THE SWEEP OF LONG WATER WAVES ACROSS THE PACIFIC OCEAN

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Summary

Seismic sea waves (tsunamis) are shallow water waves. The leading tsunami wave from the Chilean earthquake of May 22, 1960 at 19 hr 11 min 20 s G.M.T. arrived at Hobart in 12 hr. The tsunami was also recorded on tide gauges up the east coast of Australia and at Norfolk and Lord Howe Islands. The wave took 14 hr 04 min to reach Auckland, N.Z., but this is because of the low speed of the wave over the extensive submerged continental structure off the eastern coast of North Island. The tsunami was not recorded at Port Melbourne. From the travel-times the average depth of the Pacific Ocean between Tasmania and South America is 5500 m.

I. Introduction

Recently, Jaeger (1960) discussed many of the types of surface waves recorded by tide gauges. Subsequently, one special type of wave, the seismic sea wave or tsunami which was propagated all the way across the Pacific Ocean from Valdivia in Chili has been recorded in Australia and New Zealand. The wave on arriving at Hobart and Sydney caused unusual and spectacular ebbs and flows in the tides of these two harbours and the phenomenon attracted widespread public interest and press and radio comment.

The tsunami had its origin in a violent earthquake of magnitude $8\frac{1}{4}$ that occurred at Valdivia, Chili (lat. $39\frac{1}{2}°$ S., long. 73° W.) in the afternoon of May 22 at 19 hr 11 min 20 s G.M.T. It is often presumed that geological faulting and sudden changes in the depth of the sea-bed cause a disturbance to the sea's surface and the disturbance is propagated as a seismic sea wave. On the other hand, Gutenberg (1939) noticed that invariably the first movement on a tide gauge is a recession of the sea and furthermore some earthquakes with epicentres on land have been associated with tsunamis and he suggests that the mechanism for the generation of tsunamis is the sudden movement of thick sedimentary deposits down the continental slope. The precise mechanism of the cause of the tsunami from Valdivia is not investigated in this paper.

The question of allocating an arrival time for the initial movement of a train of tsunami waves is difficult. The criterion which has been followed is to pick the first recognizable long period depression. This criterion appears to be decidedly satisfactory in that all the records show a similar character with long period oscillations preceding the more obvious shorter period oscillations. Reports of the wave have been received from many parts of the Pacific Ocean and this analysis for the Tasman Sea is based on the tide gauge records at Hobart, Mel-

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TABLE 1

THE FUNDAMENTAL DATA AS READ FROM THE TIDE GAUGE RECORDS AT TWELVE STATIONS IN AUSTRALIA AND NEW ZEALAND

Tide Gauge	Arrival Time May 23, 1960 E.S.T.= U.T.+10 hr (hr min)		Travel-time Observed (hr min)		Travel-time Calculated (hr min)		Arc Distance (degrees)	Average Speed (km/hr)	Average Depth of Ocean (m)
Hobart	17	10	12	00	13	30	89	824	5340
Camp Cove ..	18	45	13	34	14	55	95	779	4770
Fort Denison ..	18	45	13	34	14	55	95	779	4770
Newcastle ..	19	30	14	19	15	40	96	750	4410
Eden	19	00	13	49	14	50	93	746	4400
Norfolk Island ..	19	05	13	54	15	05	90	720	4090
Lord Howe I. ..	19	20	14	09	15	30	94	739	4300
Manukau (W) ..	19	15	14	04	15	40	81	641	3230
Waitemata (E)	19	15	14	04	15	05	81	641	3230
Melbourne ..	not recorded								
Pt. Lonsdale ..	indefinite								
Welshpool ..	indefinite								

bourne, Port Lonsdale, Port Welshpool, Eden, Norfolk Island, Lord Howe Island, Camp Cove and Fort Denison (Sydney), Newcastle, and Manukau and Waitemata (Auckland). The primary data taken from these records are given in Table 1.

II. WATER WAVES

For a uniform train of long crested waves of small amplitude (i.e. excluding capillary waves) Coulson (1952) gives the following expression for the velocity of the wave

$$C^2=(g\lambda/2\pi)\tanh 2\pi h/\lambda, \tag{1}$$

where λ is the wavelength, C the speed of the wave, g the gravitational acceleration, and h the depth of water.

From Table 1 it can be seen that the average value for the speed of the waves is of the order of 700 km/hr and from the records of Hobart and Sydney tide gauges (see Figs. 3, 4, and 5), the period of waves is of the order of $\frac{1}{2}$ hr. Hence the wavelengths of the water waves in the open ocean are of the order of 300–400 km, in which case the waves in crossing the Pacific Ocean, where typical depths are 4–5 km, behave like shallow water waves. In such cases where $h \ll \lambda$, equation (1) can be simplified to

$$C^2=gh. \tag{2}$$

The speed of the wave is not dependent upon wavelength and there is no dispersion. Hence the group velocity is the same as the phase velocity, and over water of uniform depth a pulse is propagated with unchanged shape. If the depth of water is different from place to place it can be seen from equation (2) that changes in speed and wavelength of the wave will result and the invariability of the pulse shape no longer holds.

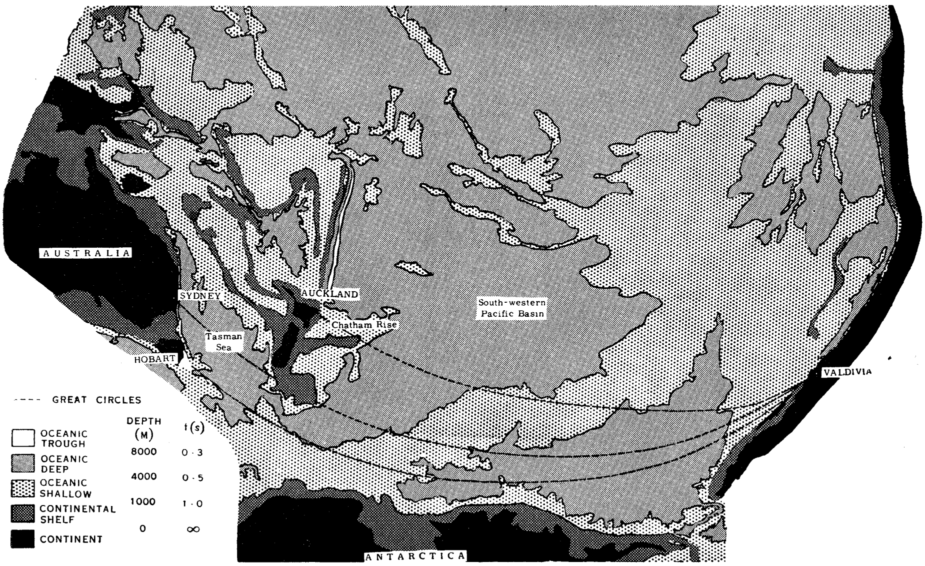

Fig. 1.—Map of the Pacific Ocean on Lambert's zenithal equal-area projection, 1 : 75,000,000. Contours are shown giving the depth of the water in terms of $f(s)$, which is the time taken for a tsunami to cover unit distance. The great circle arcs (shortest distances) between Valdivia and Hobart, Sydney, and Auckland are given. Notice that much of the path to Hobart is over deep water.

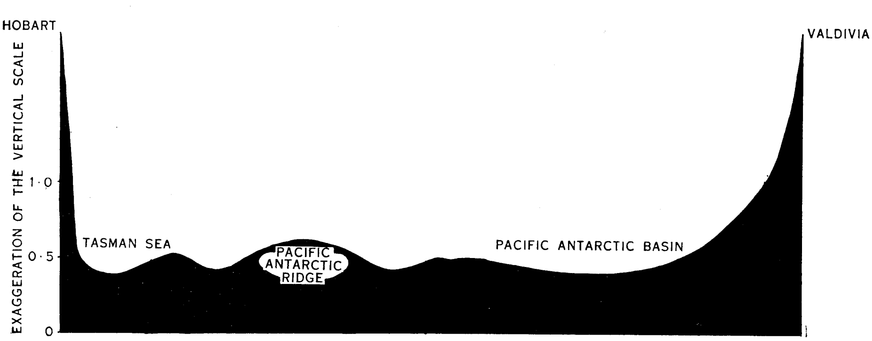

Fig. 2.—A profile of $f(s)$ along the direct path joining Valdivia to Hobart. The increased time for the tsunami to cross the South Eastern Pacific Plateau and the Pacific Antarctic Ridge is clearly indicated.

III. A New Method of Predicting Travel Times

In practice, the speed of these waves is very rarely measured directly; it is usual for the time of travel over a given variable-speed path length to be measured. For a given ray along a path of length S, the expected travel time τ is given by

$$\tau=\int_0^S \frac{\mathrm{d}S}{C}, \tag{3}$$

and from (2) and (3)

$$\tau=\frac{1}{g^{\frac{1}{2}}}\int_0^S \frac{\mathrm{d}S}{h^{\frac{1}{2}}}. \tag{4}$$

Numerical calculations of τ can be greatly simplified by means of the following transformation. Let

$$f(S)=1/h^{\frac{1}{2}}, \tag{5}$$

in which case from (4) and (5)

$$\tau=1/g^{\frac{1}{2}}\int_0^S f(S).\mathrm{d}S. \tag{6}$$

The integral in (6) is conveniently the area under the curve $f(S)$. If the path length S is given in kilometres and the depth h is also in kilometres, the travel time τ in hours is given by

$$\tau=1/356\int_0^S f(S).\mathrm{d}S. \tag{7}$$

Figure 1 shows not the depth of water in the Pacific Ocean but contours of equal values of $f(S)$ for use in (7). Figure 2 shows the profile of $f(S)$ along the direct path joining Valdivia to Hobart, and the computed time, which is 1/356 of the area under the profile of $f(S)$ between the two towns, is found to be 13 hr 30 min. It will be appreciated that it is much simpler and quicker and more accurate to draw a profile and to take the area under the curve than to determine and sum piecemealwise the travel times of successive portions of the entire path. The fact that the calculated time is slightly greater than the observed time may be because the Pacific is deeper than present-day contour maps show. On the other hand, as pointed out by Green (1946), when discussing the tsunami generated by the Alaskan earthquake of May 1, 1946, the sea wave is invariably more successful than the geophysicist in deciding the path of minimum time between two points.

IV. The Tide Gauge Records

Figure 3 shows the tide gauge records made at Hobart on May 23–24. The first arrival of the tsunami is indicated by a slight drop in sea level at 05 10 p.m. (Australian E.S.T.). Thereafter the frequency and amplitude of the oscillations build up reaching a maximum some 12 hr later.

Figure 4 is a tracing from the Camp Cove (N.S.W.) tide gauge. This instrument is more damped than the Hobart gauge and consequently wave action is less apparent. The arrival of the tsunami can be seen as a recession at 06 45 p.m. E.S.T.

Figure 5 is a tracing from the Fort Denison (N.S.W.) tide gauge. It is very similar to the Camp Cove record. On this record the first arrival time of the tsunami has been placed at 06 45 p.m. E.S.T.

Figure 6 is a tracing of the Newcastle record. Late in the night of May 23 large amplitude waves were set up in the harbour but the first arrival of the tsunami is indicated by a drop in sea-level at 07 30 p.m.

The Melbourne tide gauge reported that the tsunami was not detected. The Point Lonsdale and Port Welshpool tide gauges recorded small amplitude tsunami wave oscillations with an indefinite beginning. Mr. C. O'Malley, Port Officer for Victoria, reported in a personal communication that " The disturbances at Point Lonsdale were similar in magnitude to those at Port Welshpool, although

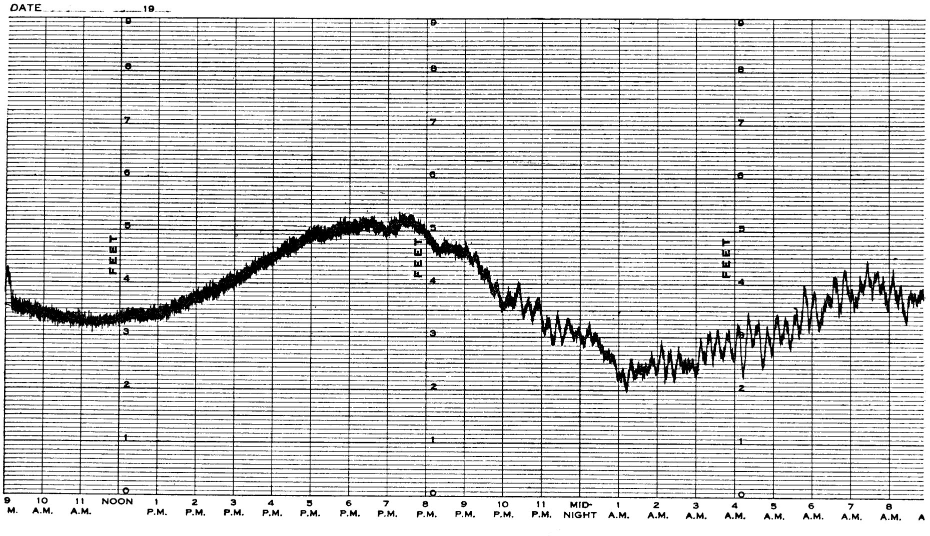

Fig. 3.—Tide gauge record made at Hobart on May 23–24. The first long depression is taken as the arrival of the tsunami.

the maximum occurred some seven hours later ". It would appear that the shallow, island-studded Bass Strait presents serious resistance to the progress of the tsunami. This is in marked contrast to the towns on the New South Wales coast which border the Tasman Sea.

Eden on the New South Wales coast recorded the first arrival at 07 00 p.m. E.S.T. and clear large amplitude waves built up from 10 30 p.m. E.S.T. Lord Howe Island recorded the first movement at 07 20 p.m. E.S.T. and large amplitude waves built up from 09 20 p.m.

The first arrival at Norfolk Island was placed at 07 00 p.m. E.S.T.

In New Zealand the tide gauges at Manukau (Auckland—Tasman Sea coast) and Waitemata (Auckland—Pacific Ocean coast) both recorded the effects of the tsunami. A tracing of the records is shown in Figure 7. Both of these gauges are over-damped for recording of tsunami waves. The first positive

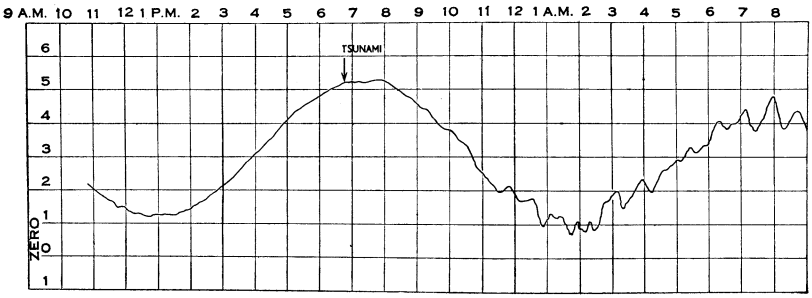

Fig. 4.—Tide gauge record made at Camp Cove, N.S.W., May 23–24.

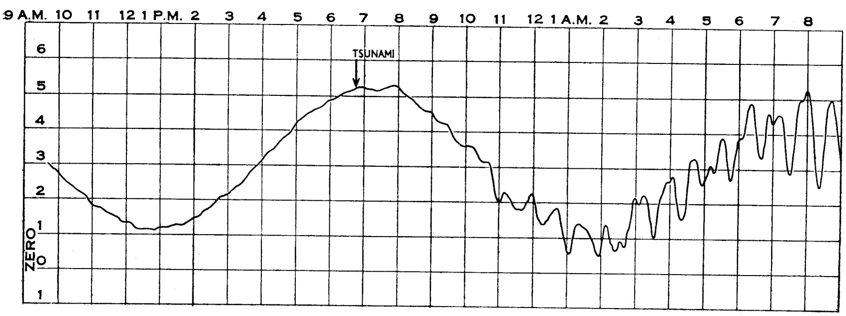

Fig. 5.—Tide gauge record made at Fort Denison, N.S.W., May 23–24. If Figure 4 is compared with Figure 5, a high order of correlation is found. This is probably due to seiches being set up in Port Jackson.

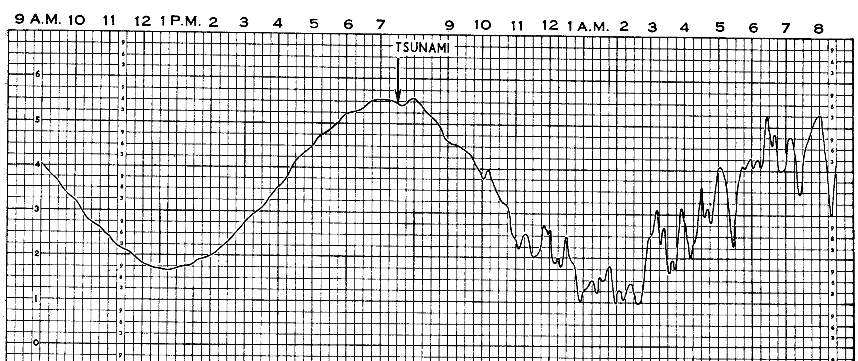

Fig. 6.—Tide gauge record made at Newcastle on May 23–24.

movement of the Waitemata gauge was at 07 15 p.m. Australian E.S.T. On the Manukau gauge the first arrival of the tsunami is most indefinite; using the criteria as set out in Section I for the identification of the initial tsunami wave, the arrival time is placed at 07 15 p.m. Australian E.S.T.

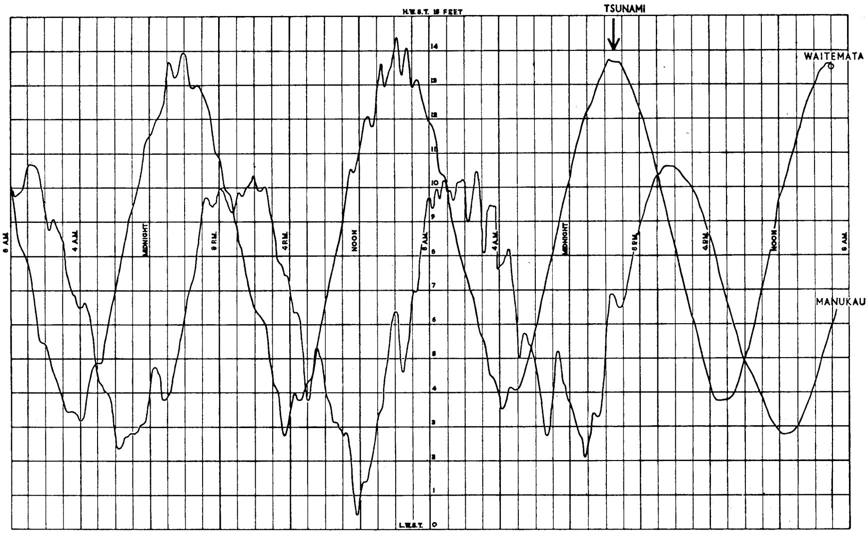

Fig. 7.—Tide gauge records made at Auckland in Manukau (Tasman Sea Coast) and Waitemata (Pacific Ocean Coast) harbours.

V. Comments on the Results

In Table 1 the calculated travel-times by the method given in Section III are compared with the observed times. The consistently greater value for the calculated travel-time compared with the observed travel-time suggests that the South Pacific Ocean is deeper than recent charts suggest (Bathymetric charts—Monaco Hydrographic Institute). Also listed in Table 1 are the average ocean depths between Valdivia and the Australasian recording stations. The average depth between Valdivia and Hobart along the path traversed by the tsunami is 5340 m. Proceeding up the Australian coast, the computed average depth decreases. A surprising result is the Eden record which shows the first wave arriving 15 min after Sydney's first arrival. The early arrivals at Sydney could be due to the influence of the Ulladulla trough off Sydney and Newcastle.

The New Zealand station gives a value of 3230 m. This calculated average depth is clearly too low, but it must be remembered that the 87° of arc which was used in the calculation as the great circle distance from Valdivia to Auckland is less than the actual path traversed by the wave. Part of the great circle between Auckland and Valdivia lies across the North Island of New Zealand. The seismic sea wave must have, in consequence, travelled over a longer path and even so, a large part of any path to Auckland is over submerged continental crust with water depths less than 1000 m where the speed of a shallow water wave will be less than 356 km/hr compared with an average speed of a wave to Hobart of 824 km/hr.

Tsunami waves are slowed down and quickly reduced in amplitude when they enter a shallow shelf-area which is studded with islands such as Bass Strait. Melbourne shows no trace of the tsunami and from the Point Lonsdale and Port Welshpool records very little can be gleaned.

VI. Conclusions

It can be expected that from earthquakes originating off-shore of South America the seismic sea wave will arrive first in Tasmania in 12 hr and then sweep up the eastern coast of Australia reaching Newcastle some 2 hr later. The forward crest of the wave would travel up the mid Tasman deep and towns on the Tasman Sea side of New Zealand would be affected by this wave at roughly

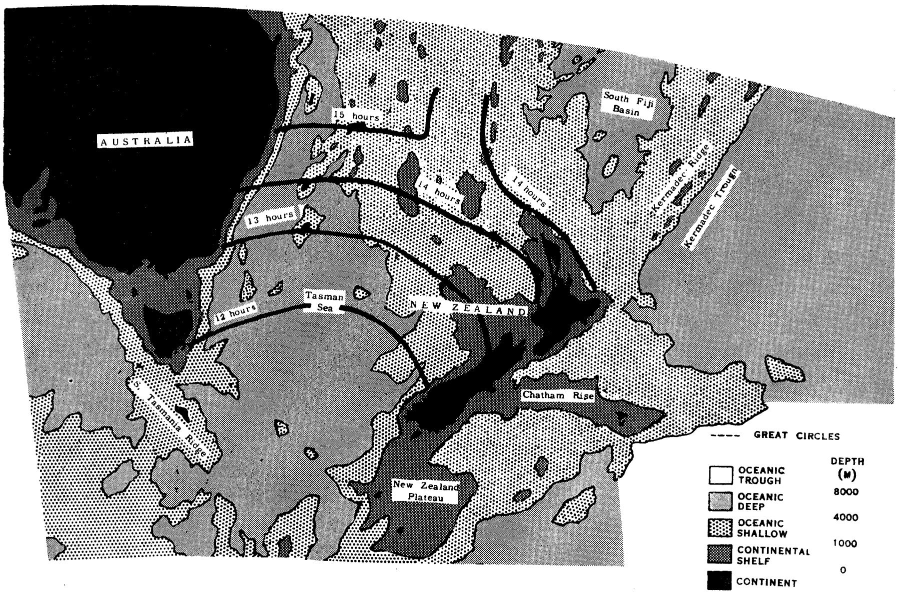

Fig. 8.—This shows the tsunami spreading over the Tasman Sea. The map in Bonnes projection 1 : 28,000,000. By means of the Antarctic Basin the wave quickly arrives in the South Tasman Sea. Notice the interference pattern obtained off the Queensland coast. Notice also the retarding effect of shallow water on the progress of the wave.

the same time as towns on the eastern coast of Australia. It would be expected that the tsunami would arrive at towns in the South Island of New Zealand (see Fig. 1) considerably earlier than at Auckland.

The spreading of the tsunami over the Tasman Sea is shown in Figure 8. This figure is based on calculations of the type in Section III for the form of the wave fronts, and on tide gauge observations for the numerical values of the isochronous fronts.

Much of the Queensland coast (see Fig. 1) is protected by a submerged continental shelf over which the speed of the wave would be greatly reduced similarly as in the approach to Auckland. It would be expected that the effect of the wave would be small on Queensland coastal towns. Also shown in Figure 8 is that the initial wave may arrive at places in the northern part of the Tasman Sea by two widely different paths ; one path via the Antarctic Basin—Tasman Sea and the other path more directly across the Pacific Basin and the South Fiji Basin. The wave front for the former case will be travelling northwards, whereas in the latter case it will be travelling westwards, and the two sets of waves will interfere with one another off the Queensland coast.

The phase relationships between the waves recorded by the Camp Cove and Fort Denison gauges are interesting. These two gauges in Sydney Harbour show very little difference in phase for the first few hours after the arrival of the tsunami but as time elapses the phase difference becomes large as Sydney Harbour is excited into a resonant seiche.

The seismic sea waves are often destructive in Japan and Hawaii but it is very unlikely that a " tidal wave " will inundate Australian towns because, as Figure 1 shows, nowhere in Australia is the coast flanked by a great ocean deep ($\simeq$9000 m). The Ulladulla deep is our nearest approach to this type of structure but even the Ulladulla deep is only of the order of 5000 m.

VII. Acknowledgments

I wish to thank the various harbour authorities and other organizations for copies of their records : The Hobart Marine Board, the Maritime Services Board of New South Wales, The Auckland Harbour Board, The Melbourne Harbour Trust Commissioners, The Department of Public Works (Victoria), The Division of Fisheries and Oceanography, C.S.I.R.O., and the Department of Geophysics, Australian National University.

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