDERSON, W.; REED, W.E.; STEEL, G.; CALVIN, M. 1971: Isolation and identification of sterols from a Pleistocene sediment. *Nature, London 231* : 308-10.

HODGSON, G.W.; BAKER, B.L. 1967: Spectra of selected geochemically significant porphyrins and chlorins. *Chemical Geology 2* : 187-98.

HODGSON, G.W.; USHIJIMA, N.; TAGUSHI, K.; SHIMADA, I. 1963: The origin of petroleum porphyrins : Pigments in some crude oils, marine sediments and plant material of Japan. *Science Reports of the Tohoku University, Third Series, Sendai, Japan 8* : 483-513.

HUNT, J.M. 1961: Distribution of hydrocarbons in sedimentary rocks. *Geochimica et Cosmochimica Acta 22* : 37-49.

KOONS, C.B.; JAMIESON, G.W.; CIERESZKO, L.S. 1965: Normal alkane distributions in marine organisms; possible significance to petroleum origin. *Bulletin of the American Association of Petroleum Geologists 49* : 301-16.

KVENVOLDEN, K.A. 1970: Evidence for transformations of normal fatty acids in sediments. *In* Hobson, G.D. (ed.) "Advances in Organic Geochemistry, 1966". : 335-66.

LISITSYN, A.P. 1955: Distribution of organic carbon in Bering Sea sediments. *Doklady Akademii Nauk, SSSR 103* : 299-302.

McIVER, R.D. 1962: Ultrasonics - A rapid method for removing soluble organic matter from sediments. *Geochimica et Cosmochimica Acta 26* : 343-5.

NISSENBAUM, A.; KAPLAN, I.R. 1972: Chemical and isotopic evidence for the in situ origin of marine humic substances. *Limnology and Oceanography 17* : 570-82.

PAKHOMOVA, K.F. 1961: Organic matter in the bottom deposits of the Caspian. *Trudy Gosudarstvennogo Okeanograficheskogo Instituta 6.*

PEAKE, E.; CASAGRANDE, D.J.; HODGSON, G.W. 1974: Fatty acids, chlorins, hydrocarbons, sterols and carotenoids from a Black Sea core. *Memoir of the American Association of Petroleum Geologists 20* : 505-23.

PEAKE, E.; STROSHER, M.; BAKER, B.L.; GOSSEN, R.; McCROSSAN, R.G.; YORATH, C.J.; HODGSON, G.W. 1972: The potential of Arctic sediments : Hydrocarbons and possible precursors in Beaufort Sea sediments. *Proceedings of the 24th International Geological Congress, Montreal, 1972, Section 5* : 28-37.

RASHID, M.A.; KING, L.H. 1969: Molecular weight distribution measurements on humic and fulvic acid fractions from marine clays on the Scotian Shelf. *Geochimica et Cosmochimica 33* : 147-51.

RASHID, M.A.; KING, L.H. 1970: Major oxygen-containing functional groups present in humic and fulvic acid fractions isolated from contrasting marine environments. *Geochimica et Cosmochimica Acta 34* : 193-201.

RASHID, M.A.; KING, L.H. 1971: Chemical characteristics of fractionated humic acids associated with marine sediments. *Chemical Geology 7* : 37-43.

RHEAD, M.M.; EGLINTON, G.; DRAFFAN, G.H. 1971: Hydrocarbons produced by the thermal alteration of cholesterol under conditions simulating the maturation of sediments. *Chemical Geology 8* : 277-97.

SMITH, P.V. 1952: The occurrence of hydrocarbons in recent sediments from the Gulf of Mexico. *Science, N.Y. 116* : 437-9.

STARIKOVA, N.D. 1956: Organic matter in Bering Sea sediments. *Doklady Akademii Nauk SSSR 108* : 892-4.

STEEL, G.; REED, W.E.; HENDERSON, W. 1972: The organic diagenesis of steroids in sediments as related to the origin and formation of petroleum. *In* Gaertner, H.R. and Wehner, H. (eds) "Advances in Organic Geochemistry, 1971" : 353-64.

STONE, R.W.; FENSKE, M.R.; WHITE, A.G.C. 1940: Microorganisms attacking petroleum and petroleum fractions. *Journal of Bacteriology 39* : 91.

STROM, K.M. 1955: Land-locked waters and the deposition of black muds. Pp 356-72 *in* Trask, P.D. (ed.) "Recent Marine Sediments". Dover Publications Inc., New York. 736p.

TRASK, P.D.; WU, C.C. 1930: Does petroleum form in sediments at time of deposition? *Bulletin of the American Association of Petroleum Geologists 14* : 1451-63.

HYDROLOGY OF CASWELL AND NANCY SOUNDS

by

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ABSTRACT

A hydrological survey of Caswell and Nancy Sounds showed them to be typical fiords with a shallow, low density surface layer travelling seaward and a deeper, replacement inflow of coastal water. The deep water was adequately ventilated and was probably replaced during the winter. Freshwater inflow into Caswell Sound was higher than into Nancy Sound and this was reflected in the density structure which inhibited vertical mixing. Some theoretical velocity profiles were derived for Caswell Sound using a simple model.

INTRODUCTION

The hydrology of Caswell and Nancy Sounds was investigated during 26 January to 8 February 1971 as part of a wider oceanographic survey of these fiords. A few observations were made in Milford Sound for comparison purposes.

Previous hydrological work in the New Zealand fiords has been carried out in Milford Sound (Garner 1964), Doubtful Sound (Batham 1965) and Dusky Sound (Jillett and Mitchell 1973). These works show that New Zealand fiords are hydrologically similar in many respects to the fiords of Norway (Saelen 1967) and British Columbia (Pickard 1961, 1963, 1967).

Fiords are characteristically deep, narrow inlets often partially cut off from the sea by a shallow sill close to the entrance. Freshwater runoff forms a thin, low salinity surface layer which travels seaward, mixing with and entraining higher salinity water from below. Consequently, a two-layer circulation system develops with an inflow of high salinity water below the outflowing low salinity surface layer. This circulation is confined to the upper layers and below this the water in the deep basins may remain undisturbed for long periods, particularly in fiords with very shallow sills (Saelen 1967). This can result in stagnation with low oxygen levels and the development of hydrogen sulphide.

Pickard (1961), in a comprehensive study of the British Columbian fiords, has classified the fiords into hydrological types and shown the importance of freshwater runoff on the fiord characteristics. Rattray (1967) has studied the dynamics of fiord circulation and further work (Hansen and Rattray 1965, 1966) has shown important dynamic differences between fiords and estuaries.

DATA

Hydrological casts using Knudsen reversing bottles were made at station positions approximately 3 km apart along the centre of each fiord (Fig. 1). Close bottle spacing was used in the upper layers to define the salinity in greater detail and salinities were determined with an inductive salinometer. A bathythermograph drop at each station provided a detailed temperature profile. In Caswell Sound dissolved oxygen was measured at some stations using the standard Winkler method.

A thermograph monitored the surface water temperatures at the ship's engine cooling water intake and frequent surface bucket samples were taken for salinity analyses.

In Nancy Sound profiles of surface salinity and temperatures along the centre line of the fiord were obtained during the period over high water and low water.

During the survey of each fiord, an automatic tide recorder was installed at a site close to the head of each Sound (Fig. 1). A station (A328) midway along Milford Sound occupied by Garner (1964) was revisited (Stn H283) for comparative purposes. Further salinity data in Milford Sound, taken on 18 April 1971 were

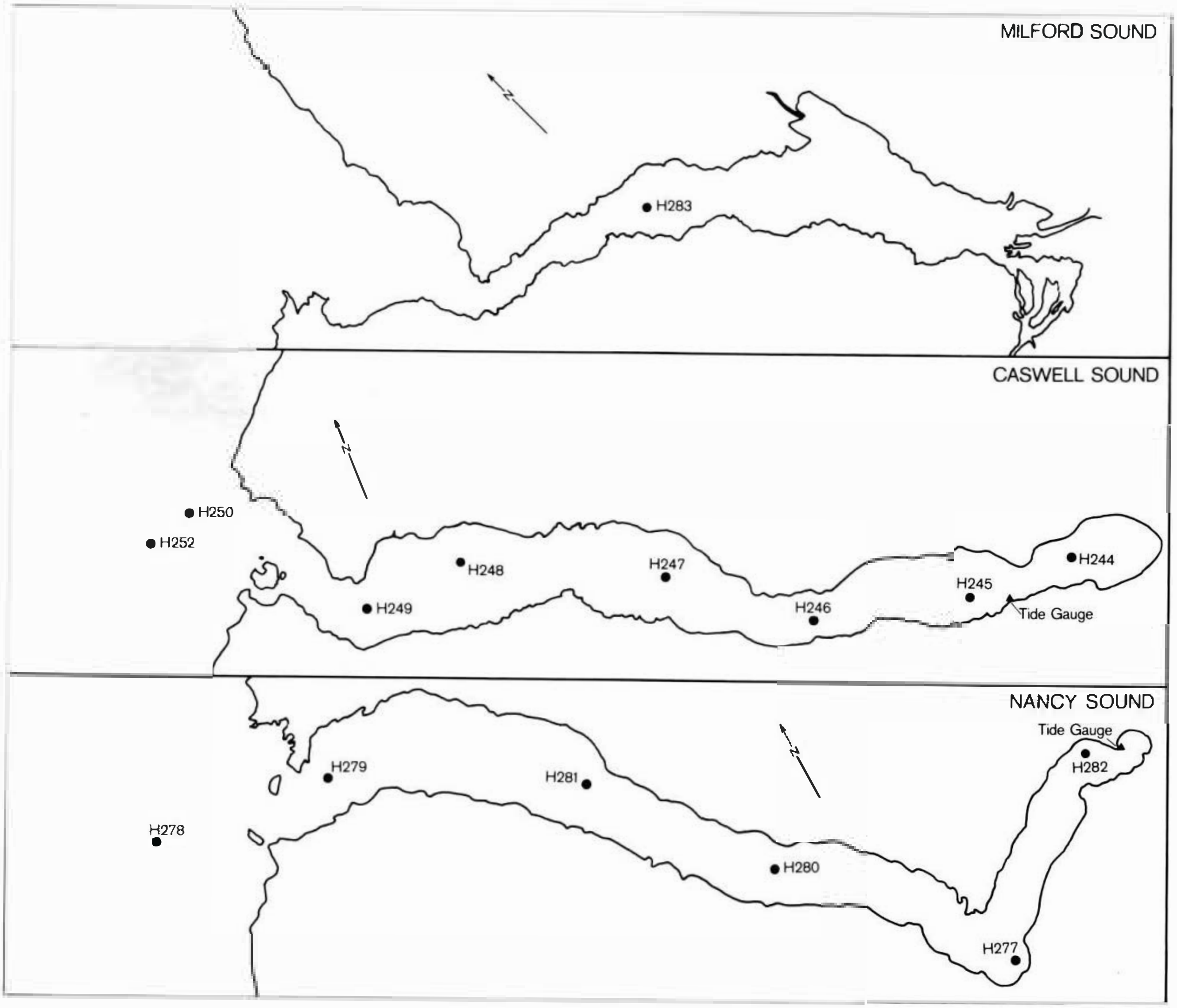

FIG. 1. Caswell, Nancy and Milford Sounds showing positions of hydrological stations.

made available by Mr P. Roberts of the Marine Department, Wellington.

Climatological data from Milford and river flow data from the Cleddau River catchment at Milford were available for the survey period.

GENERAL CHARACTERISTICS OF CASWELL AND NANCY SOUNDS

The two fiords are of similar dimensions (Table 1) and are consequently suited to a comparative study.

FRESHWATER INFLOW

The Fiordland region experiences extremely high rainfalls with an annual average precipitation at Milford of 643 cm (N.Z. Meteorological Service 1966). In spring and summer rainfall is at a maximum and this, combined with the melting of winter snow, gives a high freshwater runoff at these times.

TABLE 1. The major dimensions of Caswell and Nancy Sounds.

	Caswell Sound	Nancy Sound
Length	15.0 km	15.6 km
Mean width	1.3 km	1.0 km
Maximum depth	416 m	279 m
Entrance sill depth	143 m	77 m

An estimate of the freshwater inflow into the Sounds during the survey period was made, based on the hydrological similarity between these catchments and that of the Cleddau River at Milford, the representative basin for this hydrological region (Toebes and Palmer 1969). Catchment areas found from NZMS 19, Sheet 6, are 271 km^2 for Caswell Sound and 231 km^2 for Nancy Sound. The catchment area for Milford is 510 km^2 and for the Cleddau River 155 km^2 (Garner 1964). Mean daily discharge figures for the Cleddau River showed a generally decreasing flow throughout the survey period. These mean daily discharges averaged over the 2-day period preceding the survey of each Sound, used with the catchment areas, gave the following estimates of freshwater inflow, R, into each Sound.

Caswell Sound	$R = 71\ m^3/sec$
Nancy Sound	$R = 22\ m^3/sec$
Milford Sound	$R = 58\ m^3/sec$

The average discharge of the Cleddau River over the survey period was 24.5 m^3/sec., slightly lower than the mean annual discharge of 27.2 m^3/sec.

TIDES

No tidal information is published for Caswell and Nancy Sounds but since the available data for Fiordland (N.Z. Tide Tables 1971) show only small variations between fiords, it seems likely that the tidal ranges would be similar to those in Bligh Sound, approximately 37 km north of Caswell Sound. Mean spring range for this fiord is given as 1.8 m and mean neap range as 1.2 m.

Tidal records for five tidal cycles in Caswell Sound and three tidal cycles in Nancy Sound were obtained in the course of the survey. These showed a decreasing tidal range from the spring tide of 2.3 m on 29 January 1971. Tides in this region exhibit a marked declination with consecutive tides of different range, and consecutive fortnightly spring ranges also differ. The tidal prediction for the standard port (Westport) shows that the spring tide of 29 January was the highest spring tide for this period.

Tidal range information given on Admiralty Charts for this area shows consistently larger tidal ranges than those given in the tide tables, e.g., for Charles Sound (Hydrographic Office, Chart N.Z. 7522) spring range is 8.5 ft (2.6 m) and neap range is 7.5 ft (2.3 m). This possibly results from the asymmetry in the tides and refers to the higher spring and neap ranges.

Pickard and Rodgers (1959) found tides rise and fall almost simultaneously over the whole length of fiords, and tidal currents were observed at all depths, even below the sill depth in the inner basins. Assuming a tidal spring range of 1.8 m for Caswell Sound, an estimate of the tidal currents at the mouth can be made. The cross-sectional area of Caswell Sound at the mouth is $4.5 \times 10^4 m^2$ and the surface area is 1.54×10^7 (Irwin 1973). From these values a mean tidal current of approximately 3 cm/sec through the entrance section of Caswell Sound can be calculated and inwards of the mouth the tidal currents will decrease rapidly. Tidal streams in most parts of these fiords are small and consequently only play a small part in the mixing process.

SALINITY STRUCTURE

The longitudinal surface salinities (Fig. 2a) show typical estuarine profiles with the salinity gradient increasing towards the head of the fiord. The steeper gradient found in Caswell Sound reflects the higher freshwater inflow into this sound at the time of the survey. Surface salinity just outside the mouth of each Sound was approximately 33.8‰.

The vertical cross-sections of salinity (Table 2; Figs 2b, 2c) are broadly similar with a shallow highly stratified surface layer of low salinity and a deep zone containing water of higher coastal salinities. This is similar to the shallow and deep zones identified in the British Columbian fiords where the shallow zone was confined within the top 20 metres (Pickard 1961).

In the deep basins, water of 35.0‰ salinity was found and probably derived from the winter overspilling of water at sill depth, as outlined by Garner (1964) for Milford Sound.

The structure of the shallow zone in each fiord showed small but important differences owing to the difference in freshwater inflow. The depth of the shallow zones as measured to the 34.0‰ isohaline showed that Caswell Sound, which had the higher inflow, had the shallower surface layer. Vertical salinity gradients through this layer at three stations approximately equally spaced along the sounds (Fig. 3) illustrate this difference clearly. In Caswell Sound, with the lower surface salinities, very large gradients existed in the top 5-10 m with an abrupt change of gradient below this. In Nancy Sound the salinity showed a more gradual change of gradient with depth. This suggests that in the fiord with higher runoff the higher salinity, and consequently density gradient, in the surface layer inhibited vertical mixing whereas in Nancy Sound vertical mixing extended much deeper.

In Caswell Sound a curious flattening of the salinity gradient between 34.4‰ and 34.5‰ occurred and this band of almost isohaline water shows clearly in Fig. 3. A physical interpretation of this is difficult but it may be related to the adjustment of the fiord to the decreased runoff, as the river flow was falling rapidly at this time.

TEMPERATURE STRUCTURE

Temperatures in Caswell and Nancy Sounds (Table 2; Fig. 4) showed similar values in the deep zone and marked differences in the shallow zone.

In the deep zone a thermocline (18-14°C) existed in the 30-50 m depth range and below this temperatures decreased slowly with depth. The 13°C isotherm lay at about 100 m in both fiords and in the deeper Caswell Sound the bottom water had a temperature of 12°C.

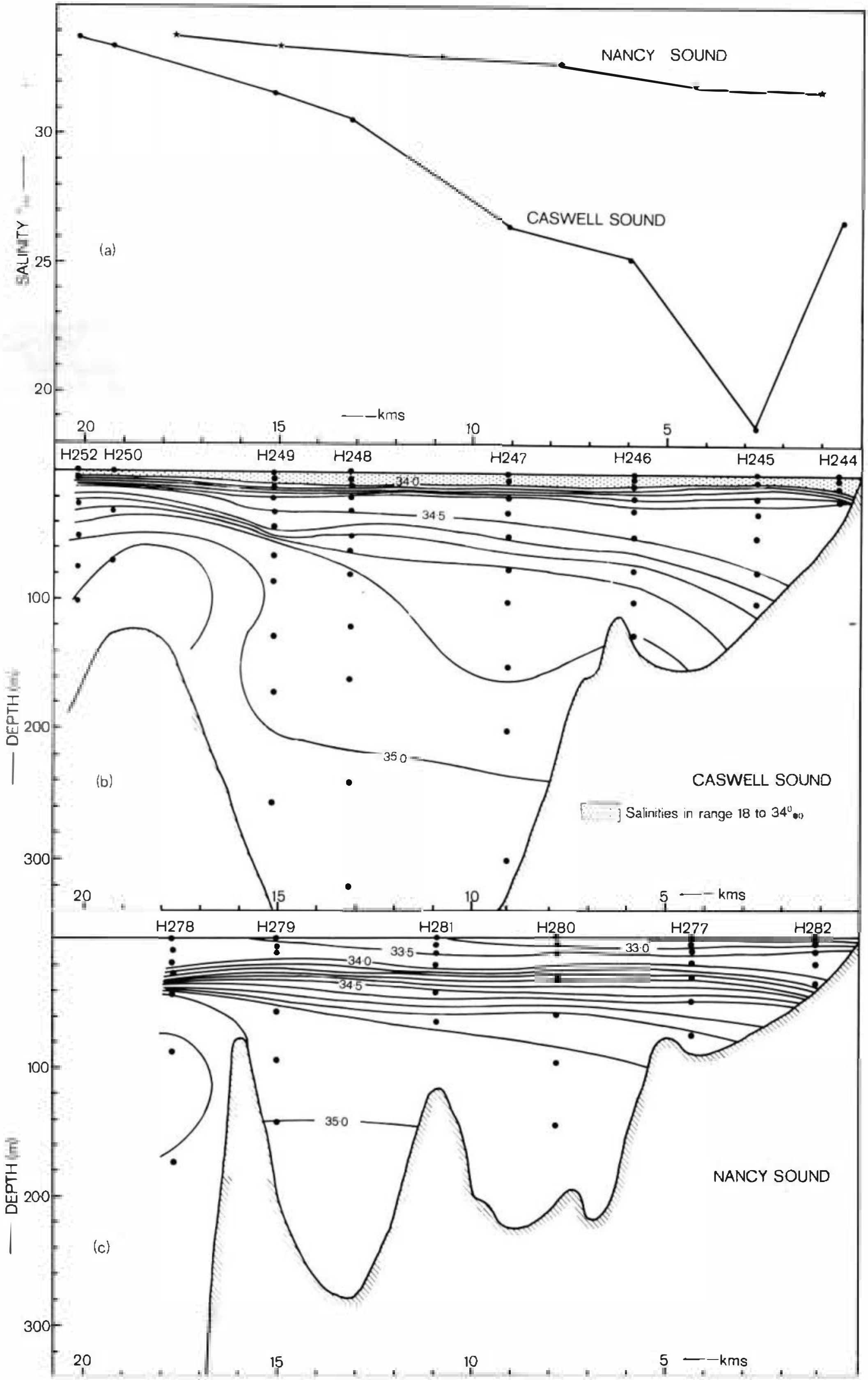
NANCY SOUND
CASWELL SOUND
SALINITY ‰
30
25
20
(a)
—kms
20
15
10
5
H252 H250
H249
H248
H247
H246
H245
H244
34·0
34·5
35·0
DEPTH (m)
100
200
300
(b)
CASWELL SOUND
Salinities in range 18 to 34‰
H278
H279
H281
H280
H277
H282
33·5
33·0
34·0
34·5
35·0
(c)
NANCY SOUND

FIG. 2. Salinity structure of Caswell and Nancy Sounds (‰). (a) Surface profiles, (b) Vertical cross-section of Caswell Sound, 31 January 1971, (c) Vertical cross-section of Nancy Sound, 3 February 1971.

The temperatures in the shallow zone, from temperature profiles at three stations (Fig. 5), showed that a subsurface maximum occurred in the upper 5 m. In Caswell Sound a very marked temperature step of 0.5 - 1.5°C existed at around 2.5 m, while in Nancy Sound the maximum is much less distinct and a little deeper. The freshwater inflow was slightly cooler than the coastal waters in the area and consequently this water formed a cool surface layer which mixed only slowly with the water below. In Nancy Sound, which had a lower inflow and smaller density stratification, vertical mixing of the surface water took place more quickly.

Observations of the freshwater layer in Caswell Sound were made during diving operations to install the tide gauge. The surface layer had a brownish hue with low visibility (6 m) and smelt of beech in a manner reminiscent of some lakes. Around 2 m depth a clearly defined transition zone, approximately half a metre thick was encountered. In this zone visibility was almost nil and the water had the oily appearance often seen at the mixing interface between liquids of different density. Below this the water was markedly warmer, visibility improved (20 m), and the water had the characteristic green hue associated with coastal waters. In this region animals and vegetation appeared much more abundant. These observations suggest that a closer sampling interval than the 5 m used here is required to define fully the brackish layer. The question also arises as to how a 3-4 m draft vessel such as MV *Taranui* affects this 2 m deep brackish layer.

The temperature profiles (Fig. 5) also show that surface waters in the upper 30 m were warmer in Nancy Sound than in Caswell Sound. This may be caused by the total effect of a lower runoff of fresh water.

OXYGEN

Dissolved oxygen determinations (Fig. 5) for Caswell Sound show high levels with only a small decrease with depth. At 300 m oxygen concentration was still 4.8 ml/l compared with surface values of about 5.5 ml/l. Surface oxygen values were higher at the head of the Sound. Oxygen values show a similar trend to those found by Garner (1964) in Milford Sound in January 1957 and show that the deep water was not anoxic but was probably renewed around August when coastal surface waters are coolest and therefore most dense. At this

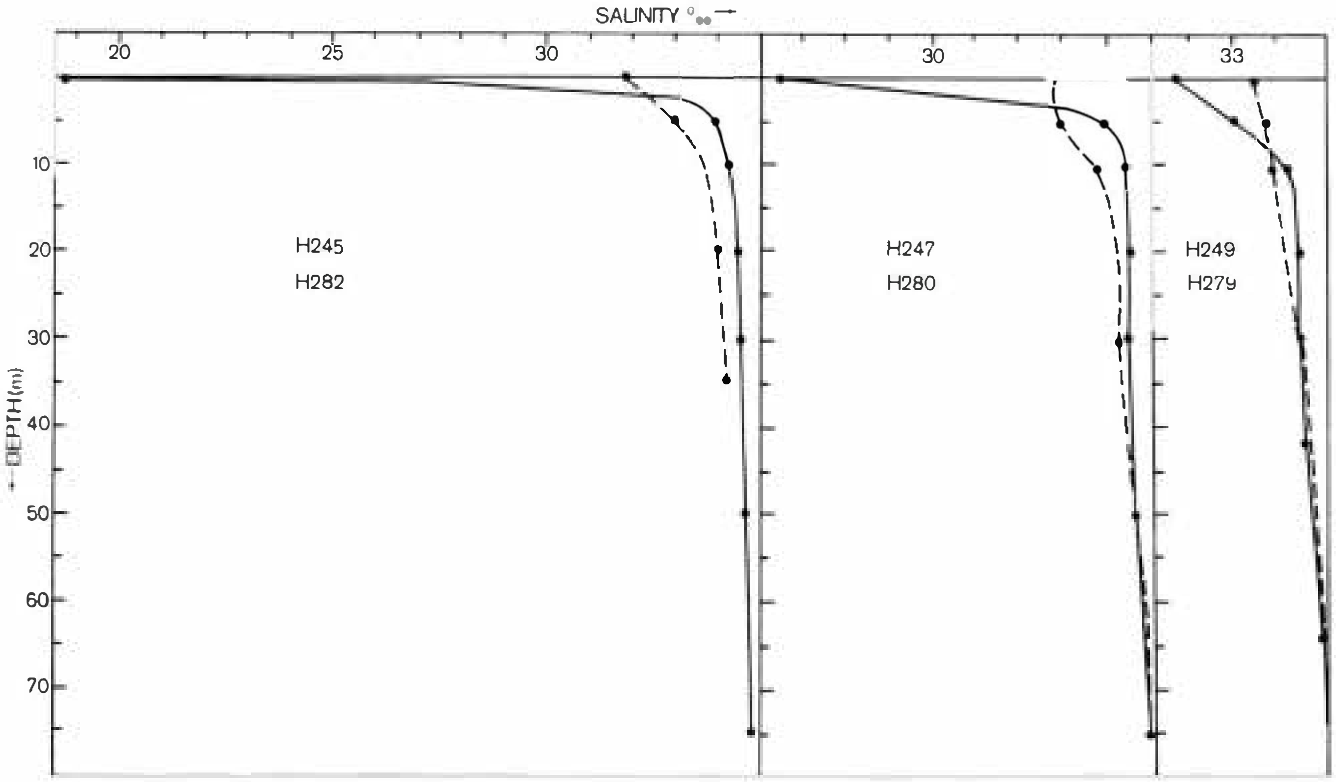

FIG. 3. Vertical salinity profiles at three stations in each of Caswell and Nancy Sounds. ——— Caswell Sound
- - - - - Nancy Sound.

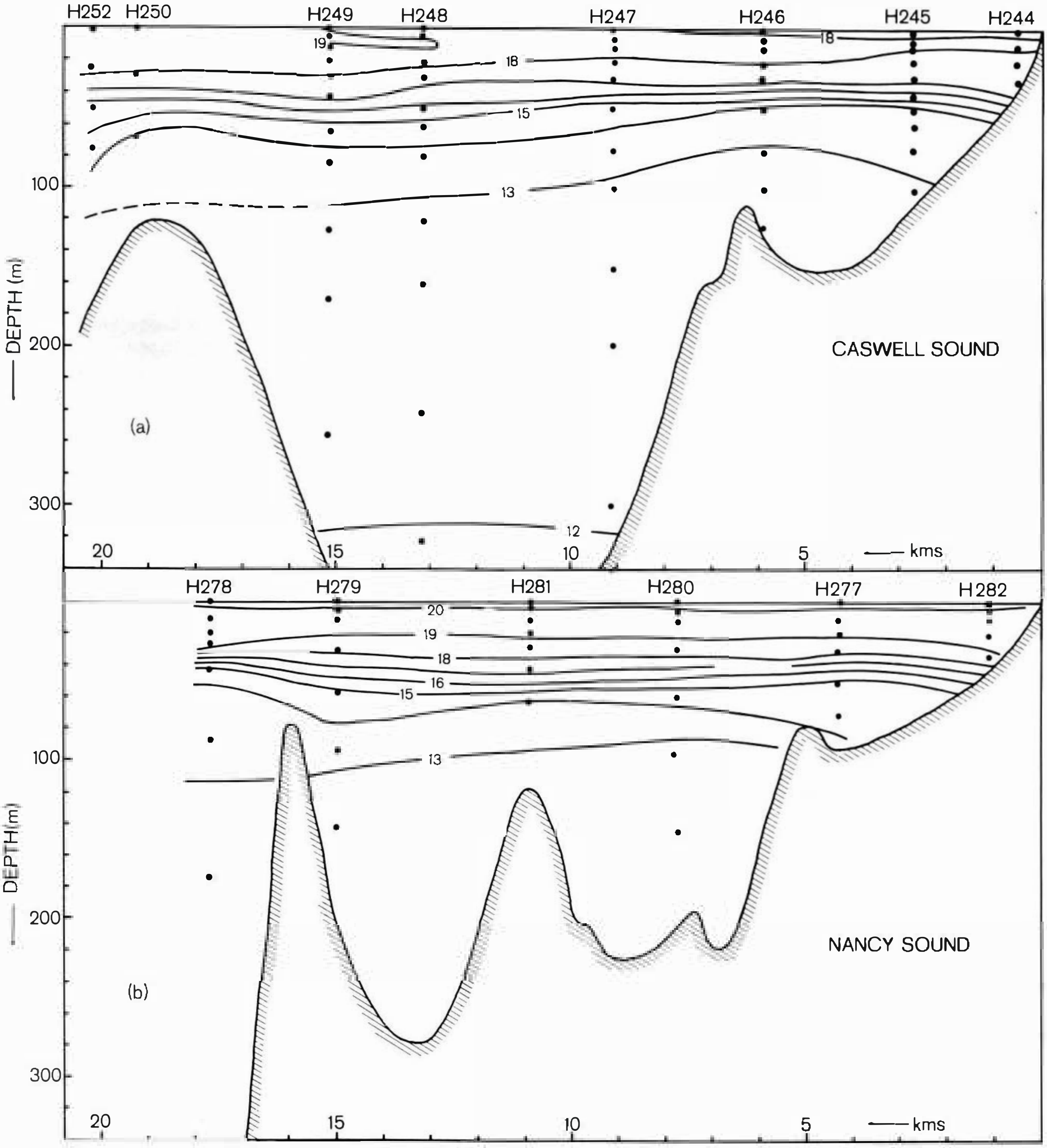

FIG. 4. Temperature structure of Caswell and Nancy Sounds (°C). (a) Vertical cross-section of Caswell Sound, 31 January 1971; (b) Vertical cross-section of Nancy Sound, 3 February 1971.

time near-surface coastal water is sufficiently dense to spill over the sill and into the deep basins of the fiords. Recent work has shown that local climatic effects can also be important in the deep water renewal mechanism (Ozretich 1975).

CIRCULATION

In estuaries the velocity and salinity field are interdependent since density is a function of salinity to a first order approximation. Hansen and Rattray

TABLE 2. Hydrological Station Data.

NZOI Stn No.	Depth (m)	Temp. (°C)	Salinity (‰)	Dissolved Oxygen * (ml/1)
Caswell Sound				
H244	0	17.65	26.71	
	5	18.44	33.71	
	10	18.25	33.74	
	20	17.78	34.40	
	30	17.49	34.42	
H245	0	17.09	18.66	5.86
	5	18.40	33.81	5.63
	10	18.07	34.13	5.50
	20	17.80	34.34	5.54
	30	17.30	34.43	5.48
	50	13.88	34.49	5.40
	75	13.16	34.50	
	100	12.92	34.69	5.37
H246	0	17.55	25.29	
	5	18.59	33.85	
	10	18.50	34.02	
	20	18.01	34.29	
	30	17.29	34.44	
	50	13.70	34.50	
	75	12.94	34.75	
	100	12.71	34.84	
	125	12.43	34.90	
H247	0	18.43	26.42	5.98
	5	18.85	33.90	5.42
	10	18.56	34.33	5.63
	20	17.74	34.41	5.41
	30	17.35	34.45	5.33
	50	14.67	34.55	
	75	13.72	34.85	5.30
	100	12.83	34.81	5.21
	150	12.42	34.87	5.10
	200	12.47	34.99	5.91
	300	12.02	35.00	4.82
H248	0	18.54	30.61	
	5	18.92	33.67	5.45
	10	19.05	33.93	5.39
	20	18.42	34.48	5.40
	30	17.59	34.50	5.42
	50	15.80	34.74	6.16
	60	14.93	34.78	5.72
	80	13.74	34.94	5.53
	120	12.47	34.86	5.11
	160	12.58	34.97	5.29
	240	12.19	35.01	5.09
	320	11.98	34.98	4.93
H249	0	18.78	31.62	5.46
	5	19.16	32.95	5.74
	10	18.98	34.24	5.53
	20	18.59	34.43	5.54
	30	18.01	34.49	5.45
	42	17.20	34.52	5.72
	64	14.56	34.91	5.81
	85	13.64	34.99	5.47
	127	12.61	34.92	5.25
	170	12.51	34.99	5.39
	255	12.31	34.96	6.33
H250	0	19.00	33.48	
	30	17.80	34.85	
	69	13.30	35.11	
H252	0	19.90	33.72	
	25	18.67	34.74	
	50	15.54	34.98	
	75	14.66	35.00	
	100		35.11	
Nancy Sound				
H277	0	-	31.94	
	5	-	32.59	
	10	19.71	33.62	
	20	19.16	33.93	
	30	18.24	34.26	
	50	14.74	34.62	
	75	14.14	34.82	
H278	0	19.70	33.81	
	10	19.70	33.80	
	19	19.61	33.80	
	26	19.37	34.20	
	43	14.91	35.00	
	87	13.28	35.13	
	173	12.58	35.09	
H279	0	19.18	33.44	
	5	19.57	33.67	
	10	19.60	33.89	
	29	18.56	34.44	
	57	14.95	34.94	
	94	13.29	34.98	
	141	12.43	35.00	
H280	0	19.53	32.79	
	5	20.02	32.95	
	10	19.65	33.79	
	30	18.54	34.28	
	59	14.29	34.82	
	96	12.57	34.93	
	144	12.22	34.99	
H281	0	19.43	33.01	
	5	19.70	33.31	
	10	19.70	33.44	
	19	-	34.20	
	28	19.25	33.82	
	42	17.22	34.54	
	64	13.88	34.89	
H282	0	19.83	31.74	
	5	20.06	32.98	
	10	19.59	33.65	
	20	19.56	33.88	
	35	18.54	34.07	
Milford Sound				
H283	0	-	27.00	
	5	20.10	27.96	
	10	20.20	32.43	
	18	19.09	33.74	
	28	18.84	34.29	
	39	17.89	34.56	
	79	13.21	34.90	
	106	12.44	34.98	
	142	12.26	34.99	

* Measured by G.P. Glasby

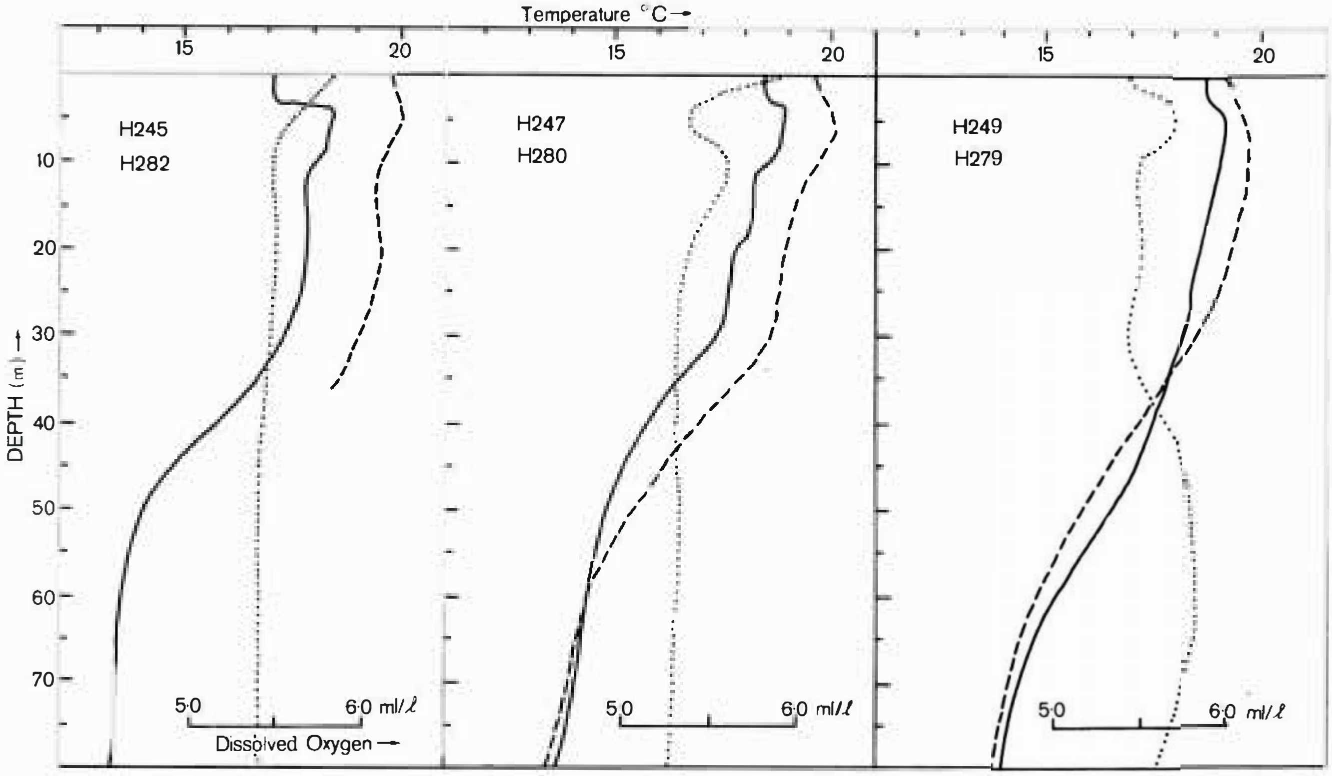

FIG. 5. Vertical temperature profiles at three stations in each of Caswell and Nancy Sounds and dissolved oxygen profiles for Caswell Sound. ——— Caswell Sound temperature, - - - - Nancy Sound temperature, ... Caswell Sound dissolved oxygen.

(1965) have shown that estuarine salt flux is divided amongst three interacting modes : the river discharge or forced mode, the gravitational convection or induced mode, and the horizontal diffusive mode. In fiords the horizontal diffusive mode is normally negligible (Hansen and Rattray 1966). Rattray (1967) solved the gravitation convection equations to obtain a solution for the outer reaches of fiords where the total circulation is large compared to the freshwater inflow.

The Rattray (1967) equations give good agreement with experiment when runoff is large enough to produce a distinct two-layer salinity structure but also show that the velocity field cannot be derived from the salinity field without some knowledge of the vertical eddy viscosity coefficient. Caswell Sound is suitable for application of these equations. A simple approximation to the sound was taken assuming constant width, zero wind stress and total freshwater entry at the head of the Sound (x = o). The best agreement between theory and observed properties (Fig. 6) was obtained using

$$\rho = 0.9992 + (7.4 \times 10^{-4})\, S$$

$$S = 35\left[1 - \frac{2.046 \times 10^{10}}{x\,\frac{11}{6}} \exp\left(- \frac{3.736 \times 10^{8}}{x\,\frac{11}{6}}\, z\right)\right]$$

where ρ = density (gm cm^{-3}); S = salinity (‰); x, z = horizontal and vertical distance respectively (cm).

Conditions in Caswell Sound were similar to those in Silver Bay (Rattray 1967) and consequently a likely maximum value of the vertical eddy viscosity coefficient of 25 cm^2/sec was assumed, allowing the velocity profile to be calculated from

$$u = [1 + h - 2.5\, h^2 + 0.5\, h^3] \exp\,(-\,h)$$

where

$$h = \frac{1.868 \times 10^{8}}{x\,\frac{11}{6}}\, z$$

The theoretical velocity profiles at the three outer stations (Fig. 6) show that the depth of the surface layer increases towards the mouth (as the total circulation increases) and the maximum velocity shear coincides with the maximum gradient in the halocline. At the most seaward station the induced transport was six times larger than the original river input. These results when compared with other fiords (Rattray 1967) show similar overall features but must not be taken too literally because of the simplifications made in the model.

CONCLUSIONS

The hydrological survey of Caswell and Nancy Sounds showed them to be typical fiords with a shallow low density surface layer travelling seawards and a deeper replacement inflow of coastal water.

Water properties, particularly oxygen values, suggest that the deep water was adequately ventilated and was probably replaced during the winter (around August) at the time of maximum density in the coastal water. At the time of the survey the deep water was denser than the coastal water at sill depth and consequently was cut off from it.

Freshwater inflow was slightly lower than the yearly average based on the known flow in the Cleddau catchment and consequently was probably considerably lower than the mean summer inflow. As a result surface salinity values were higher than those found by Garner (1964) in Milford Sound.

At the time of the survey freshwater inflow into Caswell Sound was three times larger than into Nancy Sound and this was reflected in the salinity and density structure. The low salinity surface layer was more clearly defined in Caswell Sound and the resulting density stratification inhibited vertical mixing to a greater extent than in Nancy Sound. Temperature profiles reflected the difference in stratification, with Caswell Sound exhibiting a sharp temperature maximum at around 2.5 m because the inflowing fresh water was cooler than coastal water.

Theoretical velocity profiles from Rattray (1967) were derived for a simplified model of Caswell Sound and gave a picture of the circulation comparable with that found in other fiords. Further understanding of the physical processes in this fiord circulation would require measurements of velocity or vertical eddy coefficients.

ACKNOWLEDGMENTS

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REFERENCES

BATHAM, E.J. 1965 Rocky shore ecology of a southern New Zealand fiord. *Transactions of the Royal Society of N.Z. Zoology 6* : 215-27.

GARNER, D.M. 1964: The hydrology of Milford Sound. Pp 25-33 *in* Skerman, T.M. (ed.) "Studies of a Southern Fiord". *Memoir N.Z. Oceanographic Institute 17. (N.Z. Department of Scientific and Industrial Research Bulletin 157).* 101 p.

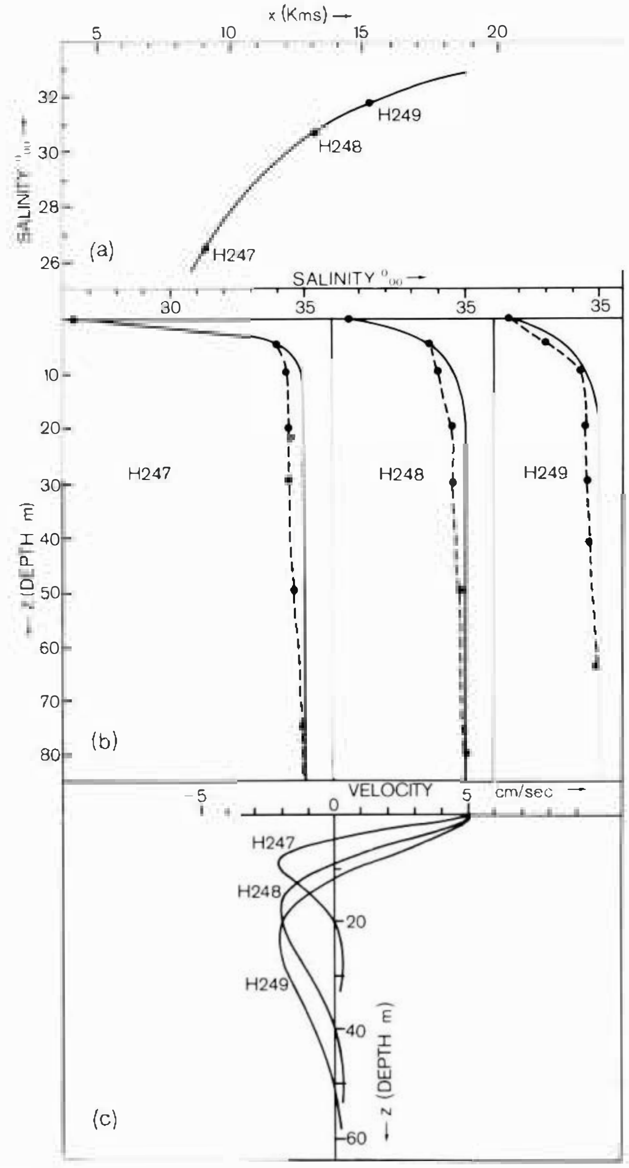

FIG. 6. A theoretical salinity and velocity field (solid lines) for Caswell Sound from the Rattray (1967) model (solid circles are observed data). For the three outer stations, (a) surface salinity, (b) salinity profiles, and (c) velocity profiles.

HANSEN, D.V.; RATTRAY, M. 1965: Gravitational circulation in straits and estuaries. *Journal of Marine Research 23* : 104-22.

HANSEN, D.V.; RATTRAY, M. 1966: New dimensions in estuary classification. *Limnology and Oceanography 11* : 319-26.

HYDROGRAPHIC OFFICE, ROYAL NEW ZEALAND NAVY, 1959: Daggs Sound to Caswell Sound 1:72,000. *Chart N.Z. 7522.*

IRWIN, J. 1973: Caswell Sound Bathymetry 1:15,840. *N.Z. Oceanographic Institute Chart, Miscellaneous Series 23.*

JILLETT, J.B.; MITCHELL, S.F. 1973: Hydrological and biological observations in Dusky Sound, south-western New Zealand. Pp 419-27 *in* Fraser, R. (comp.) "Oceanography of the South Pacific 1972". N.Z. National Commission for UNESCO, Wellington. 524 p.

NEW ZEALAND METEOROLOGICAL SERVICE, 1966: Summaries of climatological observations at New Zealand stations to 1960. *N.Z. Meteorological Service Miscellaneous Publication 122.*

NEW ZEALAND MARINE DEPARTMENT, 1971: New Zealand Tide Tables for the year 1971.

OZRETICH, R.J. 1975: Mechanisms for deep water renewal in Lake Nitinat, a permanently anoxic fjord. *Estuarine and Coastal Marine Science 3* : 189-200.

PICKARD, G.L. 1961: Oceanographic features of inlets in the British Columbian mainland coast. *Journal of the Fisheries Research Board of Canada 18* : 907-99.

PICKARD, G.L. 1963: Oceanographic characteristics of inlets of Vancouver Island, British Columbia. *Journal of the Fisheries Research Board of Canada 20* : 1109-44.

PICKARD, G.L. 1967: Some oceanographic characteristics of the larger inlets of south-eastern Alaska. *Journal of the Fisheries Research Board of Canada 24* : 1475-506.

PICKARD, G.L.; ROGERS, A.M. 1959: Current measurements in Knight Inlet, British Columbia. *Journal of the Fisheries Research Board of Canada 16* : 653-78.

RATTRAY, M. 1967: Some aspects of the dynamics of circulation in fjords. Pp 52-62 *in* Lauf. G.H. (ed.) "Estuaries." *American Association for the Advancement of Science Publication 83*: 757 p.

SAELEN, G.M. 1967: Some features of the hydrography of Norwegian fjords. Pp 63-70 *in* Lauf, G.H. (ed.) "Estuaries." *American Association for the Advancement of Science Publication 83* : 757 p.

TOEBES, C.; PALMER, B.R. 1969: Hydrological regions of New Zealand. *Miscellaneous Hydrological Publication 4*: 45 p.

CHEMICAL ANALYSIS OF FRESH WATERS FROM THE CASWELL AND NANCY SOUND AREAS

by

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ABSTRACT

Fresh waters draining into Caswell and Nancy Sounds are characterised by high SO_4^{2-}/Cl^- ratios compared to waters from other regions in New Zealand. The low Cl^- contents of the waters suggests that atmospheric transport of sea spray is not a major contributor to the waters as might have been anticipated.

DISCUSSION

Water samples were collected from Lake Marchant at the head of Caswell Sound and the river draining into Heel Cove, Nancy Sound, for chemical analysis in order to gain some indication of the chemical composition of fresh waters draining into the fiords (Table 1). The most characteristic feature of the data is the extremely high SO_4^{2-}/Cl^- ratio compared with previously reported data for rainwater, river-water and lake-waters (Hutchinson 1957; Eriksson 1960; Livingstone 1963; Lahermo 1970; Glasby and Edgerley 1974; Glasby and Main 1977).

Three factors normally influence the composition of fresh waters: atmospheric precipitation, the solution of minerals in the drainage basins, and the chemical exchange between ground waters and the surrounding media during transport of the waters.

TABLE 1. Analysis of water samples from Lake Marchant and the river draining into Heel Cove, Nancy Sound.*

	SO_4^{2-} (mg/l)	Cl^- (mg/l)
Surface water, Lake Marchant (sample collected during period of heavy rainfall)	110	2
River water, Heel Cove, Nancy Sound	140	4

* Samples analysed by Mr W.H.L. Edgerley, Chemistry Division, DSIR.

Although the data are insufficient to give any precise understanding of the origin of the fresh waters draining into Caswell and Nancy Sounds, the high SO_4^{2-}/Cl^- ratios may reflect the direct contribution of atmospheric precipitation to the lake- and river-waters, with very little exchange of anions with the natural environment. The situation could be anticipated for an open lake system (such as Lake Marchant) in a high precipitation regime where the annual rainfall exceeds 600 cm (Poole 1951) and the rate of discharge of waters from the lake is correspondingly high (Livingstone 1963; Gibbs 1970; Hem 1970). The low chloride ion content of the waters suggests a negligible contribution of atmospherically derived sea spray to the lake waters. This is somewhat surprising in view of the proximity of the lake to the coast (*see also* Mackareth 1957; Gorham 1958, 1961; Barker 1970) and the assertion of previous authors that atmospherically derived sea spray is a major contributor to precipitation processes in the coastal regions of New Zealand (Wilson 1959a, b; Miller 1961; Dean 1963; Mizutani and Rafter 1969). There is no evidence to suggest that the high SO_4^{2-} ion content of the waters is due to leaching of either sulphides or gypsum from the surrounding region (Hem 1970).

REFERENCES

BARKER, M.A. 1970: Physico-chemical features of Lake Pupuke, Auckland. *N.Z. Journal of Marine and Freshwater Research 4* : 406-30.

DEAN, G.A. 1963: The iodine content of some New Zealand drinking waters with a note on the contribution of sea spray to the iodine in rain. *N.Z. Journal of Science 6* : 208-14.

ERIKSSON, E. 1960: The yearly circulation of chloride and sulfur in nature. Meteorological, geochemical and pedological implications. Part II. *Tellus 12* : 63-109.

GIBBS, R.J. 1970: Mechanisms controlling world water chemistry. *Science, N.Y. 170* : 1088-90.

GLASBY, G.P.; EDGERLEY, W.H.L. 1974: Geochemistry of lake waters from the South Island, New Zealand. *Pacific Science 28* : 505-13.

GLASBY, G.P.; MAIN, W.deL. 1977: Some analyses of major water constituents, Lake Waikaremoana, New Zealand. *NZOI Records 3(6)* : 41-52.

GORHAM, E. 1958: The influence and importance of daily weather conditions in the supply of chloride and sulphate and other ions to fresh waters from atmospheric precipitations. *Philosophical Transactions of the Royal Society of London 241B* : 147-78.

GORHAM, E. 1961: Factors influencing supply, of major ions to inland waters, with special reference to the atmosphere. *Bulletin of the Geological Society of America 72* : 795-840.

HEM, J.D. 1970: Study and interpretation of the chemical characteristics of natural water. *U.S. Geological Survey Water-supply Paper 1473* : 1-362.

HUTCHINSON, G.E. 1957: "A Treatise on Limnology." Vol. 1. John Wiley, New York. 1015p.

LAHERMO, P. 1970: Chemical geology of the ground and surface waters in Finnish Lapland. *Bulletin de la Commission Geologique de Finlande 242* : 1-106.

LIVINGSTONE, D.A. 1963: Chemical composition of rivers and lakes. *U.S. Geological Survey Professional Paper 440G* : 61 p.

MACKARETH, F.J.H. 1957: Chemical analysis in ecology illustrated from Lake District farms and lakes. 1. Chemical analysis. *Proceedings of the Linnean Society of London 167* : 159-64.

MILLER, R.B. 1961: The chemical composition of rainwater at Taita, New Zealand, 1956-1958. *N.Z. Journal of Science 4* : 844-53.

MIZUTANI, Y.; RAFTER, T.A. 1969: Oxygen isotopic composition of sulphates. 5. Isotopic composition of sulphate in rain water, Gracefield, New Zealand. *N.Z. Journal of Science 12* : 69-80.

POOLE, A.L. (comp.) 1951: Preliminary reports of the New Zealand-American Fiordland Expedition investigations in Fiordland, New Zealand in 1949. *N.Z. Department of Scientific and Industrial Research Bulletin 103* : 99 p.

WILSON, A.T. 1959a: Organic nitrogen in New Zealand snows. *Nature, London 183* : 318-9.

WILSON, A.T. 1959b Surface of the ocean as a source of airborne nitrogenous material and other plant nutrients. *Nature, London 184* : 99-109.

BENTHIC ECOLOGY OF CASWELL AND NANCY SOUNDS

by

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ABSTRACT

Benthic infaunas from grab, trawl, and camera samplings in Caswell, Nancy and Milford Sounds are described. In shallower waters (above about 200 m) of Caswell and Nancy Sounds, a distinctive fauna characterised by *Nemocardium pulchellum*, *Amphiura* spp., and *Echinocardium cordatum* is present and is considered referable to the "*Nemocardium pulchellum - Dosinia lambata*" community (McKnight 1969). In deeper waters of Caswell Sound another fauna, characterised by *Psilaster*, *Trichopeltarion*, *Hyalinoecia*, *Lucinoma* and *Fissidentalium* is present and is referred to the "*Neilo australis - Brissopsis oldhami*" community (McKnight 1969). The deepest samples in Nancy Sound, 252 and 256 m, contained an infauna intermediate between the above two. In addition, an epifaunal community dominated by *Madrepora* was found in Caswell Sound. Differences between samples from Caswell and Nancy Sounds and other Fiordland localities previously described suggest the variation between samples even in the same fiord may be quite marked, and also that each fiord may support its own distinctive benthic fauna.

INTRODUCTION

The Fiordland region of south-western New Zealand exhibits a physiography not found elsewhere in the country. The benthic fauna of the Fiordland region has been discussed by Fleming (1950) and Fell (1952), and also by Hurley (1964) for Milford Sound and McKnight (1969) for Preservation and Chalky Inlets. In addition, McKnight (1969) has discussed some of the faunal communities of Fleming (1950) and Hurley (1964).

Samples of benthic fauna were collected with a small orange-peel grab, of surface area approximately 0.2 m^2, and with a small Agassiz trawl, which had a mouth width of approximately 0.9 m. Eleven grab samples and six trawl samples were obtained during the survey. Of the grab samples, five were from Caswell Sound and six from Nancy Sound; while three trawls were made in Caswell Sound, two in Nancy Sound and one in Milford Sound. Underwater photographs were taken with the camera system described by Singleton and Cole (1972). Each photograph shows an area of 0.36 m^2 of the bottom, the length of each side being 60 cm. Station positions and details are given in the Appendix and summarised in Fig. 1.

SAMPLING RESULTS

CASWELL SOUND

Grab samples were taken at the following depths : 37 m (2), 150 m (1), 205 m (1), 405 m (1).

At 37 m (Stns H224, H242) the fauna varied slightly in the two samples, but both show the same general assemblage. Echinoderms present were *Amphiura rosea* and *Echinocardium cordatum*; numerically dominant bivalves were *Nemocardium pulchellum* or *Nuculana bellula* (live). Other bivalves represented were *Divaricella huttoniana*, *Dosinula zelandica*, *Neilo australis* (live), *Notocallista multistriata*, *Thyasira peroniana*, and *Pleuromeris zelandica*. The gastropod *Zeacolpus delli* was also present. Polychaetes were represented by *Notomastus latericeus*, *Aglaophomus verrilli*, maldanids, and empty tubes of *Phyllochaetopterus* sp. In addition a single valve of the epifaunal bivalve *Chlamys* sp. was present.

Echinoderms were absent from the grab sample at 150 m (Stn H218). *Nemocardium* was the dominant bivalve with *Nucula hartvigiana* subdominant. *Linnucula gallinacea* and *Thyasira* were also present,

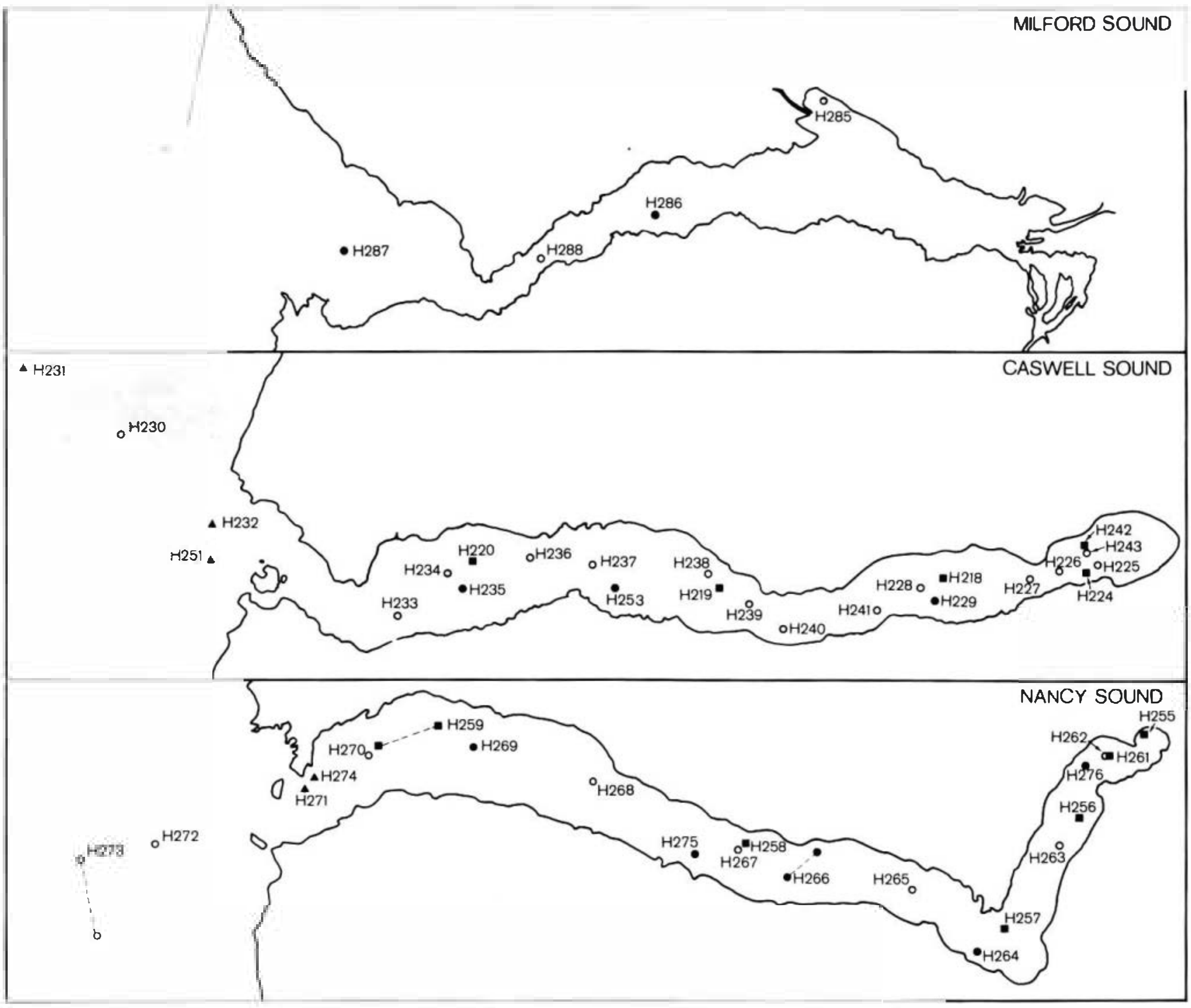

FIG. 1. Schematic diagram showing positions of biology stations in Caswell, Nancy and Milford Sounds.

as were the scaphopods *Cadulus delicatus* (numerically subdominant) and *Dentalium nanum*, and the gastropod *Uberella denticulifera*. Polychaetes present were *Aglaophomus verrilli* and maldanids. The underwater photograph (Fig. 2) shows pits or burrows up to 4 cm across, rather larger than would be expected of the animals taken in the grab. Their appearance suggests formation by a burrowing crustacean.

At 205 m (Stn H219) the grab sample contained *Echinocardium* fragments, the bivalves *Nemocardium* (dominant), *Nucula, Neilo*, and fragments of *Cuspidaria* sp.; the scaphopods *Cadulus* (subdominant) and *Dentalium*, the gastropod *Uberella*, and a valve of *Chlamys* sp. Polychaetes were represented by *Notomastus*, ?*Heteromastus* sp., *Heterospio* sp., and *Lumbrineris* spp. In addition a small fragment of the coral *Madrepora vitiae* was collected. The underwater photographs (Figs 3-5) show many small surface traces of the burrowing animals found in the grab. The origin of the linear markings in Fig. 3 is unknown. The occupant of the large burrow in Fig. 4 and the coelenterate with encrusting organisms in Fig. 5 were not represented in the grab haul.

At 410 m (Stn H220) the grab sample contained fragmentary *Echinocardium* and spines of the temnopleurid *Pseudechinus albocinctus*; bivalves present were *Maorithyas marama* (dominant), *Nemocardium* and *Lucinoma galatheae* (live). Also present were the scaphopod *Fissidentalium zealandicum* and the polychaetes *Lysilla* sp. and *Marphysa disjuncta*.

Trawl samples were taken at 146 m, 271 m, and 405 m.

At 146 m (Stn H223) the trawl contained the ophiuroid *Amphiura correcta; Nemocardium;* a small fragment

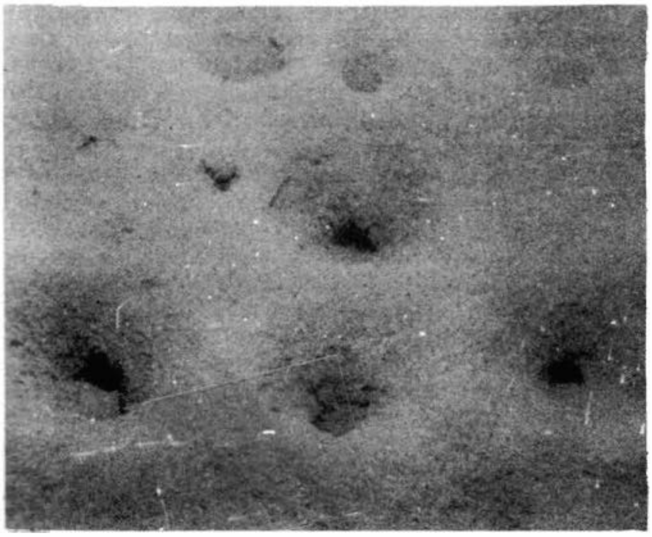

FIG. 2. Underwater photograph NZOI Stn H218, depth 150 m, Caswell Sound. Soft blackish mud with pits and burrows up to 4 cm across.

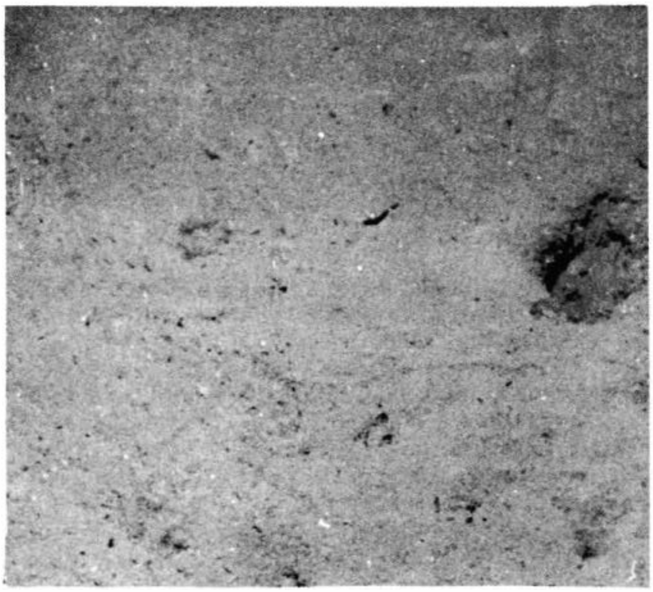

FIG. 4. Underwater photograph NZOI Stn H219, depth 205 m, Caswell Sound. Muddy sand with large burrow on the right.

FIG. 3. Underwater photograph NZOI Stn H219, depth 205 m, Caswell Sound. Muddy sand. Linear markings of unknown origin.

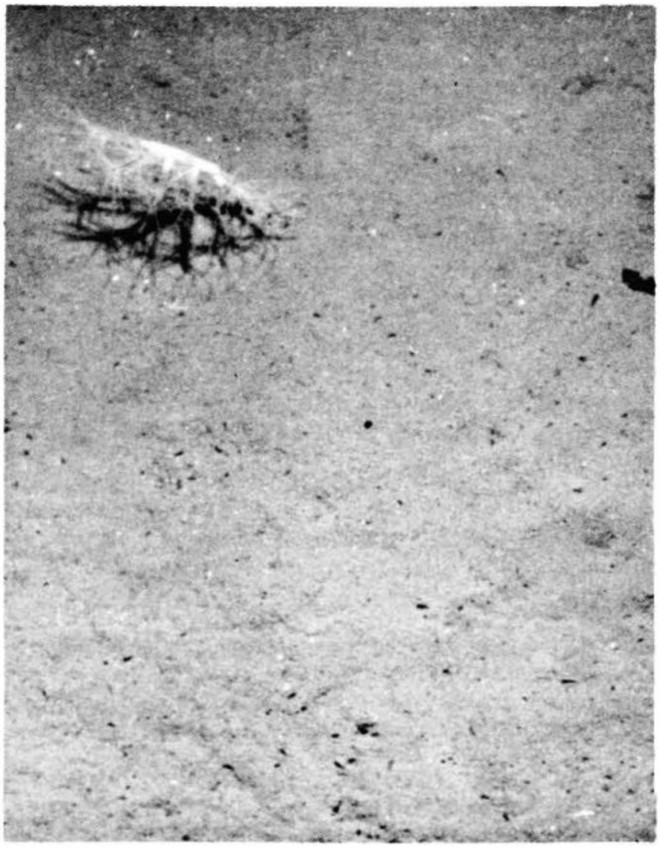

FIG. 5. Underwater photograph NZOI Stn H219, depth 205 m, Caswell Sound. Muddy sand, also coelenterate with encrusting organisms.

of *Madrepora;* the polychaetes *Asychis trifilosa, A. theodori, Glycera americana, Cirriformia anchylochaeta* and *?Nicomache* sp.; and some spionids.

At 271 m (Stn H222) there were no echinoderms present in the trawl, which took the molluscs *Nemocardium* (dominant, live), *Neilo, Fissidentalium* (live), *Cominella nassoides*, and *Zeatrophon ambiguus*; the polychaete *Hylinoecia tubicola*; a small branching bryozoan; a small fragment of a sponge; a large pennatulacean; a large amount of *Madrepora*; and the brachyuran *Trichopeltarion fantasticum*.

At 405 m (Stn H221) the trawl contained the asteroid *Psilaster acuminatus, Echinocardium, Trichopeltarian, Fissidentalium* (live, dominant), *Neilo, Maorithyas*, and *Hylinoecia*, also *Archeopsis* sp. (Brachyura) and *Eunice australis* (Polychaeta).

NANCY SOUND

Grab samples were taken at 18 m, 64 m, 89 m, 102 m, 204 m, and 252 m.

At 18 m (Stn H255) the grab sample contained *Echinocardium, Amphiura rosea*, and two species of holothurians. The bivalve fauna contained *Divaricella* (dominant, live), *Notocallista* (live), *Dosinula* (live), *Nemocardium, Lucinoma, Dosinia greyi, Leptomya retiaria, Tellinella huttoni* (live), *Thracia vitrea* (live), *Myadora antipodum*, and fragments of the epifaunal *Pecten novaezealandiae*. Gastropods present were *Maoricolpus roseus* and *Trochus viridis*. The polychaetes obtained were *Notomastus. Lumbrinereis brevicirra, ?Nicomache* sp., and empty tubes of *Phyllochaetopterus* sp.

At 64 m (Stn H261) only a nemertine worm and the following molluscs were present : *Nemocardium* (dominant), *Nucula, Linnucula* (live), *Pleuromeris, Thyasira, Divaricella*, and *Zeacolpus*.

At 89 m (Stn H256) the polychaete *Marphysa disjuncta* and five molluscs were present : *Nemocardium* (dominant), *Tellinella, Myadora, Cadulus*, and *Austrofusus glans*.

At 102 m (Stn H257) polychaetes were not obtained; the sample contained *Echinocardium, Nemocardium* (dominant, live), *Lucinoma* (live), *Dentalium, Cadulus*, and *Uberella*.

At 204 m (Stn H258) an isopod and capittelid worms were present with the molluscs *Thyasira, Lucinoma* (live), *Maorithyas, Cadulus, Dentalium* (dominant), and *Cominella adspersa*.

At 252 m (Stn H259) the molluscan fauna contained *Dentalium* (dominant), *Cadulus, Nemocardium, Nucula, Neilo*, and a turrid; polychaetes present were *Aglaophomus verrilli, Eunice vittata, Diplocirrus* sp., *Marphysa disjuncta*, and *Terebellides stroemi*. Also present were a sipunculid and empty pogonophoran tubes. The underwater photograph (Fig. 6) shows many small burrows and also projecting tubes approximately 2 mm in diameter. As the polychaetes in the grab sample were all larger, the tubes are probably those of pogonophora, although the clean tubes in the grab sample were only 1 mm in diameter.

Trawl samples were taken at 100 m and 256 m.

At 100 m (Stn H260) the trawl contained the molluscs *Nemocardium* (live), *Lucinoma* (live), *Dosinula, Cuspidaria* (fragments), *Dentalium, Cadulus, Cominella*, and *Poirieria zelandica*; the polychaetes *Hyalinoecia, Eunice, ?Mystides* sp., and *Phyllochaetopteris* sp.; the ophiuroids *Amphiura correcta* (dominant) and *A. rosea*; a large pennatulacean, a gorgonid; and the crustaceans *Munida* sp. and *Leptomithrax longipes*.

At 256 m (Stn H259) the trawl contained *Nemocardium* (dominant), *Dosinula, Dentalium, Maoricolpus, Cominella, Zeatrophon, Amphiura correcta, Trichopeltarian*, and a pagurid.

MILFORD SOUND

The sole trawl, in 278 m (Stn H284), contained *Nemocardium* (live, dominant), *Lucinoma* (live), *Munida* sp., ascidians, and the macrourid fish *Coelorhynchus oliverianus*.

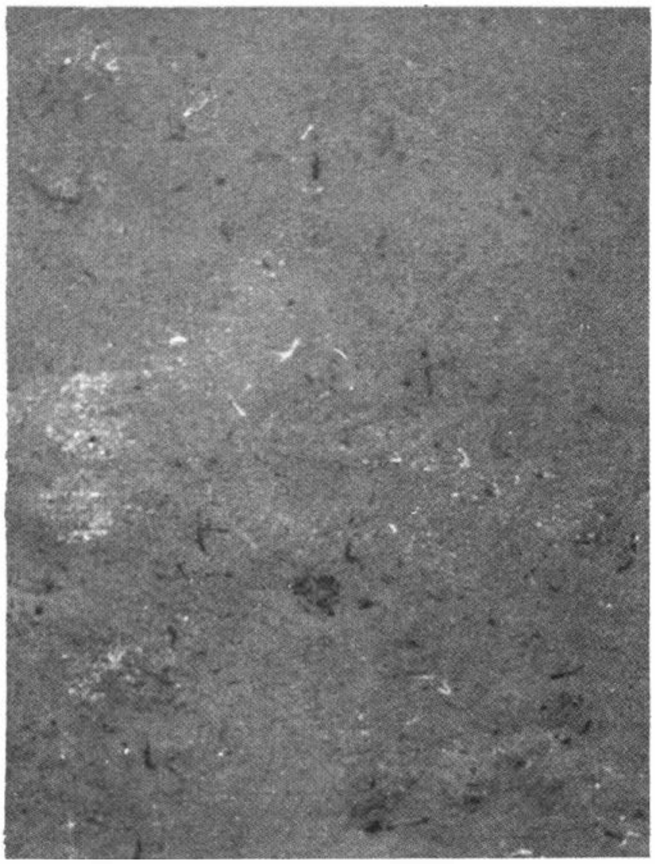

FIG. 6. Underwater photograph NZOI Stn H259 depth 252 m, Nancy Sound. Fine muddy sand.

DISCUSSION

In Caswell Sound, the fauna in each sample show clear similarities. *Nemocardium* is either dominant or subdominant in all, and *Echinocardium* occurs in all but one sample. In this respect the entire fauna could be considered a single community. However, there are noticeable differences in the composition of the samples - *Nuculana* and *Amphiura rosea* occur only at 37 m; *Cadulus* is subdominant between 146 m and 205 m; and *Fissidentalium* occurs only between 271 m and 410 m. Similar differences are apparent in the distribution of the polychaetes : of four species recorded from 37 m, two also occur at 146 m to 150 m (where seven additional species are present), but do not occur in deeper samples (which contain three other species). Notably distinctive species of the deeper waters (271-400 m) are *Fissidentalium, Maorithyas, Lucinoma, Hyalinoecia, Trichopeltarion*, and *Psilaster*. These samples appear to be a development of the "*Neilo australis - Brissopsis oldhami*" community (McKnight 1968, 1969) previously described from the Fiordland and southern Cook Strait regions, although *Brissopsis* and *Ophiuroglypha irrorata* are not present in the samples and *Neilo* is not dominant. Distinctive species in the shallower samples are *Nemocardium, Amphiura* spp., *Nuculana, Nucla*, and *Cadulus*. These samples appear to be from the "*Nemocardium pulchellum-Dosina lambata*" community (McKnight 1969) previously recorded from Fiordland and other localities.

At 271 m (Stn H222) a separate epifaunal community was sampled. This included small amounts of sponge and bryozoa but was dominated by the branching coral *Madrepora vitiae*.

A fauna similar to that of the shallower parts of Caswell Sound can be recognised in Nancy Sound. Samples from depths of 102 m or less have molluscan fauna dominated by *Nemocardium* with *Echinocardium* and *Amphiura* spp. present. Below 200 m the dominant mollusc was *Dentalium* with *Cadulus* also present. Samples were not obtained from depths greater than 256 m and the only distinctive member of the deeper water fauna of Caswell Sound present was the crab *Trichopeltarion*. The sample in which this species occurred (Stn H259) had a molluscan fauna dominated by *Nemocardium*, but it was taken by the trawl and is not comparable with the grab samples. Nancy Sound shallow samples appear referable to the "*Nemocardium pulchellum - Dosinia lambata*" community (McKnight 1969), as for the shallower samples from Caswell Sound.

There are distinct differences between samples from one fiord and between samples from both fiords. While a correlation with depth is evident in both fiords, the samples are limited both in number and size and differences between them should not be accorded too great a significance. The most noticeable correlation with depth appears to be the replacement of *Nemocardium* as dominant by the scaphopods *Cadulus* or *Dentalium* below about 200 m. The deeper fauna from Caswell Sound is similar to that from Preservation and Chalky Inlets in depths of 177 m to 367 m and partially unites this fauna and the "*Nemocardium pulchellum - Dosinia lambata*" community. However, some characteristic species - notably *Brissopsis* and *Ophiuroglypha* - are not recorded from Caswell Sound. Similarly, in the shallower water, *Dosinia lambata* is not present in Caswell or Nancy Sounds although quite common in Milford Sound (Hurley 1964). Such differences indicate the need for a greaterrange of comparable samples from the various fiords, so that this variability can be more closely examined. If periodic overturn of Fiordland waters does occur (Garner 1964; Hurley 1964), then the bottom faunas may be characterised by the larvae present immediately after the overturn, assuming the larvae survive. Each fiord has a particular physiography, in which the sill depth, bottom topography, freshwater input, and fauna inter-relate to determine the physical and biological environment. The overturn cycle of any one fiord may bear no relationship to that of another and hence the faunas sampled at any time may be expected to show some differences.

REFERENCES

FELL, H.B. 1952: Echinoderms from southern New Zealand. *Zoology Publications from Victoria University College 18* : 1-37.

FLEMING, C.A. 1950: The molluscan fauna of the fiords of western Southland. (A report of the New Golden Hind Expedition 1946). *N.Z. Journal of Science and Technology B31* : 20-40.

GARNER, D.M. 1964: The hydrology of Milford Sound. Pp 25-33 *in* Skerman, T.M. (ed.) "Studies of a Southern Fiord". *Memoir N.Z. Oceanographic Institute 17. (N.Z. Department of Scientific and Industrial Research Bulletin 157).* 101 p.

HURLEY, D.E. 1964: Benthic ecology of Milford Sound. Pp 79-89 *in* Skerman, T.M. (ed.) "Studies of a Southern Fiord". *Memoir N.Z. Oceanographic Institute 17. (N.Z. Department of Scientific and Industrial Research Bulletin 157).* 101 p.

HYDROGRAPHIC OFFICE, ROYAL NEW ZEALAND NAVY, 1959: Daggs Sound to Caswell Sound 1:72,000. *Chart N.Z. 7522.*

IRWIN, J. 1973: Caswell Sound Bathymetry 1:15,840. *N.Z. Oceanographic Institute Chart, Miscellaneous Series 23.*

IRWIN, J. 1974: Nancy Sound Bathymetry 1:15,840. *N.Z. Oceanographic Institute Chart, Miscellaneous Series 24.*

McKNIGHT, D.G. 1968: Features of the benthic ecology of Chalky and Preservation Inlets. *N.Z. Journal of Marine and Freshwater Research 2* : 716-20.

McKNIGHT, D.G. 1969: Infaunal benthic communities of the New Zealand continental shelf. *N.Z. Journal of Marine* *and Freshwater Research 3* : 409-44.

SINGLETON, R.J.; COLE, A.G. 1972: An underwater camera system for deep sea bottom photography. *N.Z. Journal of Marine and Freshwater Research 6* : 185-92.

APPENDIX. Summary of Station Data for the Southern Fiords Cruise, 26 January - 8 February 1971. U.W. - underwater, GHO - orange peel grab, TAS - small Agassiz trawl.

NZOI Stn No.	POSITION *		Sampling Equipment	Depth (m)	Remarks
	Latitude (°S)	Longitude (°E)			
Caswell Sound					
H218	45 01.82'	167 18.0'	U.W. camera	150	U.W. camera. 4 frames.
			Grab		GHO. Soft blackish mud, humus-like. Wood, leaves. Little life : 1 polychaete, *Nemocardium* valves. No H_2S smell.
H219	45 01.05'	167 14.73'	U.W. camera	205	U.W. camera. 4 frames.
			Grab		GHO. Muddy sand, wood, leaves, polychaetes, scaphopods, *Chlamys, Nemocardium, Neilo*. No H_2S smell.
H220	44 58.88'	167 11.44'	U.W. camera	410	U.W. camera. 4 frames.
			Grab		GHO. Muddy sand, finer than H219. Much wood and leaves. Bivalves, scaphopods, spatangoid fragments, *Pseudechinus* spines.
H221	44 59.95'	167 11.4'	Trawl	410	TAS. Large amount of woody material and leaves. Dead *Neilo* and other bivalves, spatangoid fragments, *Psilaster, Trichopeltarion, Archaeopsis*.
H222	45 01.00'	167 14.5'	Trawl	271	TAS. Wood and leaves, worms including *Hyalinoecia, Neilo, Nemocardium, Trichopeltarion*.
H223	45 01.90'	167 17.76'	Trawl	146	TAS. Wood and leaves. Shell, amphiurids.
H224	45 02.3'	167 20.05'	U.W. camera	37	U.W. camera. 4 or 5 frames.
			Grab		GHO. Blackish muddy sand with mica flakes. Wood and leaves. Worms, bivalve fragments, amphiurid.
			Trawl		TAS. Nil.
H225	45 02.28'	167 20.25'	Foram core	30	Organic-rich black sandy mud with overlying white surface sand layer.
H226	45 02.15'	167 19.65'	Foram core	40	Black organic-rich sandy mud.
H227	45 02.12'	167 19.2'	Foram core	47	Black organic-rich muddy sand containing white sand fragments.
H228	45 01.82'	167 17.65'	Foram core	148	Black organic-rich mud. Marked smell of H_2S.
H229	45 02.01'	167 17.75'	Piston core	148	456 cm core of organic-rich mud.
			Foram core		Black organic-rich mud. Strong smell H_2S.
H230	44 57.2'	167 07.3'	Foram core	329	No sample. Very steep topography.
H231	44 56.2'	167 06.2'	Pipe dredge	580-610	Very steep topography. Grey muddy sand. Gravel size fragments of eroded metamorphics collected on washing through cheese cloth.
H232	44 58.5'	167 08.05'	Dredge	69-62	Coarse shelly sandy gravel.
H233	45 00.1'	167 10.16'	Foram core	384	Black organic-rich sandy mud. Rugged topography.
H234	44 59.88'	167 11.05'	Foram core	413	Black organic-rich mud. Smooth basin topography.
H235	45 00.1'	167 11.19'	Piston core	402	116 cm core black organic-rich mud overlying whitish sand layer.
			Foram core		Black mud very rich in organic matter.

* Station positions are relative to the only available navigation chart for the region (Hydrographic Office, Chart N. Z. 7522). Latitudes and longitudes of the fiords on this chart differ from those obtained during more recent surveys. Station positions recorded here are therefore *not* corrected relative to the NZOI bathymetric chart produced as a result of this study (Irwin 1973, 1974).

NZOI	POSITION				
Stn No.	Latitude (°S)	Longitude (°E)	Sampling Equipment	Depth (m)	Remarks
H236	45 00.02'	167 12.26'	Foram core	411	Black organic-rich sandy mud. Thin surface layer (1 cm) of lighter brown sediment.
H237	45 00.35'	167 13.1'	Foram core	369	Grey organic-rich mud. Rugged topography.
H238	45 00.87'	167 14.07'	Foram core	315	Black organic-rich mud containing whitish sand sized particles.
H239	45 01.30'	167 15.1'	Foram core	154	Black organic-rich mud containing whitish sand sized particles.
H240	45 01.71'	167 15.5'	Foram core	95	Hard bottom. Small pebbles and plant debris.
H241	45 01.9'	167 16.87'	Foram core	90	Dark grey muddy sand.
H242	45 02.02'	167 20.15'	Grab	37	GHO. Soft blackish muddy sand. Much wood and leaves. Worms, small bivalves including *Neilo, Nemocardium,* amphiurid.
H243	45 02.1'	167 20.18'	Foram core	37	Black organic-rich sandy mud. Plant material.
H244	45 02.1'	167 20.18'	Hydrology	37	Depths 0, 5, 10, 20, 30 m.
H245	45 02.12'	167 18.48'	Hydrology	110	Depths 0, 5, 10, 20, 30, 50, 75, 100 m.
H246	45 01.75'	167 16.10'	Hydrology	132	Depths 0, 5, 10, 20, 30, 50, 75, 100, 125 m.
H247	45 00.78'	167 14.19'	Hydrology	324	Depths 0, 5, 10, 20, 30, 50, 75, 100, 150, 200, 300 m.
H248	44 59.87'	167 11.34'	Hydrology	406	Depths 0, 5, 10, 20, 30, 50, 75, 100, 150, 200, 300, 400 m.
H249	44 59.99'	167 09.75'	Hydrology	336	Depths 0, 5, 10, 20, 30, 50, 75, 100, 150, 200, 300 m.
H250	44 58.26'	167 07.91'	Hydrology	126	Depths 0, 30, 70 m.
H251	44 58.88'	167 07.86'	Dredge	68-66	Green shelly sand.
H252	44 58.47'	167 06.95'	Hydrology	175	Depths 0, 25, 50, 75, 100 m.
H253	45 00.65'	167 13.79'	Piston core	337	498 cm core black organic-rich mud. Core badly slurried in middle.
			Foram core		Black-organic rich mud. Smell of H_2S.
H254	Shore collection, head of Caswell Sound				Whitish sand.
Nancy Sound					
H255	45 10.6'	167 09.1'	U.W. camera	18	U.W. camera. 4 frames.
			Grab		GHO. Fine black sand and a little mud. Broken shell, wood, ascidian, polychaetes, *Notocallista, Tawera, Divaricella, Pecten* fragment, *Echinocardium.*
H256	45 10.65'	167 07.9'	U.W. camera	39	U.W. camera. 3 frames.
			Grab		GHO. Sandy mud. Strong H_2S smell. Much wood, one polychaete, small dead shells.
H257	45 10.94'	167 06.44'	U.W. camera	102	U.W. camera. 4 frames.
			Grab		GHO. Fine muddy sand. Much wood. Dead bivalves, one amphiurid.
H258	45 09.03'	167 04.93'	U.W. camera	196	U.W. camera. 4 frames.
	45 09.08'	167 04.85'	Grab	204	GHO. Muddy sand. Much wood including some large pieces. H_2S smell.
H259	45 06.50'	167 02.55'	U.W. camera	252	U.W. camera. 4 frames.
			Grab		GHO. Fine muddy greyish sand with black streaks. A few shells, no wood.
	45 06.64'	167 03.2'	Trawl	256	TAS. Small haul, wood and leaves, scaphopod. *Nemocardium, Trichopeltarion, Evechinus* fragment.

NZOI Stn No.	POSITION Latitude (°S)	Longitude (°E)	Sampling Equipment	Depth (m)	Remarks
H260	45 10.95'	167 06.4'	Trawl	100	TAS. Mainly wood and leaves. Bright orange pennatulid, scaphopod, thyasirid, *Neilo*, holothurian.
H261	45 10.42'	167 08.64'	Grab	64	GHO. Black smelly muddy sand. Little biological material.
H262	45 10.42'	167 08.60'	Foram core	35	Black organic-rich mud containing small whitish sand sized particles.
H263	45 10.7'	167 07.5'	Foram core	88	Black organic-rich mud. Some partly undecomposed plant material. Strong smell H_2S.
H264	45 10.91'	167 06.3'	Piston core	99	502 cm core black organic-rich mud.
			Foram core		Black organic-rich mud containing some partly undecomposed plant material. Smell H_2S.
H265	45 10.2'	167 06.0'	Foram core	110	Black organic-rich mud. White sand sized particles.
H266	(45 09.5' (45 09.45'	167 05.46' 167 05.05'	Piston core	201	531 cm core black mud. Lost top 10 cm.
			Foram core		Black organic-rich mud. Strong smell H_2S. Black surface staining (pyrite?).
H267	45 09.05'	167 04.80	Foram core	205	Black organic-rich sandy mud. No smell.
H268	45 07.85'	167 04.1'	Foram core	261	Black organic-rich mud. Very faint smell H_2S.
H269	45 06.98'	167 03.35'	Piston core	271	500 cm core black mud. Lost top 10 cm. Strong smell H_2S.
			Foram core		Black organic-rich mud.
H270	45 06.5'	167 02.4'	Foram core	267	Dark grey muddy sand with light brown surface layer.
H271	(45 06.32' (45 06.32'	167 01.58' 167 01.41'	Dredge	86-67	Very small sample of sand with coral. Steep topography.
H272	45 05.85'	167 00.0'	Foram core	614	Small sample. Rocky bottom. Steep topography.
H273	(45 05.55' (45 06.10'	166 59.2' 166 58.8'	Foram core	980	No sample.
			Dredge	764-761	No sample.
H274	45 06.3'	167 01.75'	Dredge	95	Shelly sand. No sample collected.
H275	45 08.4'	167 04.4'	Piston core	199	492 cm core black organic-rich mud. Decaying plant material at base of core. Slurrying.
			Foram core		Black organic-rich mud. Smell H_2S.
H276	45 10.4'	167 08.35'	Piston core	44	500 cm core very badly slurried. Containing high proportion of sand sized material.
			Foram core		Black organic-rich mud.
H277	45 11.29'	167 06.46'	Hydrology	90	Depths 0, 10, 20, 30, 50, 75 m.
H278	45 05.9'	167 00.0'	Hydrology	1097	Depths 0, 10, 20, 30, 50, 100, 200 m.
H279	45 06.43'	167 01.89'	Hydrology	201	Depths 0, 5, 10, 30, 60, 100, 150 m.
H280	45 09.4'	167 05.1'	Hydrology	203	Depths 0, 5, 10, 30, 60, 100, 150 m. Secchi disc. Disappearance 7 m. Overcast. Rain. Rippled surface.
H281	45 07.88'	167 04.1'	Hydrology	117	Depths 0, 5, 10, 20, 30, 50, 75 m. Secchi disc. Disappearance 8 m. Overcast. Light rain. Smooth surface in wake of ship. Rough sea.
H282	45 10.38'	167 08.62'	Hydrology	42	Depths 0, 5, 10, 20, 35 m. Secchi disc. Disappearance 9 m. Calm. Overcast. Mirror surface in shadow.
Milford Sound					
H283	44 36.99'	167 51.91'	Hydrology	281	Depths 0, 5, 10, 20, 30, 50, 100, 150, 200 m.
H284	44 38.08'	167 53.7'	Trawl	278	TAS. Small haul, wood and leaves. ***Nemocardium***, one other bivalve, ***Munida***, one rattail.

NZOI Stn No.	POSITION Latitude (°S)	Longitude (°E)	Sampling Equipment	Depth (m)	Remarks
H285	44 37.72'	167 54.95'	Foram core	70	Dark grey sandy mud.
H286	44 37.05'	167 51.86'	Piston core	297	449 cm core. Dark grey sandy mud.
			Foram core		Dark grey mud with sand. Light brown muddy surface layer.
H287	44 34.65'	167 48.26'	Piston core	124	437 cm core. Dark grey sandy mud.
			Foram core		Dark sandy mud with brown muddy surface layer.
H288	44 36.4'	167 50.1'	Foram core	132	Grey sandy mud. Light brown surface muddy layer.