Ocean disposal of ash. January 1963.

Author:
Foster, D. N.; Stone, D. M.

Publication details:
Commissioning Body: Electricity Commission of New South Wales.
Report No. UNSW Water Research Laboratory Report No. 65

Publication Date:
1963

DOI:
https://doi.org/10.4225/53/579576b4caad2

THE UNIVERSITY OF NEW SOUTH WALES

WATER RESEARCH LABORATORY

REPORT No. 65

Ocean Disposal of Ash

https://doi.org/10.4225/53/579576b4caad2

by

D. N. Foster & D. M. Stone

JANUARY, 1963

The University of New South Wales

WATER RESEARCH LABORATORY.

OCEAN DISPOSAL OF ASH.

by

D. N. Foster and D. M. Stone

Report submitted to Electricity Commission of New South Wales, January 1963.

* * * *

PREFACE

This study forms part of a series of hydraulic investigations undertaken by the Water Research Laboratory of The University of New South Wales at the request of the Electricity Commission of New South Wales. The study was commenced in December 1960. Work is still proceeding on some aspects.

Throughout the course of the study, close liaison has been maintained with the Electricity Commission through engineers on the staff of the Commission's Project Development Section, Messrs. Ken Watson and Garth Coulter, whose co-operation in the supply of all necessary data is gratefully acknowledged. Internal progress reports of test results have been forwarded to the Commission as experimental data became available.

The study was carried out at the Water Research Laboratory, Manly Vale, N.S.W. The Electricity Commission program is under the direct supervision of Mr. D. N. Foster of the Laboratory Research staff.

H. R. Vallentine,
Assoc. Professor of Civil Engineering,
Officer-in-Charge of the Water
Research Laboratory.

January 1963.

<u>TABLE OF CONTENTS</u>

* * * * * *

SUMMARY

Marine disposal of fly-ash from power stations near the coast has been proposed as capable of offering economic and aesthetic advantages over land disposal. Investigations into the probable behaviour of the ash after it has been discharged into the sea are reported. Analytic studies have been combined with the results of laboratory and field experiments to predict the movement of ash after disposal and to define the extent of the nuisance that could be caused.

Though some aspects of the study have not proceeded beyond the preliminary stage, others are complete; and the data is here assembled for initial feasibility assessment and definition of direction of future work.

It has been found that material as fine as fly ash will not remain on beaches and will be transported at some rate to very great depths in the ocean. The rate is not yet known. Transport may take place under the action of a turbidity current or by the action of natural forces such as waves and currents on material in suspension. Both phenomena will probably be in evidence, the dominance of either one over the other varying in time and space.

Deposition of ash near the outfall is certain, the extent of the deposit being defined by the relative rate of supply of material to the area and of removal of material by the transporting forces described above. Bed deposits will be subject to intermittent erosion when the wave forces are strong enough to entrain the settled ash.

Because of the high degree of turbulence in the ocean, diffusion of ash throughout substantial volumes of water may occur. The degree of discolouration will be inversely proportional to the quantity of water through which the ash disperses. It is deemed improbable that the discolouration will present any appreciable aesthetic degradation, but more work would be needed to forecast exact colour changes and lateral extent of discolouration.

NOTATION

A	cross sectional area of a wave
a	double amplitude of oscillation of water particle in horizontal direction
b	double amplitude of oscillation of water particle in vertical direction, subscript referring to breaking waves
C	wave celerity, $\sqrt{\frac{8g^*}{f(1+\alpha)}}$
D	depth of frictional resistance
d	particle diameter
E	energy per unit width of crest per wave length, entrainment coefficient
e	base of natural logarithm
F	fetch length
$\mathbb{F}^*$	densimetric Froude Number
f	friction factor, function
g	gravitational acceleration
g^*	$\frac{\rho-\rho_o}{\rho}g$
H	wave height from trough to crest
h	a measure of the thickness of a density flow
i	slope
K	pressure attenuation factor
l	distance from shore to breaker line, halfwidth of column of heavy fluid
n	proportion of total energy advancing with wave form
o	subscript referring to deep water or ambient fluid

R	$\frac{8 A_b \cos \alpha_b}{f l T}$
Ri	Richardson number = $\frac{\rho - \rho_a}{\rho} \quad \frac{g h \cos \alpha}{U^2}$
T	wave period
t	wind duration
U	velocity
$\bar{U}$	mass transport velocity
U_L	longshore current velocity
U_s	velocity of travel of disturbances in collapsing column
U_w	sea surface wind drift velocity
u	horizontal component of velocity
v	vertical component of velocity
W	wind velocity
w	particle fall velocity
Y	water depth, subscript referring to values at the bed
y	vertical distance below still water level (negative downwards), depth of flow
α	slope, angle between shore and wave crest, angle between wave crest and bottom contour, ratio between shear stress at interface and shear stress at boundary
γ	weight of fluid per unit volume
λ	wave length
ρ	fluid density
ϕ	latitude
τ	shear stress
ν	kinematic viscosity

1. INTRODUCTION

1.1 The General Problem

In New South Wales, as in many other countries, electricity is generated mainly at thermal power stations. Coal is the chief fuel used. The residue from the burning of coal is known as "ash". Large modern stations almost invariably use pulverised fuel in their boilers and the residual ash is then of two distinct types: bottom ash and fly-ash. Bottom or furnace ash is collected in hoppers at the bottom of the furnace and is a rather coarse material with particles of the size of small gravel. Fly-ash or "dust" is collected by electrostatic precipitators from the flue gases of the furnace and is a fine powdery substance with silt-sized particles.

As demand for electricity increases, ever larger quantities of ash are produced. Some industrial uses have been found for both types of ash, such as the application of fly-ash as a pozzolan for concrete. The commercial demand for ash, however, takes only a small fraction of that produced; and, unless some new use requiring large quantities of ash is discovered, the bulk of this material must be regarded as waste. Its disposal then presents a problem.

At present, ash from several power stations in New South Wales is pumped, as a slurry in water, into "ash ponds", usually formed by the construction of dams. As stations increase in size and number and the most suitable disposal sites are used up, higher dams and longer pipelines are required; and getting rid of waste ash becomes more and more expensive. Under these circumstances, the ocean offers itself as a possible economic alternative for absorbing waste from power stations built near the coast.

Barges transport power station ash and other waste materials to sea in many parts of the world. In Great Britain, for example, large quantities of ash are continually being dumped by barges "in approved areas beyond the 20-fathom contour" (Harwood and Wilson, 1957). The present investigation deals with a somewhat different proposal, namely continuous pumping to the ocean by pipe-line of a slurry of fly-ash and water.

1.2 The Particular Problem

Ocean disposal of ash is envisaged first for Munmorah Power Station which is located west of Lake Munmorah (Figure 1) some 50 miles north of Sydney. The station is expected to start operating

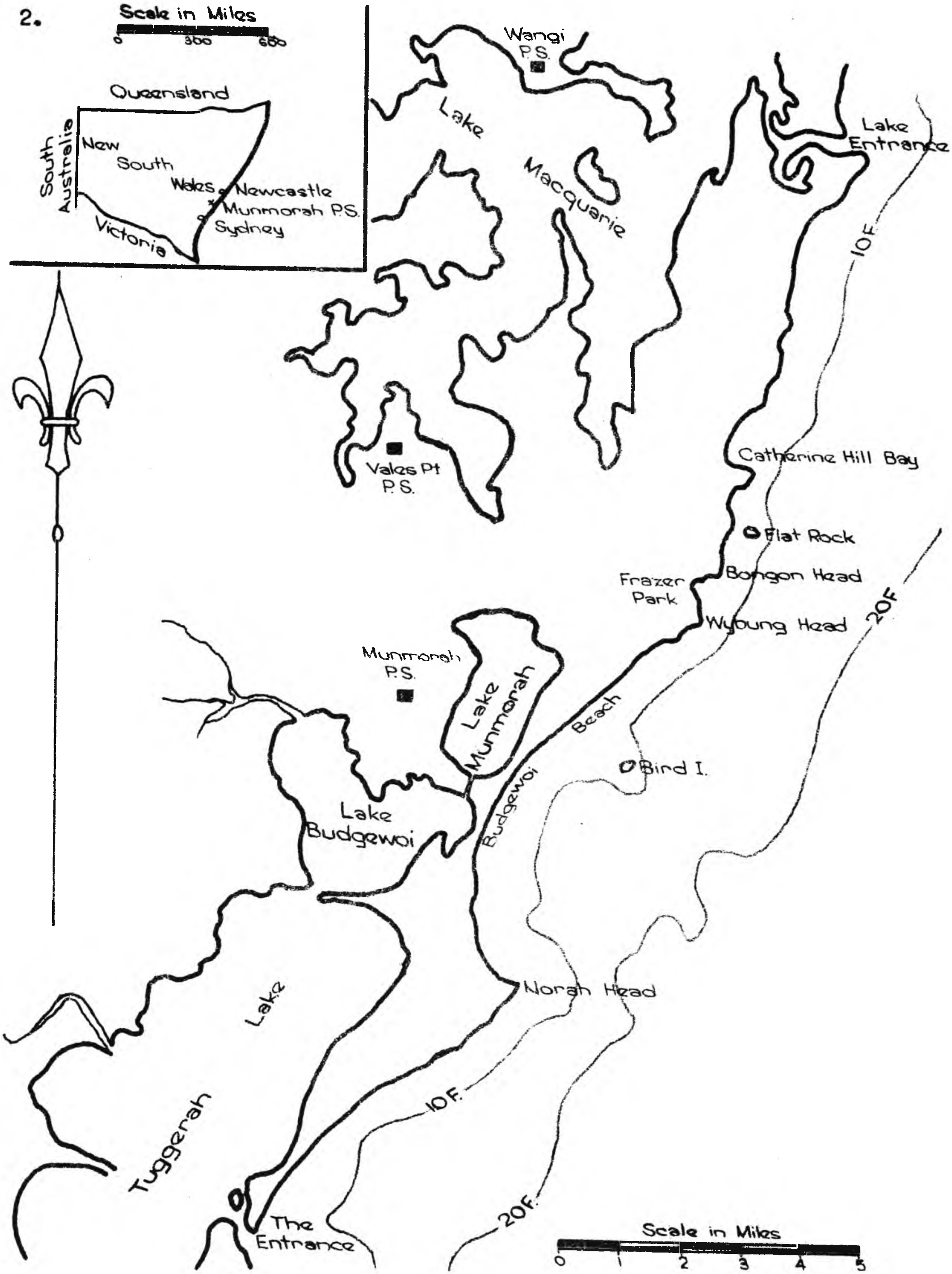


Figure 1: Location Map

about 1968 with two 350 M.W. units. At a later date two further units of similar size are to be installed. Some 600 tons of waste ash per unit per day will be produced. Thus, from 1968 onwards, over 1000 tons of ash from Munmorah Power Station will have to be disposed of daily, and in the future this figure may be increased to 2,500 tons. Several other power stations are planned for the future in this area, to take advantage of the vast coal reserves in the vicinity. These stations may also find the ocean a suitable recipient for some or all of their waste ash.

For many reasons, including the fashion in which the ocean handles various materials submitted to its forces, it has seemed unwise to consider ocean disposal for bottom ash, unless it be ground to a sufficiently small size before pumping. For Munmorah Power Station, land disposal of this material is currently envisaged. Bottom ash, with its larger size, has an immediate application for land reclamation or "filling". However, this ash constitutes only about 20 percent of the residue from a power station, the other 80 percent being fly-ash. This is the material which presents most problems in disposal, and which it is proposed to pump to the ocean. The fly-ash seems a suitable material for ocean disposal, except perhaps for a small quantity, of the order of 0.1 percent of the total, which floats, and which may have to be disposed of separately.

The studies described in this report have been directed to the investigation of what happens to the material after it reaches the sea. Additional work has still to be carried out on specific aspects to complete the investigation, but sufficient information has been obtained to assist in the initial assessment of the feasibility of the proposal.

Some inquiries have been directed specifically to the Wybung Head area, as it seems to present a suitable place for discharging ash from Munmorah into the ocean. Here the cliff face drops away steeply, reaching a depth of 40 feet of water at a distance of 150 feet from the headland (Figure 2). At a distance of 600 feet, 60 feet of water is found, representing an average slope over this distance of 1 in 10. Normal continental shelf slopes averaging 1 in 300 are then encountered until a depth of 600 feet is attained 20 to 30 miles offshore. The edge of the shelf then drops away sharply, with slopes of the order of 1 in 10, to depths of thousands of fathoms. It is hoped that, by discharging the ash in an area where a considerable depth of water is available close to shore, it will more rapidly betake itself to regions where its possible nuisance value is reduced to a minimum.

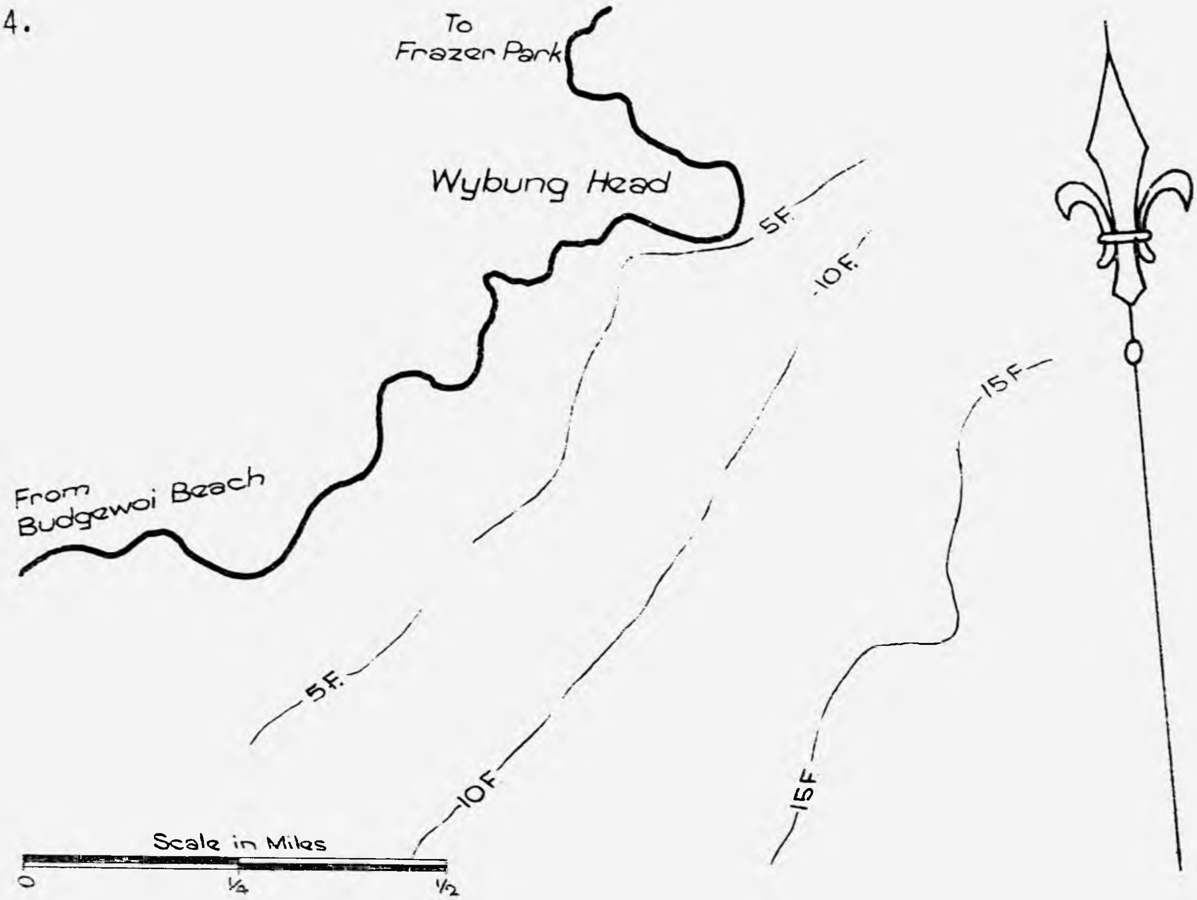


Figure 2a: Coastline and Ocean Bed Contours.

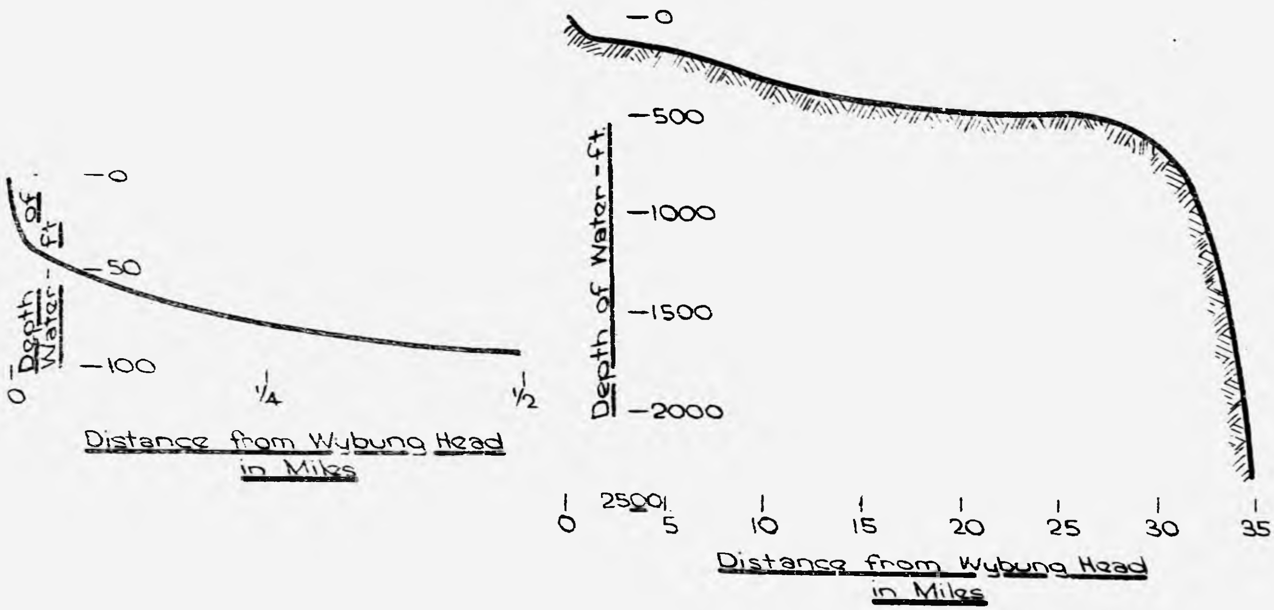


Figure 2b: Vertical Section on Line E.S.E. from Wybung Head.

In the removal of ash from its point of deposition, many factors are involved. The forces of the sea, waves, tides and currents, need to be investigated, as well as the possibility of formation of a turbidity current, carrying the material seaward as an "underflow". This report gives some information on these aspects of the investigation and discusses some of the implications.

2. ASH PROPERTIES

2.1 General Description

Fly-ash is a fine, powdery substance often referred to as "dust". It consists mainly of angular to sub-angular silt-sized particles of specific gravity about 2, the particle shape and size and specific gravity varying somewhat from one ash to another, depending on the type of coal burnt. The colour ranges from silvery-grey to black, and fly-ash produced in New South Wales has a higher electrical resistivity than many overseas ashes.

2.2 Chemical Composition

Analysis of a sample of dust obtained from the burning of Wallarah coal in a pulverised fuel furnace at Pyrmont Power Station, Sydney, yielded the results given in Table 1. Munmorah Power Station is to be fed partly from the Wallarah seam, and the furnaces and dust precipitators planned for Munmorah are of a type that should produce ash similar to that produced at Pyrmont, so that the Pyrmont sample can be regarded as indicative of ash to be expected from Munmorah, except that more efficient combustion may reduce the carbon content.

TABLE 1.

Chemical Analysis of Wallarah Fly-ash

Loss on ignition	8.3	percent
Silica SiO_2	50.3	"
Total Sulphur calculated as S	0.12	"
Total Sulphur calculated as SO_4	0.37	"
Total Sulphur calculated as SO_3	0.31	"
Total Sulphur after ignition SO_3	0.30	"
Total Sulphate SO_4	0.32	"
Alumina Al_2O_3	28.2	"
Iron Oxide Fe_2O_3	5.0	"
Titanium Oxide TiO_2	1.3	"
Calcium Oxide CaO	4.12	"
Magnesium Oxide MgO	1.10	"
Alkalis - Na_2O	0.29	"
K_2O	0.30	"
Phosphorus calculated as P_2O_5	0.37	"
Chlorides Cl	Nil	
Water Soluble Salts	0.78	"

Chemical tests also show that fly-ash is usually very slightly acidic, and is completely sterile and non-toxic. Although minor variations in composition occur, silica and alumina are always the main constituents.

2.3 Specific Gravity

Average specific gravities as low as 1.5 and as high as 2.35 have been found for New South Wales fly-ashes. Ash resulting from the burning of Wallarah coal in pulverised fuel furnaces has an average specific gravity very close to 2.0. The low specific gravity of the material, as compared with that of many naturally occurring alumino-silicates, such as sand, silt and clay, has been attributed to the fact that some particles have fused and bubbles of air or gas have been trapped during rapid cooling to the solid state. In the extreme case, enough gas is trapped to reduce the specific gravity to less than 1, and a small proportion of the ash will float in water. The temperature of the furnaces and the duration of the process are not sufficient to fuse all the particles, some of which are subjected only to the intermediate stage known as "sintering", or incipient fusion of sharp protuberances, while others do not seem to leave the solid state at any time.

The amount of floating ash has been estimated to be of the order of 0.1 percent of the total. This means that something of the order of one ton per day of this material will require disposal. Its specific gravity averages about 0.7, but ranges from very close to 1 down to some undetermined figure. An investigation of methods for removing the floating fraction before the ash is pumped to sea is being made, as well as a study of the probable behaviour of such floating material if disposed of in the ocean.

2.4 Particle Size

2.41 Method of Analysis

Most fly-ash contains particles so fine that standard sieve analysis cannot be used to define the grading. At the Water Research Laboratory, analyses have generally been made by bottom withdrawal tube (A Study of methods used in measurement and analysis of sediment loads in streams: report no. 7, 1943). Standard hydrometer analyses have

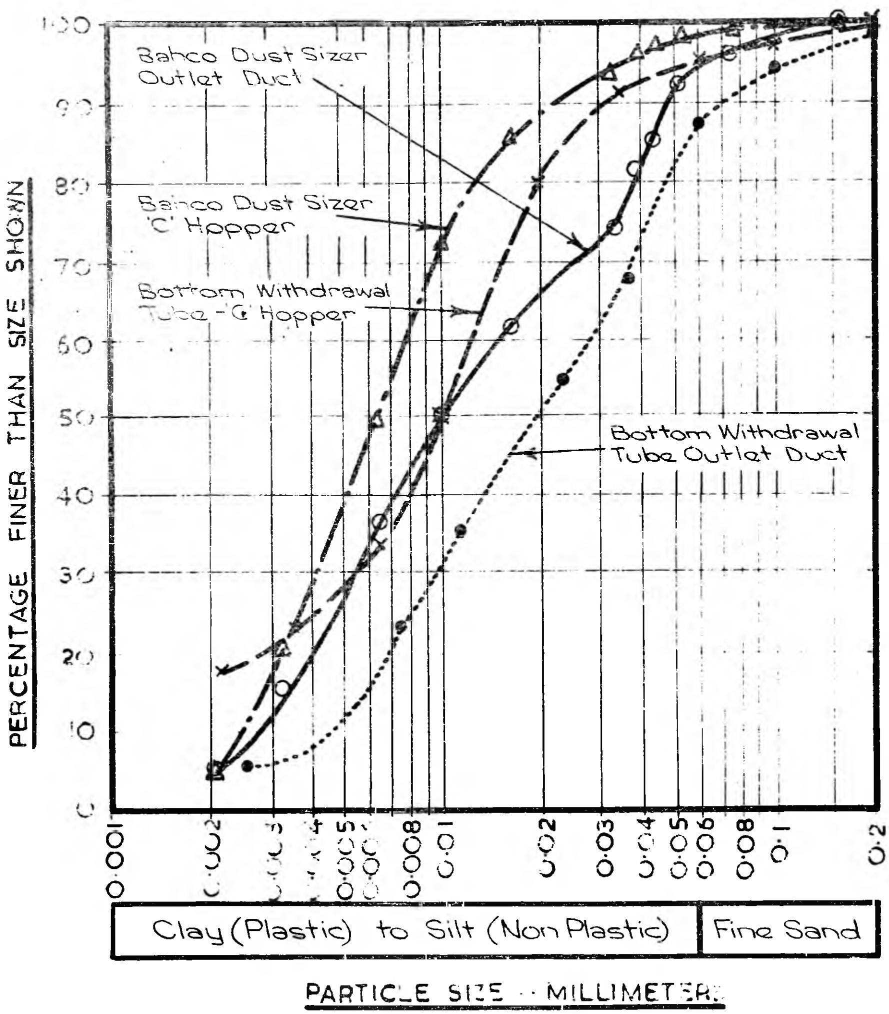


Figure 3: Particle Size Analysis of Wangi Fly-Ash by Bottom Withdrawal Tube and Bahco Dust Sizer.

been performed on a few samples. Both of these methods depend on the fact that particles settle in a still fluid at rates differing with the size and specific gravity of the particles, and the density and viscosity of the fluid medium; but the techniques differ somewhat. In the bottom withdrawal tube analysis, samples are withdrawn at various time intervals from the bottom of a long tube, and the amounts of material settling out at the various times are measured. By the application of Stokes's Law for settling velocities (corrected for the larger grain sizes) and Oden's Dispersion Law, the percentage of material in any grain size range is then calculated. Hydrometer analysis differs from bottom withdrawal analysis in that it measures the amount of material left in suspension at any time instead of the amount settling. In ideal circumstances the results of these tests should agree. The theory on which the tests are based is, however, developed for spheres; and any departure from sphericity can cause discrepancies because of the different parameters measured.

It is important to note that size gradings of dust as quoted in many reports are based on analysis by a Bahco dust-sizer. Generally speaking, size gradings obtained by this method differ from those obtained by bottom withdrawal tube analysis and care must be used when comparing gradings of different samples obtained by the two techniques. Comparison between size gradings for the same samples of dust collected from the precipitators of the Wangi Power Station as obtained by the two methods is given in Figure 3. It can be seen that the Bahco dust-sizer indicates smaller particles.

2.42 Size Gradings by Bottom Withdrawal Tube Analysis

Figure 4 indicates the range of gradings obtained for fly-ash from New South Wales Stations by bottom withdrawal tube analysis. Samples of ash from any one station obtained at different times have shown gradings extending over nearly the full range. Stations represented were Bunnerong, Pyrmont, Tallawarra and Wangi; and the coal burnt came from various seams including Big Ben, Fassifern, Great Northern, Nattai River and Wallarah.

The range of bottom ash as found for some samples from Wangi Power Station is also shown on Figure 4 for comparison. It can be seen that fly-ash falls mostly in the silt size category, while bottom ash is of the size of sand or small gravel.

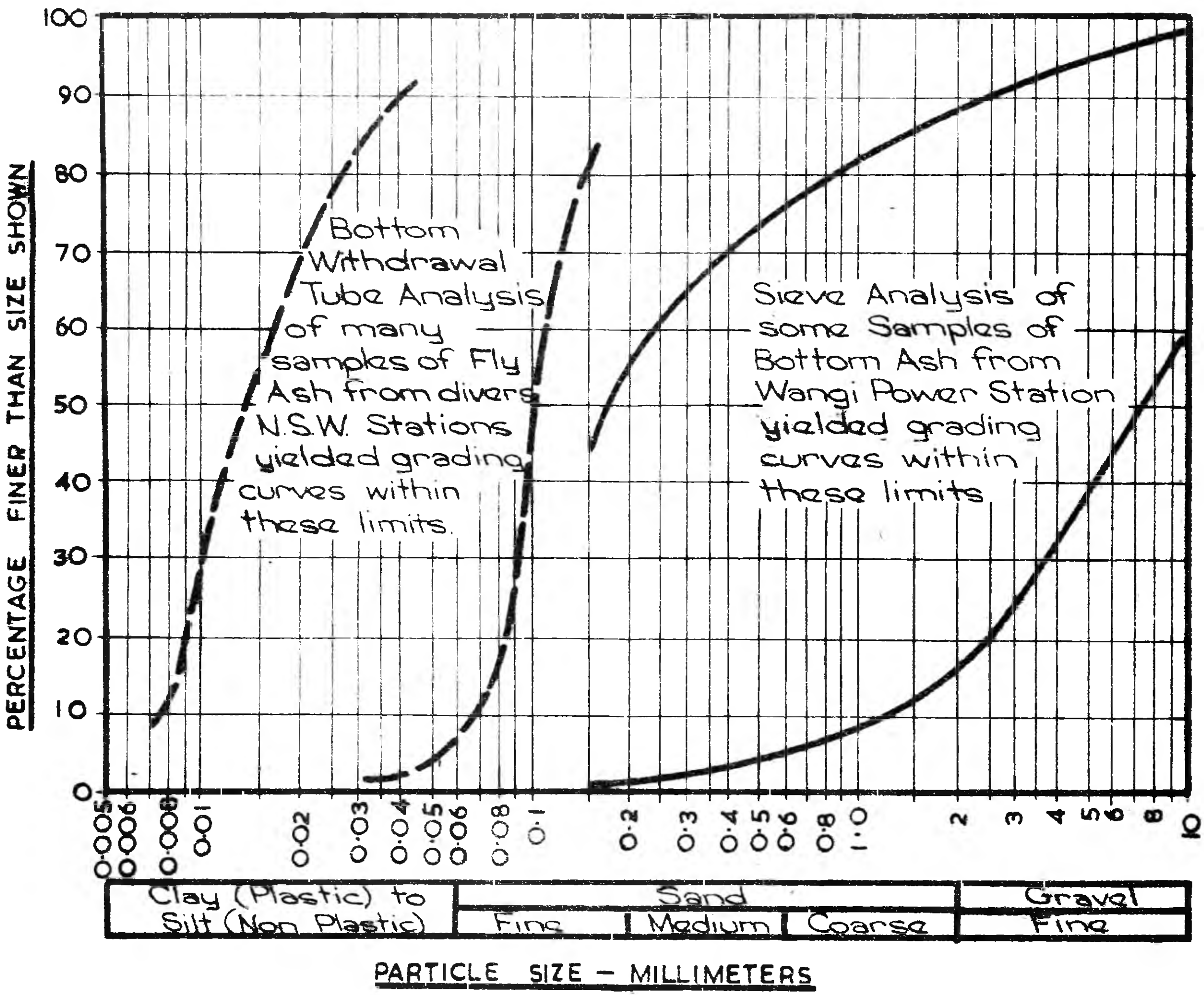


Figure 4: Particle Size Analysis of Ash.

2.5 Floccing Properties

2.51 General

To forecast the behaviour of an ash slurry discharged into the ocean, it is necessary to know not only the absolute particle size of the ash, but also the extent to which it is susceptible to floccing. Many silts exhibit this phenomenon, especially in sea water. Hunter River silt, for example, shows negligible floccing in distilled or tap water, whereas in sea water all particles below about 0.03 mm floc to an almost constant particle size between 0.02 and 0.03 mm. Figure 5 shows particle size gradings for flocced silt (tested in sea water) and the unflocced material (tested with deflocculent)*.

Should fly-ash show marked floccing either in fresh water or in sea water, this would have to be taken into account in considering the mechanics of flow from an ocean outfall. The rate of deposition from any turbidity current that may be formed, for example, would depend on the size and density of the particles. Were turbulence insufficient to prevent floccing, each floc would act as a particle of greater size and lower density than an individual particle of ash, and the deposition characteristics of the turbidity currents would differ vastly. Moreover, if fly-ash were to exhibit different floccing characteristics in sea water from those it exhibited in fresh water, laboratory testing would either have to be performed in sea water, or corrections would have to be made in extrapolating the results of fresh water testing to prototype.

Fortunately, though fly-ash flocs to a degree in both fresh and sea water, the extent of floccing is not great, the difference between flocced and unflocced material being less than differences between samples collected from the same power station at different times; and furthermore, negligible difference exists between fresh water and sea water conditions. The floc formed is of the type known as "pin point", the ultimate particles being still very small compared with the loose gelatinous type flocs formed by many chemical processes. For fly-ash, the process of floccing seems to be incomplete when compared with silt floccing, so that sizes covering a wide range continue to co-exist. That fly-ash floccing is probably a permanently incomplete process was evidenced by observations of suspensions of ash in sea water after several days. Figure 6 shows particle size gradings carried out in various media by both bottom withdrawal tube and hydrometer analysis. To understand this figure, it is necessary to know something of the testing on which the curves are based.

---

* Data based on bottom withdrawal tube tests carried out by N.S.W. Public Works Department, Hydraulic Laboratory, Manly Vale.

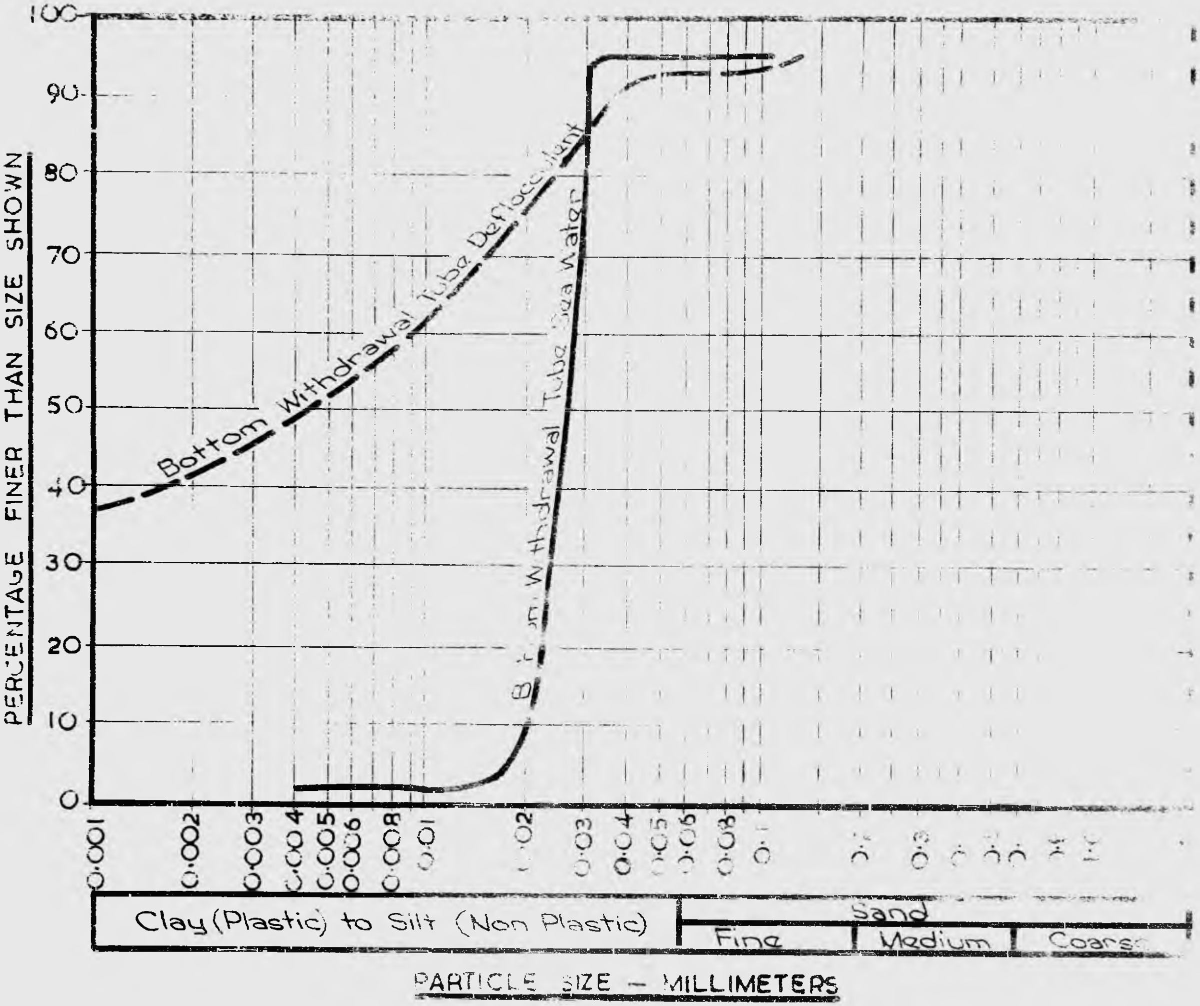


Figure 5: Particle Size Analysis of Hunter River Silt Showing Floccing in Sea Water.

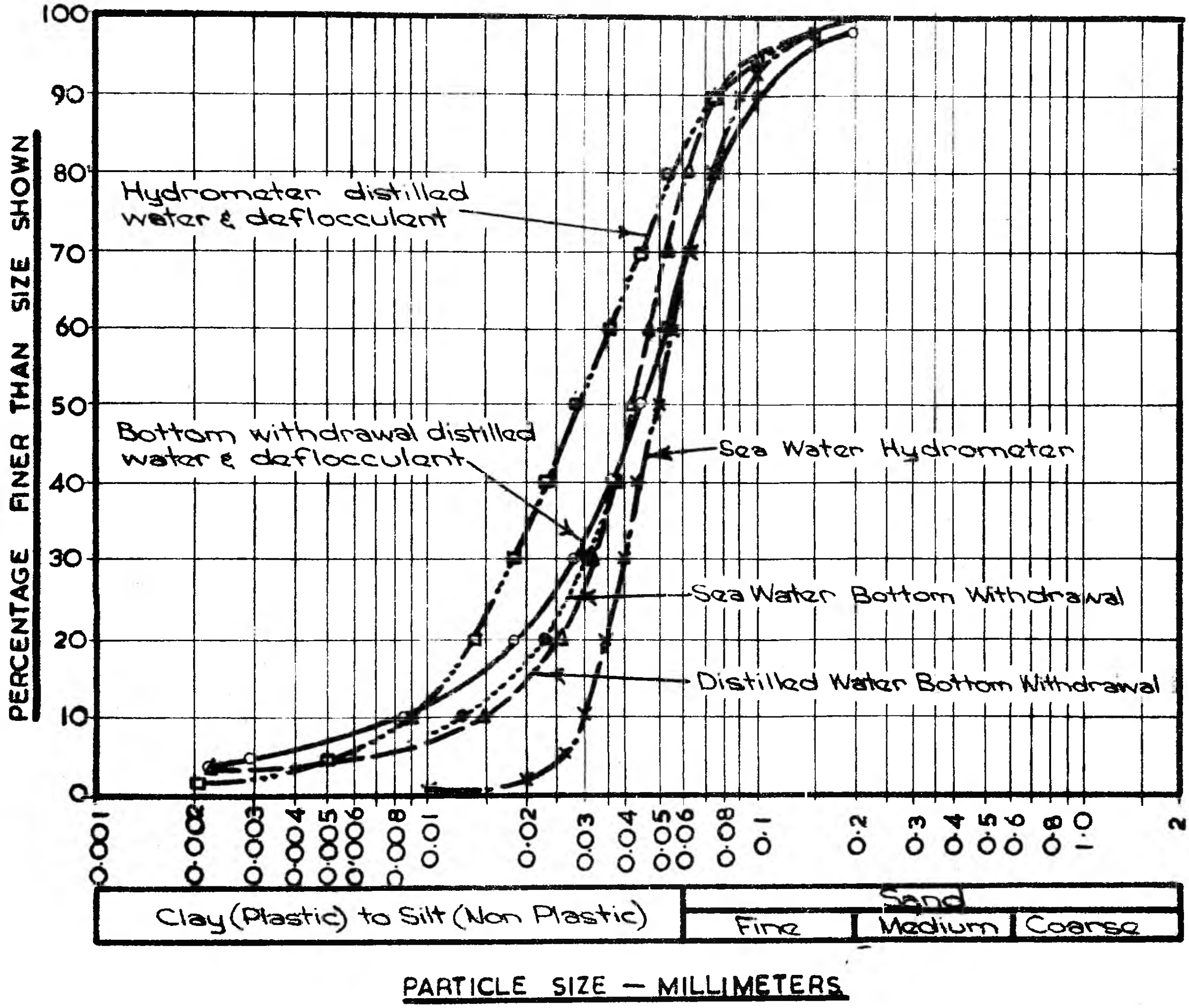


Figure 6: Particle Size Analysis of Bunnerong Fly-Ash Showing Floccing Tendency.

2.52 Floccing Tests

Fly-ash from Bunnerong power station was used for the tests whose results are recorded. Other tests have been performed with ash from various power stations; but, as these tests were not in controlled series, numerical data are not given. The tests showed that the fly-ash from different sources flocs in the same way, and the Bunnerong results are regarded as indicative of the floccing to be expected of Munmorah fly-ash.

Where a floc exists, important discrepancies between gradings obtained by bottom withdrawal tube and hydrometer analysis are manifest. Firstly, the floc does not form instantaneously but gradually, and of necessity while the test is in progress. Secondly, the specific gravity of the floc is lower than that of individual particles and calculations based on the specific gravity of the material therefore do not give exact results for floc sizes. In spite of these inaccuracies, the tests suffice to show the floccing properties well enough for the purposes of this study. Results of bottom withdrawal tests are, however, not comparable with results from hydrometer tests, because the effects of the differences described in Section 2.41 are accentuated by floccing.

Test results are shown in Figure 6. Three bottom withdrawal tests were performed - one using the alkali household Calgon as a deflocculent for the slightly acidic fly-ash, one with distilled water and one with sea water. Floccing of very similar intensity is evident in the grading curves for distilled water and sea water. The fact that the curve for sea water does not extend below the 0.01 mm size is not regarded as evidence that smaller particles are necessarily absent; for, with the small percentages of fly-ash of finer sizes and the large amount of salt present, measurements below this range give results of dubious accuracy.

Results of bottom withdrawal tests indicate that there is a smaller amount of the coarser grains when distilled or sea water is used than with deflocculent. If the curves give a true indication of particle sizes, some breakdown of larger grains must be hypothesised. This hypothesis is untenable, and the applicability of the procedure is therefore called into question. Wrong assumptions of specific gravity for flocced material could be a factor tending to invalidate the curves, but the main factor is probably the physical reality of eddy currents in the withdrawal tube during the floccing reaction. Quite strong rising currents have been observed near the perimeter of the tube, especially in the early stages of the test, with both distilled and sea water. These currents tend to maintain material in suspension. The presence of flocced material of lower fall velocity may also have an effect, not entirely accounted for by applying Oden's

Dispersion Law, in retarding the fall of larger particles and therefore making them appear smaller in the results.

Hydrometer analyses performed first with deflocculent and then with sea water confirm the floccing tendency of the ash. The upper parts of the ash-in-sea-water hydrometer analyses do not exhibit the anomalies found in the bottom withdrawal tube curves. However, below a particle size of 0.02 mm the grading curve is very badly defined by the results, as the hydrometer reading changes very slowly and is therefore highly susceptible to inaccuracies in reading. In the hydrometer analysis, the concentration of ash was 8 times as high as in the bottom withdrawal tube analysis; with so much material present there is a good chance that the extensive floc formed will carry with it in its fall the smaller particles which would otherwise remain in suspension. This may partly explain why the hydrometer curve for ash in salt water shows a much lower percentage of fine material than does the corresponding bottom withdrawal curve. The true curve for the flocced material probably lies somewhere between the curves found by hydrometer and bottom withdrawal tube.

3. WAVES

3.1 Wave Theory

3.10 General

Waves and currents are major forces likely to affect the movement of ash discharged in the ocean. The importance of waves cannot be over-estimated: the water movements at depth caused by waves create an atmosphere radically different from that existing in the absence of wave action, and the transport of ash in such an atmosphere is consequently markedly different from ash transport in quiescent waters. Fine ash in suspension undergoes similar movements to the water particles, unless it is travelling in the form of a turbidity current. In this case the waves also make their presence felt, for the turbulence they induce hinders deposition and favours entrainment, and the initiation and especially the maintenance of turbidity current action is subject to a modified set of conditions. When ash has settled, its re-entrainment is most likely to be effected by wave action, as other currents are generally insufficient, so close to the bed, to move the ash. Once the material has been put into suspension by the waves, it is then available to the other currents and forces of the sea.

The theory outlined below is essential to an understanding of the role of the wave in ash transport. It has been made as descriptive as possible, consistent with complete presentation of relations used for quantitative analyses in subsequent sections of the report.

3.11 Characteristics of Ocean Waves

Of the many mathematical models proposed, the irrotational theory (Stokes, 1847) seems to represent most closely the natural phenomena associated with ocean waves. For waves whose height is very small compared with the wave length and water depth, Stokes's theory taken to the first approximation indicates a sinusoidal wave form as given by the Airy-Laplace analysis (Airy, 1845; Laplace, 1775-76). Wave height, H, is defined as the vertical distance from trough to crest and wave length, λ, as the distance between two successive crests. As with all periodic wave motions, the basic equation is given as:

$$\lambda = C\,T \qquad (1)$$

where C = celerity
T = period

The equation for sinusoidal motion (Lamb, 1932), omitting surface tension effects which may be neglected for ordinary gravity waves on the ocean, is given as:

$$C^2 = \frac{g\lambda}{2\pi} \tanh \frac{2\pi Y}{\lambda} \qquad (2)$$

where g = acceleration due to gravity

Y = water depth.

As Y increases, $\tanh \frac{2\pi Y}{\lambda}$ approaches 1, and (2) becomes:

$$C_o^2 = \frac{g\lambda_o}{2\pi} \qquad (3)$$

where the subscript o refers to deep water conditions.

Use of this formula for values of Y greater than 0.5 λ gives a good approximation to the exact values. The error at Y = 0.5 λ is, for example, less than 1%. An arbitrary division of waves into "deep water waves" and "shallow water waves" has been made at this point.

By combining (1) and (3) the relation between wave length and period for deep water sinusoidal waves is obtained:

$$\lambda_o = \frac{gT_o^2}{2\pi} \qquad (4)$$

In deep water, the motion of a water particle at any depth is circular, with orbital diameters decreasing exponentially from the surface (Figure 7a). As a wave proceeds into shallow water, bottom effects elongate the orbits in such a way that an elliptical orbit results, the vertical axes of the ellipses decreasing linearly from the surface to a value of zero at the bottom (Figure 7b). The orbits

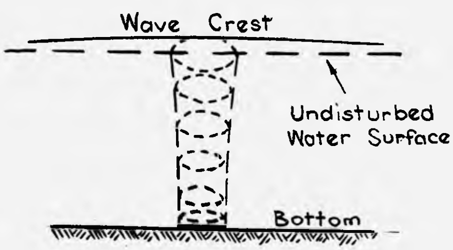


Figure 7b: Orbital Motion for Shallow Water Wave.

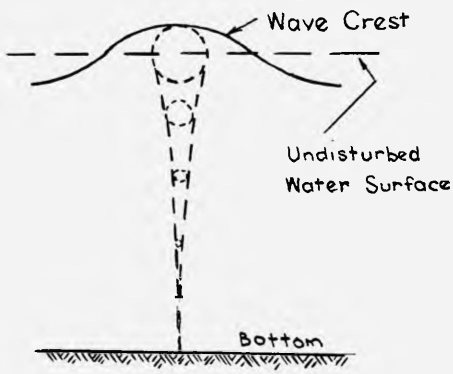


Figure 7a: Orbital Motion for Deep Water Wave.

are defined by the theory in terms of the displacement at any time of a particle from its initial position. The double amplitude of oscillation, or total travel of a fluid particle, at any depth y measured negatively downward from the surface is given by:

$$\frac{a}{H} = \frac{\cosh \frac{2\pi(Y+y)}{\lambda}}{\sinh \frac{2\pi Y}{\lambda}} \quad \text{horizontally}$$

and

(5)

$$\frac{b}{H} = \frac{\sinh \frac{2\pi(Y+y)}{\lambda}}{\sinh \frac{2\pi Y}{\lambda}} \quad \text{vertically}$$

where a and b are double amplitudes of oscillation in the horizontal and vertical directions respectively. In particular, at the bottom y = -Y and

$$\frac{a_Y}{H} = \frac{1}{\sinh \frac{2\pi Y}{\lambda}} ; \quad \frac{b_Y}{h} = 0$$

The orbital velocity is obtained by differentiating the displacement with respect to time. The maximum velocities attained during the orbit are given by:

$$(u_y)_{max.} = \frac{\pi a}{T} \quad \text{horizontally}$$

and (6)

$$(v_y)_{max.} = \frac{\pi b}{T} \quad \text{vertically}$$

The ratio of maximum orbital bottom velocity to wave height is shown in Figure 8 for various wave periods and water depths. Average velocities are given by:

$$(u_y)_{ave.} = \pm \frac{2a}{T} \quad \text{horizontally}$$

(7)

and

$$(v_y)_{ave} = \pm \frac{2b}{T} \quad \text{vertically}$$

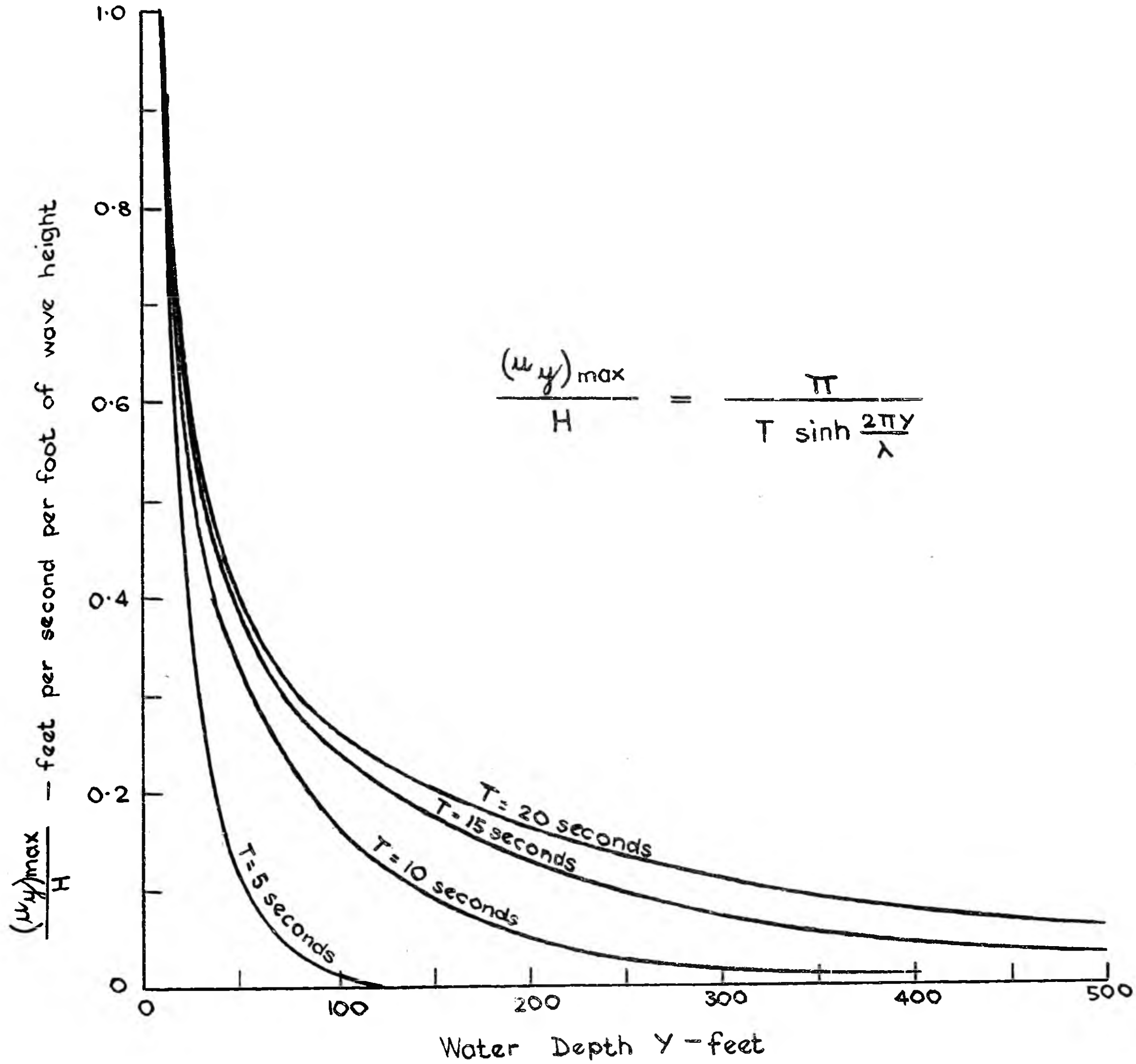


Figure 8: Maximum Orbital Velocity of Water Particles on the Bottom for Various Depths and Periods.

3.12 Energy

The total energy is the sum of the kinetic energy due to the motion of the particles and the potential energy due to the elevation of the particles with respect to the undisturbed level. The resultant total energy for deep water waves is given by:

$$E = \frac{\gamma \lambda_o H_o^2}{8} \qquad (8)$$

where γ = weight of water per unit volume.

Half of this energy is kinetic and half potential.

3.13 Sub Surface Pressures

By assuming an incompressible non-viscous fluid, the pressure changes during the passage of a wave may be calculated for any point beneath the water surface as a fraction, K, of the pressure changes associated with the orbital motion at the surface (Lamb, 1932). At any depth y measured negatively downwards from the still water surface, the pressure attenuation factor K is given as:

$$K = \frac{\cosh\left[\frac{2\pi Y}{\lambda}\left(1+\frac{y}{Y}\right)\right]}{\cosh\frac{2\pi Y}{\lambda}} \qquad (9)$$

Figure 9 is a dimensionless representation of this equation.

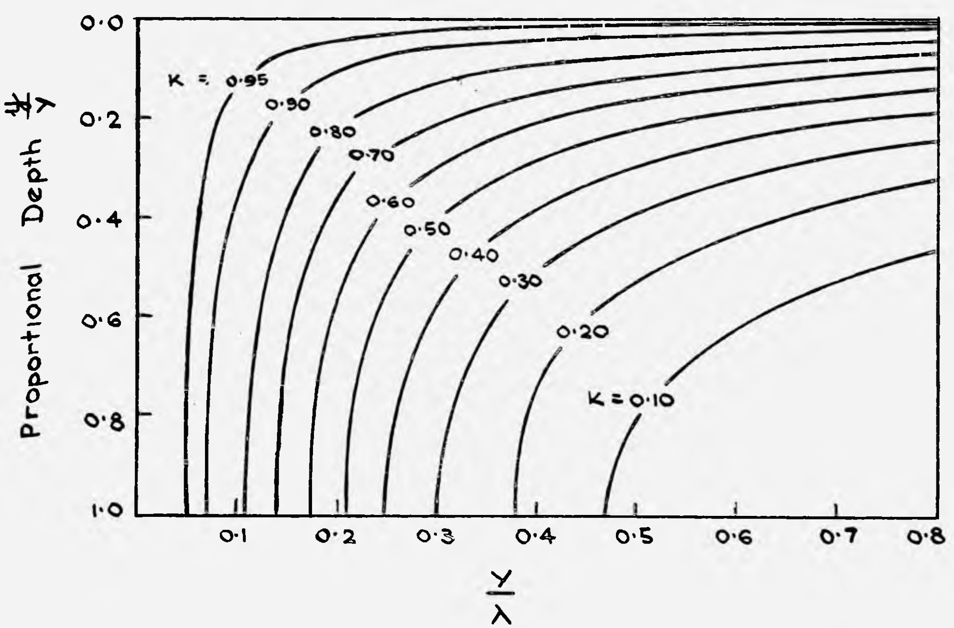


Figure 9: Pressure Attenuation Factor.

Experiments have shown that this gives a reasonable approximation to the true values for water waves of finite height.

3.14 Mass Transport

The theory outlined above was developed for waves of small amplitude. Experiments have proved that the equations also hold for waves of appreciable magnitude. Some approximations, however, cease to be valid, and one of the most notable is that of closed orbits, such that a particle returns after an orbit to its initial position. In fact, theoretical analysis for waves of finite height (Stokes, 1847) shows that the particle motion is greater in its forward movement (under the crest) than in its backward movement (under the trough). A water particle therefore arrives, after one complete wave, down-wave of its initial position, as shown in Figure 10 for a shallow water wave.

Figure 10: Open Orbit for Shallow Water Wave.

The net movement of water particles occasioned by the fact that the orbits are open rather than closed is termed mass transport. Stokes predicted a value for mass transport on the assumption of a perfect non-viscous fluid. For deep water, Stokes's equation becomes:

$$\bar{U} = \frac{\pi^2 H_o^2}{\lambda T_o} e^{\frac{4\pi y}{\lambda}} \qquad (10)$$

where $\bar{U}$ = mass transport velocity. This indicates a second order drift in the direction of propagation of the wave. Figure 11 is a diagrammatic sketch of the mass transport and return flow for a closed system, and Figure 12 gives values of mass transport per foot of wave height for various depths and periods.

Experiments have indicated that Stokes's solution is acceptable for deep water waves, but for shallow water waves the assumption of zero velocity gradient at the bed inherent in the theory leads to gross errors. Longuet-Higgins has recently evolved a theory which gives good agreement with experiments for shallow water waves (Longuet-Higgins 1953). The mass transport velocity at the bottom predicted by this theory is given as:

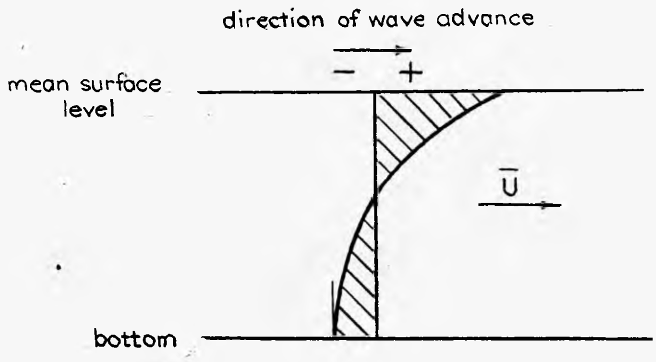


Figure 11: Mass Transport for Deep Water Waves (after Stokes)

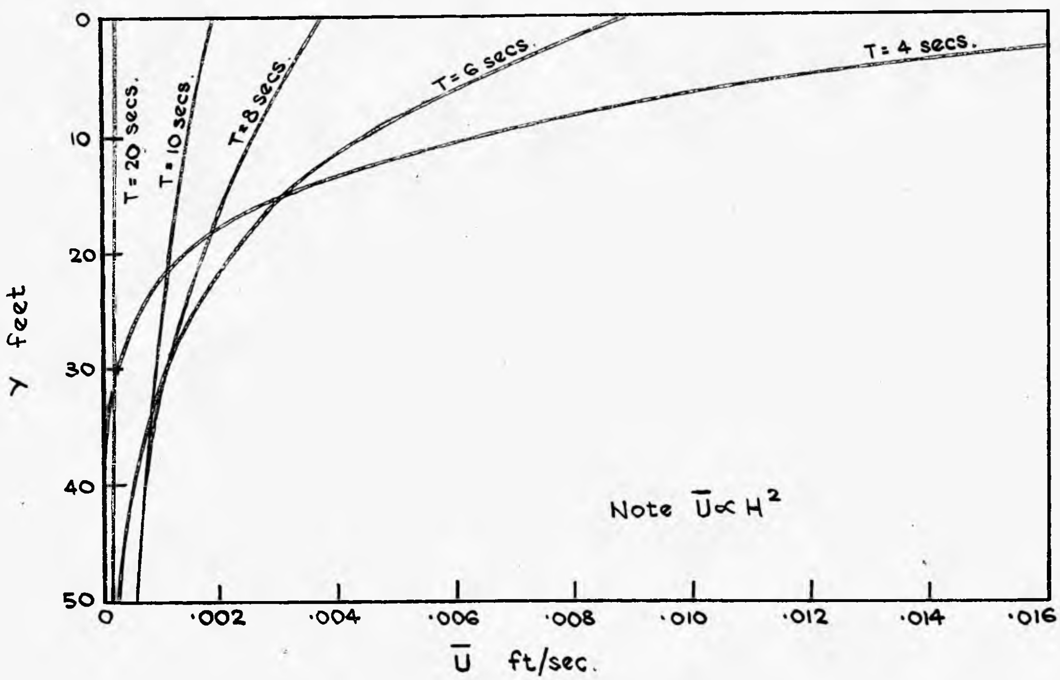


Figure 12: Mass Transport Values per Foot of Wave Height for Deep Water Waves (after Stokes).

$$\bar{U}_y = \frac{5}{4}\,\frac{\pi^2 H^2}{\lambda T}\,\frac{1}{\sinh^2 \frac{2\pi Y}{\lambda}} \tag{11}$$

The variation of velocity with depth "in the interior of the fluid" was predicted by Longuet-Higgins only for the case where wave amplitude is small compared with the thickness of the boundary layer on the bottom; however, it has been found that this solution agrees well with experimental values in most practical cases (Russell and Osorio, 1958). The solution gives for any value of y:

$$\bar{U}_y = \frac{\pi^2 H^2}{4\lambda T \sinh^2 \frac{2\pi Y}{\lambda}}\left[2\cosh\frac{4\pi}{\lambda}(y+Y) + 3 + \frac{2\pi Y}{\lambda}\sinh\frac{4\pi Y}{\lambda}\left(\frac{3y^2}{Y^2}+\frac{4y}{Y}+1\right) + 3\left(\frac{\sinh\frac{4\pi Y}{\lambda}}{\frac{4\pi Y}{\lambda}}+\frac{3}{2}\right)\left(\frac{y^2}{Y^2}-1\right)\right] \tag{12}$$

Some values are shown in Figure 13.

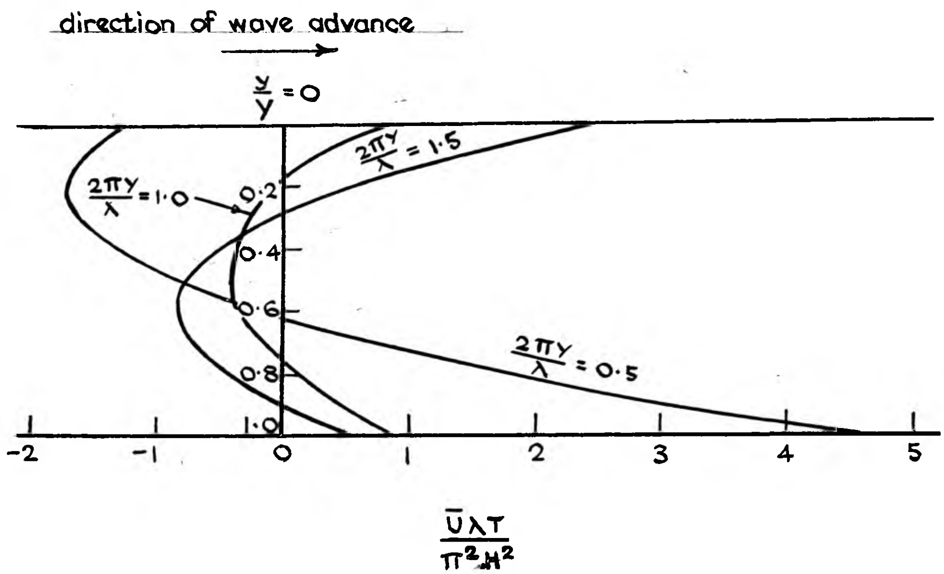


Figure 13: Mass Transport in Interior of Fluid for Shallow Water Waves (Conduction Solution of Longuet-Higgins).

3.15 Propagation of Wave Groups

Though a group of waves, once generated, maintains its identity over a considerable distance, the individual waves in the group do not. New waves are continually being formed as the old waves die away. This phenomenon is associated with the mechanism of transmission of energy. As a result of this method of propagation, the wave group moves forward with a velocity less than that of the individual waves in the group. In deep water the group velocity may be shown from energy considerations to be half the wave velocity. As the water depth decreases, the wave train moves with a velocity closer to that of the individual waves until, near breaking, when each wave is travelling more like a solitary wave, the group velocity becomes equal to the wave velocity.

3.16 Shoaling and Breaking of Waves

The theory outlined in the preceding pages was developed for waves in water of constant depth. Waves approaching a coastline progress through water of continuously changing depth. The orbital motion associated with such waves has been shown to agree with that predicted by this theory. Since it is through the change of water particle motion that the bottom makes its presence felt in the wave form, the changes in wave characteristics due to shoaling can be computed from energy considerations on the basis of the foregoing theory. In deep water half the total energy advances with the wave form at a speed equal to the wave celerity. In shallow water an increasing proportion of the total energy advances with the wave form. This additional energy is allowed for in the following equation by the quantity n, the proportion of the total energy advancing with the wave form. By assuming that the period and the power transmitted per unit width of wave crest remain constant, the relation between wave height and length is found to be:

$$\frac{H}{H_o} = \sqrt{\frac{1}{2n} \frac{\lambda_o}{\lambda}} \qquad (13)$$

The ratio $\frac{\lambda}{\lambda_o}$ is computed for any depth from equation (2). This quantity decreases with decreasing depth, while n increases with decreasing depth. The relative rates of decrease of $\frac{\lambda}{\lambda_o}$ and increase of n vary, with the result that the wave height $\frac{H}{H_o}$ first decreases to about 0.91, and then increases rapidly as the wave moves into more shallow water (Mason, 1951; U.S. Navy Hydrographic Office 1944). The changes of various wave parameters with shoaling are shown in Figure 14.

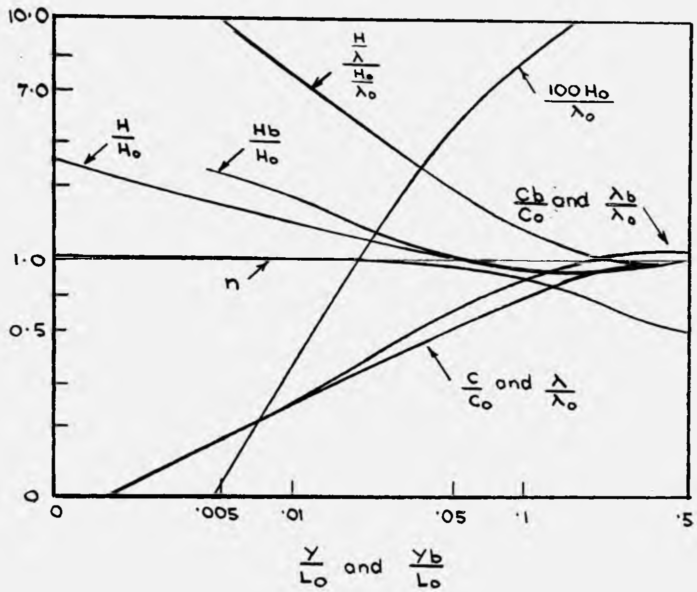


Figure 14: Shoaling Effects on Waves.

The increase of wave height associated with decrease in wave length causes the wave to become steeper. Steepness is defined as the ratio of wave height to wave length. Eventually a point is reached where the steepness is such that a wave can no longer hold its form and breaks. Stokes' theory indicates that a wave cannot survive with a crest angle smaller than 120^{o}. This theoretical limit is attainable in practice, indicating the range of validity of Stokes's theory. The limiting steepness is given as 0. 14.

As waves progress into shallow water near the breaking zone, they depart more and more markedly from the sinusoidal form, and tend to become a series of short, sharp crests separated by long, low troughs. In this condition, they approach more nearly the solitary wave; and, for relationships in or very close to the breaking zone, the solitary wave theory has been found to apply (Sverdrup and Munk, 1946; Ippen and Kulin, 1955). This theory gives the following equations for conditions at breaking:

$$Y_b = 1{\cdot}28\ H_b \qquad (14)$$

and

$$C_b = \left[g\,(Y_b + H_b)\right]^{1/2} \qquad (15)$$

where b = subscript referring to conditions at breaking.

3.17 Wave Refraction

The phenomenon known as wave refraction arises as a logical extension of the shoaling of waves. When a wave crest approaches the shore at an angle to the bottom contours, that end of the crest closest to the shore is affected by shoaling, while the part of the crest farther offshore is still moving as a deep water wave. The reduction in velocity at the inshore end causes a bending of the crest such that it tends to align itself parallel to the shore. By analogy with the refraction of light rays, this phenomenon is termed 'refraction'.

Wave refraction obeys similar laws to those governing refraction of light rays. By Snell's Law, the sine of the angle between the wave crest and the bottom contour is proportional to the wave velocity:

$$\sin \alpha \propto C \qquad (16)$$

where α is the angle between the wave crest and the bottom contour. By combining this law with equation (2), the bending of the wave crest as it moves from one depth to another can be calculated. Graphical methods can be used for the successive solution of these equations as a wave moves through gradually shoaling water (Arthur, Munk and Isaacs, 1952). In many of these, the resultant "refraction diagram" shows wave rays, orthogonal to the crests, rather than the crests themselves.

Refraction diagrams find a ready use in computing the changes in wave height due to differential refraction round headlands and bays. It is assumed that the energy contained between two rays remains constant as the wave advances into shallow water. Since the energy is proportional to the square of the height, the height is given as inversely proportional to the square root of the spacing between rays:

$$\frac{H_1}{H_2} = \sqrt{\frac{\text{distance between rays at } 2}{\text{distance between rays at } 1}} \qquad (17)$$

where 1 and 2 are any two points on a ray.

Under certain conditions the rays on refraction diagrams are seen to cross. This condition of "crossed orthogonals" corresponds theoretically to a finite amount of energy contained within an infinitesimal area, and consequently a wave of infinite height. A wave in attempting to attain infinite height would break, and, were it not for lateral flow of energy along the crest, "crossed orthogonals" would indicate breaking waves. Before such breaking can occur, destruction of the wave train frequently ensues in nature. Subsequent water movements seem to vary greatly with local topography. The subject has not been exhaustively examined, but a theory exists which postulates a wave train set up after a point of "crossed orthogonals" with half the period of the original wave train (Beach Erosion Board, 1951).

Refraction diagrams are also used in predicting littoral transport. Littoral transport is the longshore current set up by waves breaking at an angle to the shore. Though refraction tends to align the wave crests parallel with the shore, this alignment is never completely effected, and the waves break at some angle to the shore which can be ascertained from refraction diagrams. The intensity of the littoral current engendered in the surf zone depends on this residual angle.

Wave refraction can be effected by currents as well as during shoaling. Naturally, a current running counter to a wave will increase its height and decrease its length, thus steepening the wave. A current running with a wave will have the reverse effect. When a wave encounters a current running at some angle to it, that part of the crest which first meets the current will be affected first, causing bending of the crest of the same type as that occasioned when a wave approaches the shore at an angle to the bottom contours (Johnson, 1947).

3.18 Wave Diffraction

Again by analogy with light, the term "diffraction" is used to define the phenomenon where the propagation of water waves continues into a sheltered region formed by a breakwater or similar barrier that interrupts part of an otherwise regular wave train. Diffraction is often responsible for the existence of small waves in a locality that would be otherwise sheltered from the approaching waves. The force responsible for the diffraction of waves is due to the differential elevation between the water in the sheltered area and that in the ocean during the passage of a wave. Diffraction diagrams can be constructed to give the wave pattern within the sheltered area (Johnson, 1952).

3.19 Wave Reflection

Waves that run up a gently sloping beach dissipate most of their energy in breaking and the subsequent uprush onto the beach. At the other end of the scale, a wave that meets a vertical barrier may have none of its energy absorbed, and may be totally reflected in the form of a wave of the same height that travels back to sea. As with reflection of light rays, the direction of the reflected wave depends on the angle of incidence. Waves approaching rocky headlands like Wybung Head are frequently subject to a degree of reflection. Because of refraction, the angle of incidence is generally not great, and, as the wave travels back to sea, under the same laws of refraction, it meets the incident wave and a partial "clapotis" or standing wave is formed.

With topography as complex as that at Wybung Head, waves reflect from many surfaces in different directions and a confused picture results. Clapotis has been observed, as well as breaking induced when waves run into moving masses of water that have accumulated from previous waves washing over the rocks. Small changes of water level caused by tidal variations, wind set-up or surf beat, cause appreciable differences to wave reflection and associated water movements in and around the rocky foreshore.

3. 2 Wave Measurement

3. 21 Continuous Wave Record

For a complete analysis of the effects of waves on ash discharged to sea, knowledge of the waves likely to be encountered in the vicinity is required. The parameters of wave height, period and direction uniquely determine the wave in any given water depth, and these quantities must be measured. As statistical analysis is inevitable, records must extend over a protracted period of time. For preliminary analysis, a record over one year is sufficient, but several years of record are required to define the extreme values.

The method proposed for obtaining such a record for the Wybung Head area depends on the fact that a fluctuating pressure is induced at any point below the surface of the ocean as waves pass over that point. A pressure transducer installed near the sea-bed converts these pressure fluctuations into electrical impulses which are transmitted by a cable to a shore recording station. These impulses can be made to drive a pen recorder so that a visual record of the state of the sea can be obtained. A complication arises because of the variation of the pressure attenuation factor with wave period.* It is expected that equipment can be devised to allow for this, so that the record obtained will give a true picture of the sea surface. Since wave groups in nature are not composed of a series of regular waves, analysis of the records is necessary to determine some mean parameter specifying the state of the sea. Analysis may be performed manually from the wave records, or by various forms of equipment which process the data either during or after the actual recording. When data extending over a considerable period are to be analysed, mechanical processing is usually more economic.

Since knowledge of the waves is required over a considerable area near the discharge point rather than at some specific location,

* Section 3. 13.

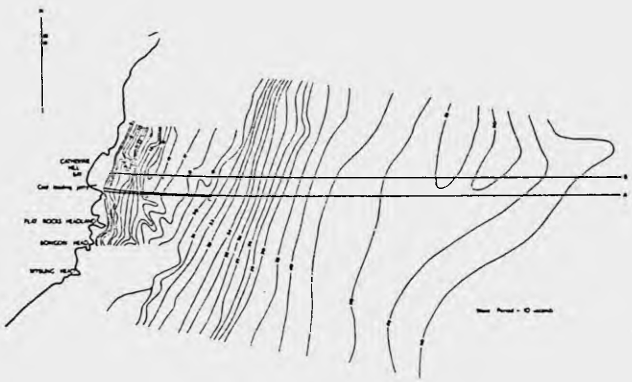
and since this knowledge can best be obtained from a record of ocean wave conditions, an ideal installation would involve the locating of the transducer above the sea-bed in a place where the ocean waves are not affected by the decreasing water depth. The cost of the cable for such an installation would be prohibitive, and some compromise is necessary. Installation of the transducer a few feet above the sea bed where a water depth of about 100 feet exists was decided upon as a resonable compromise. Waves of less than 6 seconds period will not be registered by the recorder. Waves of period 7, 10 and 15 seconds will register at fractions of about 0.2, 0.5 and 1.0 respectively of the pressure fluctuations at the surface. The filtering out of the shorter wave periods is a desirable feature, as minor fluctuations superimposed on the main waves tend to confuse the record. Such short period waves with their associated lower heights do not have enough power to be a major factor in the transport of ash.

The pressure transducer for this installation is currently undergoing laboratory testing and calibration.

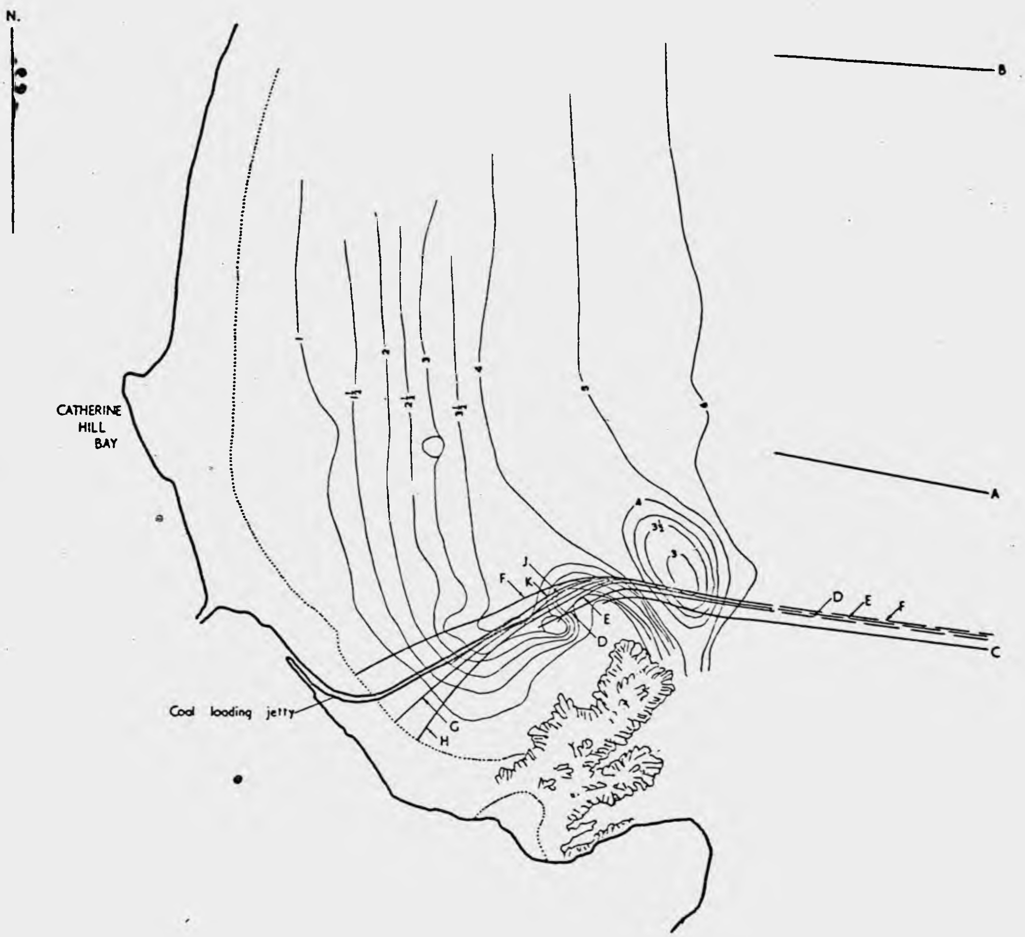
3.22 Intermittent Wave Measurement

Pending a permanent installation for wave measurement, some estimate of wave action near Wybung Head is required for correlation with other data being collected. Wave hindcasting, to be described later, is one method of obtaining estimates. Two other methods have been investigated, namely surface float measurements and wave run-up measurements.

The technique of using surface floats to measure waves consists of driving a pen recorder by the up and down movement of a float which rises and falls with the water surface. A fixed frame of reference is required for any simple installation, and the Catherine Hill Bay coal loading wharf suggested itself as a possibility. Depths of some 20 feet are available at the jetty. Waves in such depths have, of course, already suffered the effects of shoaling and refraction, but in favourable circumstances these effects can be calculated and the ocean wave characteristics deduced from those of the transformed waves. Unfortunately, the jetty at Catherine Hill Bay is sheltered from waves approaching from the south and south-east and only a small amount of diffracted energy enters. The resultant water movements are confused by reflection from the rocky headland, and a wave record obtained at the jetty would not be amenable to interpretation as far as estimating concomitant ocean waves is concerned. Refraction diagrams for waves approaching from the east exhibit the condition of "crossed orthogonals" (Figure 15). With the breakdown of the wave train that such a condition represents, the formation

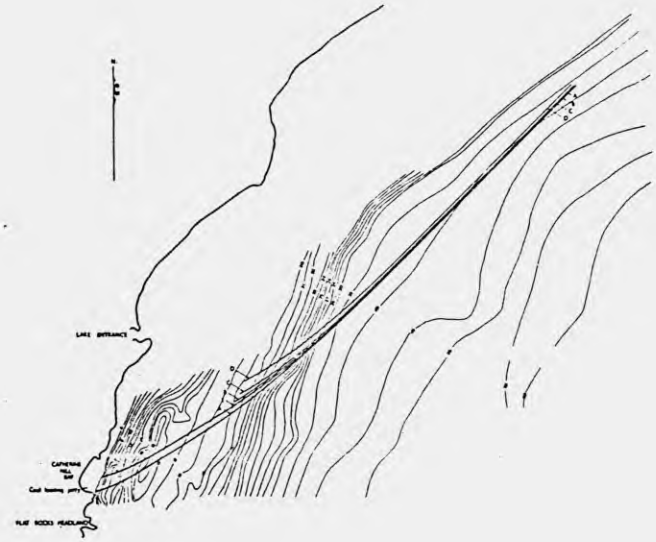


(a) Refraction from Deep Water

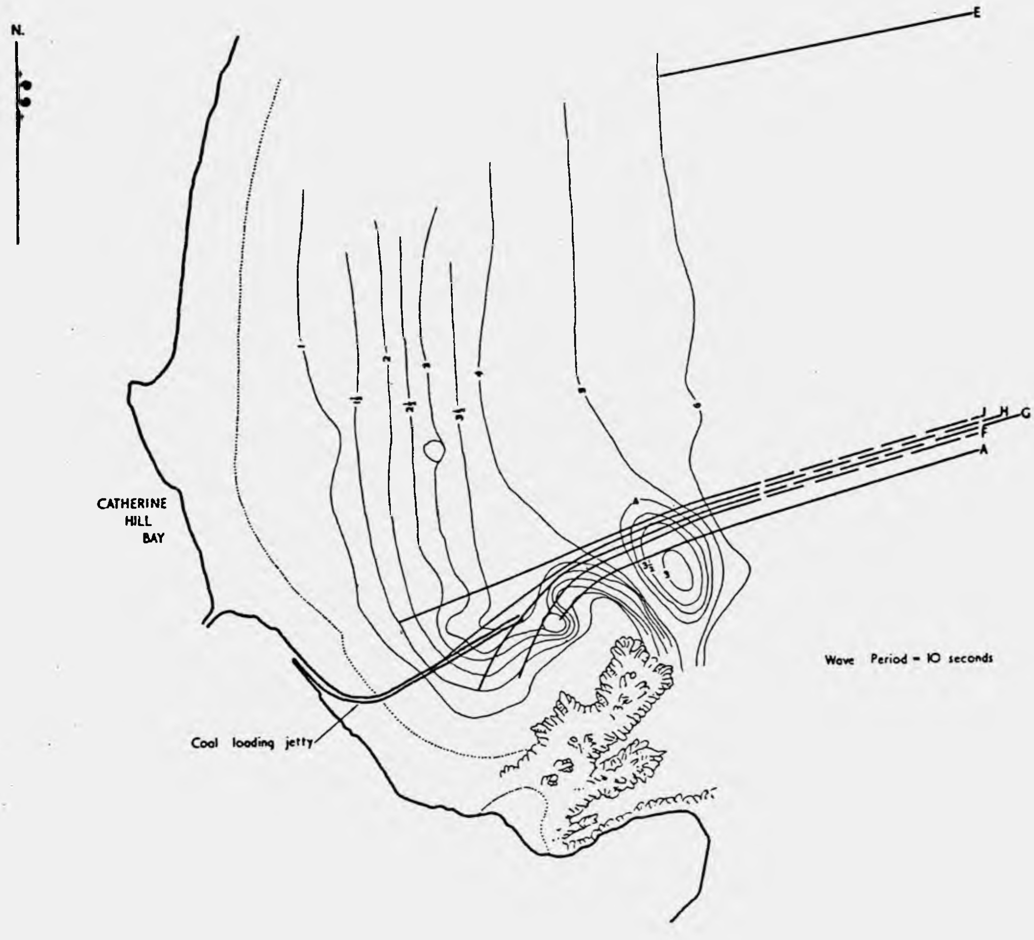


(b) Enlarged View of Refraction Close to Jetty

Figure 15: Refraction Diagram for Easterly Waves of 10 second Period Approaching Catherine Hill Bay.



(a) Refraction from Deep Water



(b)Enlarged View of Refraction Close to Jetty

Figure 16: Refraction Diagram for North-Easterly Waves of 10 second Period Approaching Catherine Hill Bay.

of new wave trains and ancillary confusion, records obtained at the jetty would once more be virtually useless for estimating ocean waves. A record was obtained under easterly conditions which confirmed the refraction analysis. Waves of period about $\frac{1}{2}$ that obtained by hindcasting and of substantially greater height were recorded at the jetty. Waves from the north-east could be recorded at the jetty and the ocean waves calculated from the records. Figure 16 shows refraction effects for north-east waves. As will be seen later, large scale north-east weather conditions occur infrequently and play a very small role in the movement of ash. Recording at Catherine Hill Bay is therefore seen to have limited application.

The alternative method of wave estimation used in the field depends on the fact that a relation exists between the height of the ocean wave and the uprush on the beach that follows breaking. The relationship is complicated and has not been theoretically determined. Laboratory tests (Savage, 1958) have defined relations between "run-up" and wave height for various values of wave period and beach slope, roughness and permeability; and some confirmatory field data have been obtained. "Run-up" is defined as the maximum vertical height above still water level attained by the wave at the limit of its uprush. Wave estimation from measurements of run-up is more reliable under conditions of swell than when locally derived storm waves are present, because of the more restricted variety of waves present in the swell wave spectrum. During ash-dumping trials at Wybung Head in June and July 1962, run-ups were measured usually at the northern end of Budgewoi Beach, and less frequently on the beach at the northern end of Catherine Hill Bay. The stations were located far enough from headlands to eliminate deleterious effects due to reflection and differential refraction. At times, the existence of sand-bars causing preliminary breaking out to sea interfered with measurements and on one occasion the confused state of the sea, due to the co-existence of two appreciable wave trains from different directions, rendered measurement futile. With the unseasonably calm weather prevailing at the time, run-up measurements were subject to errors due to local wind ripples and other minor phenomena that would be masked by larger waves; but a fair picture of ocean wave conditions was obtained, particularly as regards comparisons from one day to another.

3.3 Wave Hindcasting for Wybung Head

3.30 General

Until actual measurements of wave characteristics become available, estimates of wave statistics can be made by techniques described as "wave forecasting" or "wave hindcasting". Such techniques depend on the relation between wind and wave and use synoptic weather maps for determination of wind. From the statistics obtained by hindcasting, good estimates of average values and reasonable estimates of extreme values can be made. The frequency of various phenomena concerned in the action of waves on ash movement can then be predicted.

3.31 Wave Generation

Ocean waves range in period from milliseconds to years, but virtually all the energy of the spectrum is contained in two of the classes into which waves have been somewhat arbitrarily sorted. These are the ordinary gravity waves ranging in period from 1 to 30 seconds and the ordinary tides ranging in period from 12 hours to 24 hours. The tides are largely the result of astronomical forces and, apart from the changes in water level and the small rotating currents they induce, need not be considered further as far as their effects on ash discharged near Wybung Head are concerned. Ordinary gravity waves, on the other hand, are induced by wind blowing over the surface of the ocean, and these waves are expected to play a major part in the transport of ash discharged in the ocean.

The characteristics of the wave depend on the wind speed, the length of time the wind has been blowing, and the "fetch" or area over which the wind blows. Wave heights and periods increase with increase of any of these variables, subject to certain limitations. After the waves leave the area of generation, they progress through the "decay area", decreasing in height and increasing in period. Waves reaching Wybung Head may have been generated locally (storm waves), or they may have travelled up to thousands of miles from their area of generation (swell waves). The coastline configuration indicates that waves may reach the Wybung Head area from directions north-east through east to south. Several major wind systems can cause such waves. Two of the most important are the extra-tropical cyclone and the tropical cyclone. Extra-tropical cyclones track from west to east, frequently across the Great Australian Bight, farther north in winter than in summer (Figure 17a). These are responsible for the "southerlies" experienced in Sydney, and can send waves towards Wybung Head mainly from the south or south-east. A typical tropical cyclone tracks south-west from the lower latitudes and at some stage curves eastward (Figure 17b). These cyclones occur mainly between January and April and are responsible for severe destruction along the Queensland coast, but are rarely felt further south. Waves

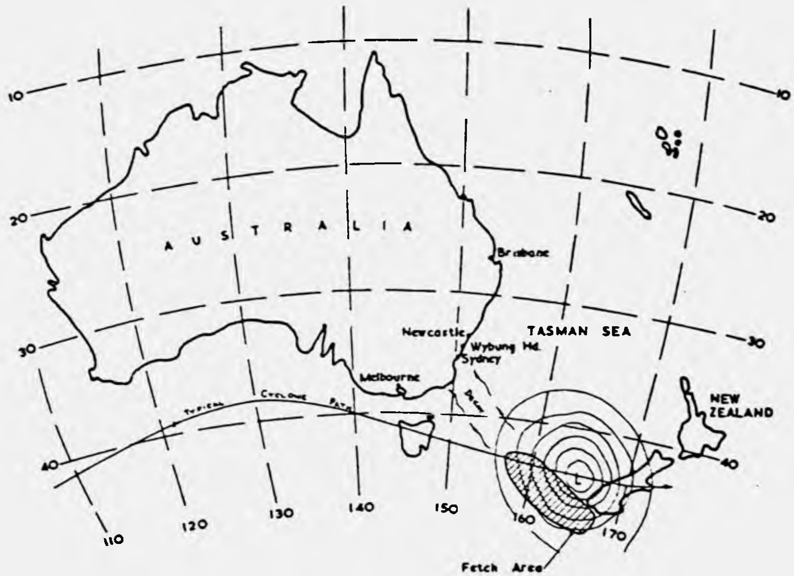


Figure 17(a): Extra Tropical Cyclone.

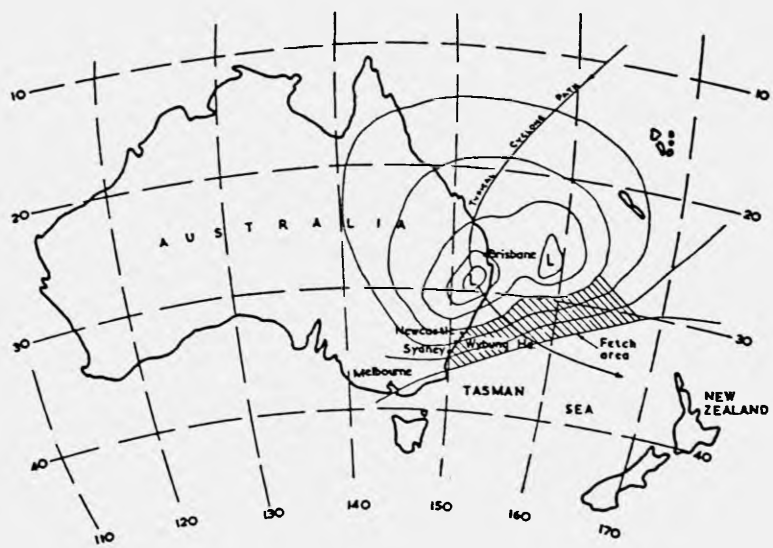


Figure 17(b): Tropical Cyclone

created by these systems can, however, travel to Wybung Head, the direction of approach may be from north-east through east to south-east depending on the position of the depression.

3.32 Hindcasting

Hindcasting is the name given to the process of estimating, from wind data on weather maps, the characteristics of the waves at any required location. Several techniques are used, based on somewhat differing concepts and all semi-empirical. Each one fits best the data used in devising it; and, since no data are available in Australia, an arbitrary choice must be made. The S. M. B. (Sverdrup, Munk and Bretschneider) method has been used for this investigation. This method was originally evolved by Sverdrup and Munk during the 1939-1945 war when enquiring into landing conditions for amphibious craft (Sverdrup and Munk, 1947). Later revisions by the original authors and especially C. L. Bretschneider have refined and extended the technique (Bretschneider, 1958). Since winds blowing over effectively "deep" water (with respect to wave length) are responsible for the generation of most ocean waves influencing the Wybung Head area, forecasts have been made initially for the deep water case, and transformations due to the progress of the waves into shallow water taken into account thereafter.

The data required for hindcasting by the S. M. B. technique are the wind speed, direction and duration, and the fetch and decay distances. These are obtained from weather charts. A brief account of the wind generating forces is given here, partly for understanding of the application of weather maps to wave hindcasting, and partly for comparison with the account of current generating forces given later.*

Air is set in motion by pressure differences. The main forces which determine the subsequent speed and direction of the resulting wind are the pressure gradient, cyclostrophic and Coriolis forces (Linsley, Kohler and Paulus, 1949). On weather maps, lines of equal pressure, or isobars, are used to obtain the speed and direction of the wind. The combination of pressure gradient, cyclostrophic and Coriolis forces causes the wind to blow along the isobars, clockwise around an area of low pressure and anti-clockwise around an area of high pressure in the southern hemisphere. Where isobars are closely spaced, the wind is high, and vice versa. The wind found from isobar patterns is that which previals at altitudes from about 2000 feet upwards, and is known as the Geostrophic Wind.

---

* Section 4.2

Close to the earth's surface, the effects of friction are felt by the wind. These effects cause a decrease in the wind speed and consequent lessening of the Coriolis and cyclostrophic forces. The resultant wind blows at an angle to the isobars, outwards from a high and inwards towards a low. Over land the deflection of the wind from the direction of the isobars is 30^{o} to 40^{o}, but over the sea the friction is not so high and the deflection is generally of the order of 10^{o} to 20^{o}. These are the sea surface winds which transmit their energy to the water in the form of waves and currents.

The fetch and decay distances are found by direct observation of weather maps. Winds produce waves in different directions as the isobars change direction. Some percentage of the energy from various directions acts to reinforce waves in any given direction. For practical purposes, winds may be deemed to be totally effective in reinforcing waves while within 15^{o} in either direction from the originating wind, and the effects of all other winds may be neglected. The limits of fetch can be delineated on this basis. Six hour synoptic charts have been considered practicable for hindcasting, and the duration of any wind system can therefore be computed as a multiple of six hours.

Once the direction, speed and duration of the wind have been found and the limits of fetch delineated, the characteristics of the waves resulting from any prevailing weather system can be estimated. The S. M. B. forecasting technique yields two parameters known as the significant wave height and the significant wave period. The significant wave height is the average of the heights of the highest one-third of the waves in a wave-train. The significant wave period is the mean period associated with the significant wave height and is approximately equal to the mean period of all waves. The concepts on which this technique for wave hindcasting is based yield the following functional relations:

$$\frac{gH}{W^2} = f_1 \left(\frac{gF}{W^2} , \frac{gt}{W} \right) \qquad (18)$$

and

$$\frac{C_o}{W} = f_2 \left(\frac{gF}{W^2} , \frac{gt}{W} \right) \qquad (19)$$

where H = significant wave height
T = significant wave period
W = wind speed
t = wind duration
F = fetch length

The exact forms of the functions are theoretically discernable only for certain limiting conditions over a restricted part of the range. Forecasting curves are devised by reducing recorded data to the same terms of reference to fill in the gaps. Figure 18 shows forecasting curves for use with the S. M. B. method. To enable a statistical forecast to be made in a limited time, it was necessary to average the wind speed and duration and the fetch and decay distances for each distinct weather pattern before applying the curves to the data.

3.33 Statistical Analysis

A five year period of record was chosen as being sufficient to yield reasonable estimates of both average and extreme values, and the six-hour synoptic charts for the period 1951-1955 were analysed. A few records were missing, notably those for October 1955 and November 1955; but a subsequent check indicated that this lack would have negligible effect on the validity of the analysis.

One limitation of the analysis is due to the fact that weather charts usually show isobars for "upper-air" conditions, thereby excluding the diurnal effect responsible for land and sea breezes, whose influence is not felt above about 1000 feet. These breezes blow close to the coast, the wave making sea breezes running generally from the north-east for the New South Wales coast. Except in rare instances, they are not powerful enough to produce waves of appreciable height or period because of their limited fetch, duration and intensity. A 15 knot wind, for example, - which is quite high for a sea breeze - would produce waves of maximum significant height 2 feet and period 3 seconds after blowing over a fetch of 10 miles for at least 2 hours. A 10 knot wind blowing for 12 hours would produce waves limited, no matter what the fetch, to a significant height of 2 feet and period 4 seconds. It will be seen that the existence of sea breezes which have not been included in the analysis affects the results only to the extent that certain periods registered as "calm" should probably be allocated waves of small height and period. The frequencies given for waves above 2 feet significant height and 4 seconds period will not be affected. Since quantitative data on sea-breezes are restricted, particularly as to fetch, no exact analysis is possible.

A further limitation is imposed by the paucity of meteorological records at distances greater than about 1000 miles east and south from Wybung Head. Waves coming from such great distances have usually decayed to a height of no more than a few feet with rather long periods. As an extreme example, a 40 knot wind blowing continuously for 12 hours over an unlimited fetch 1000 miles distant from Wybung Head would produce a wave of 5 feet significant height and 15 seconds period at the headland. A classic example of waves reaching Wybung Head

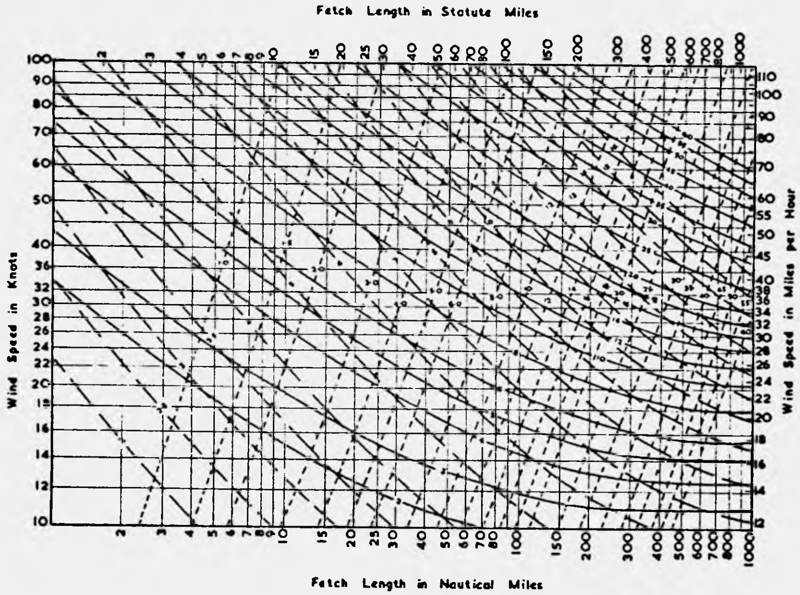


Figure 18(a): Forecasting Curves for Wave Heights and Periods at End of Fetch.

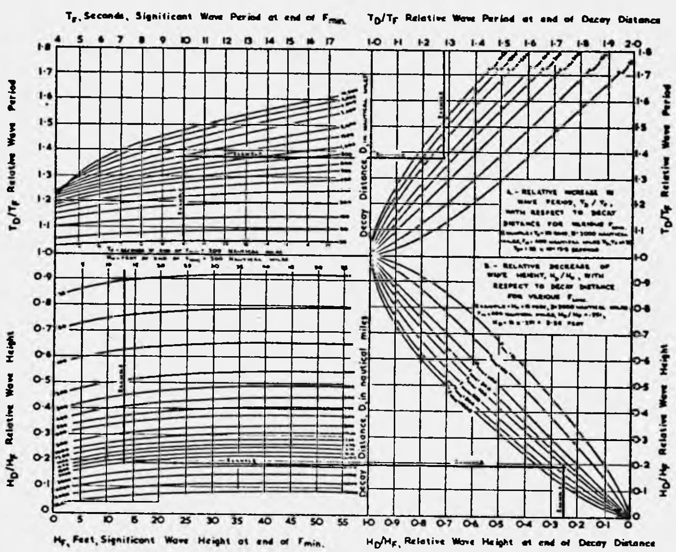


Figure 18(b): Forecasting Curves for Wave Heights and Periods at End of Decay.

from great distances was observed during ash dumping trials in June 1962. At the time the winter anti-cyclones were tracking much farther south than they generally do, and the intervening area was characterised by exceedingly calm weather. Under these conditions, waves up to 4 feet high were observed at Wybung Head which could not be forecast from available weather maps. Waves generated so far away would not often have a major effect at Wybung Head, as closer weather systems would be producing the dominant waves. The only appreciable effect on the statistics would again be some reduction of the period labelled "calm". The slight increase of frequency for the longer periods would not be significant.

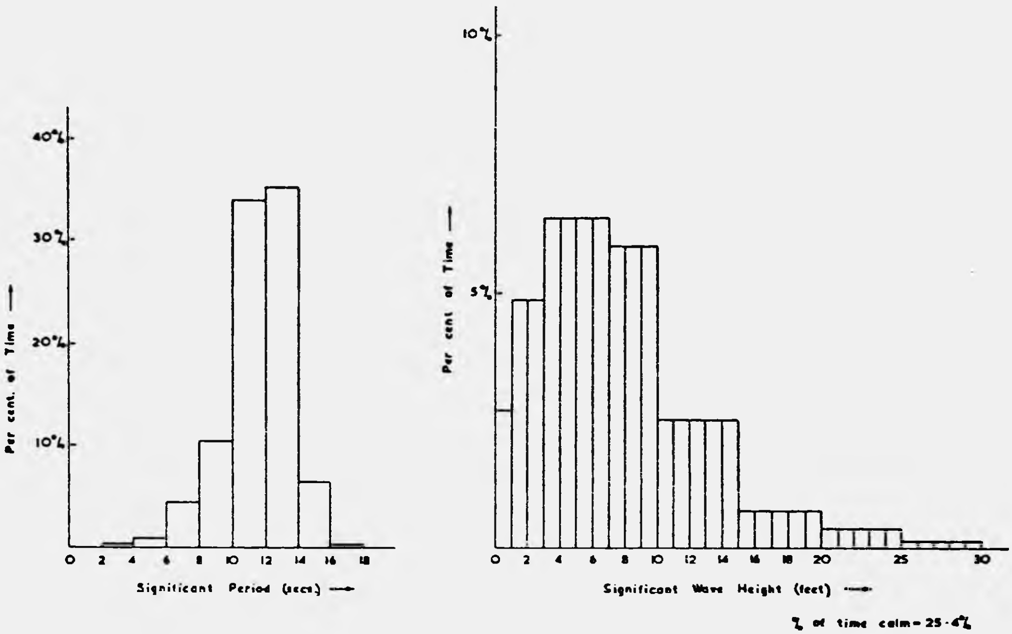
For each six-hourly synoptic weather chart during the period 1951-1955, the speed and direction of the wind and the limits of fetch and decay were recorded. The duration of each distinct weather system was noted, and other parameters averaged over this time. The significant height and period of the waves generated by each weather system were obtained from the forecasting curves. The limiting depth of water in which each wave would be capable of entraining settled ash was also computed from data to be discussed later.*

Preliminary statistical analysis of all forecasted waves yielded the information contained in Tables 2 and 3 and Figures 19 and 20. About 25% of the total time, the weather charts showed no wind systems capable of generating waves travelling towards Wybung Head. Table 2 and Figure 19a show that, for another 52% of the time, waves between 10 and 14 seconds in period existed. The median wave period was 11 seconds. Wave height analyses are shown in Table 3, Figure 19b and Figure 20. About 6% of the total time waves higher than 15 feet were experienced and 19% of the time waves higher than 10 feet. The median wave height was 5 feet.

No attempt was made to perform a combined statistical analysis of wave heights and periods. It is not necessary for the purposes of this study It was noted from the wave data that the highest waves were generally associated with periods in the 12 to 14 second range, waves of higher period usually having decreased in height over a long decay distance.

---

* Section 3.43



(a) (b)

Figure 19: Histograms of Significant Wave Heights and Periods.

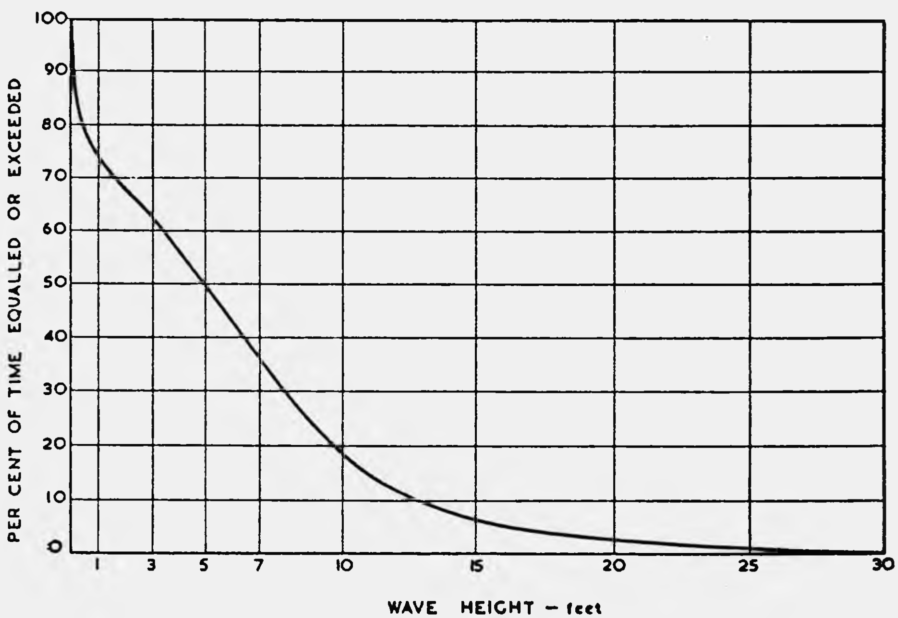


Figure 20: Cumulative Frequencies for Wave Heights.

Table 2

Frequency Analysis of Wave Periods

Significant Wave Period (seconds)	Total No. of Hours	% of Total Time
Calm and waves less than 1 foot high	11,442	25.4
2-4	6	0.02
4-6	318	0.77
6-8	1,398	3.4
8-10	5,676	13.8
10-12	10,428	25.4
12-14	10,830	26.4
14-16	1,950	4.7
16-18	48	0.11

Table 3

Frequency Analysis of Wave Heights

Significant Wave Height (feet)	Total No. of Hours	% of Total Time
Calm	10,698	25.4
0-1	744	1.8
1-3	4,100	9.8
3-7	11,074	26.2
7-10	7,488	17.8
10-15	5,334	12.7
15-20	1,650	3.9
20-25	756	1.8
25-30	252	0.6

The maximum significant wave height found during the 5-year period of analysis was 30 feet. From this figure and theoretical limitations it may safely be assumed that significant wave heights greater than 40 feet would be exceedingly rare. An extreme value statistical analysis could yield exact probabilities but it is not considered warranted for this investigation. It should, however, be borne in mind that the significant wave height does not mean the highest wave height in a train, but only the average of the one third highest.

Analyses of waves from different directions over the total time yielded the wave rose shown in Figure 21. This shows that about half the waves reaching Wybung Head arrive from the south, the remainder being divided between south-east and east, with very little contribution from north-easterly weather. Wave heights from directions east to south as high as 30 feet were found, but no north-easterly waves higher than 15 feet.

Figure 22 shows wave roses for each month of the year. The predominant southerly weather of the winter months is obvious in these roses. Also in evidence are some high waves from the east between January and May - the result of tropical cyclones.

3.34 Refraction and Shoaling

The analysis described above gives the statistics for the waves in effectively "deep water" off Wybung Head. As the waves approach the headland through decreasing water depths, their form is affected by shoaling and refraction. In depths greater than about 200 feet these effects are negligible, but for the shallower depths they can be appreciable. Refraction diagrams indicate, in general, a concentration of energy around the headland, leading to increased wave heights, and a dispersion of energy on either side with consequent decrease of wave height. Shoaling effects at first decrease the wave height which reaches a minimum of about 0.9 of its original height in about 100 feet of water. In progressively shallower depths the wave height increases, reaching its initial height again at a depth of the order of 30 feet, after which the height continues to increase more and more rapidly until the wave breaks. All periods remain substantially constant.

Since refraction and shoaling vary with the period of the incident wave, it would be necessary, for a complete analysis, to draw refraction diagrams for many period ranges. The waves with longer periods "feel bottom" in greater water depths and consequently begin

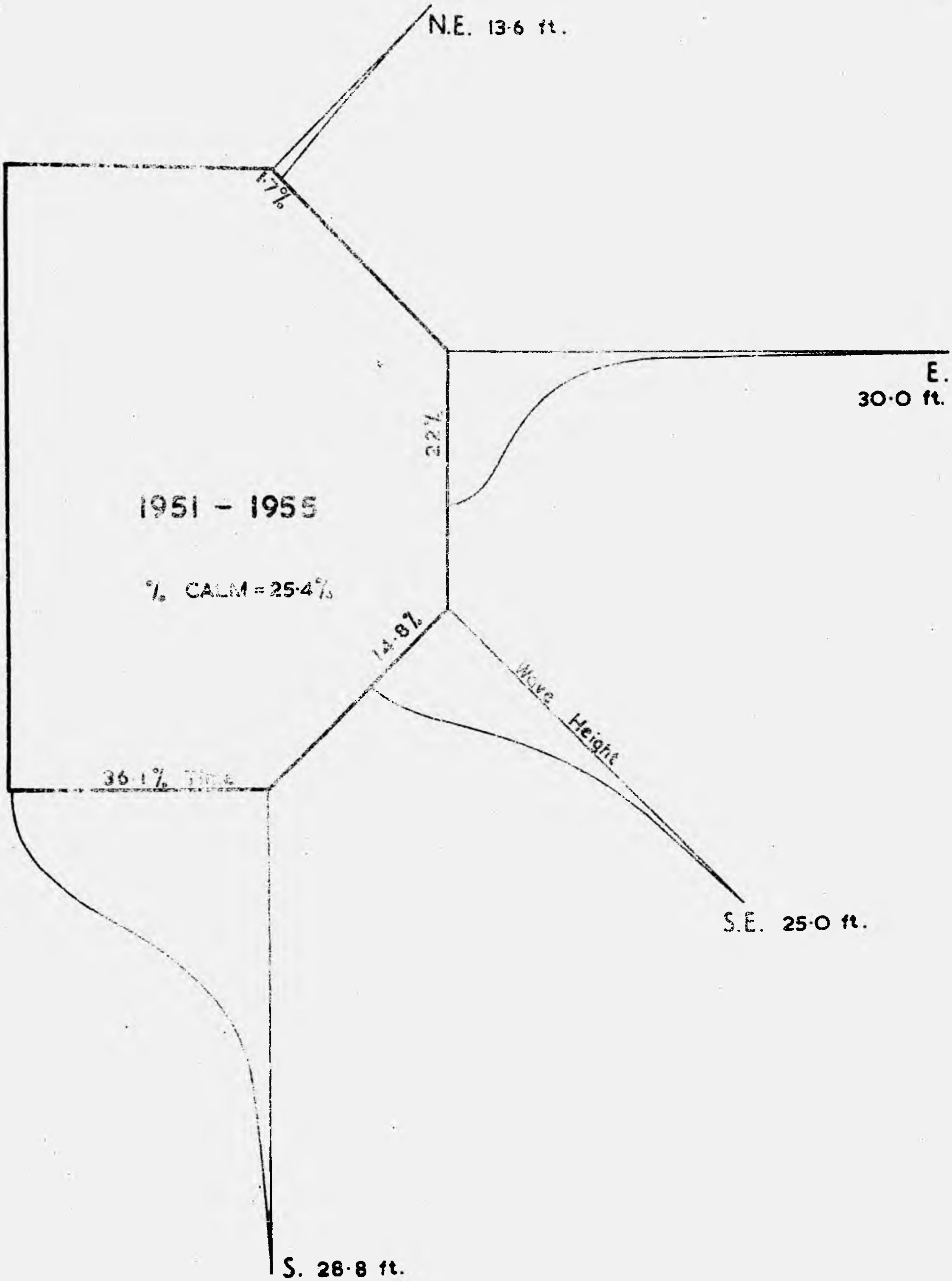


Figure 21: Wave Rose for the Wybung Head Area.

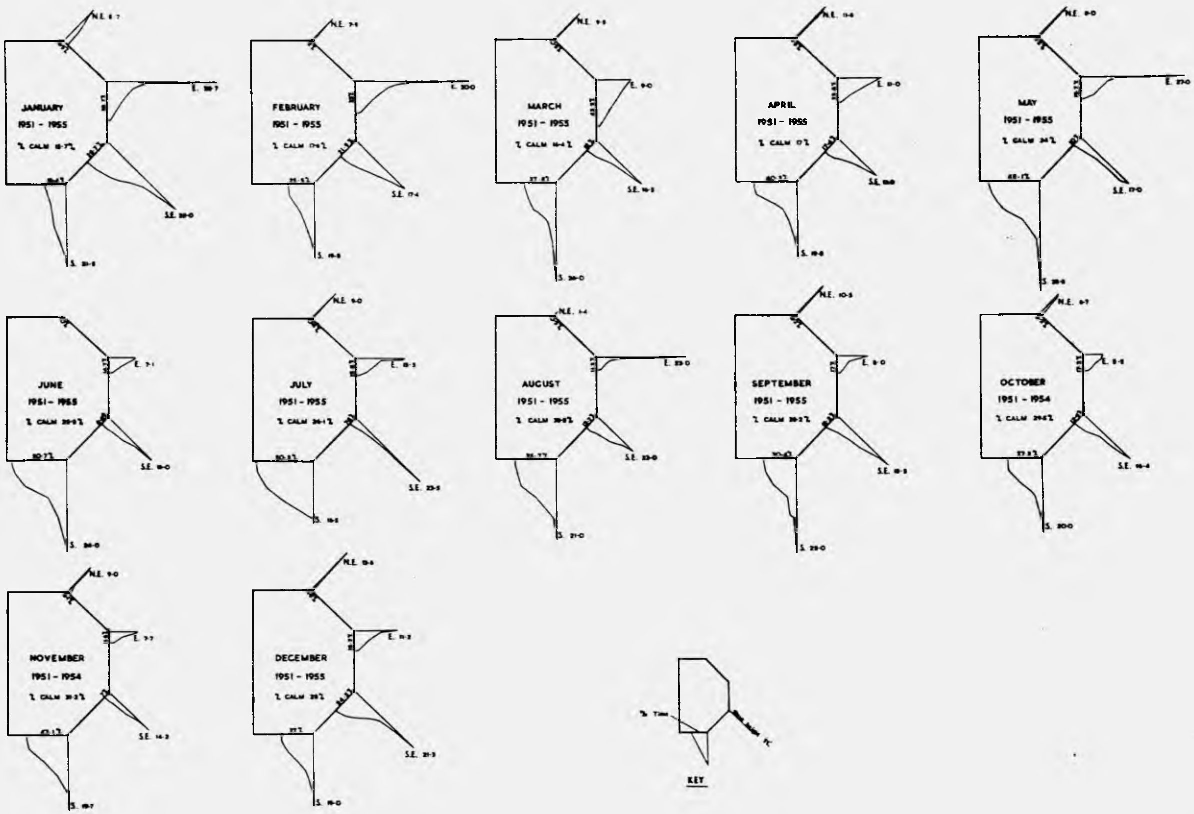


Figure 22: Monthly Wave Roses for Wybung Head.

to suffer refraction before waves of smaller period. At any specified depth, the rate of turning of the wave rays also varies with the period. Wave refraction diagrams were drawn corresponding to a period of 10 seconds for waves approaching Wybung Head from directions north-east, east, south-east and south (Figures 23, 24, 25 and 26). Table 4 gives an indication of the refraction and shoaling effects at depths of 50 feet and 100 feet off Wybung Head.

Table 4.

Shoaling and Refraction Effects for 10 Second Waves.

Wave Direction	Water Depth	Shoaling Coefficient	Refraction Coefficient	Ratio of Wave Height at Given Depth to Deep Water Wave Height
N. E.	50	0.93	0.78	0.73
	100	0.91	0.96	0.87
E.	50	0.93	1.15	1.07
	100	0.91	1.11	1.01
S. E.	50	0.93	1.00	0.93
	100	0.91	1.00	0.91
S.	50	0.93	1.03	0.95
	100	0.91	1.10	1.00

These figures show that for depths greater than 50 feet, shoaling tends to counteract the increase of wave height caused by refraction, except in the case of north-east waves where both effects tend to reduce the wave height. Cyclonic wave action from the north-east is slight and infrequent, and the reductions in wave height due to shoaling and refraction tend to make its role in ash disturbance even less important. For all other waves, the height is not subject to change of more than 10%. For wave periods other than 10 seconds, the changes would be within the same order. The wave roses presented for deep water therefore give a reasonable representation of waves in depths greater than 50 feet. For depths less than about 30 feet shoaling and refraction both induce marked increases of height.

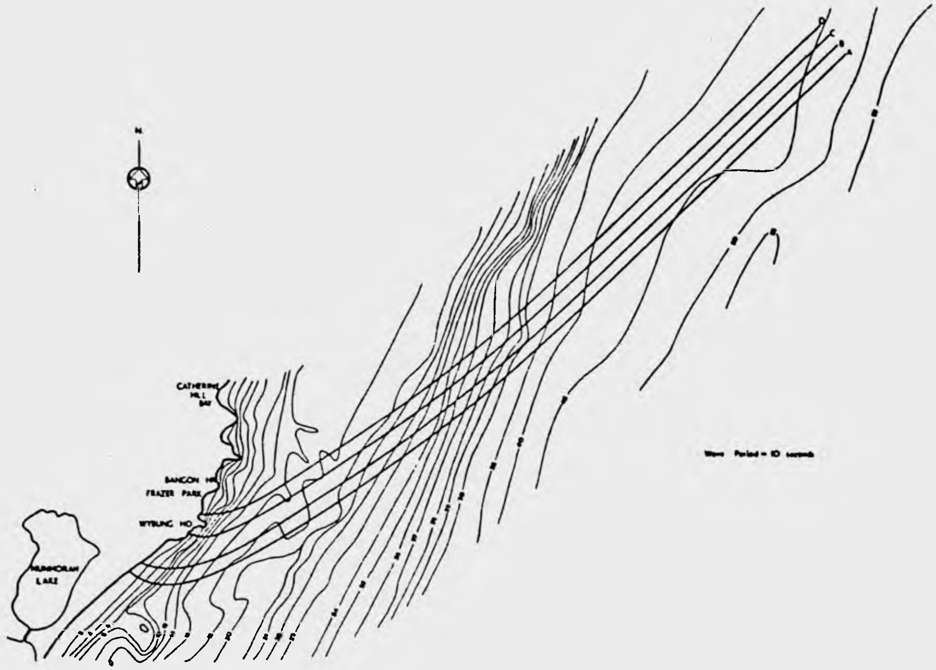


Figure 23: Refraction Diagram for 10-second Waves Approaching Wybung Head from the North-East.

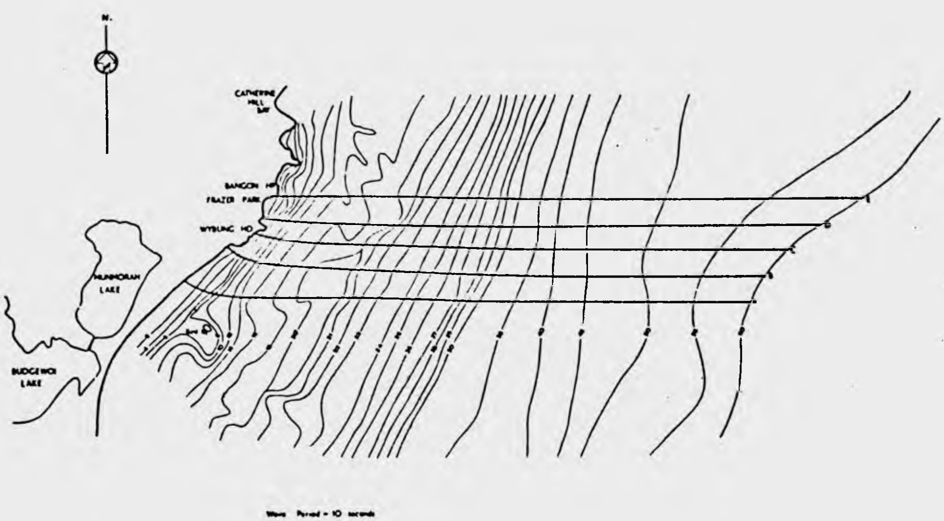


Figure 24: Refraction Diagram for 10-second Waves Approaching Wybung Head from the East.

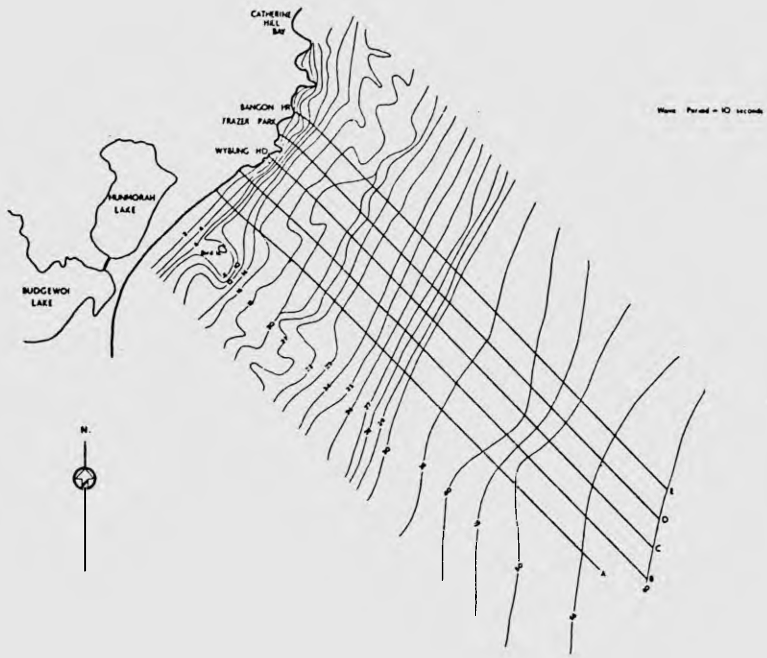


Figure 25: Refraction Diagram for 10-second Waves Approaching Wybung Head from the South-East.

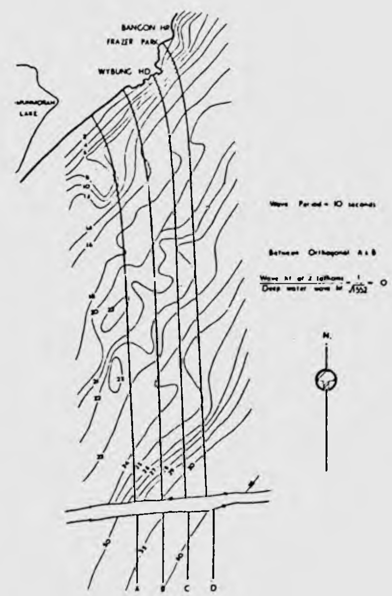


Figure 26: Refraction Diagram for 10-second Waves Approaching Wybung Head from the South.

Since refraction and shoaling do not produce effects of really large magnitude in water depths found immediately off Wybung Head, it is unnecessary to proceed with detailed analyses for other wave periods.

3.4 Ash Entrainment by Waves

3.41 General

Ash is expected to deposit on the bottom of the ocean for some distance from the discharge point. This ash will be disturbed and entrained during periods of sufficiently heavy wave action. It therefore becomes necessary to know what wave action is required to disturb settled ash, how frequently such wave action can be expected to occur, and how long at one time ash will remain on the bottom undisturbed by wave action. The strength of wave action necessary to entrain settled ash was investigated experimentally, and the statistics obtained by wave hindcasting applied to the results to obtain frequency estimates.

3.42 Laboratory Test Programme

Laboratory equipment allowed waves of period 0.5 seconds to 6 seconds to be generated in a flume 2 feet deep and 120 feet long. Wave height could be varied from a small ripple to nearly a foot. A range of still water depths between 6" and 16" was used; and, for such depths and periods between 0.5 and 6 seconds, movement of material on the bottom was effected by waves of height 0.5" to 1.6". The paddle used to generate waves was suspended from a mechanism such that the relative motion at various depths could be adjusted to correspond closely to the water particle motion for the particular period and water depth being used.

Ash from Wallarah coal burnt in the pulverised fuel furnaces at Pyrmont Power Station was used for the tests. The ash was introduced through a funnel after the flume had been filled with water, and allowed to settle before wave generation started. Some turbidity current action occurred after the ash left the funnel, causing a degree of stratification in the ash. However this was not as deleterious as effects resulting from other placement methods, such as laying and screeding the ash before covering with water. Introduction of ash through the funnel gave an ash layer resembling the prototype as closely as could be achieved.

Each test series was conducted as follows. The length of throw of the connecting rod to the wave paddle was chosen, and thereafter held fixed throughout the series. Three depths, about 6", 11" and

16", were used in each series. For each depth, the wave period was gradually reduced until movement of the material occurred. Wave height and period were measured, and bottom velocities calculated.

3.43 Test Results

The point at which waves start to re-suspend settled ash in water is not very clearly defined. As wave period is reduced with associated increase of wave height causing higher velocities and greater oscillation amplitudes on the bottom, the ash passes through several phases. Fine particles on the surface of the layer start to roll backwards and forwards before general movement of the whole surface commences. This phase gradually gives way to a condition where most of the surface particles are moving. This is known as "general rolling". General rolling will initiate and sustain ripple formation on the bed if left long enough: the previous phase will not. Once ripples are initiated, they help in their own propagation and a stable ripple formation for the particular wave conditions soon results. As the wave period is reduced still further, a point is reached where the waves "pick up" some ash particles and throw them into suspension. A low cloud soon forms. If the waves are strong enough to pick up only the very finest material, light transient clouds will form, dissipating as this very fine material is diffused throughout the water depth. However, with slightly stronger wave action, a large fraction of the material will be thrown into suspension and remain for a considerable time in a dense cloud within a few inches of the bed. This condition is known as "clouding".

During the condition characterised as "general rolling", ash in the prototype will be rolled backwards and forwards with probably a net-on-shore motion under the influence of the waves (Ippen and Eagleson, 1955; Tainsh, 1962). As the depth of water decreases, so that the "clouding" condition is reached, the waves will "pick up" the ash and submit it to the combined effects of wave currents, tidal currents, general ocean currents and any other transient or permanent currents operating at the time.

In the flume tests two points were observed, general rolling and clouding. This was done for the sake of completeness and because of the ill defined boundaries between different phases of movement. When the velocities at which rolling and clouding commenced were plotted against the period (Figure 27), a very distinct line could be drawn on one side of which lay scattered "rolling" values and on the

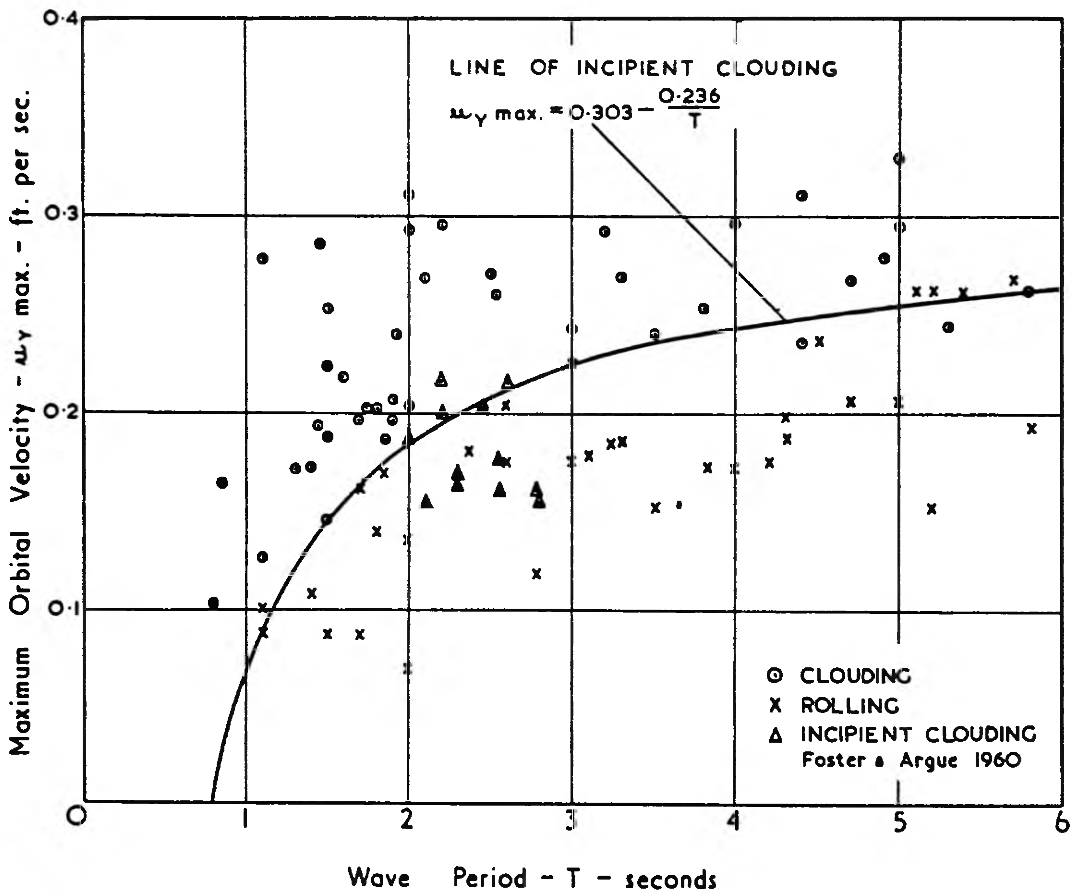


Figure 27: Entrainment Velocities for Settled Ash under Wave Action

other side "clouding" values. This line is regarded as a line of incipient clouding and defines the relation $u_Y(max) = 0.303 - \frac{0.236}{T}$ where $u_Y(max)$ is expressed in ft/sec and T is expressed in seconds. The scatter of points on either side is probably caused by observation difficulties.

3.44 Dimensional Analysis

Factors likely to affect the pick up of ash under wave action are wave height and period and water depth, and the velocity induced at the bed by the wave, and the particle size and fall velocity of the material. These may be grouped into dimensionless parameters as follows:-

(1) $\frac{u_Y max}{w}$ or $\frac{u_Y ave.}{w}$ $\left(\frac{\text{orbital velocity of wave}}{\text{fall velocity of particle}}\right)$

(2) $\frac{T}{\frac{d}{w}}$ $\frac{\text{(wave period)}}{\frac{\text{(particle size)}}{\text{(fall velocity)}}}$

(3) $\frac{H}{Y}$ $\frac{\text{wave height}}{\text{water depth}}$

Since these experiments deal only with ash, and material of similar grading was used for all experiments, the particle size and fall velocity of the material have been fixed. Dimensionless plotting involving these quantities is therefore not considered necessary. Furthermore, examination of test results revealed that no observable systematic variation with $\frac{H}{Y}$ existed within the test range. Therefore it appears that orbital velocity at clouding can be expressed as a function of wave period.

In order to determine the functional relation, values of maximum orbital velocity were plotted against values of wave period (Figure 27). The graph indicated that a linear relation could exist between total travel of a fluid particle and period for conditions of incipient clouding. This was found to be the case (Figure 28). The relationship defined on Figure 28 by the straight line separating values at rolling and clouding has been transferred to Figure 27, as maximum orbital velocity rather than total travel of a fluid particle is frequently used as a measure of wave force.

3.45 Comparison with Previous Results for Ash

Some values obtained previously (Foster and Argue, 1960) are shown on Figure 27 for comparison. These are the results of tests with waves

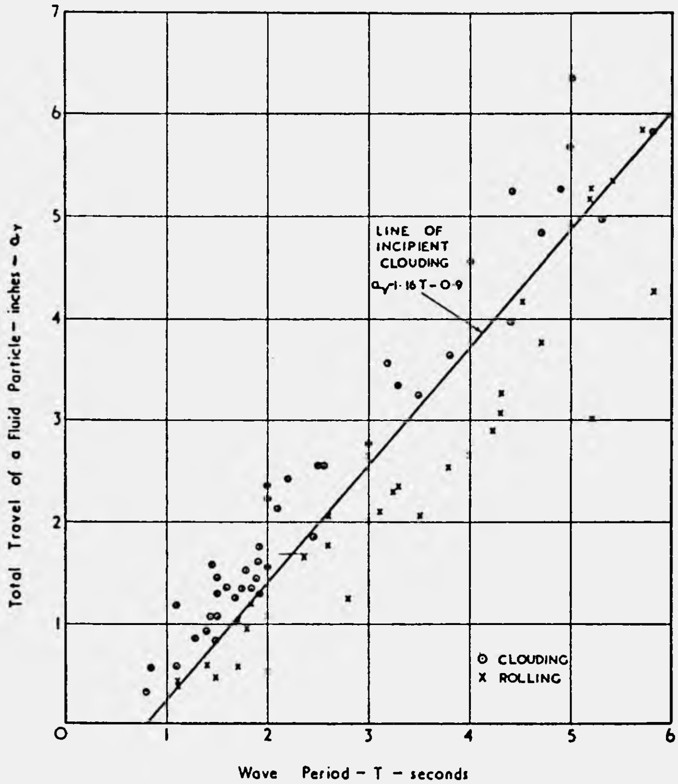


Figure 28: Ash Entrainment by Waves - Test Results Plotted as Total Travel of a Fluid Particle.

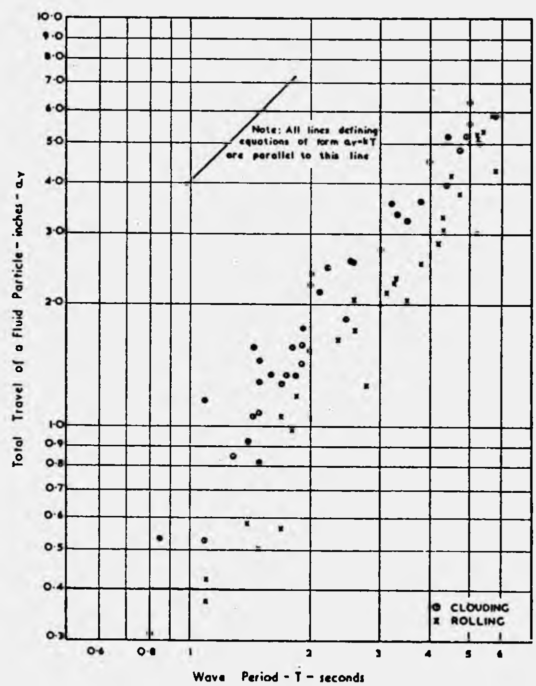


Figure 29: Ash Entrainment by Waves - Logarithmic Plotting of Test Results.

of greater height in greater depths of water, giving similar $\frac{H}{Y}$ values. They represent incipient clouding points, and give values of velocity comparable to the more recent tests. It should be noted that the more extended test series has disproved the notion that entrainment of settled ash is dependent solely on orbital velocity.

3.46 Comparison with Tests on Different Materials

No other comprehensive series of tests with waves and ash is known. However, some results are available for other materials (Vincent, 1959, Toru Sawaragi, 1962). Vincent of Sogreah gives results for various materials for a limited range of periods. Plotting total travel of a fluid particle at the bed, a_Y against period leads him to adopt a series of graphs defined by equations of the form $a_Y = kT$ where k is a constant depending on the material. Figure 29 shows the ash results plotted logarithmically for comparison. It is obvious that the results do not conform to an $a_Y = kT$ type formula which would yield a line at 45° to each axis. Since Vincent's tests covered such a limited range of periods, it is felt that the ash results are more dependable for the form of the relation. Sawaragi of Japan gives results for sand in dimensionless form. The only record of his work obtained to date was not detailed enough to draw firm conclusions, but it does appear that the ash results may conform to a relation of the type suggested.

3.47 Extrapolation to Prototype Waves

Laboratory waves ranged in period from $\frac{1}{2}$ to 6 seconds. Most prototype waves lie within the range 6 to 16 seconds. The form of the relation, including the tendency of orbital velocities required to distrub ash to approach a constant value at periods above about 3 seconds, indicates that the equation found by the laboratory testing can be applied to prototype results with confidence. Based on this extrapolation, values for waves required to entrain ash in various water depths are given in Figure 30.

3.48 Frequency of Ash Movement by Wave Action

From Figures 20 and 30, with account taken of predominant periods, directions and corresponding degrees of refraction, the percentage of time when ash will be disturbed in various water depths can be computed for the forecast waves. Sea-breeze waves will rarely disturb ash in depths of 50 feet or more, and no correction is necessary on this count. There will be some minor correction to the frequencies for depths up to 200 feet because of the existence of long low swell from distant storms which have not been accounted for in the analysis.

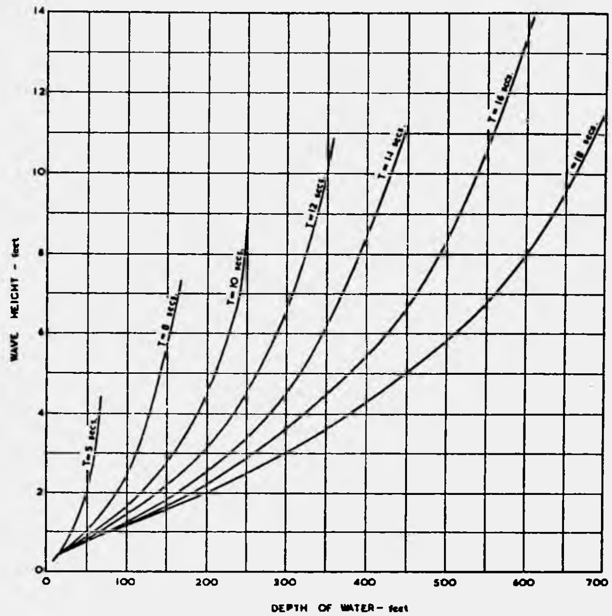


Figure 30: Waves Required to Disturb Settled Ash in Various Depths of Water.

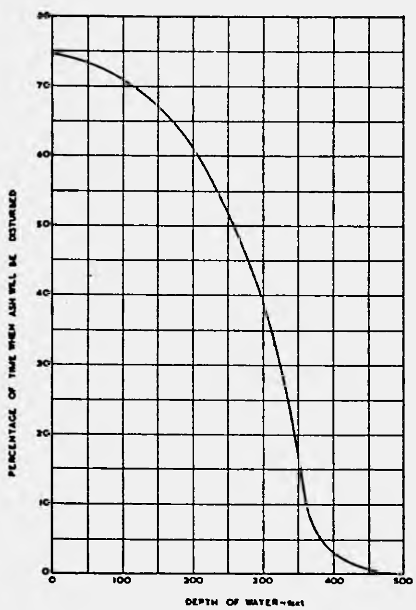


Figure 31: Frequency of Entrainment of Settled Ash by Wave Action off Wybung Head.

No quantitative estimate can be given, but the figures presented may be regarded as slightly conservative.

Figure 31 gives an indication of the average percentage of time during which waves will move ash in various depths of water. About 75% of the total time waves above 1 foot high will occur, producing disturbance of ash in about 50 feet of water, a depth which occurs about 100 yards seaward of Wybung Head. Waves $1\frac{1}{2}$ feet and higher, which will disturb ash in any depth up to about 100 feet, occur about 70% of the time. A depth of 100 feet exists about $\frac{3}{4}$ of a mile east of Wybung Head. Waves of the order of 3 feet and capable of disturbing ash in depths of the order of 200 feet occur 60% of the time. A depth of 200 feet is found about 6 miles east of Wybung Head.

3.49 Frequency Analysis of Periods During Which Ash Remains Undisturbed at Various Depths

For the five-year period of analysis, each weather system producing waves was allocated, from the information in Figure 30, a limiting water depth at which the waves would be just powerful enough to disturb settled ash. The records were then scanned for continuous periods during which ash would remain unaffected by wave action at various depths.

Figure 32 shows the average number of times per year that periods of non-disturbance equal to or exceeding various lengths of time up to 6 days were experienced. For smaller depths there are many short periods of non-disturbance, several of which may be incorporated in one longer period of non-disturbance at a greater depth. On account of this, the total number of periods of non-disturbance is smaller at greater depths, although the total amount of time for non-disturbance must, of course, be greater.

The five largest values of duration of non-disturbance at various depths have been plotted on Figure 33 to show the probabilities of the longer periods of non-disturbance. The skew has been retained in these curves to show that undue extrapolation would not be wise. Extrapolation is permissible for estimates to about 10% probability. For example, it may reasonably be surmised that ash will remain unaffected by waves in 50 feet depth for a period as long as 10 to 15 days once in 10 years on the average.

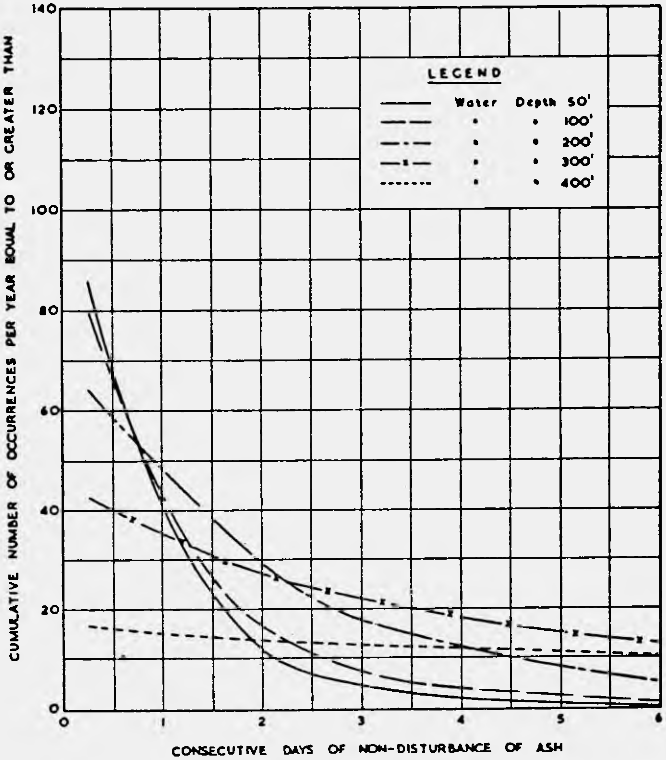


Figure 32: Frequencies of Non-Disturbance of Ash for Periods up to Six Days.

Consecutive Days of Non-Disturbance of Ash.

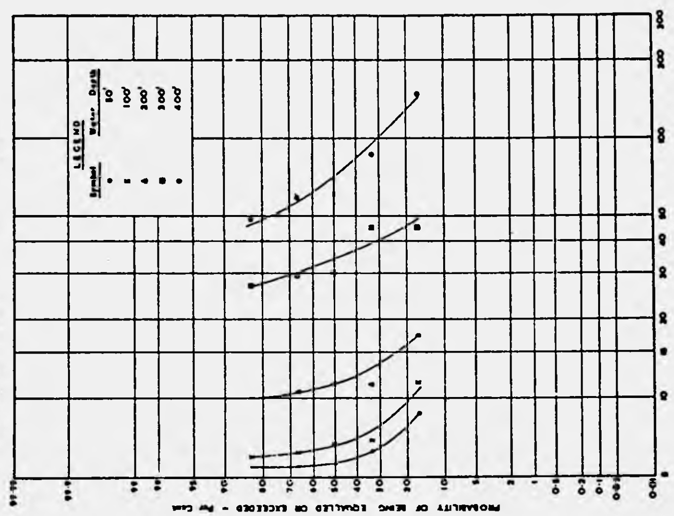


Figure 33: Extreme Frequencies for Periods of Non-Disturbance of Ash Based on Annual Exceedances.

4. CURRENTS

4.0 General

Currents likely to affect the transport of ash discharged to sea range from the large scale oceanic circulations to localised and ephemeral effects induced by changing winds, waves and tides. The strength of the currents is frequently out of all proportion to that of the generating forces, and it is necessary when considering oceanic water movements to be aware of the truth of the paradox that small causes do not ipso facto produce small effects.

Of major interest for ocean disposal investigations are the currents in the waters above that part of the continental shelf lying within a few miles of the shore. Though a reasonable amount of data are available for currents in the "nearshore" enviroment, landward of the breaker zone, in general continental shelf currents have not been widely studied in any part of the world, and their dynamics and kinematics are not completely understood. Presently accepted theories do, however, give some explanation of observed phenomena; and on the basis of these theories a picture of the changing currents in the proposed disposal area can be built up with the aid of the rather restricted measurements that have been made.

4.1 Major Ocean Currents

The major ocean currents are largely those related to the distribution of mass in the oceans. This statement is intentionally vague, as no exact determination of cause and effect has been made. It is thought that a secondary effect of the wind, whose direct effect creates the wind-induced currents to be described later, may be a factor in the generation and maintenance of these currents. Whatever the origin, the relationship between ocean currents and the distribution of density in the ocean is based on the simple physical concept of flow from an area of higher pressure to one of lower pressure. Coriolis force is brought into play by the existence of flow, and the net result, unless friction forces interfere, is a current directed along lines of equal pressure, in the same way as the winds associated with the distribution of mass in the atmosphere. *

Hamon has recently described the main features of the large scale oceanic circulation off the east coast of New South Wales as follows (Hamon, 1961):

---

* Section 3.32

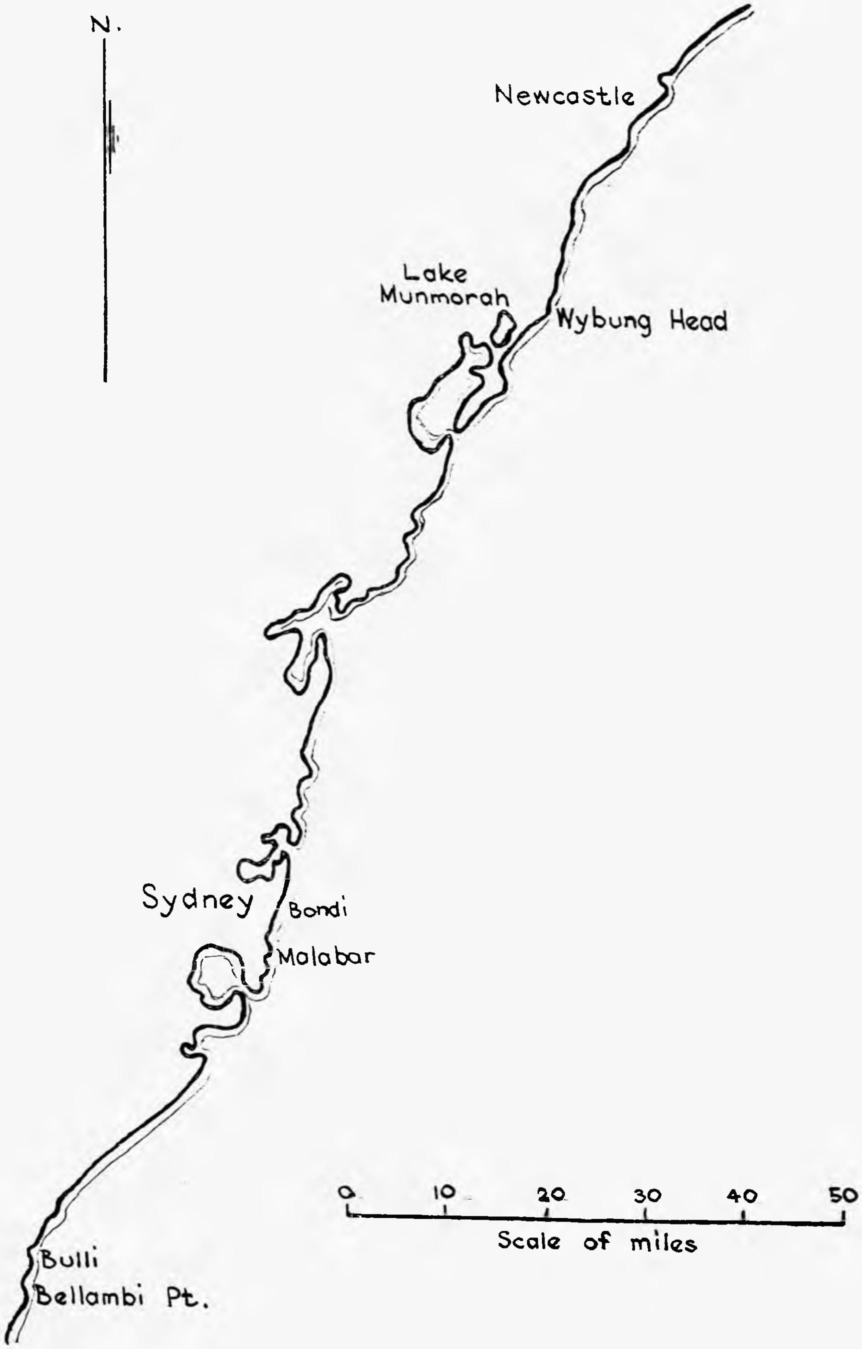


Figure 34: Location of Coastal Current Measurements.

" (1). A southerly or south-easterly current usually just beyond the edge of the continental shelf. In accordance with established usage, this will be referred to as the "East Australian Current".... The current is usually within about 60 miles of the edge of the shelf but on two occasions ......was between 80 and 110 miles from the edge. On these occasions, there appeared to be a weak northward countercurrent between the East Australian Current and the edge of the shelf.

(2) A northerly or north-easterly current, here called the "countercurrent", whose axis is from 70 to 200 miles to the east of the axis of the East Australian Current."

The East Australian Current referred to has been observed for many years mainly by shipping, and speeds as high as 4 knots have been recorded some 30 miles from the coast. Until measurements in connection with ash disposal investigations were started in 1961, data on currents closer inshore had not been collected in the vicinity of Wybung Head. Some measurements within about 1 mile from shore had been made by the Metropolitan Water Sewerage and Drainage Board at Bondi, Malabar, Bellambi and Bulli (Figure 34), but the area between 1 mile and 30 miles from shore had not been investigated either in these areas or near Wybung Head. Because of this, the inshore penetration of the East Australian Current must remain for the present an unknown quantity, and hence the effect of such penetration on the coastal waters near Wybung Head. It is reasonable to suppose that a current as high as 4 knots, 30 miles from the shore, could have a marked influence on inshore waters, either by direct shear transmission of southerly flow to adjoining layers of water, or by the formation of back eddies.

4.2 Wind Induced Currents

The immediate effect of wind stress on the surface of the sea is the pure wind drift current. The transport of water by such currents causes secondary effects because of the changes it makes in the distribution of mass. In this section only the primary effect of the wind, namely the pure drift current, will be considered.

Wind transfers momentum to the water by friction at the surface and by the pressure exerted by the wind on waves. Both of these act in the same direction and may be combined for purposes of analysis into a single tangential force. With low winds, the sea surface acts

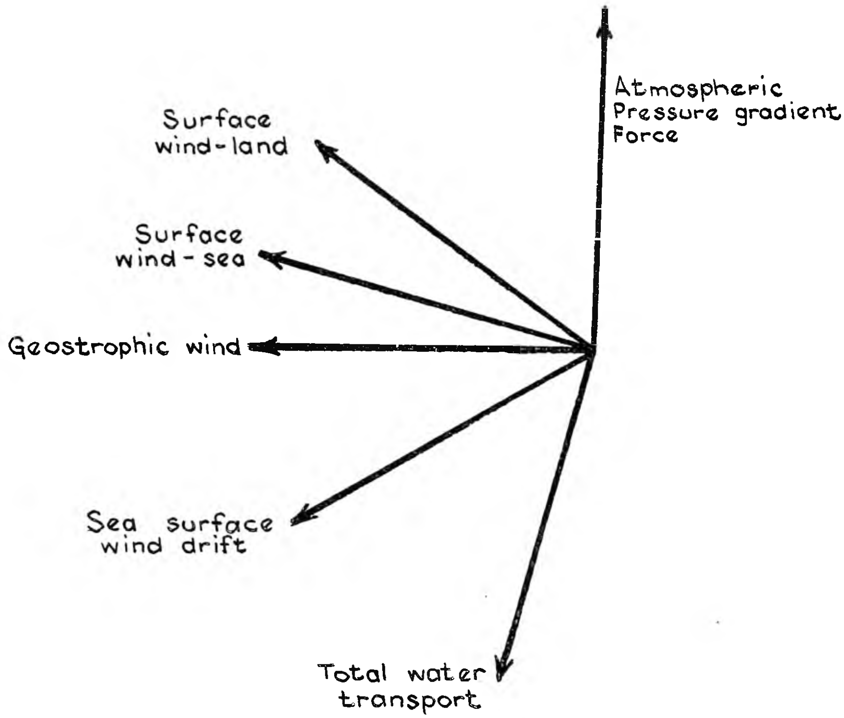


Figure 35: Diagrammatic Sketch of Some Concomitant Wind and Current Directions for the Southern Hemisphere.

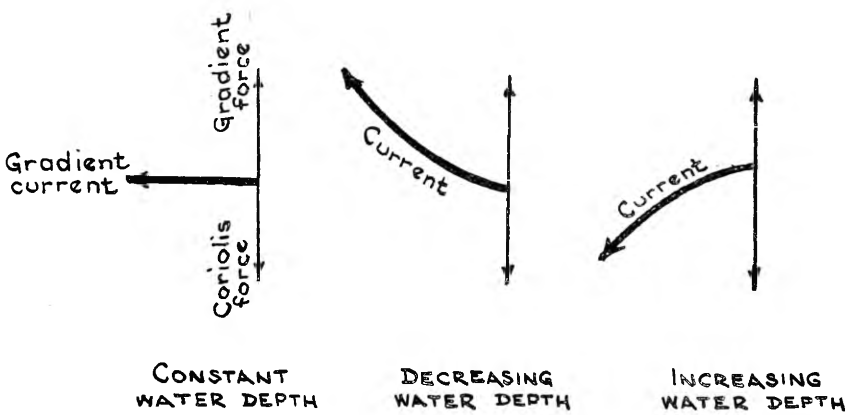


Figure 36: Deviation of Current for Variable Depths.

as a hydrodynamically smooth surface with transfer largely by friction With higher winds, transfer by pressure on waves becomes important. For the higher winds it has been found that, no matter what wave height is attained, the surface is characterised by a constant roughness parameter, and the current speed bears a constant ratio to the wind speed (Berry, Bollay and Beirs, 1945). The division between the two conditions seems to occur at a wind speed of about 6 to 10 knots. At wind speeds lower than this, the relation between wind and current speeds is complicated, but a rough estimate can be made by halving the current speeds obtained using the relationship for the higher winds.

Where a pure wind drift current exists, the stress of the wind is balanced by the Coriolis force acting on the entire body of water that is set in motion. The total transport of water is consequently at 90^{o} to the wind stress, anticlockwise in the Southern Hemisphere (Figure 35). The wind stress acts in a direction very close to that of the surface wind, which blows about 15^{o} clockwise from the isobaric or geostrophic wind. Because of the difference in friction, land-surface winds blow 15^{o} to 30^{o} clockwise from sea-surface winds, a fact which must be taken into account when comparing ocean currents with land recorded winds.

The result that the total mass transport acts at right angles to the wind stress is derived without making any assumptions as to the viscosity of the water. To find the currents at various depths which combine to effect this total transport, a distribution of viscosity is required. For deep water the classical spiral of Ekman, based on constant eddy viscosity throughout the mass of water, gives a picture which seems to agree with observed phenomena, although existence of such a spiral has not yet been rigorously demonstrated in the ocean (von Arx, 1962). Ekman's analysis yields, for the Southern Hemisphere, a surface current directed 45^{o} anticlockwise from the wind stress (Figure 35). With increasing depth, the angle between the wind stress and the current increases and the velocity decreases exponentially. A depth can always be found at which the current flows in a direction exactly opposite to that of the surface current. At this depth the velocity has decreased to a small fraction of that of the surface current, and below this depth the currents are negligible. Ekman termed this "the depth of frictional resistance". For wind speeds higher than about 10 knots, an approximate value is given by:

$$D = \frac{7.6W}{\sqrt{\sin \phi}} \qquad (20)$$

where D = depth of frictional resistance in feet
W = wind speed in feet per second
ϕ = latitude.

The velocity of the sea surface wind drift is given by the same analysis as:

$$U_w = \frac{0.013W}{\sqrt{\sin \phi}} \qquad (21)$$

where U_w = sea surface wind drift in feet per second.

In deep water off Wybung Head the values of D and U_w corresponding to a 10 knot wind are given by these equations as 180 feet and 0.03 feet per second respectively. Equations (20) and (21) cannot be expected to apply for very low winds, which have been seen to act in a different manner. For these, an equation due to Thorade is suggested (Sverdrup, Johnson and Fleming, 1942). This gives:

$$D = \frac{2.03\sqrt{W^3}}{\sqrt{\sin \phi}} \qquad (22)$$

for D in feet
W in feet per second.

For a 10 knot wind off Wybung Head, the value of D is similar to that given by (20). For lower winds, values of D decrease more and more rapidly. With a 5 knot wind, (22) gives D = 70 ft.

Ekman extended his analysis to the case of shallow water, and found a surface deflection less than 45° and a slower turning with depth. This, however, was based on assumptions of zero velocity at the bottom and constant eddy viscosity throughout the depth. These assumptions have since been found invalid, and Ekman's analysis for shallow water does not give results comparable with observed phenomena. In shallow water, the eddy viscosity decreases towards the bottom, resulting in a greater angle between wind and currents at all depths and increased current velocities (Sverdrup, Johnson and Fleming, 1942). Measurements by Sverdrup in some 70 feet of water have found a surface angle closer to 60° than the

45° given for deep water. In extremely shallow water, currents have been found to flow nearly in the direction of the stress at all depths.

4.3 Wave Currents

4.31 Mass Transport

Some of the currents associated with waves have already been explicitly or implicitly discussed. Mass transport currents predicted by the theories of Stokes and Longuet-Higgins* give surface velocities of 0.2 feet per second in deep water (Stokes) and 0.5 feet per second in 100 feet water depth (Longuet-Higgins) for a wave 10 feet high and 10 seconds period. Since the magnitude of the currents is proportional to the square of the wave height, mass transport can be appreciable for high waves. Mass transport velocity also increases with decreasing period, the Stokian transport for a 4 second wave being about 10 times as great at the surface as that for a 10 second wave of the same height. Such short period waves are rarely found in the ocean, except for small amplitude waves produced by sea breezes and offshore winds, and in the storm wave spectrum. The mass transport associated with these waves is reduced because of the small wave height.

The mass transport current near the bed flows always in the direction of propagation of the wave. At the surface, the mass transport is usually in the direction of propagation, except for very small ratios of wave height to wave length. For a wave in 2 dimensions progressing towards a solid boundary, the mass transport in between the surface layer and the bottom layer is opposite to the direction of propagation and provides the necessary return flow. In 3 dimensions the return flow may be provided by other means, such as rip currents, and the total transport between rips may be landward.

4.32 Nearshore Currents

The nearshore currents associated with wave action are the littoral or longshore current engendered by a wave breaking at an angle to the shoreline, and the rip current which allows for a flow to sea, at some point of favourable topography, of water piled up by the waves flowing shoreward. Strong rip currents are often associated with the littoral drift induced by a wave breaking at an angle to the shore, but rip currents are not restricted to this condition and may occur with waves approaching normal to the shoreline (Shepherd, Francis and Inman, 1951).

---

* Section 3.14

Littoral currents can be predicted with some degree of reliability (Putnam, Munk and Traylor, 1949), though the assumptions necessary to make these currents amenable to analysis are rarely conformed with by nature. The momentum approach to the generation of littoral currents has been found to give results consistent with natural occurrences. The basic concept is that, as the wave breaks, a certain water mass is thrown into motion in the direction of wave propagation, and the longshore component of this motion provides the driving force for the littoral current. On the assumptions of a straight shoreline and uniform bottom slopes, the velocity U_L of the longshore current is given as:

$$U_L = \frac{R}{2} \left(\sqrt{1 + 4 \frac{C}{R} \sin \alpha_b} - 1 \right) \qquad (23)$$

where α_b = angle between shore and breaker line

$$R = \frac{8 A_b \cos \alpha_b}{l f T}$$

where A_b = cross sectional area of wave at breaking

f = friction factor ($\doteq$ 0.06 for sand)

l = distance from shore to breaker line

The wave form at breaking is assumed that of a solitary wave, which it closely resembles.*

4.4 Tidal Currents

Tidal currents of any significance are generally restricted to narrow bodies of water connecting larger water masses. North of Wybung Head, tidal currents in and out of Lake Macquarie are appreciable, but the distance precludes any effect in the vicinity of the headland. A small tidal current is engendered because of the presence of an embayment between Wybung Head and Norah Head, but this again is some orders of magnitude lower than the currents due to other effects. In the open ocean, tidal currents are usually rotary, due to the effect of the Coriolis force. The magnitude and direction change continuously: for the Pacific Ocean with semi-diurnal tides one complete rotation of current directions is performed about every 12 hours. Speeds of the order of 0.05 knots have been measured in the open sea off the west coast of the United States.

---

* Section 3.16

4.5 Effect of Local Topography on Currents

4.51 General

The effect of boundary conditions has already been indicated with respect to wind induced currents in shallow water. Naturally all currents will be profoundly affected by boundary conditions. Coastlines and shallow bottoms impose a new set of boundary conditions with which the current developed by any stress must conform.

4.52 Changing Water Depth

A current occupying the full depth of water is deflected if it flows towards a different water depth because of the change of current velocity with change of cross-section and consequent change in Coriolis Force (Defant, 1961). In the Southern Hemisphere the current will be deflected clockwise for decreasing water depth and anticlockwise for increasing water depth (Figure 36). In this way coastal currents, no matter what their original direction, will tend to flow along the coast. This relation is true for currents in middle and high latitudes, but in low latitudes where Coriolis forces are less important, currents tend to flow east-west independent of the slope of the bottom (Sverdrup, Johnson and Fleming, 1942).

4.53 Bottom Friction

The state of the current very close to the bottom must be governed by the roughness. Very little information is available, but some measurements made of San Diego tidal currents gave values of 0.5, 0.7 and 0.85 feet per second at distances above the bottom of 0.7, 1.7 and 4.1 feet (Sverdrup, Johnson and Fleming, 1942). These figures agree with a bottom characterised as "rough", with turbulent rather than laminar flow, and with a "roughness parameter" of the same type as that used to characterise pipe or channel flow of about 1 inch. Concomitant values of surface tidal currents are not immediately available, but something of the order of 1 knot could be expected. It therefore seems that substantial velocities penetrate to within a few feet of the bottom.

4.54 Upwelling and Sinking

Other phenomena associated with boundary conditions are "sinking" and "upwelling". These are regarded as being caused by winds blowing along the coast, disturbing the distribution of mass in the coastal waters and causing currents on- and off-shore at different depths. For the east coast of Australia, a wind from the south produces onshore flow at the surface with return flow at depth (sinking). Winds

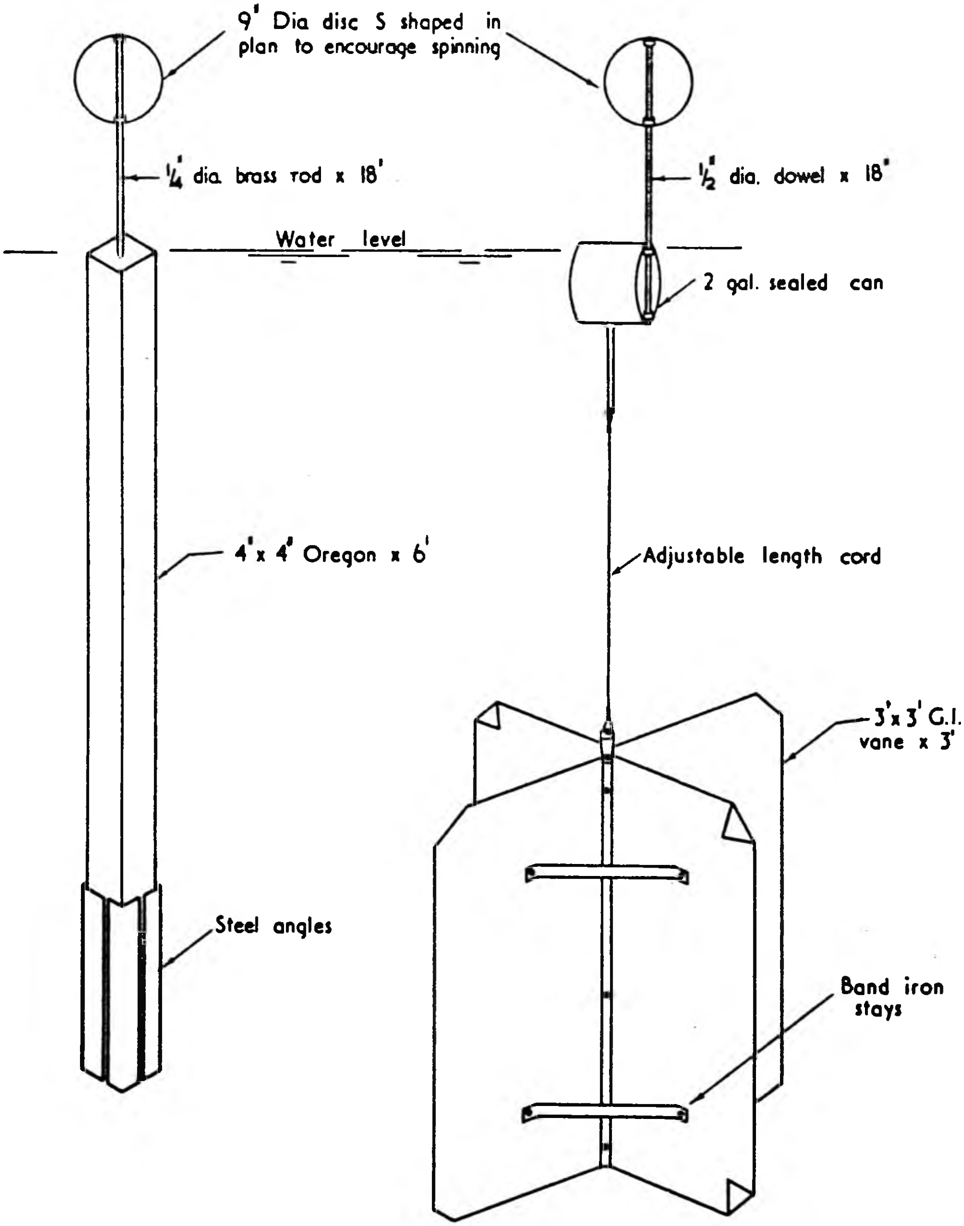


Figure 37: Two Devices Used for Current Tracking

from the north cause offshore surface flow and onshore flow at depth (upwelling). These currents are not defined by the flow in one vertical plane, but are 3-dimensional with flow up-or down-coast with the wind. These phenomena have not yet been exhaustively examined, but it is expected that the associated currents would tend to break up into eddies and that the forced vertical circulation would limit the development of the current.

4.55 Effect of Irregular Coastline

Macrospoic eddies associated with an irregular coastline must also be taken into account. A current flowing in a given direction past a bay is likely to induce a circulation in the bay with a current close to shore flowing in the opposite direction. This is generally termed a "back-eddy".

4.6 Currents Near Wybung Head

4.61 Coastal Currents

Some current measurements have been undertaken in the vicinity of Wybung Head. These generally do not extend much beyond 2 miles from shore, corresponding to a depth of about 100 feet. A suitable method of measuring these coastal currents was found in the tracking by 2 land-based surveyors of flags surmounting vanes or "current crosses". The vanes were launched from a vessel at sea and registered the current at various depths, depending on the length of cord between the vane and a small partially submerged float. Sketches of current-crosses and pole type floats, which were used for some of the early surface current measurements, are shown in Figure 37. In some instances these "float-runs" were supplemented by measurements at various locations made with a Kelvin and Hughes Direct Reading Current Meter. The accuracy of the current meter was impaired at low speeds (which generally prevail in the area) by its vertical movement under wave action.

Currents were measured at various times of the year and under various sea and weather conditions. In general they were found to be mostly alongshore, as theory and experience would predict, and to change rapidly with relatively minor changes in weather. Four factors were discernable as affecting the currents, being:

(i) Strength and inshore penetration of the East Australian current.
(ii) Local weather (winds).
(iii) Distant weather (swell).

(iv) Local topography.

The interplay of these and other factors results in a highly unstable current system. Sometimes one factor has appeared to predominate and its effect could be seen in the resulting current, but frequently it seemed that many factors in play contributed effects of similar magnitude and the measured currents were then not easy to interpret.

Figures 38 to 60 give an indication of the currents measured off Wybung Head. A brief resume of some observed phenomena is given in the following pages.

At distances greater than about $\frac{1}{2}$ mile from shore a southerly set was observed on nearly every occasion when measurements were made at such distances. When strong northerly currents were encountered closer to shore, the southward flow seemed to be displaced up to $\frac{1}{2}$ mile farther to sea. Northerly inshore flows were frequently found to be connected to the seaward southerly set by an easterly flow, which occurred about $\frac{1}{2}$ mile to 1 mile from shore. On one occasion, 23.6.1962, a strong northerly current associated with heavy swell from the south persisted as far as 3 miles from Wybung Head. Though the number of days on which currents have been observed at distances greater than some $\frac{1}{2}$ mile from shore does not exceed about 10, there seems to be evidence of a dominant southerly set, disturbed only by quite strong weather conditions.

Under calm weather conditions, especially at night when winds are generally low, the southerly has been found to penetrate to within 1/4 mile from the coast. On the night of 15.6.1962 to 16.6.1962, for example, south-flowing currents were registered 1/4 mile from Wybung Head, although floats tracked north on both days at distances up to $\frac{1}{2}$ mile from the coast. On 20.6.1962, a southerly current was found as close as 200 yards from shore, in spite of strong local winds that would theoretically induce currents with a direction between north and east. Figure 54 would indicate that a marked intrusion of the offshore southerly set was occurring.

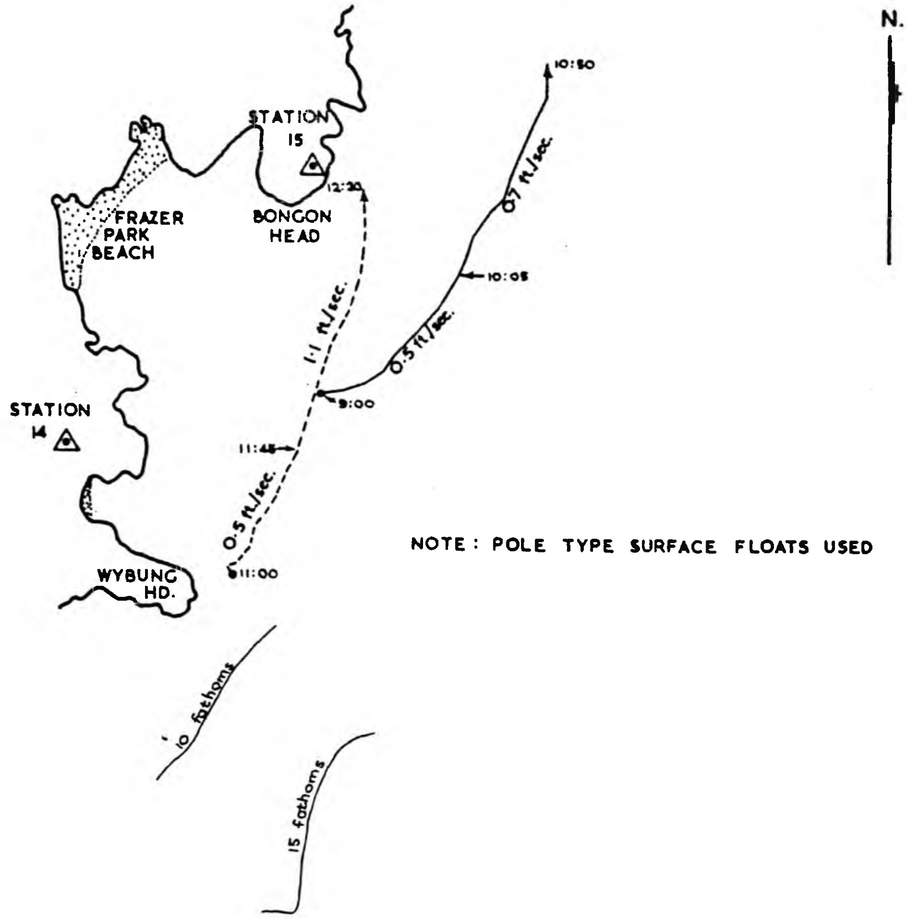
The existence with strong swell of a current running with the swell has already been instanced for 23.6.1962. Every time that a heavy swell has been observed, swell-driven currents have been registered. Swells from the south only have been encountered during current measurements, and these occurred on 24.3.1961, 5.7.1961 and 15.6.1962 as well as 23.6.1962. The only time that a substantial northerly current, at least inshore, was not associated with the swell was on 5. 7. 61, when the swell was slight and the local winds high. The mass transport currents associated with these swells are lower than the observed currents,* and it would appear that a redistribution of mass effected by the swell-producing forces is responsible for the strong currents experienced.

Wind effects are at once the most probable cause of many of the currents encountered, and the least amenable to analysis. The pure wind drift, even for winds as high as 30 knots, cannot be expected to exceed 0. 1 knots at the surface. The secondary effects of the wind in altering the distribution of mass in the ocean and in causing such coastline phenomena as upwelling and sinking are, however, important, and these have not yet been subjected to any degree of quantitative analysis. On many occasions, when no other over-riding effects seemed to be in evidence, currents measured corresponded in direction with the pure wind drift currents associated with the prevailing wind, account being taken of the fact that currents running towards changing water depths tend to turn and follow the bottom contours. Inshore currents measured on 11. 6. 1962, 16. 6. 1962 and 21. 6. 1962 are some examples of currents associated with local winds.

Insufficient measurements have been made to define all the effects on the currents of the coastline geometry and local topography. Exceedingly calm water within a mile or so of the coast associated with heavy offshore chop during strong westerly winds is one effect that was noted on 5. 7. 1961 and 6. 7. 1961. The southerly circulation very close to shore north of Wybung Head on 13. 6. 1962 with northerly currents farther offshore, indicating a back eddy in Frazer Park Bay, is another example of boundary effects that was observed.

The coastal currents are seen to be partially explained on the basis of presently accepted theories, particularly when one influence is powerful enough to over-ride the effects of the other phenomena. In the absence of strong weather or sea conditions, light and variable currents, which are not readily explained, characterise the inshore waters. Though insufficient records are available to make definite statistical inferences, it may be stated that there appears to be a dominant southerly set with a variable shoreward limit about $\frac{1}{2}$ mile from Wybung Head, and that the waters between this distance and the coastline seem to flow generally north or south along the coast with no significant dominance for either direction.

* Section 4. 31



NOTE : POLE TYPE SURFACE FLOATS USED

Tides at Fort Denison

Time	Height
1:50 a.m	4ft. 8 ins.
8:39 a.m	1ft. 10 ins.
2:38 p.m	3ft. 8 ins
8:22 p.m	2ft. 2 ins

Sea : rising southerly swell

Wind at Nobby's

Time	Speed	Direction
6 a.m	12	N.W
9 a.m	17	W.N.W
12 noon	17	S.S.W
3 p.m	29	S.S.W

0 ¼ m. ½ m. ¾ m. 1 mile

SCALE

24·3·61 A.M CURRENTS

Figure 38

Wind at Nobby's

Time	Speed	Direction
6 a.m	2	N.W
9 a.m	9	N.W
12 noon	22	W.N.W
3 p.m	17	N.W

Tides at Fort Denison

Time	Height
1:27 a.m	5 ft. 0 ins
8:04 a.m	11 ins
2:26 p.m	4 ft. 7 ins
8:30 p.m	1 ft. 8 ins

Sea: slight southerly swell

SYMBOL	AVE. VELOCITY ft./sec.
×———×	0·5
×—×—×	0·3
●———●	0·4
△———△	0·3
□———□	0·1

NOTE: ALL POLE TYPE SURFACE FLOATS

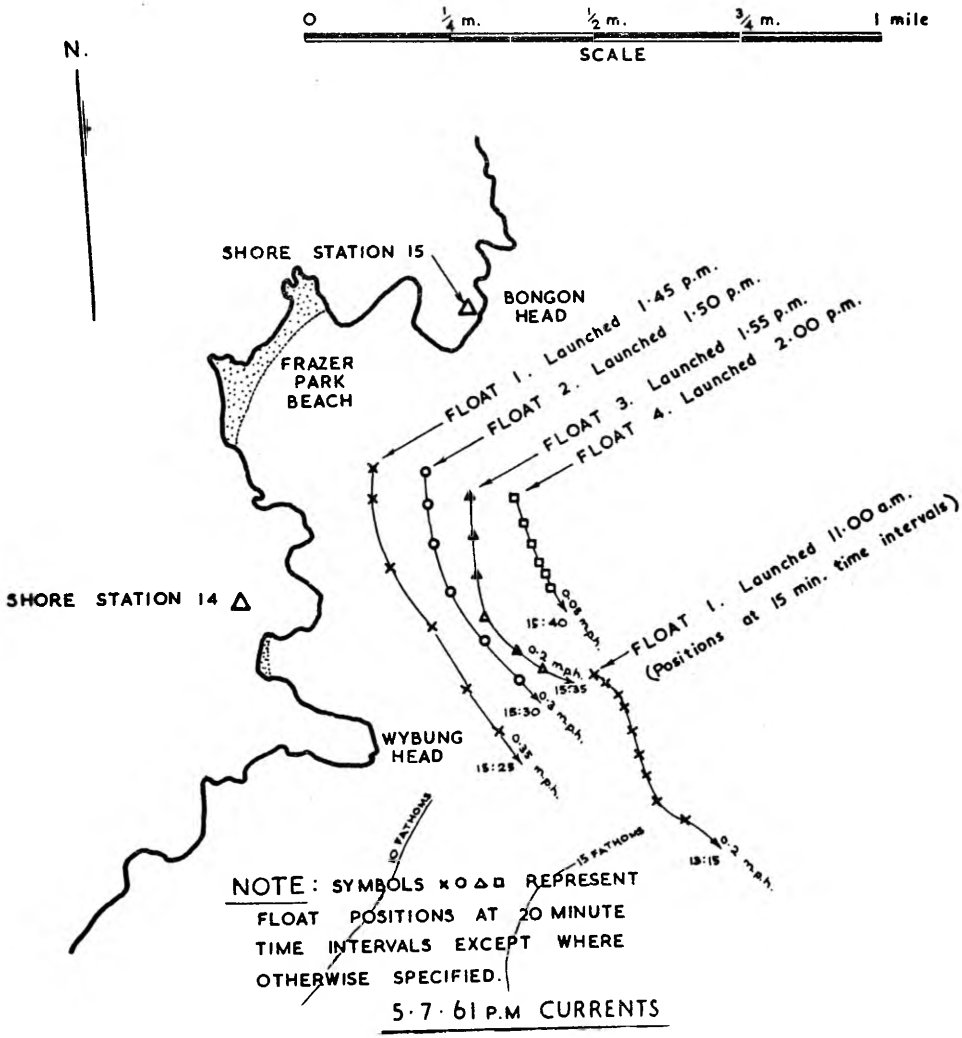


Figure 39

Wind at Nobby's

Time	Speed	Direction
6 a.m	26	N.W
9 a.m	30	N.W
12 noon	30	N.W
3 p.m	30	N.W

Tides at Fort Denison

Time	Height
2:32 a.m	4ft. 7 ins
9:00 a.m	1ft. 1 in
3:28 p.m	4ft. 8 ins
9:45 p.m	1ft. 8 ins

Sea: calm inshore, choppy offshore

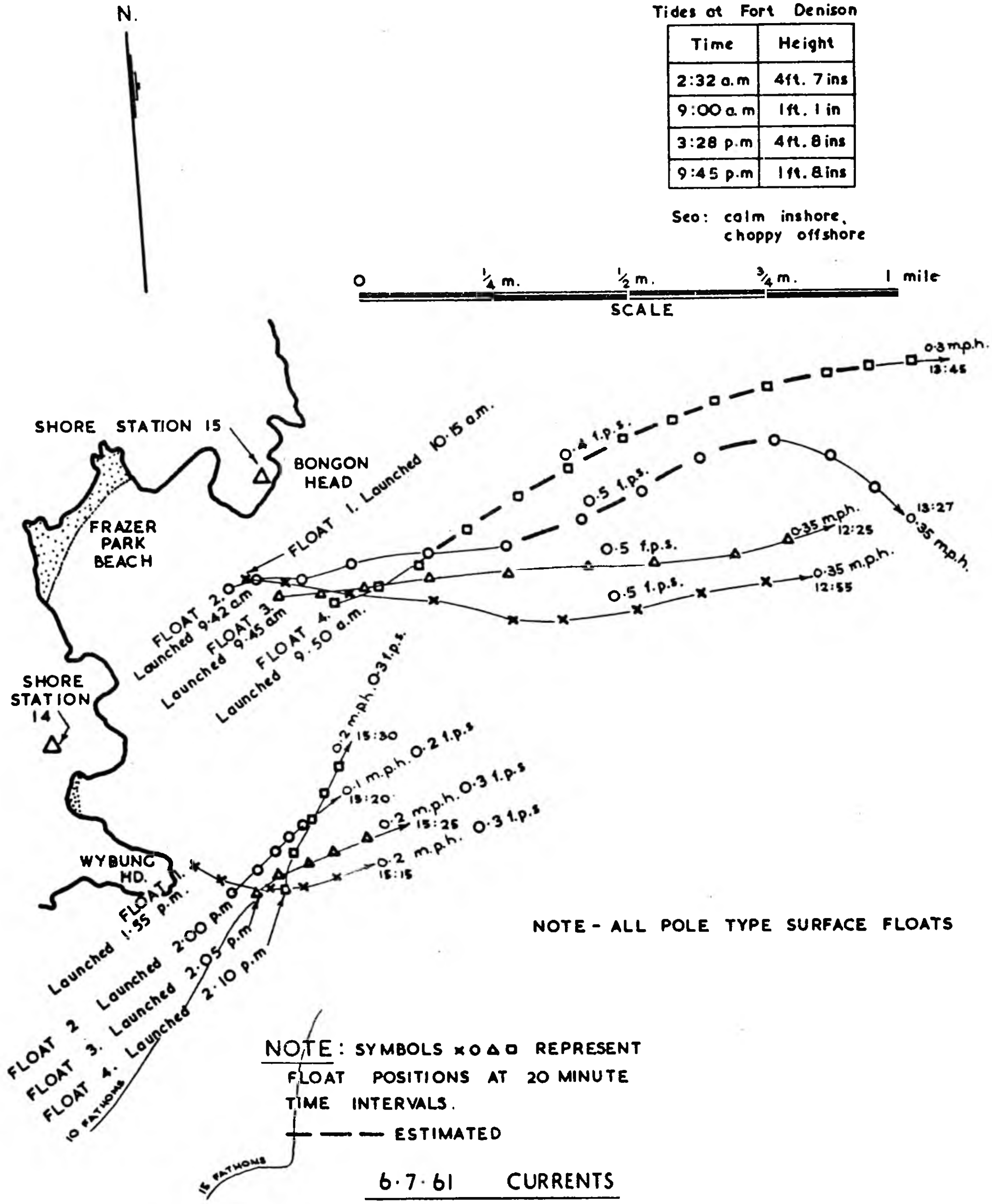
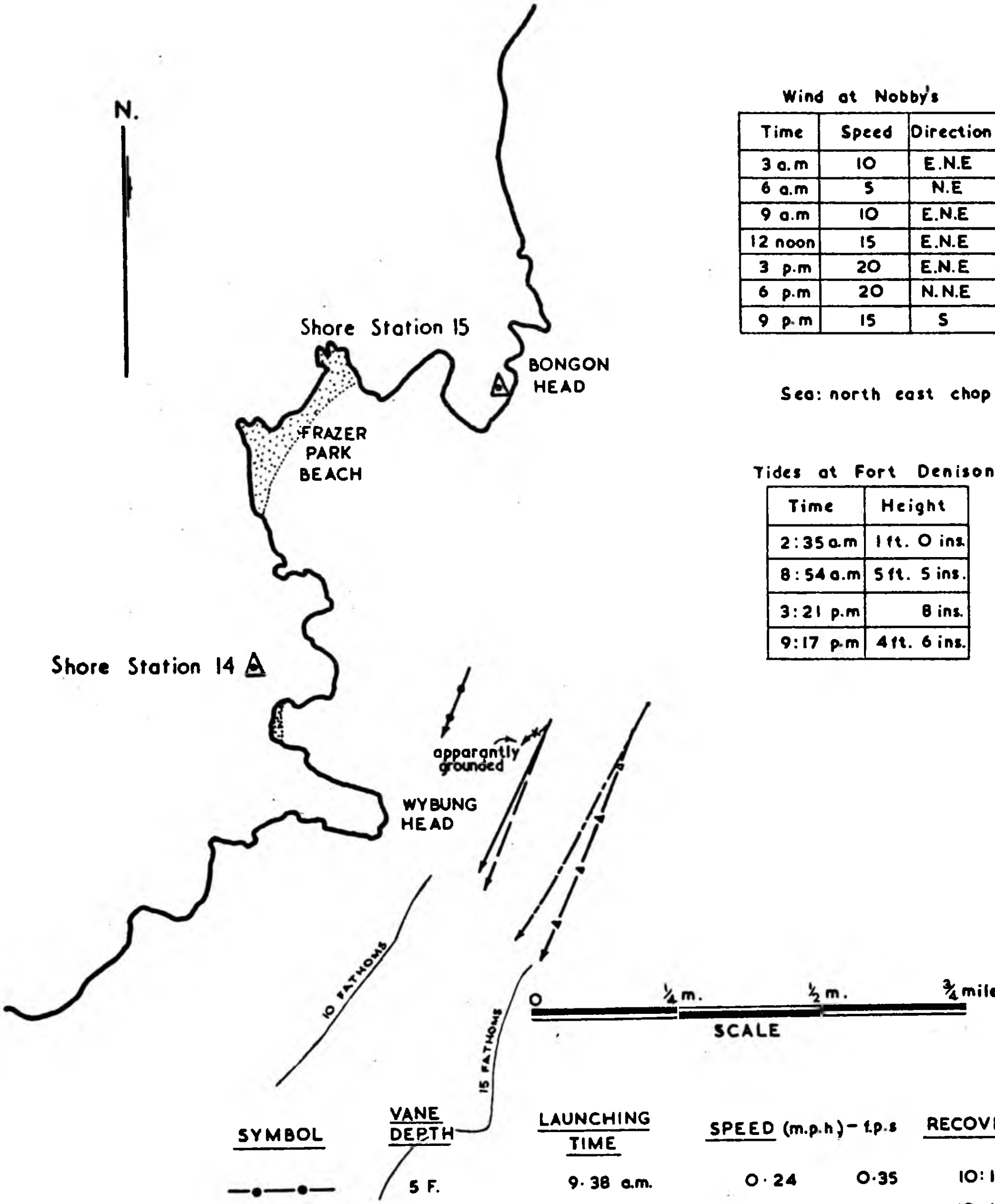


Figure 40



Wind at Nobby's

Time	Speed	Direction
3 a.m	10	E.N.E
6 a.m	5	N.E
9 a.m	10	E.N.E
12 noon	15	E.N.E
3 p.m	20	E.N.E
6 p.m	20	N.N.E
9 p.m	15	S

Sea: north east chop

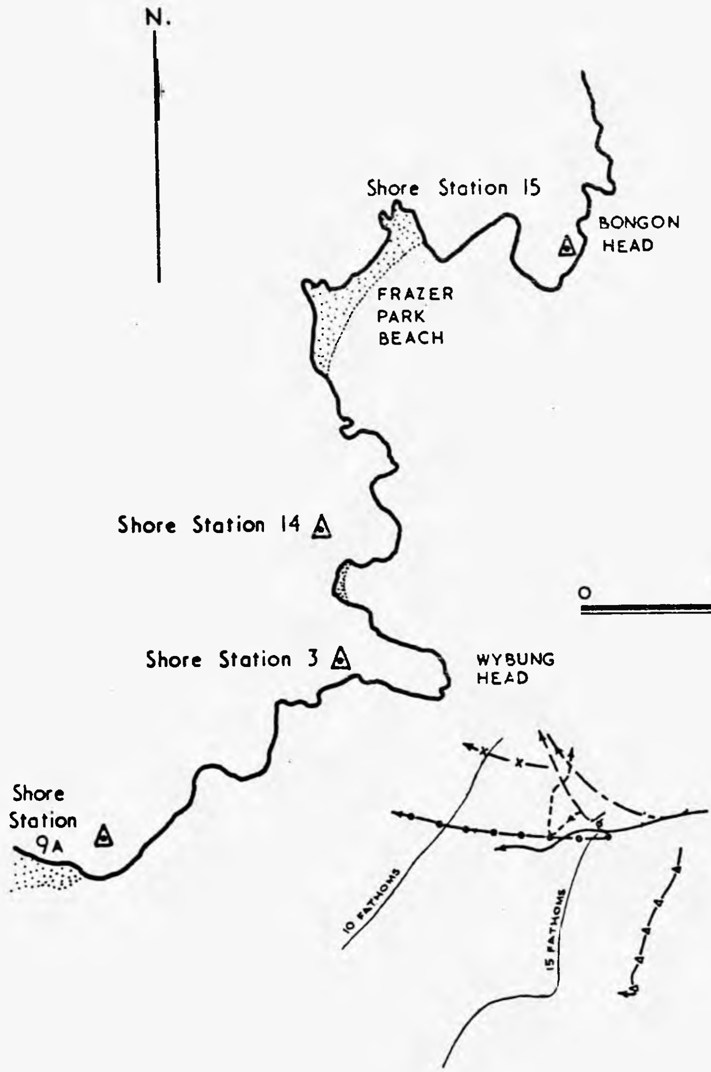
Tides at Fort Denison

Time	Height
2:35 a.m	1 ft. 0 ins.
8:54 a.m	5 ft. 5 ins.
3:21 p.m	8 ins.
9:17 p.m	4 ft. 6 ins.

SYMBOL	VANE DEPTH	LAUNCHING TIME	SPEED (m.p.h)	– f.p.s	RECOVERY
—•—•—	5 F.	9·38 a.m.	0·24	0·35	10:11 a.m
———	5 F.	9·59 a.m.	0·43	0·6	10:40 a.m
—x—x—	10 F.	10·01 a.m.	–	–	11:35 a.m
—— ——	Surface pole	10·02 a.m.	0·61	0·9	10:30 a.m
—— - ——	10 F.	10·32 a.m.	0·52	0·75	11:26 a.m
——▲——	5 F.	10·37 a.m.	0·52	0·75	11:27 a.m

20·2·62 A.M CURRENTS

Figure 41



Wind at Nobby's

Time	Speed	Direction
3 a.m	10	N.N.E
6 a.m	10	N.N.E
9 a.m	calm	–
12 noon	10	S.S.E
3 p.m	15	S.S.E

Sea: calm

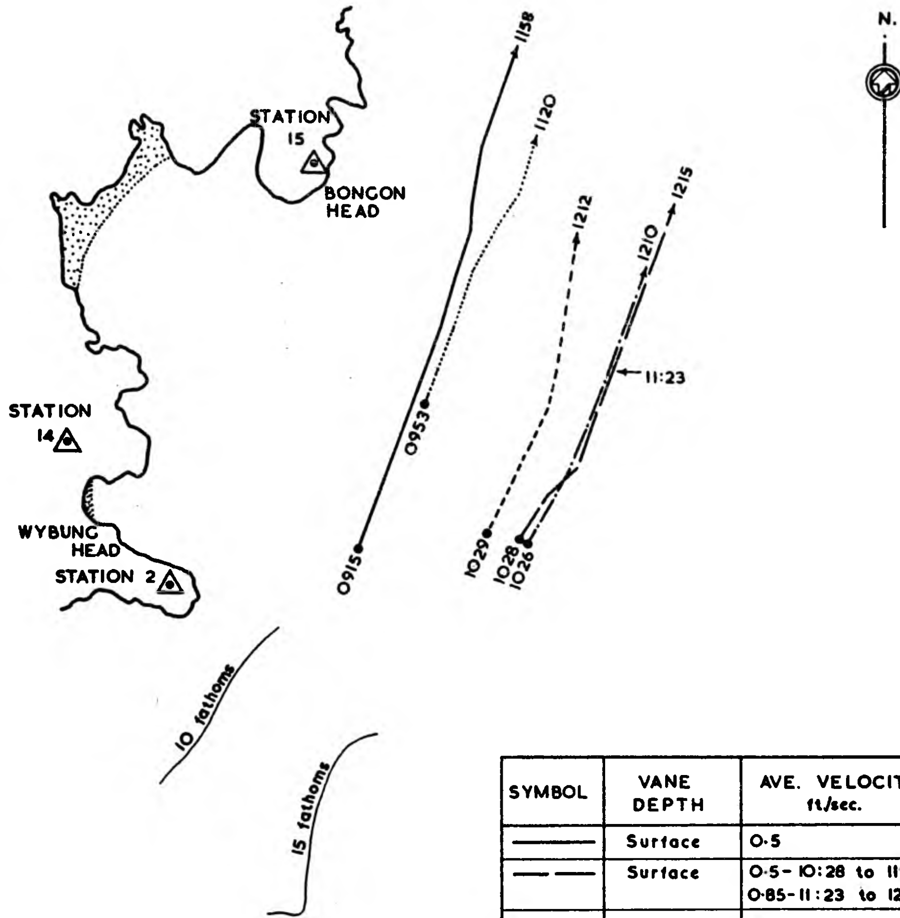
Tides at Fort Denison

Time	Height
3:10 a.m	1 ft. 0 ins.
9:27 a.m	5 ft. 4 ins.
3:51 p.m	8 ins.
9:50 p.m	4 ft. 7 ins.

SYMBOL	VANE DEPTH	LAUNCHING TIME	SPEED (m.p.h.)	– f.p.s	RECOVERY
—▲—	10 F.	9·57 a.m	0·115	0·15	12:39 p.m
———	Surface vane	9·35 a.m	0·1	0·15	12:40 p.m
—— – —	5 F.	9·50 a.m	0·125	0·2	12:27 p.m
—— ——	5 F.	9·40 a.m	0·11	0·15	12:14 p.m
- - - - - - -	10 F.	9·44 a.m	0·09	0·1	12:42 p.m
——●——	Surface pole	9·42 a.m	0·23	0·35	11:52 a.m
——x——	Surface pole	12 07 p.m	0·23	0·35	12:44 p.m

21·2·62 A.M CURRENTS

Figure 42



SYMBOL	VANE DEPTH	AVE. VELOCITY ft/sec.
————	Surface	0·5
— —	Surface	0·5 – 10:28 to 11:23 0·85 – 11:23 to 12:15
··············	5 Fathoms	0·5
– – – – – –	5 Fathoms	0·45
—·—·—	10 Fathoms	0·45

11·6·62 A.M. CURRENTS

Sea : calm

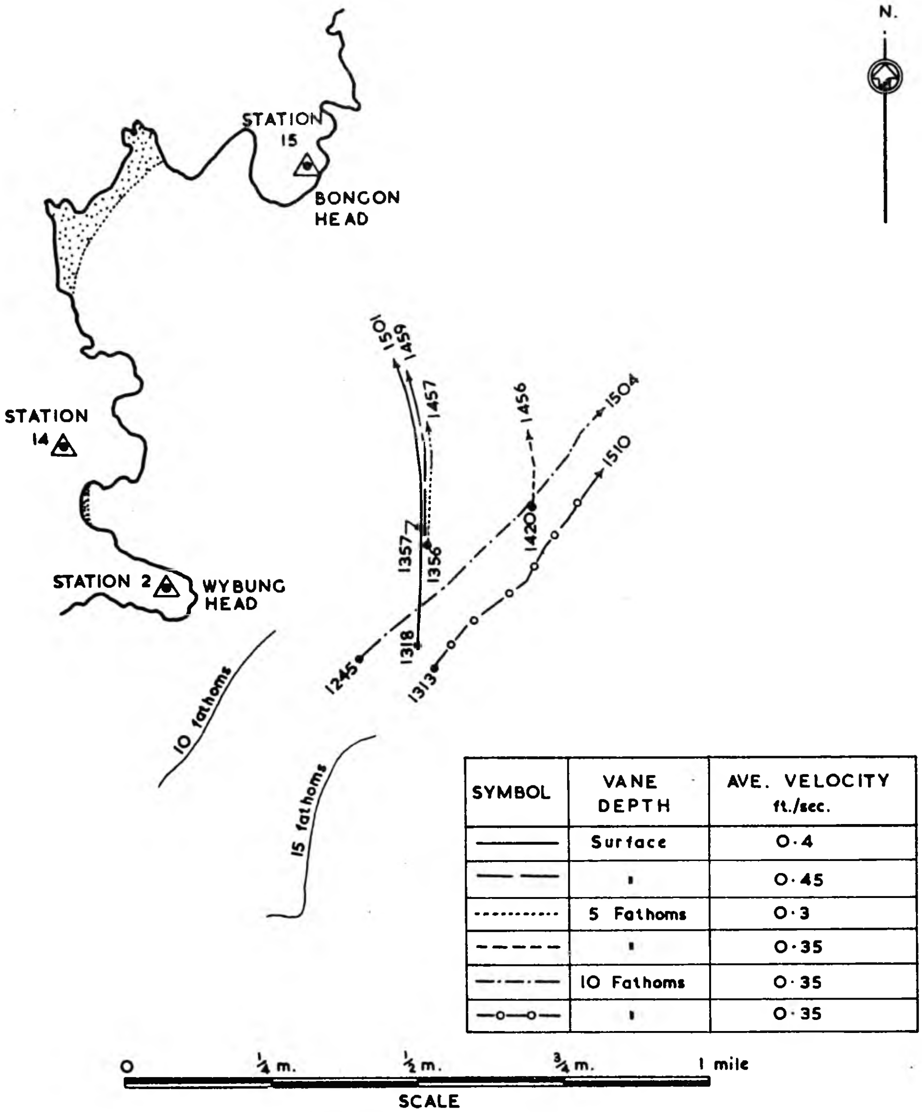
Tides at Fort Denison

Time	Height
2:33 a.m.	4 ft. 5 ins.
9:13 a.m.	1 ft. 6 ins.
3:38 p.m.	4 ft. 5 ins.
9:31 p.m	2 ft. 4 ins.

Wind at Nobby's

Time	Speed	Direction
3 a.m.	10	S.W.
6 a.m.	< 5	S.W.
9 a.m.	10	N.W.
12 noon	10	N.W.
3 p.m	calm	—
6 p.m	calm	—
9 p.m	10	W. S.W

Figure 43



SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec.
———	Surface	0·4
— —	"	0·45
....	5 Fathoms	0·3
- - - - -	"	0·35
—·—·—	10 Fathoms	0·35
—o—o—	"	0·35

11·6·62 P.M. CURRENTS

Sea: calm

Tides at Fort Denison

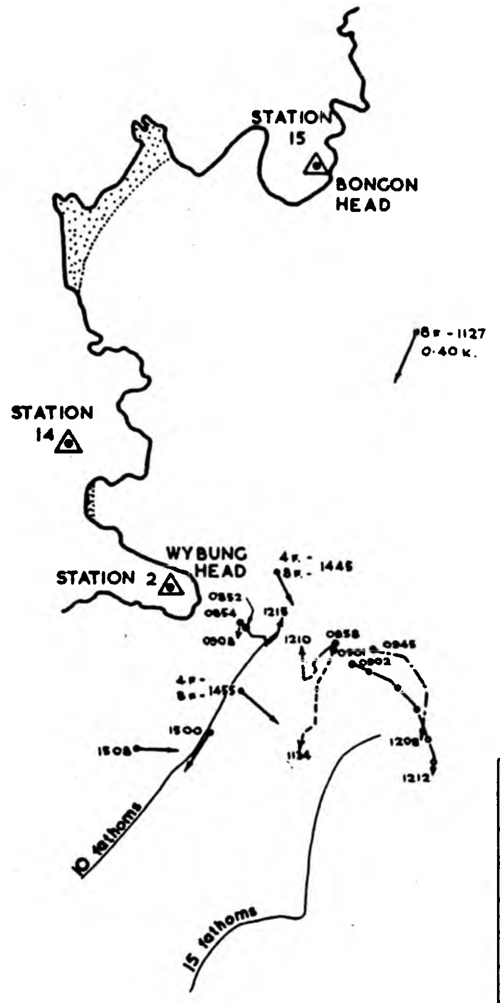
Time	Height
2:33 a.m.	4 ft. 5 ins.
9:13 a.m	1 ft. 6 ins.
3:38 p.m	4 ft. 5 ins.
9:31 p.m.	2 ft. 4 ins.

Wind at Nobby's

Time	Speed	Direction
3 a.m.	10	S.W.
6 a.m.	<5	S.W.
9 a.m.	10	N.W.
12 noon	10	N.W.
3 p.m	calm	—
6 p.m	calm	—
9 p.m	10	W.S.W.

Figure 44

N.



NOTE:

Where directions only given for current meter observations, no speeds were measured.

Where depths are not given, the direction indicated from surface to bottom was the same.

point depth - time
velocity, knots

Key

SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec.
————	Surface	0·1
— —	"	0·1
....	5 Fathoms	0·1
------	"	0·1
—·—·—	10 Fathoms	0·15
—o—o—	"	0·15

0 — ¼ m. — ½ m. — ¾ m. — 1 mile

SCALE

12·6·62 CURRENTS

Sea: calm

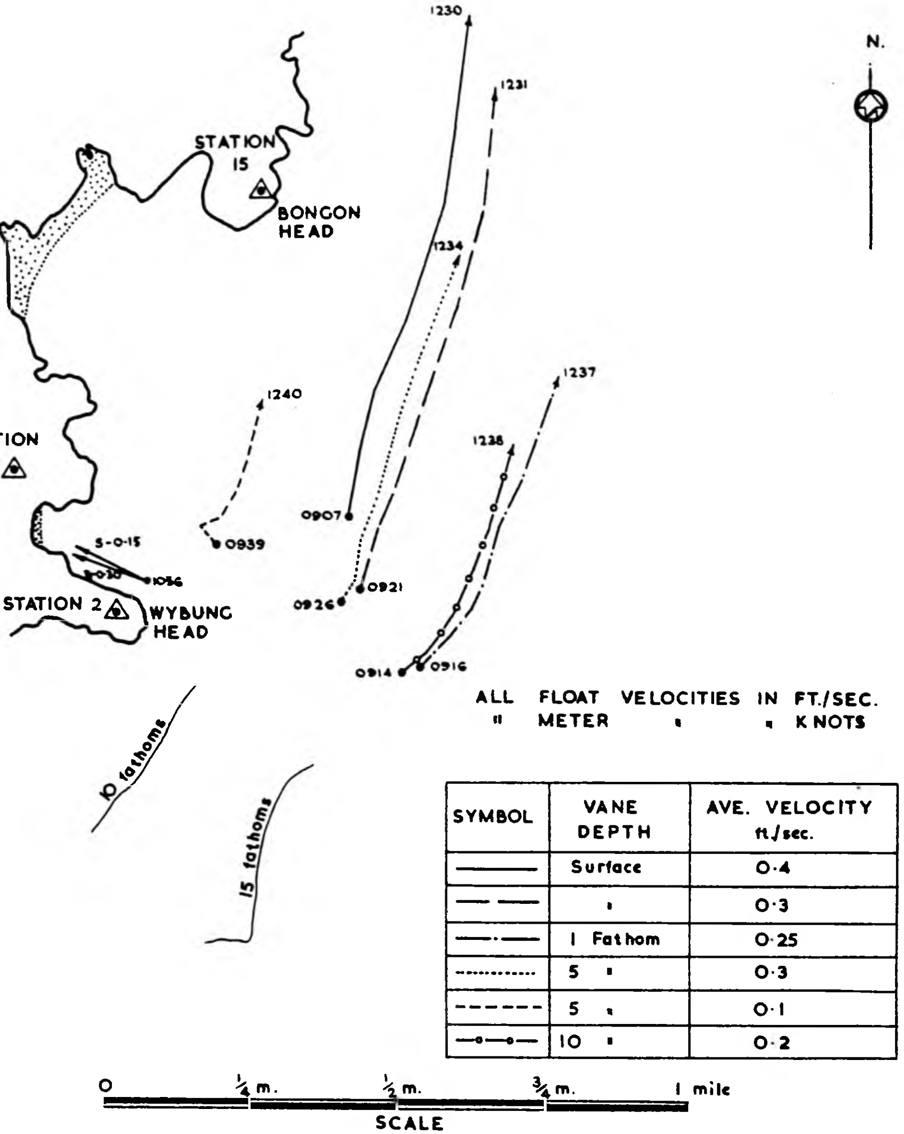
Tides at Fort Denison

Time	Height
3:29 a.m	4 ft. 5 ins.
9:58 a.m	1 ft. 6 ins.
4:29 p.m	4 ft. 7 ins.
10:28 p.m	2 ft. 2 ins.

Wind at Nobby's

Time	Speed	Direction
3 a.m.	<5	N.W.
6 a.m.	<5	N.W.
9 a.m.	5	S.W.
12 noon	calm	-
3 p.m	calm	-
6 p.m	5	S.E
9 p.m	calm	

Figure 45



SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec.
————	Surface	0·4
—— ——	"	0·3
——·——	1 Fathom	0·25
············	5 "	0·3
------	5 "	0·1
—o—o—	10 "	0·2

13·6·62 A.M. CURRENTS

Sea: calm

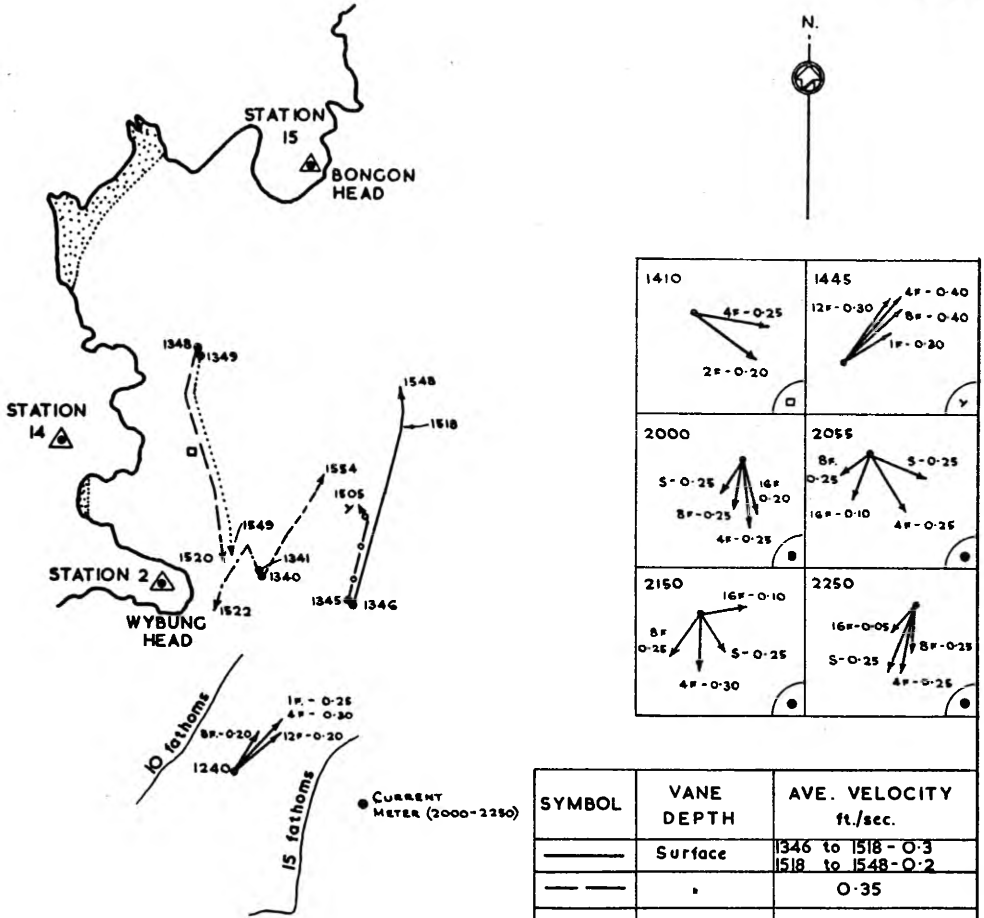
Tides at Fort Denison

Time	Height
4:24 a.m.	4 ft. 5 ins.
10:41 a.m.	1 ft. 5 ins.
5:15 p.m.	4 ft. 11 ins.
11:22 p.m	1 ft. 11 ins.

Wind at Nobbys

Time	Speed	Direction
3 a.m.	<5	N.W.
6 a.m.	5	N.W.
9 a.m.	5	N.W.
12 noon	calm	–
3 p.m.	<5	E.
6 p.m.	calm	–
9 p.m.	10	N.

Figure 46



SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec.
———	Surface	1346 to 1518 - 0·3 1518 to 1548 - 0·2
— —	"	0·35
—·—	1 Fathom	0·15
········	3 "	0·25
- - - - -	5 "	0·15
—o—o—	10 "	1345 to 1433 - 0·25 then apparantly grounded

ALL FLOAT VELOCITIES IN FT./SEC.
" METER " " KNOTS

13·6·62 P.M. CURRENTS

0 ¼ m. ½ m. ¾ m 1 mile
SCALE

Sea: calm

Tides at Fort Denison

Time	Height
4:24 a.m	4 ft. 5 ins.
10:41 a.m	1 ft. 5 ins.
5:15 p.m	4 ft. 11 ins.
11:22 p.m	1 ft. 11 ins.

Wind at Nobbys

Time	Speed	Direction
3 a.m.	< 5	N.W
6 a.m.	5	N.W
9 a.m.	5	N.W
12 noon	calm	—
3 p.m	<5	E
6 p.m	calm	—
9 p.m	10	N

Figure 47

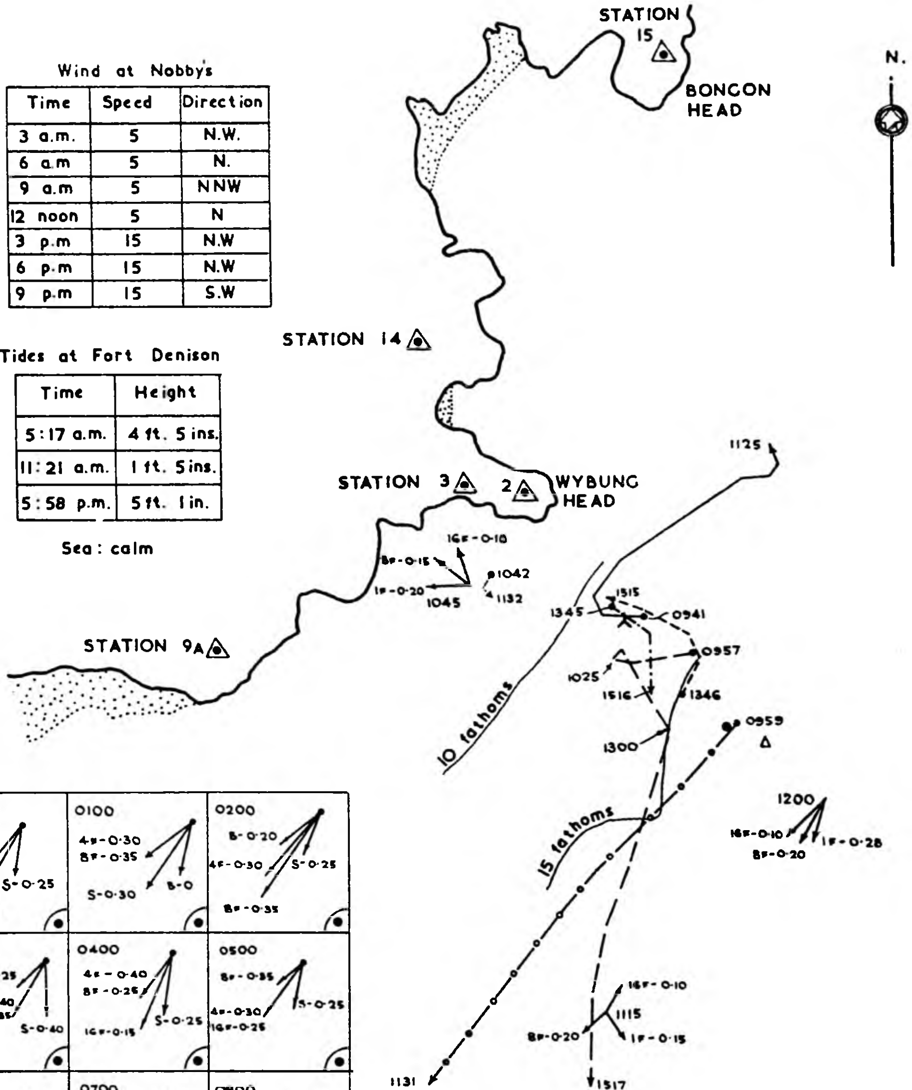
Wind at Nobby's

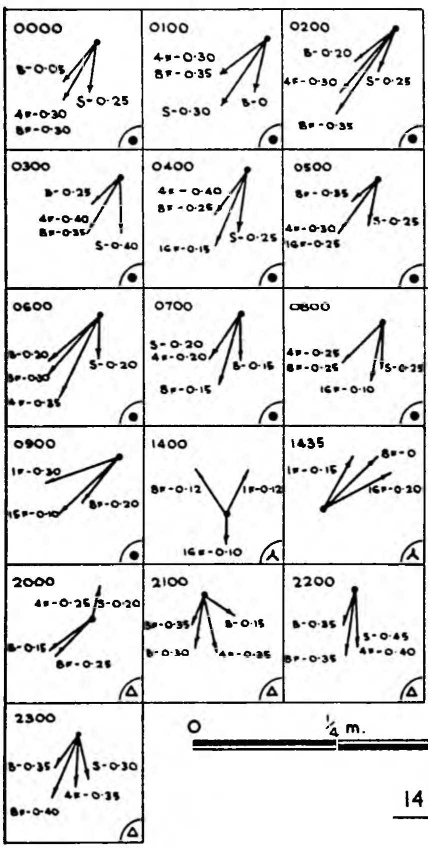
Time	Speed	Direction
3 a.m.	5	N.W.
6 a.m	5	N.
9 a.m	5	NNW
12 noon	5	N
3 p.m	15	N.W
6 p.m	15	N.W
9 p.m	15	S.W

Tides at Fort Denison

Time	Height
5:17 a.m.	4 ft. 5 ins.
11:21 a.m.	1 ft. 5 ins.
5:58 p.m.	5 ft. 1 in.

Sea: calm





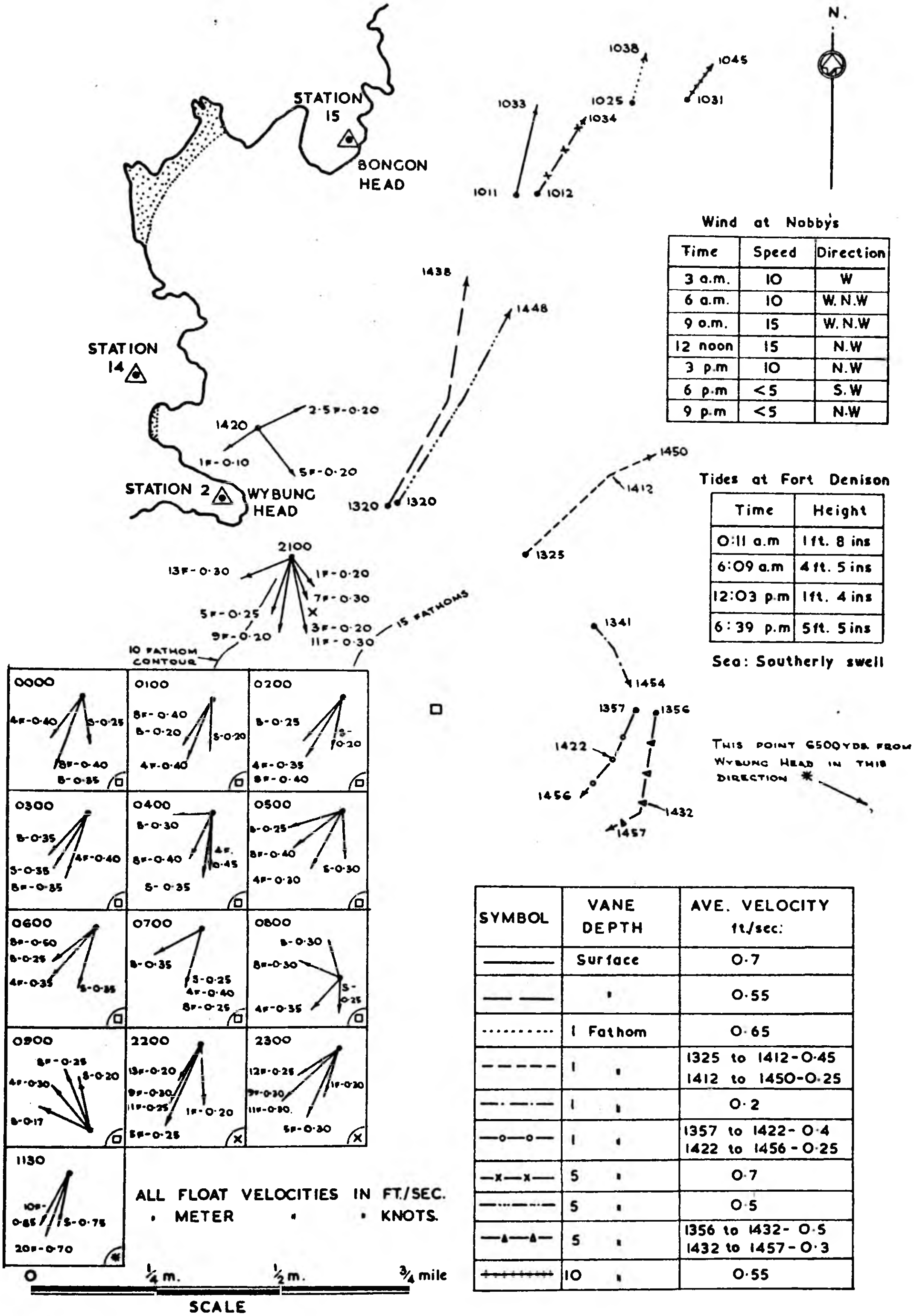
SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec.
———	Surface	0·15
··········	1 Fathom	0·1
- - - - - -	1 "	0·2
— —	1 "	0957 to 1025 - 0·35 1300 to 1517 - 0·55
—o—	5 "	0·35
—·—·—	7 "	0·2

ALL FLOAT VELOCITIES IN FT./SEC.
" METER " " KNOTS

0 — ¼ m. — ½ m. — ¾ m. — 1 mile
SCALE

14·6·62 CURRENTS

Figure 48



Wind at Nobbys

Time	Speed	Direction
3 a.m.	10	W
6 a.m.	10	W.N.W
9 a.m.	15	W.N.W
12 noon	15	N.W
3 p.m	10	N.W
6 p.m	<5	S.W
9 p.m	<5	N.W

Tides at Fort Denison

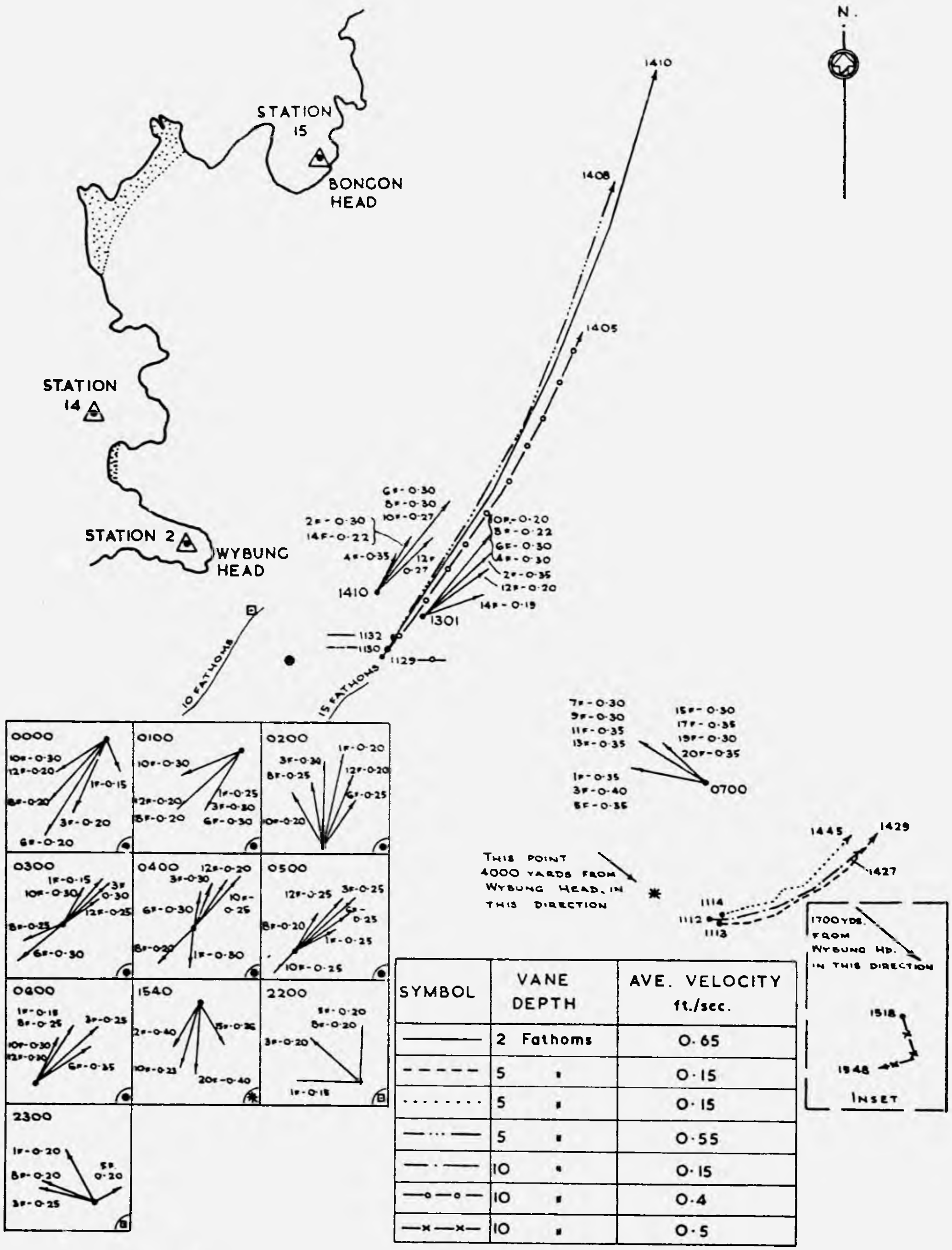
Time	Height
0:11 a.m	1 ft. 8 ins
6:09 a.m	4 ft. 5 ins
12:03 p.m	1 ft. 4 ins
6:39 p.m	5 ft. 5 ins

Sea: Southerly swell

SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec:
———	Surface	0·7
— —	"	0·55
··········	1 Fathom	0·65
- - - - -	1 "	1325 to 1412 - 0·45 1412 to 1450 - 0·25
—·—·—	1 "	0·2
—o—o—	1 "	1357 to 1422 - 0·4 1422 to 1456 - 0·25
—x—x—	5 "	0·7
—··—··—	5 "	0·5
—▲—▲—	5 "	1356 to 1432 - 0·5 1432 to 1457 - 0·3
++++++++	10 "	0·55

15 · 6 · 62 CURRENTS

Figure 49.



SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec.
————	2 Fathoms	0·65
– – – – –	5 "	0·15
· · · · · · · ·	5 "	0·15
—··· —	5 "	0·55
—·—	10 "	0·15
—o—o—	10 "	0·4
—x—x—	10 "	0·5

Wind at Nobby's

Time	Speed	Direction
3 a.m	10	N.W
6 a.m	10	W
9 a.m	calm	–
12 noon	15	N.W
3 p.m	10	N.W
6 p.m	calm	–
9 p.m	5	N

ALL FLOAT VELOCITIES IN FT./SEC.
" METER " " KNOTS.

0 ¼ m. ½ m. ¾ mile
SCALE

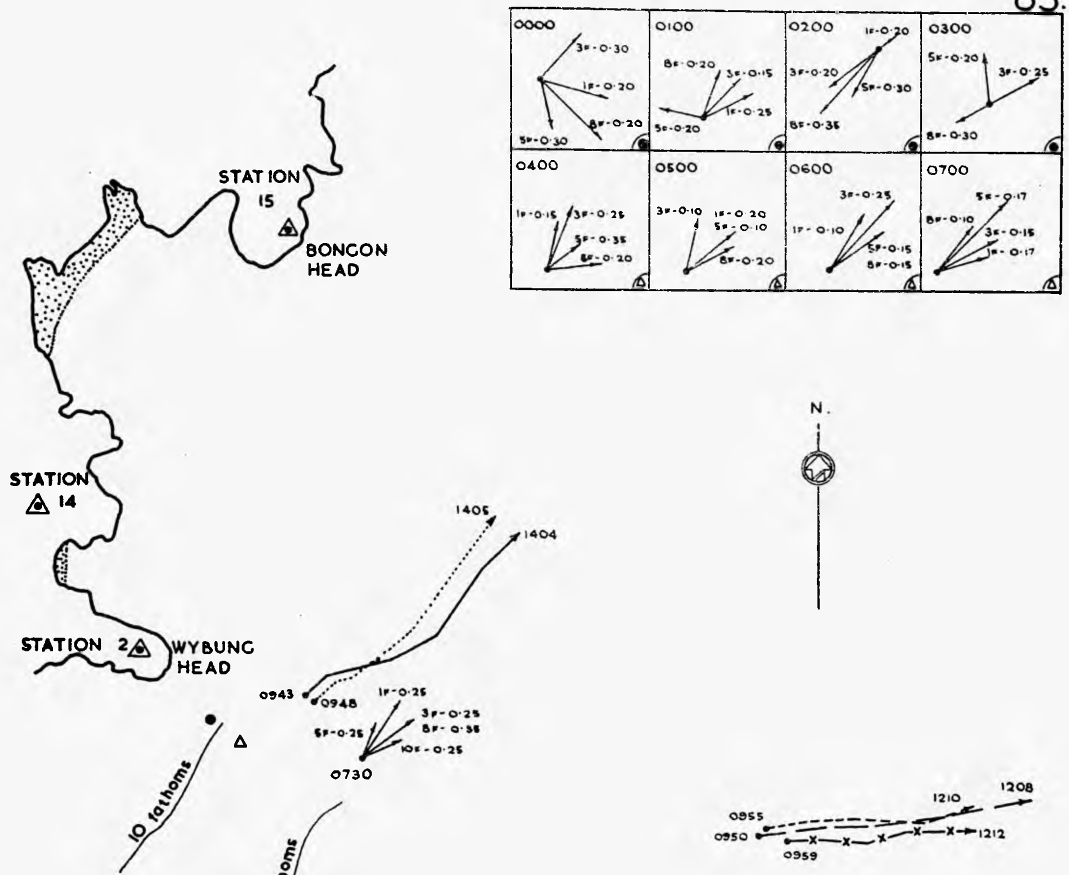
16·6·62 CURRENTS

Tides at Fort Denison

Time	Height
1:00 a.m	1 ft. 5 ins
6:58 a.m	4 ft. 5 ins
12:44 p.m	1 ft. 4 ins
7:19 p.m	5 ft. 8 ins

Sea : calm

Figure 50



SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec.
————	2 Fathoms	0·15
— —	2 "	0·30
············	5 "	0·15
------	5 "	0·25
—x—x—	10 "	0·25

ALL FLOAT VELOCITIES IN FT./SEC.
" METER " " KNOTS

Sea: calm

Tides at Fort Denison

Time	Height
1:47 a.m	1ft. 2 ins.
7:44 a.m	4ft. 6 ins.
1:26 p.m	1ft. 4 ins.
7:59 p.m	5ft. 11 ins.

17·6·62 CURRENTS

Wind at Nobby's

Time	Speed	Direction
3 a.m	20	W
6 a.m	20	N.W
9 a.m	30	N.W
12 noon	—	—
3 p.m	20	N.W
6 p.m	10	N.W
9 p.m	25	N.W

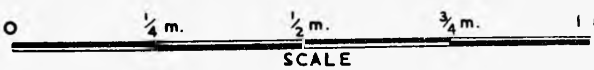
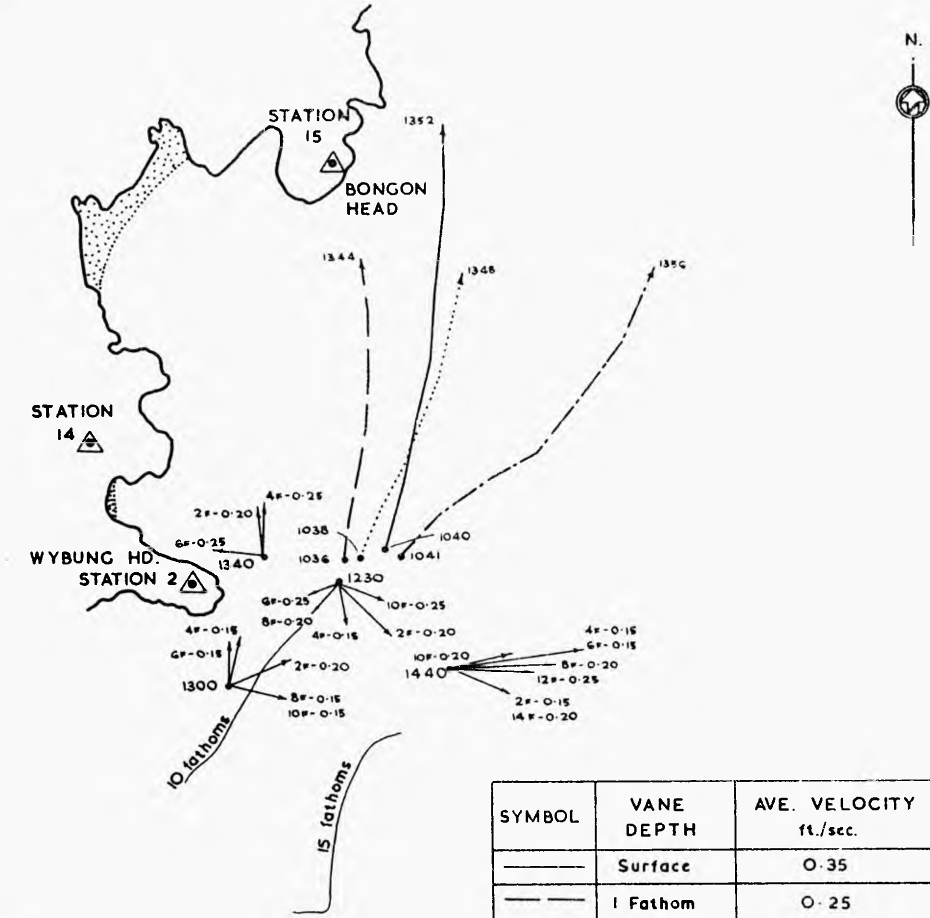


Figure 51



SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec.
————	Surface	0·35
—— ——	1 Fathom	0·25
··············	5 "	0·25
—·—·—	10 "	0·35

ALL FLOAT VELOCITIES IN FT./SEC.
" METER " " KNOTS

0 ¼ m. ½ m. ¾ m. 1 mile
SCALE

Sea: calm

Tides at Fort Denison

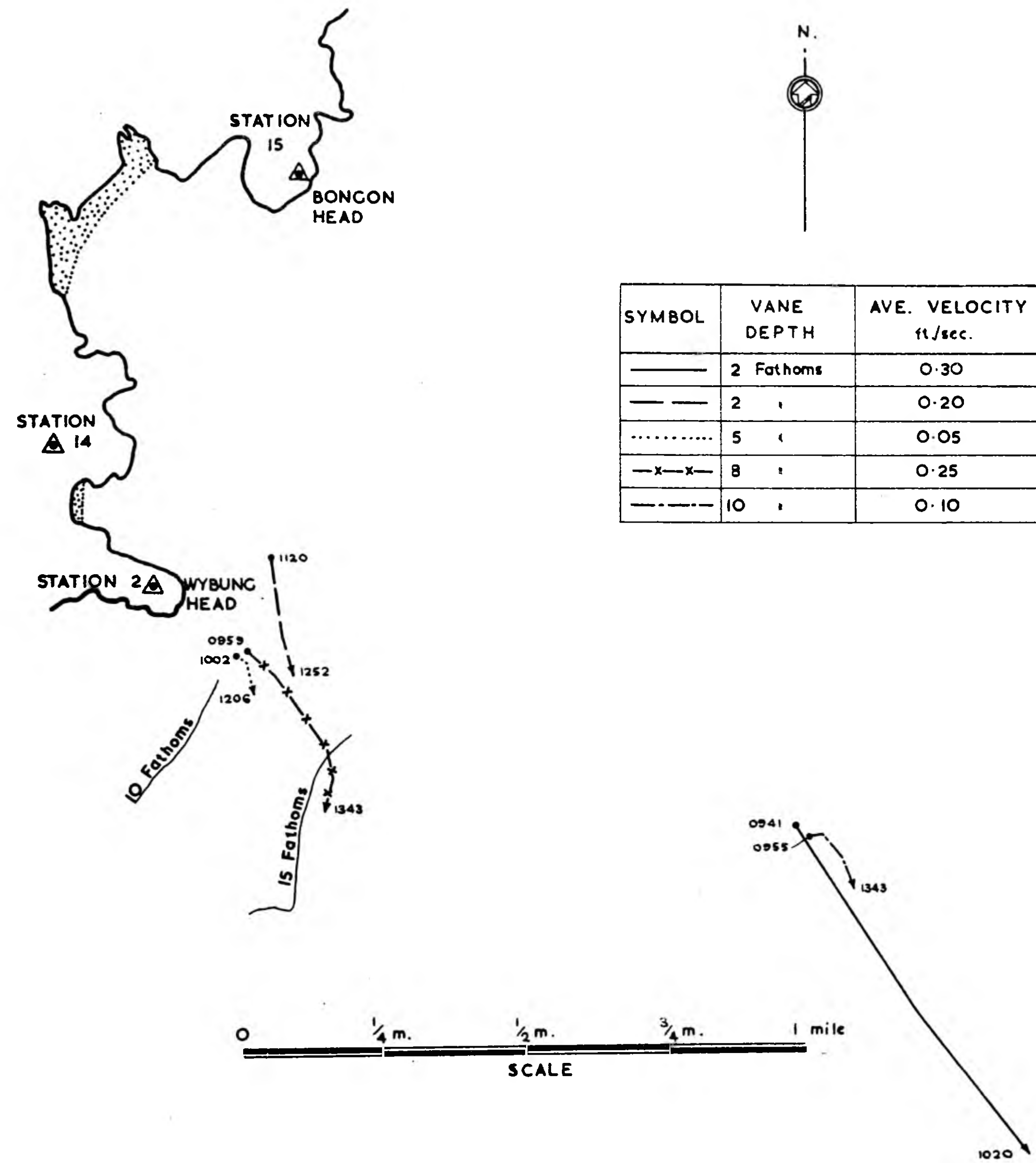
Time	Height
2:31 a.m	11 ins.
8:29 a.m	4 ft. 6 ins
2:08 p.m	1 ft. 4 ins
8:39 p.m	6 ft. 1 in.

18·6·62 CURRENTS

Wind at Nobby's

Time	Speed	Direction
3 a.m	10	N.W
6 a.m	10	W.N.W
9 a.m	5	N.W
12 noon	calm	—
3 p.m	<5	E.S.E
6 p.m	5	N.E
9 p.m	5	N

Figure 52



SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec.
————	2 Fathoms	0·30
— — —	2 "	0·20
....	5 "	0·05
—x—x—	8 "	0·25
—·—·—	10 "	0·10

Sea: calm

19·6·62 CURRENTS

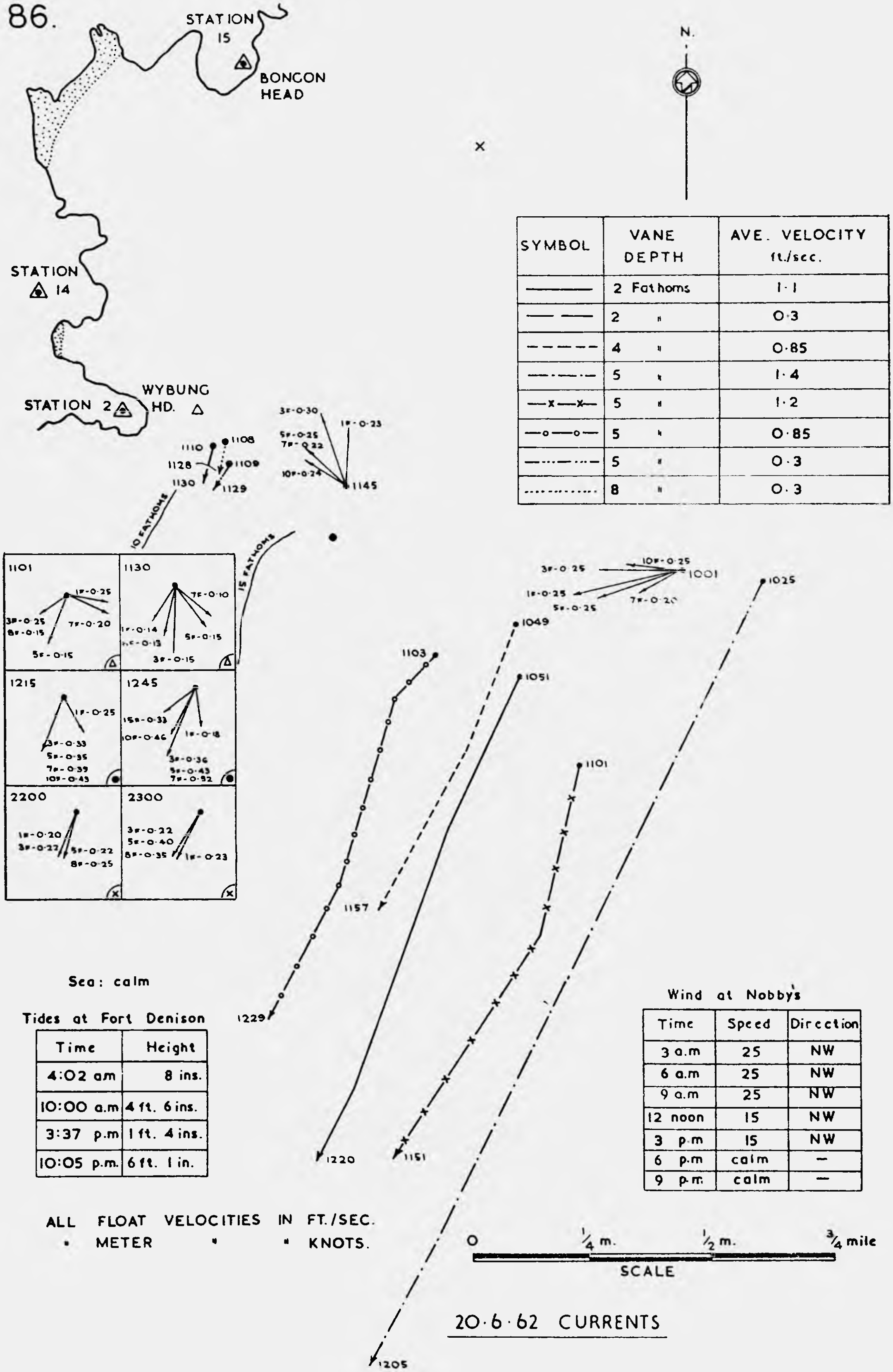
Tides at Fort Denison

Time	Height
3:17 a.m	10 ins.
9:15 a.m	4 ft. 6 ins.
2:52 p.m	1 ft. 4 ins.
9:20 p.m	6 ft. 1 in.

Wind at Nobbys

Time	Speed	Direction
3 a.m	15	N.W
6 a.m	15	N.W
9 a.m	20	N.W
12 noon	25	N.W
3 p.m	25	N.W
6 p.m	—	—
9 p.m	10	N.W

Figure 53



SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec.
————	2 Fathoms	1·1
—— ——	2 "	0·3
- - - - -	4 "	0·85
—·—·—	5 "	1·4
—x—x—	5 "	1·2
—o—o—	5 "	0·85
—···—···	5 "	0·3
··········	8 "	0·3

Tides at Fort Denison

Time	Height
4:02 am	8 ins.
10:00 a.m	4 ft. 6 ins.
3:37 p.m	1 ft. 4 ins.
10:05 p.m.	6 ft. 1 in.

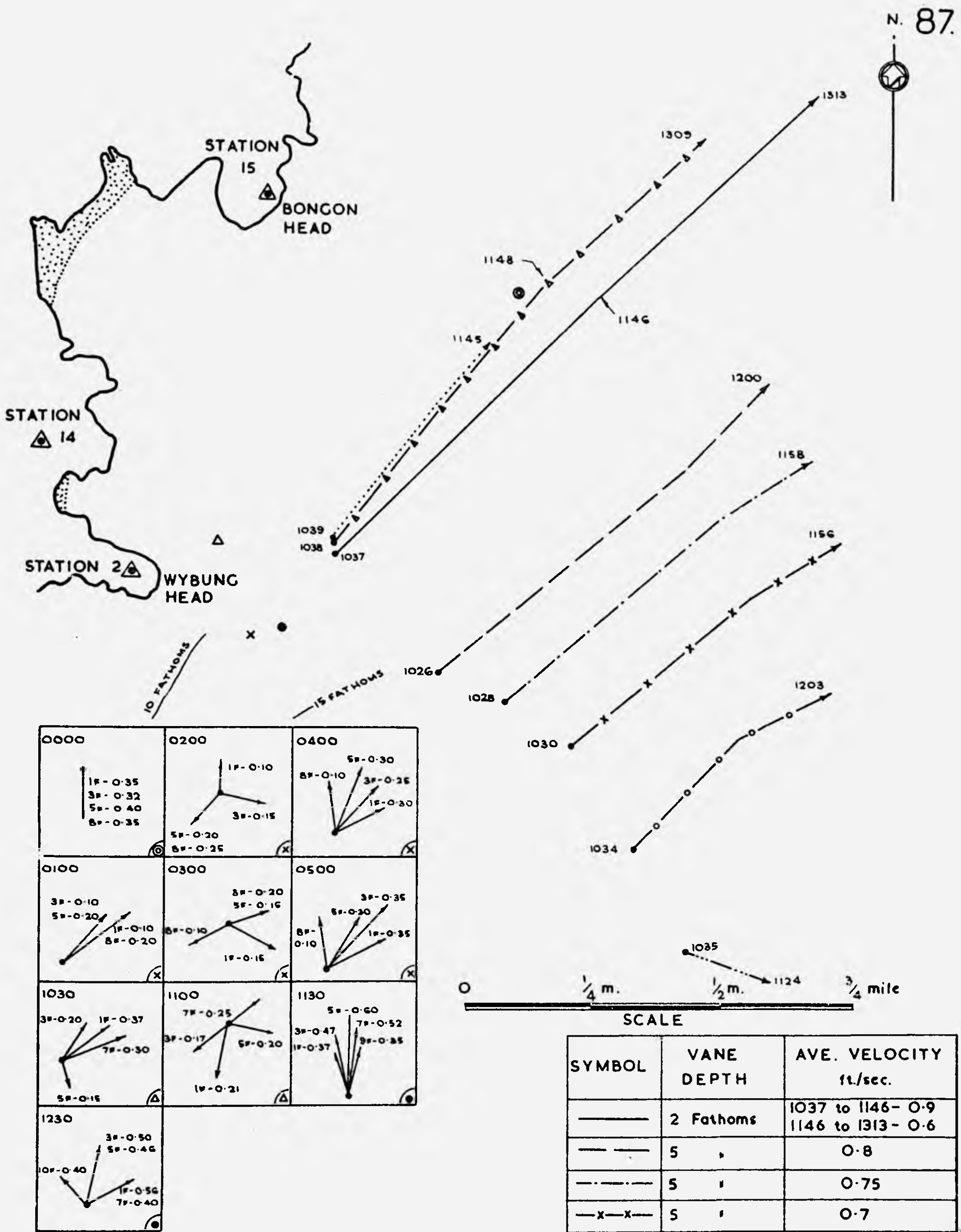
Wind at Nobby's

Time	Speed	Direction
3 a.m	25	NW
6 a.m	25	NW
9 a.m	25	NW
12 noon	15	NW
3 p.m	15	NW
6 p.m	calm	—
9 p.m	calm	—

20·6·62 CURRENTS

Figure 54

N. 87.



SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec.
———	2 Fathoms	1037 to 1146 – 0·9 1146 to 1313 – 0·6
— —	5 "	0·8
—·—·—	5 "	0·75
—x—x—	5 "	0·7
—o—o—	5 "	0·5
—···—	5 "	0·3
—Δ—Δ—	5 "	1038 to 1148 – 0·8 1148 to 1309 – 0·45
············	8 "	0·7

ALL FLOAT VELOCITIES IN FT./SEC.
" METER " " KNOTS.

Wind at Nobby's

Time	Speed	Direction
3 a.m.	10	W
6 a.m.	—	—
9 a.m.	15	N.W
12 noon	25	N.W
3 p.m	15	N.W
6 p.m	15	S.W
9 p.m	35	W.N.W

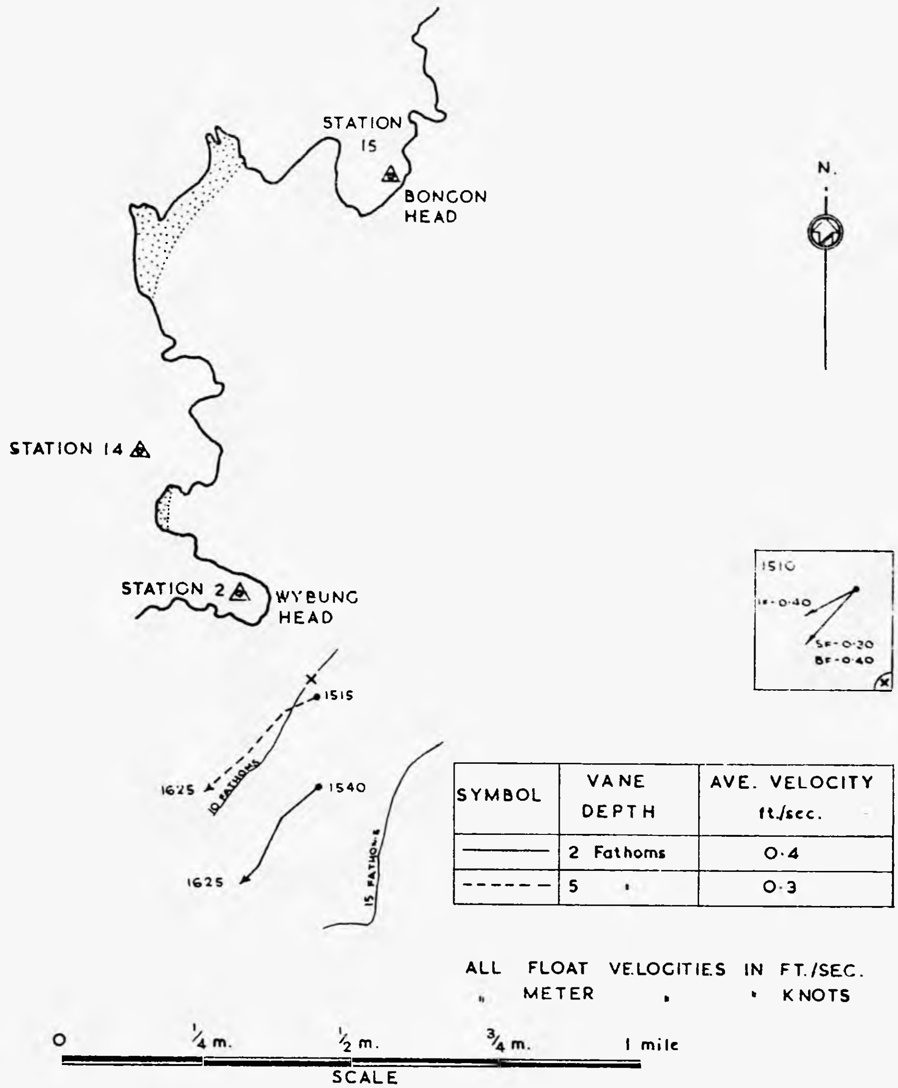
Tides at Fort Denison

Sea: calm

Time	Height
4:47 a.m.	7 ins.
10:49 a.m.	4 ft. 5 ins.
4:24 p.m.	1 ft. 5 ins.
10:52 p.m.	6 ft. 0 ins.

21·6·62 CURRENTS

Figure 55



SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec.
————	2 Fathoms	0·4
- - - - - -	5 "	0·3

ALL FLOAT VELOCITIES IN FT./SEC.
" METER " " KNOTS

Sea: strong southerly swell

22·6·62 CURRENTS

Tides at Fort Denison

Time	Height
5:35 a.m	8 ins.
11:40 a.m	4 ft. 5 ins.
5:17 p.m	1 ft. 6 ins.
11:43 p.m	5 ft. 10 ins.

Wind at Nobbys

Time	Speed	Direction
3 a.m	10	N.W
6 a.m	10	W
9 a.m	5	N.W
12 noon	–	–
3 p.m	–	–
6 p.m	15	N.W
9 p.m	5	N.W

Figure 56

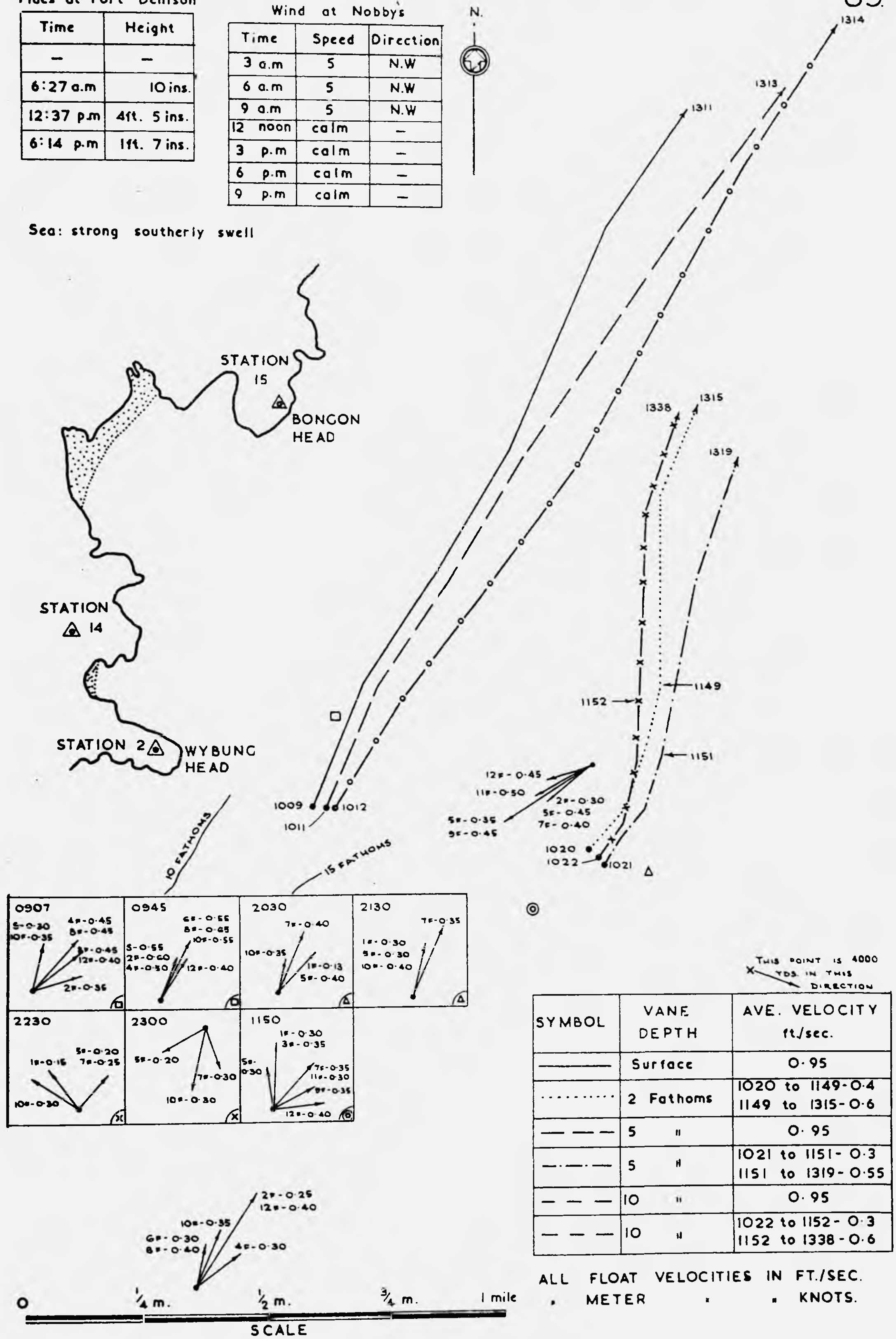
Tides at Fort Denison

Time	Height
–	–
6:27 a.m	10 ins.
12:37 p.m	4ft. 5 ins.
6:14 p.m	1ft. 7 ins.

Wind at Nobbys

Time	Speed	Direction
3 a.m	5	N.W
6 a.m	5	N.W
9 a.m	5	N.W
12 noon	calm	–
3 p.m	calm	–
6 p.m	calm	–
9 p.m	calm	–

Sea: strong southerly swell

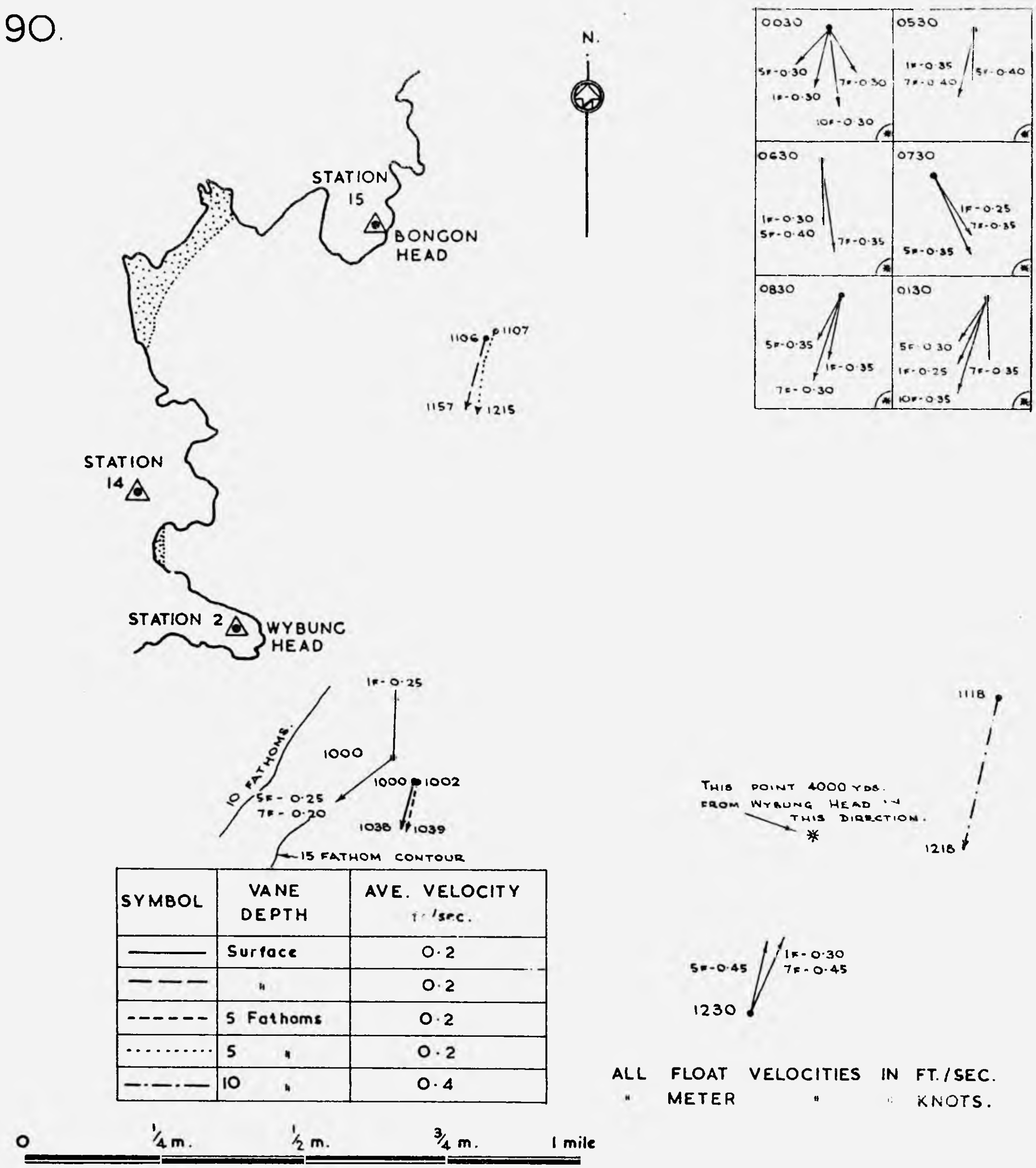


SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec.
————	Surface	0·95
··········	2 Fathoms	1020 to 1149 - 0·4 1149 to 1315 - 0·6
— — —	5 "	0·95
—·—·—	5 "	1021 to 1151 - 0·3 1151 to 1319 - 0·55
— — —	10 "	0·95
— — —	10 "	1022 to 1152 - 0·3 1152 to 1338 - 0·6

ALL FLOAT VELOCITIES IN FT./SEC.
" METER " " KNOTS.

23·6·62 CURRENTS

Figure 57



SYMBOL	VANE DEPTH	AVE. VELOCITY ft/sec.
———————	Surface	0·2
— — — —	"	0·2
- - - - - -	5 Fathoms	0·2
··········	5 "	0·2
—·—·—·	10 "	0·4

24·6·62 CURRENTS

Sea: calm

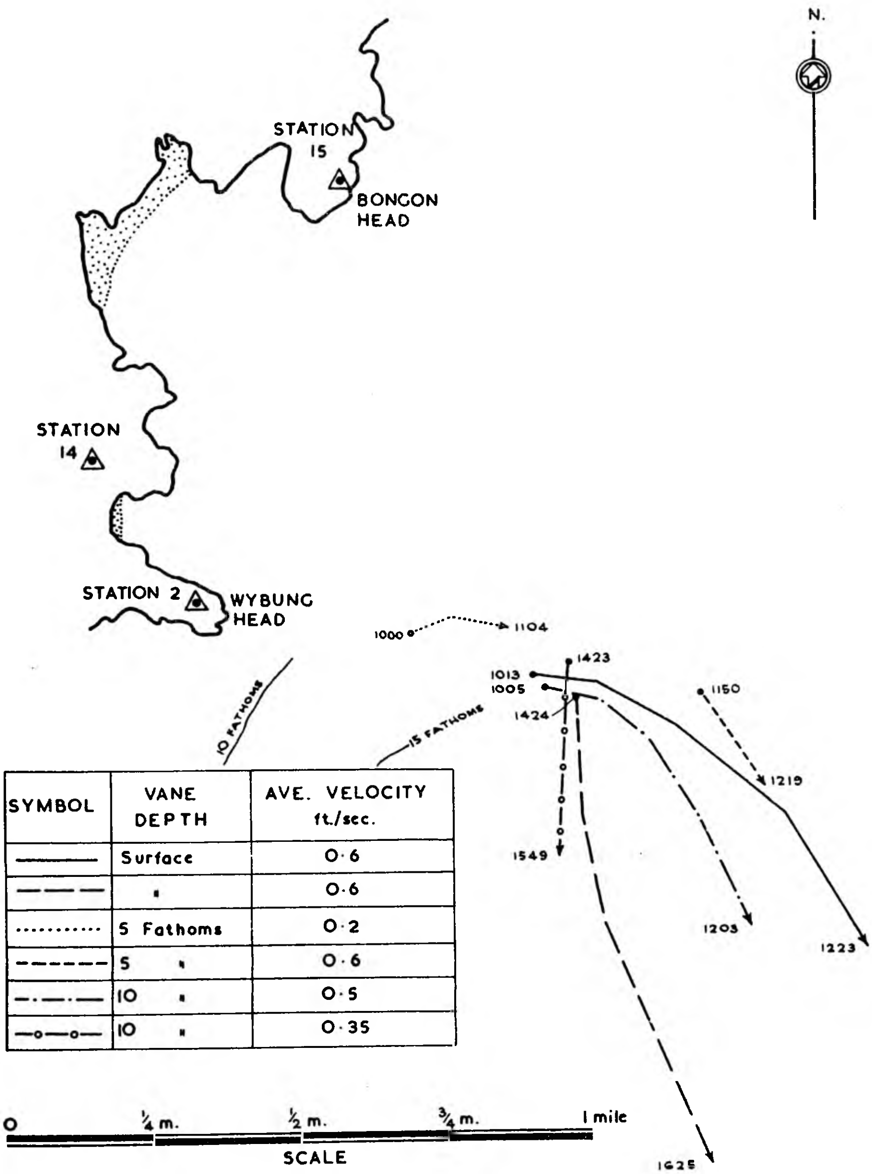
Tides at Fort Denison

Time	Height
0:38 a.m	5 ft. 6 ins.
7:20 a.m	11 ins.
1:37 p.m	4 ft. 7 ins.
7:22 p.m	1 ft. 8 ins.

Wind at Nobbys

Time	Speed	Direction
3 a.m	5	N.W
6 a.m	15	N.W
9 a.m	20	N.W
12 noon	—	—
3 p.m	10	N
6 p.m	10	N
9 p.m	10	N.W

Figure 58



SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec.
———	Surface	0·6
— — —	〃	0·6
············	5 Fathoms	0·2
- - - - - -	5 〃	0·6
—·—·—	10 〃	0·5
—o—o—	10 〃	0·35

3·7·62 CURRENTS

Sea: calm

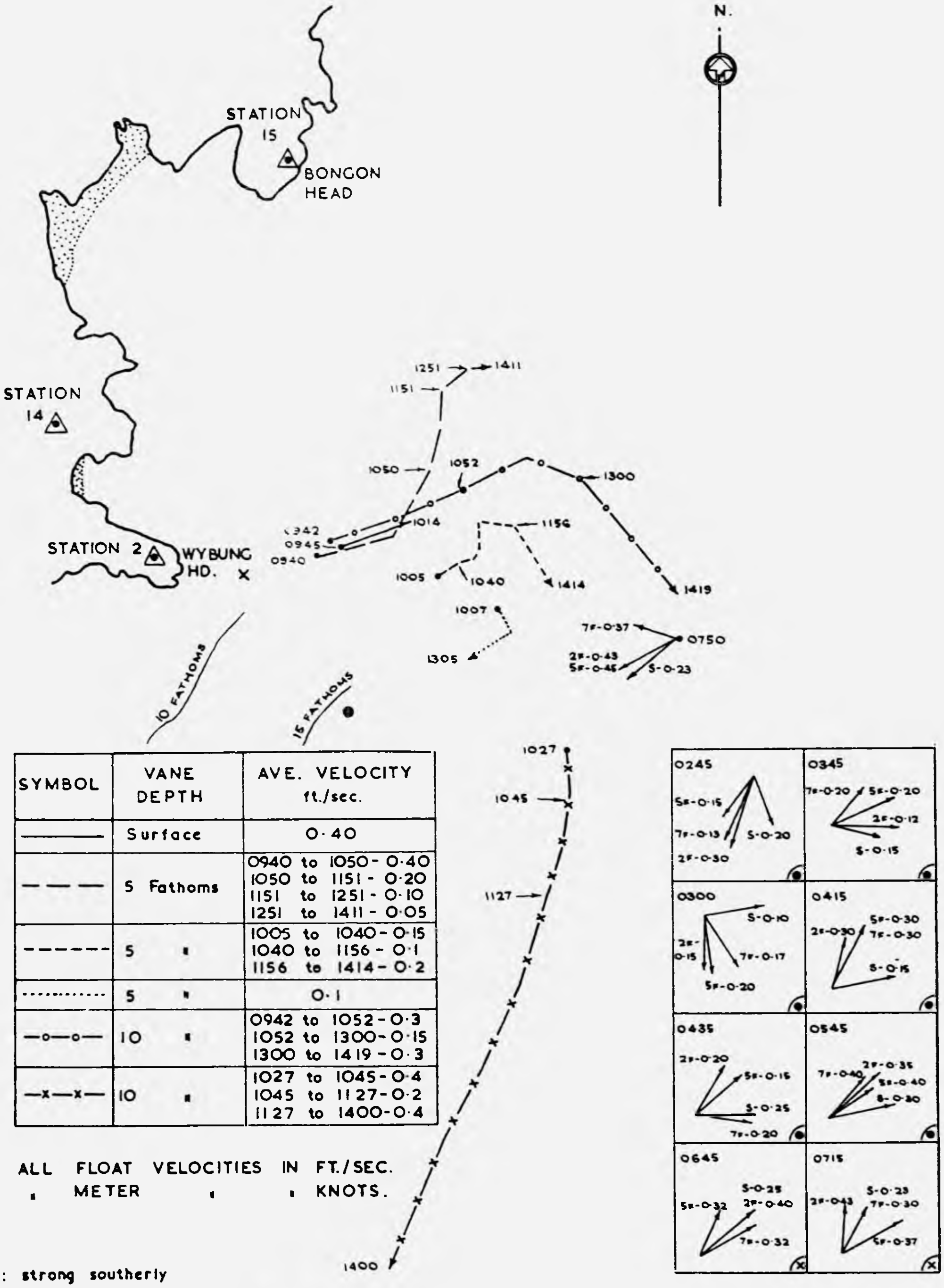
Tides at Fort Denison

Time	Height
3:28 a.m	7 ins.
9:21 a.m	4 ft. 1 in.
2:57 p.m	1 ft. 2 ins.
9:25 p.m	5 ft. 10 ins.

Wind at Nobby's

Time	Speed	Direction
3 a.m.	5	W
6 a.m	5	N.W
9 a.m	20	N.W
12 noon	20	N.W
3 p.m	25	W.N.W
6 p.m	15	W
9 p.m	20	W

Figure 59



SYMBOL	VANE DEPTH	AVE. VELOCITY ft./sec.
———	Surface	0·40
— — —	5 Fathoms	0940 to 1050 - 0·40 1050 to 1151 - 0·20 1151 to 1251 - 0·10 1251 to 1411 - 0·05
- - - - - -	5 "	1005 to 1040 - 0·15 1040 to 1156 - 0·1 1156 to 1414 - 0·2
···········	5 "	0·1
—o—o—	10 "	0942 to 1052 - 0·3 1052 to 1300 - 0·15 1300 to 1419 - 0·3
—x—x—	10 "	1027 to 1045 - 0·4 1045 to 1127 - 0·2 1127 to 1400 - 0·4

ALL FLOAT VELOCITIES IN FT./SEC.
" METER " " KNOTS.

Sea: strong southerly

0 ¼ m. ½ m. ¾ m. 1 mile
SCALE

Tides at Fort Denison

Time	Height
4:08 a.m	8 ins
10:02 a.m	4 ft. 1 in.
3:38 p.m	1 ft. 5 ins.
10:04 p.m	5 ft. 7 ins.

4·7·62 CURRENTS

Wind at Nobby's

Time	Speed	Direction
3 a.m	15	N.W
6 a.m	calm	—
9 a.m	5	N
12 noon	15	N.N.W
3 p.m	10	S.E
6 p.m	20	S
9 p.m	5	S.S.W

Figure 60

4.62 Nearshore Currents

Any particles of ash that travel landward as far as the breaking zone will be carried with the littoral currents until they reach a rip which will transport them back to sea. In the uprush zone between breakers and shore, sufficient turbulence is engendered to prevent the settling of such fine material. To obtain an idea of the rate of travel of ash particles in this area, littoral currents were estimated from (23)*for waves of 10 seconds period and 10 feet height.

In the immediate vicinity of Wybung Head, assumptions of straight shoreline and uniform bottom slope would be patently false. Near-vertical cliff faces cause practically total reflection in some places; and irregular rocks give unstable conditions at other places, such that a minor change of wave or tide completely alters the direction of transport. The best that can be obtained in this area is a rough indication of the predominant directions of drift. This was found by the construction of refraction diagrams (Figures 23 to 26), estimation of the position of the breaker line and observation of the orientation of the breaker line with respect to the general direction of the shoreline. Very close to the headland, breaking may be totally inhibited by the steepness of the cliffs.

Ash moving northwards could arrive in Frazer Park Bay. Here again, quantitative estimates could not be made, as the littoral currents are so vitally dependent on bottom topography, which is not sufficiently defined by the soundings. An indication of the predominant directions of drift was obtained in the same way as for the Wybung Head area.

Quantitative estimates have been made for the northern end of Budgewoi Beach, an area which could conceivably be invaded by southward-moving ash. These and the direction estimates for the other areas are given in Table 5. Because of the approximations, even these quantitative estimates should be regarded as estimates or order only.

This table shows that waves from the north-east and the east produce relatively strong littoral currents flowing southward. Waves from the south-east and the south give weaker currents generally flowing northward.

For wave heights other than 10 feet, currents may be assumed roughly proportional to wave height. Most ocean wave periods

---

* Section 4.32

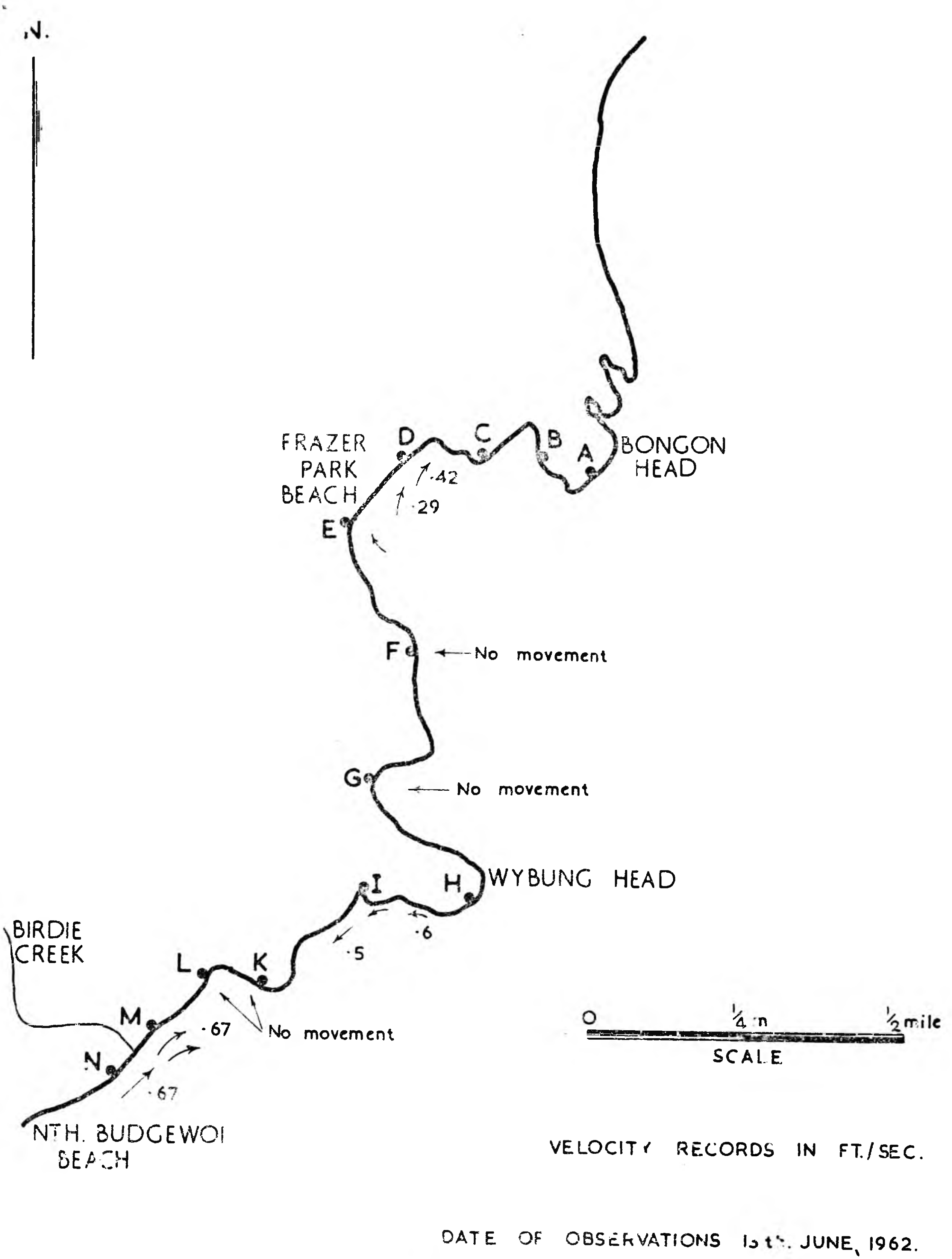


Figure 61: Littoral Drift Measurements

Table 5

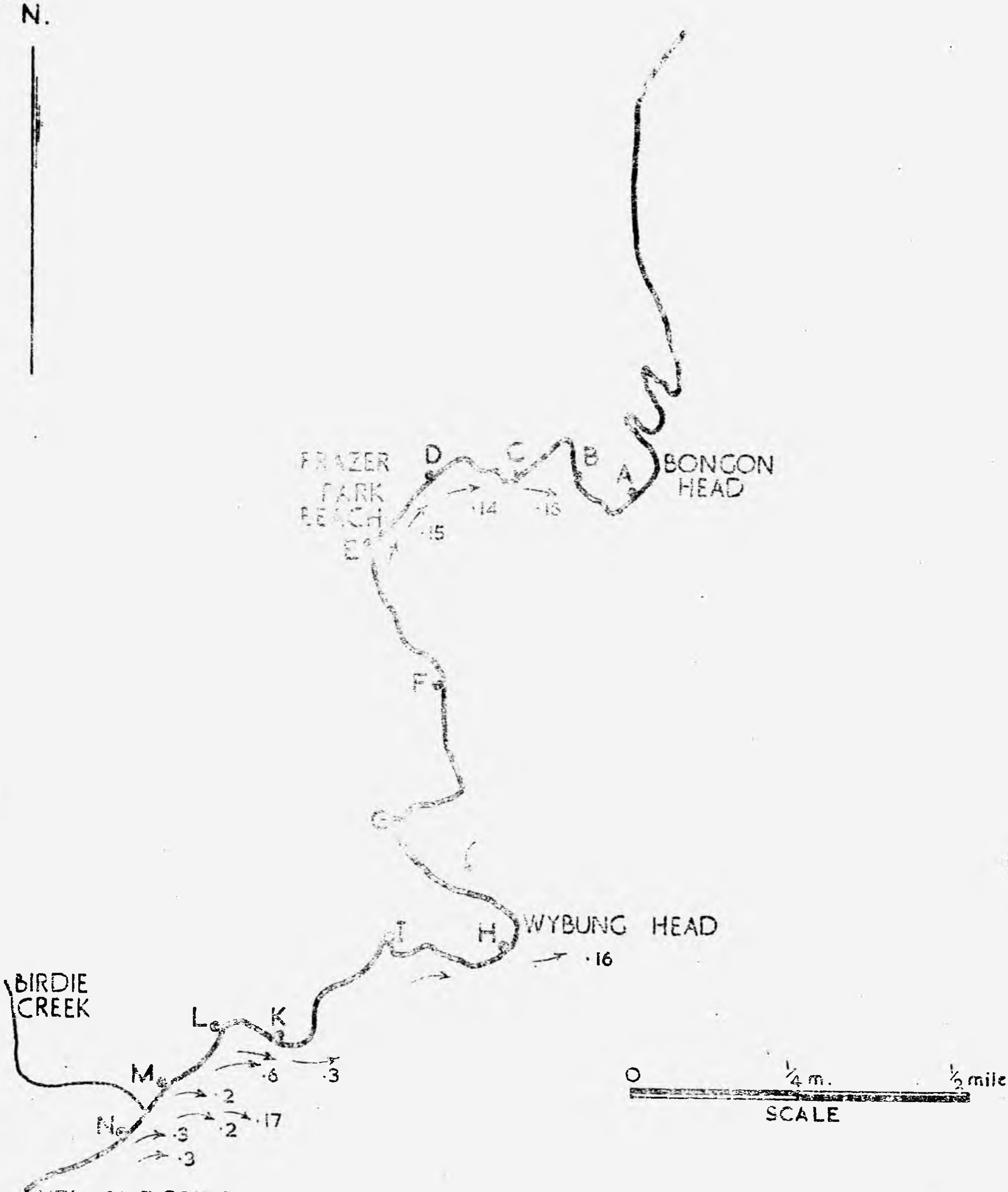
Estimated Littoral Currents near Wybung Head for Wave Height 10' and Period 10 seconds.

Wave Direction	Area	Littoral Current
N.E.	(1) Northern end Budgewoi Beach (2) Rocks south of Wybung Head (3) Frazer Park Beach	S at 4 ft sec. S S
E.	(1) Northern end Budgewoi Beach (2) Rocks south of Wybung Head (3) Frazer Park Beach	S at 3 ft/sec. S -
S.E.	(1) Northern end Budgewoi Beach (2) Rocks south of Wybung Head (3) Frazer Park Beach	S at 1.5 ft/sec. N slight N
S.	(1) Northern end Budgewoi Beach (2) Rocks south of Wybung Head (3) Frazer Park Beach	N at 2 ft/sec. N slight N

produced by storms off the New South Wales coast will result in currents of the same order of magnitude as those predicted for 10 second period.

Application of the wave statistics found by hindcasting* yields an indication of the relative importance of drift in the two directions. It is seen, for example, that, although waves from north-east give a very strong southerly drift at the northern end of Budgewoi Beach, such waves only occur about 2% of the time and do not exceed about 15 feet in height. Therefore, ash is unlikely to move into the breaker zone and travel south very far or very frequently under the effect of north-easterly weather. Easterly weather also causes a predominant southerly drift. Waves from this direction can reach heights of 35 feet at 50 feet water depth after refraction and shoaling, and a littoral current of the order of 10 feet per second can then be expected. Such waves are, however,

* Section 3.33



VELOCITY RECORDS IN FT/SEC.

DATE OF OBSERVATIONS 14th. JUNE, 1962.

rare, and the littoral current will normally range from 0 to 5 feet per second. Waves from east reach Wybung Head about 25% of the time, and during this time the littoral drift will be southerly. Waves from south-east cause a slower littoral current flowing south at the northern end of Budgewoi Beach and north around Wybung Head and Frazer Park Beach. These waves occur about 15% of the time. Waves from the south, which occur some 35% of the time and reach heights up to 35 feet, cause quite strong northerly drifts. The drift at the northern end of Budgewoi Beach would reach values between 5 and 10 feet per second under these conditions, but will not exceed 2 feet per second for more than 20% of the time. This information may be summed up in the statements that littoral currents from 0 to 5 feet per second will normally exist, and that stronger drifts either to north or south could be experienced in the breaker zone, but this is not likely to happen very frequently.

Some surface littoral currents were measured by timing the movement of dye patches on 13. 6. 1962, 14. 6. 1962 and 15. 6. 1962. The periods of the waves on these days were estimated at 11 seconds, 9 seconds and 8 seconds, and the ocean wave heights calculated from beach run-up measurements were 3 feet, 3 feet and 5 feet respectively. The directions from which these waves approached the Wybung Head area could not be ascertained with any great exactitude from weather maps, and, for the smaller waves, were difficult to observe at sea. On 15. 6. 1962 the waves constituted a distinct southerly swell observed both at sea and from land. Table 6 and Figures 61 to 63 show the observed littoral drift velocities.

Table 6

Observed Littoral Currents near Wybung Head

Area	Littoral Currents		
	on 13. 6. 1962	on 14. 6. 1962	on 15. 6. 1962
(1) Northern end Budgewoi Beach	N. at 0. 7 ft/sec.	N. at 0. 3 ft/sec.	not measured
(2) Rocks south of Wybung Head	S. at 0. 5 ft/sec.	N.	not measured
(3) Frazer Park Beach	N. at 0. 3 ft/sec.	N. at 0. 15 ft/sec.	N. at 0. 15 ft/sec.

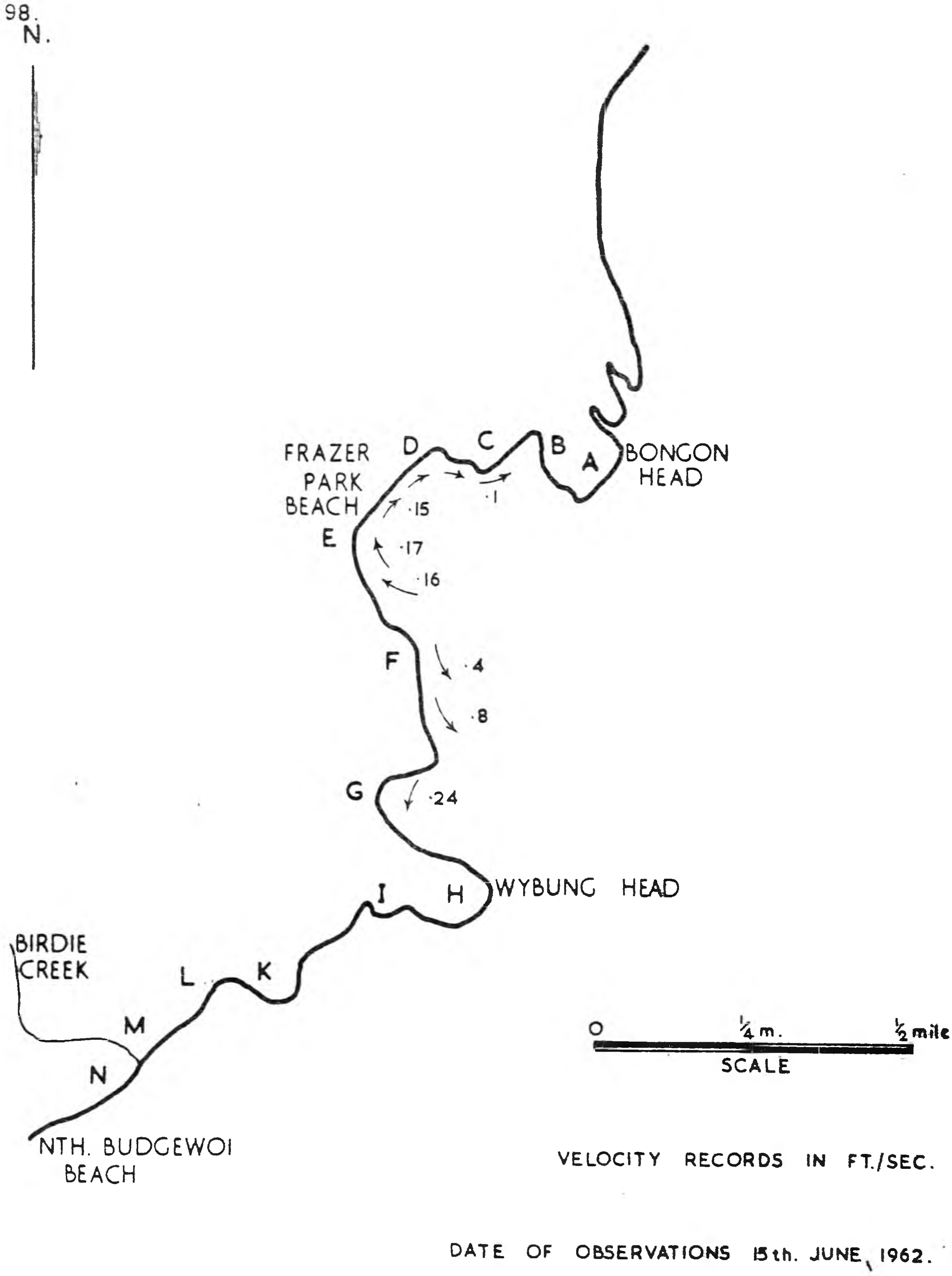


Figure 63: Littoral Drift Measurements

Comparison of the directions with those found analytically indicates that all waves must have travelled from some direction between south-east and south. The speeds observed indicate that littoral currents in Frazer Park Bay, which could not be predicted quantitatively, are generally lower than those at the northern end of Budgewoi Beach under wave action from the south. A speed of $\frac{1}{2}$ foot per second could be assumed for a 10 foot wave from the south or south-east. The northerly currents of 0.7 and 0.3 ft/sec. observed at Budgewoi Beach on 13.6.1962 and 14.6.1962 would indicate an average drift of 1.7 feet per second for 10 foot waves, which compares well with the analytic result of 2 feet per second for 10 foot waves from the south. Figures 25 and 26 show that a wave running from a direction somewhat east of south rather than due south would be more likely to produce a southerly current of the intensity of 0.5 ft/sec. as observed on 13.6.1962 off the rocky area south of Wybung Head. The variability of the current in this area is manifest by the fact that a northerly current was observed on the following day, though other conditions seemed little changed.

Thus, though insufficient data renders comparison of observed and estimated littoral currents rather tenuous, no major inconsistencies are apparent between the measured velocities and the analytic findings. Analytic results for wave directions other than south may therefore be accepted with some degree of confidence.

4.7 Effect of Currents on Ash Movement

Ash movement under current action was forcibly demonstrated during ash dumping trials at Wybung Head in June and July 1962. Streams of ashy water flowed from the dump area in the direction of currents measured at the same time. With its small particle size and low specific gravity, ash can be expected to remain in suspension for a considerable time. During this time it moves with the water mass in which it is located and therefore in the direction of the prevailing current. That is, of course, unless some other direction of movement is induced in the ash by such a phenomenon as the formation of a turbidity current. Marine currents right at the bottom of the sea are generally not strong enough to entrain settled ash, but wave action is frequently strong enough to throw the ash into suspension. It seems that such an ash cloud does not have to rise more than a foot or so above the bottom before it will be at the mercy of quite substantial currents. Ash clouds engendered by waves in laboratory flumes rise to such heights. It can therefore be seen that currents will play an important part in the movement of ash discharged into the ocean.

5. ASH TRANSPORT

5.0 Introduction

Once ash has been pumped into the ocean, the manner in which it will subsequently be moved is of prime importance. Such movement will determine whether beach pollution will occur; where the ash will finally settle; the degree of discolouration that may result in the immediate area; and the most desirable method of and location for introducing the ash into the ocean. In this section, the modes of transport of the ash and the results of laboratory and field tests undertaken to investigate them are discussed.

5.1 Turbidity Current Formation

5.11 General

When, under the action of gravity, one fluid flows over, under, or through a fluid of different density, the resultant flow is known as a density current. When the flowing fluid achieves its density difference by virtue of material in suspension, the flow is more properly called a turbidity current. Turbid underflows in lakes have been observed for many years (Howard, 1953). Silt-laden river waters, some distance after their entry into a lake, often plunge quite sharply to the bottom and thereafter flow along the floor of the lake as a turbidity current. Turbid underflows in lakes have been followed for more than 100 miles (Bell, 1942), and concentrations as low as 800 parts per million have been measured (Howard, 1953). More recently, certain marine phenomena, such as the breaking of transoceanic cables and the formation of abyssal plains on the sea floor, have been explained by the hypothesis of mud slumps followed by turbidity currents flowing on the ocean bed (Johnson, 1962).

Turbidity currents of the finer ash particles have been observed in the comparitively still water of ash ponds (Foster and Argue, 1960). In this case, it was not considered that they had a marked influence on the deposition pattern and the biggest proportion of the ash discharged from the pipeline settled out quickly as a delta at the pipe outlet. During the early tests into ocean disposal, it became evident that when ash is discharged into water in which waves are present, a much stronger turbidity current occurs (Plate 1). This is due to the fact that the waves cause the ash to be stirred up at the bed and at least partially prevent settlement.

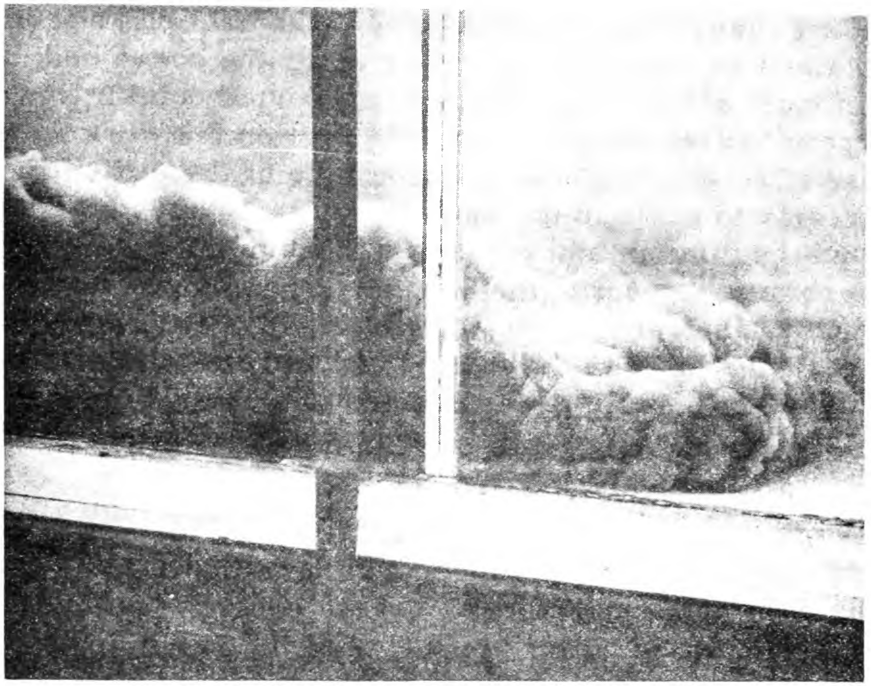


Plate 1: Ash Turbidity Current with Waves.

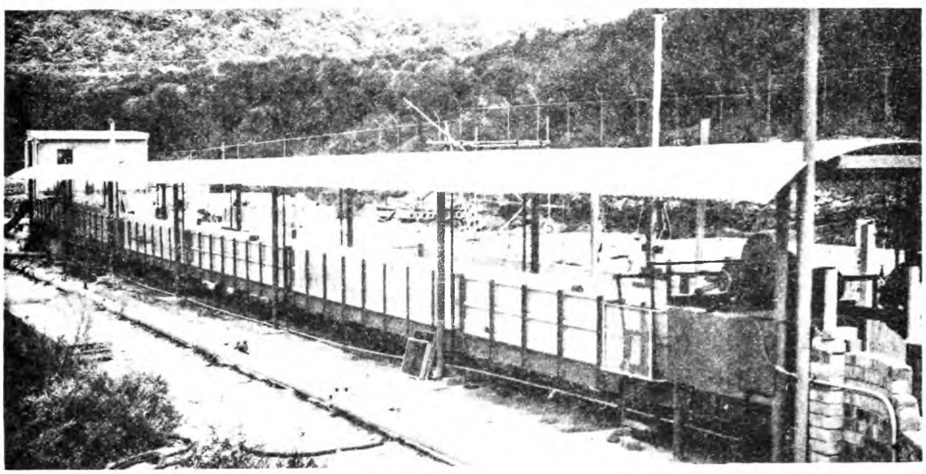


Plate 2: Tilting Wave Flume.

There are many obvious advantages if the ash inflow from the pipeline can be maintained as a density underflow along the ocean bed; discolouration will be a minimum and the ash will be transported quickly down the natural offshore slope into deep water. In this section the work so far carried out to study these effects is discussed. Because of the difficulty of reproducing turbidity currents to scale in the laboratory, tests have so far been confined to a semi-qualitative study in two dimensions. In actual practice, the role of the turbidity current in the ocean will be complicated by a variety of factors such as lateral spread, wave effects, ocean currents and sea bed topography. Additional field and laboratory tests are planned to study these aspects and these will be reported on at a later date.

5.12 Theory

If a heavy fluid is immersed in a lighter fluid, there will be an apparent loss of weight due to its submergence, and the effective specific weight governing the movement under gravity of the heavier fluid will be equal to the difference between the specific weights of the two fluids.

That is

$$\Delta\gamma = \gamma - \gamma_o = \rho g \frac{\rho - \rho_o}{\rho} = \rho g^* \qquad (24)$$

where $\Delta\gamma$ = effective specific weight of heavy fluid

γ = specific weight of heavy fluid

γ_o = specific weight of lighter fluid

and $g^* = g \frac{\rho - \rho_o}{\rho}$

Hence the fluid will respond to gravitational effects, such as flow down a slope, in much the same way as does free surface flow, but with a lower acceleration.

If the depth of the overlying fluid is large and shear stresses at the interface can be neglected, then as a first approximation, many of the equations governing flow with a free surface can be applied to density flows by replacing g by g*.

For example, if there is negligible mixing between the two fluids, then the component down the slope of the effective weight of a layer of denser fluid must be balanced by the forces due to the frictional shears at the bed (τ_o) and at the interface (τ_1). In this case, the velocity of the density current can be expressed by an equation similar to the Chezy equation for flow with a free surface:

$$U = C\sqrt{yi} \quad (25)$$

where $C = \sqrt{\frac{8g^*}{f(1+\alpha)}}$

y = depth of flow

i = slope

f = friction factor

α = the ratio between the shear stress at the interface and the shear stress at the boundary.

For two-dimensional laminar flow ($\frac{Uy}{\nu}$ less than 1000) the value of α is found to be 0.64 (Ippen and Harleman 1952) and about 0.4 for turbulent flow (Streeter, 1961).

The above equations assume negligible mixing at the interface between the two fluids. In the same way that the Froude number is used as a criterion for instability in free surface phenomena, the "densimetric" Froude number ($\mathbb{F}^* = \frac{U}{\sqrt{g^*y}}$) can be used to classify instability in stratified flow. It is more common, however, to use the Richardson number which is equal to the reciprocal of the square of the densimetric Froude number:

$$Ri = \frac{g^*y}{U^2} = \frac{\rho-\rho_o}{\rho}\frac{gh\cos\alpha}{U^2} \quad (26)$$

Two-dimensional laboratory studies (Siyali 1962) have indicated that mixing will occur for values of Ri less than 10, when waves formed at the interface start to break. Tests on a two-dimensional plume (Ellison and Turner 1959) indicate, however, that such mixing is probably small for values of Ri greater than 0.8. For values of Ri less than 0.8, turbulent mixing occurs, and entrainment of the lighter fluid by the denser fluid becomes more and more marked as Ri decreases.

The Richardson number associated with ash flowing from a pipeline into the ocean is likely to be about 0.4 at exit. However, because of the small bed slopes in the nearshore region, the normal Richardson number associated with the slope and effective density of the current will be substantially higher. Consequently, as the jet from the pipe spreads, the Richardson number will increase rapidly, and at a short distance from the pipe, will be much greater than 0.8, entrainment thereafter being negligible.

Because of their sediment load, turbidity currents may behave somewhat differently from non-suspension density currents. The effective density of the current can be reduced not only by entrainment at the interface, but also by deposition of the sediment. The sediment bearing capacity of a turbidity current depends on the velocity in a similar way to that for normal river flow. If sediment is introduced from the pipe at a size larger than that which the velocity will carry or at a concentration greater than the bearing capacity of the flow, then deposition will occur, with a resultant decrease in density. Knapp (1938) hypothesized that the maximum size of particle that can be carried in suspension is that which has a settling velocity (w) equal to the vertical component of the current velocity ($U \sin \alpha$).

Johnson (1962) has proposed that if w is much less than $U \sin \alpha$ negligible settlement will occur, and the general theory of a non-suspension density current should apply to a turbidity current.

The theory discussed above has been based on observations of density currents in two dimensions. In the particular case under study, lateral spreading of the ash jet after it leaves the pipeline will occur. The extent of such lateral spreading will be restricted where sea bed topography capable of confining the flow exists. Canalisation of this type can be expected only in a few localities, and generally for rather short distances. In these circumstances, the two dimensional theory is applicable. For the more usual circumstances where lateral spreading is not physically impeded, some idea of the rate of spread can be formed from data obtained by Penney and Thornhill while investigating the collapse of a homogeneous column of heavy fluid in a lighter medium (Penney and Thornhill, 1952). After allowing for the presence of a suspension of discrete particles rather than a homogeneous heavy fluid and making assumptions regarding variations of concentration within the column, Johnson (1962) derives from Penney and Thornhill's data an expression for the velocity, U_s, of travel of disturbances which move outward at the bottom and inward at the top from the sides of the column:

$$U_s = \sqrt{\frac{g^*h}{8}} \tag{27}$$

If the column is assumed to have initially a width of $2l$ and height of h, the time taken for an inward moving disturbance to reach the centre line of the column is given as $\frac{l}{U_s}$. From Penney and Thornhill's data, the height of the column after time $\frac{2l}{U_s}$ is reduced to $0.42h$, and after time $\frac{4l}{U_s}$ to $0.18h$, while the breadth at the base has increased to $6l$ and $10l$ respectively. Application of these results to a turbidity current with an initial concentration of about 40% by weight and an initial thickness of a few feet flowing down a slope of the order of 1:10 yields a figure of about 30° to 40° for the included angle of spread of the flow. By the time the flow reaches the more gently sloping areas offshore, the concentration of particles is considerably reduced, largely because of deposition during lateral spreading; and the combination of slight slope and small density excess causes a marked decrease in the rate of forward progress of the turbidity current. The rate of sideways spreading will also be decreased, but the ratio of lateral spreading to forward progress may well increase, giving effectively larger angles of spread of the flow.

5.13 Effect of Waves

Waves in the ocean will affect the flow of a turbidity current in several ways, two important modifying forces due to waves being mass transport and turbulence.

The mass transport associated with the wave can be expected to act either with or against the turbidity current flow depending on the profile of mass transport and the thickness of the turbidity current. For shallow water waves, mass transport very close to the bed is in the direction of propagation of the waves and hence generally towards the shore. The turbidity current flowing downhill away from the shore is therefore hindered very close to the bed by mass transport. However, the mass transport changes to the opposite direction at a small height above the bed compared with the expected thickness of the turbidity current, and thereafter reinforces it.

Qualitative observations in a flume have indicated that waves up to a certain intensity appear to create a favourable degree of turbulence for the maintenance of material in suspension in the turbidity current. Since the force of the turbidity current is caused by the action of gravity on the suspension of particles, the turbidity current is enabled to progress farther under such wave action than in still water. With such waves, there is also a change in the character of the interfacial mixing between the turbid layer and the overlying water, as compared with that observed in the absence of waves. The depth of the zone of interfacial mixing between the turbid underflow and the clear water above does not appear from laboratory tests to alter, but the line of demarcation between this zone and the water above becomes more distinct and appears as a straight interface. The macroscopic vortex characteristics of the zone seem to be largely destroyed by the turbulence induced by the waves.

Waves of an intensity still higher seem capable of effectively destroying the characteristics of the underflow and dispersing the ash throughout the total depth of water.

It should be noted that in an experimental wave flume, turbulence is limited to a zone of small depth near the bed, unless currents other than the pure oscillatory wave motion exist to promote turbulence. In the case under study, the zone of turbulence was more marked as a result of the turbidity flow. This was particularly the case towards the nose of the current.

In the prototype, extremely small currents are sufficient to promote turbulence. For example, in a water depth of 50 feet, a velocity of 0.003 feet per second would have a Reynolds number of 10,000, which is in the turbulent range. Such a velocity will always exist as a result of longshore or mass transport currents and turbulence can be expected to extend throughout the full depth.

5.14 Effect of Currents

As ocean currents are generally directed alongshore, ash turbidity currents would frequently be subjected to a cross-flow. The strength of the marine currents decreases close to the sea bed, so that a variation of effect can be expected within the thickness of the turbid layer. Turning of the turbidity current alongshore would therefore be induced at different rates throughout its depth, and, in the process of re-establishing equilibrium after turning, diffusion and dispersion may be increased. The turbid underflow, with its driving force reduced, would then be subject to the forces tending to dissipate it. The effect of ocean currents is a function of the relative velocities of currents and underflow and quantitative estimates have not yet been made. Onshore and offshore currents would respectively hinder or assist turbidity current flow. The turbulence associated with the ocean currents of appreciable velocity may be sufficient to diffuse the ash suspension through a greater volume of water and thus reduce the efficacy of the turbidity current to transport material.

5.15 Effects of Temperature and Salinity Differences

The density difference responsible for the flow of the turbidity current is occasioned in the first place by the particles of ash carried in suspension. Initially the concentration of ash is so high as to swamp any density differences due to temperature, salinity, or the presence of other dissolved or suspended material. If pumping is carried out at a concentration of 40% by weight for example, the initial density of the turbid underflow is 1.25, while temperature differences as high as 10° F cause a density difference of only 0.005, and even the salinity difference between fresh and sea water causes a density difference of only 0.025.

As the turbidity current dissipates with deposition and lateral spreading, the other differences are no longer masked by the overwhelming increase of density caused by the ash. It must then be taken into account that the water used for making the ash slurry will be derived from the nearby lakes. Because of their relatively shallow depth, there will be occasions, especially during the summer months, when the temperature of the lake water will be naturally higher than that of the ocean. This temperature difference will be increased further by the use of the lake for cooling water re-circulation. An extreme temperature difference resulting from these phenomena has been estimated at 10°F. As regards salinity, the lakes are connected to the ocean, and, with the balance of inflow and evaporation, normally maintain a salinity akin to that of sea water. However in times of high fresh flow, the salinity may be markedly reduced. Supposing that ash is introduced in a flow of zero salinity at a temperature 10°F warmer than the ocean, then it is obvious that a turbidity current would no longer be possible once the concentration of ash had decreased below 3%, corresponding to that required to cause a density of about 1.03. This is 30,000 p.p.m. In fact, laboratory testing has revealed that after the concentration has dropped below this minimum, the ashy water rises almost vertically and thereafter proceeds as an overflow above the more dense salt water.

5.16 Laboratory Tests of Turbidity Currents

5.161 Introduction

Exact scaling of turbidity currents is not possible, owing to the conflicting requirements of the scaling laws for the many phenomena involved. In particular, if the same sediment is used in the laboratory as in the prototype, reproduction of the sediment carrying capacity of the flow is not possible. In addition, because waves are necessary for the maintenance of an ash turbidity current in the particular case under study, reproduction would be required of the effect of the waves not only on the sediment but also on the flow of the turbidity current. These factors are not compatible with each other for scale modelling in the laboratory. For these reasons, laboratory tests carried out to study turbidity currents have of necessity been semi-qualitative.

In general, test conditions have aimed at reproducing, at the pipe outlet, Richardson numbers of the same order of magnitude as that proposed for the prototype. Tests have been performed for a variety of wave conditions. If the effects of lateral spread and reduction of density resulting from deposition within the turbidity current are neglected, equivalence of Richardson numbers should ensure similarity of interfacial mixing.

It must be emphasized however, that, because of the reasons stated above, the results of the two-dimensional flume tests carried out to date should be considered only as indicative of what will happen in the prototype. The results of the field tests discussed in Section 5.17 have supported many of the laboratory results; but additional three-dimensional tests, both in the laboratory and the field, would be required before quantitative prediction of the behaviour of ash turbidity currents could be obtained. The importance of these tests cannot be over-emphasized. If the major portion of the ash flow can be maintained as a density underflow along the ocean bed, water discolouration can be minimized and ash can be rapidly transported away from the nearshore region.

5.162 Description of Tests

All tests were carried out in a 2 feet by 2 feet tilting wave flume 120 feet long (Plate 2). Ash-water mixtures were introduced through a pipe set in the floor of the flume, and allowed to spread as a three-dimensional jet until contained by the walls of the flume. Tests have been run with the floor horizontal and at various slopes. Waves ranging from less than half the height required to entrain settled ash to twice that height have been used, as well as undisturbed still water. The ash slurry has been introduced through various sizes of pipe at various velocities and concentrations. For the final series of tests in which some measurements have been taken for comparative purposes, the ash was introduced through a $\frac{3}{4}$ inch pipe at a concentration of 40% by weight (ratio of ash weight to weight of ash-water mixture) and a velocity of about 1 foot per second. Thus, the concentration and pipe exit Richardson number of about 0.4 expected for the prototype have been reproduced.

5.163 Ash Turbidity Currents in Still Water

When ash suspension was introduced into still water in a sloping flume, the major portion of the ash settled out quickly as a mound immediately adjacent to the pipe outlet. Downstream of the mound a weak turbidity current was evident which flowed down the bed slope at a slow velocity for about 30 feet from the pipe outlet. It was evident that no substantial transport of ash by turbidity currents would occur in still water.

5.164 Ash Turbidity Currents with Waves

When the ash slurry was discharged into the wave flume with a sloping bed in which shallow water waves were present, a marked increase in the persistence and carrying power of the turbidity current was evident. The periodic motion produced by the waves at the bed and the resulting turbulence tended to maintain a greater proportion of the ash in suspension, thus allowing a stronger density underflow to occur than was the case with still water.

In all tests, the turbidity current flowed down the full length of the flume until reflected by the wave paddle at the far end, the velocity of travel of the nose being of the order of 0.1 feet per second.

The nose of the turbidity current was extremely turbulent and considerable entrainment occurred in this region. Behind the nose, there was a dense layer of ash suspension several inches deep. This layer had a very sharp interface, above which a lower concentration and irregular ash cloud occurred throughout almost the full water depth. Whether this cloud resulted from the ash entrained at the nose as the turbidity current moved down the flume or whether it was due to mixing at the interface was difficult to observe. Because of the high Richardson numbers from a short distance downstream of the pipe outlet, it is doubtful whether entrainment could occur as a result of the turbulent mixing generated by the turbidity current. Whether the waves themselves were producing some mixing at the interface could not be determined with certainty.

During the tests, some deposition of the ash in suspension occurred along the flume, indicating that either the sediment load was greater than the sediment bearing capacity of the stream or else the velocity was insufficient to transport the coarse fraction of the ash.

Insufficient measurements were taken to define the differences between turbid underflows on horizontal beds and those on sloping beds. Visual observation could not define a difference within the range of slopes and over the length of flume used. It was noted that turbidity currents successfully negotiated marked changes of slope without losing their characteristic form.

Substantial reduction of the Richardson number at the exit from the discharge pipe, either by increase of the exit velocity or decrease of pipe diameter, seemed to increase the amount of entrainment within the first few feet downstream of the pipe, thus reducing the ash concentration. Frequently with the smaller pipes a more slowly moving turbidity current resulted, as the Richardson number at exit was decreased. This resulted from increased entrainment immediately downstream of the pipe exit. For the larger pipe diameters at similar Richardson numbers the same effect was not immediately obvious, although the depth of the density layer was increased, indicating increased entrainment at the exit. For constant ash discharge in the prototype, high exit velocities would no doubt encourage entrainment near the pipe exit, thus reducing the driving force available to the turbidity current.

Tests were carried out to check the behaviour of a slurry of ash in fresh water introduced into a flume of saline water. Introduced at a low Richardson number, the inflow rapidly entrained saline water near the pipe exit, and the underflow with its velocity thus reduced did not persist more than about 10 feet before deposition robbed it of most of its ash, and the ash-fresh water mixture rose as a vertical current and thereafter flowed on top of the saline water as an overflow. Introduced at a higher Richardson number, the inflow entrained less and carried on for more than 30 feet before showing any tendency to rise. These tests were carried out under worse conditions than could be experienced in the prototype, the inflow being equivalent to 10°F warmer than the flume water and a density difference equal to the full difference between fresh and sea water being maintained. However, they show that, in the prototype, entry conditions could sometimes determine the extent of progression of a turbidity current, and the pipe exit needs to be designed and located with due consideration given to the effects of salinity differences.

As has been noted* there appears to be a limiting wave below which the progress of a turbidity current is assisted by the presence of waves,

---

* Section 5.13

and above which the waves tend to destroy the form of the turbidity current. No exact line of demarcation has been found, but to diffuse the ash throughout the depth of the laboratory flume waves substantially higher than those required to entrain settled ash are needed. It could therefore be hoped that once settled ash had been disturbed it would form a turbidity current. Laboratory tests seemed to indicate that this is not the case, for the same wave that would assist the action of a turbidity current that had been formed from a pipe discharge would diffuse entrained ash throughout the entire water depth before the ash concentration could become sufficient to develop any appreciable turbidity current action. Some slight action may have been present within the ash dispersion - such fine discriminations are not easily discernible in a medium of ashy water.

Laboratory testing has therefore shown that waves assist turbidity current action though incapable of initiating it. Other factors seem to be not inconsistent with theories developed for similar phenomena. A more complete and quantitative picture will be presented at a later date, based on available knowledge and data collected from flume and field experiments. Some estimates of order may then be available, which can be confirmed by three-dimensional laboratory tests and further field experiments.

5.17 Field Observation of Turbidity Currents

In collaboration with the Electricity Commission, two field tests were carried out at Wybung Head in June and July 1962. During the first test 500 tons of ash were dumped by a 2 yard grab from a collier anchored approximately 100 yards offshore, and its underwater movement was observed by skin divers. In the second test, 250 tons of ash were dumped in a similar manner and the underwater movement of the ash was tracked by radioactive methods.

In the first test, a diver reported "a 2 foot layer of ash moving along the bed in an offshore direction". Unfortunately, no further reports of this ash movement were obtained. In the second test, the ash was observed to move seaward near the bed at a velocity of less than 1 foot per second. The initial spread of this flow included an angle of between 60° and 90°, this angle being gradually reduced as the ash flow progressed into deeper water. Unfortunately, because of limitations on the length of the cables available for the scintillation counters, the ash flow could be traced for only about $\frac{1}{4}$ mile from the coast. These observations would indicate the presence of turbidity currents during both field trials, although the characteristics of the turbidity currents could not be quantitatively determined.

In both cases, the observations indicated that a considerable quantity of the dumped ash remained on the sea bed in the vicinity of the collier until later removed by wave action and ocean currents. Whether this resulted from direct deposition or the fall out from a depositing turbidity current could not be determined; but both actions would be likely. During these tests, however, ash was dumped intermittently on the sea surface, a method which would not be as favourable for the initiation of an underflow as would horizontal and continuous discharge from a pipeline at the sea bed.

5.2 Diffusion

Turbulent mixing of a high order is known to exist in the ocean. This mixing is sufficient to create a layer of substantially uniform temperature and salinity to a depth of some hundreds of feet of water in spite of the differential heating caused by the exposure of the surface layers. Many forces including those due to waves and currents help to maintain oceanic turbulence. Fine particles of ash in suspension can be expected to diffuse under the influence of such turbulent mixing through a great depth and over a large area, unless other forces such as that of the turbidity current are overriding. Such diffusion would result in rapid dilution of an ash suspension.

5.3 Ash Deposition Close to Outlet

The percentage of material of any given size that can be carried indefinitely in suspension in a turbidity current depends on the velocity of flow, the size of the particles and the amount of material in suspension. Rather slow-flowing turbidity currents in lakes do not seem to maintain in suspension material above the silt range (upper limit 0.06 mm). Below this limit, varying amounts of material of smaller sizes are retained. As long as the silt load does not exceed the carrying capacity of the current, most of the material below about 0.02 mm is maintained in suspension for very great distances. More powerful turbidity currents in the ocean have been postulated to maintain in suspension material up to the size of small gravel (2 to 6 mm). The carrying power of any turbidity current is, of course, limited by internal friction. At higher concentrations, internal friction increases to an extent where deposition of some particles of any size occurs.

It is expected that many of the coarser particles of ash, and even some of the finer particles, will deposit quite close to the disposal point and will form an asymmetric concical mound just in front of the outlet pipe, and the possibility of eventual blockage of the outlet must be considered, particularly when the waves are not strong enough to assist in the erosion of the mound. However, the mound, as it grows higher, will be subject to the erosive force of the slurry discharging from the pipe. In laboratory testing the pipe exit has always maintained itself free of blockage, in spite of the fact that pipe velocities lower than 1 foot per second have been used and mounds several times as high as the pipe have accumulated. It would therefore appear that obviating pipe outlet blockage is not an insurmountable problem.

5.4 Entrainment of Settled Ash by Waves

Any ash that settles on the bottom of the ocean, either as a mound near the pipe outlet or by deposition from the turbidity current, will thereafter be available for re-entrainment by any wave capable of disturbing settled ash in the relevant water depth. It is unlikely that ash so entrained can create a layer of sufficient density to form a turbidity current, since immediately erosion occurs the ash suspension will be dispersed by the prevailing ocean currents. Under certain conditions such as mass transport or ocean currents directed towards the beach, this dispersion of ashy water will travel towards the beach. For the water depths used in laboratory tests no turbidity flow occurred. Rather, the ash formed a cloud which, under the action of the waves, eventually dispersed throughout the total depth of the water. The breaker zone seemed to be a partially effective barrier in preventing any really dense ash suspension from travelling up the beach, but suspensions of low concentration were observed in the laboratory to travel right through the breaker zone and discolour the total volume of water landward of the breakers.

5.5 Selective Sorting of Material by Waves

5.51 Wave Sorting

On none of the open ocean beaches of the world has material of silt size been found (Bascom, 1951; Hoyle and King, 1958). Such material exists farther out to sea, as well as in mud flats along river banks and in other protected localities. Since the material is derived from the same sources as that found on beaches, namely cliff erosion and river sediment, there must be a natural agency which prohibits the deposition of fine material on beaches. Waves are mainly responsible for such

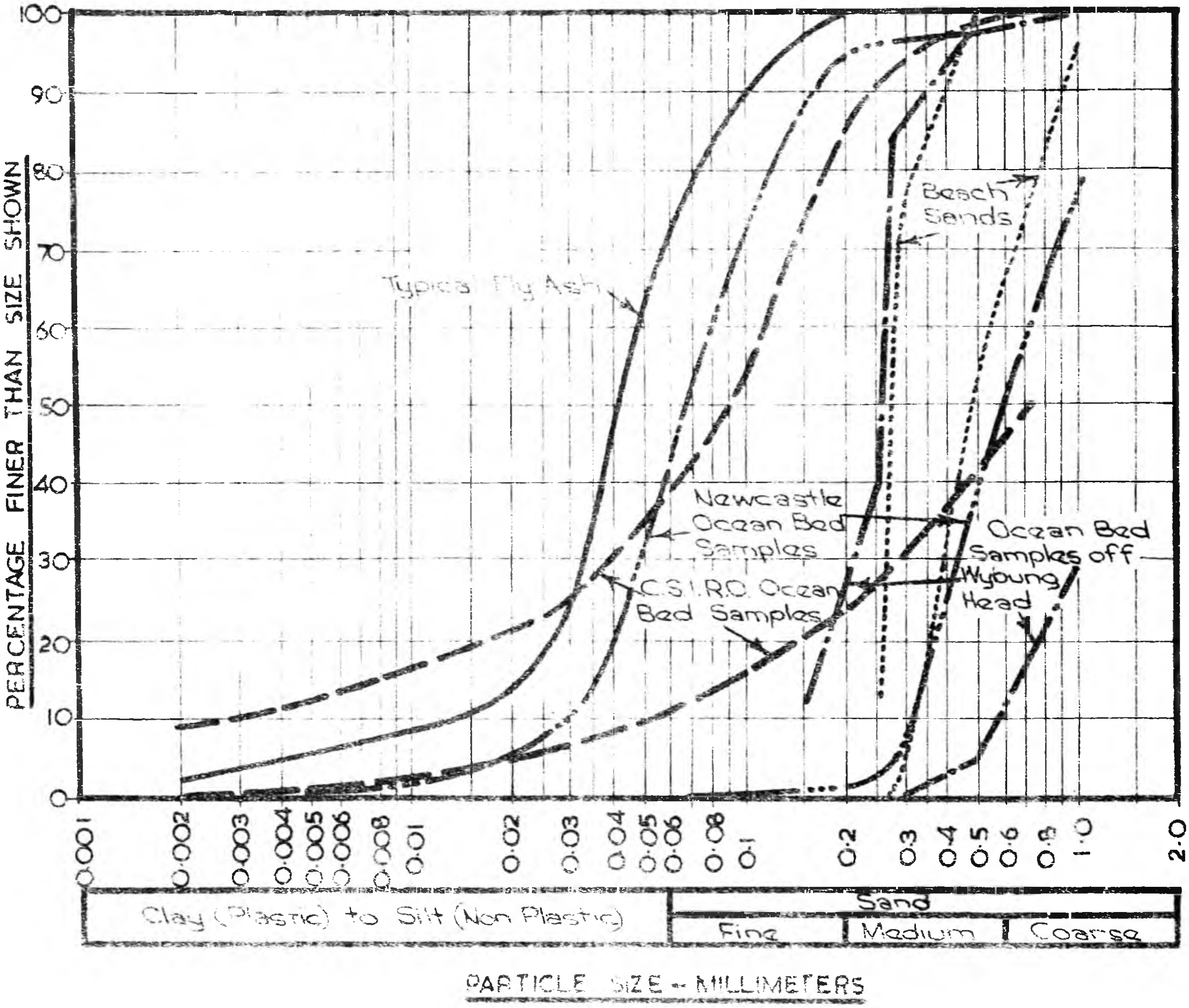


Figure 64: Particle Size Analyses of Beach Sands and Ocean Sediments

selective sorting of material. The intensity of this sorting may be gauged from the fact that, when beaches have been artificially nourished using material with a silt content, the silt has been rapidly removed, leaving only material of sand size on the beach (Beach Erosion Board, 1954).

In the breaker zone, the turbulence engendered by the breaking wave is sufficient to throw into suspension a large variety of material. The coarser material settles rapidly and is not transported any great distance from the breaker zone. The finer material is retained in suspension and carried, often over great distances, until it reaches an area with a much reduced level of turbulence where it settles. The deep ocean offers suitable conditions, and it is here that the finest material eventually finds its way. Very fine material transported landward during the passage of any one breaking wave will be re-entrained by subsequent waves, until eventually carried seaward by littoral and rip currents. It is only when the material has settled in deep water beyond the range of the waves that it is permanently lost to the system. Thus, although the breaking wave may initially send a particle either shoreward or seaward, the net movement of material fine enough to be carried in suspension is seaward.

5.52 Beach Sands

Local confirmation of the hypothesis that material below a certain critical size does not remain on beaches was obtained by sampling beaches north and south of Wybung Head. The beaches at Catherine Hill Bay, Moon Island, Frazer Park and the beach from Wybung Head south to Norah Head (known as Budgewoi Beach) were investigated by sampling along and across the beach. No material finer than 0.1 mm was found (Figure 64). The "black sands" found on beaches sometimes contain up to 5 or 10 % of material of grain size less than 0.1 mm, but these particles are equi-settling with normal beach sands of much larger size, as the specific gravity of the heavy minerals that form "black sand" is so much higher (4.65 as against 2.65). Fly ash, with its lower specific gravity, would require a size greater than that of normal sand before it could remain on a beach.

5.53 Behaviour of Ash Dumped on Budgewoi Beach

Two tons of fly-ash were dumped between high and low water on the northern end of Budgewoi Beach. Weather on the dump day and for a few days beforehand was westerly, following a strong southerly during the preceding week. A gentle southerly swell was still in evidence, and there was a marked northerly littoral drift opposite the point of ash deposition with a rip current farther north. The beach was "accreting", or building up. Part of the ash was dumped directly on the beach, forming a layer above the beach surface. This ash was immediately scoured by the breaking waves and transported in suspension, moving generally with the littoral drift and then to sea with the rip. Such was the rapidity of removal that within half an hour no trace of ash remained on, or close to, the beach.

The remainder of the ash was deposited in a trench some 10' x 5' in area and 6" deep, so that the ash surface after filling was flush with the beach. This ash behaved in a markedly different fashion from that dumped directly on the beach. Under the accreting conditions, the ash was quickly covered with a layer of sand. This layer protected it from immediate erosion by the waves. Twentyfour hours later the ash was covered by sand to a depth of a few feet. Two weeks later the area was re-visited and no trace of the ash could be found. It is assumed that, in the interim, a period of erosion had occurred, during which the ash was acted on by the breaking waves and transported to sea.

5.6 Location of Eventual Ash Deposits

5.61 Wave Effects Seaward of the Breaker Zone

The influence of the waves is not limited to the breaking zone. To seaward, ocean waves cause orbital water movements on the bottom strong enough to move material at depths up to hundreds of feet. The forces acting on a particle so disturbed are the gravity force tending to roll the particle down the slope in a seaward direction and the oscillating force of the wave which has a net onshore direction. Depending on the slope of the bed, the characteristics of the particle and the force of the wave, the net transport may be onshore, offshore or nil. There arises the concept of a "null point" for any combination of the above parameters, corresponding to no net movement. This is characterised by the depth at which a given particle will remain stationary under specified conditions of slope and wave. At greater depths the force of the wave is not sufficient to balance the force of gravity and the particle will move seaward, whilst at smaller depths the particles move shoreward. If this were the only system of forces effecting onshore-offshore transport of material, then a natural sorting of the particles would occur with a grain of any given diameter being found at the point of incipient motion, at the "null" point and at the breaker zone. The point of incipient motion defines the maximum depth at which wave action will move the particle. It must be emphasized, however, that other mechanisms do exist. In particular, the lighter particles are put into suspension by turbulence generated at the sea bed and are carried away by the prevailing currents. Experimental evidence (Ippen and Eagleson, 1955; Tainsh, 1962) indicates that, other things being equal, the null point depth increases with decrease of particle size and density. Particles of sand would commonly have null points in less than 100 feet of water with conditions of wave and bed slope as experienced near Wybung Head, while particles of silt or fly ash would commonly have null points in depths greater than 100 feet, and points of incipient motion at depths exceeding 200 feet. This indicates that silt transported to the depths of the ocean receives no help from this onshore-offshore sorting mechanism until it has already achieved a depth of some hundreds of feet. In the meantime, it must rely on the turbulence of the wave induced oscillatory motion, which throws it well clear of the bed and makes it available to the seaward mass transport current which exists as and from some very small distance above the bed.

5.62 Ocean Bed Samples

In an attempt to locate fine material derived from cliff erosion, attrition of sand particles in the breaker zone and the contributions of silt carrying streams, an investigation of the ocean floor seaward of Wybung Head was made. Samples taken from depths up to 35 fathoms (200 feet) (Figure 65) showed no material within the silt range (Figure 64). Many of the samples contained substantial quantities of material coarser than beach sand. Shells and gravel constituted this material. It is presumed to have derived from underwater reefs, several of which are known to exist seaward of Wybung Head. Samples obtained in depths of the order of 100 fathoms (600 feet)(Figure 66) during cruises made by the C.S.I.R.O. off the east coast of New South Wales were examined, and silt sized material was found (Figure 64). Some decrease of size with increasing depth was apparent, but the number of samples available was not sufficient to warrant detailed investigation of this phenomenon.

5.63 Deposition of River Silt

Hydrographic maps for the coast of New South Wales indicate the nature of the bottom at many locations. Fine sand is indicated along the entire length of coast at minimum depths between 75 and 100 fathoms. Offshore from the mouths of many rivers, mud is indicated in depths upwards of 50 fathoms. The fact that indications of mud are found offshore of river mouths reinforces the theory, based on mineralogic analyses (Loughnan and Craig; 1962) that very little longshore movement

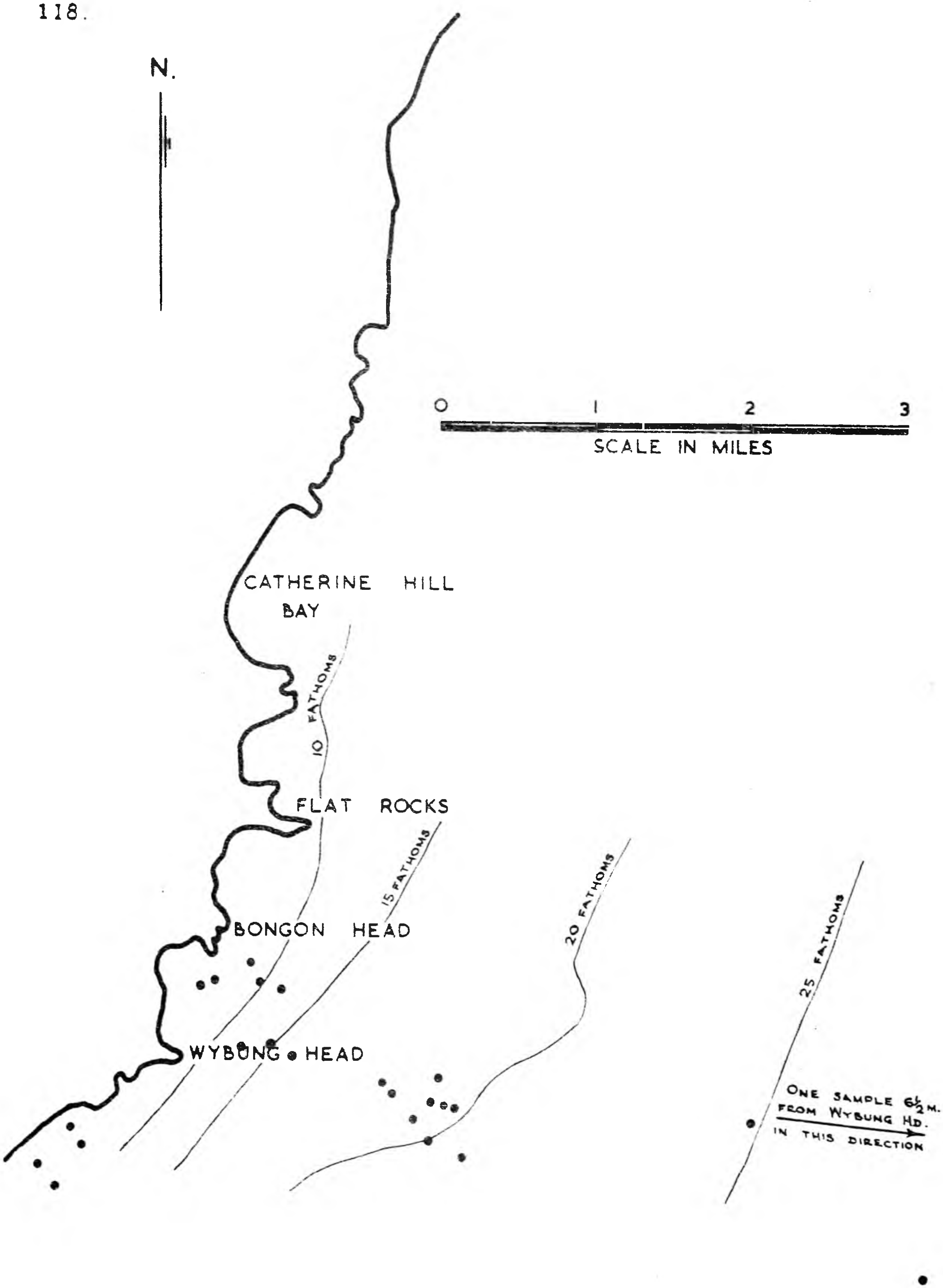


Figure 65: Location of Ocean Bed Samples Near Wybung Head.

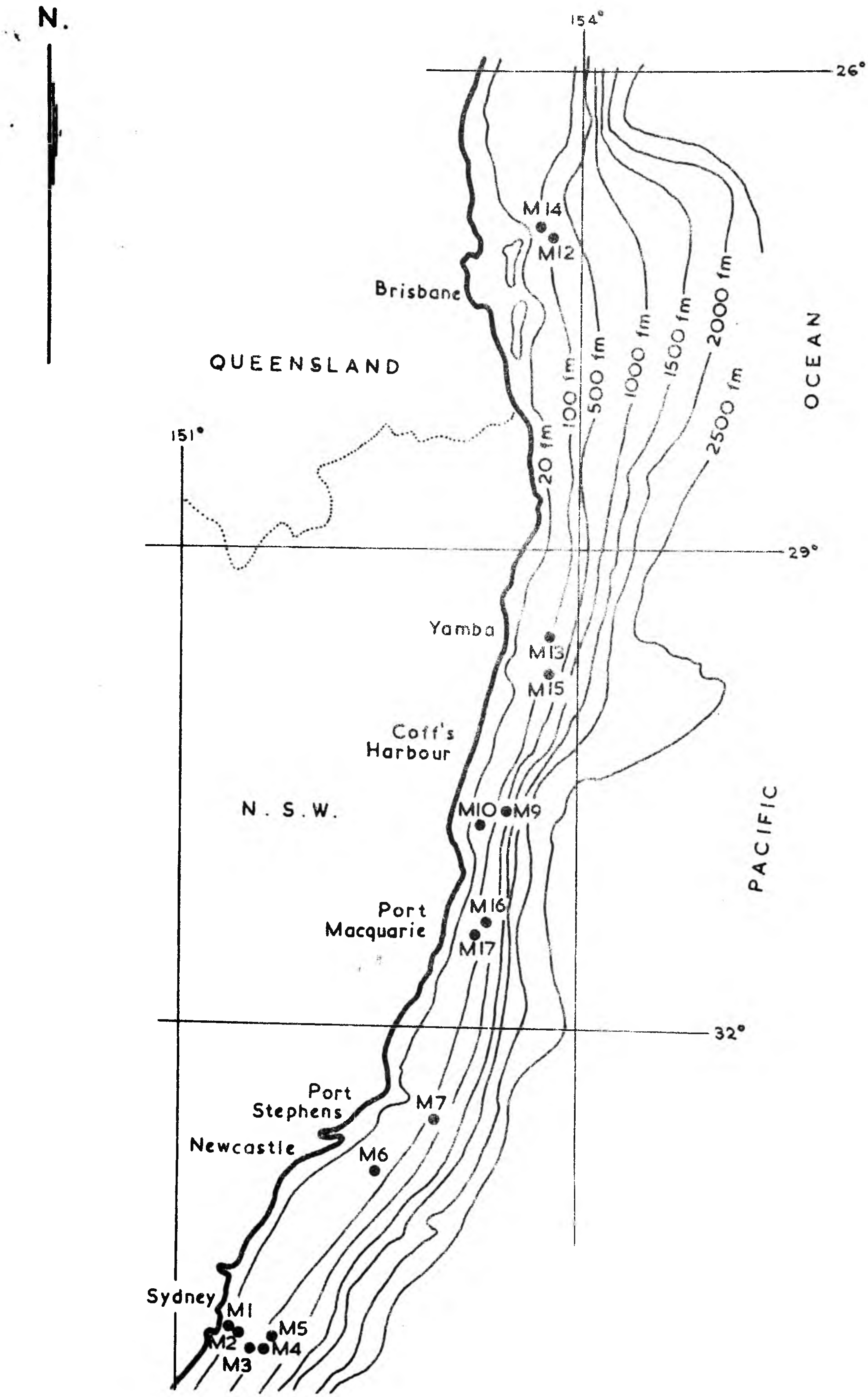


Figure 66: Location of C. S. I. R. O. Ocean Bed Samples.

of material takes place in these waters.

Some 20 miles north of Wybung Head, the Hunter River discharges to the sea. This river carries one of the largest silt burdens of all Australian streams, quantities of the order of 10 million tons having been discharged during a few days of flood. During July 1961, samples from the ocean floor were obtained just seaward of the mouth and a few miles farther along Stockton Beach (Figure 67). Many of these samples contained appreciable quantities of fine material. The sample taken closest to Stockton Beach (about $\frac{1}{2}$ mile from the beach, in 10 fathoms water depth) was one of the finest. In spite of this, Stockton Beach has at all times remained a clean sandy beach.

5.64 Deposition of Ash

With such a variety of forces at work, nearly all of them subject to variations in time and space, the movement of ash discharged into the ocean is likely to be complex and variable. Initially, turbidity current formation may assist the seaward progress of portion of the ash. Waves and currents will affect the turbidity current, as well as local topography, but considerably more detailed study in the field and the laboratory would be required before the characteristics of such a current could be predicted. Ash which is not carried away as a turbidity current will be transported in suspension by the prevailing wave and ocean currents and/or will settle to the bottom of the sea bed. Field and laboratory tests indicate that some settlement will occur near the pipe outlet under most weather conditions. Such deposition will result in a mound of ash which will increase in height and areal extent, until the average rate of transport out of the area as a result of erosion by waves and currents is equal to the rate of ash supply to the area. Because of the extremely small angle of repose of submerged fly ash, the bed deposits are likely to extend over a large area of the ocean floor before any substantial change in depth occurs. No data are available on which to base an estimate of the likely extent of this deposit. It should be noted however, that, as in the case of silt discharged from the Hunter River, the nearshore region and in particular the breaker zone will form an effective barrier against bed deposits of ash extending into the region of the beaches. Within the breaker zone turbulence engendered by the breaking waves will maintain the light ash particles in suspension, enabling littoral and rip currents to move them seaward. The ash in suspension which is transported by the ocean currents may be expected to diffuse over a considerable area as a result of turbulent mixing. Under certain

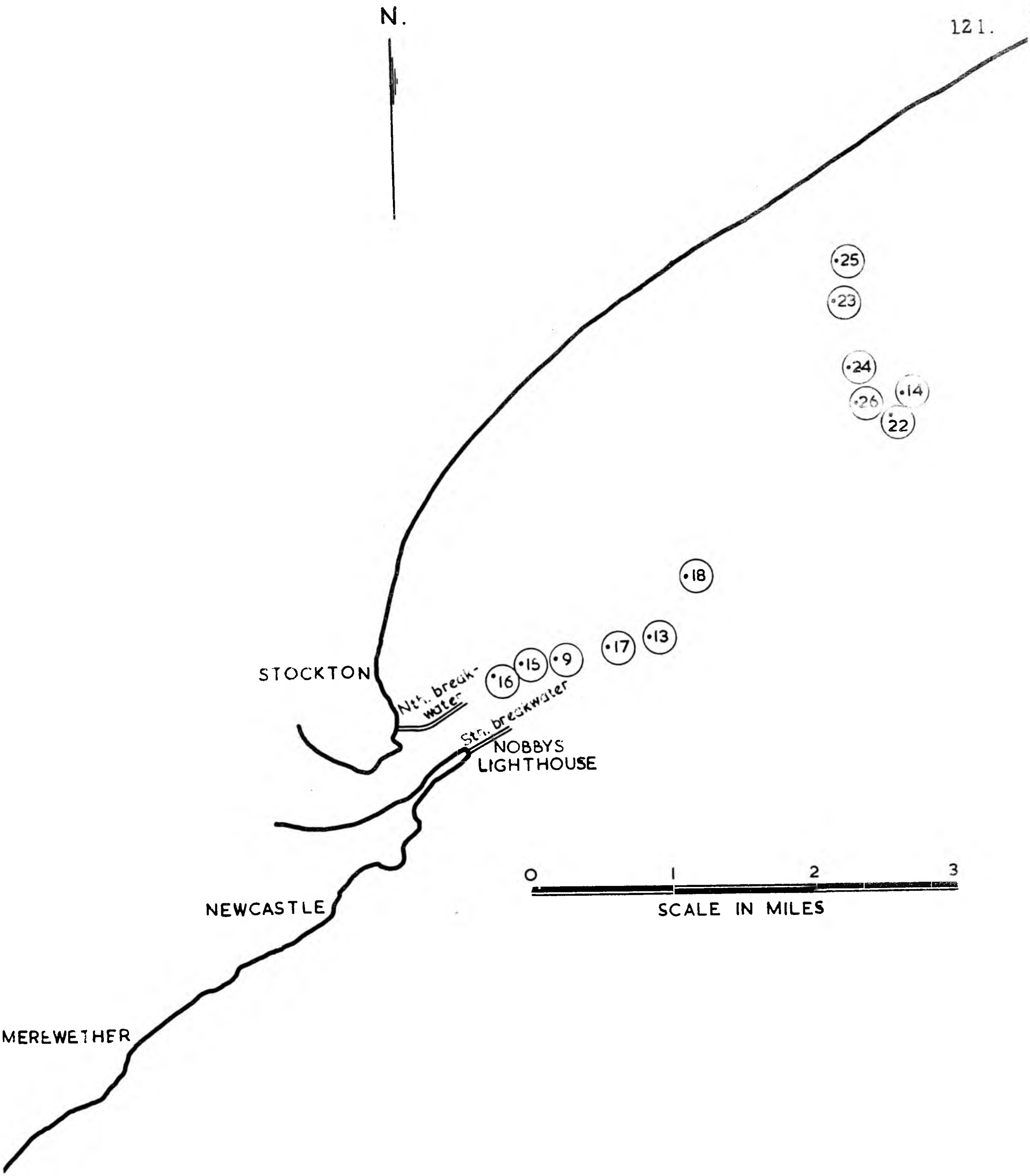


Figure 67: Location of Ocean Bed Samples near Newcastle.

conditions some of the suspension will be carried towards the beach; but, for the reasons described above, settlement within this region is unlikely to occur. In the long term, the action of waves and ocean currents will transport the fly-ash, as the fine silts to which it is akin, into depths of several hundreds of feet. With its lower specific gravity, the ash will no doubt be eventually carried even farther to sea than silt of similar sizes.

6. CONCLUSIONS

The analytic and experimental investigations detailed in the foregoing pages lead to the following postulates for the behaviour of ash discharged from an ocean outfall:

(1) Pure fly-ash of size grading and specific gravity similar to that produced at power stations already in production in New South Wales can be discharged into the Pacific Ocean close to Wybung Head without causing pollution of the nearby beaches. Some of the ash so discharged will flow seaward along the bed of the ocean as a turbidity current, whilst some will be taken into suspension and transported by the prevailing ocean and wave currents. If these two transporting media do not remove material from the area at a rate equal to the rate of supply, then deposition will occur on the ocean bed, increasing the area of ash subject to wave attack until a state of equilibrium between supply and re-entrainment by wave action is reached. Natural sorting mechanisms prevailing in the nearshore regions, and in particular in the breaker zone, will prevent the bed deposits from penetrating into the surf zone.

The ash which is re-entrained from the bed deposits and which is taken into suspension at the discharge point will produce some discolouration of the water. Because of the rapid dilution of this suspension as a result of the high turbulent diffusion in the ocean, it is considered that the degree of discolouration will rapidly decrease with increasing distance from the discharge point and would not be aesthetically objectionable, whilst material which is carried into the surf zone would be of such low concentration that it would not be noticeable to the casual observer.

After completion of operations of the power stations supplying the ash to the area, all the material will in the long term be transported well offshore as a result of the action of waves and currents on light material of this nature.

Further work is required to refine the study and to fix the most desirable location and method of introduction of the ash into the ocean. If a large proportion of the ash can be carried as a turbidity flow, then the extent of marked discolouration may be reduced. In addition, it may be desirable to extend the pipeline for some distance into the sea in order to reduce deleterious effects due to such nearshore phenomena as wave reflection.

Further conclusions related to specific aspects of the investigation are:

(2) The formation of a turbidity current carrying part of the ash to sea is probable. More analytic, laboratory and field studies are required to define what quantity of ash can be transported in this manner. If the pipe outlet can be located so that the flow can be canalised between reefs, such a turbidity current may be expected to carry material to a much greater distance from the outfall than if unrestricted lateral spreading cannot be avoided.

Turbulence induced by wave action and currents over ocean depths of some hundreds of feet will mitigate against deposition within the turbidity current and will maintain in suspension much material which would be deposited in calm water. In spite of this, any turbidity current formed will still be of the depositing type, the larger particles settling out first and the particle size decreasing with increasing distance from the outlet as the velocity is reduced initially by entrainment and then by deposition and lateral spreading. Particles larger than about 0.05 mm, which may comprise up to 50% of the ash, will be deposited very close to the outfall, since turbidity currents with velocities of the order of one foot per second cannot carry material of these sizes any appreciable distance.

Turbulence, especially that induced by heavy wave action, may sometimes be sufficient to diffuse the ash throughout the whole water depth and destroy the turbidity current action.

Coastal currents, which nearly always flow alongshore, will turn a seaward flowing turbidity current towards the longshore direction, the extent of the turning being a function of the ratio of the strengths of the marine current and the underflow.

(3) Re-entrainment of material deposited on the ocean bed will occur during periods when wave action is strong enough to disturb this settled ash. It has been estimated that for about 70% of the total time, for example, waves will entrain ash settled in 100 feet of water, and for 60% of the time in 200 feet of water. Extreme value analysis indicates that ash may remain undisturbed on the ocean bed in 100 feet of water for as long as 15 days once in 10 years, and in 200 feet of water for as long as 25 days once in 10 years. Ash re-entrained by waves is unlikely to produce strong turbidity current action. More probably it will be swept away by the various

marine currents before sufficient concentration is built up to propagate an underflow. These marine currents, although not strong enough to entrain settled ash, will largely determine the subsequent movement of ash after it has been stirred up by the waves.

(4). Ash, carried in suspension other than as a turbidity current, will be transported by the predominant ocean currents in the area. Ash still in suspension several miles from shore will no doubt be caught up in the dominant southerly stream that is the landward limit of the East Australian Coast Current. Closer to shore, prevailing currents are generally such as to direct any ashy suspension alongshore, either northerly or southerly depending on the combination and relative strength of such factors as swell, local weather and inshore penetration of the East Australian Coast Current. Only under rarely occurring combinations of these phenomena will coastal currents be directed onshore or offshore.

When coastal currents are directed onshore, ash may be carried into the breaker zone, but this ash will be returned seaward by littoral and ripcurrents.

(5). Because of selective sorting of material by the forces of the sea, discharged ash may be expected to find its way to areas where similar fine material is deposited. Very fine sand and silt created by cliff and shoreline erosion and that produced by attrition of larger sand particles in the turbulence of the breaker zone settles in the ocean some miles from shore in water depths of a few hundred feet and greater. Cursory observation of hydrographic charts of the New South Wales Coast confirms this, as well as analysis of samples collected from the ocean floor specifically for this investigation. Seaward of the mouths of rivers along the New South Wales Coast, hydrographic charts indicate "mud" in depths exceeding 300 feet. This indicates where the coastal rivers eventually drop their silt load. Also it supports the contention, derived from mineralogic analysis of ocean bed samples, that very little longshore movement of material occurs at such depths in the open ocean.

(6) Because of the sorting caused in and landward of the breaker zone by wave action, no fine material is permitted to remain on open ocean beaches. The differential transport of material of different sizes determines the movement of fine material either to great depths in the ocean or else to some much protected locality

where turbulence is low enough to allow it to settle. On none of the open ocean beaches of the world has silica sand of size smaller than 1 mm been found. This is above the size range of fly-ash. Furthermore, ash has a lower specific gravity (2.0 as compared with 2.65 for sand), and any ash particle acts and is acted on in a similar way to a sand particle of smaller size. Some tons of fly-ash dumped on the beach in the vicinity of the proposed disposal area were rapidly scoured and carried to sea as expected.

REFERENCES.

1. Airy G. B. (1845) "On tides and waves". Encyclopaedia Metropolitana Vol. 5 (mixed sciences) London.

2. Arthur R. S., Munk W. H. and Isaacs J. D., (1952). "The direct construction of wave rays". Trans. A. G. U. Vol. 33 No. 6 Dec. 1952.

3. A study of methods used in the measurement and analysis of sediment loads in streams. Report No. 7, 1943. "A study of new methods for size analysis of suspended sediment samples". June 1943.

4. Bascom W. N. (1951) "Sand size and beach slope". Trans. A. G. U. Vol. 32 No. 6 Dec. 1951.

5. Beach Erosion Board (1951). "The interpretation of crossed orthogonals in wave refraction phenomena". Tech. memo No. 21, Nov. 1951.

6. Beach Erosion Board (1954) "Shore protection planning and design". Tech. Report No. 4 June, 1954.

7. Bell H. S. (1942) "Stratified flow in reservoirs and its use in prevention of silting". Misc. Pub. No. 491 U. S. Dept. of Agriculture. Sept. 1942.

8. Berry F. A., Bollay E. and Beirs N. R. (1945) "Handbook of meteorology". McGraw Hill 1945.

9. Bretschneider C. L. (1958) "Revisions in wave forecasting: deep and shallow water". Proc. Sixth Conference on Coastal Engineering 1958.

10. Defant A. (1961) "Physical Oceanography" Pergamon Press 1961.

11. Ellison T. H. and Turner J. S. (1959) "Turbulent entrainment in stratified flow". Jnl. Fluid Mech. Vol. 6 Part 3 Oct. 1959.

12. Foster D. N. and Argue J. R. (1960) "Hydraulic disposal of power station ash". University of New South Wales, Water Research Laboratory Report No. 27, Dec. 1960.

13. Hamon B. V. (1961) "The structure of the East Australian Current". C.S.I.R.O. Division of Fisheries and Oceanography Tech. Paper No. 11, 1961.

14. Harwood F. L. and Wilson K. C. (1957) "An investigation into a proposal to dispose of power-station ash by discharging it into the sea at low water". Proc. I.C.E. Vol. 8, Sept. 1957.

15. Howard C. S. (1953) "Density currents in Lake Mead". Proc. Minnesota International Hydraulics Convention, 1953.

16. Hoyle J. W. and King G. T. (1958) "The origin and stability of beaches". Proc. Sixth Conference on Coastal Engineering 1958.

17. Ippen A. T. and Eagleson P. S. (1955) "A study of sediment sorting by waves shoaling on a plane beach". Beach Erosion Board. Tech. Memo No. 63 Washington 1955.

18. Ippen A. T. and Keilin, G. (1955). "The shoaling and breaking of the solitary wave". Proc. Fifth Conference on Coastal Engineering, 1955.

19. Johnson J. W. (1947) "The refraction of surface waves by currents". Trans. A.G.U. Vol. 28 No. 6 Dec. 1947.

20. Johnson J. W. (1952) "Generalised wave diffraction diagrams". Proc. Second Conference on Coastal Engineering, 1952.

21. Johnson M. A. (1962) "Turbidity currents" Science Progress April 1962.

22. Lamb H. (1932) "Hydrodynamics". Cambridge University Press Sixth ed. 1932.

23. Laplace P. S. (1775-76) "Recherches sur quelques points du systeme du monde" Mem. Ac. Royal Soc.

24. Linsley, Kohler and Paulhus (1949) "Applied hydrology". McGraw Hill 1949.

25. Longuet-Higgins M. S. (1953). "Mass transport in water waves". Trans. Royal Soc. Vol. 245 A. 903 March 1953.

26. Loughnan F.C. and Craig D.C. (1962) "A preliminary investigation of the recent sediments off the east coast of Australia". Aust. Jnl. of Marine and Freshwater Research Vol. 13 No. 1, 1962.

27. Mason M. A. (1951) "The transformation of waves in shallow water". Proc. First Conference on Coastal Engineering, 1951.

28. Penney W.G. and Thornhill C.K. (1952) "The dispersion, under gravity, of a column of fluid supported on a rigid horizontal plane". Trans. Royal Soc. A. Vol. 244, 1952.

29. Putnam J.A., Munk W.H. and Traylor M.A. (1949) "The prediction of longshore currents". Trans. A.G.U. vol. 30 No. 3 June 1949.

30. Russell R.C.H. and Osorio J.D.C. (1958) "An experimental investigation of drift profiles in a closed channel". Proc. Sixth Conference on Coastal Engineering 1958.

31. Savage R.P. (1958) "Wave run-up on roughened and permeable slopes". Proc. A.S.C.E. Waterways and Harbours Division vol. 84 No. W.W.3 May, 1958.

32. Shepherd F.P. and Inman D. (1951) "Nearshore Circulation" Proc. First Conference Coastal Engineering, 1951.

33. Siyali M.S. (1962) "A study of interfacial waves in a two-liquid system". Thesis submitted for M. Tech. Degree University of New South Wales, Jan. 1962.

34. Stokes G.C. (1847) "On the theory of oscillatory waves". Trans. 1847 Cambridge Philosophical Society vol. 8 and Supplement Scientific Papers vol. 1.

35. Sverdrup H.A., Johnson M.W. and Fleming R.H. (1942) "The oceans, their physics, chemistry and general biology". Prentice Hall, 1942.

36. Sverdrup H. V. and Munk W. H. (1946) "Theoretical and empirical relations in forecasting breakers and surf". Trans. A. G. U. vol. 27 - VI.

37. Sverdrup H. V. and Munk W. H. (1947) "Wind, sea and swell; theory of relations for forecasting". H. O. Pub. No. 601 U. S. Navy Dept. 1947.

38. Tainsh, J. McA. (1962) "The movement of sand under the action of waves". Thesis submitted for M. Tech. University of New South Wales Jan. 1962.

39. Toru Sawaragi (1962) "Fundamental study of dynamics of sand drifts" Civil Engineering in Japan 1961. Ed. Japan Soc. Civ. Engineers March 1962.

40. U. S. Navy Hydrographic Office (1944) "Breakers and surf - principles in forecasting" Nov. 1944.

41. Vincent G. E. (1959) "Contribution to the study of sediment transport on a horizontal bed due to wave action". Proc. Sixth Conference on Coastal Engineering 1959.

42. von Arx W. S. (1962) "An introduction to oceanography". Addison-Wesley Pub. Co. 1962.