THE DUNEDIN EARTHQUAKE, 9 APRIL 1974

PART 1: SEISMOLOGICAL STUDIES

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ABSTRACT

The Dunedin earthquake of 9 April, 1974 was of magnitude 5.0, and is the largest known to have originated in eastern Otago. The shock was centred about 10 km south of the city centre, with a shallow focus, probably about 20 km deep. Damage to a value of about $250,000 occurred, and many brick chimneys were broken or damaged in the worst affected areas, where the intensity reached MM VII. The areas of greatest damage were the southern suburbs, on alluvial soils, where results from a survey of natural seismic noise show strong amplification effects due to the unconsolidated nature of the ground.

INTRODUCTION

The earthquake in the early evening of Tuesday, 9 April, 1974 was the strongest known to have affected the city of Dunedin since its founding in the middle of the last century. The earthquake was of moderate magnitude (M_L = 5.0) and centred close to the city. A large amount of minor damage was caused, and in particular many domestic brick chimneys were damaged.

Dunedin is a city of about 110,000 inhabitants, situated at the head of Otago Harbour, a long embayment into the late Tertiary volcanic complex about 20 km across that forms the Otago Peninsula and adjacent areas of the mainland. The city rises from alluvial deposits at the head of the harbour, up hills predominantly of basalt, a few hundred metres high. To the south of the central city an isthmus of low-lying alluvium about 3 km wide separates the Otago Peninsular from the hills of St. Clair. Inland from the city are the peneplained hills of the schist belt that extends north-westwards across Central Otago (Benson, 1968[4]; McKellar, 1966[5]).

PREVIOUS SEISMICITY OF DUNEDIN AREA

The area of eastern Otago which includes Dunedin is one of the more tectonically stable areas of New Zealand. Small earthquakes do occur there, however, and some have been large enough to have been felt in Dunedin, but most earthquakes felt there originate in the highly active Fiordland seismic region 200 to 300 km to the west, where 20 to 30 shallow earthquakes a year reach or exceed a magnitude of 4. The only active fault mapped near Dunedin is the Akatore Fault, that trends south-westwards, parallel to the coast, from the Taieri River mouth, about 30 km southwest of the city (McKellar, 1966[5]).

Earthquakes were regularly reported as being felt in Dunedin during the latter part of last century. Between 1860 and 1890 there was no year without at least one earthquake reported, and in 1863 there were five. It is difficult now to determine whether these reports arose from nearby earthquakes or from larger shocks in Fiordland. The occurrence of damage in Oamaru in 1876, however, supports the contention that at least some earthquakes originated in eastern Otago.

In recent years, fewer earthquakes have been reported from Dunedin. From 1958 to 1968 there were four years with no shocks reported felt, and an additional three with only one. The most recent occasions on which intensities of MM V were reached in Dunedin appear to have been on 8 May, 1943, from a shock of magnitude 6¼ about 160 km to the northwest, and on 25 May, 1960, from a magnitude 7.0 earthquake near Milford Sound.

Earthquake locations in south Canterbury and east Otago have been reliable only since the expansion of the New Zealand seismograph network in the last decade. Fig. 1 maps all earthquakes located in these regions from 1964 to the time of the Dunedin earthquake of 9 April, 1974. Only those earthquakes are plotted that lie southeast of a line that runs along 44°S to 170°E, thence southwestwards to 47°S, 167°E. The western boundary is drawn to exclude from the diagram the numerous earthquakes that occur in the Fiordland seismic region. In the northwest of the region of interest, a cluster of activity, including two shocks of magnitude 5, is evident near Lake Benmore. The significance of these earthquakes in relation to the filling of the lake is discussed elsewhere (Adams, 1974[1]). Earthquakes are seen to have occurred near Timaru, and fairly widely through north Otago, to the south of the Waitaki Valley. No shocks have been located near the lower Clutha River, and only four shallow shocks to its west. The only earthquake close to Dunedin occurred about 20 km to the north-west, on 21 June, 1965. Its magnitude was only 3.3, and it was felt in the city at intensity MM III.

Fig. 1 also shows the positions of the earthquakes of 9 April, 1974 to the south of Dunedin, and the seismograph stations used in their locations. The main earthquake

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is as large as any of those plotted; only the two largest shocks of those near Lake Benmore have similar magnitudes. There is nothing in the pattern of past seismicity to suggest that an earthquake of such magnitude was more likely to occur close to Dunedin, rather than elsewhere in the region. The recent traces of the Akatore Fault, however, might have been taken as geological evidence that such an event could be expected. The occurrence of this earthquake reinforces the contention that all parts of New Zealand must be prepared to experience damaging earthquakes, and that the lack of previous events in a region does not mean that it is immune from earthquake risk.

EARTHQUAKE OF 9 APRIL, 1974

The earthquake was located using readings at the nearest seven seismograph stations; the most distant of these was Gebbies Pass in Banks Peninsula. Positions of these stations are shown in Fig. 1, and detailed readings are given in Table 1.

The formal solution is :-

1974 April 9^d 07^h 49^m $46^s.1 \pm 0^s.4$ U.T.
(April 9^d 19^h 49^m $46^s.1$ N.Z.S.T.)

$45^o.97 \pm 0^o.02$S, $170^o.52 \pm 0^o.02$E

Focal depth: 12 km (restrained)

Standard error of origin: $0^s.7$ (from 15 phases at 7 stations)

Richter local magnitude (M_L): 5.0.

The position is 10 km south of central Dunedin, and about 7 km offshore to the south of St. Kilda, where the water depth is about 50 m. The formal standard error is about 2 km, but this is largely a measure of the consistency of the readings, and the true error could be several times as great.

FOCAL DEPTH

As the closest stations are about 100 km away, there is little geometrical control over the determination of depth. In such cases the Seismological Observatory assigns depths of either 12 or 33 km. For this earthquake the focus was restrained at 12 km; placing it at a depth of 33 km moved the computed epicentre about 10 km to the northeast, but resulted in slightly larger errors. Several factors suggest, however, that the focus may be rather deeper than 12 km, possibly closer to 20 km. These factors are:-

1. Crustal phases. The phases Pg and Sg were not strongly developed. These phases have paths in the upper crust and are generated more strongly by earthquakes originating at depths of less than 12 km.

2. Aftershocks. The number of aftershocks recorded was smaller than might be expected following a very shallow earthquake. For example, the Te Aroha earthquake of 1972, which was of comparable size, had 17 aftershocks of magnitude 3.5 or greater, compared with only 2 for the Dunedin earthquake (Adams et al., 1972[2]).

3. Felt Effects. Various empirical formulae exist connecting focal depth (h), magnitude (M), and epicentral intensity (I_o). One given by Shebalin (1961[7]) is

$$I_o = 1.5M - 3.5 \log h + 3.0.$$

Substituting $I_o = 7$, and $M = 5.0$ gives $h = 20$ km.

Similarly, the spacing of outer isoseismals (Fig. 2) is consistent with a depth of about 20 km, according to relations given by Shebalin.

Thus, although the focal depth cannot be determined reliably, a depth of about 20 km would best fit the observed features of the earthquake. The depth of the earthquake would then be greater than its horizontal distance from Dunedin, which could help explain the comment independently expressed by many people that the vibration during the earthquake appeared vertical rather than horizontal. The earthquake was generally described as an "upward jolt".

DIRECTIONS OF FIRST MOTION

These were unusually clear for a shallow earthquake, and are included in Table 1. The stations at azimuths between WSW and NNW, that is, MNW, ROX and MSZ recorded dilatations, and the others, OMZ, MJZ and WPZ compressions. This number and distribution of observations is not enough to determine a unique orientation of nodal planes, but is consistent with a focal mechanism of predominantly strike-slip faulting, with steeply dipping nodal planes. Movement would be either dextral on a fault striking ENE, or sinistral on one striking NNW. Such a compressive stress pattern, with the pressure axis horizontal in a WNW-ESE direction has been found by Scholz et al. (1973[6]) for earthquakes in Fiordland, and by Adams et al. (1974[3]) for micro-earthquakes near Lake Benmore, and seems to prevail over much of the South Island.

AFTERSHOCKS

Only two aftershocks were large enough to be located instrumentally. These occurred about 20 minutes and about 2 hours after the main shock; both had magnitudes of 3.7 and were generally felt in Dunedin. Their origins are :-

1974 April 9^d 09^h 11^m $00^s.7$ (U.T.)
$45^o.97$S, $170^o.51$E, h = 12 km (restrained)

1974 April 9^d 09^h 50^m $32^s.1$ (U.T.)
$45^o.96$S, $170^o.47$E, h = 12 km (restrained).

The computed positions are not significantly different from that of the main shock. A few further minor shocks were reported felt by some observers, but no consistent times can be established.

FELT EFFECTS

A map of felt intensities reported on the standard Seismological Observatory questionnaires is shown in Fig. 2. The earthquake was generally felt out to Oamaru, Roxburgh and Balclutha, with isolated reports from as far afield as Waipapa Point and Gore. The isoseismals have the regular configuration usually found for shallow earthquakes, with the radii of the MM V, MM IV and MM III isoseismals being about 35, 90 and 150 km respectively.

Damage was almost entirely confined to the Dunedin area, and Part 2 of this paper deals with effects there. From standard felt report forms submitted to the Seismological Observatory, and a visit to Dunedin two months after the earthquake, it was established that the intensity reached MM VII in the worst affected areas of Dunedin. These were mainly the southern suburbs on the alluvium between Otago Peninsula and St. Clair. Little damage beyond that to domestic chimneys occurred even in these areas, but chimney damage was consistent and widespread, and although the standard of construction was commonly poor, the proportion of chimneys in which the brick-work was broken prevents the allocation of a lower intensity. Chimney damage occurred, but less densely, over most of the rest of the city, including the hill suburbs, but was usually more superficial and restricted to fall of pots and plaster. In these areas, MM VI would be appropriate.

The Earthquake and War Damage Commission has received nearly 3000 claims, at least half of which involved damage to chimneys. The total cost of the claims is estimated to be about $250,000, which is more than for any other single earthquake since that at Inangahua in 1968.

SOIL AMPLIFICATION EFFECTS

The worst affected parts of the city are the areas of recent alluvium and reclaimed land on the isthmus that joins the Otago Peninsula to the mainland. The more severe effects here are likely to be due not so much to the closer position to the epicentre, as to the unconsolidated nature of the ground causing amplification of the incident earthquake waves. In such areas the amplitude of the waves increases due to the physical properties of the soil itself, and there are also resonance effects which can greatly amplify vibrations of certain frequencies that depend on the size and thickness of the layers involved and on the direction of incidence of the exciting energy.

Both natural and earthquake-generated vibrations may be expected to be amplified in such unconsolidated areas, and, to test this concept, a survey of natural ground noise was made at 67 sites in the Dunedin area early in June, 1974. At each site measurements were made in three different frequency bands.

At a frequency of about 0.8 Hz, the predominant ground noise seemed to originate from surf on the southern beaches, and diminished northwards, with only slight amplification on the alluvial areas, compared with sites on bedrock. At the highest frequencies sampled, 10 to 20 Hz, the level of recorded noise depended predominantly on local disturbances, and no consistent pattern emerged. In the frequency range from 5 to 8 Hz, however, there was a systematic pattern of increased noise level crossing the alluvial areas at the head of the harbour, and extending through the isthmus to the beaches of St. Clair and St. Kilda. The areas with the highest noise amplification appeared to be the reclaimed land at the immediate head of the harbour and in South Dunedin. Here the level of ground noise was at least 30 times that generally recorded on bedrock, and at one site the amplification was 60 times. The noise level on natural alluvium in the middle of Victoria Road, which runs parallel to the southern shore of the isthmus, was 20 times that on the hills at either end.

The noise values recorded are shown in Fig. 3, in which areas of alluvium and recent fill are also indicated. The alluvium in the north of the city is not thick, and no local amplification is produced there. In the south the noise contours closely follow the edge of the alluvium, and the area of high amplification of natural noise corresponds in general with the area of maximum damage. The details do not always match, however, and an area near Ings Avenue, immediately at the foot of the St. Clair hills, sustained particularly severe damage, even to well-built chimneys (see Part 2 of this paper), although it is not an area of unduly high noise level. This concentration of damage could have arisen from local increase of vibration due to an "edge effect" of the hill meeting the alluvium, or from some other local focussing effect. Similarly, the slight increase in felt intensity along ridges of the hill suburbs (see Part 2) could be a topographic focussing effect.

The noise level survey gives indirect information about the thickness of the alluvium in the south of the city. The increase of ground noise at a frequency of 5 Hz would suggest that the thickness of the alluvium was at least one quarter of the wavelength appropriate for this period. If a shear velocity of 1 km/s is assumed in the saturated alluvium, then its thickness would be at least 50 m. On the other hand, the fact that waves of frequency 0.8 Hz were not greatly amplified would suggest a thickness less than about 300 m. These suggested limits for the thickness of alluvium could be verified either by drilling or geophysical methods.

The dominant frequency of the ground noise tended to be lower in the areas of high amplification. At sites of greatest noise level at the head of the harbour, the frequency dropped to 3 to 4 Hz compared with the more usual values of 5 to 8 Hz. This drop in resonant frequency may be explained by a thickening of the unconsolidated material, by its being even less consolidated than its surrounding material, or by a combination of both.

CONCLUSION

This earthquake is the largest known to have occurred in eastern Otago, and is the most damaging that Dunedin has experienced; the cost of damage is greater than for any other earthquake in New Zealand since the 1968 Inangahua earthquake of magnitude 7.1. Shallow earthquakes of the magnitude of the Dunedin shock are not uncommon in New Zealand, about 10 being recorded in a typical year. They are also widespread, as shown by their occurrence not only in areas of more frequent earthquake activity, but also in less active areas, such as Northland in 1963, Te Aroha in 1972, north Taranaki in 1962, Christchurch in 1968, and close to Dunedin in 1974.

Earthquakes of the size of the Dunedin earthquake can cause substantial damage when close to centres of population, and the occurrence of this earthquake strengthens the contention that Dunedin, with other places in the less active parts of the country, must be prepared to be shaken from time to time by close earthquakes.

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TABLE 1.

STATION READINGS OF DUNEDIN EARTHQUAKE, 9 APRIL, 1974

Station	Code	Distance km	Azimuth deg.	Phase	Arrival Time h. m. s. (U.T.)	First Motion	Residual s
Oamaru	OMZ	105	17	P*	07 50 03.1	U	-0.2
Roxburgh	ROX	108	300	P*	07 50 02.8	D	-1.0
				S*	17.0		0.0
Waipapa Pt	WPZ	150	238	Pn	07 50 09.9	U	0.0
				P*	11.0		0.8
				S*	27.0		-1.2
Mt John	MJZ	220	359	Pn	07 50 18.0	U	-0.7
				P*	22.8		1.7
				S*	47		-0.3
Monowai	MNW	226	274	Pn	07 50 20.1	D	0.7
				Sn	44		-0.2
Milford Sound	MSZ	250	304	Pn	07 50 23.0	D	0.7
				P*	26.0		0.4
Gebbies Pass	GPZ	304	34	Pn	07 50 29		0.1
				S*	51 09		-0.8

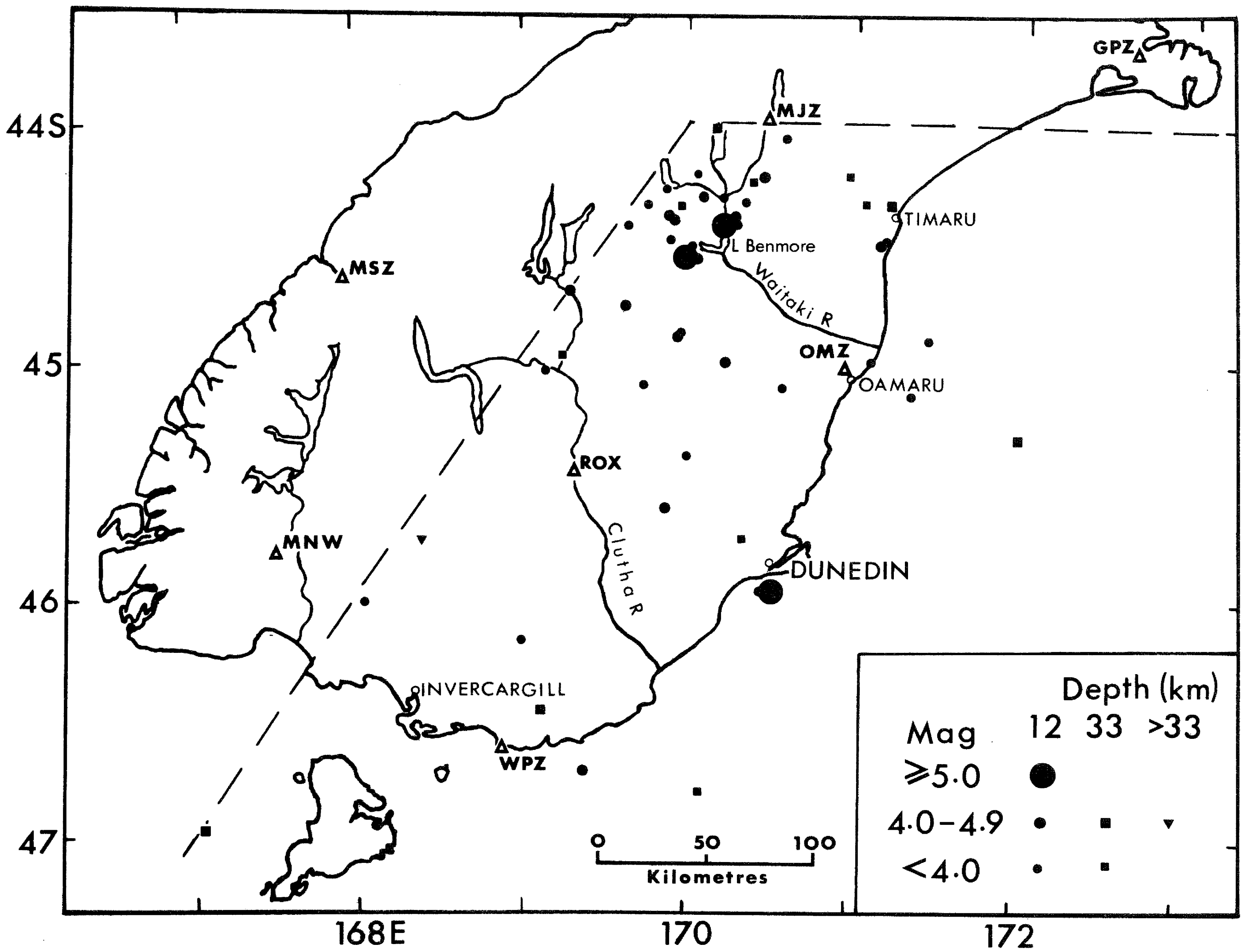

FIGURE 1: INSTRUMENTALLY LOCATED EARTHQUAKES IN SOUTH CANTERBURY AND EAST OTAGO FROM 1964 to APRIL 1974. SEISMOGRAPH STATIONS ARE SHOWN BY OPEN TRIANGLES, AND IDENTIFIED BY THEIR STANDARD THREE-LETTER CODES.

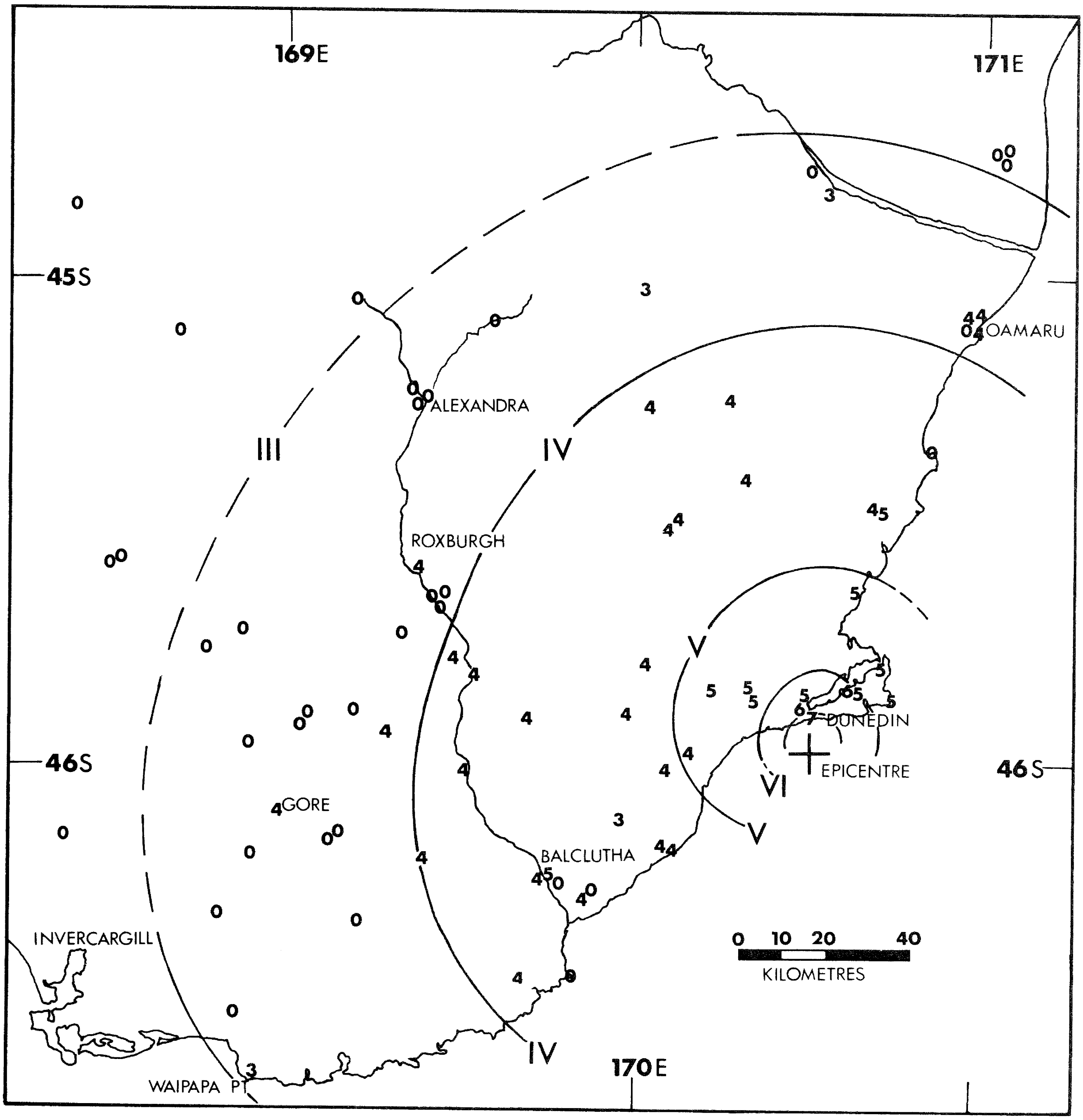

FIGURE 2: FELT OBSERVATIONS AND ISOSEISMALS FOR DUNEDIN EARTHQUAKE. INTENSITIES ARE ON MODIFIED MERCALLI SCALE. 0 INDICATES A DEFINITE REPORT FROM A PARTICULAR LOCALITY THAT THE EARTHQUAKE HAS NOT BEEN FELT THERE.

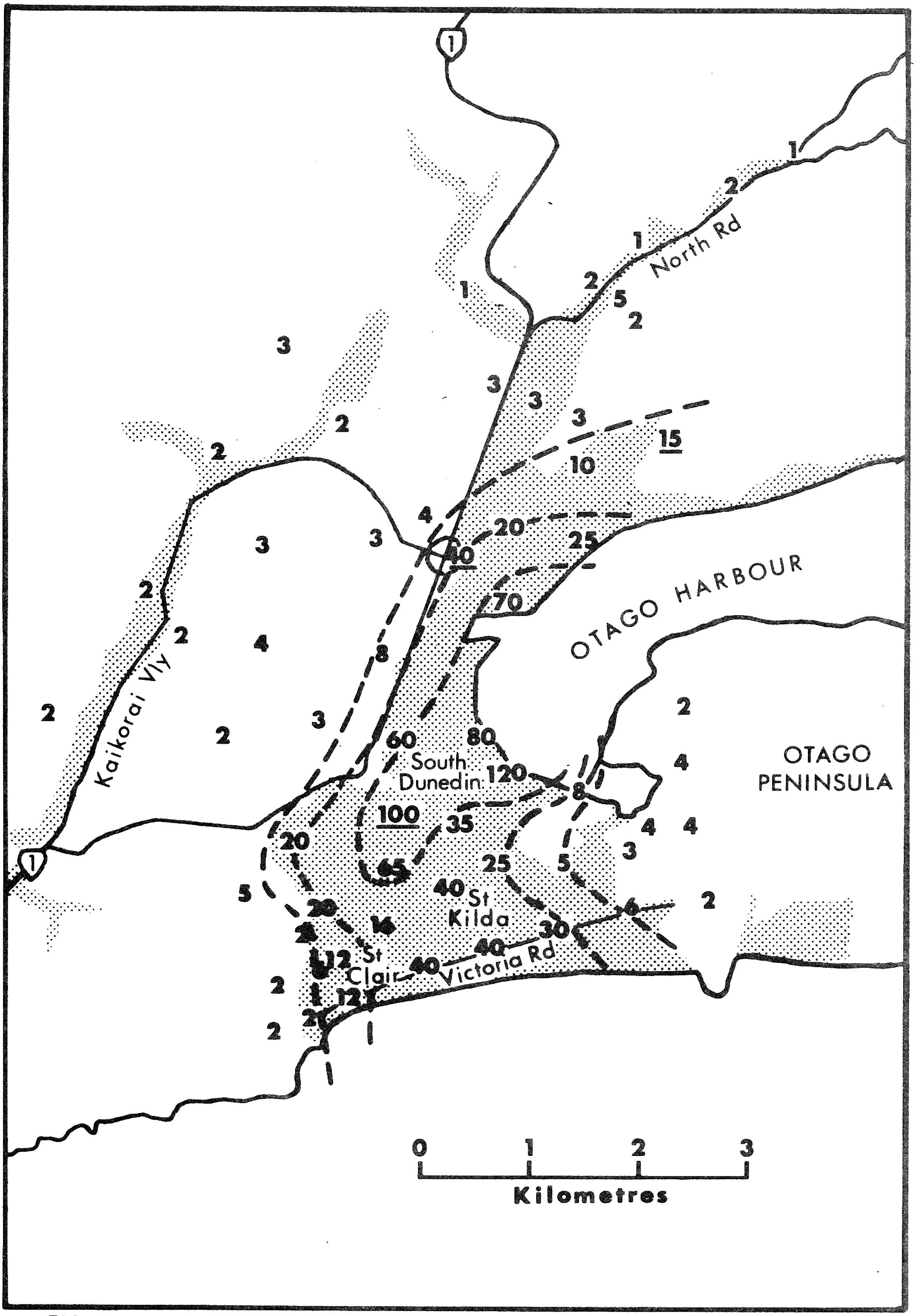

FIGURE 3: RELATIVE MICROSEISMIC NOISE LEVELS IN DUNEDIN CITY FOR THE FREQUENCY RANGE 5 TO 8 Hz. UNDERLINED VALUES ARE UNCERTAIN BECAUSE OF INTERFERENCE FROM LOCAL NOISE SOURCES. CONTOURS ARE DRAWN AT RELATIVE NOISE LEVELS 6, 20 AND 60. AREAS OF ALLUVIUM AND FILL ARE SHOWN SHADED.