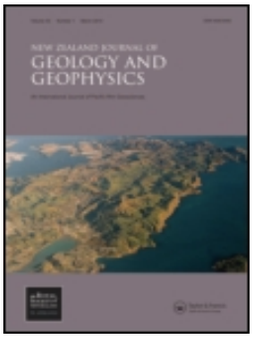

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Tidal asymmetry on the New Zealand coast and its implications for the net transport of sediment

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Abstract Available tidal observations indicate a significant asymmetry in the tide around northernmost New Zealand and in Cook and Foveaux Straits. However only around northernmost New Zealand does the tidal asymmetry dominate the time-averaged mean flow and determine the direction of peak flow; there the tidal asymmetry may have a strong influence on the present development of Pandora Bank.

The relatively large M_4/M_2 tidal elevations in Cook Strait lead to significant tidal asymmetry in the Marlborough Sounds, with the ebb speeds exceeding the flood, and they play an important role in determining the direction of net bedload sediment transport.

Keywords tidal asymmetry; sediment movement; North Cape; Foveaux Strait; Cook Strait; Marlborough Sounds

INTRODUCTION

Tidal elevations and flows commonly are not symmetrical with respect to time; the time interval from high to low tide differs from that between low and high tide, and the time intervals for ebb and flood tidal flows also differ. This tidal asymmetry is illustrated here by tidal flow records from Pelorus Sound, which is situated at the northern end of the South Island (Fig. 1). The time interval from high to low tidal elevation is shorter than from low to high tidal elevation in Pelorus Sound and, consequently, although the net tidal flow is zero over a tidal cycle, the ebb tidal flow is faster than the flood (Fig. 1).

Asymmetry in the tides results from the superposition of overtides (or compound tides) on the fundamental tides. The fundamental tides arise directly from the gravitational forcing from the moon and sun, whereas the overtides arise from non-linear effects on the fundamental tides.

When asymmetrical tidal flows are present, any process which depends non-linearly on the water speed, or has a speed threshold of operation, may have a non-zero mean when averaged over a tidal cycle, even though the mean flow may be zero. Bedload transport of sediment is subject to both these criteria: a threshold speed before movement is initiated, and dependence on a bottom stress which itself has a non-linear dependence on the water speed.

The importance of tidal asymmetry in determining the net sediment bedload transport has been emphasised for the United Kingdom continental shelf (Stride 1963, 1973; Pingree & Griffiths 1979).

In the first section of this paper the available information on the M_4 (the overtide of the principal lunar semidiurnal tide, M_2, which is the largest tidal component around New Zealand) tidal elevations and flows around New Zealand is presented to allow areas with significant M_4 tides to be distinguished. The implications in terms of potential of the M_4 tide to determine the direction of sediment movement are then discussed.

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THE OBSERVED M_4 TIDAL ELEVATIONS AROUND NEW ZEALAND

Elevation amplitudes and phases of the M_2 and M_4 tide on the New Zealand coast are listed in Table 1; these harmonic constants were kindly provided by the Hydrographic Branch, Royal New Zealand Navy. The M_2 and M_4 tidal elevations are given by $A \cos(\omega t - \theta)$ and $B \cos(2\omega t - \phi)$ respectively, A, B the amplitudes, θ, ϕ the phase, with ω the M_2 tidal frequency.

Departures of the composite M_2 and M_4 tide time interval from high to low tide from the 6.2 h associated with the M_2 tide alone have been calculated for various values of B/A and $\phi - 2\theta$ (Fig. 2). Values of B/A and $\phi - 2\theta$ for New Zealand coastal observations have been plotted on Fig. 2.

Amongst the published harmonic constants, only in coastal inlets and in Cook Strait does the M_4 tidal elevation lead to significant asymmetry in the time difference between peak elevations. Unpublished tidal elevation observations from Te Hapua, immediately south of North Cape, made in January and February 1978 have a M_4/M_2 tidal elevation ratio of 5% with a phase ($M_4 - 2xM_2$) of 132° indicative of significant asymmetry (Fig. 2) also near North Cape.

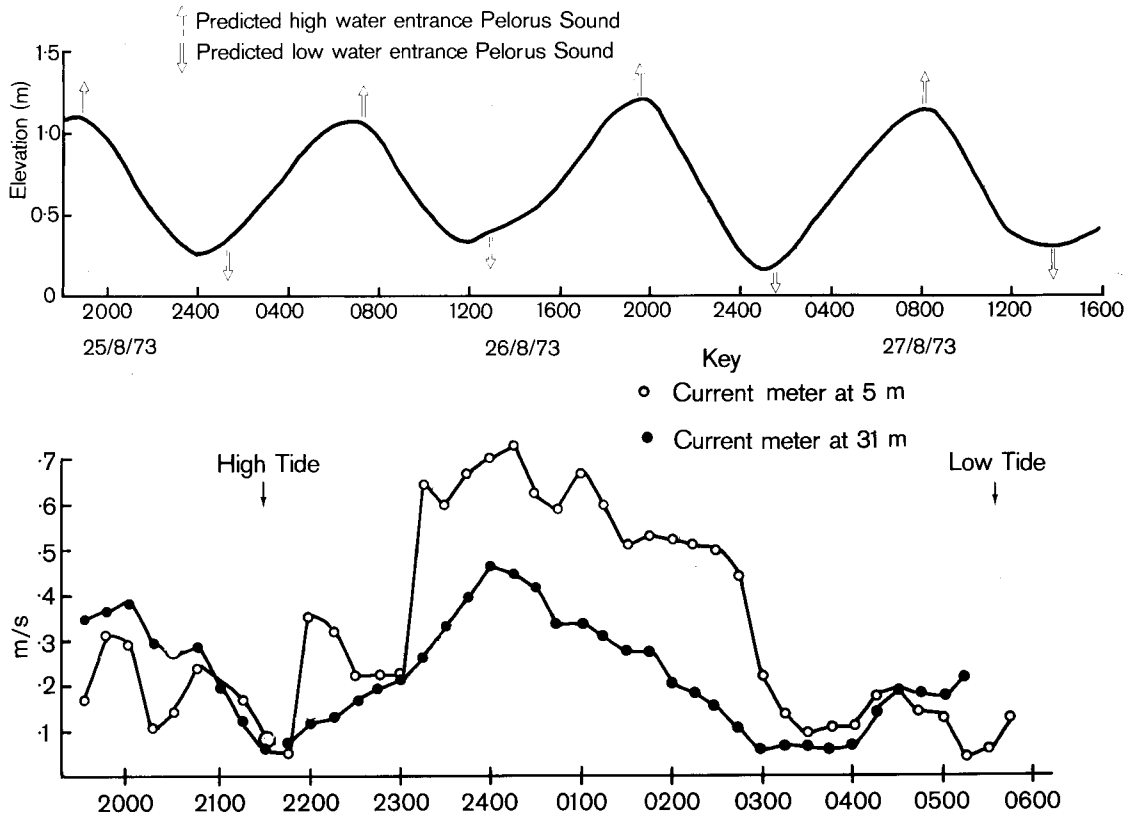

Fig. 1 Tidal elevation in Beatrix Bay, Pelorus Sound (after Heath 1974, fig. 7) and current velocity components in Pelorus Sound at position 41°07.15′S, 173°53.61′E (after Heath 1976, fig. 5).

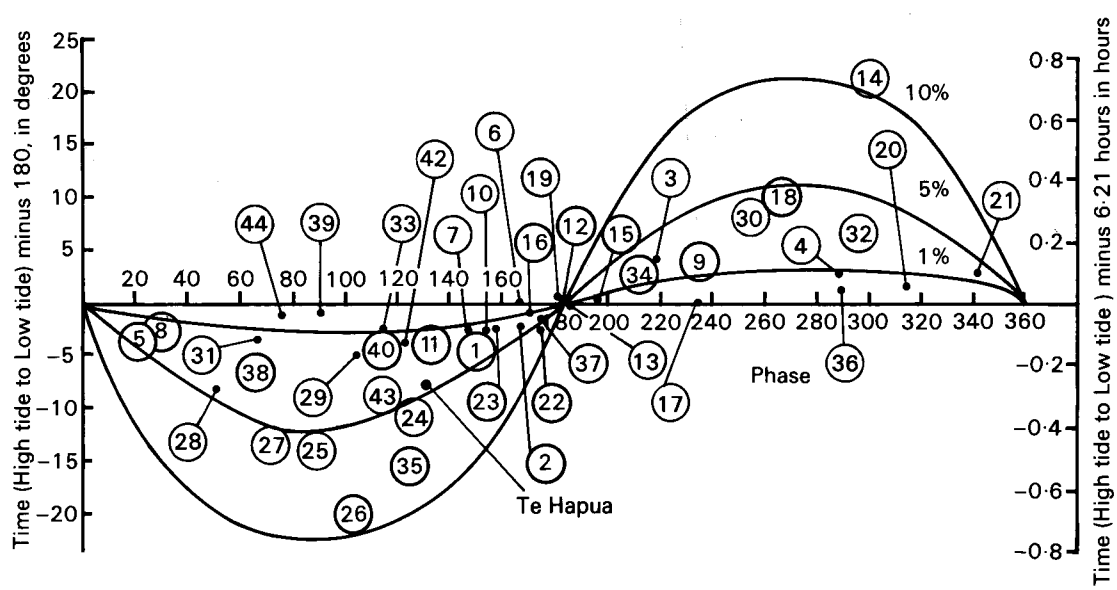

Fig. 2 Variations with relative phase ($M_4 - 2xM_2$, tidal elevation phases) of the departure from half an M_2 tidal period (6.21 h) of the time interval from high to low tide for M_4/M_2 tidal amplitude ratios of 1, 5, and 10%. Encircled numbers refer to the locations given in Table 1.

Table 1 Elevation amplitude (m) and phases (° referred to Greenwich) of the M_2 and M_4 tide on the New Zealand coast.

Location	M_2 Amplitude (m)	M_2 Phase (°)	M_4 Amplitude (m)	M_4 Phase (°)	Ratio Amplitude $\frac{M_4}{M_2}$ %	Phase M_4 - 2 x Phase M_2
Manukau Harbour						
Paratutai 1	1.07	289	0.04	10	3.7	152
Onehunga 2	1.33	304	0.06	58	4.6	168
New Plymouth 3	1.22	277	0.02	052	2.0	218
Wanganui 4	0.77	303	0.01	170	1.0	284
Nelson 5	1.30	280	0.04	305	3.4	21
Westport 6	1.14	309	0.02	063	1.5	165
Greymouth 7	0.96	316	0.02	066	1.9	154
Deep Cove 8	0.70	343	0.01	356	1.3	30
Colac Bay 9	0.81	359	0.01	233	1.5	235
Bluff 10	0.87	048	0.03	255	3.1	155
Paterson Inlet 1	0.80	044	0.02	220	1.9	132
Nugget Point 12	0.74	076	0.02	333	2.4	181
Otago Harbour						
Port Chalmers 13	0.72	109	0.01	271	1.7	183
Dunedin 14	0.73	129	0.08	196	10.4	296
Oamaru 15	0.67	089	0.01	010	0.4	192
Timaru 16	0.77	079	0.02	328	1.9	170
Lyttelton 17	0.88	126	0.00	125	0.5	233
Kaikoura 18	0.67	140	0.03	186	4.5	266
Cook Strait						
Cape Campbell 19	0.64	151	0.01	120	1.9	178
Lyall Bay 20	0.47	136	0.00	225	0.6	313
Wellington Harbour 21	0.49	139	0.01	258	2.2	340
Oteranga Bay 22	0.21	204	0.05	229	2.2	176
	(0.21)	(195)	(0.05)	(206)		
Lucky Bay 23	0.38	199	0.01	197	2.3	159
Tory Channel						
Okukari 24	0.33	219	0.02	200	6.1	122
West Head 25	0.33	211	0.02	146	6.1	84
Picton 26	0.49	249	0.05	231	9.3	103
Makara 27	0.31	255	0.02	223	5.8	73
Plimmerton 28	0.44	265	0.02	222	4.1	52
French Pass						
Greville Harbour 29	1.16	272	0.02	295	2.1	111
Rock Cod Bay 30	1.23	270	0.05	076	4.1	256
Elmslie Bay 31	0.82	258	0.02	222	1.8	66
Castlepoint 32	0.55	143	0.02	221	3.6	290
Napier 33	0.65	166	0.01	87	1.7	115
Gisborne 34	0.65	168	0.01	187	1.4	211
Ohiwa 35	0.72	207	0.06	180	8.1	126
Whale Island 36	0.74	182	0.01	290	0.8	286
Tauranga 37	0.69	202	0.02	218	2.6	174
Mercury Bay 38	0.73	179	0.02	064	2.5	66
Great Barrier Island 39	0.87	185	0.00	102	0.3	92
Waiheke 40	1.17	187	0.02	129	1.5	115
Auckland 41	1.16		0.03			
Whangarei Harbour						
Marsden Point 42	0.88	198	0.01	157	1.4	121
Whangarei 43	1.00	221	0.04	193	3.9	111
Opua 44	0.78	214	0.00	147	0.4	79

ASYMMETRY IN THE TIDAL FLOW AROUND NEW ZEALAND

Of interest in terms of sediment dispersion is the M_4 tidal flow. The phase and amplitude of the M_4 flow depend on the mode of generation of the M_4 tide from the M_2 tide and therefore they are not readily discernible from the M_4 elevations alone (Heath 1980a).

A source of information on the M_4 tidal flow, or at least the resultant asymmetry in the tidal flow, is contained in current measurements published on the hydrographic charts. These measurements are obviously not ideal for they are surface values. However, the phases of these current observations are consistent with barotropic tidal models fitted to the New Zealand tidal elevations (Bye & Heath 1975; Heath 1978) giving confidence to the observations being representative of the barotropic tide. The barotropic tidal speed and tidal ellipse orientation do change with depth due to bottom friction (see, e.g., May 1979). The speed ratio (M_4/M_2) is therefore likely to be slightly underestimated, and the change in tidal ellipse orientation is small and within the present observational limits.

The presence of an M_4 tide is recognised by the peak flood tide speed (taken relative to the time-averaged mean speed) differing from that of the ebb speed, and by the time interval of flood tide (the time interval for which the speed exceeds the mean) differing from that for the ebb tide. Significant asymmetry in the tidal flow on the New Zealand coast is found in the 3 areas of known strong tidal flow: northernmost New Zealand (Fig. 4), Cook (Fig. 7) and Foveaux (Fig. 3) Straits. The hourly current observations over a 13-hourly period have been resolved into components parallel and perpendicular to the adjacent coast, and the mean value over the M_2 tidal cycle has been calculated. Peak values generally parallel the coast and only these alongshore components are therefore displayed (Fig. 3, 4, 7). Presently available current measurements from elsewhere on the open coast exhibit tidal speeds generally less than the critical speed needed to initiate sediment movement (Carter & Heath 1975) and minimal tidal asymmetry. However, new current measurements may reveal other areas on the open coast of unexpectedly strong tidal asymmetry arising from special circumstances. Such an example is in Tasman Bay where strong M_4 tidal flow results from non-linear field accelerations in the semidiurnal tide, forcing a local resonance in the M_4 tide (Heath 1979).

IMPLICATIONS OF THE TIDAL ASYMMETRY FOR THE NET TRANSPORT OF SEDIMENT

Carter & Heath (1975) have indicated that on the New Zealand continental shelf the mean time-averaged flow under calm conditions is generally too slow to initiate bedload sediment movement. Only in the tidally dominated Cook and Foveaux Straits and northernmost New Zealand are the tides sufficiently strong to move sediments. Carter and Heath therefore concluded that on most of the New Zealand coast, bedload transport results only under storm conditions when all 3 components—wind wave, tide and storm induced mean flow—reinforce each other to produce a water speed above the critical value to initiate sediment movement. The direction of bedload transport is then determined by the tidal and storm induced unidirectional flows. On much of the New Zealand shelf the non-tidal flows result mainly from boundary forcing and local winds (see, e.g., Heath 1973, 1978, in press), and it is these flows which probably determine the direction of net sediment transport on the open coast away from the littoral zone. In areas of strong tidal flow, the net movement of bedload sediment may, however, be determined by the asymmetry in the tide. We will look separately at the 3 areas of strong tidal flow—Foveaux Strait, northernmost New Zealand, and Cook Strait.

Foveaux Strait

The M_4 tidal flow, as evidenced by asymmetry in the differences between the peak flows from the mean, is insignificant compared to the mean in eastern Foveaux Strait (Stations A, D, B, Fig. 3). In northeastern Foveaux Strait the mean flow is towards the southeast (Stations A, B, Fig. 3) whereas in southeastern Foveaux Strait the mean flow is towards the northwest (Station D, Fig. 3). The movement of fine and very fine sand in eastern Foveaux Strait appears to parallel the mean flow (Cullen 1967, fig. 6). The significant quantity determining the direction of sediment movement is the direction of net energy loss expended by the water moving over the bottom calculated for those time intervals of the tidal cycle when the bottom stress exceeds the critical stress needed to initiate sediment movement. In eastern Foveaux Strait, with a small M_4 tide, this direction of net energy loss parallels the mean flow.

There is significant asymmetry in the flow in the narrowest section of Foveaux Strait (Station C, Fig. 3) which is not just the result of the east-directed 0.19 m/s mean flow, and this presumably indicates the presence of a significant M_4 flow. However, the net bottom stress over the tidal cycle is governed by the mean flow and is directed towards the east

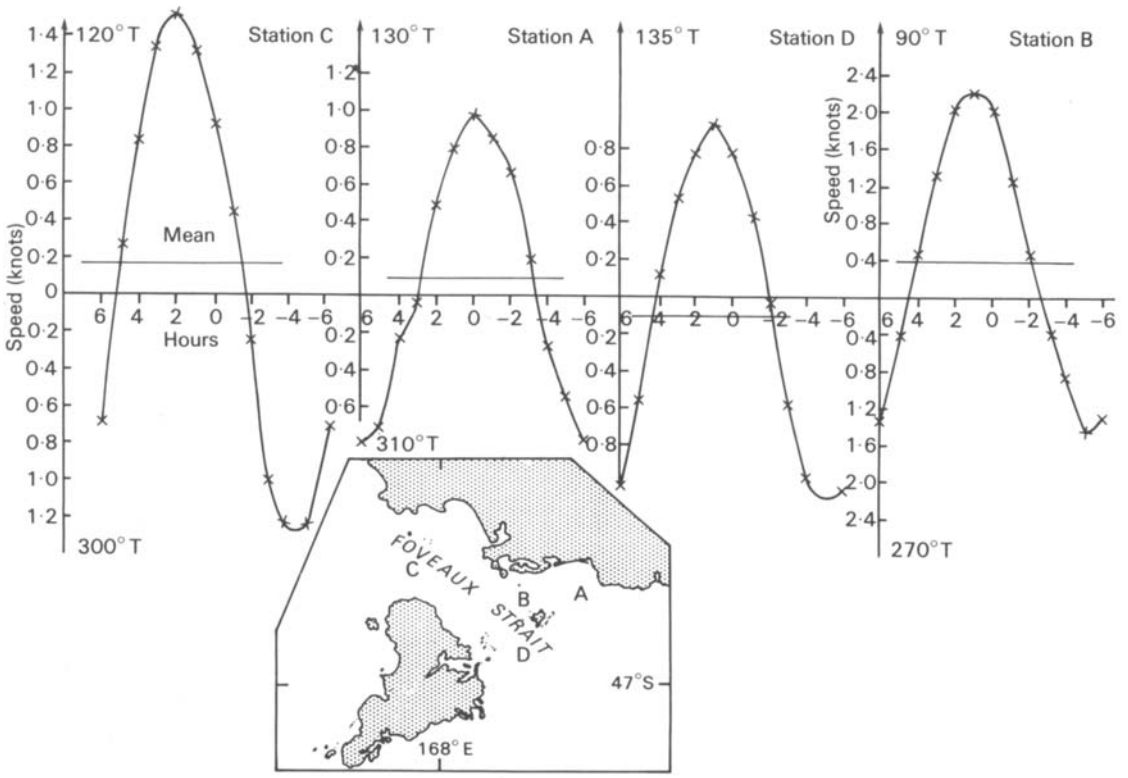

Fig. 3 Hourly surface current components parallel to the adjacent coast, over a spring tidal cycle in Foveaux Strait, as given in Hydrographic Branch, Royal New Zealand Navy (1952). Station A at latitude 46°41.7′S, longitude 168°45.9′E; Station B 46°41.9′S, 168°25.5′E; Station C 46°33.9′S, 167°51.8′E; Station D 46°54.3′S, 168°23.4′E. Station positions are shown in the inset. Times are referred to high tide at Bluff.

(Station C, Fig. 3). The seafloor of central Foveaux Strait is composed of relict gravels overlain intermittently by fine sands with movement of the finer sediments towards the east (Cullen 1967) in the direction of the mean flow.

Northernmost New Zealand

Current observations near northernmost New Zealand indicate small mean flows (Fig. 4). There is, however, strong asymmetry in the peak flow. Offshore (Stations A, B) the strongest flow is directed towards the northeast.

Close inshore, the peak flow is strongest towards the west between North Cape and Cape Reinga (Station G, Fig. 4), symmetrical off Cape Reinga (Station F, Fig. 4), and southeastwards off Cape Maria van Diemen (Station E, Fig. 4). This dominance of the M_4 tide in determining the direction of peak bottom stress is likely to produce interesting effects in interaction with the wind wave induced movement of sediment close inshore.

The sediment distribution around northernmost New Zealand has been described by Summerhayes (1969a). More recently, Schofield (1970) has analysed the coastal sands of Northland and Auckland. Summerhayes (1969a, fig. 14b) shows a convergence of sediment towards Cape Reinga, westwards on the north coast and northwards on the west coast. His conclusion is based on coastal profiles, the texture of the beach sand, and the distibution of heavy minerals. This movement of sediment close inshore on both the north and west coasts is in the opposite direction to the reported current system—the eastwards directed flow on the north coast contributing to the East Auckland Current (Brodie 1960, Heath 1980b) and the southwards directed West Auckland Current on the west coast (Brodie 1960; Garner 1961; Sanderson 1979). However, Summerhayes' (1969a) pattern of sediment movement is for the region close inshore where the wave-induced longshore drift may have a strong influence. The prevalence of wind waves from the south to southwesterly direction on the

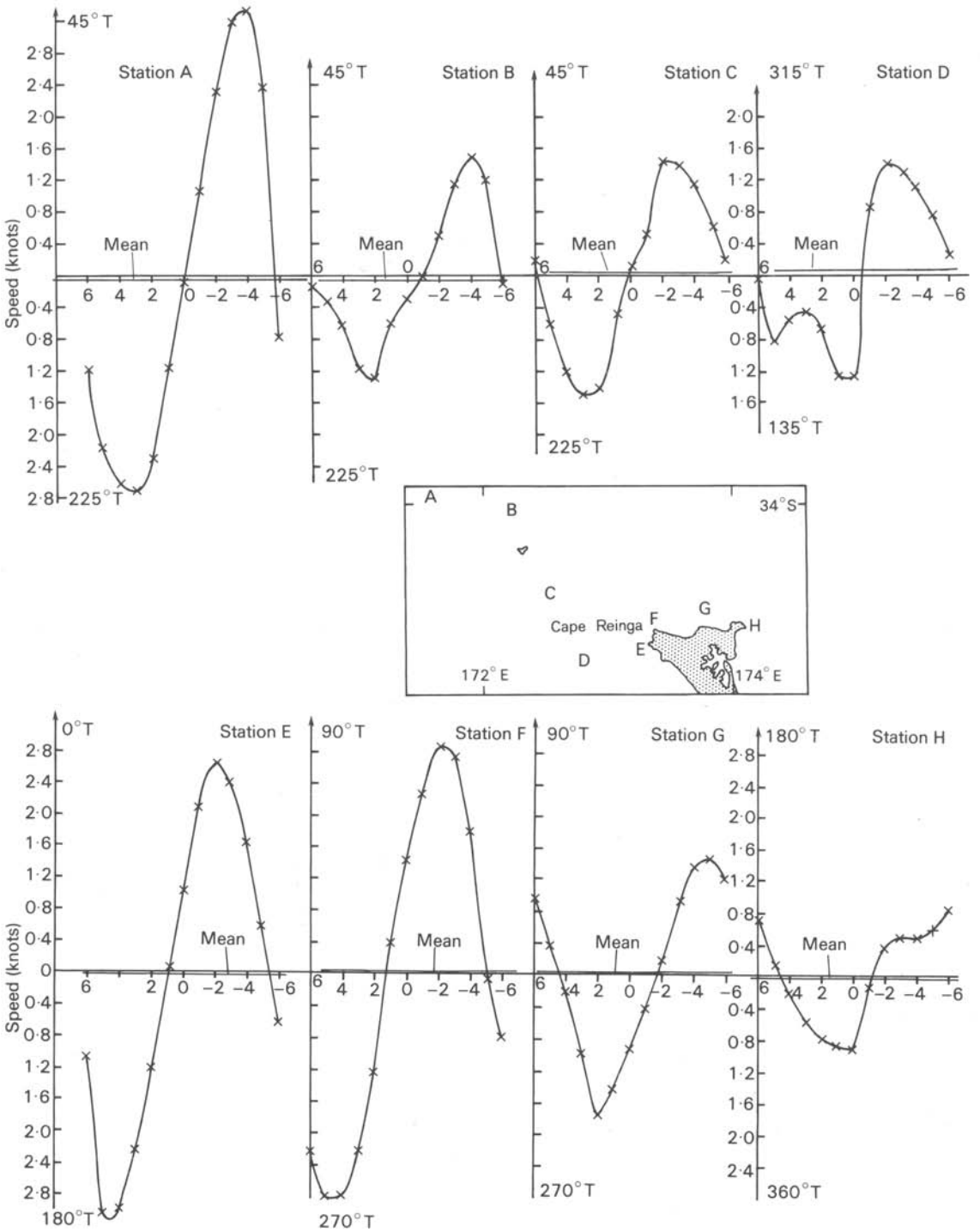

Fig. 4 Hourly surface current components approximately parallel to the adjacent coast, over a spring tidal cycle near North Cape, as given in Hydrographic Branch, Royal New Zealand Navy (1972). Station A latitude 33°59′S, longitude 171°47′E; Station B 34°02′S, 172°08′E; Station C 34°18′S, 172°15′E; Station D 34°31′S, 172°23′E; Station E 34°29′S, 172°37′E; Station F 34°23′S, 172°40′E; Station G 34°20′S, 172°51′E; Station H 34°26′S, 173°07′E. Station positions are shown in the inset. Times for Stations A, B, C and D are referred to high tide at Westport, and for Station G and H to high tide at Auckland.

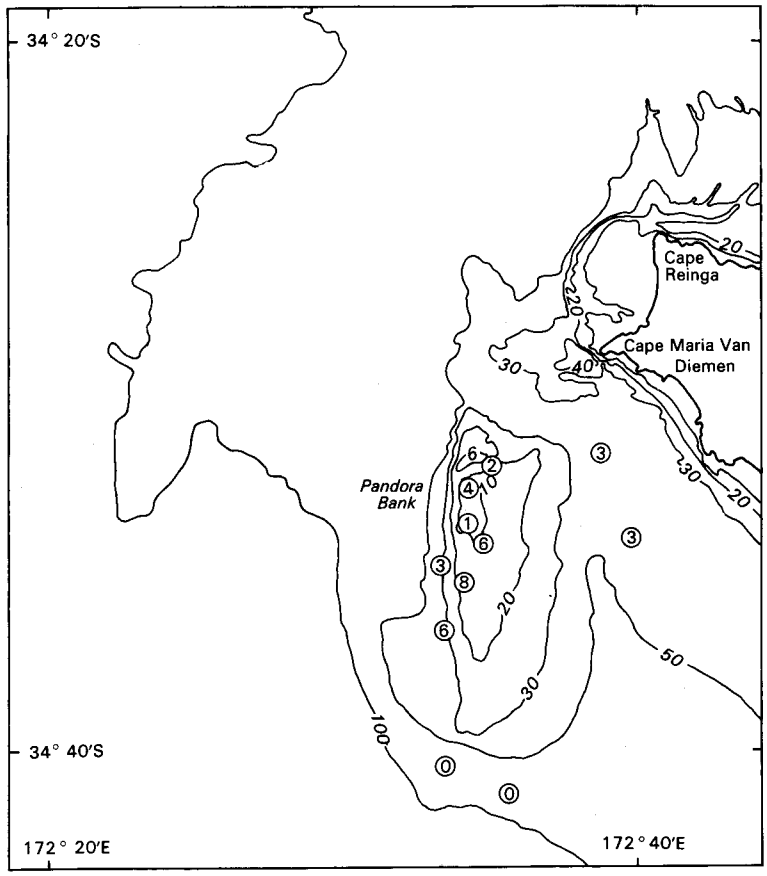

Fig. 5 Bathymetry (m) of Pandora Bank as indicated from surveys in 1969–70 (Hydrographic Branch, Royal New Zealand Navy 1972), and the decrease in depth (m) between the 1849–55 (Hydrographic Office, Admiralty 1907) and 1969–70 bathymetric survey (encircled numbers).

west coast of the North Island, north of Cape Egmont (Pickrill & Mitchell 1979, fig. 2), would provide the energy consistent with Summerhayes' analysis of movement of sediment towards the north on the west coast of the North Island. The east to west sediment movement on the north coast is probably not dominantly wind wave induced but is consistent with the direction of peak bottom stress due to the strong asymmetry in the tides.

In contrast to Summerhayes (1969a), Schofield (1970) concludes that the distribution of sand along the west coast of the North Island is dominated by the coastal current, the southwards directed West Auckland Current and the northwards directed Westland Current (Brodie 1960). Schofield's interpretation appears to be mainly based on the direction of formation of the barriers across the entrance to the harbours. The barriers across those harbours north of Kaipara Harbour extend towards the south, indicative of a southwards movement of sediment, while those barriers south of Kaipara Harbour extend to the north indicative of a northwards movement of sediment. Schofield (1970, p. 815) suggests that the West Auckland and Westland Currents, and the associated sediment movement, converge at an area opposite Kaipara Harbour. However, the average feldspar-quartz ratio in the nearshore sands appears to increase towards the north on the west coast north of Kaipara Harbour, and Schofield (1970, p. 821) concludes that this may be due to the sand in the northern region being transported over greater distances (i.e., to the north, in conflict with the direction implied from barrier development) or related to a potash-rich source in the north. Both Summerhayes and Schofield comment on the difficulty in determining the direction of sediment movement, because the mineralogical content for the West Auckland Sand Facies (Schofield 1970, p. 821) shows little spatial variation.

Some clue as to the direction of sediment movement around the North Cape Peninsula is given by the present interpretation of the influence of the tidal asymmetry. As mentioned above, the westwards movement of sediment from North Cape towards Cape Reinga is consistent with the peak

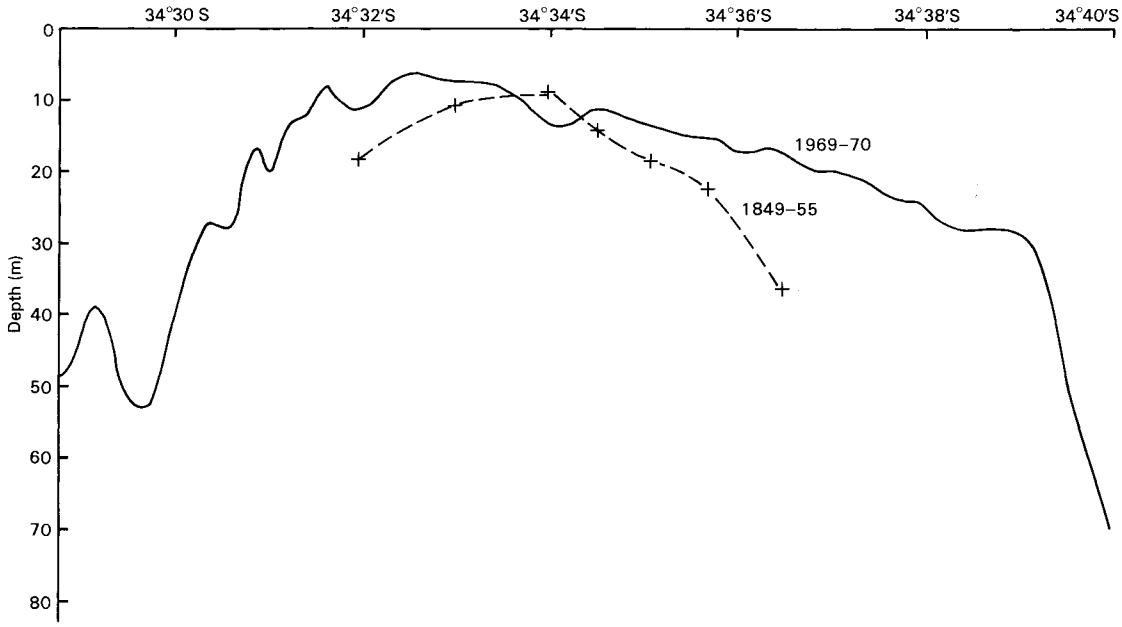

Fig. 6 Bathymetry along longitude 172°34.25'E from latitudes 34°29'S to 34°40'S over Pandora Bank. The 1969–70 bathymetry was taken from the collector on which chart NZ41 (Hydrographic Branch, Royal New Zealand Navy 1972) is based, and the 1849–55 bathymetry was taken from chart BA2525 (Hydrographic Office, Admiralty 1907).

tidal flow in that direction. Near Cape Reinga (Station F, Fig. 4) the tidal flow is symmetrical; this may provide an explanation for the large sand deposit at the adjacent Sandy Bay (Summerhayes 1969a, fig. 2). At Station E (Fig. 4), offshore from Cape Maria van Diemen, there is a strong asymmetry in the tidal flow with the peak flow towards the southeast. If there is a supply of sediment on the beach towards Cape Maria van Diemen, the effect of the tidal flow would be to direct this sediment towards the south. With the reduction in current speed south from Cape Maria van Diemen a sand deposit might be expected in the area. Such a deposit is found in the form of Pandora Bank (Fig. 5, 6). If the mechanism of sediment movement is as described above (and Pandora Bank is not a relict feature) the bathymetry on or near Pandora Bank might be expected to be changing with time.

The first published soundings in the vicinity of the North Cape Peninsula were from surveys in the period 1849–55. Subsequent to the loss of the collier *Kaitawa* near Pandora Bank in May 1966, a resurvey of the bathymetry near Pandora Bank was carried out in July 1966 and a comprehensive survey was made of the area in the 1969–70 summer. Changes in the depth between the 1849–55 and 1969–70 surveys (Fig. 5) have been determined by superimposing an enlarged image of the earlier survey (shown on chart BA2525 of the Hydrographic Office, Admiralty 1907) over the latest survey (shown on Chart NZ41, Hydrographic Branch, Royal New Zealand Navy 1972), and fitting the coastline as near as possible. The position of Pandora Bank relative to the coast coincides for the 2 surveys giving some confidence in the positional accuracy which one might otherwise suspect.

Examination of the soundings on the original collector for the 1969–70 survey reveals that in the area offshore west from Cape Reinga, in depths greater than 50 m, there are numerous localised areas of strong relief protruding through the coarse shell sand, making any change in depth difficult to determine.

That there is a significant decrease in depth on Pandora Bank between the surveys is evident both from the superimposed surveys and the line of soundings along longitude 172° 34.25'E (Fig. 6). The earlier soundings in Fig. 6 were taken from the chart and the later soundings (1969–70) were from the original collector. Pandora Bank now extends further to the south, and its present shape gives the impression of a southwards directed plume. Sediments on Pandora Bank are similar to those on the adjacent west coast (see Summerhayes 1979a, fig. 2, 4, 5) and are fine, well-sorted sands with a low shell fraction.

Summerhayes (1969b) suggests that the topographic high on which Pandora Bank is sited might have had its western side shaped by erosion at a

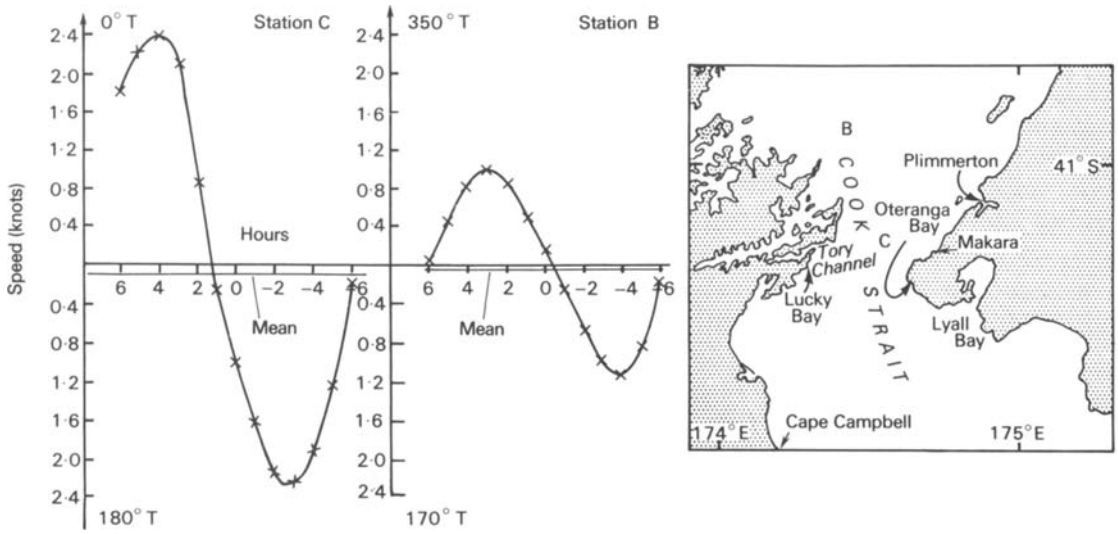

Fig. 7 Hourly surface current components directed through Cook Strait over a spring tidal cycle as given in Hydrographic Branch, Royal New Zealand Navy (1960). Station C latitude 41°13.9′S, longitude 174°29.6′E; Station B 40°56.0′S, 174°25.0′E. Station positions are shown in the inset. Times are referred to high tide at Westport.

previous lower stand of sealevel. The channel between the present Bank and the mainland may have been a former river channel whose direction was originally tectonically controlled. Alternatively, Pandora Bank may have formed as a connected shoal (see, e.g., Duane et al. 1972) at a previous stand of sealevel, which has since been separated from the coast by a saddle (Fig. 5), and therefore it would generally be thought of as relict. That the Bank is growing clearly indicates it is not relict, and notwithstanding the genesis of Pandora Bank it seems very likely that its present development is closely associated with the tidal asymmetry near Cape Maria van Diemen. There is, however, a clear need for more current information and observations to determine the underlying structure of Pandora Bank.

Cook Strait including the Marlborough Sounds

The flow in Cook Strait is dominated by the semidiurnal tidal signal, making determination of the time-average flow difficult. Observations for the centre of Cook Strait (Hydrographic Branch, Royal New Zealand Navy 1960) give mean meridional flows of 0.06 m/s and 0.04 m/s to the south, under spring and neap tidal conditions respectively (Fig. 7). The mean flow, calculated by fitting relative tidal flow harmonic constants, as analysed from electric potential measurements made by Gilmour (1960), to the tidal amplitudes evident from trajectories of Cook Strait swimmers, is 0.03 m/s towards the north (Heath 1980c). Bowman et al. (1980) have estimated the tidal residual flow generated by a non-linear M_2 tidal numerical model of the greater Cook Strait region. The southwards tidal residual of 0.3 m/s in their model is however much larger than that observed.

Taking the data from the hydrographic chart (Hydrographic Branch, Royal New Zealand Navy 1960) and assuming the asymmetry in the tidal flow results from the M_4 and S_4 (the overtide of the principal solar semidiurnal tide, S_2) flows being in phase with the M_2 and S_2 flows to the north (and hence out of phase with the semidiurnal flow to the south), gives estimates of the M_2, S_2, M_4, and S_4 tidal flow amplitudes of 0.91, 0.3, 0.06, and 0.02 m/s respectively. There are obviously many limitations on these estimates, but they do indicate the magnitude of the M_4 flow.

Tidal elevations of the M_4 tide in Cook Strait have a nearly constant phase of about 200° with the largest observed amplitude of 0.05 m in the narrows.

A recent analysis by the author of the generating mechanism for the M_4 tide in Cook Strait indicates the largest contribution to the M_4 tidal elevation is that arising from the bathymetric constriction of Cook Strait producing strong field accelerations. The largest contribution to the M_4 flow results from influence of the topographic constriction on the mass flux.

The small M_4 tidal flow in Cook Strait would appear to have only a minor role in determining the directon of net movement of bedload sediment transport; the direction of net transport in the deep water is likely to be determined by the southwestern

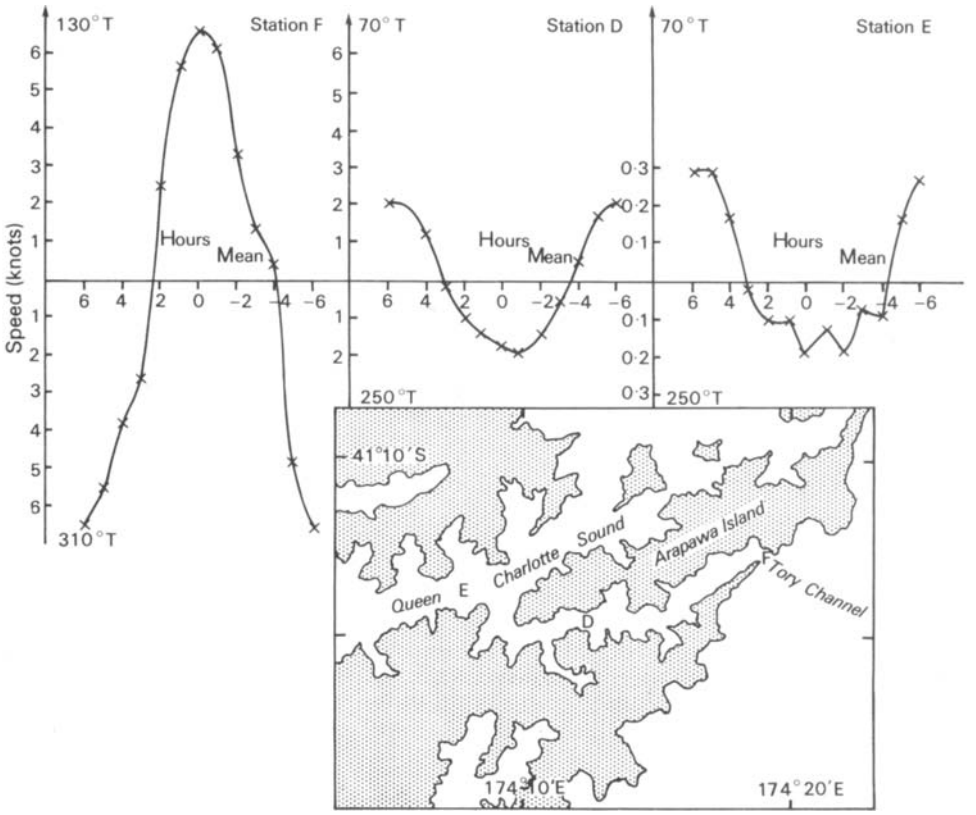

Fig. 8 Hourly surface current components parallel to the adjacent coast over a spring tidal cycle in Queen Charlotte Sound as given in Hydrographic Branch, Royal New Zealand Navy (1966). Station D at latitude 41°14.7′S, longitude 174°11.5′E; Station E 41°13.8′S, 174°07.9′E; Station F 41°12.7′S, 174°18.9′E. Station positions are shown in the inset. Times for Stations D and E are referred to high tide at Wellington, and for Station F to high tide at Westport.

littoral drift being intercepted by the Cook Strait Canyon which protrudes into Cook Strait from the east.

Although the M_4 tidal elevation in Cook Strait is small, the M_2 tidal elevation is also small in the narrows of Cook Strait (Table 1), and the relatively large M_4/M_2 tidal elevation ratio is significant in determining the tidal asymmetry in the Marlborough Sounds whose entrances open into Cook Strait. The M_4 tide at the entrance to both Queen Charlotte and Pelorus Sounds induces M_4 tidal flow and associated M_4 standing wave elevations in these Sounds. This accounts for the observed large M_4 tidal elevations at Picton (within Queen Charlotte Sound) and the observed large asymmetry in the tidal flow in Pelorus Sound (Fig. 1). Significant tidal asymmetry is found in shallow coastal inlets (Table 1, Fig. 2) where non-linearity on the fundamental tides in the form of the field accelerations, friction, and the large change in water depth over a tidal cycle lead to strong overtide generation. However, in the deep Marlborough Sounds, the M_4 overtide is not produced locally but is excited from the entrance. The strong asymmetry in the tide is a consequence of the large M_4/M_2 tidal elevation ratio in Cook Strait tides.

Landwards, from where Tory Channel meets the main arm of Queen Charlotte Sound, the phase of the M_2 and M_4 flood tide flows will lead the elevations by 90°, the tide being predominantly in the form of a standing wave. The phase of the M_2 and M_4 tidal elevations at Picton near the head of Queen Charlotte Sound are 249° and 231° respectively. Accordingly the phase difference of the flow will be approximately 183° (assuming no local M_4 generation) which is indicative of a net bottom stress out of the Sound, because the net bottom stress is in the directon of the ebb flow for the phase ($M_4 - 2xM_2 = \phi - 2\theta$) in the range 90–270°. Current observations from within Queen

Charlotte Sound confirm the existence of a net bottom stress out of the Sound (Station E, Fig. 8).

Current observations east of Arapawa Island in Tory Channel show only slight asymmetry (Stations F and D, Fig. 8) with the strongest flow out towards Cook Strait. The phase of the M_2 flood flow within Tory Channel is about 157° (as indicated by the tidal stream predictions, e.g., Hydrographic Branch, Royal New Zealand Navy 1966). For an M_4 standing wave with the phase the same as at Picton (141°), the phase of the flow $\phi - 2\theta$ is 187° indicative of a peak ebb flow.

West of Arapawa Island in Queen Charlotte Sound the flow is continuous with that in Tory Channel in that on the rising tide the flow is out of the Sound. The phase $\phi - 2\theta$ will be approximately the same as in Tory Channel and is indicative of a net bottom stress out of the Sound.

High tidal elevation at the entrance to Pelorus Sound occurs about 1.9 h before that at Westport (Hydrographic Branch, Royal New Zealand Navy 1966) where the phase of the M_2 tide is 309°. The phase of the M_2 flood tide at the entrance to Pelorus Sound is therefore estimated at 164°. Assuming the phase of the M_4 elevation is that observed in Cook Strait of 200° (local M_4 tidal generation in French Pass, 10 km west of the entrance to Pelorus Sound, probably also contributes to the M_4 tide in Pelorus Sound) the associated phase of the M_4 flood tide at the entrance to Pelorus Sound will be 110°. The phase difference $\phi - 2\theta$ in Pelorus Sound is then 142°, indicative of a net bottom stress directed seawards out of Pelorus Sound. This agrees with the observation of the peak ebb flow in Pelorus Sound exceeding the peak flood flow. However the observed flow field can also be strongly influenced by internal tides generated near the head of the Sound (Heath 1976). There is not, however, a net seawards movement of sediment out of Pelorus Sound, for the Sound acts as a double-ended sediment trap for river-derived sediment brought in mainly near the head, and sediment brought in from the open sea (Carter 1976). Sediment deposition is closely correlated with the cross-sectional area of the Sound (the bottom sediment cover decreases where the cross-sectional area of the Sound decreases) and hence, through continuity, with the strength of the flow (Carter 1976).

CONCLUSION

Available tidal flow observations from the New Zealand coast indicate significant asymmetry over a tidal cycle around northernmost New Zealand and in Cook and Foveaux Straits. However, only around northernmost New Zealand might the asymmetry associated with the M_4 tide be a major contributor in determining the direction of net movement of bedload sediment; close inshore, near Cape Maria van Diemen, the peak flow is towards the southeast and probably has a strong influence on the present development of Pandora Bank. In Foveaux Strait the eastwards mean flow dominates the asymmetry associated with the M_4 tide.

In Cook Strait the mean flow dominates the tidal asymmetry associated with the M_4 tide. However the relatively large M_4/M_2 tidal elevation ratio in Cook Strait leads to a strong tidal asymmetry in the adjacent Queen Charlotte and Pelorus Sounds, an asymmetry with stronger ebb than flood tidal flows. This situation is in contrast to most inlets were local M_4 tidal generation generally leads to stronger flood than ebb flows (Doodson & Warburg 1941; Heath 1980a).

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