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Abstract

Seismic surveys in Wellington Harbour (Port Nicholson) show that the greywacke basement under the harbour is an undulating erosional surface which has been depressed to a depth of about 400 m in the northwestern part. For most of the harbour the basement lies at a depth of 200 to 300 m. The depression is likely to be a fault-angle depression caused by tilting in a westerly direction. No signs of faults or fault-block structures were found in the basement under the harbour. A ridge of basement rocks with high seismic velocity crosses the harbour and crops out at Somes Island and Miramar Peninsula. It is inferred that this ridge and other morphological features in the Wellington area aligned approximately north-south are not of tectonic origin but are erosional features.

The seismic velocity structure of rocks in the direct vicinity of the transcurrent Wellington Fault, aligned along the northwestern side of the harbour, is not known in detail. The crush zone of the Wellington Fault is, however, likely to be about 500 to 1000 m wide under the harbour, and this zone has a subsurface slope about 30° to 50°. On land, near Thorndon and at Petone, the crush zone is about 200 to 400 m wide. The inferred widening of the fault zone under the harbour is probably a consequence of the curving of the Wellington Fault in this region.

Introduction

Seismic measurements using the refraction method were made in Wellington Harbour (Port Nicholson), New Zealand, in September and October 1970 to determine the shape of the greywacke basement (Torlesse Supergroup) under the harbour and hence to elucidate the structure of the basement depression. Information was also sought about the exact position of the Wellington Fault, an active fault which forms the northwestern margin of the depression. Similar measurements have been made on land along the Petone foreshore between May 1963 and April 1966 (R. A. Garrick, unpublished Geophysics Division report) and, more recently, near Thorndon in August 1971.

It has been postulated that the depressions in which Wellington Harbour and the Hutt Valley lie are tectonic basins which occupy a fault-angle depression and which were formed by downwarping of a peneplain of presumbly late Tertiary age (Cotton 1914, 1921, 1957). These basins were subsequently filled with Pleistocene sediments. The tectonic processes which caused downwarping are presumably connected with those which produced the large-scale faulting exemplified by the Wellington Fault. This has been identified as a transcurrent fault with a variable downthrow to the southeast (Cotton 1951), the scarp of which forms the northwestern margin of the Wellington Harbour and Hutt Valley depressions. The fault plane cannot readily be identified, but lies within a wide, approximately vertical, crush zone (Stevens 1958). The Wellington Fault is one of a set of nearly parallel transcurrent faults which Lensen (1958) interpreted as branch faults of the Alpine Fault. Evidence for recent westward tilting in the greater Wellington Harbour area has been presented by Wellman (1967).

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The only geophysical study published so far which contains some information on the structure of Wellington Harbour and the Wellington Fault is that of Cowan and Hatherton (1968), who interpreted marine and land gravity measurements made in the Wellington Harbour-Hutt Valley area. The residual gravity anomalies in Wellington Harbour pointed to a dissected basement covered by a thick sequence of sediments reaching a maximum thickness of about 1.2 km between Ngauranga Gorge and Somes Island. The north-south alignment of these anomalies gave some support for a complex, but similarly aligned, fault-block structure of the greywacke basement under the harbour, a structure which had been postulated by Bell (1910), who assumed that north-south-trending morphological features such as Evans Bay, Miramar Peninsula and Somes Island were fault-block relicts. Although refuted by Cotton (1912), the hypothesis of a fault-block structure for Wellington Harbour remained attractive and was revived more recently, for example, by Lauder (1962) who explained the formation of Wellington Harbour by a "ploughshare" action produced by the skewed fault plane of the Wellington Fault.

Cowan and Hatherton (1968) also deduced from the gravity data that near the Petone foreshore the Wellington Fault is approximately vertical, lying about 300 m to the east of the present-day scarp and having a downthrow of about 300 m to the east. A preliminary interpretation of seismic refraction measurements along Petone foreshore by R. A. Garrick (unpublished Geophysics Division report) essentially confirmed the gravity model and gave evidence for a concealed greywacke platform near the scarp. A re-interpretation of these seismic measurements is given later in this paper.

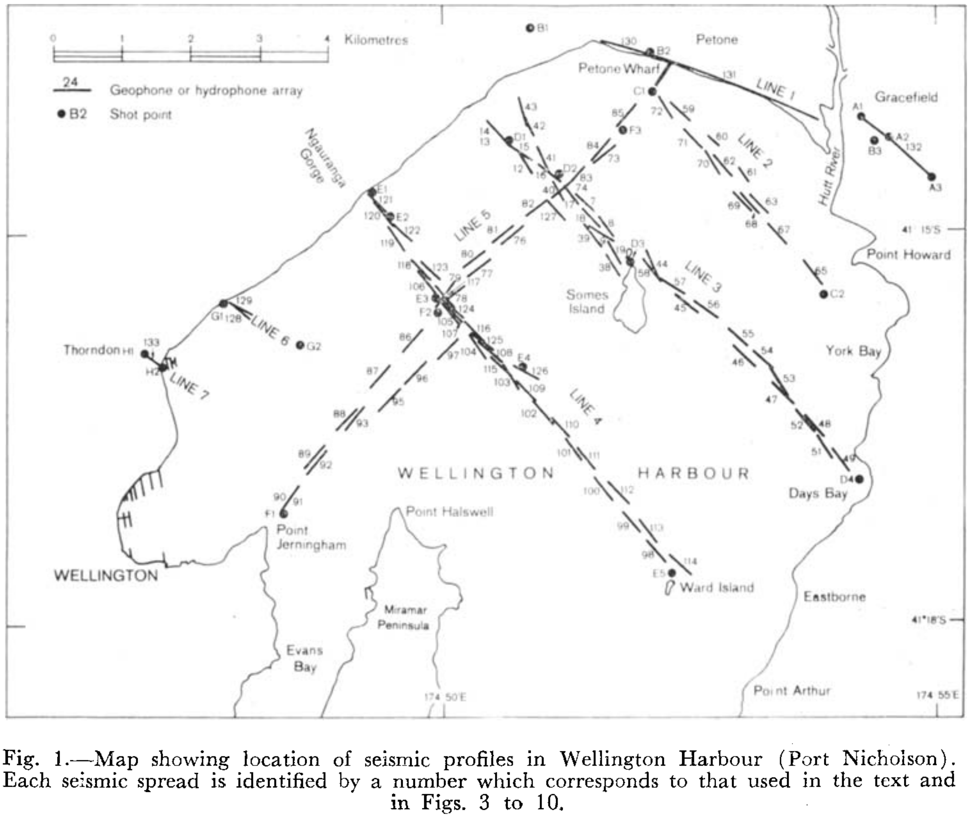

Fig. 1.—Map showing location of seismic profiles in Wellington Harbour (Port Nicholson). Each seismic spread is identified by a number which corresponds to that used in the text and in Figs. 3 to 10.

Various geological and geophysical models have been decribed in some detail to stress what information was available for the planning of the seismic survey in the harbour. Most of the seismic profiles (Fig. 1) were located so that certain features of the models could be tested. For example, the centre of the gravity low between Ngauranga Gorge and Somes Island was probed by line 5 (Fig. 1), which also served as a tie for lines 2, 3, and 4 (Fig. 1), which were investigated to check whether a fault-block structure exists under the harbour. Line 1, line 2, and the southeastern part of line 3 were covered to assist ground-water resource studies. The location of the Wellington Fault in the harbour was examined by line 6 and the northwestern parts of line 3 and line 4. The position of the fault on land was investigated by the western part of line 1 and by line 7 which was designed to assess foundation problems in the vicinity of the fault. Both of these lines provided crucial information for the interpretation of the seismic measurements in the harbour, and for this reason the data obtained on land are presented here together with the data from the marine studies.

DISCUSSION OF METHOD AND FIELD PROCEDURES

The cores from a well 300 m deep at Petone (Hutt Valley Underground Water Authority Well No. 1 = H.V.U.W.A. No. 1) show that the sediments in Wellington Harbour consist mostly of Pleistocene non-marine sediments (Grant-Taylor and Taylor 1967). This probably explains why no reflections were observed from depths greater than 30 to 50 m during a seismic sparker survey of the harbour made in 1970 by Alpine Geophysical Associates Inc. for the Wellington Harbour Board. Since reflections from the greywacke-Pleistocene interface have also not been observed elsewhere in New Zealand, it was decided to use the seismic refraction method for the mapping of the greywacke basement under the harbour. The same method was also employed on land (line 1 and line 7). A systematic, though unsuccessful, effort was made to record wide-angle reflections along line 3.

For the marine studies a "two-ship" technique was used. A series of shots were detonated from a stationary shooting launch and the resulting seismic signals were observed on a moving recording ship which towed a hydrophone array. The explosives were lowered onto the seafloor and fired electrically. The seismic signals were picked up by means of an 8-channel floating cable 550 m long with single hydrophones as detectors which were spaced 61 m apart and suspended at a depth of 2 m. The signals were recorded using an SIE PSU-19 seismic refraction unit and an Electro-Tech magnetic tape recorder. Further details of the equipment are given in a report by Davey (1971).

The positions of the shooting launch and the recording ship were surveyed from land by theodolite, and the azimuth of the array was measured from the recording ship for each shot. These data were used to plot the positions of the arrays shown in Figure 1. The exact distance between shot point and each hydrophone, however, was obtained from the travel time of the water wave. Both the time interval between successive shots and the speed of the recording ship were adjusted so that a nearly continuous cover of the profile by successive spreads was achieved.

For seismic measurements on land, shots were fired in 5- to 15-m deep shot holes and recorded with a 24-channel SIE PT-100 reflection-refraction unit. The distance between successive geophones varied between 30 and 33.5 m on line 1 and was 10 m on line 7.

DATA ANALYSIS

Refracted arrivals coming from the greywacke basement as first arrivals, or from the sediments either as first or second arrivals, together with the water-wave arrivals could in nearly all cases be identified in the harbour records by their cross-spread velocity. Strong arrivals coming after the water-wave were observed on some records and could be identified as " bubble pulses" by using an empirical relationship between charge size, charge depth, and frequency of pulse (Cole

1948). Two records from the harbour survey are shown in Figure 2. Shot instant, first arrivals from the greywacke basement, later arrivals from the Pleistocene sediments, direct water wave, and a "bubble pulse" can be seen clearly. On land the attenuation of seismic waves was greater, and only first arrivals coming either from sediments or from the greywacke basement could be identified with certainty. The terms "direct wave", "refracted wave", "arrival", and "velocity" used throughout refer to compressional waves.

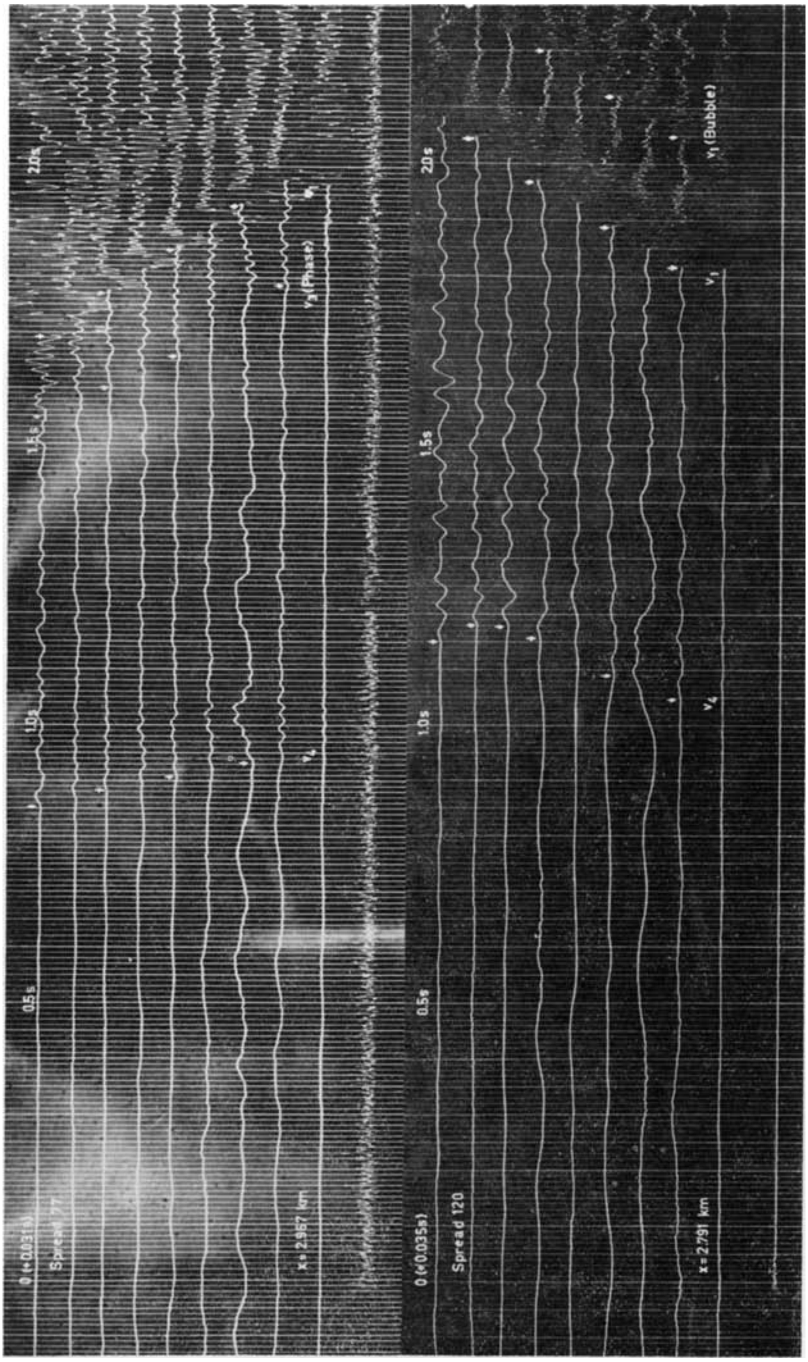

Fig. 2.— Two unfiltered seismograms recorded during the Wellington Harbour survey. Channel 1 is the upper trace of each record. The distance between shot point and shot nearest hydrophone is shown above channel 9 (water wave channel). The shot instant is given by the onset of the decay of a 400 Hz signal on channel 10. In both seismograms the water wave arrivals (v_1) and the refracted arrivals from the greywacke (v_4) are clearly visible on channels 1 to 8; later phases of arrivals from the sediments (v_3 phase) are recognisable in the seismogram from spread 77. The event marked by v_1 (bubble) in the seismogram from spread 120 was identified as bubble pulse (Cole 1948).

During the marine survey electric induction between channels or low gain settings made it sometimes difficult to identify arrivals in the original records. In this case the signals recorded on magnetic tape were replayed through the PT-100 unit at different gain and filter settings, and the records thus obtained were examined. The travel times of first and second arrivals were plotted against distance, and these plots are shown in the upper half of Figures 4 to 10.

Water Velocity

Water velocities were derived for each profile from the surveyed distances between shooting launch and recording ship and from the observed travel times of the water wave along the hydrophone array. The velocities were plotted against distance to check whether "layering", caused, for example, by dense saline water underlying fresh water, is present, but no such effect was detected. The water velocity, however, was found to increase continuously with increasing distances

TABLE 1.—Mean waterwave velocities in Wellington Harbour.

Group	Line	Velocity	N
A	2		
		1.476 ± 0.011	13
	3 (southeast)		
B	3 (northwest)		
		1.486 ± 0.01	19
	5 (northeast)		
C	4		
		1.509 ± 0.01	46
	5 (southwest)		

N gives the number of individual measurements

of the line segments from the mouth of the Hutt River. The average velocities of these segments together with their standard deviations are listed in Table 1. These velocities were used to calculate the distance in the travel time–distance curves in Figures 5, 6, 7, 8, and 9.

The observed changes in water velocity are most likely related to changes in salinity. The water velocity of group C, for example, is about the same as that of sea water (Albers 1965) at 13.5°C, the temperature of the harbour water during the survey. The velocity of group A, on the other hand, is similar to that of fresh water (Press 1966) at the same temperature, thus pointing to a coherent body of fresh water which extended up to 3 km from the mouth of the Hutt River at the time of the measurements.

Sediment Velocities

As a first step in the interpretation of the travel time-distance curves shown in Figures 4 to 10, the influence of the water layer and of a low-velocity layer forming the top of the sediments was removed, taking into account the depth of the shot point. For this the "delay-time" approach (Gardner 1939) was used, which requires that the thickness and average velocity of each layer be known at both the shot point and the receiving station.

After removing the effect of the water layer (water depths were obtained from the chart N.Z. 4633, Hydrographic Branch, Navy Office 1969), it was found from the "intercept-times" (Dobrin 1960) that the refracted arrivals with an apparent velocity of 1.8 to 1.9 km/s, observed at distances between 0.5 to 1 km, were not coming from the sea bottom but from a deeper layer. The velocity of the sea-bottom sediments was assumed to be similar to that (1.55 to 1.65 km/s) observed during a small seismic survey made in the entrance (grid reference N164/184 407) of Wellington Harbour in 1958, when geophones and explosives were placed on the sea floor (unpublished Geophysics Division report by R. A. Garrick). With this information the thicknesses of the low-velocity sediments within the harbour could be calculated; they were found to be between 20 and 48 m. A low-velocity layer, with a velocity between 1.2 and 1.6 km/s and a thickness between 18 and 33 m, also exists on land under line 1. This layer, from now on referred to as "mud-layer", can be correlated with a 30 m thick layer made up mainly of marine sand and mud, which lies on top of the sediments in the H.V.U.W.A. No. 1 well (Grant-Taylor and Taylor 1967). It increases slightly in thickness towards the Wellington Fault under line 1 and line 3, which might reflect recent tilting towards the west or north-west similar to that found by Wellman (1967).

The true velocity of refracted arrivals coming from the sediments underneath the "mud-layer" is plotted in Figure 3 against distance (i.e., shot point to centre of array) for those spreads in the harbour which give clearly recognisable phases on each channel. The velocities at distances less than 1.7 km lie closely around a value of about 1.9 km/s, but at greater distances the scatter increases and the velocities tend to be greater. It can be inferred from model calculations that the velocity of the sediments does not change much with depth. The refracted waves are moderately attenuated in the sediments, which explains the observed fading of the arrivals and the resultant "backstepping" of the first recognisable phases of the later arrivals (Figs. 6 to 8).

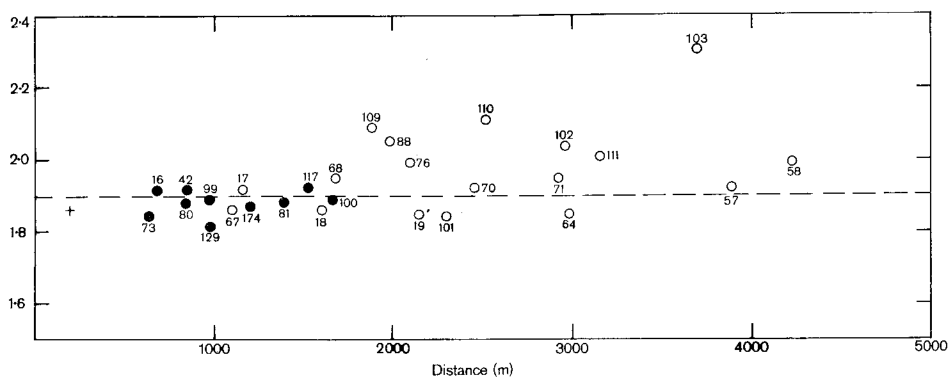

Fig. 3.—Cross-spread velocities of arrivals from sediments observed in Wellington Harbour. Velocities derived from the onset of the wave train are shown by solid dots, velocities from later phases are shown by circles. The average velocity of sediments in shallow water in Lyall Bay (Davey 1971) is marked by a cross.

The velocity of sediments lying under the low velocity layer on land was found to lie between 1.8 and 2.1 km/s. "Uphole-times" observed at two deep wells (H.V.U.W.A. No. 1 and No. 3 in Fig. 4) gave a velocity between 1.89 and 1.97 km/s for the Pleistocene sediments between 30 and 200 m depth under line 1, thus confirming results obtained in the harbour. For consistency, unless stated otherwise, a velocity of 1.90 km/s was used for all sections in computing the thickness of these sediments.

In the vicinity of the Wellington Fault, namely the northwestern shore of the harbour, and near Point Jerningham, refracted arrivals were observed at distances between 0.1 and 0.5 km with velocities of 2.4 km/s (spread 130 on line 1) and between 2.7 and 2.9 km/s (spreads 120 and 121 on line 4, spread 91 on line 5, spread 133 on line 7). These arrivals came from an interface lying not deeper than 20 m below the "mud-layer". There was no information available about the nature and the vertical extent of the material beneath this interface, which according to the observed velocities and the location could have been compacted sediments, landslide material, or shattered or deeply weathered greywacke. The uncertainty as to the nature and extent of this material with intermediate velocities caused uncertainties in the interpretation, as will be seen later.

Depth and Velocity of the Greywacke Basement

Depths to the greywacke basement for profiles with reserved sections were computed using the "plus-times" method (Hagedoorn 1959). The basement velocities and the approximate locations of boundaries separating adjacent parts of the basement with different velocities were obtained from the "minus-times" (Hagedoorn 1959). Basement depths for unreversed sections were calculated from "delay-times" (Gardner 1939); the average basement velocity of these sections was determined by a trial-and-error approach and by minimising the time residuals at a set of stations in reversed and unreversed sections of the same profile.

The greywacke velocities obtained lie between 3.4 and 5.1 km/s, but significant velocity changes occur over small distances (about 500 m). These changes cannot be explained by errors in the method, which were found to be less than 5 percent by using a wave front method (Schenck 1967) in checking independently the velocity of sections with irregular basement topography. Neither can the changes be explained by anisotropy; the velocities at the intersections of line 2 and line 4 with line 5, for example, differ by less than 5 percent. The greater difference at the intersection of line 3 and line 5 is probably caused by an error in determining the boundary of the section with high basement velocity (4.9 km/s) on line 5 in this vicinity. Greywacke velocities are known to change with the present depth of burial but even within the depth range of 200 to 300 m, the observed velocities vary from 4.1 to 5.1 km/s. Hence, it can be concluded that the changes in basement velocity in the sections of Figures 4 to 8, and the resultant velocity pattern shown later in Figure 12, are real. The concept of an average greywacke velocity in the Wellington area with an assumed small standard deviation as has been used in the past (Jones 1946; Eiby 1957; Garrick 1968) may therefore be misleading.

Significant changes in greywacke velocity also occur in a thin weathered layer at the top of the greywacke. Refracted arrivals were not observed coming from this layer, and rather than making an arbitrary assumption about the thickness of this layer, its influence was neglected throughout.

The total error in the computed basement depths is less than 12 percent. This has been assessed (a) from a comparison of computed depths and logged depths at drillholes, (b) from the differences between the individually computed depths at intersections of seismic profiles, and (c) from the differences of depths determined by "delay-times" and "plus-times" for identical segments of the profiles.

PRESENTATION AND DISCUSSION OF SEISMIC SECTIONS

The observed travel-time–distance curves shown in the upper half of Figures 4 to 10 were interpreted in terms of seismic velocity sections which represent geological sections and which are shown in the lower half of Figures 4 to 10. The vertical scale of the seismic sections is exaggerated by a factor of 2 to enhance any structure that may be evident. More than one solution was obtained for sections in the vicinity of the Wellington Fault. The most likely solution will be discussed later.

Line 1: Gracefield–Petone (Fig. 4)

The low-velocity layer on top of the section increases in thickness towards the west from about 18 m at A3 to 33 m at B2. Information about the depth to weathered near-surface greywacke up to 400 m east from the Hutt Road comes from a series of shallow drill holes not shown in Figure 4 (T. L. Grant-Taylor, pers. comm.). Representative sediment velocities beneath the surface layer are known from well shooting at 215 m depth in H.V.U.W.A. No. 1 and at 180 m depth in H.V.U.W.A. No. 3, and are listed in Figure 4 alongside each well. An average velocity of 1.90 km/s was used for the basement depth calculation of the section Hutt River-Hutt Road, whereas a velocity of 1.97 km/s was used for the Gracefield section.

A basement platform occurs under the Gracefield section (spread 132) at a depth of 160 m. This platform also occurs beneath a second profile which runs about due north from shotpoint A3 but which is not presented here. The computed depth to basement H.V.U.W.A. No. 3 agrees within 5 m of that observed. For the Hutt River-Hutt Road Section (spread 131) a series of shots was fired in the Horokiwi Quarry (shot point B1) and at the bottom of the H.V.U.W.A. No. 3 well (shot point B3). For refracted arrivals coming from the basement, the "delay-time" at the shot point is zero in each case, so that basement depths could readily be obtained for most of the section. The computed basement depth under the H.V.U.W.A. No. 1 well lies within 15 m of the drilled depth of 304 m. A basement ridge with a velocity of 4.64 km/s occurs about 1 km to the east of H.V.U.W.A. No. 1. This ridge has already been outlined by gravity measurement (Cowan and Hatherton 1968). A 470-m wide, slightly eastward-dipping greywacke platform lies to the east of the Hutt Road.

Various solutions can be given for the basement scarp between the eastern edge of of the greywacke platform and the H.V.U.W.A. No. 1 well. The ambiguity in positioning the scarp arises in part from the uncertainty about the nature and the thickness of the material with an intermediate velocity of 2.42 km/s, which lies directly underneath the low velocity layer to the west of shot point B2, and in part from the lack of energy of basement arrivals in the same area. In solution A it was assumed that sediments with a velocity of 1.9 km/s have been replaced by a material with a velocity of 2.42 km/s, whereas in solution B it was assumed that this material occurs only in a thin layer underlain by sediments with a velocity of 1.9 km/s. In each case only a small portion of the basement could be constructed, and this is outlined by a dash-dotted line in Figure 4. The observed decrease in amplitude of waves emerging from the lower part of the scarp can be explained if one assumes that these waves are strongly attenuated across the scarp.

Line 2: Point Howard–Petone Wharf (Fig. 5)

The thickness of the low-velocity layer at shot points C1 and C2 is 40 and 44 m respectively; a constant thickness of 45 m was assumed for the section shown in Figure 5. A basement scarp occurs near shot point C2, and greywacke crops out to the east of C2 at a shoal. The basement ridge found under line 1 shows up as a prominent feature in Figure 5, exhibiting a high velocity as in Figure 4. The top of the ridge lies at a depth of about 130 m.

Line 3: Days Bay–Somes Island–Hutt Road (Fig. 6)

Few sediment arrivals were observed along the Days Bay–Somes Island section, and it was assumed that the "mud-layer" is 45 m thick throughout the section, a value taken from the northwestern part of this line and the adjacent line 2. In the Days Bay–Somes Island section the basement forms a rather regular basin, attaining a maximum depth of about 250 m in the centre. The basement velocity changes across the basin, but an average velocity of 4.50 km/s was used for all the section since the location of the velocity changes is not certain. This section is separated from the northwestern part of the profile by the northern extension of Somes Island, which is the emerging part of the ridge found under line 1 and line 2 which will be referred to from here on as "Somes Island Ridge".

The Somes Island–Hutt Road section of line 3 was investigated at the beginning of the harbour survey when instrumental and noise problems had still to be solved. Hence, certain segments were covered twice and the position of the various spreads in the section shows a greater scatter (Fig. 1). This also resulted in a greater scatter of basement depths and a greater uncertainty in basement velocities. Besides shooting at the end of the section at D1 and D3, shots were also fired at D2 in an attempt to obtain wide-angle reflections from the bottom of the sediments at spreads 38 to 43. No such reflections from the bottom of the sediments at spreads 38 to 43 were observed, although reflections coming presumably from the bottom of the "mud-layer" were recorded at spread 42. This layer is 43 and 46 m thick

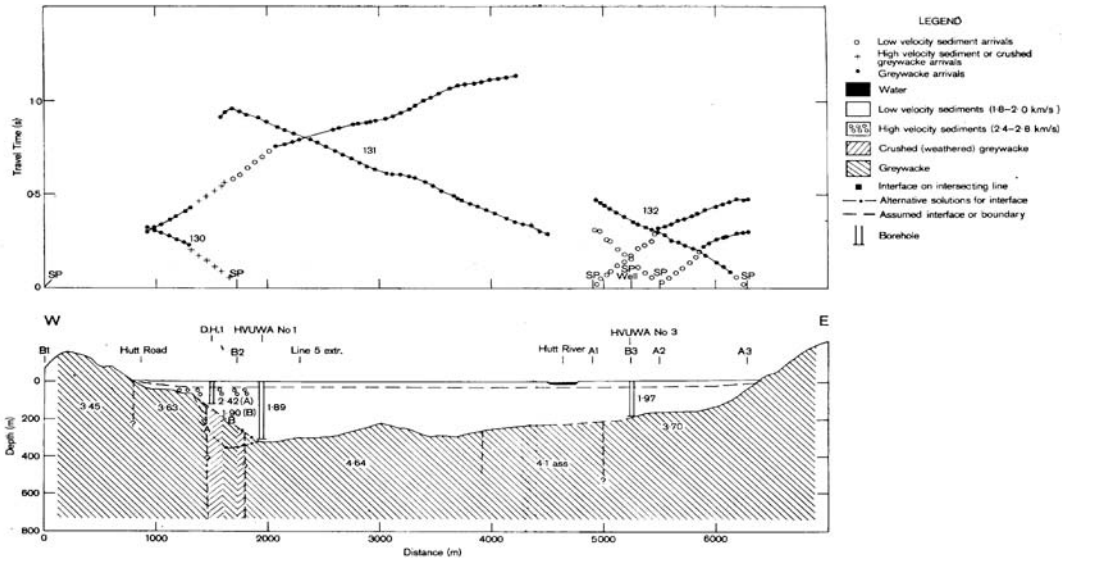

Fig. 4.—Travel time–distance plot of refracted arrivals (upper half of figure) observed along the Petone foreshore–Gracefield profile (line 1) and seismic velocity section based on the interpretation of these arrivals (lower half). The horizontal scale is common to both halves. Figures in the seismic section denote seismic velocities in km/s, *ass.* refers to an assumed velocity. Alternative solutions A and B are discussed in the text.

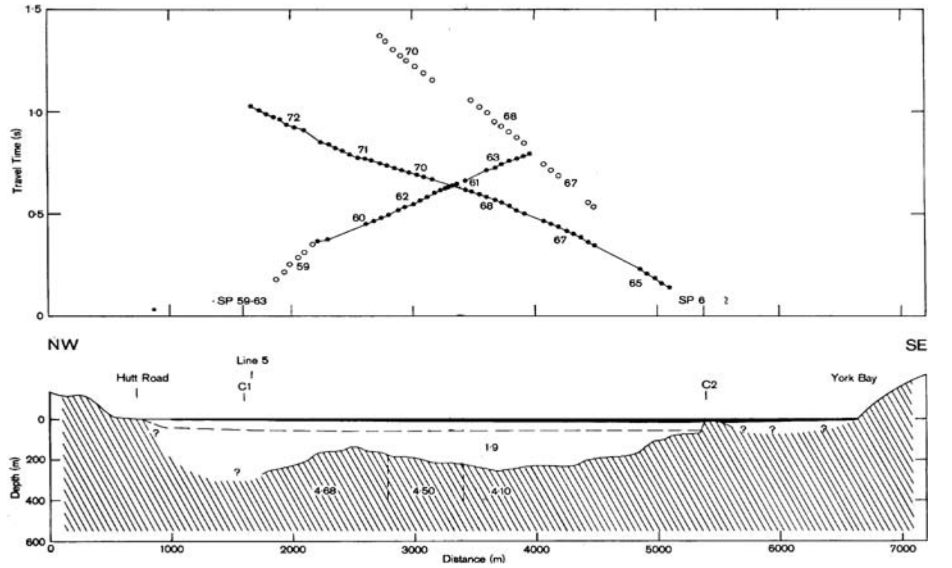

Fig. 5.—Travel time–distance plot and seismic section of the Point Howard–Petone Wharf profile (line 2). For explanation of symbols and shadings see legend in Fig. 4.

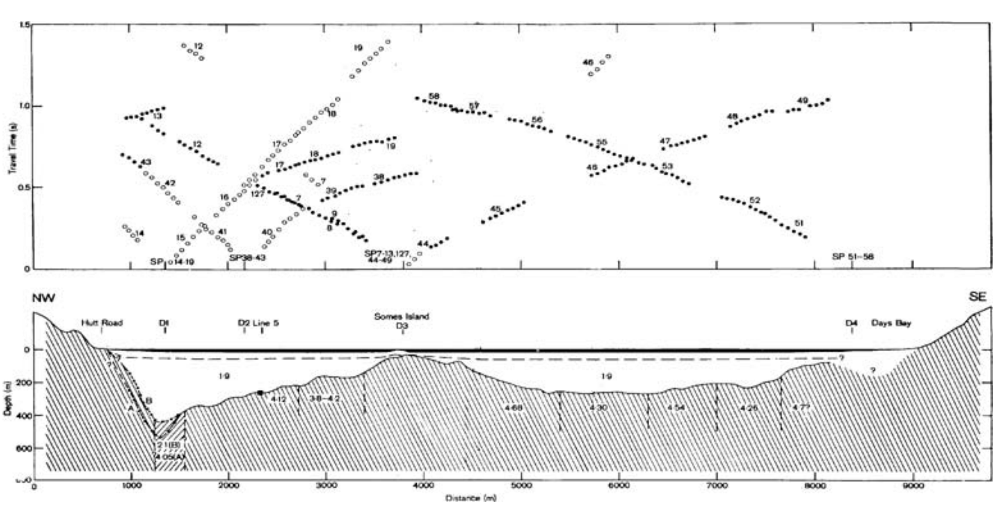

Fig. 6.—Travel time–distance plot and seismic section of the Days Bay–Somes Island–Hutt Road profile (line 3). For explanation of symbols and shadings see legend in Fig. 4. Alternative solutions A and B are discussed in the text.

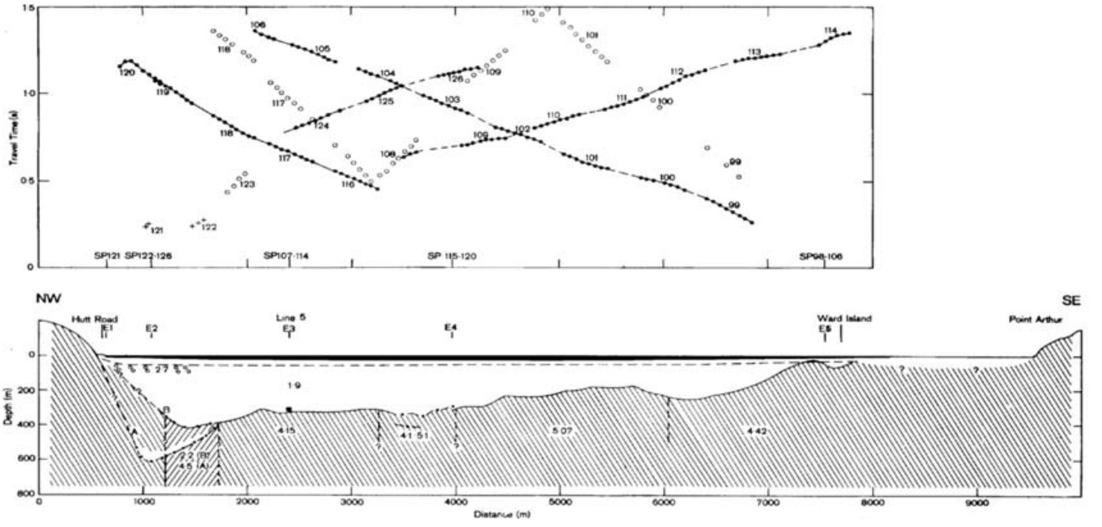

Fig. 7.—Travel time–distance plot and seismic section of the Ward Island–Ngauranga Gorge profile (line 4). For explanation of symbols and shadings see legend in Fig. 4. Alternative solutions A and B are discussed in the text.

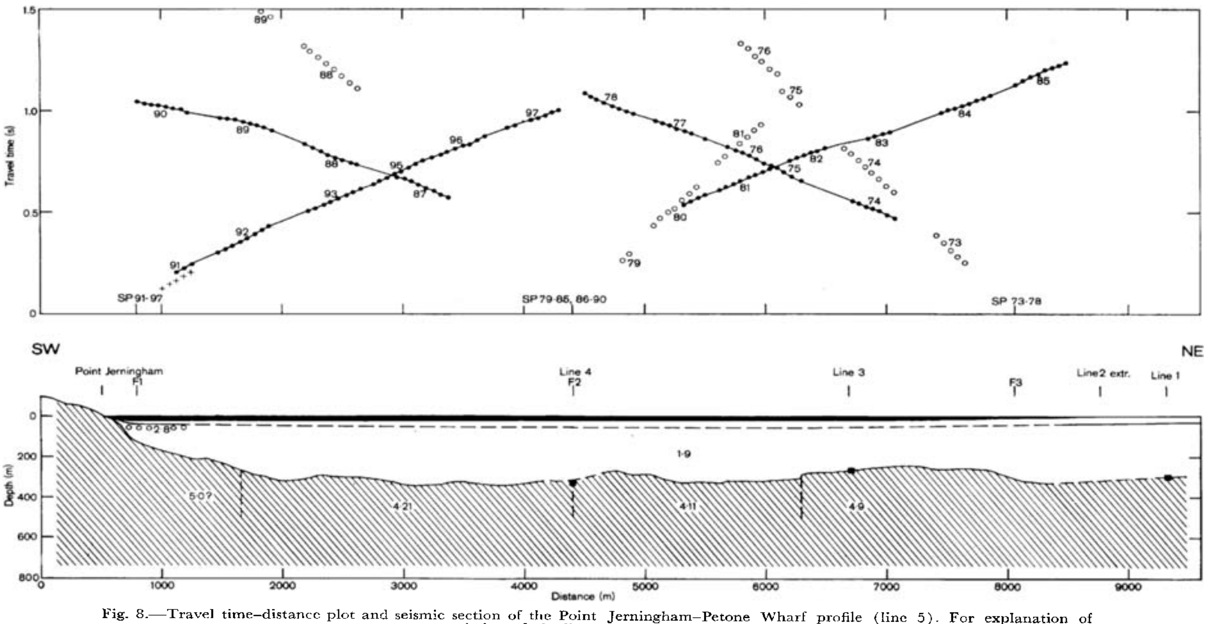

Fig. 8.—Travel time–distance plot and seismic section of the Point Jerningham–Petone Wharf profile (line 5). For explanation of symbols and shadings see legend in Fig. 4.

(Printed with the assistance of the Benson Fund)

under the shot points D1 and D2 respectively. The basement profile indicates some smoothed bench-like features on the northwestern subsurface slope of the Somes Island Ridge, which dips about 8° to the north-west.

Information about the shape and the maximum depth of the greywacke basement between D1 and the Hutt Road comes from two sets of arrivals on the record from spread 13 exhibiting a positive and a negative spread velocity. The arrivals with a positive spread velocity are interpreted as a continuation of the refracted arrivals coming from the northwest-dipping greywacke basement. The arrivals with a negative spread velocity were found to be refracted arrivals coming from an interface dipping to the southeast. The alternative interpretation that these were reflected arrivals, also from the interface steeply dipping to the southeast, is discounted as the amplitude of these arrivals and that of the "positive velocity" arrivals are similar. Using a basement velocity of 4.05 km/s, a change in dip of the basement from 8° to 30° to the northwest under D1 has to be introduced to obtain the correct travel time for the "negative velocity" arrivals (solution A in Fig. 6). This marked change in dip is difficult to reconcile with the geological model of a fault angle depression. An alternative solution, B in Figure 6, was obtained by introducing a low velocity zone, at the base of the southeast-facing scarp, to account for the total travel times of the "negative velocity" arrivals. This zone is about 300 m wide and has a velocity of about 2.1 km/s. The southeast-facing scarp or slope has an average dip of about 40° for an assumed velocity of 4.05 km/s for the rock forming the scarp. This velocity can be as low as 3.0 km/s and still be consistent with the data. In this case the scarp could form part of a wider fault but its dip would be increased to about 50°.

Line 4: *Ward Island–Ngauranga Gorge* (Fig. 7)

The low-velocity layer at the bottom of the harbour is about 20 m thick under shot point E5 near Ward Island, and increases gradually to about 34 m under E3 and 40 m under spread 122. At the northwestern end of the profile, refracted arrivals with a velocity of 2.8 km/s were observed at spread 121 and 122, and these come from material lying directly underneath the low velocity layer. This material is probably thin since second arrivals observed along spread 119 (from shot point E4), with a travel time of greater than 1.5 s, have a velocity not greater than 2.1 km/s. For the calculation of basement depths it is assumed that the influence of the layer with a velocity of 2.8 km/s is negligible.

No arrivals were observed from the unthrown basement at spread 121 although a shot was fired as near in-shore as possible. If a basement platform exists near E1 it is probably not more than 100 m wide. For most of the section the basement relief is fairly smooth, except for a 700-m wide strip to the northwest of E4 where data from three partly-overlapping spreads give different velocities; for the solution shown in Figure 7 an average velocity of 4.55 km/s was used. A basement ridge with a high velocity of 5.07 km/s, part of the Somes Island ridge, occurs about 1.5 km southeast of E4, the top of the ridge lying at a depth of about 180 m. Two solutions are given in Figure 7 for the basement scarp of the northwestern end of the profile, for a similar reason as for line 3. In solution A it was assumed that the velocity of the basement is 4.15 km/s northwest of E3; the resulting basement profile exhibits a marked change in dip from about 3.5° to about 18° between E2 and E3 and reaches a maximum depth of 610 m under E2. In solution B it was assumed that the northwesterly dip of the basement between E2 and E3 does not exceed 6°, which results in a maximum basement depth of 420 m. In this case it is necessary to postulate a low velocity zone at least 450 m wide in which the greywacke velocity decreases to about 2.2 km/s. In solution B there is insufficient information to fix the northwestern boundary of this low-velocity zone.

Line 5: Point Jerningham–Petone Wharf (Fig. 8)

Reliable thicknesses of the "mud-layer" were obtained under F1 (22 m), F2 (35 m), and F3 (32 m). This layer is underlain by material with an intermediate velocity of 2.8 km/s near shot point F1. The basement depth under spread 91 was computed assuming that the influence of the intermediate velocity layer can be neglected.

The basement profile is smooth compared with that of other lines. A step resembling a fault occurs about 400 m southwest of the intersection with line 3. The basement depths for most of the section shown in Figure 8 lie around 300 m. These results, together with those for line 3 and line 4 show that there are no thick sediments between Somes Island and Ngauranga Gorge as indicated by sea gravity measurements (Cowan and Hatherton 1968).

Line 6: Kaiwharawhara Profile (Fig. 9)

Measurements were made along this short profile to find out whether a basement platform exists under spreads 128 and 129. For this the northwestern end of the floating array was brought as near as possible to the shore; shots were fired close to the shoreline at G1 and in deeper water, but offset to the southeast, at G2. The low-velocity layer is absent at G1. The velocity of the near-shore sediments is higher than that of sediments further offshore. Neglecting the influence of the weathered layer of the greywacke basement, the sediments were found to be about 30 m thick and to rest on a greywacke platform about 250 m wide. The cutoff of the greywacke arrivals in spread 128 is similar to that observed over the platform at the northwestern end of line 1.

Line 7: Thorndon Profile (Fig. 10)

This profile was investigated to obtain information about the depth and shape of the greywacke basement in the vicinity of the Thorndon railway bridge on the Johnsonville railway line. The bridge lies on the northwestern side of a bench barely 150 m wide, of mostly reclaimed land which in practice constitutes the main access by road and rail to Wellington City. The Wellington Fault was thought to lie either at the bottom of the greywacke cliff or somewhere underneath the bench.

The measurements showed that no high velocity arrivals, typical of solid greywacke, could be observed along spread 133, although shots were fired at the northwestern end in a 15 m deep shot hole (H1) which was sunk in what appeared to be slightly weathered but otherwise solid greywacke. However, uphole time and first arrivals at the bottom of the cliff gave a velocity of 2.2 km/s, thus pointing to shattered greywacke in this locality. Refracted arrivals with a velocity of 2.7 km/s were observed along the northwestern part of the spread; these arrivals were coming from material lying at a depth of about 15 to 20 m under sediments with a velocity of 1.80 km/s. There was no information on whether this material extends to greater depths, and for a preliminary interpretation it was assumed that this material represents the shattered and weathered greywacke which had been found nearby at the bottom of a 14 m deep hole drilled in 1940 (L. E. Oborn, unpublished N.Z. Geological Survey report, 1971). This interpretation, however, had to be revised once results from a recently drilled hole (D.H.2 in Fig. 10) became available, and these will be discussed later.

THE WELLINGTON FAULT IN THE LIGHT OF SEISMIC MEASUREMENTS

Although the seismic measurements presented so far give a clear picture of the greywacke basement under Wellington Harbour, they contain no specific information about the position and nature of the Wellington Fault. Some notable features of the seismic sections occur only in the vicinity of the fault, namely platforms of solid or shattered greywacke with a well-defined southeastern edge; material of unknown vertical extent with an intermediate velocity of 2.4 to 2.8 km/s; and an inferred zone of low velocity or high attenuation in the basement.

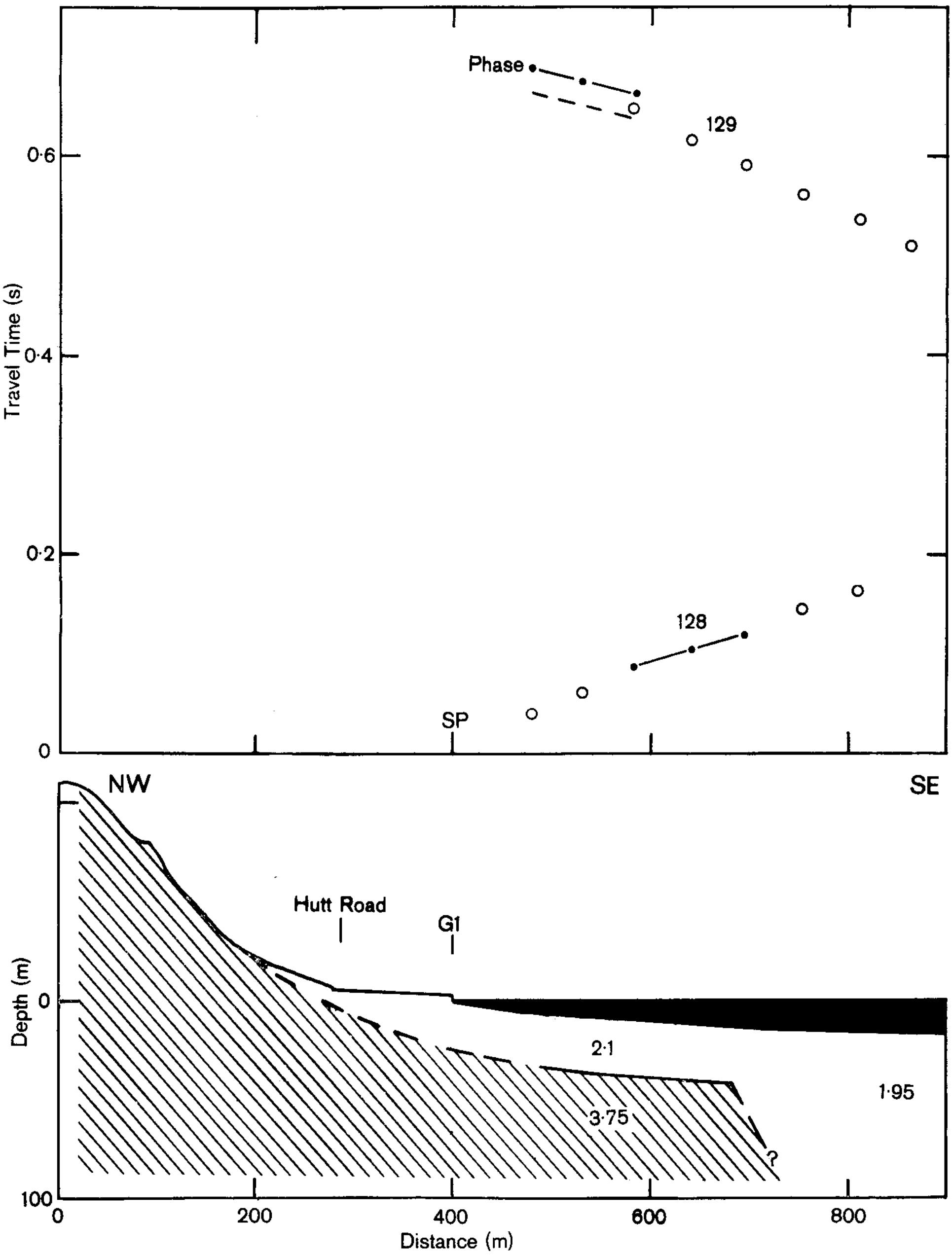

Fig. 9.— Travel time–distance plot and seismic section of the Kaiwharawhara profile (line 6). For explanation of symbols and shadings see legend in Fig. 4.

Other studies suggest that crush zones in the Wellington area are associated with a low seismic velocity. Seismic measurements, made by R. A. Garrick in 1959 (unpublished DSIR Geophysics Division report) across the concealed Wellington Fault near Taita Gorge (grid reference N160/533 389), about 14 km northeast of line 1, showed that this fault is accompanied by the low-velocity (2.8 to 3.0 km/s) zone which is 80 to 130 m wide, with solid greywacke (3.71 km/s) on either side. Recently, seismic measurements were made in a pilot tunnel across the Lambton

Fault (grid reference N164/218 322), and these also showed that seismic velocities in the 60 to 90 m wide crush zone lie between 2.35 and 2.8 km/s (Ingham 1971).

As mentioned in the introduction, the Wellington Fault is not simply a plane of movement but rather a crush zone which presumably varies in width and within which bands of fault breccia dip approximately vertically (Stevens 1958), but there is no information available as to whether this zone is continuous.

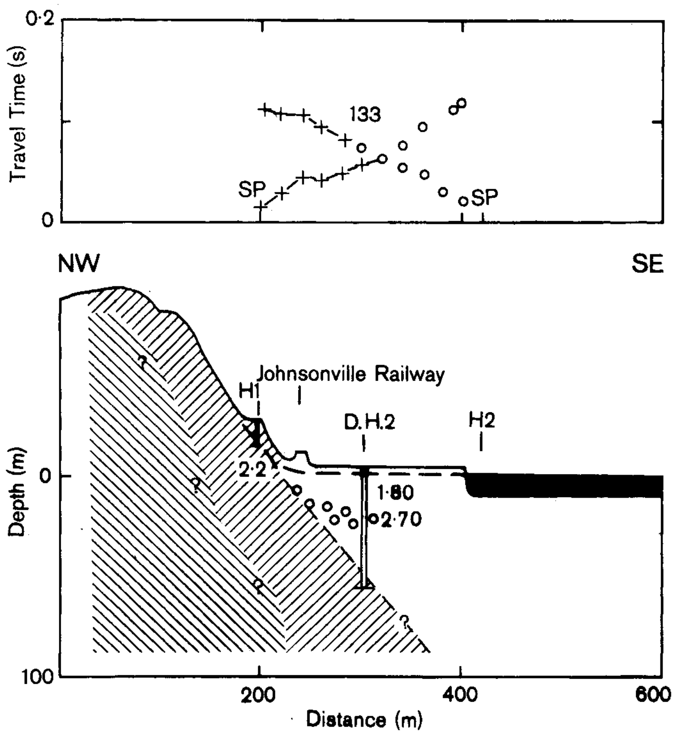

Fig. 10.—Travel time–distance plot and seismic section of the Thorndon profile (line 7). For explanation of symbols and shadings see legend in Fig. 4.

Assuming that the crush zone of the Wellington Fault is narrow, one can identify the southeastern edge of the basement platforms under lines 1, 6 and probably also line 7, with the edge of the upthrown fault-block. This location of the fault has been proposed by Grant-Taylor (1967) for line 1. The resulting fault trace (broken line A in Fig. 12) would not differ significantly from that shown in most publications which describe this fault. This model would imply that neither the material with an intermediate velocity of 2.4 to 2.8 km/s, nor the inferred low velocity zone, is directly connected with the fault. It also leaves unexplained why the subsurface scarp adjacent to the fault shows a rather moderate dip of 30° to 50° to the southeast.

If the crush zone is wider, say 300 to 500 m, the inferred low velocity zone can be identified with the crush zone of the Wellington Fault. Since the northwestern boundary of the low velocity zone is undetermined except possibly under line 3, this zone cannot be defined accurately. It would lie, however, at the foot or in the lower part of the subsurface scarp, which can be interpreted as a fault-scarp dipping about 30° to 50° to the southeast. In this model the near-shore platforms and the near-surface material with an intermediate velocity of 2.4 to 2.8 km/s are not directly connected with the fault zone. Widths of 350 to 550 m have been reported for the crush zone of the Wellington Fault where it is exposed at the southern end of Long Gully, about 11 km southwest of line 7 (Brodie 1953) and at Raroa Road about 3.7 km southwest of line 7 (Stevens 1958).

Assuming that the crush zone extends from the edge of the platform to the southeastern boundary of the inferred low velocity zone, which implies widths between 500 to 1100 m for this zone under the harbour, the two features can be combined in one model. The maximum width of this crush zone occurs under line 4 where the curvature of this zone is also a maximum (see Fig. 12). In this model, material with an intermediate velocity is not related to the fault zone. The subsurface scarp would consist mostly of crushed greywacke, and its moderate dip of 30° to 50° could be explained by erosion which took place in a relatively short period.

In each of the three models discussed so far the dip of the subsurface scarp in the vicinity of the fault or fault zone lies between 30° and 50°, which includes the range of dips of stable greywacke surface slopes in the Wellington area (T. L. Grant-Taylor, pers. comm.). A buried scarp of such a dip in direct proximity to a near-vertical transcurrent fault is difficult to reconcile with the tectonic model of a basin slowly subsiding along the fault, for which a significantly steeper scarp would be expected. If, however, the near-surface material with an intermediate velocity of 2.4 to 2.8 km/s is in fact deeply weathered or crushed greywacke lying along the upthrown side of the fault, then a significantly steeper scarp could be postulated. Although this model is difficult to reconcile with arrivals coming from greater depths underneath the much wider platform, it explains all the arrivals observed on land along line 1 and line 7.

At this stage of the interpretation it became evident that only the drilling of a hole through the material with intermediate velocities into the subsurface scarp would settle the question as to which model is valid. Before drilling, however, an effort was made to find whether an interpretation of detailed gravity measurements made along line 1 could solve the problem.

INTERPRETATION OF GRAVITY MEASUREMENTS ALONG PETONE FORESHORE

To decide whether the near-surface material with a seismic velocity of 2.4 km/s is the near-surface expression of a zone of crushed greywacke parallel to the fault, a set of detailed gravity measurements along Petone foreshore was analysed. These measurements were taken at stations most of which were only 30 m apart, whereas the data used by Cowan and Hatherton (1968), who interpreted gravity anomalies along a profile which nearly coincides with that discussed here, were obtained from measurements at stations about 500 to 1000 m apart.

Starting from Bouguer anomalies, the influence of deeper-seated masses were removed in the same way described by Cowan and Hatherton (1968), and "observed gravity anomalies", shown in the upper half of Figure 11, were obtained. Theoretical anomalies were computed using a procedure described by Talwani *et al.* (1959) and assuming that the basement structure is two-dimensional. Since basement depths were known for the greater part of the section (see Fig. 4), the density contrast between sediments and greywacke basement could be treated as an unknown, and a value of -0.4 Mg/m^3 was obtained, a density contrast identical to that used by Cowan and Hatherton (1968). A value of -0.2 Mg/m^3 was taken for the contrast between solid and intensely crushed greywacke, and was derived from measurements in a tunnel across the crush zone of the Lambton Fault (Ingham 1971).

Two models, A and B, corresponding to seismic solution A and B of line 1, were considered. In model B it was assumed that the greywacke scarp has an apparent dip of 25° and that the influence of any fault zone which might intersect this scarp can be neglected. This infers that the density contrast between greywacke and the material forming the fault zone is small. In model A it was assumed that all the material with a density contrast of -0.2 Mg/m^3 consists of intensely crushed

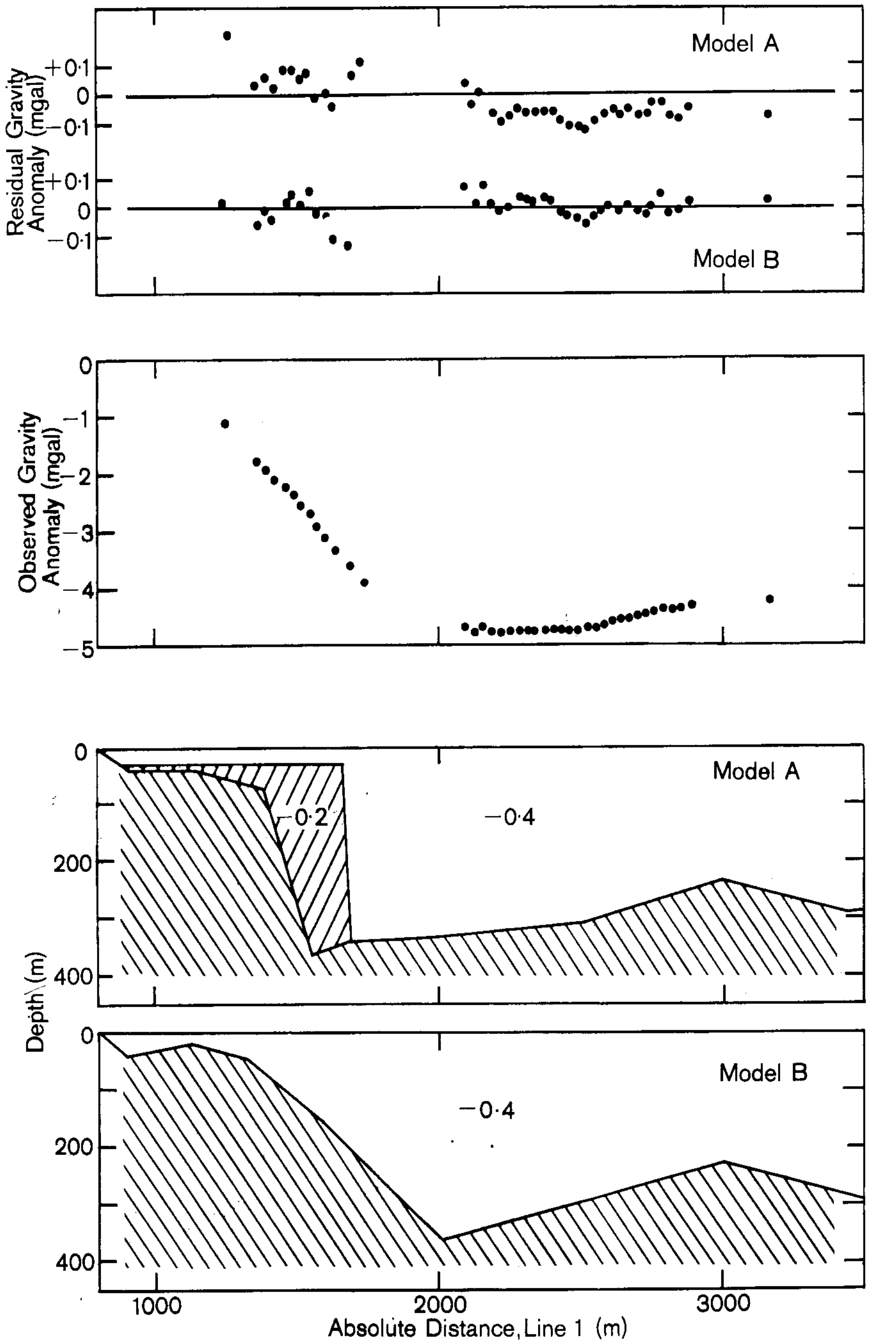

Fig. 11.—Observed gravity anomaly, residual gravity anomalies and density sections of a gravity profile along Petone foreshore. The horizontal scale is common. The distance is related to an arbitrary origin which is identical to that used in Fig. 4. Figures in the density sections denote density contrasts in Mg/m³ relative to the average wet density of greywacke (2.67 Mg/m³).

greywacke which might represent the central part of a crush zone. The scarp in model A has a dip of 80° and represents a nearly vertical fault plane. The influence of deeper parts of the fault zone was neglected, mainly to fit the gravity models closely to the seismic models shown in Figure 4.

A comparison of the residual gravity anomalies of models A and B shows that although the residuals are smaller for model B, there is no significant difference, considering that the resultant error of the measurements and the reduction is about ± 0.1 mgal. Hence, neither of the models discussed in the previous paragraph can be rejected on the basis of gravity measurements along Petone foreshore.

DRILLING RESULTS

To check which model is valid, two holes were drilled into the inferred fault zone. Information from the seismic surveys was used in siting these holes.

The first hole D.T.1 (grid reference N164/293 418) was drilled on line 1 about 45 m west of H.V.U.W.A. No. 1 in February 1972 (see also Fig. 4). The upper 110 m of the hole passed through a sequence of gravel and silts which are similar to those found in H.V.U.W.A. No. 1. There was no change in facies between 30 and 60 m depth, and the intermediate velocity of 2.4 km/s probably reflects a greater compaction of gravel and silts below 30 m depth. Weathered and shattered greywacke was reached at a depth of 113 m. A core from 117- to 119-m depth was found to consist of non-coherent pieces of weathered greywacke which were not greater than about 30 to 50 mm in diameter, and it can be inferred that this hole was sunk into the Wellington Fault Zone (T. L. Grant-Taylor, pers. comm.). The basement depth agrees well with that predicted by seismic solution B (135 m) and thus favours model B of the gravity interpretation. Shooting at the bottom of the well showed that the near-surface layer, with an intermediate velocity of 2.4 km/s, is thin (<15 m).

The results of the hole D.H.1 led us to check whether rocks with a velocity of 2.7 km/s under line 7 were shattered greywacke or sediments of the type found in D.H.1. The second hole D.H.2 (grid reference N164/344 246) was drilled near the centre of line 7 in July 1972 (see also Fig. 10). Bench gravel and greenish silts and sands were found in the upper 12.5 m and these were underlain by an 8.5 m thick layer of brownish-yellow angular, fragmented greywacke presumably deposited by a landslide. Below 21 m the sequence continued with greenish silts and sands until weathered and intensely crushed greywacke was reached at a depth of 50 m. Cores from 50 to 58.5 m consist of brownish pug with just recognisable, steeply inclined fractures, indicating that this hole had also reached the Wellington Fault Zone. Well shooting gave evidence that the intermediate velocity of 2.7 km/s is confined to the landslide material; sediments below this layer have a velocity of about 1.95 km/s. Density and porosity measurements of cores from D.H.2 (Geophysics Division Lab. No. 7154 to 7174) were made to find out whether there is any abnormal compaction of sediments lying on top of the fault zone which might have been brought about by stresses acting along this zone. No evidence for such compaction was found, but the average porosity of water-saturated sediments below the landslide material was found to be higher (22 ± 2 percent) than that of sediments above this layer (15 ± 7 percent), pointing to a potential instability in the event of strong vibrations (local earthquake).

The drilling has shown that the material with an intermediate velocity of 2.4 to 2.8 km/s occurs in the form of a thin layer and consists of compacted gravel or crushed greywacke deposits presumably by a landslide. Layers with a similar velocity (spreads 91, 121, 122) are also thin; if these layers are landslides it is possible that they have a common origin, for instance formed during a major earthquake. Another important finding is that the crush zone into which the holes were sunk forms the upper part of the subsurface scarp, and that the slope of this upper part lies between 30° and 40°, which is about the same as that inferred from solution B (lines 1, 3, 4) for the whole of the scarp. Thus the entire scarp probably lies within the crush zone, but this would not only explain the stable slope of this feature, but also the inferred zone of low velocity at the foot of the scarp. The inferred high velocity (<3.0 km/s) for the rock forming the scarp on line 3 could suggest that the scarp defined on this profile is close to, or at, the northwestern edge of the low-velocity zone,

CONCLUSIONS

The seismic surveys and the other studies described in this paper have shown that the Wellington Harbour and the Hutt Valley lie in a depression which can be explained as a fault angle depression caused by a westerly tilt of all or part of a block, presumably about 20 km wide, lying to the east of the transcurrent Wellington Fault. The depression has been filled by mostly non-marine Pleistocene sediments. The depressed undulating erosional surface has been constructed from basement depths determined on various seismic sections and is shown in Figure 12, in which the level of the concealed and exposed greywacke is shown by a set of contours. The basement depths in the vicinity of the crush zone of the transcurrent Wellington Fault are taken from the preferred solution B of the seismic sections. The greywacke surface lies at a depth of not more than 400 m in the vicinity of this zone and between 200 and 300 m over most of the harbour. Hence, it can be concluded that previously published gravity measurements made in the harbour, which indicated sediment thicknesses of greater than 1000 m, contain a systematic error, as does the pattern of the gravity anomalies in the harbour which is not compatible with that of the seismic results shown in Figure 12.

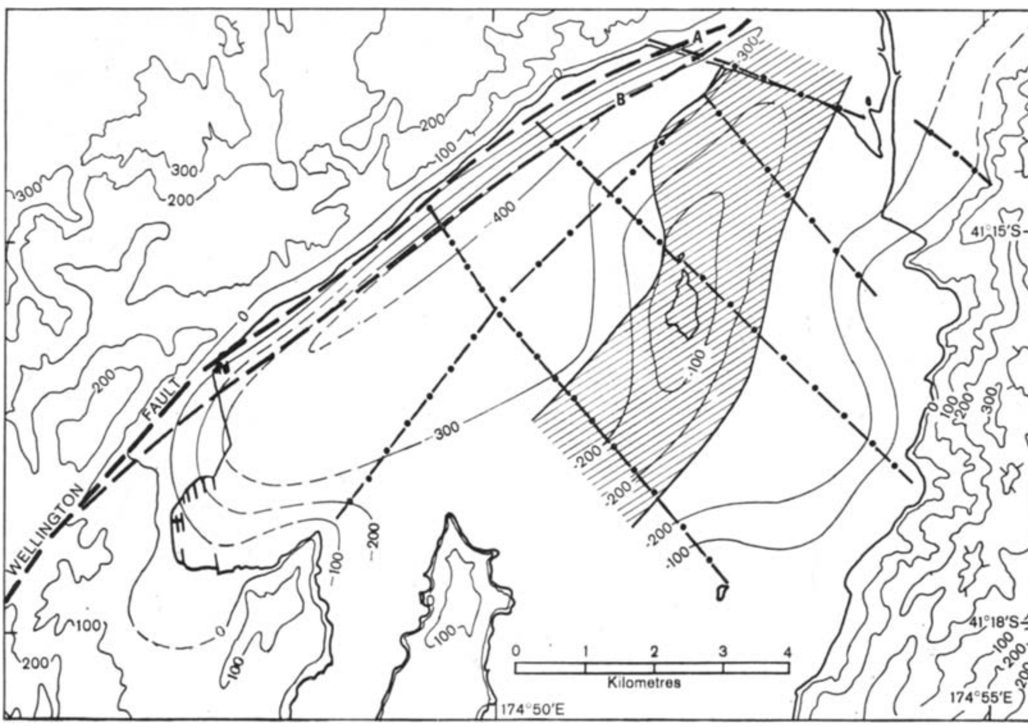

Fig. 12.—Map showing the level of the top of the greywacke relative to sea level in the Wellington Harbour area (contour values in metres). Inferred levels are indicated by dashed lines. The location of the more extensive seismic profiles (lines 1 to 5) is shown by dashed-dotted lines. Contours in the vicinity of the Wellington Fault are based on seismic solution B for lines 1, 3, and 4. The greywacke basement with velocities greater than 4.5 km/s is outlined by shading. The Wellington Fault Zone lies between the two dashed lines of which line A marks the position of the south-eastern edge of the greywacke platform and line B the position of the centre of the zone with inferred low seismic basement velocity and high attenuation.

A basement ridge with basement velocities greater than 4.5 km/s runs from the Hutt Valley to Somes Island and continues towards Miramar Peninsula. Similar high velocities also occur north of Point Jerningham. It can be inferred that this north-northeast–aligned ridge, and presumably other near-parallel morphological features, are caused primarily by erosion and probably reflect different degrees of jointing and shearing in the basement rocks (T. L. Grant-Taylor, pers. comm.). At the time of burial, therefore, this surface could not be classified as a peneplain. The degree of hardness or resistance to weathering is reflected in the seismic velocity of these features. Their non-tectonic origin is further strengthened by the fact that no signs of fault or fault-block structure were found within the basement under the harbour itself. Hence, theories about the origin of Wellington Harbour which postulate faults under the harbour are rejected.

The seismic velocity structure in the vicinity of the Wellington Fault is not known in full detail, and the interpretation of this structure is therefore ambiguous. Recent drilling on land into the crush zone of this fault has helped to clarify the structure, although some uncertainty remains as to the width of the crush zone. In the solution which is preferred (model B in Figs. 4, 6, 7, and 11) the crush zone of the Wellington Fault is about 500 to 1000 m wide under the harbour (see Fig. 12). The dip of the subsurface slope of this zone is about 30° to 50° to the southeast. This slope might have been caused by relatively rapid erosion of a steeper scarp which was fully exposed at an earlier stage of the development of the depression, although a step-by-step exposure of such a wide crush zone would equally well produce a stable slope. Both alternatives would be consistent with the development of the extensive slips and en-echelon faults which have been observed on the southeastern margin of the upthrown block and which run about parallel to the Wellington Fault; the concealed greywacke platforms west of the low velocity zone at the northwestern shore are probably relicts of slips. It is possible that the inferred widening of the fault zone under the harbour is a consequence of the curving of the Wellington Fault in this region. The concealed fault zone is about 200 to 400 m wide on land near Thorndon and at Petone.

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