DEPARTMENT OF NATIONAL RESOURCES
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

BULLETIN 164

Seismicity and Earthquake Risk in Eastern Australia

A Symposium held in Canberra on 5 December 1973

EDITED BY

D. DENHAM

AUSTRALIAN GOVERNMENT PUBLISHING SERVICE
CANBERRA, 1976

DEPARTMENT OF NATIONAL RESOURCES
MINISTER: THE RT HON. J. D. ANTHONY, M.P.
SECRETARY: J. SCULLY

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS
DIRECTOR: L. C. NOAKES
ASSISTANT DIRECTOR, GEOPHYSICAL BRANCH: N. G. CHAMBERLAIN

Published for the Bureau of Mineral Resources, Geology and Geophysics
by the Australian Government Publishing Service

ISBN 0 642 02011 6

MANUSCRIPT RECEIVED: AUGUST 1974
ISSUED: SEPTEMBER 1976

Printed by Graphic Services Pty Ltd, 516-518 Grand Junction Road, Northfield, SA 5085

Foreword

This Bulletin contains ten of the papers, and the abstracts of four others, given at a symposium on the seismicity and earthquake risk in eastern Australia, which was held at the Bureau of Mineral Resources in Canberra on 5 December 1973.

There were two main themes for the meeting: (1) the tectonics of the eastern part of the Australian Continent, and (2) economic aspects of earthquakes, e.g. earthquake damage, earthquake insurance, and increased building costs caused by earthquake risk factors.

Earthquake activity in continental regions is one of the major problems facing seismologists and earthquake engineers today. The theory of Plate Tectonics explains about 95 percent of the world's earthquakes—namely those associated with the boundaries of the major plates—but the other 5 percent, which take place in supposedly stable continental regions, are not fully understood. They appear to result from predominantly horizontal stresses in the Earth's crust, but their haphazard distribution and comparative infrequency make statistical studies difficult.

Except for a few localized zones, such as the one near Dalton and Gunning, eastern Australia is one of those areas where the earthquake pattern is diffuse. Sporadic earthquakes include those at Robertson in 1961 and Picton in 1973. The Picton earthquake was one of the main topics at the symposium. It was the most damaging Australian shock since that at Meckering, Western Australia, in 1968, and four papers were devoted to it; this Bulletin will serve as a useful reference to its effects.

DAVID DENHAM

Page iv is blank.

CONTENTS

THE STRUCTURE OF THE CRUST AND UPPER MANTLE BENEATH SOUTHEASTERN AUSTRALIA

by J. R. CLEARY

Research School of Earth Sciences
Australian National University
Canberra

SUMMARY

Seismic refraction data for the Palaeozoic region of southeastern Australia are consistent with a crustal model in which the seismic velocities are as follows:

P_1 : 6.00 km/s S_1 : 3.62 km/s
P_2 : 6.5 km/s
P_n : 7.86 km/s

The crustal thickness for the model varies from 25 km at the continental margin to 42 km beneath the Snowy Mountains. There is evidence for the existence of a low-velocity channel in the upper mantle beneath the region.

The P velocities and crustal thicknesses are very similar to those in the northern end of the Palaeozoic belt, in the vicinity of Cape York Peninsula. On the other hand, P_1 and P_n velocities are significantly higher in the Australian shield than in eastern Australia.

INTRODUCTION

The division between the Palaeozoic region of eastern Australia and the Precambrian shield, represented as the eastern limit of exposed Precambrian basement, may be approximated very roughly by a line extending from Cape York Peninsula to the southeastern corner of South Australia (cf. Howard & Sass, 1964). The first large-scale seismic refraction experiments on the continent, in 1956-1957, failed to establish the presence of significant differences between these two regions. Differences have emerged from experiments conducted since that time, but the evidence tends to be confused by the scatter in the published results. The purpose here is to justify the structural model recently proposed for southeastern Australia (Cleary, 1974), by a reconciliation of the various data and by reference to other geophysical information.

THE DATA

For convenience of later discussion, the experiments in southeastern Australia, and the associated results, will be enumerated and summarized. The approximate directions of the traverses are shown in Figure 1.

(1) Doyle, Everingham & Hogan (1959) analysed data from three large explosions at Eaglehawk quarry in the Snowy Mountains, N.S.W., and derived P_1, S_1, and P_n velocities of 6.04 ± 0.04, 3.62 ± 0.03, and 8.03 ± 0.20 km/s. P_n was observed at four stations, two on each side of the shot-point. Treating the data from the two directions independently, they found P_n velocities cf 8.3 km/s to the northeast and 7.96 km/s to the southwest. S_n arrivals were weak or absent. Calculations based on a single-layer model gave a crustal thickness of 37 ± 6 km.

By comparison, Bolt, Doyle, & Sutton (1958) calculated P_1, S_1, and P_n velocities of 6.03 ± 0.09, 3.55 ± 0.04, and 8.21 ± 0.005 km/s and crustal thicknesses of 32 km (from P) and 39 km (from S) within the shield, using observations along a line west of the 1956 atomic explosions at Maralinga in South Australia.

(2) Cleary & Doyle (1962) accurately located an earthquake of magnitude 5.5 near Robertson, about 100 km southwest of Sydney, from P_1 observations at near stations. P_n and S_n

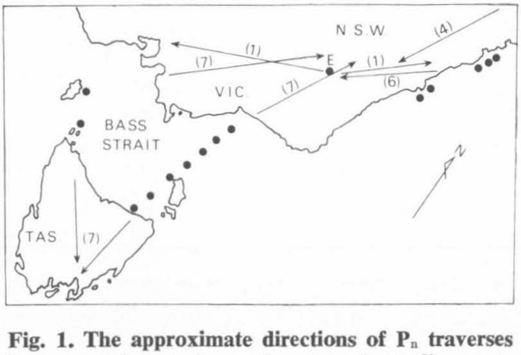


Fig. 1. The approximate directions of P_n traverses from experiments in southeastern Australia, numbered according to the text. Dots represent the shot positions for: experiment (1) labelled E; experiment (6) off the central coast of N.S.W.; and experiment (7) in Bass Strait.

velocities of 8.16 ± 0.03 and 4.7 ± 0.2 km/s were then derived from eight P_n readings (at distances from 2° to 15°) and five S_n readings (5.5° to 10°). The S_n arrivals were weak and emergent.

(3) Bolt (1962) used timed quarry blasts at Prospect, in the central region of the Sydney Basin, to obtain P_1 and S_1 velocities of 5.88 ± 0.14 and 3.51 ± 0.02 km/s.

(4) Cleary (1962) measured times from blasts at several quarries in southeastern Australia, and calculated a P_1 velocity of 6.04 ± 0.05 km/s. Data from two quarries to the north of the region gave a P_n velocity of 7.84 ± 0.25 km/s. Travel-time data from earthquakes in the Gunning area strongly indicated the presence of a P_2 phase with a velocity of about 6.5 km/s.

(5) Sutton & White (1966) analysed P arrivals from eleven Australian earthquakes. The P_n times out to 18.5° were in general consistent with the model of Bolt (1958), but there were indications of a lower P_n velocity in southeastern Australia. They interpreted some late readings and second arrivals at eastern stations in terms of an abrupt decrease in velocity at a depth of about 60 km.

(6) Doyle, Underwood & Polak (1966) obtained P_2 and P_n velocities of 6.67 and 7.58 ± 0.17 km/s from signals recorded southwest of a series of timed depth charges off the central coast of New South Wales. Using these results as an approximate reversal of those of (1) northeast of Eaglehawk, they inferred P_2 and P_n velocities of 6.52 and 7.86 km/s in that region. From a combination of the data in (1) northeast and southwest of Eaglehawk, they suggested that the P_n velocity increased to 8.02 km/s beneath the Snowy Mountains. The Conrad and Mohorovicic discontinuities in their model dip at approximately 2° and 4° respectively to the southwest, with a crustal thickness of 25 km at the continental margin and 42 km beneath the Snowy Mountains.

(7) Underwood (1969) examined data from the BUMP experiment, which consisted of ten 1-ton charges fired along two traverses in Bass Strait and recorded by permanent and temporary stations in Victoria, New South Wales, and Tasmania. Least-squares analyses of data from the eastern line (7 shots) gave P_1, P_2, and P_n velocities of 6.10, 6.63, and 7.88 km/s on the mainland and 6.01, 7.12, and 7.83 km/s across Tasmania. Data from stations northeast of the western line gave a P_n velocity of 7.96 km/s. Underwood noted that the latter approximately reversed the southwest data of (1), and he combined the two to obtain a P_n velocity of 7.86 km/s. In his two-layer crustal model for the region, the Mohorovicic discontinuity dips at about 1° southwest, with crustal thicknesses of 41 km and 25 km beneath the Snowy Mountains and Bass Strait respectively.

DISCUSSION

A least-squares analysis of the combined P_1 data from (1) and (4) gives a P_1 velocity of 6.00 ± 0.03 km/s, from 24 observations. Bolt's data (3) from the Sydney Basin area are suspect, because of the uncertain effects of the basin sediments: elimination of the Prospect-Riverview time (probably corresponding to a direct wave through the sediments) brings the derived velocity into closer agreement with the above (cf. Cleary, 1962). The BUMP experiment (7) was designed for the determination of upper mantle structure, and the P_1 and P_2 observations were too few for the results to be considered reliable.

The S_1 velocity of 3.62 km/s from (1) is the only reliable value available for the region.

The P_2 velocity is not very well determined, but both (1) and (4) suggest a value of about 6.5 km/s.

The P_n data of (1), (4), (6) and (7) are generally consistent with a model in which the crustal thickness varies from 42 km beneath the Snowy Mountains to about 25 km at the continental margin, with a velocity of 7.86 km/s below the Mohorovicic discontinuity. It is interesting to examine the data of (2) in this light. Beyond a distance of about 8° the data points deviate from the general trend of the observations, and there is evidence from experiments in other regions (see, for example, Green & Hales, 1968, and Simpson, 1973) that a discontinuity in the travel-time curve occurs at about this distance. The remaining observations can be fitted to a straight line corresponding to a P_n velocity of 8.0 km/s. However, the two readings at shorter distances are from stations in the Snowy Mountains, which according to the model are down-dip from the earthquake focus. These two readings can be fitted by the down-dip velocity of 7.6 km/s given in (6), and the remaining two observations are then consistent with a velocity of 7.86 km/s. The distance range of the 'S_n' observations in (2) is also such that the validity of their identification is questionable. The fitting of P_n data to a straight line out to 18.5° in (5) may be criticised on similar grounds.

The small amplitudes of S_n arrivals in the region indicate a low S-velocity gradient at the top of the upper mantle. A recent study of surface-wave dispersion across eastern Australia by Goncz (1974) has confirmed the existence of an S low-velocity channel in the upper mantle. The positive P travel-time anomalies found by Cleary (1967) for stations in southeastern Australia suggest the associated presence of a P low-velocity channel in the upper mantle, giving some support to the interpretation of later P arrivals in (5).

On the basis of the available data, it seems unnecessary to postulate variations in the velocities of the crust and uppermost mantle in southeastern Australia. Indeed, the P_1, P_2, and P_n velocities of 5.94, 6.62, and 7.84 km/s obtained from the CRUMP experiment by Finlayson (1968) for the Palaeozoic region of Cape York Peninsula in northern Queensland suggest that these velocities are stable throughout the Palaeozoic belt. (The P_2 and P_n velocities found by Finlayson on the western side of the Palaeozoic/Precambrian boundary, in the same area, were higher by a slight but possibly significant amount.) The crustal thicknesses found in that experiment are also similar to those of southeastern Australia, ranging from 25 km at the edge of the continent to 45 km in central Cape York Peninsula and the region northwest of Charters Towers.

In contrast to this apparent uniformity, the P_1 and P_n velocities in the shield, although subject to some regional variation, are significantly higher than those in eastern Australia (cf. Cleary, 1974). Differences between the shear velocity structures in the upper mantle beneath the two regions have also been found from surface-wave studies by Goncz (1974). The variation of structure across the Palaeozoic/Precambrian boundary remains to be investigated in detail, but a study of P station anomalies across the boundary by Cleary, Simpson & Muirhead (1972) suggests that the change is fairly gradual.

REFERENCES

BOLT, B. A., 1962—A seismic experiment using quarry blasts near Sydney. *Aust. J. Phys.*, 15, pp. 293-300.

BOLT, B. A., DOYLE, H. A., & SUTTON, D. J., 1958—Seismic observations from the 1956 atomic explosions in Australia. *Geophys. J. R. Astr. Soc.*, 1, pp. 135-45.

CLEARY, J. R., 1962—Near-earthquake studies in southeastern Australia. *Aust. Nat. Univ., Ph.D. Thesis* (unpublished).

CLEARY, J. R., 1967—P times to Australian stations from nuclear explosions. *Bull seis. Soc. Am.*, 57, pp. 773-781

CLEARY, J. R., 1974—Australian crustal structure. *Tectonophys.*, 20, pp. 241-248.

CLEARY, J. R., & DOYLE, H. A., 1962—Application of a seismograph network and electronic computer in near earthquake studies. *Bull. seis. Soc. Am.*, 52, pp. 673-682.

CLEARY, J. R., SIMPSON, D. W., & MUIRHEAD, J. J., 1972—Variations in Australian upper mantle structure, from observations of the Cannikin explosions. *Nature*, 236, pp. 111-112.

DOYLE, H. A., EVERINGHAM, I. B., & HOGAN, T. K., 1959—Seismic recordings of large explosions in southeastern Australia. *Aust. J. Phys.*, 12, pp. 222-230.

DOYLE, H. A., UNDERWOOD, R., & POLAK, E. J., 1966—Seismic velocities from explosions off the central coast of New South Wales. *J. Geol. Soc. Aust.*, 13, pp. 355-372.

FINLAYSON, D. M., 1968—First arrival data from the Carpentaria Region Upper Mantle Project (CRUMP). *J. Geol. Soc. Aust.*, 15, pp. 33-50.

GONCZ, J. H., 1974—Surface wave studies of the Australian upper mantle. *Aust. Nat. Univ., Ph.D. Thesis* (unpublished).

GREEN, R. W. E., & HALES, A. L., 1968—The travel times of P-waves to 30° in the central United States and upper-mantle structure. *Bull. seis. Soc. Am.*, 58, pp. 267-289.

HOWARD, L. E., & SASS, J. H., 1964—Terrestrial heat flow in Australia. *J. geophys. Res.*, 69, pp. 1617-1626.

SIMPSON, D. W., 1973—P wave velocity structure of the upper mantle in the Australian region. *Aust. Nat. Univ., Ph.D. Thesis* (unpublished).

SUTTON, D. J., & WHITE, R. E., 1966—A study of P travel-times from some Australian earthquakes. *Aust. J. Phys.*, 19, pp. 157-166.

UNDERWOOD, R., 1969—A seismic refraction study of the crust and upper mantle in the vicinity of Bass Strait. *Aust. J. Phys.*, 22, pp. 573-587.

Page 4 is blank.

SEISMIC RISK IN NEW SOUTH WALES

by LAWRENCE DRAKE

Macquarie University

SUMMARY

In the last 60 years, three regions of New South Wales have each experienced two earthquakes of Richter magnitude 5.5 or greater: the south central part, the region around Gunning, and the region at the southwestern edge of the Sydney Basin. In each of these three regions the return periods for earthquakes of magnitude 5.5 and 6.5 are approximately 30 years and 300 years, respectively. Sydney itself and the South Coast of New South Wales are much less seismic than these three regions. Ground displacement in Sydney from an earthquake of magnitude 5.5 near the southwestern edge of the Sydney Basin is approximately 500 micrometres at a period of 1 second. The earthquakes of 18 December 1925, 18 May 1959, and 9 March 1973 are of interest in view of the construction of dams in New South Wales.

INTRODUCTION

Seismographs at Riverview College Observatory have been recording ground motion in the Sydney region since 1909. From felt reports of earthquakes in New South Wales from 1788 until 1909, Drake (1974) judged that the seismicity of New South Wales in that period was similar to what it has been since 1909. He included in his paper a list of earthquakes of Richter magnitude 4.0 or greater that have occurred in New South Wales since 1909. The Richter magnitudes of nearby earthquakes are based on amplitudes measured on standard Wood-Anderson seismographs. In this present paper, the larger of these earthquakes since 1909 are tabulated again. Then, in view of the enormous amount of building currently going on in and around Sydney, an illustration of ground motion in Sydney resulting from one of these earthquakes is given. Finally, an assessment is made of seismic risk in New South Wales.

TABLE 1. EARTHQUAKES IN NEW SOUTH WALES, 1909-1973

Date	*Time* (G.C.T.) h m s	*Epicentre* °S	°E	*Mag.* ML	*Region*
1919 Aug. 15	10 21 21	33.5	150.7	4.6	Kurrajong, Sydney
1921 May 30	14 51 59	35.0	145.0	5.5	Hay, Tocumwal
1925 Dec. 18	10 47 10	33.0	152.0	5.2	Sydney, Wingham
1930 Oct. 27	02 03 51	34.5	149.0	5.0	Boorowa
1932 May 22	10 46 28	32.3	148.3	4.5	Narromine, Dubbo
1933 Jan. 11	20 10 51	34.8	149.5	4.8	Gunning
1934 Jan. 30	20 27 54	34.8	149.5	4.7	Gunning
1934 Nov. 10	23 47 40	34.9	150.0	4.8	Goulburn, Canberra
1934 Nov. 18	21 58 41	34.5	149.5	5.6	Gunning
1934 Nov. 21	06 32 06	34.5	149.2	4.8	Crookwell
1938 Mar. 24	20 03 33	35.5	146.0	5.5	Berrigan
1938 June 27	22 38 47	30.4	151.8	4.7	Armidale, Guyra
1947 May 5	04 43 48	35.0	149.5	4.5	Goulburn, Canberra
1947 Sep. 25	10 56 27	34.0	148.6	4.6	Cowra, Orange
1949 Mar. 10	22 30 33	34.8	149.2	5.5	Dalton, Gunning
1952 Sep. 7	05 41 14	34.8	149.3	4.7	Gunning, Yass
1952 Nov. 19	01 59 16	34.8	149.3	4.9	Gunning, Yass
1952 Nov. 22	07 57 20	34.8	149.3	4.6	Gunning, Yass
1959 May 18	06 12 59	36.2	148.7	5.3	Berridale, Cooma
1959 Oct. 12	21 23 40	31.0	151.5	4.7	Uralla, Tamworth
1961 May 16	06 52 54	31.0	147.5	4.8	Coonamble
1961 May 21	21 40 03	34.6	150.5	5.6	Bowral, Robertson
1968 Mar. 8	11 48 46	34.2	149.1	4.6	Cowra, Orange
1968 Dec. 31	16 08 33	31.0	149.3	5.0	Coonabarabran
1973 Mar. 9	19 09 15	34.2	150.3	5.5	Burragorang Valley

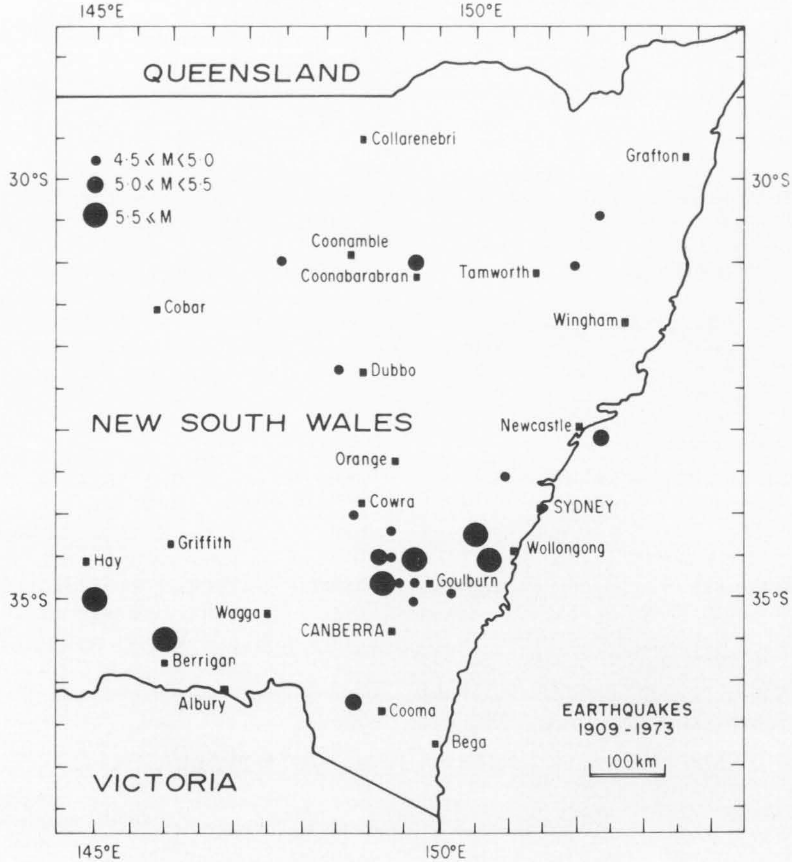


Fig. 1. Earthquakes in New South Wales, 1909-1973.

THE SEISMICITY OF NEW SOUTH WALES

Table 1 shows the locations, origin times, and magnitudes of earthquakes of magnitude 4.5 or greater in New South Wales recorded at Riverview since 1909. These earthquakes are plotted in Figure 1. The earthquake of 15 August 1919 has been described by Cotton (1921). The earthquakes of 30 May 1921 and 24 March 1938 were earthquakes of magnitude 5.5 in the south central part of New South Wales. The earthquake of 18 December 1925 was felt in Sydney and Wingham, and is of interest in view of dam construction by the Hunter River Water Board. The earthquakes of 18 November 1934 and 10 March 1949 were earthquakes of magnitude 5.5 or greater in the region around Gunning. The seismicity of this region has been discussed by Cleary (1967). The earthquake of 18 May 1959 occurred very close to the large Eucumbene and Jindabyne reservoirs in the Snowy Mountains. Cleary, Doyle, & Moye (1964) noted that the earthquake occurred before the filling of Lake Eucumbene had proceeded very far and hence was unlikely to have been caused by the weight of water in the lake. The epicentre and origin time of the earthquake of 21 May 1961 are those of Cleary & Doyle (1962). This earthquake, and that of 9 March 1973, were of magnitude 5.5 or greater, near the southwestern edge of the Sydney Basin. The seismicity of the Sydney Basin has been considered by Doyle, Cleary, & Gray (1968a). The earthquake of 9 March 1973 occurred under the southern end of the reservoir behind Warragamba Dam, and may have been caused partly by the weight of the water in this reservoir. However, recent work has shown that the axis of compressive stress for earthquakes away from lithospheric plate boundaries is usually horizontal (Sykes & Sbar, 1973). The axis of compressive stress for this earthquake was northeast-southwest (Gray, 1973; Fitch, 1973).

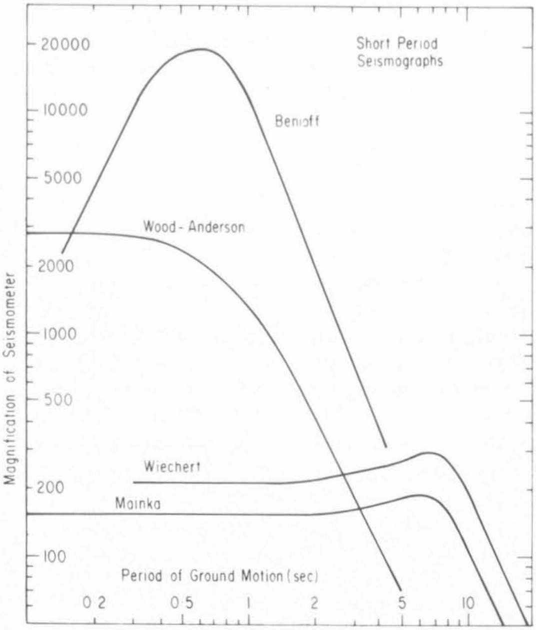


Fig. 2. Response of seismographs at Riverview College Observatory compared with that of a Wood-Anderson seismograph.

Horizontal stress is not likely to be caused by the weight of water.

Figure 2 shows the short-period response of the seismographs at Riverview College Observatory compared with that of a Wood-Anderson seismograph. Drake (1974) has made three observations concerning the calculation of Richter magnitudes from Riverview seismograms. First, as far as possible, attention has to be paid to waves on the seismograms of periods less than 1 sec, because the Wood-Anderson seismograph has a higher magnification at these short periods. Second, there is less attenuation of local earthquake motion in New South Wales than in California, and Richter magnitudes calculated for New South Wales using Richter's table (Richter, 1957) have to be reduced. Third, Wood-Anderson seismographs often have a static magnification nearer 2000 than 2800, which is the value shown in Figure 2. Again, this leads to slightly high values of magnitudes calculated for New South Wales. The second and third of these effects can easily be corrected. It is perhaps worth noticing that the magnitudes tabulated in Table 1 are estimated primarily from ground amplitudes at only one station, Riverview. They may be in error by about one-third of a unit of magnitude on account of the radiation patterns of the earthquakes.

It is clear from Figure 2 that the Benioff seismographs installed at Riverview College Observatory in 1962 are much more sensitive to waves of period approximately 0.8 sec than are the Wiechert and Mainka seismographs. Hence, prior to 1962, earthquakes of magnitude less than 5.0 occurring more than 400 km from Sydney, especially in the northwestern and western parts of New South Wales, may have gone unrecorded. Table 1 and Figure 1 are probaby incomplete, especially for the northwestern and western parts of New South Wales.

Figure 3 is a sketch of the north-south ground motion recorded by the Mainka seismograph at Riverview College Observatory resulting from the earthquake of 21 May 1961. The S-P time is 12 sec, which corresponds to a distance of the focus of the earthquake from Riverview of approximately 100 km. The large S or Love wave motion on the sketch corresponds to a ground motion of approximately 500 micrometres, apparently at a period of a little over 1 sec. This corresponds to a ground velocity of approximately 3 mm/sec. It is of interest to note that an earthquake of magnitude 8 in New Zealand or the Loyalty Islands,

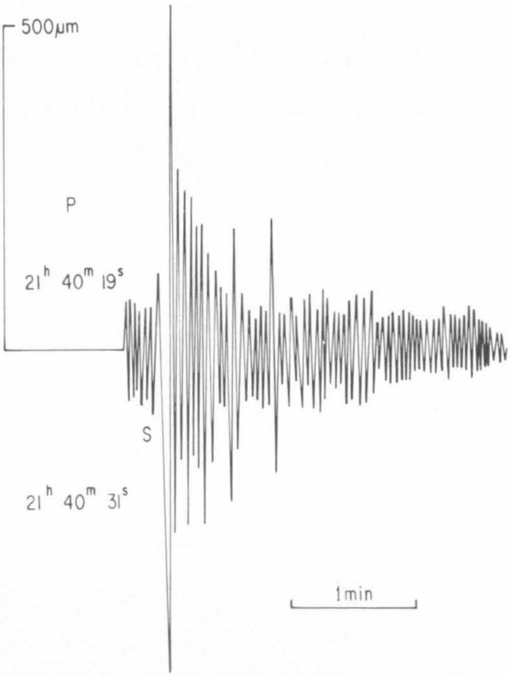


Fig. 3. Sketch of north-south ground motion recorded by Mainka seismograph at Riverview College Observatory, 21 May 1961. South is up.

20 degrees east or northeast of Sydney, would cause a ground displacement in Sydney of 1 cm at a period of 20 sec. This also corresponds to a ground velocity of approximately 3 mm/sec.

SEISMIC RISK IN NEW SOUTH WALES

Howell (1973) has noted recently that the seismically active region of eastern United States and Canada appears to have migrated. Thus, there was an earthquake of intensity X (Modified Mercalli scale) in Quebec in 1663, there were three earthquakes of intensity XII in southeastern Missouri in 1811 and 1812, there was an earthquake of intensity XI in South Carolina in 1886, and there was an earthquake of intensity X near Grand Banks in 1929. Howell argues that the history of this region is too short for all parts to have experienced typical seismicity. However, he has determined Seismic Hazard Indices for each of 10 regions of eastern United States and Canada from past seismicity.

New South Wales resembles eastern United States and Canada in that it is not near the boundary of a lithospheric plate. Its seismicity is, and can be expected to remain, low. Although 200 years is too short a time for New South Wales to have experienced typical seismicity, the simplest available means of estimating seismic risk is past seismicity. There are three principal seismic regions in New South Wales, each of which has experienced two earthquakes of magnitude 5.5 or greater in the last 60 years. These regions are the south central part of New South Wales, the region around Gunning, and the region of the southwestern edge of the Sydney Basin (Fig. 1). The return period for earthquakes of magnitude 5.5 in these regions can be taken to be approximately 30 years. Sydney itself and the region of the South Coast appear to be much less seismic (Doyle, Cleary, & Gray, 1968). The only available means of estimating the return time of larger earthquakes in New South Wales is to use the approximate frequency/magnitude relation suggested by Doyle, Everingham & Sutton (1968). The return period of an earthquake of magnitude one unit larger than a particular magnitude is approximately ten times the return period of an earthquake of that magnitude. Thus, for the three principal seismic regions of New South Wales, the return period of an earthquake of magnitude 6.5 can be taken to be very roughly 300 years. This time may appear short for regions away from the boundary of a lithospheric plate. Perhaps it should be lengthened. However, it is worth recalling that Quebec, southeastern Missouri, South Carolina, and Grand Banks are also regions away from the boundary of a lithospheric plate. Though it is unlikely, it is not impossible that earthquakes of magnitude 6.5 or 7 could occur in New South Wales.

It is worth noting again that, even in less seismic regions, allowance must always be made for possibly active faults, ground with poor bearing capacity, and potential landslide areas. Thus, at Picton, within the Sydney Basin, the Nepean Fault dips westward to the more seismically active region at the southwestern edge of the Sydney Basin. Alluvial ground near Picton has poor bearing capacity, and some of the slopes around Picton are potential landslide areas (Drake, 1974).

REFERENCES

CLEARY, J. R., 1967—The seismicity of the Gunning and surrounding areas, 1958-1961. *J. Geol. Soc. Aust.*, 14, 23-29.

CLEARY, J. R., & DOYLE, H. A., 1962—Application of a seismograph network and electronic computer in near earthquake studies. *Bull seism. Soc. Am.*, 52, 673-682.

CLEARY, J. R., DOYLE, H. A., & MOYE, D. G., 1964—Seismic activity in the Snowy Mountains region and its relationship to geological structures. *J. Geol. Soc. Aust.*, 11, 89-106.

COTTON, L. A., 1921—The Kurrajong earthquake of August 15, 1919. *J. Proc. R. Soc. N.S.W.*, 55, 83-104.

DOYLE, H. A., CLEARY, J. R., & GRAY, N. M., 1968—The seismicity of the Sydney Basin. *J. Geol. Soc. Aust.*, 15, 175-181.

DOYLE, H. A., EVERINGHAM, I. B., & SUTTON, D. J., 1968—Seismicity of the Australian Continent. *J. Geol. Soc. Aust.*, 15, 295-312.

DRAKE, L. A., 1974—The seismicity of New South Wales. *J. Proc. R. Soc. N.S.W.*, 107, 35-40.

FITCH, T. J., 1973—The Picton earthquake: a seismic view of the source. *This volume.*

GRAY, N. M., 1973—Seismicity and earthquake risk in eastern Australia: a geological appreciation of the seismicity of the southern portion of the Sydney Basin. *This volume.*

HOWELL, B. F., 1973—Earthquake hazard in the eastern United States. *Earth and Mineral Sciences, Pennsylvania State College,* 42, 41-45.

RICHTER, C. F., 1957—ELEMENTARY SEISMOLOGY. *San Francisco, Freeman.*

SYKES, L. R., & SBAR, M. L., 1973—Intraplate earthquakes, lithospheric stresses and the driving mechanism of plate tectonics. *Nature,* 245, 298-302.

GEOLOGICAL APPRECIATION OF THE SEISMICITY OF THE SOUTHERN PORTION OF THE SYDNEY BASIN

by N. M. GRAY

Metropolitan Water Sewerage and
Drainage Board, N.S.W.

SUMMARY

A network of Benioff seismic stations operated by the Metropolitan Water Sewerage and Drainage Board since 1958 monitors the seismicity of the Sydney area to determine possible seismic effects of the storages of large dams.

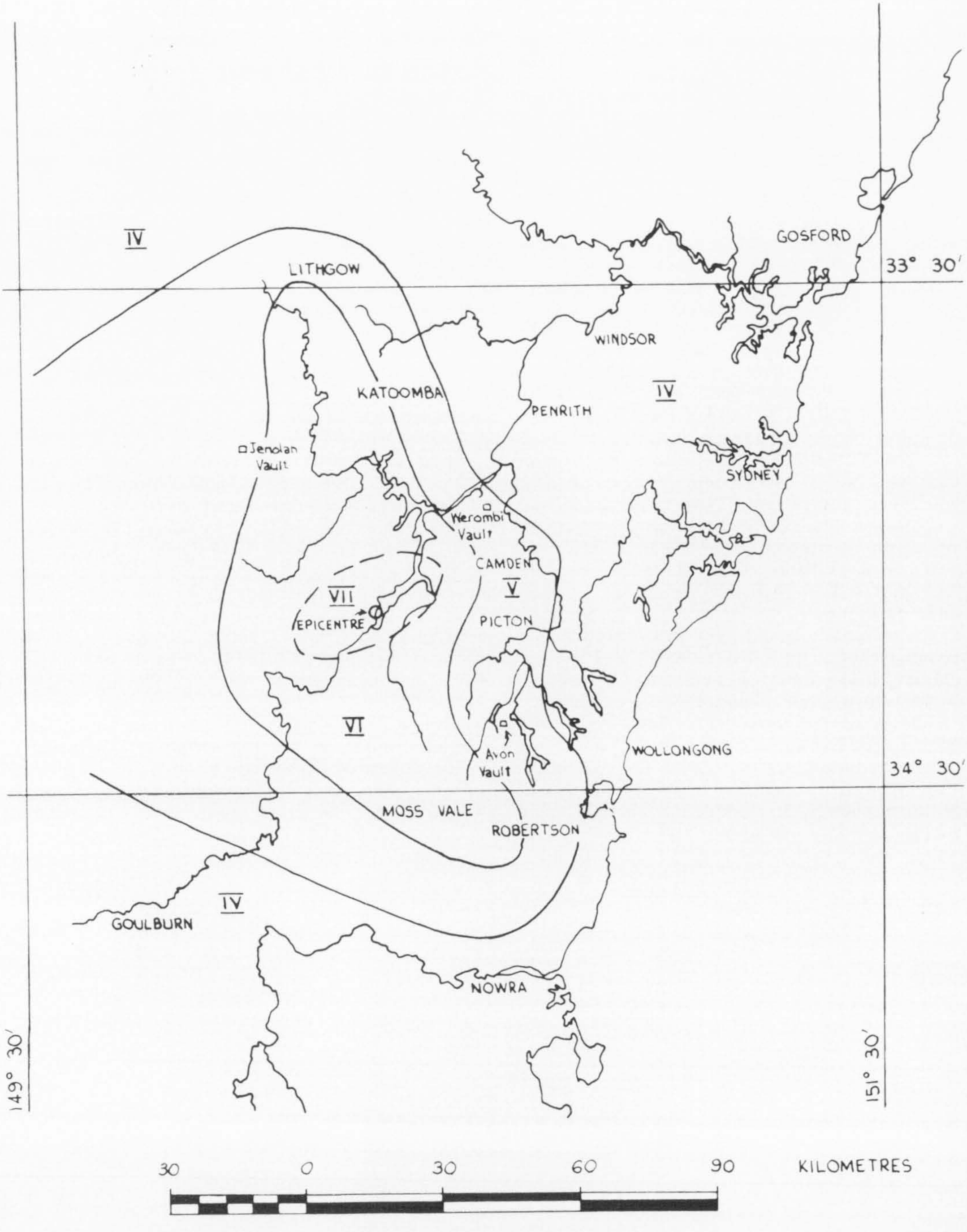
During this period, two large earthquakes of magnitude 5.5 have occurred: one at Robertson in 1961; and one near the southern end of stored waters of Warragamba Dam in Burragorang Valley, known as the Picton Earthquake or Burragorang Earthquake. The preferred mechanism for the Robertson Earthquake is for movement along a high-angle reverse fault striking 030° with the west side moving upwards and to the south. The preferred mechanism for the Picton Earthquake is a strike-slip fault striking 006° with the east side moving south. Both earthquakes can be explained by a horizontal north-south stress field. This direction of stress is roughly at right angles to that which formed the Sydney Basin and its structures. The present movements may be along these old basement structures but in a different direction to the original movement.

The Picton Earthquake caused no damage to any of the Board's structures. The only recorded temporary effects were some increases in drainage flows at Cordeaux, Avon, and Nepean Dams and possibly in the Nepean Tunnel. An isoseismal map of the earthquake is shown overleaf.

At the time of the Robertson Earthquake, the return period of an M5.5 earthquake in the Sydney Basin region would have been at least 150 years, but with the Picton Earthquake only 12 years later, on a probably contemporaneous structure, the return period could be much less. However, large earthquakes have been too few for an accurate assessment of return periods to be made. For both these earthquakes, the acceleration in Sydney was assessed at between 0.006 and 0.01g; areas closer to the epicentres would have experienced higher acceleration. New works under construction in the Shoalhaven Catchment Area have been designed for an acceleration of 0.1g. The Board's older dams did not incorporate aseismic design specificially though the actual design was such that an aseismic component was not necessary.

Most of the earthquakes that have been located in the Sydney Basin area seem to occur in specific zones. The zones cannot be delineated with complete confidence, but they appear to follow major geological lineaments that define the basement structural pattern of the Sydney Basin.

The Board, concerned that deformation of the Sydney Basin may conceivably endanger its engineering structures, is considering precise levelling surveys to monitor strain release across the seismic zones.



Isoseismal map of the Picton earthquake of 9 March 1973.

THE PICTON EARTHQUAKE OF 9 MARCH 1973: A SEISMIC VIEW OF THE SOURCE

by T. J. FITCH

Research School of Earth Sciences
Australian National University

SUMMARY

The main shock occurred beneath the Sydney Basin at a mid-crustal depth of 21 km. Slip that was predominantly in the sense of a thrust took place on an eastward dipping surface that nearly parallels the western margin of this basin. Axes of maximum and minimum compressive stress in the source region of this earthquake have nearly the same orientation as stress axes measured in a mine in the interior of New South Wales. Aftershock locations are better resolved if ray parameters for crustal P and S waves are compatible with a two-layer crust.

INTRODUCTION

The coastal margin of eastern Australia has been block faulted, and widespread, mainly basaltic, volcanism has occurred since late Cretaceous (Wellman & McDougall, 1974). In this period the continental margin of south-eastern Australia evolved during two major episodes of seafloor spreading: opening of the Tasman Basin from 80 to 60 m.y. ago (Hayes & Ringis, 1973) and rapid separation of Australia and Antarctica, beginning 55 m.y. ago (Weissel & Hayes, 1971). Wellman & McDougall (op. cit.) suggest that cessation of continuous volcanism in New South Wales 10 m.y. ago corresponds to a change in regional tectonics from tensional to compressive. This study and that by Stephenson & Murray (1970), using an entirely different approach,

Fig. 1. Southeast Australia. Concentrations of recent shallow earthquakes are mapped as dotted regions. Aftershocks of the Picton earthquake were located with data from seismic stations identified by 3-letter codes.

show that contemporary deformation in this part of Australia can be explained by horizontal compression.

Earthquakes are concentrated in the uplifted coastal regions (Doyle, Everingham & Sutton, 1968). Figure 1 gives locations of the more intense activity in southeastern Australia, where the seismological group at the Australian National University has recorded and located earthquakes since 1958. Of the hundreds of recorded events only the Picton earthquake of 9 March 1973 provides definitive information on the state of stress and mode of crustal deformation.

LOCATIONS

The Picton Earthquake and the Robertson earthquake of 21 May 1961 occurred at mid-crustal depths near the western margin of the Sydney basin. Both events are among the largest recorded in this region; each had a body-wave magnitude (MB) of about 5.5. Cleary & Doyle (1962) showed that the earlier event and the better recorded of its aftershocks lie in a northwest-trending zone about 10 km long. Each location was computed by adjusting an approximate location to minimize differences between observed arrival times and those calculated from a velocity model appropriate for the local region. This location technique has now become standard practice.

The better recorded of Picton earthquakes were located relative to a master earthquake chosen from among the aftershocks. The main shock was unacceptable as a master because seismograms recorded at distances less than 200 km from the focus are overdriven before the arrival of the S-wave train. Data were limited to arrival times of crustal P and S phases. The eight stations shown in Figure 1 are in the distance range where these phases are the first arrivals in their respective wave trains. The closest stations, WER and AVO, are each approximately 30 km from the source region.

In the context of this study the essential advantage of the master earthquake technique is that crustal models can be changed by merely assigning different take-off angles for rays leaving the focus of the master earthquake. Near-source velocities for P and S waves are taken to be the average velocities for the crust in this part of Australia, viz. 6.0 and 3.6 km/s respectively (Cleary, 1974). The basic relation between near-source velocities, take-off angles, and arrival times is given in Figure 1 of Fitch & Muirhead (1974).

At the three closer stations, JNL, WER and AVO, angles of incidence are fixed by the assumption of straight ray paths from the master. At the five more distant stations, RIV, LER, INV, CAH and CAN, a common angle of incidence was chosen from a range of values consistent with one-layer and two-layer crusts. Trial and error established beyond any reasonable doubt that angles consistent with a two-layer crust fit the data very much better than angles consistent with a single-layer crust. The 'best fitting' solutions were computed with a common angle of incidence of 50°. These solutions are projected in Figure 2. With modest imagination, an eastward dipping zone of aftershocks can be seen in the vertical section, and this trend is more clearly revealed by better determined locations near the centre of the activity. The down-dip length of the zone is about 6 km and its strike dimension is about 4 km. This zone is about one-half the size of the zone from an earthquake of equivalent

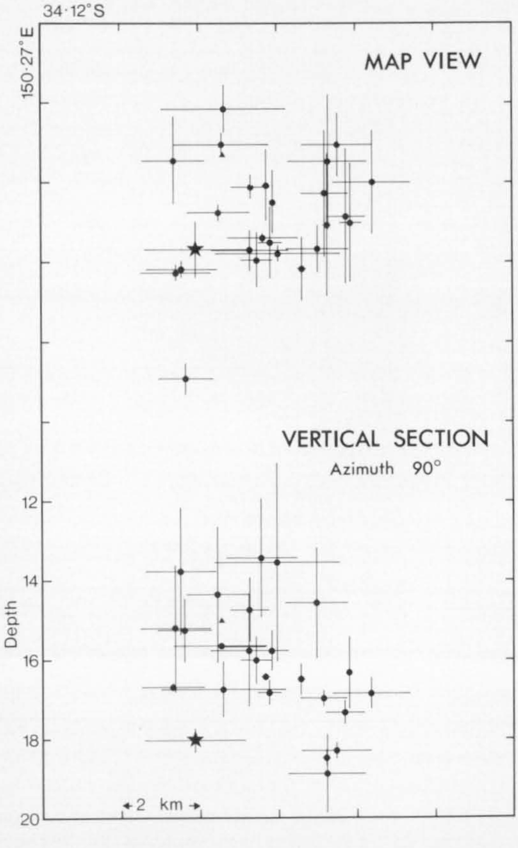


Fig. 2. Aftershocks. Triangle and star identify master earthquake and main shock respectively.

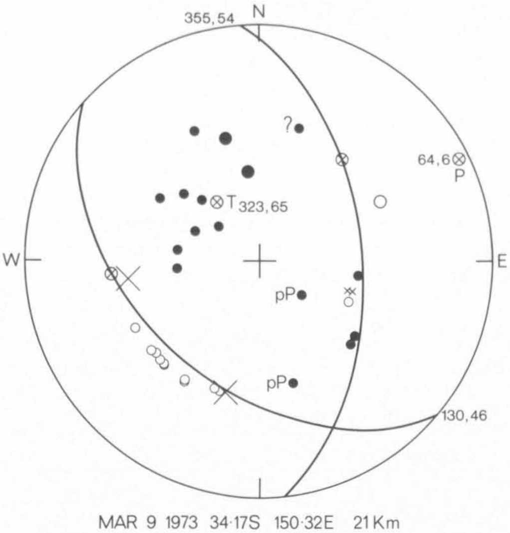


Fig. 3. Focal Mechanism Solution. Data are displayed on an equal-area projection of the lower half of the focal sphere. Solid circles, open circles, and crosses represent compressive, dilatational, and indeterminate first motions respectively. Smaller symbols identify data from short-period seismograms only. P and T stand for axes of maximum and minimum compressive stress respectively. Azimuth and plunge (in that order) are given for both axes. Nodal planes, heavy curves, represent possible planes of shear failure. Azimuth and dip of these planes are given as well as pole positions (circled crosses). For pP see text.

magnitude occurring on the San Andreas fault system in California.

The main shock is located near the base and toward the southern end of the aftershock zone. Consequently the inferred rupture was propagated northward and upward. The vertical section shows the main shock about 2 km west of the centre of the aftershock zone. Uncertainty in this location is mainly in its horizontal position. Consequently this horizontal offset can be explained by incomplete data. Only S arrival times at CAN are included in the data set for the main shock.

FOCAL MECHANISM

A first-motion study illustrated in Figure 3 shows that the Picton earthquake resulted from shear failure with the kinematics of a combined thrust and strike-slip fault. The thrust component is dominant. Key constraints on the mechanism are two first motions pP from the compressional phase reflected near the source, and the easterly dip of the aftershock zone. Experience has shown that first motions from the phase pP are seldom readable from a shallow earthquake unless its focus is at a mid-crustal depth or deeper and its mechanism is that of a thrust or normal fault. High-amplitude compressional waves are radiated vertically and horizontally by these mechanisms. Consequently near-source reflections of compressional energy are relatively strong arrivals.

The nodal plane on the right hand side of Figure 3 has the required dip and is therefore thought to represent the actual fault surface. The strike of this plane is nearly parallel to the western margin of the Sydney Basin.

pP minus P times are consistent with a mid-crustal depth for the main shock. A depth of 21 km was computed from arrival times of crustal P and S waves. The signals identified as pP are the first in a wave train that contains a prominent second arrival; probably sP, a conversion from S to P at the free surface near the source.

CONCLUDING REMARKS

If thrust faulting is a regional phenomenon in southeastern Australia then, at least at crustal depths, block movements are driven by horizontal compressive stress. First motions from the Robertson earthquake at local as well as at distant stations are about 80 percent compressive (Cleary, 1963), as would be expected from thrust faulting; however, the orientation of nodal planes cannot be resolved. Consequently a mechanism with a large or even dominant strike-slip component is possible.

At Cobar Mines in New South Wales, *in situ* stress measurements (Stephenson & Murray, 1970) reveal axes of maximum and minimum compressive stress that have nearly the same orientation as those axes taken from the first-motion study of the Picton earthquake. This agreement is particularly striking for stress orientations measured in the deeper level of the mine(1800 ft). The axis of maximum compression from the mechanism solution trends 060° whereas in the mine these axes show a nearly east trend.

Combined thrust and strike-slip faulting accounts for all well-determined mechanism solutions to earthquakes in Australia. In addition to the Picton earthquake there are the Meckering and Calingiri earthquakes in extreme southwestern Australia (Fitch, Worthington & Everingham, 1973), Lake Mackay earthquake in the northwest (Fitch et al., op.

cit; Denham, Everingham & Gregson, 1974) and a Simpson Desert earthquake (Stewart & Denham, 1974). Similar results are obtained from earthquakes in oceans and other continental regions far removed from active plate margins (Sykes & Sbar, 1973). A nearly horizontal axis of maximum compressive stress is a common feature of these mechanisms. Sykes & Sbar argue that intraplate tectonics is generally a response to horizontal compression, albeit of unknown origins.

ACKNOWLEDGEMENTS

Discussions with J. R. Cleary have been helpful throughout this research project. J. Weeks and C. Krayshek read the seismograms. L. Hodgson prepared the data for the computer. I wish to thank the Director of the Bureau of Mineral Resources for seismograms from stations operated by BMR. Also I wish to thank the Sydney Water Board for operating the three recording stations closest to this activity—AVO, WER, and JNL.

REFERENCES

CLEARY, J. R., 1963—Near earthquake studies in southeastern Australia. *Thesis, Australian National University*.

CLEARY, J. R., & DOYLE, H. A., 1962—Application of a seismograph network and electronic computer in near earthquake studies. *Bull. Seis. Soc. Am.*, 52, 673-682.

DENHAM, D., EVERINGHAM, I. B., & GREGSON, P. J., 1974—East Canning Basin earthquakes. *J. Geol. Soc. Aust.*, 21(3).

DOYLE, H. A., EVERINGHAM, I. B., & SUTTON, D. J., 1968—Seismicity of the Australian continent. *J. Geol. Soc. Aust.*, 15, 295 et seq.

FITCH, T. J., & MUIRHEAD, K. S., 1974—Depths to large earthquakes associated with crustal loading. *Geophys. J. Roy. Astr. Soc.*, 37, 285-296.

FITCH, T. J., WORTHINGTON, M. H., & EVERINGHAM, I. B., 1973—Mechanisms of Australian earthquakes and contemporary stress in the Indian Ocean Plate. *E.P.S.L.*, 18, 345-356.

HAYES, D. E., & RINGIS, J., 1973—Sea floor spreading in the Tasman Sea. *Nature*, 243, 454-458.

STEPHENSON, B. R., & MURRAY, K. J., 1970—Application of the Strain Rosette Relief Method to measure principal stresses through a mine. *Int. J. Rock Mech. Min. Sci.*, 7, 1-22.

STEWART, I. C. F., & DENHAM, D., 1974—Simpson Desert earthquake, central Australia, August 1972. *Geophys. J. Roy. Astr. Soc.*, 39, 335-341.

SYKES, L. R., & SBAR, M. L., 1973—Intraplate earthquake, lithospheric stresses and the driving mechanism of plate tectonics. *Nature*, 245, 298-302.

WEISSEL, J. K., & HAYES, D. E., 1971—Asymmetric seafloor spreading south of Australia. *Nature*, 231, 518 et seq.

WELLMAN, P., & MCDOUGALL, I., 1974—Cainozoic igneous activity in eastern Australia. *Tectonophysics*, 23, 49-65.

EFFECTS OF THE 1973 PICTON AND OTHER EARTHQUAKES IN EASTERN AUSTRALIA

by D. DENHAM

Bureau of Mineral Resources, Canberra

SUMMARY

The earthquakes of eastern Australia tend to take place in the eastern highlands and coastal regions. Although they result from regional stress in the crust the cause of the stress is not known. The epicentres do not fall into large regional patterns, but are widely diffused, with a few localised clusters where the activity rises above the regional level. A typical active cluster occurs in the Dalton/Gunning zone about 50 km north of Canberra, and several earthquakes which caused damage to structures have taken place there in the last 50 years.

Since 1900 no earthquakes having magnitudes greater than 6 (ML) have been recorded from eastern Australia and all the damage has been caused by earthquakes in 5-6 magnitude range. On average, nearly one earthquake of magnitude 5 or greater occurs each year in this region. Isoseismal maps are presented to indicate typical effects from those events.

The most recent earthquake to cause damage was the Picton or Burragorang earthquake of March 1973. This earthquake was felt over an area of about 60 000 km^2 and light damage was caused over a wide area (4000 km^2). Most of the structures affected were very old (some more than 100 years). Minor damage was caused to plaster, brickwork, and the tops of chimneys where the heat from the fires had destroyed the adhesive properties of the mortar. No reports were received of complete chimneys breaking at roof level, and only one instance is known (at a glass works in Wollongong) of significant damage to goods or stores. The maximum intensity experienced was MM VI-VII, and the total damage is estimated to be about $500 000.

INTRODUCTION

Earthquake activity in the Australian continent is at least an order of magnitude less than that experienced in Indonesia and Papua New Guinea, at the northern boundary of the Australian plate. Figure 1, which shows all known earthquakes from 1900 to 1973.4 that had magnitudes of 6 or greater, illustrates the comparative levels of seismicity between the Australian continent and the regions to the north. Not only have there been considerably more earthquakes along the northern plate margin but also they occur there in more regular spatial patterns.

Even if more continental events are considered by including smaller magnitude earthquakes, no well defined trends are revealed that extend over long distances (say greater than 500 km). This is shown in Figure 2 where all known earthquakes of magnitude 4 or greater that have taken place in the period 1900-1972, and for which a reliable epicentre can be determined, are plotted. Unfortunately this map does not contain a complete data set for the 73-year period it purports to cover, and 86 percent of all the earthquakes plotted date from 1960. Before 1958 there were never more than six seismographs operating in Australia (Doyle & Underwood, 1965) and seldom were more than ten earthquakes located each year on the continent. Since then, however, with the development of regional networks in all States except Queensland, and improved instrumentation at older stations, the number of locatable earthquakes has increased to about 50 per year.

Figure 3 shows the total number of Australian earthquakes located each year since 1900 and demonstrates the rapid upswing in the late 1950s due to the improved regional coverage.

SEISMICITY—EASTERN AUSTRALIA

Figure 2 shows that although there are no major zones of seismic activity crossing the continent there are areas where the level of activity is high enough for moderate (and in some instances, large) earthquakes to occur. In eastern Australia the earthquakes tend to take place within the crust in the Tasman Geosyncline. There are no major lineations of epicentres; rather, a diffuse distribution of shocks over a wide area, with a few localized clusters where the activity rises above the regional level. The best defined clusters are near Wilsons Promontory 150 km southeast of Melbourne, and in the Dalton/Gunning region about 70 km north of Canberra. North of Sydney the level of activity appears to decline, but this is probably due to the poor station coverage in Queensland and northern New South Wales, where several earthquakes larger than magnitude 4 are recorded each year but are still not being located.

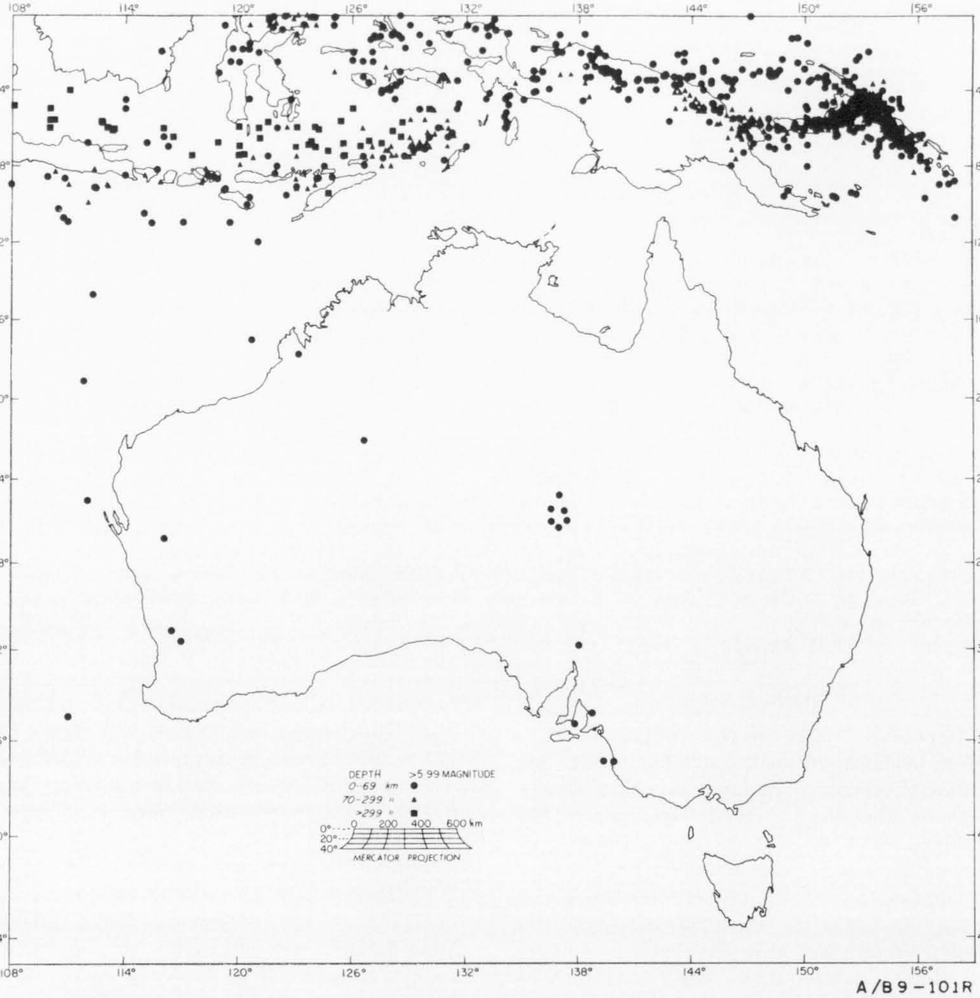


Fig. 1. Earthquakes of magnitude 6 and above for the Australian, East Indonesian, and Papua New Guinea region 1900-1973.4.

All the earthquakes in the Tasman Geosyncline result from regional stresses in the crust. Earthquake focal mechanism studies by Cleary (1967) and Fitch (1974) indicate that in the Dalton/Gunning and Picton regions the principal stress axes are compressional and almost horizontal. It is inferred that the crust is probably weaker in the east than in central and western Australia, because no earthquakes larger than magnitude 6 have occurred in the Tasman Geosyncline region since 1900; whereas several earthquakes in the western and central parts of the continent have had magnitudes larger than 6 in the period (BMR, 1974).

Most of the earthquakes in the east have been moderate in size, and they have caused only slight damage. On average, nearly one earthquake of magnitude 5 or greater occurs each year in the Tasman Geosyncline. Figures 4 to 7 show isoseismal maps of some recent earthquakes in the Dalton/Gunning (Joklik, 1951), Gippsland (Wilkie, 1970), and Robertson (Cleary & Doyle, 1962) regions. Both the 1949 Dalton/Gunning and the 1961 Robertson earthquakes had a maximum intensity of VII or greater on the Modified Mercalli scale and caused slight damage close to the epicentres.

1973 PICTON EARTHQUAKE

On 10 March 1973 at 05 h 09 m EST an earthquake of Richter magnitude 5.5 took place near the Burragorang Valley in New South

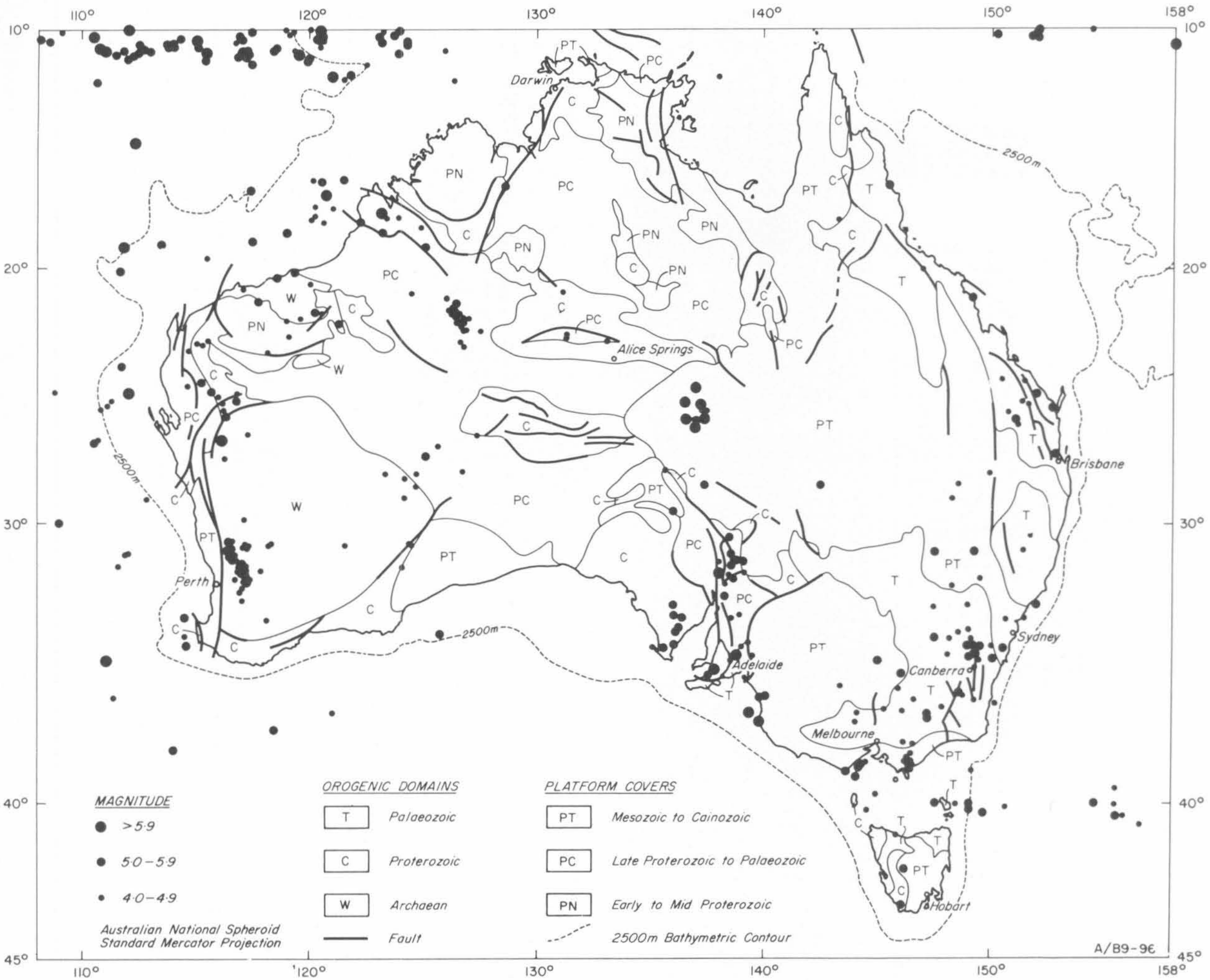


Fig. 2. Earthquakes of magnitude 4 and above for the Australian continent, 1897-1972.

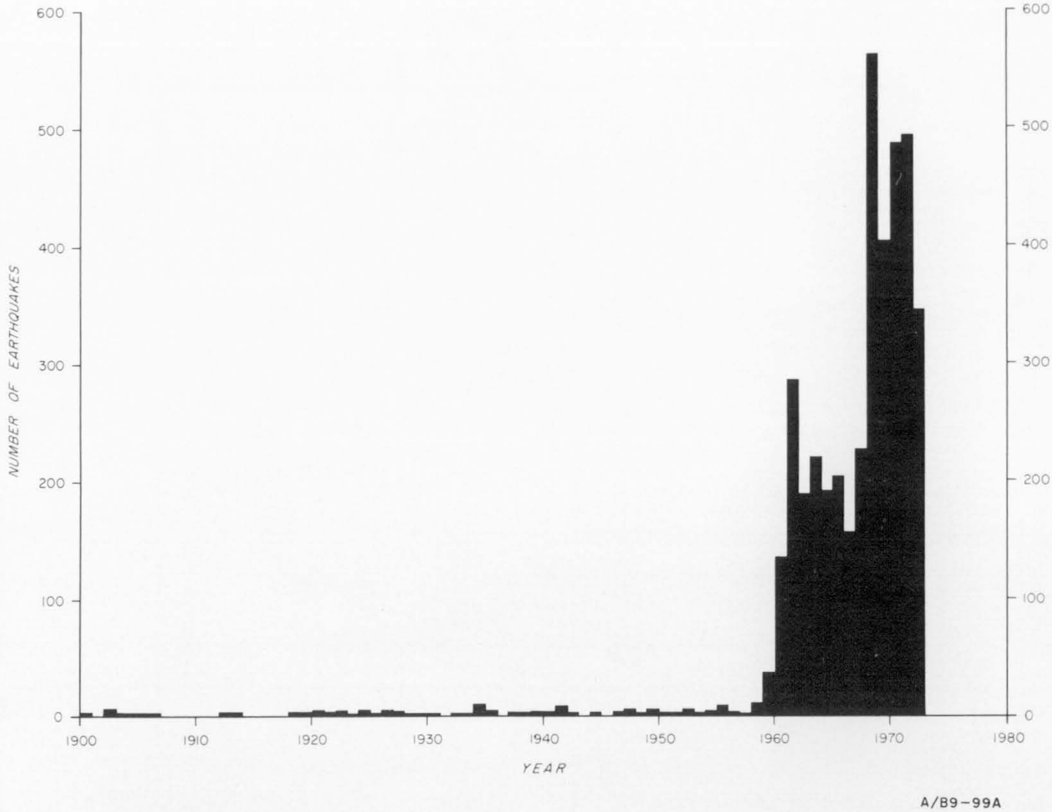


Fig. 3. Annual numbers of earthquakes located in the Australian continental region 1900-1972.

Wales and was felt over an area of about 60 000 km^2. Using P-wave arrival times at Australian seismographs and a relocation technique based on Bolt's (1960) program the epicentre was calculated as 34.13°S, 150.29°E and the depth as 27 km.

The earthquake was most strongly felt in the towns of Picton, Robertson, and Wollongong, and about 300 questionnaires were distributed to these and other towns in NSW. It was soon evident that although most places escaped unscathed there were enough reports of structural damage to warrant a field inspection. This was carried out on 30-31 March and most of the main centres of population in the epicentral region were visited. A résumé of the finding is given below.

Goulburn (37.76°S, 149.71°E)

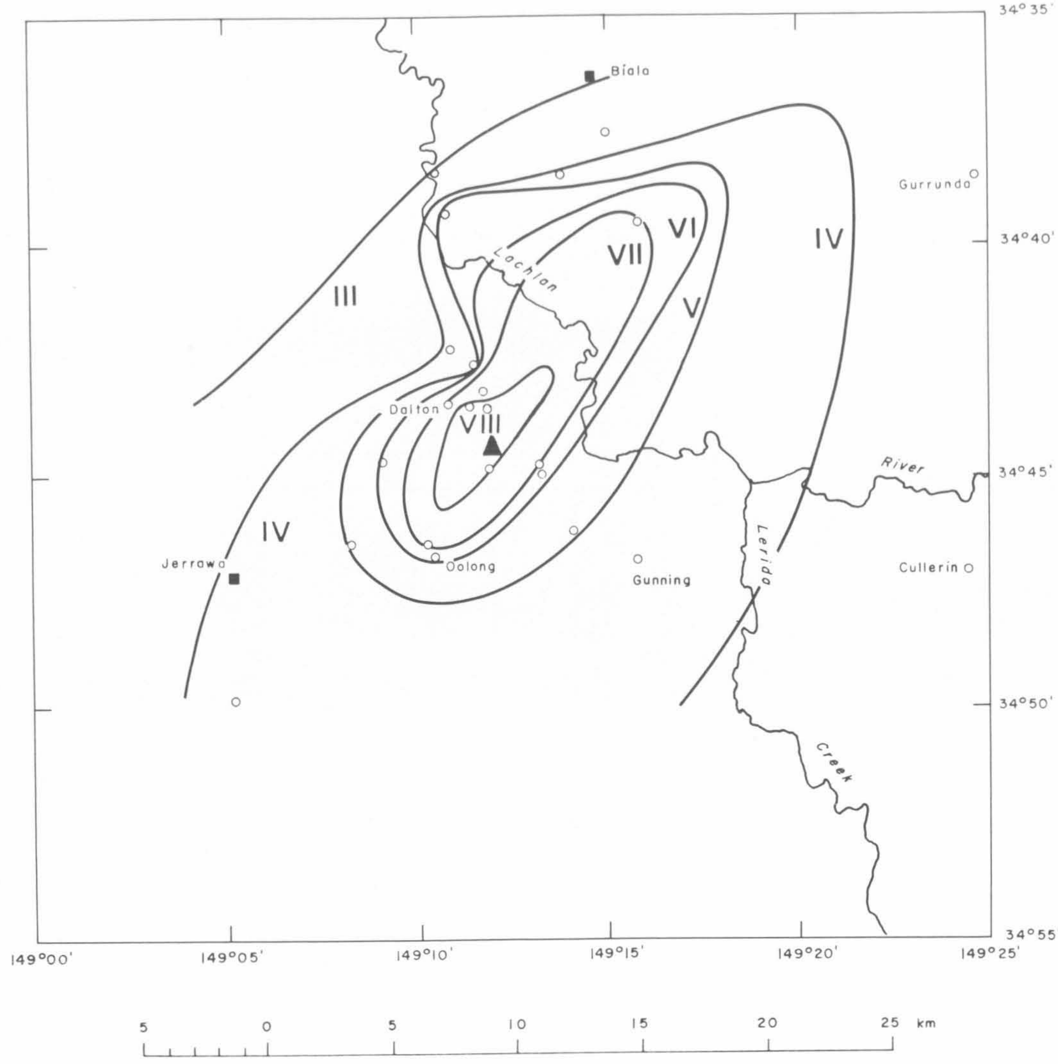
An informant at Goulburn reported slight damage to brick, masonry, and concrete in the Goulburn area, but questioning elicited that apart from some hairline plaster cracks and the loosening of some bricks in a free-standing brick wall there was little damage to report The earthquake had apparently awakened most people in the community and frightened a few. The report in the *Goulburn Evening Post* of 12 March 1973 appeared to give an accurate assessment for the Goulburn region: 'Goulburn and district escaped serious damage following Saturday's earth tremor, which struck metropolitan and country centres in southeastern NSW.

'Houses shook and some windows broke but water and sewer mains remained intact, according to officials with Goulburn City and Mulwaree Shire Councils.

'Some minor cracking was reported in buildings scattered over the area, but building firms early this morning reported no rush for repair work to damaged property.

'No immedate reports of electrical blackouts or major lines down had been received by the Southern Tablelands County Council.

Despite large stocks of glassware on shelves at Knowlman's department store, the chairman, Mr. John Knowlman said this morning that none had been dislodged during the brief earth-



DATE: 10 MARCH 1949
TIME: 22:30:33·0 UT
MAGNITUDE: 5·3 MB, 5·5 ML
HYPOCENTRE: 34·74°S 149·20°E
DEPTH: 33 km

▲ EPICENTRE
○ EARTHQUAKE WAS FELT
IV ZONE INTENSITY DESIGNATION (MM)

I55/B9-9A

Fig. 4. Isoseismal map of the 1949 Dalton/Gunning earthquake (after Joklik, 1951).

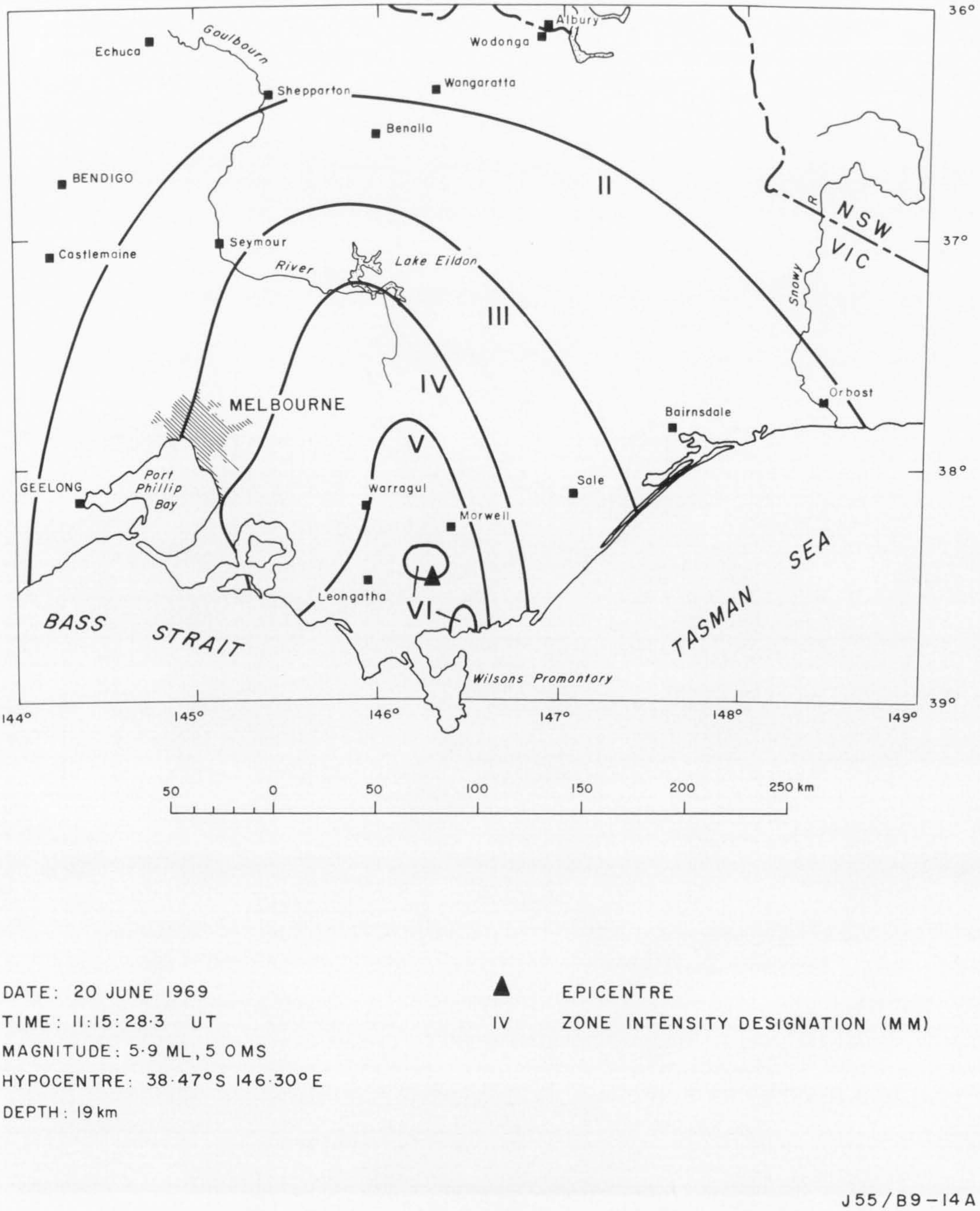


Fig. 5. Isoseismal map of the 1969 Gippsland earthquake (after Wilkie, 1970).

quake. "It was very frightening," he said, "but fortunately we've had no damage here." Goulburn supermarkets were likewise unaffected'.

Exeter (34.62°S, 150.31°E)

The postmistress at Exeter had reported cracked plaster and chimneys. Further questioning revealed that at least three buildings in and around Exeter had been damaged slightly. A chimney in a weatherboard house in School Lane was damaged: the top three layers of brick were displaced and some had fallen onto the roof. It was evident that the mortar in these

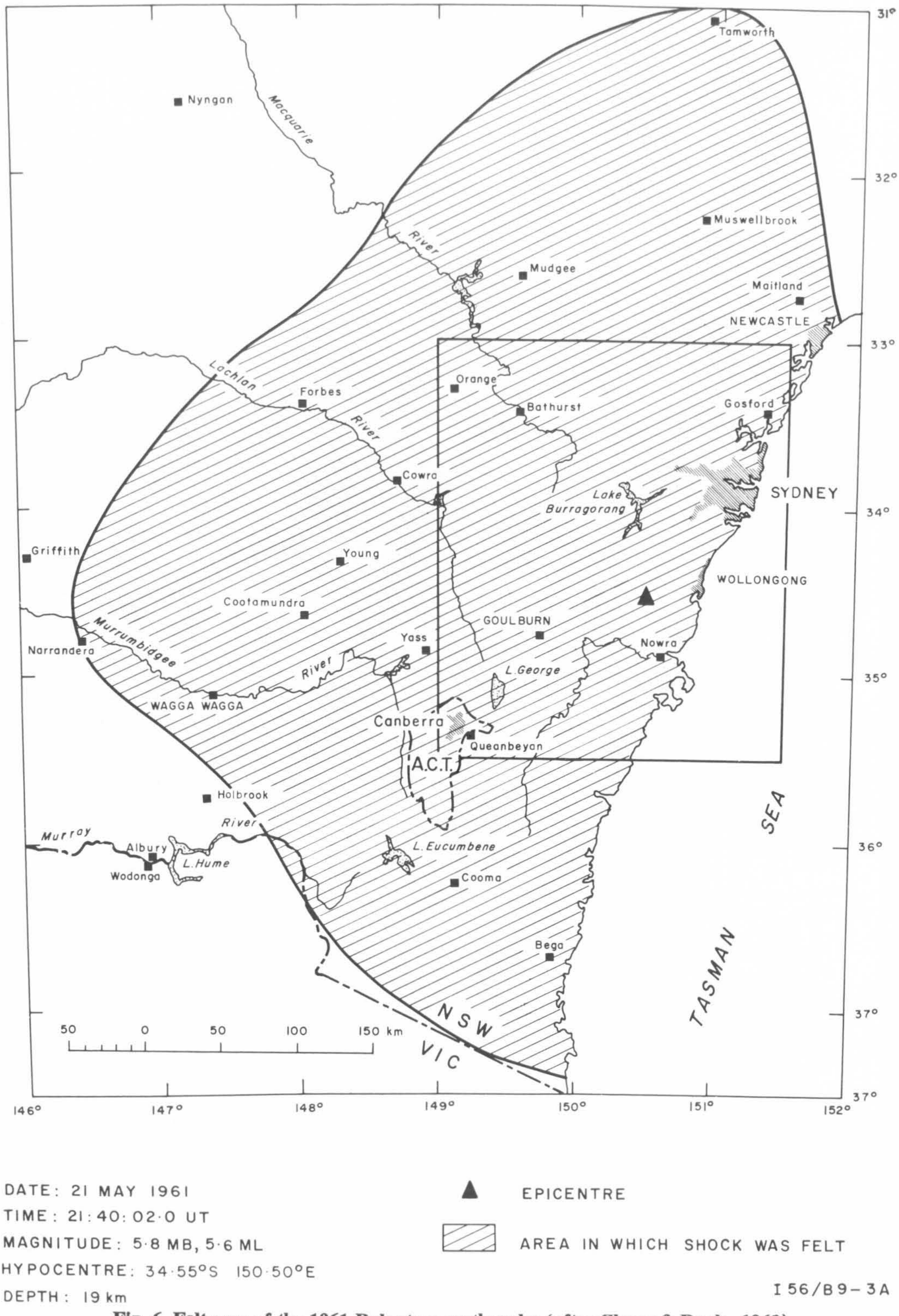
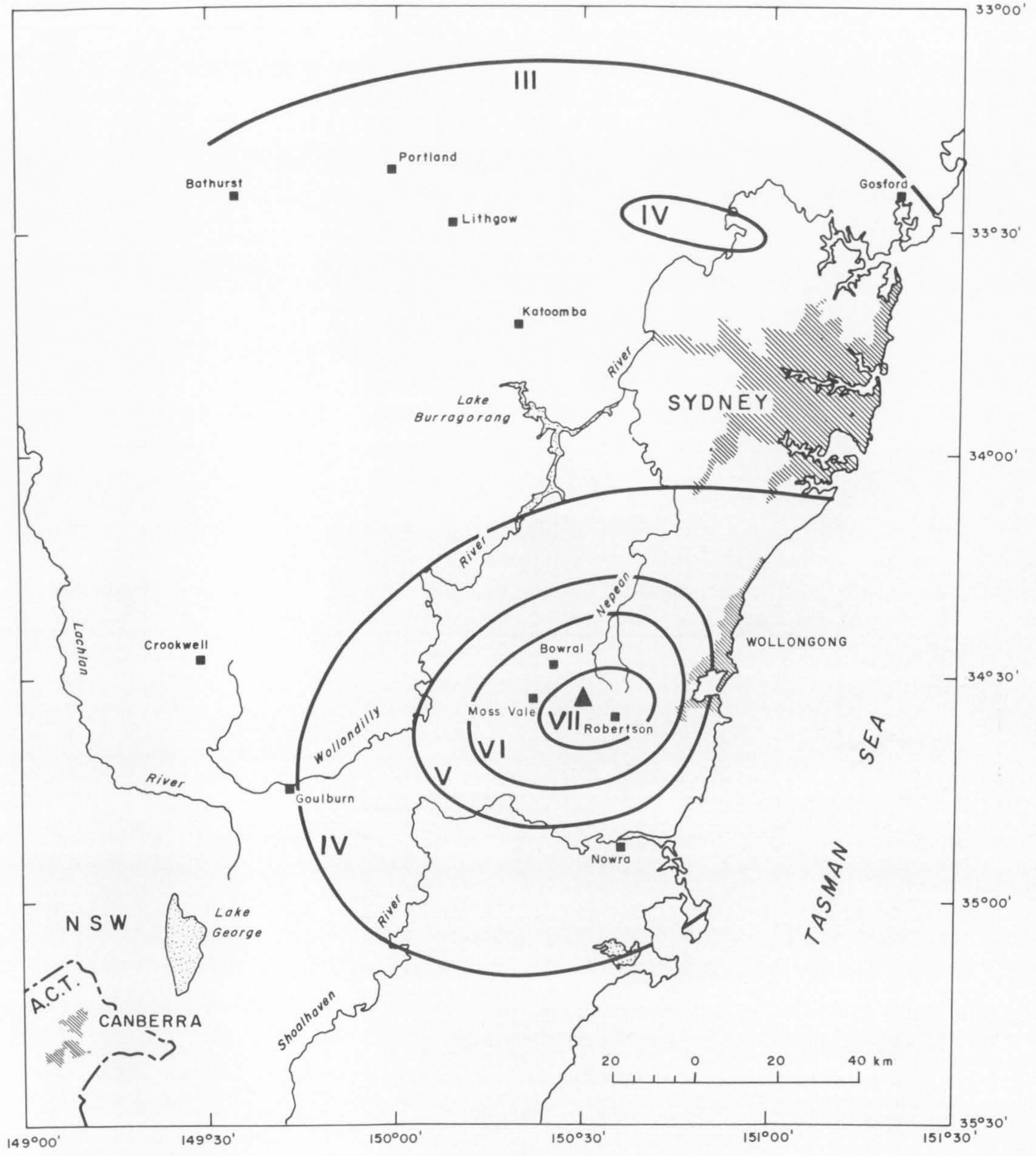


Fig. 6. Felt area of the 1961 Robertson earthquake (after Cleary & Doyle, 1962).



DATE: 21 MAY 1961
TIME: 21:40:02·0 UT
MAGNITUDE: 5·8 MB, 5·6 ML
HYPOCENTRE: 34·55°S 150·50°E
DEPTH: 19 km

▲ EPICENTRE
IV ZONE INTENSITY DESIGNATION (MM)

I56/B9-4A

Fig. 7. Isoseismal map of the 1961 Robertson earthquake (after Cleary & Doyle, 1962).

layers had lost most of its adhesive properties and this had contributed to the fall of the bricks.

At Karrarre homestead about 3 km from Exeter on the west side of the road to Bundanoon the newly renovated plaster cornices were cracked extensively. It is possible that some of the damage was caused by shrinkage cracks.

In the Anglican church at Exeter the earthquake caused cracks in the south wall and in the vestibule. They appeared to be caused by local subsidence and emanated from the corners of one of the windows. The largest crack was about 0.6 m long and had a maximum width of about 5 mm.

Berrima (34.49°S, 150.34°E)

Damage was reported at the Berrima Training Centre, the Berrima Court House, and the Surveyor-General Hotel. The most serious damage took place at the Training Centre, where some displacement and cracking of main perimeter walls occured. These walls are about 6 m high and are built of large sandstone blocks about 0.6 m thick. They form the sides of a large quadrangle which surrounds the main building complex and are probably over 100 years old (the building dates from 1830). The earthquake caused the west wall to buckle inwards and force the west end of the north wall about 0.1 m out of alignment at the top of the wall. The break in the wall was a clear fracture and had to be repaired for safety reasons. The northeast corner was similarly affected but the cracking was not so severe.

Some of the inmates' cells were also damaged. These form the inner quadrangle of the building complex. The cell in the southwest corner had cracks in the brickwork which penetrated the wall through to the adjacent cell, and repairs were required. The wall of another cell was cracked above the window, but not to the same extent as the cell in the southwest corner.

It was not evident whether local ground subsidence during the earthquake or the actual ground shaking had caused the damage to the cells, but the Department of Works suggested that for the perimeter wall, 'Cracking was primarily caused by long term subsidence of foundation material merely aggravated by the earth tremor of March 1973'. The estimated cost of repair was $1200.

Sandstone mortar joints in the Berrima Court House were cracked. It was estimated that repairs would cost $100.

In the rear wing of the Surveyor-General Hotel, the walls aligned northwest were also cracked. This building is about 100 m from the Training Centre and is over 100 years old (established in 1834). The cracks indicated that subsidence beneath this part of the building had probably taken place during the earthquake. Surprisingly, no damage was done to the bottles or stock in the hotel, although the earthquake awakened all the residents and frightened several of them.

Moss Vale (34.55°S, 150.36°E)

The questionnaires returned from Moss Vale did not reveal any damage, but members of the Fire and Accident Underwriters Association of New South Wales (FAUA) reported 13 claims totalling $26 000 from Moss Vale (see Appendix). Most of the claims resulted from cracks in brickwork and plaster.

Bowral (34.47°S, 150.42°E)

Inquiries at Bowral failed to find any major structural damage in the town, but there were reports of minor cracks in brickwork and plaster from Una and Holly Streets and Gladstone Road; 27 insurance claims, totalling $22 601, were reported from Bowral. The *Berrima District Post* of 13 March 1973 reported 'Lights in Bowral-Moss Vale area blacked out ten minutes after Saturday's rumble.

'Little damage is reported in the Bowral-Moss Vale area, however some brick houses received minor damage.

'Stock tumbled from shop shelves and a number of burglar alarms were set off'.

Mittagong (34.45°S, 150.44°E)

Preliminary reports from Mittagong indicated that minor damage occurred at several buildings. The walls of a squash court at the corner of Duke Street and Oxley Drive were cracked around the doors, at the corners of the walls, and where the roof meets the walls. Minor cracking was reported in several homes, and FAUA lists 17 claims assessed at $5683.

Two buildings affected in the town centre were the Commonwealth Bank and the Mittagong Hotel. At the hotel the outside walls were all cracked. These cracks were small at ground level and increased in size towards the top, where the largest was about 4 m long. It is possible that they had been caused by the 1961 earthquake and were reactivated by the 1973 earthquake. No bottles were broken in the hotel although all the residents were awakened and most were frightened. In the Commonwealth Bank, which is situated next door but one to the hotel, the earthquake caused cracks in the east wall of the building. These cracks in the brickwork were approximately parallel to the slope of the roofline.

Nattai River (34.07°S, 150.42°E)

Nattai River township is close to the epicentre (about 10 km) and consists of two separate areas. One is situated on the Southern Highlands plateau at an elevation of about 450 m and the other is near the mine workings close to the Warragamba reservoir (about 150 m). As far as could be ascertained most of the inhabitants were awakened by the main shock and several of the larger aftershocks were felt. Nevertheless no stock at the Post Office was damaged and the only remaining evidence of the earthquake was the collapse of part of a chimney in a coalminer's cottage at the lower level. The chimney, of stone and cement mortar, had been built onto the side of the house by the occupant, and during the earthquake about 2 m^2 of the outside wall of the chimney collapsed. Fortunately this was part of the lower portion of the structure and no further damage resulted.

The fact that no further damage was caused at Nattai River is strong confirmatory evidence that the earthquake did not take place at a very shallow depth.

Wollongong (34.43°S, 150.87°E)

Although the Wollongong district was 60 to 70 km from the epicentre, the earthquake was felt as strongly in this region as it was at Nattai River, much closer to the epicentre.

One of the biggest losses sustained there was at the Albion Park Glass Factory, where mirror glass valued at more than $1000 was smashed by the earthquake.

A block of flats at Shellharbour was damaged in the roof and the top flats; the ceiling in the Library at Wollongong Teachers' College was damaged; the cornices in the Mayoress's room at the Town Hall were cracked; and a number of hot water tanks in the ceilings of Wollongong homes overflowed.

Widespread blackouts occurred and power was not restored to the inner city area for 52 minutes.

The Open Hearth Hotel at Warrawong, Port Kembla, had 16 windows broken and the outside walls cracked. The windows were all broken because the lintels above the windows failed. They consisted of thin iron bars, and during the shaking these bent causing the window frames to buckle and the panes of glass to crack.

Fifty-seven insurance claims totalling $15 909 were recorded by FAUA.

Scarborough (34.26°S, 150.96°E)

At Scarborough, north of Wollongong, several dwellings near the Post Office and a house at Buttenshore Drive were damaged.

The concrete floor at the Post Office was cracked and the top of the chimney of the adjoining house had collapsed. At the end of the garden (about 50 m from the house) a subsidence crack about 30 m long appeared after the earthquake. The seaward side of this crack was displaced downwards a maximum of about 0.4 m. The land involved was very recent fill material and appeared to be unconsolidated.

The walls of a small brick cottage near the Post Office were cracked above the doors and near the ceilings. No damage was reported to crockery or ornaments.

The house in Buttenshore Drive was a wooden-framed dwelling resting on a brick and timber base. The wooden frame had not been adequately tied to the foundations and during the earthquake shifted about 30 mm on the base. This movement caused the rear entrance steps to the laundry (about 2 m above the ground) to be pushed over and one of the walls supporting the laundry to collapse. Three jacks had been installed to support the laundry, pending permanent repairs to the building.

None of the damage at Scarborough was listed by FAUA.

Picton (34.18°S, 150.61°)

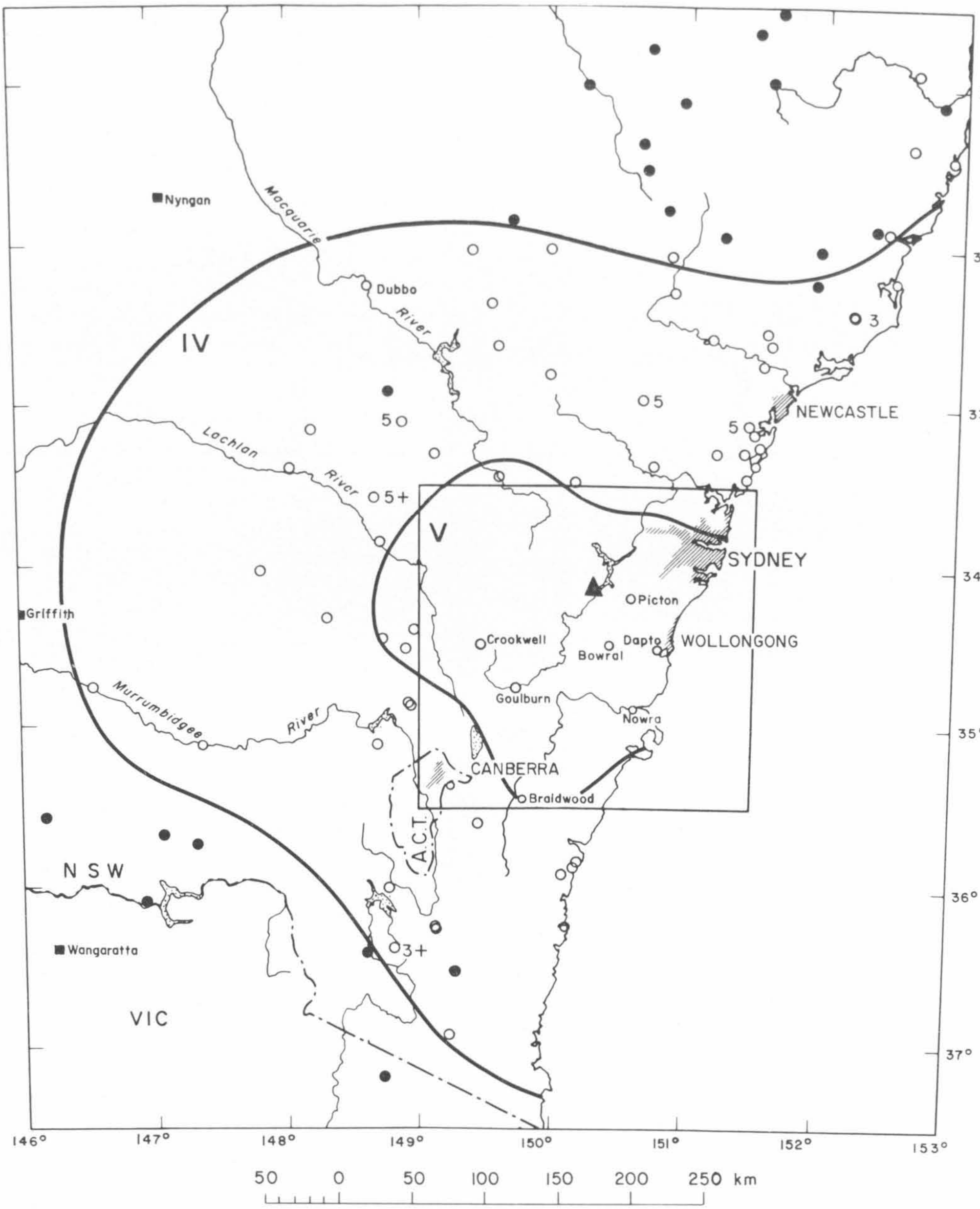
Damage at Picton appeared to be confined to the town's two oldest buildings—the Post Office and the Commercial Bank. It was not possible to inspect the bank but a report by Taune and Heath, Architects, indicated fairly extensive cracking to all rooms of both residence and the banking area. The damage was confined to the finish of the building and there did not appear to be any structural damage. They estimated the cost to restore the premises to their original condition at about $13 000.

In the Post Office the interior walls in the part of the building that supports the clock tower were badly cracked, and the plaster work throughout the building was affected in the same way.

No insurance claims for Picton were presented to FAUA.

Tahmoor (34.22°S, 150.59°E)

Some of the most intense shaking was experienced in a small region of Tahmoor, where three houses in Progress Street on the eastern side of the Hume Highway were damaged. These are sited on top of a slight undulation, composed of about 10 m of uncon-



DATE: 9 MARCH 1973
TIME: 19:09:14 UT
MAGNITUDE: 5·5 ML
HYPOCENTRE: 34·14°S 150·29°E
DEPTH: 20 km

▲ EPICENTRE
○ EARTHQUAKE WAS FELT
● EARTHQUAKE WAS NOT FELT
IV ZONE INTENSITY DESIGNATION (MM)

Small figure beside open circle indicates intensity is different from zone designation

I56/B9-6A

Fig. 8. Isoseismal maps of Picton earthquake, 1973.

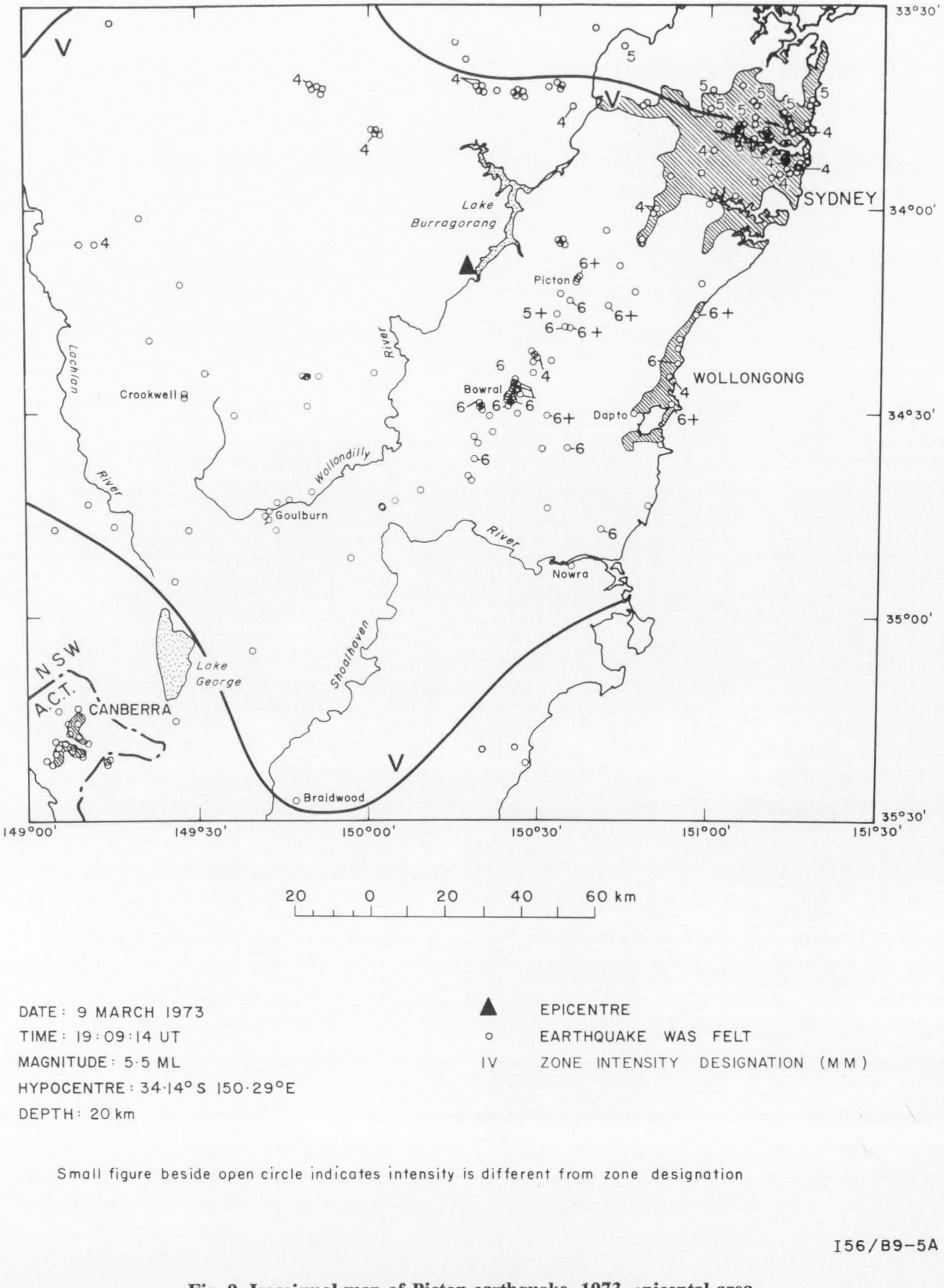


Fig. 9. Isoseismal map of Picton earthquake, 1973, epicental area.

solidated marl, in the relatively flat countryside. The topography and ground composition probably accentuated the shaking.

At Mr Whitfield's house the chimney was shattered and numerous cracks were formed on the outside wall. The shaking was sufficient to shatter the brick wall around a boiler in the laundry.

The chimneys of the two neighbouring houses were damaged and the top four courses of bricks of one chimney moved about 60 mm.

Most of the local residents recalled feeling several aftershocks and the shaking from most of them was as severe as that experienced during the main shock closer to the epicentral region at Nattai River.

Miscellaneous damage

Appendix 1 lists the claims met by the member companies of FAUA (Tariff Insurers). These figures represent only about half the insurance industry. To obtain a total value for the damage, the claims met by the insurance companies who are not members of FAUA must be included and also the damage caused to uninsured property. The Secretary of FAUA estimates that claims to the non-Tariff Insurers would total about the same as those to the members of FAUA ($200 000). The known damage to uninsured property (nearly $18 000) is listed in Appendix 2. Perhaps another $100 000 should be added to cover the unknown uninsured property. This would bring the total damage to about $500 000.

Isoseismal maps

Figures 8 and 9 show isoseismal maps derived from the questionnaires and from intensity assessments made in the field. Although there were some small areas where the Modified Mercalli intensity approached VII (e.g. Tahmoor) and several disconnected regions where intensity VI was experienced, the highest contour value that could be drawn was for MM V. The felt observations suggest that the earthquake was comparatively deep; hence it was felt over a wide area, and high intensities were experienced in regions where the surface conditions amplified the shaking. Damage was mainly restricted to old buildings.

No reports were received of complete chimneys breaking at roof level, and only one instance is known (a glass works at Wollongong) where much damage was caused to stocks.

ACKNOWLEDGEMENTS

I thank the Director of the Bureau of Mineral Resources for permission to publish this material and the many volunteer observers who provided data on the effects of the Picton earthquake.

REFERENCES

B.M.R., 1974—Australian Earthquakes, pamphlet. *Canberra, Bur. Miner. Resour. Aust.*

Bolt, B. A., 1960—Revision of earthquake epicentres, focal depths and origin-times, using a high speed computer. *Geophys. J.*, 3, 433-440.

Cleary, J. R., 1967—The seismicity of the Gunning and surrounding area, 1958-1961. *J. geol. Soc. Aust.*, 14, 23-29.

Cleary, J. R., & Doyle, H. A., 1962—Application of a seismograph network and electronic computer in near earthquake studies. *Bull. seism. Soc. Am.*, 52, 673-682.

Doyle, H. A., & Underwood, R., 1965—Seismological stations in Australia. *Aust. J. Sci.*, 28, 40-43.

Fitch, T., 1974—Tectonics of the 1973 Picton earthquake sequence. *This Volume.*

Joklik, G. F., 1951—Dalton-Gunning Area, N.S.W., earth tremors of March 1949. *J. Proc. R. Soc. N.S.W.*, 84, 17-27.

Wilkie, J. R., 1970—The South Gippsland earthquake of 20 June 1969. *Bur. Miner. Resour. Aust. Rec.* 1970/91 (unpubl.).

Page 28 is blank.

APPENDIX 1

CLAIM DETAILS PROVIDED BY THE FIRE AND UNDERWRITERS' ASSOCIATION OF NEW SOUTH WALES

From the information supplied by member Companies as requested in Notice to Chief Representatives No. 227 dated 19 March 1973 the attached statistics have been collated. However, not all member companies completed the return.

To summarize:
Total claims reported—483
Total claims admitted—423
Total estimate on claims admitted—$196 355.
Places which had over ten claims reported were:

Albion Park	11	$5 754
Bowral	27	22 601
Mittagong	17	5 683
Moss Vale	13	2 600
Wollongong	57	15 909

Places which have estimates of $2000 or over, other than those listed above are:

Alexandria	4	4 000
Appin	3	4 060
Austinmer	9	5 100
Balmoral	3	22 200
Coogee	5	2 700
Croydon	1	2 500
Dapto	5	3 234
Dulwich Hill	6	4 900
Edgecliff	4	4 200
Kensington	2	3 050
Pymble	4	2 376
Roseville	1	2 000
Ryde	2	2 450
Ryde West	4	5 550
Shellharbour	3	9 443
Strathfield	4	2 050
Thirroul	5	2 695
Wahroonga	6	3 900
Watsons Bay	3	2 700
Wattamolla	2	2 400
Young	4	9 000

Theoretically the figures for the estimate should be higher as some members advised claims reported only and not the estimated loss attaching to those claims. The reported claims have been included in the attached table.

Area	*No. of Claims reported*	*Estimate* $
Albion Park	11	5 754
Alexandria	4	4 000
Ando	1	
Appin	3	4 060
Ashfield	1	400
Auburn	3	1 500
Austinmer	9	5 100
Avalon	1	
Balgownie	1	450
Balmoral	3	22 200
Bankstown	1	
Bathurst	4	330
Baulkham Hills	1	
Beecroft	2	1 000
Bellambi	2	
Berkeley	1	
Bexley	2	850
Bilpin	1	
Binalong	1	400
Birrong	2	50
Blakehurst	2	400
Bondi	7	324
Botany	7	1 720
Bowral	27	22 601
Brighton-Le-Sands	1	
Brookvale	1	200
Bulli	8	1 200
Bundanoon	1	200
Burrinjuck	1	40
Camden	1	1 000
Campsie	1	350
Canberra	2	400
Canowindra	2	1 200
Carlingford	2	600
Castlecrag	1	334
Castle Cove	1	350
Castle Hill	1	350
Chatswood	5	540
Church Point	1	500
Clifton Gardens	2	600
Clovelly	5	1 391
Coogee	5	2 700
Corrimal	5	1 600
Cowra	1	500
Cremorne	3	1 262
Crows Nest	2	100
Croydon	1	2 500
Croydon Park	1	130
Curl Curl North	1	
Dapto	5	3 234
Darlinghurst	1	300
Dee Why	4	1 900
Double Bay	4	1 560
Dulwich Hill	6	4 900
Drummoyne	3	1 700
Dunedoo	1	200
Earlwood	3	90
Eastwood	3	845
Edgecliff	4	4 200
Epping	1	
Erskineville	2	300
		$
Exeter	1	300
Fairfield	3	420
Fairy Meadow	4	1 478
Fairlight	1	200
Farrer (A.C.T.)	1	
Five Dock	1	100
Freemans Reach	1	
Gladesville	1	500
Glebe	1	200
Glenfield	1	200
Gosford	1	
Goulburn	1	300
Green Valley	1	150

Area	*No. of Claims reported*	*Estimate* $
Guildford	2	1 500
Harden	1	1 500
Harris Park	2	500
Hornsby	1	28
Hunters Hill	2	
Hurstville	2	20
Huskisson	1	200
Jannali	1	100
Katoomba	2	400
Kellyville	1	300
Kensington	2	3 050
Kiama	1	100
Killara	2	226
Killarney Heights	1	500
Kingsford	3	100
Kingsgrove	2	600
Kogarah	4	600
Kotara East (N' castle)	1	
Kurnell	1	200
Lane Cove	2	200
Leura	1	
Lidcombe	1	200
Lindfield	2	250
Lithgow	1	50
Lochinvar	1	100
Manly Vale	2	410
Maroubra	4	1 800
Marrickville	3	450
Marulan	4	1 000
Mascot	4	530
Merrylands	1	500
Mittagong	17	5 683
Molong	1	500
Moss Vale	13	2 600
Narellan	1	296
Narrabeen	1	100
Neutral Bay	1	750
Newtown	1	100
Northbridge	1	
North Sydney	4	1 700
Oatley	1	100
Orange	1	
Oyster Bay	1	1 050
Paddington	1	274
Palm Beach	1	
Panania	1	153
Peakhurst	1	300
Pendle Hill	1	750
Pennant Hills	1	750
Penrith	1	100
Petersham	2	35
Point Piper	3	1 220
Primbee	1	100
Port Kembla	3	262
Punchbowl	1	150
Pymble	4	2 376
Queenscliff	1	200
Randwick	3	260
Redfern	2	400
Rockdale	3	100
Rooty Hill	1	500
Rose Bay	3	350
Rosebery	1	400
Roseville	1	2 000
Rouse Hill	1	
Rozelle	2	400
Ryde	2	2 450
Ryde East	2	1 000
Ryde West	4	5 550
St. Ives	3	106
Sans Souci	2	300
Seaforth	1	
Seven Hills	2	270
Shellharbour	3	9 443
Speers Point	1	150
Spit Junction	1	1 000
Stanmore	1	200
Stanwell Park	1	400
Strathfield	4	2 050
Sutherland	2	600
Sydney	1	800
Temora	1	1 000
Tempe	2	390
Thirlmere	1	1 000
Thirroul	5	2 695
Turramurra	3	1 500
Ulladulla	1	200
Unanderra	3	1 320
Vaucluse	1	
Wagga Wagga	1	
Wahroonga	6	3 900
Warrawong	3	200
Warwick Farm	1	
Warilla	5	1 500
Waterloo	2	500
Watsons Bay	3	2 700
Wattamolla	2	2 400
Waverley	2	300
Waverton	1	300
Windang	1	413
Wollongong	57	15 907
Yagoona	1	84
Young	4	9 800
	483	196 355

APPENDIX 2

REPORTED DAMAGE TO UNINSURED PROPERTY

Commercial Banking Company of Sydney	Picton	$13 000
Post Office	Picton	150
Post Office	Warilla	1 200
Post Office	Thirroul	580
Telephone Exchange	Albion Park	380
Telephone Exchange	Warilla	420
T.V. Translator	Knights Hill	120
Court House	Berrima	100
Public School	Robertson	550
Police Sergeants' Residence	Crookwell	150
Training Centre	Berrima	1 200
		$17 850

SOME STRUCTURAL DAMAGE CAUSED BY THE 1973 PICTON EARTHQUAKE

by R. J. Dayeh

Experimental Building Station
Department of Housing and Construction
North Ryde, N.S.W.

SUMMARY

In the Robertson area, three buildings reported to have been damaged by the earthquake were inspected three days after the event. It is concluded that only trifling damage occurred to buildings of a normal standard of construction.

INTRODUCTION

On 10 March 1973 at approximately 05.00 EST an earth tremor shook eastern New South Wales. Some damage was reported in the Robertson district, and the author visited Robertson on 13 March 1973 to assess new structural damage allegedly caused by the earthquake.

The time available did not allow a general survey of buildings in the area, in fact only four buildings (three of which were reported to have been damaged) were inspected. These buildings were:

Robertson Police Station;
Robertson Public School;
A farmhouse three kilometres north of Robertson;
A brick amenities block in the same area as the farmhouse.

ROBERTSON PUBLIC SCHOOL

Construction

There are three types of construction in the school:

(i) Dimensioned-stone construction for the original school building (about 100 years old).
(ii) Brick, for a detached toilet block and extension to the original building.
(iii) Timber for a building containing three classrooms situated east of the main block.

Damage

Generally neither the brick additions nor the timber building showed any apparent damage. The old stone building, however, showed signs of strain. Externally the damage consisted of the movement of lintels over windows in the northern and southern walls and the movement of the top three courses of stonework in the southwest corner of the building (Fig. 1).

Internally the walls of the school were plastered and cracking was more detectable. Generally cracks appeared in the most likely locations, viz. at ends of lintels and sills, at junctions of walls and ceilings, and at intersections of walls (Figs. 2, 3). In addition, one of the north-south walls sustained a crack near the ceiling extending for the full length of the wall (Fig. 4). These fine cracks may extend right through to the external walls, where they would be indistinguishable from other fine cracking.

ROBERTSON POLICE STATION

Construction

The building is of brick construction. Walls were plastered internally and painted externally, so cracking was readily detectable.

Damage

The damage consisted of small hairline cracks. Cracking did not occur in all walls, but where it did occur it coincided with previously repaired cracks. No photographs were taken because of the fineness and scarcity of the cracks.

FARMHOUSE, COOLONG ROAD, NORTH OF ROBERTSON

Construction

The main part of the building is of random stone construction with brick corners and window and door surrounds. A timber addition adjoins the main house. Generally the building appeared to be of dubious structural soundness (Fig. 5).

Damage

By coincidence the building had been whitewashed recently, so cracking was easily visible. Mortar debris and fallen plaster under the cracked walls made it obvious that nothing had been touched since the earthquake.

All the walls of the farmhouse were cracked. The cracks usually followed the interfaces between brickwork, at corners and window and door surrounds, and the rest of the stone walls. Diagonal cracking also occurred at the ends of

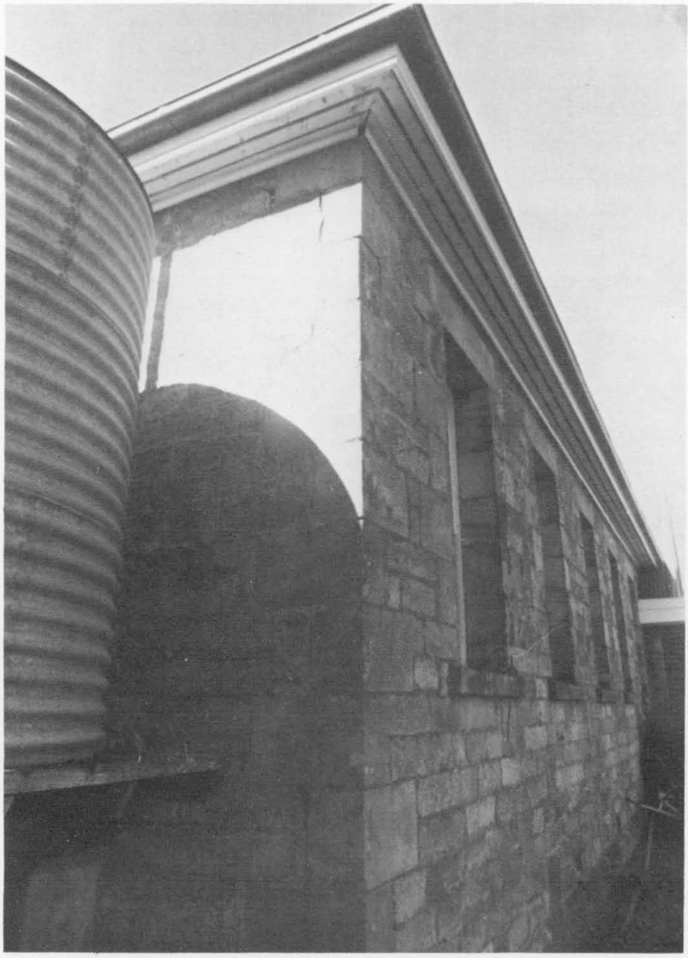


Fig. 1. Close-up of southwest corner, 25-mm north-south movement in the top three courses.

walls (Fig. 6). In addition to the wall cracks, the chimney, which is built in the timber section of the house, sheared at the collar and the top moved 50 mm (Fig. 7). Similarly one of the brick piers carrying the verandah posts sheared and the top portion of the pier moved 20 mm (Fig. 8).

Brick amenities building

This building, of standard brick construction and situated about one kilometre from the farmhouse, was inspected to compare the farmhouse damage with that experienced by a conventional building. No sign of damage to the brick building could be found.

CONCLUSION

It may reasonably be assumed that the buildings inspected were those most seriously damaged in the area, no others having been reported. It appears that the earthquake did only trifling damage to buildings of a normal standard of construction in the Robertson area.

Fig. 2. East-west internal wall, 2-mm-wide crack at doorway.

Fig. 3. East-west internal wall, cracking over window and at corner.

Fig. 4. North-south internal wall, horizontal crack for full length of wall 30 cm below ceiling.

Fig. 5. The farmhouse viewed from north.

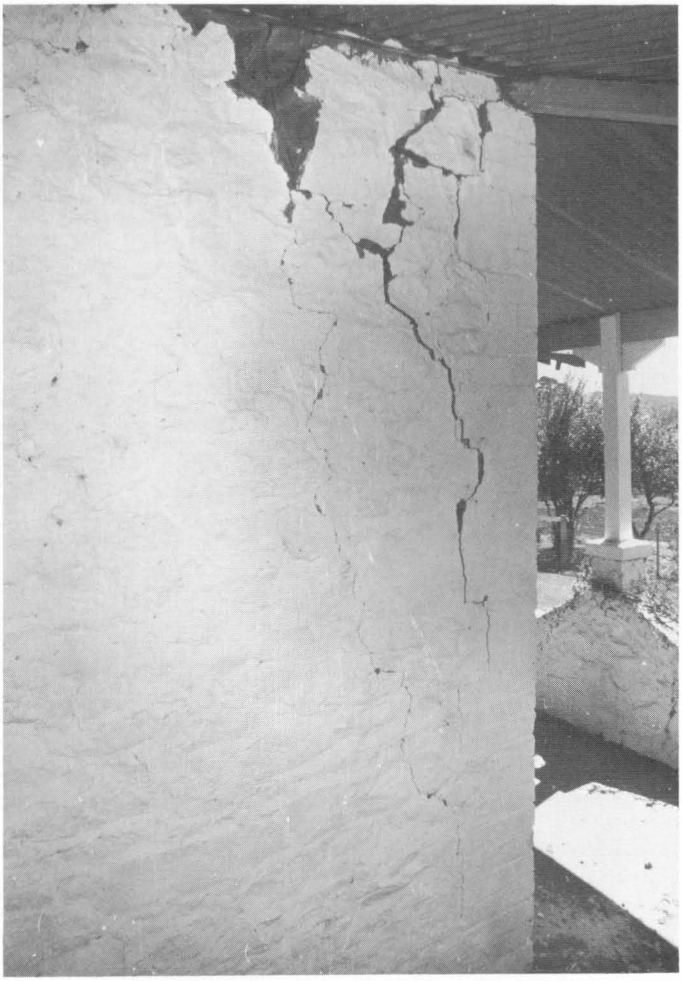


Fig. 6. Extensive corner cracking, spalling of mortar.

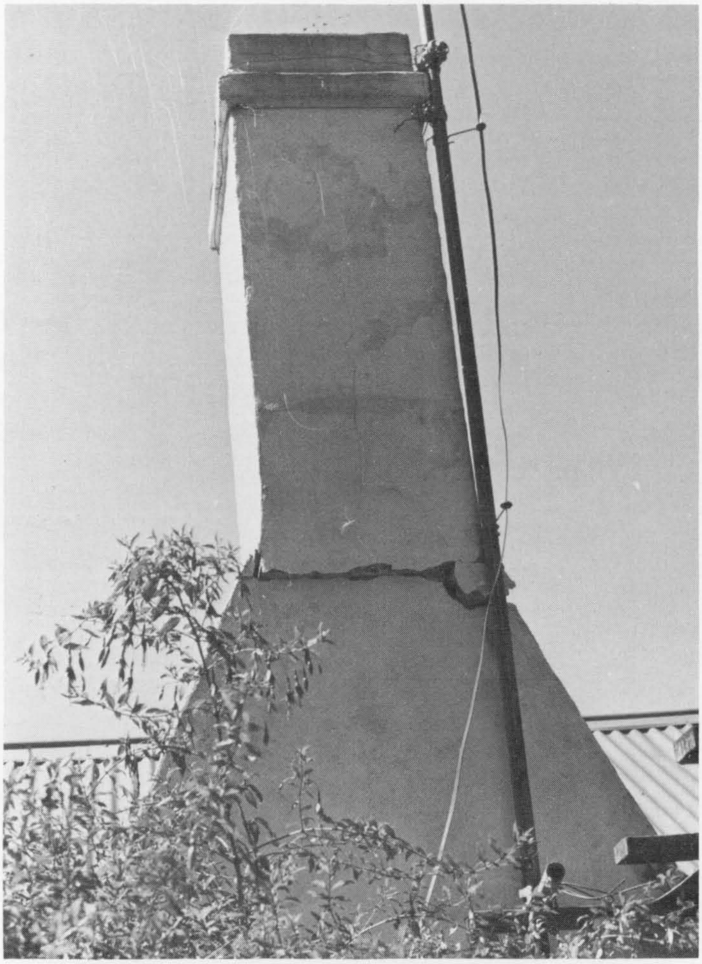


Fig. 7. Sheared chimney stack, 50-mm movement in east-west direction.

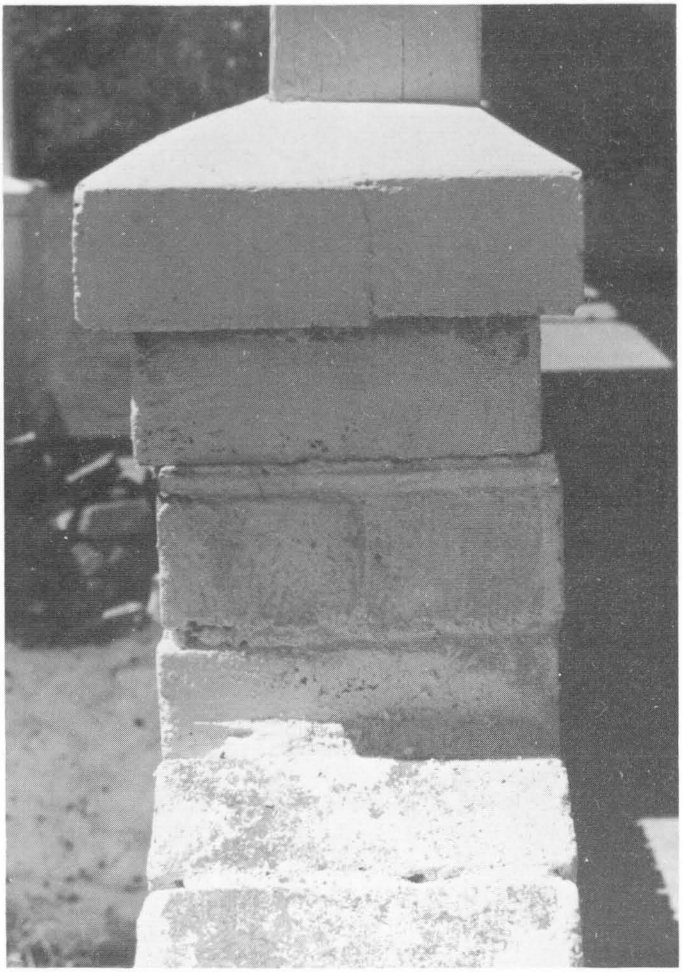


Fig. 8. Sheared brick pier under verandah post, 20 mm horizontal movement.

SEISMOTECTONICS OF SOUTH AUSTRALIA AND EARTHQUAKE TRENDS

by I. C. F STEWART*

Department of Economic Geology,
University of Adelaide

SUMMARY

Earthquake strain release maps are commonly used to delineate seismicity and to calculate risk factors. This approach ignores the variability in rate of earthquake occurrence and the interdependence in time and space of epicentres. A more rigorous method is suggested by plate tectonic studies, whereby events that occur along one section of a zone of fracturing may be expected to affect later activity along adjacent sections of the zone.

It has been shown in the Aleutians and elsewhere that large events have a greater probability of occurring in seismicity gaps than in regions of recent activity. This suggests that strain release and recurrence relations are useful for describing past activity and outlining active areas generally, but of little use in predicting events in a specific region. In South Australia an attempt has been made to define seismicity in terms of several linear zones of crustal shearing. There are insufficient data to give accurate recurrence formulae for localized areas of interest. However, as in California, the space/time occurrence of larger events in South Australia suggests a pattern, which may be of some use in indicating where the risk is greatest.

INTRODUCTION

Since the establishment of the South Australian seismograph network in 1963, most earthquakes that cause damage within the State are recorded and located. Most of the events located, currently about 100 per year, have been recorded since 1969, when high-gain equipment was first installed. The present seismograph network should detect and probably locate any event of Richter magnitude ML = 2.5 or greater within the State. Hypocentres are usually calculated to within 5 km and magnitudes to within 0.2 unit.

Seismicity studies in South Australia to 1971 have been summarized by Sutton & White (1968) and Stewart, Slade & Sutton (1973). Epicentres located since 1967 are shown in Figure 1 and indicate the main seismic regions. The paucity of small located earthquakes away from the Flinders Ranges/Mount Lofty Ranges area may reflect the problems of locating events outside the polygon of seismographs. The main activity coincides with the ancient tectonic feature known as the Adelaide Geosyncline (Fig. 2) and its extensions to the northwest and southeast of the State. The centres of population of South Australia tend to be situated within the same region.

STRAIN AND ENERGY RELEASE MAPS

Activity in a region is often represented by maps of strain release or tectonic flux per unit area in a given time (e.g. Ryall, Slemmons & Gedney, 1966). Energy release is proportional to the square of strain release (St Amand, 1956), and hence energy maps are similar in appearance to strain maps. The energy release taken over one-fifth geocentric degree squares is represented in a density form with 10 levels in Figure 3, for most of the active region of South Australia from April 1967 through October 1973. The darker areas signify greater energy release due to a combination of more or larger events than in surrounding areas. The smoothed energy density plot (Fig. 4) removes some of the minor local variations and provides a reasonable representation of the areas over which seismic activity may be expected to occur.

Strain contour maps are often used to define seismicity for risk studies and indicate return periods for ground velocities. The levels in the contour maps are often assumed to have some exact significance, but this may largely be unjustified. The return periods for ground motion of given amplitudes, velocities, or accelerations may be calculated from empirical formulae and the recurrence relations for a particular area. The parameters used for calculating the amplitudes depend considerably on site and source conditions. In South Australia, an upper limit to the amplitude A cm due to an event of magnitude ML at epicentral distance Δ km is given by

$$A = 5 \times 10^{-6} \exp(1.7ML)\Delta^{-0.8} \quad (1)$$

where the expression is taken to apply at 1 Hz.

* Present address: University of Newfoundland, St John's, Canada.

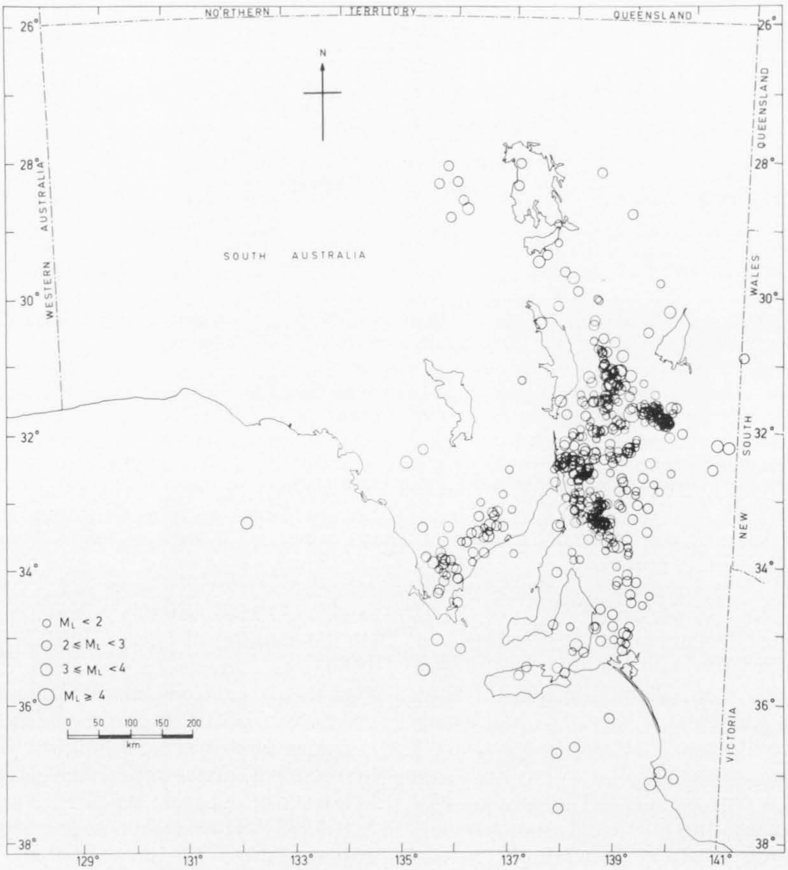


Fig. 1. South Australian earthquake epicentres, 1967-1973.

This is based on magnitude studies by Stewart (1972a).

The contour or density maps of strain release or ground velocities provide a good description of past activity, but are of limited value in prediction or risk studies since seismic activity tends to vary in space and time. Seismicity is usually expressed by recurrence relations of the form

$$\text{Log } N = a - bM \qquad (2)$$

where N is the number of events above magnitude M occurring in a given area and time interval, and a and b are constants. The values of a and b in (2) vary considerably with time (e.g. Shlien & Toksoz, 1970), and are also very sensitive to the occurrence of a few large events, and this should be remembered when extrapolating such equations to obtain the expected frequency of large earthquakes.

In studies of seismic risk, seismic areas are often subdivided into zones to obtain localized recurrence equations. But Sanford & Singh (1968) state that at least 150 events are needed to define b in equation (2), assuming constant activity, and the data available are seldom sufficient to define b accurately except on a regional scale. In South Australia about 300 events of $ML = 2$ or greater have been located since 1967, and hence b is satisfactorily defined only for the whole State.

It is pointless to extrapolate results from a few years to tens of hundreds of years in recurrence relations, except possibly over large areas where local fluctuations may tend to be smoothed out. In small areas (e.g. of the order of one degree square) the data used for short-term recurrence relations tend to represent an arbitrary subset of the long-term data, and are unlikely to give a true picture of the mean activity. Records of swarm sequences (e.g. Hagiwara & Iwata, 1968) indicate the extent to which local activity may vary.

Recent reports on Australian seismicity by Bubb (1971) and McCue (1973) have relied

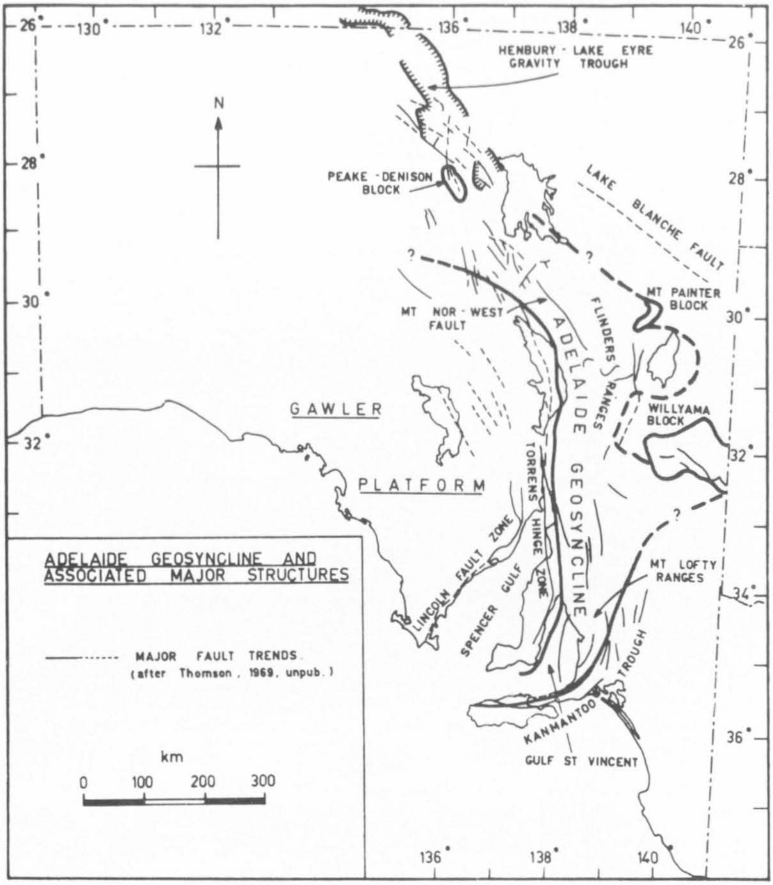


Fig. 2. Main tectonic features of South Australian seismic zones.

on subdividing seismic areas into small zones and then using contour maps of strain or ground velocity as a guide to future activity. This approach is unsound, as no allowance is made for the statistical nature of earthquakes or the underlying tectonic processes that cause them. It is also likely that the historical records of large events are incomplete, leading to false conclusions about the macroseismicity. Strain maps provide only a guide to activity during the period over which the data were recorded, and are not necessarily a reliable indication of future seismicity. Return period analysis of strain or velocity depends on the uniformitarian principle—the past is the key to the future—which is statistically unwise since the tectonic processes are irreversible.

The recurrence relation for the whole of South Australia using data from April 1967 through October 1973 (303 events) is given by

$$\text{Log } N = 3.02 - 0.69\, ML \qquad (3)$$

but the values are still subject to small variations as more data are included. From (3) it appears that at least one event of $ML > 5$ should occur every 3 years.

TECTONIC MODELS AND PREDICTIONS

A more rigorous approach to defining risk follows from an appreciation that earthquakes tend to be interdependent in space and time, and are not merely isolated processes in subsets of a seismic region.

Plate tectonic theory suggests that seismic zones cannot in general be considered as isolated. The structure and movements of an area have to be studied as a whole rather than partitioned. A structural model has been developed by Stewart & Mount (1972) which appears to account for most of the observed seismicity and many geological features of the State. The active zones of the Adelaide Geosyncline are described in terms of broad regions of sub-

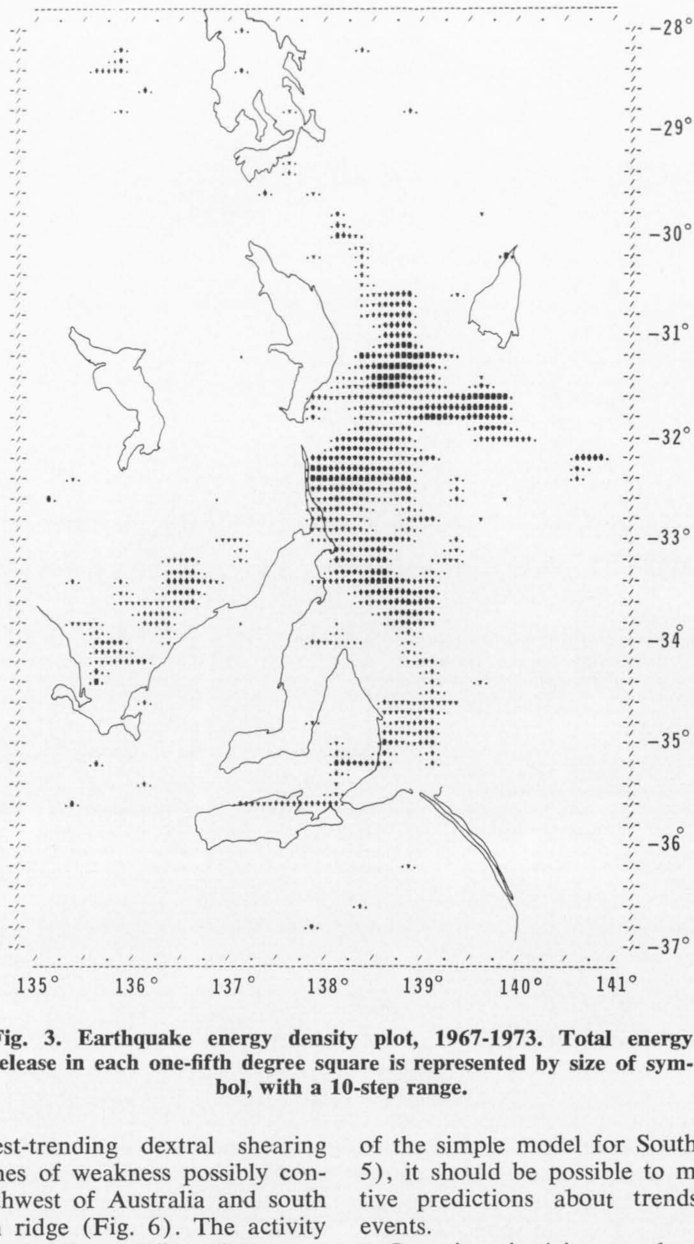


Fig. 3. Earthquake energy density plot, 1967-1973. Total energy release in each one-fifth degree square is represented by size of symbol, with a 10-step range.

parallel northwest-trending dextral shearing (Fig. 5). The lines of weakness possibly continue to the northwest of Australia and south to the mid-ocean ridge (Fig. 6). The activity is postulated to arise from differential movement between the stable areas on either side of the Geosyncline, with approximately constant rate of strain build-up along the whole zone. The majority of the earthquakes occur in the upper 20 km of the crust (Stewart, 1972b). This is similar to activity observed in the San Andreas Fault, also a region of dextral shear (e.g. Scholz, Wyss & Smith, 1969; Savage, 1971). The earthquakes at the surface appear to accommodate creep at depth. On the basis of the simple model for South Australia (Fig. 5), it should be possible to make some tentative predictions about trends in the larger events.

Gaps in seismicity on plate boundaries are likely sites for future large (ML > 7) earthquakes (Sykes, 1971; Kelleher, 1972), in order to equalize release of strain per unit length over the whole length of fault zone. Hence there is some regularity in space and time of large events, the pattern of which may progress regularly along a fault zone, leading to the possibility of prediction.

It has been suggested by Savage (1971) that kinematic waves propagated along the fault

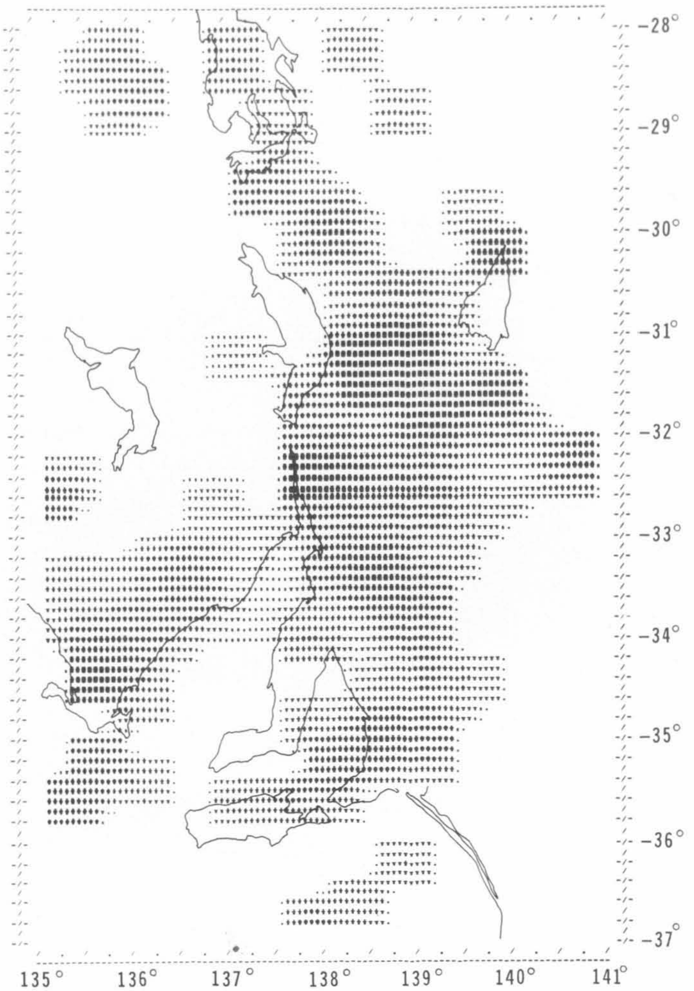


Fig. 4. Smoothed earthquake energy density plot, 1967-1973. Same data as in Figure 3, after smoothing.

zone cause slippage on locked sections of fault if the waves are of sufficient amplitude. The migration of activity is more evident from the larger events and the activity of large earthquakes appears more regular in space and time than smaller events (e.g. Kelleher, 1970). Trends applying to lower magnitudes exist over short fault lengths (of order of 100 km), and correspond to waves of lower amplitude. The effects of the smaller waves tend to be confined by the more firmly locked sections of the fault.

Trends in events of $ML > 5$ in California have been studied by Wood & Allen (1973). Taking an area within 30 km of the San Andreas Fault, the trend plotted in Figure 7 was obtained. Similar studies have been carried out in South Australia, where activity is dominated by north-south trends, and hence variation of epicentral latitude with time has been analysed. In all sequences of events, in South Australia, including the sequences of mainshock and aftershocks, there is a tendency for activity to proceed from north to south. Kelleher (1972) states that the general direction of rupturing during a major earthquake can be inferred from the progression of aftershock epicentres with time along the zone.

The latitude versus time plot of all South Australian earthquakes from 1967 through July 1973 is shown in Figure 8. The concentration of epicentres towards the middle latitudes is due in part to the detection bias of the seismo-

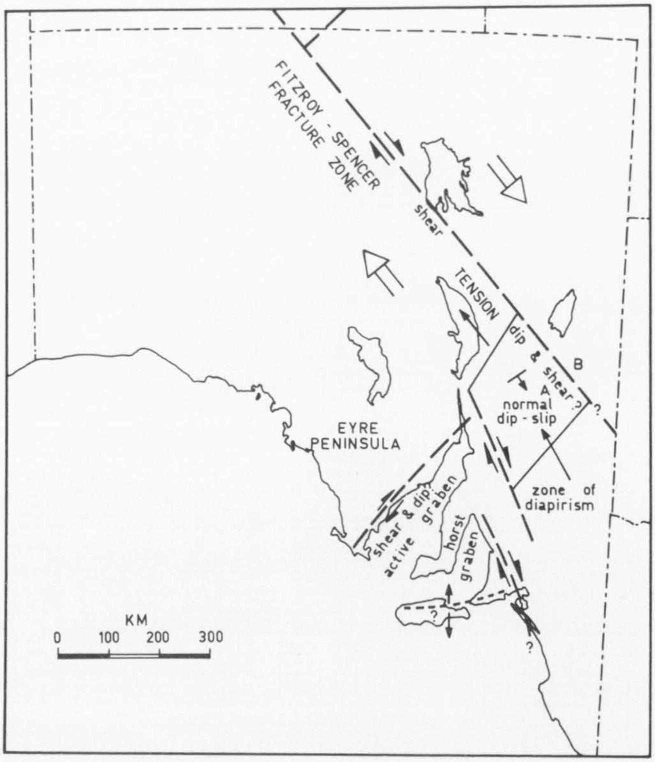


Fig. 5. Proposed plate tectonic model for South Australia.

Fig. 6. Hypothetical extensions of South Australian fracture system.

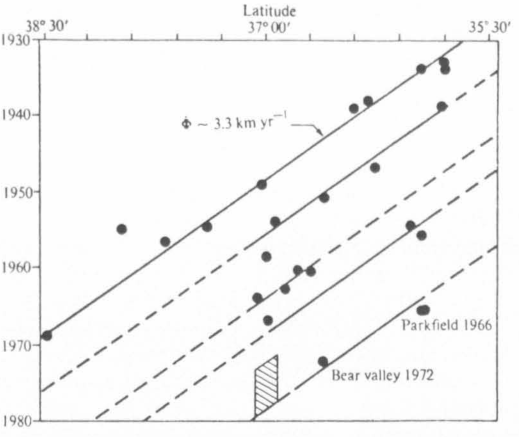


Fig. 7. Epicentre space/time trends for San Andreas Fault system (after Wood & Allen, 1973). From evidence of seismic migration pattern and latitude of maximum recurrence of events, it is predicted that the next earthquake of magnitude M $\geqslant$ 5 will occur within the hatched area.

graph network. The smaller events are too numerous to give distinct trends, and may be regarded as noise. Some of the short, apparently horizontal, trends in Figure 8 probably represent sequences up to about 100 km in length, propagated at several kilometres per day. Taking only events of ML > 3.3, some of the short trends are evident (Fig. 9). Events of ML > 4.5 for South Australia since 1930 are plotted in Figure 10. As mentioned earlier, fewer earthquakes were located before the establishment of the South Australian seismograph network in 1963. In Figure 10 a set of parallel lines are fitted to the data points; this assumes that north-to-south trends occur at approximately the same velocity and time interval throughout the seismic region. The fit of trends to data is no worse than that of Wood & Allen (Fig. 7), and may provide a basis for prediction. For example, in Figure 10 there appears to be a lack of recent larger events towards the higher south latitudes. The propagation velocity is about 17 km per year, compared with 3 km per year on the San Andreas Fault (Wood & Allen, 1973).

The larger South Australian earthquakes tend to occur in gaps of low or no recent activity, as observed elsewhere (Sykes, 1971). This is shown by a comparison of earthquakes recorded from 1967 through 1971 (Fig. 11) with those from 1972 through October 1973 (Fig. 12). It has not been possible to obtain accurate estimates of fault lengths associated with the larger shocks in South Australia, although an event of ML = 5 may have a rupture length of about 15 km (after Wyss & Brune, 1968). The 1972 Simpson Desert earthquake of ML = 6.2 had an aftershock zone 120 km in length (Stewart & Denham, 1974), indicating that strain may be released over appreciable distances in a short time. Elsewhere it has been observed that the rupture or aftershock zones of major earthquakes tend to abut closely in space (Kelleher, 1972; Kelleher, Sykes & Oliver, 1973) giving some indication of the expected maximum magnitude of adjacent events. When reliable estimates of fault lengths become available in South Australia similar studies may prove useful in predicting magnitude as well as time and location of earthquakes.

CONCLUSION

In general it appears unsound to rely on strain or other contour maps to give localized gradations of risk. The data used for recurrence

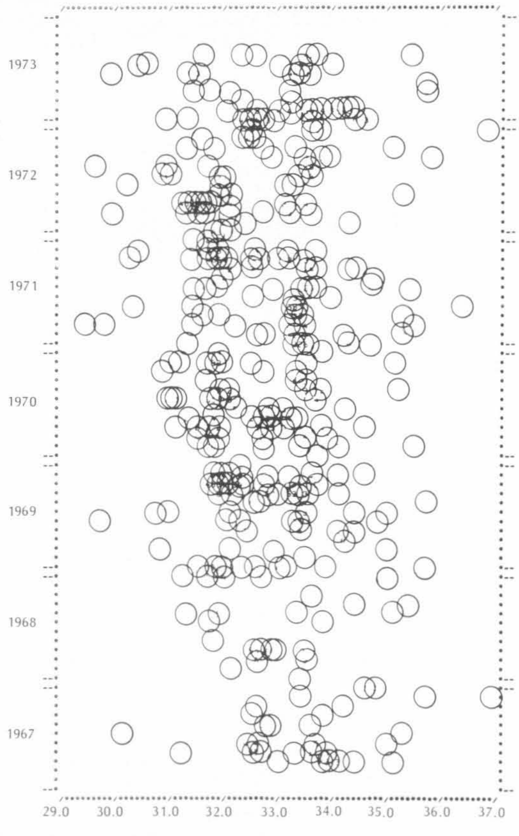


Fig. 8. Latitude versus time plot for South Australian epicentres (all data).

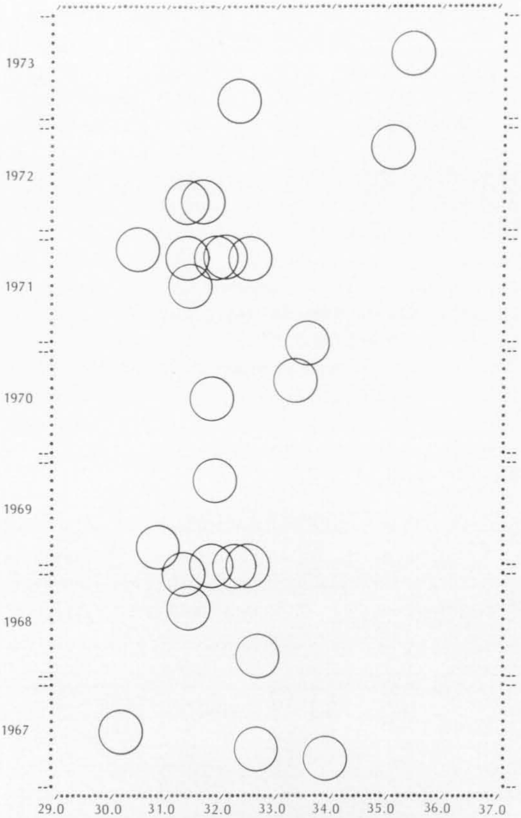


Fig. 9. Latitude versus time plot for South Australian epicentres east of longitude 137°E (ML > 3.3).

curves in small zones are only a subset of the long-term data set, and are subject to appreciable fluctuations.

In South Australia, for risk studies it is probably safest at present to consider the State as composed of at most two seismic zones, the Adelaide Geosyncline and Eyre Peninsula. Each zone, including the present seismicity gaps, should be considered as an area of uniform risk, the risk factor to be derived from the total activity and area of the zone. The earthquake trends and tectonic model can then be used to give a relatively short-term guide to the expected location of larger events. Monitoring of premonitory changes in seismic velocities may also be employed to give forewarning of large shocks in potentially active areas (e.g. Aggarwal et al., 1973; Scholz, Sykes & Aggarwal, 1973). Preliminary studies of velocity changes in the South Australian crust are inconclusive at present, possibly owing to a lack of suitable sources or to the siting of seismograph stations. All prominent faults in the seismic zones should be regarded as potentially active, since they represent the fracturing of the surface cover rocks by deep crustal and upper mantle shear forces, which may be manifest over an appreciable area.

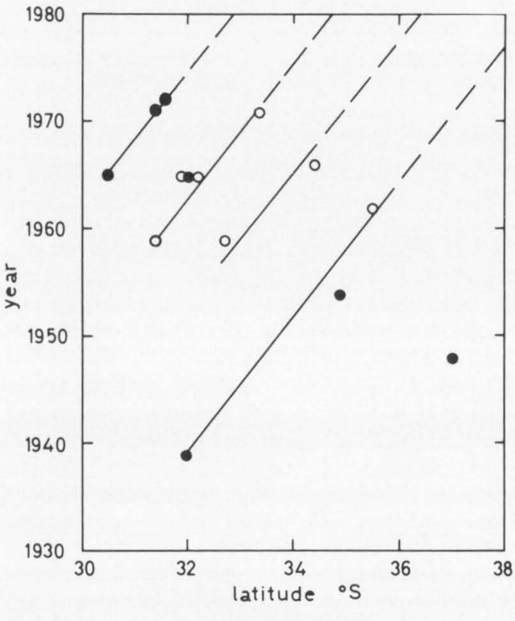


Fig. 10. Epicentre space/time trends for main South Australian earthquakes east of longitude 137°E. Open circles M = 4.5-4.9; black circles M ⩾ 5.0.

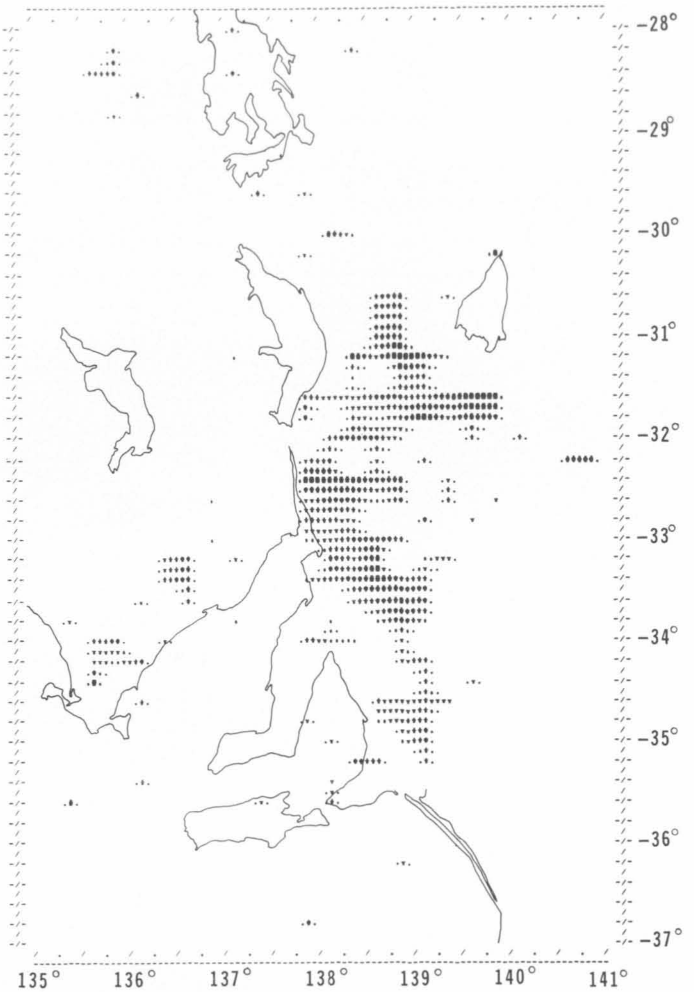


Fig. 11. Earthquake energy density plot, April 1967 through 1971. See explanation to Figure 3.

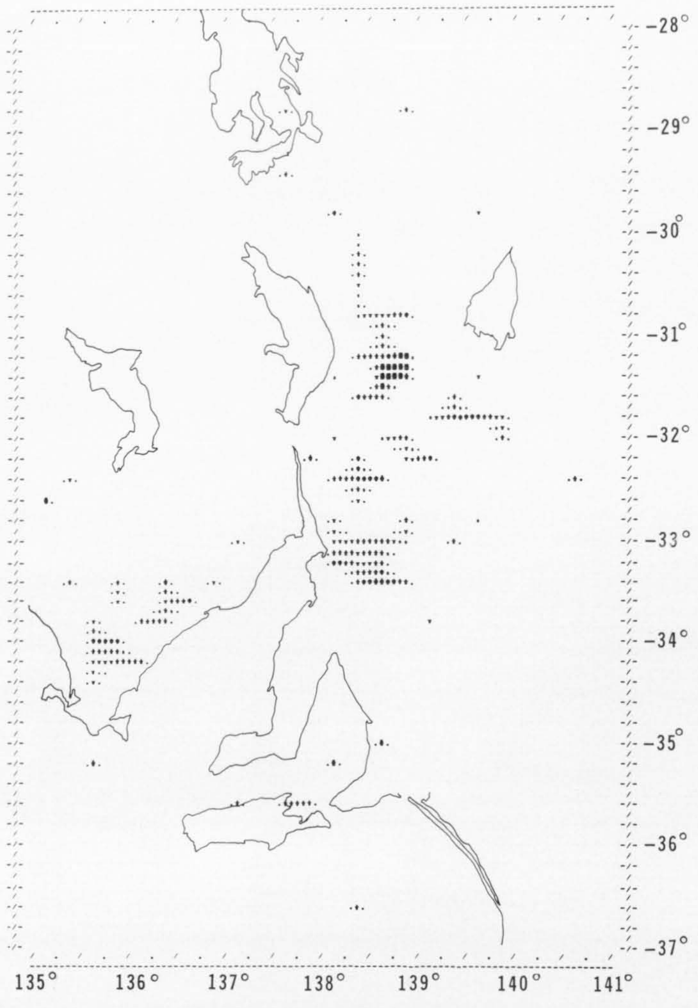


Fig. 12. Earthquake energy density plot, 1972 through October 1973. See explanation to Figure 3.

REFERENCES

AGGARWAL, Y. P., SYKES, L. R., ARMBRUSTER, J., & SBAR, M. L., 1973—Premonitory changes in seismic velocities and prediction of earthquakes. *Nature,* 241, 101-104.

BUBB, C. T. J., 1971—On the seismicity of Australia. *Aust. Comm. Dept of Works.*

HAGIWARA, T., & IWATA, T., 1968—Summary of the seismographic observation of Matsushiro swarm earthquakes. *Bull. Earthquake Res. Inst. Tokyo Univ.,* 46, 485-515.

KELLEHER, J. A., 1970—Space-time seismicity of the Alaska-Aleutian seismic zone. *J. Geophys. Res.,* 75, 5745-5756.

KELLEHER, J. A., 1972—Rupture zones of large South American earthquakes and some predictions. *J. geophys. Res.,* 77, 2087-2103.

KELLEHER, J., SYKES, L., & OLIVER, J., 1973—Possible criteria for predicting earthquake locations and their application to major plate boundaries of the Pacific and the Caribbean. *J. geophys. Res.,* 78, 2547-2585.

MCCUE, K. F., 1973—On the seismicity of Western Australia. *Report, Imperial College, London.*

RYALL, A., SLEMMONS, D. B., & GEDNEY, L. D., 1966—Seismicity, tectonism and surface faulting in the western United States during historic time. *Bull. Seismol. Soc. Am.,* 56, 1105-1135.

SANFORD, A. R., & SINGH, S., 1968—Minimum recording times for determining short-term seismicity from microearthquake activity. *Bull. Seismol. Soc. Am.,* 58, 639-644.

SAVAGE, J. C., 1971—A theory of creep waves propagating along a transform fault. *J. geophys. Res.*, 76, 1954-1966.

SCHOLZ, C. H., WYSS, M., & SMITH, S. W., 1969—Seismic and aseismic slip on the San Andreas fault. *J. geophys. Res.*, 74, 2049-2069.

SCHOLZ, C. H., SYKES, L. R., & AGGARWAL, Y. P., 1973—Earthquake prediction: A physical basis. *Science*, 181, 803-810.

SHLIEN, S., & TOKSOZ, M. N., 1970—Frequency-magnitude statistics of earthquake occurrences. *Earthquake notes*, 41 (no. 1), 5-18.

ST AMAND, P., 1956—Two proposed measures of seismicity. *Bull. Seismol. Soc. Am.* 46, 41-45.

STEWART, I. C. F., 1972a—Microearthquakes and tectonics of South Australia. *Ph.D. Thesis, University of Adelaide* (unpubl.).

STEWART, I. C. F., 1972b—The frequency-depth relation for South Australian earthquakes. *Geophys. J. Roy. Astr. Soc.*, 29, 139-145.

STEWART, I. C. F., & DENHAM, D., 1974—Simpson Desert earthquake, central Australia, August 1972. *Geophys. J. Roy. Ast. Soc.*, 39, 335-341.

STEWART, I. C. F., & MOUNT, T. J., 1972—Earthquake mechanisms in South Australia in relation to plate tectonics. *J. Geol. Soc. Aust.*, 19, 41-52.

STEWART, I. C. F., SLADE, A., & SUTTON, D. J., 1973—South Australian seismicity 1967-1971. *J. Geol. Soc. Aust.*, 19, 441-452.

SUTTON, D. J., & WHITE, R. E., 1968—The seismicity of South Australia. *J. Geol. Soc. Aust.*, 15, 25-32.

SYKES, L. R., 1971—Aftershock zones of great earthquakes, seismicity gaps, and earthquake prediction for Alaska and the Aleutians. *J. geophys. Res.*, 76, 8021-8041.

WOOD, M. D., & ALLEN, S. S., 1973—Recurrence of seismic migrations along the central California segment of the San Andreas fault system. *Nature*, 244, 213-215.

WYSS, M., & BRUNE, J. N., 1968—Seismic movement, stress, and source dimensions for earthquakes in the California-Nevada region. *J. geophys. Res.*, 73, 4681-4694.

Page 52 is blank.

THE EDEN FAULT AND ITS EFFECT ON THE DEVELOPMENT OF ADELAIDE

by JONATHAN SELBY

Engineering Division,
S.A. Department of Mines

SUMMARY

The 1954 Adelaide earthquake served to focus awareness of possible seismic effects on local civil engineering structures.

The epicentre of this tremor was traced to the Eden Fault, which forms the inland boundary of the coastal plain area now almost fully occupied by the city.

An investigation to delineate the fault line by geophysical means was carried out in 1963. Subsequently the site of a proposed multi-storey medical centre was moved away from the fault zone.

Department of Mines officers now report on most projected subdivisions in hills and foothills areas with particular reference to slope stability in the event of an earthquake.

INTRODUCTION

The effects of the Adelaide earthquake of 1954 may best be illustrated by a quotation from the original description by Kerr Grant (1956):

'In the early hours of 1 March 1954, most of the inhabitants of Adelaide were awakened by a loud rumbling noise followed by a shaking severe enough to crack the walls and loosen plaster from many houses. For most persons in Adelaide, this was their first experience of an earthquake, and it is the first record in almost a hundred years of any movements in the earth's crust in the vicinity of the city. Although a relatively minor one by the standards of countries prone to earthquakes, it was sufficiently severe to cause material damage to many buildings, as the possibility of earthquake damage had never been taken into consideration in their construction. There were no injuries as a result of the earthquake.'

A maximum intensity of 8 on the Modified Mercalli Scale was experienced; estimates of the duration of the shock ranged from 5 to 20 seconds with minor aftershocks up to two days after the event. The Richter magnitude has been estimated as ML = 6 by Dr I. C. F. Stewart of Adelaide University (pers. comm.).

The main epicentre, located by isoseismal intensity contours, was in the zone of the Eden Fault near the suburb of Darlington, with a probable second epicentre near Beaumont (Fig. 1). Another estimate of the epicentre using seismograph data, has been made by Bolt (1956). His calculations place it within 3 km of the Eden Fault, close to the area of greatest damage. The depth of focus was considered to be shallow (less than 3 km) by both Bolt (1956) and Kerr Grant (1956) but there were no reports of displacement of the Eden Fault, which is covered by alluvial outwash fans along most of its length.

The earthquake caused considerable damage (Fig. 2) to houses in the Adelaide suburban area. Two houses sited above the presumed epicentre at Darlington were irreparable. According to Kerr Grant (1956) the damage effects were misleadingly large for an earthquake of this intensity owing to the age and unsuitable construction of many suburban houses and to the pre-existence of minor cracks due to other causes.

GEOLOGY OF ADELAIDE

A simplified geological map of Adelaide (Fig. 1) shows the contrast between the strong Proterozoic siltstones and quartzites of the Mount Lofty Ranges and the generally unconsolidated soils* of the Adelaide plains. Several faults occur within the ranges and these are now regarded as potentially active. The southern extension of the Para Fault is covered, beneath Adelaide, by several hundred metres of Cainozoic silt and clay soil. An outcrop of Recent loosely consolidated estuarine deposits (St Kilda Formation) occurs north and west of the city area, and the engineering significance of this deposit will be discussed later.

REPERCUSSIONS OF 1954 EARTHQUAKE

As well as stimulating a renewed interest in earthquake seismology, the earthquake had three major long-term effects:

(1) A seismograph network, which now comprises seven stations, was set up by the University of Adelaide.

* Soil: This term is used in the Civil Engineering sense.

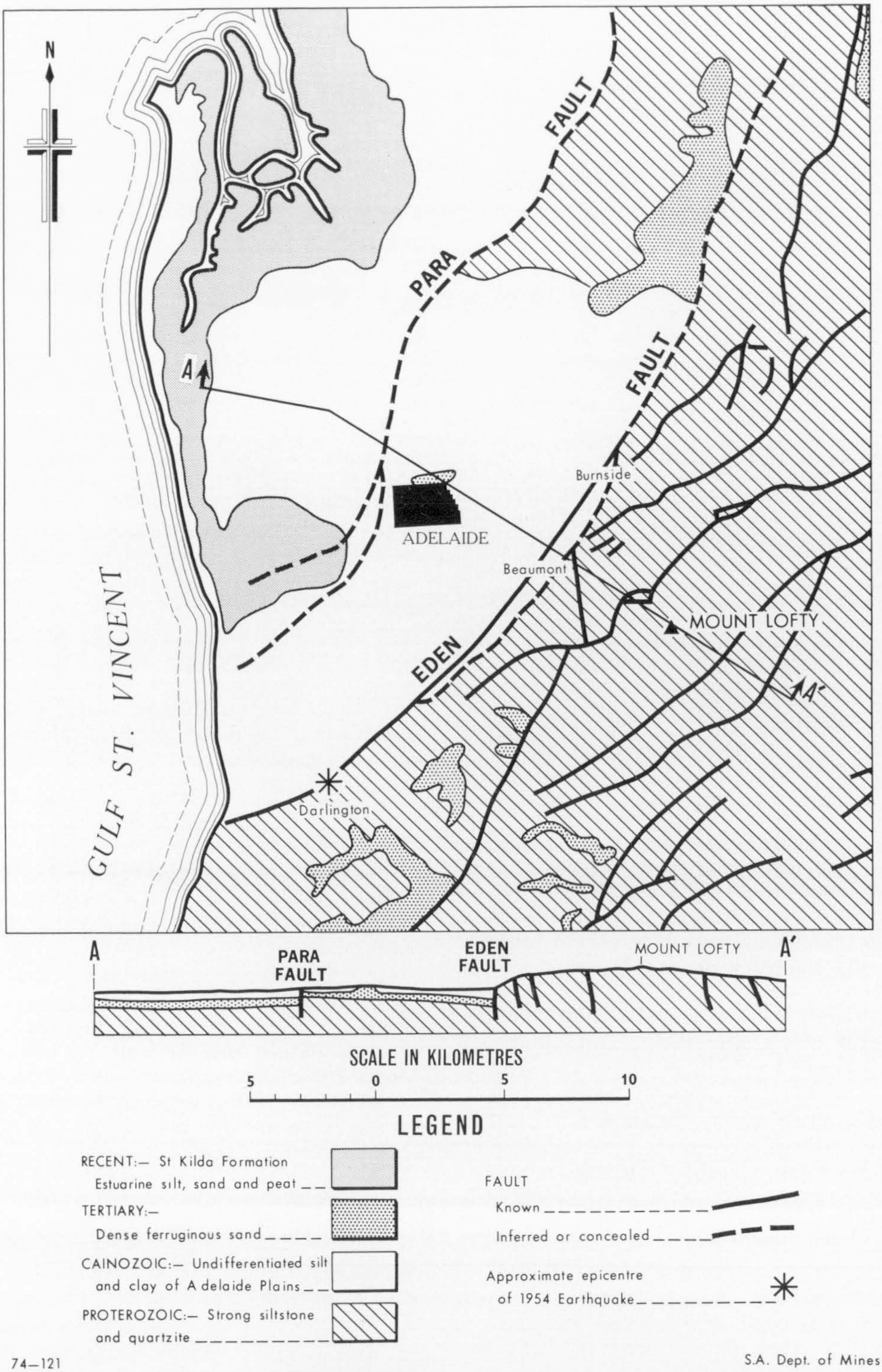


Fig. 1. Simplified geological map of Adelaide.

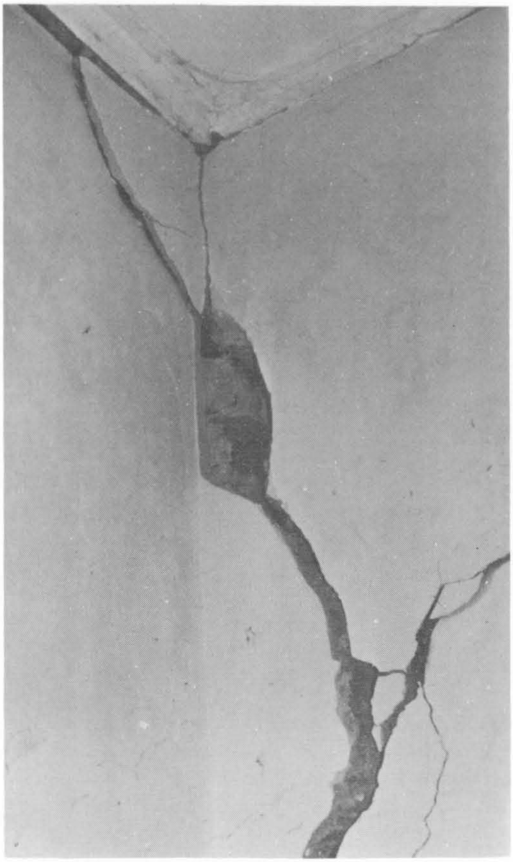


Fig. 2. House wall cracking caused by 1954 earthquake.

(2) An attempt was made to locate the Eden Fault accurately.
(3) There was increased concern for the effects of earthquakes on major civil engineering structures.

Location of Eden Fault

The fault was located successfully by the S.A. Department of Mines by exploiting the density contrast between the Cainozoic soils and Proterozoic rocks. A gravity survey was carried out by Coppin (1964), and selected traverses are shown in Figure 3. In most cases the effect of the fault is revealed by a marked change in gradient of the gravity profile, and the fault plane was assumed to lie at the mid-point of the steepest gradient. The following conclusions may be drawn from the results of this survey:

(1) Under favourable conditions of density contrast the location of the fault can be determined with an accuracy of ± 60 m.
(2) The fault is probably vertical with a maximum throw of about 400 m.
(3) North of Burnside the fault appears to split into several splinter blocks.
(4) As a result of erosion, the existing scarp (Fig. 4) has migrated a considerable distance southwards from the fault (up to 600 m in some areas).

This geophysical method has been used regularly to assist in the location of engineering structures relative to the fault.

Effects on civil engineering structures

The first major structure to be relocated as a result of the 1954 Earthquake was a medical research centre, when an investigation by the S.A. Department of Mines revealed that the originally proposed site was immediately above the fault line (Stapledon, D. H., 1966: S.A. Dept Mines, unpubl. Rep. Bk. 62/135). A new site was chosen about 500 m east of the fault.

The existence of the Kitchener Fault which passes within 180 m of the Kangaroo Creek Dam was a contributing factor in the 1966 change of design to a concrete-faced rock-fill dam, and a recent investigation of the Barossa Dam has attributed the cracking of the concrete arch wall (Fig. 5) to the effects of the 1954 earthquake (Selby, J., 1973: S.A. Dept of Mines unpubl. Rep. Bk. 73/271).

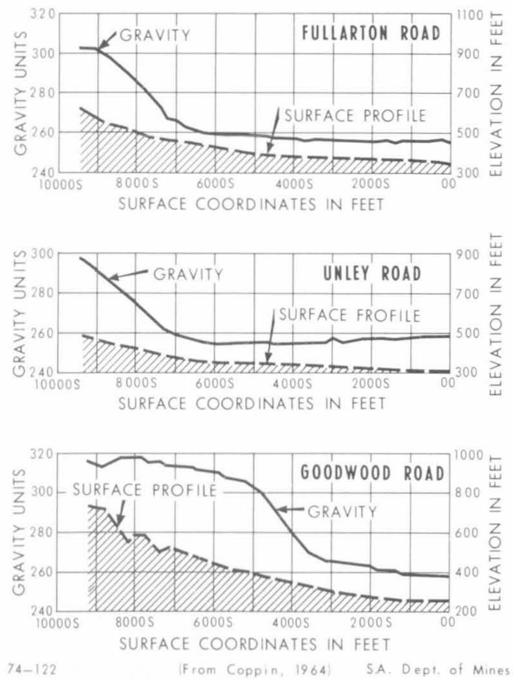


Fig. 3. Gravity profiles across Eden Fault.

Fig. 4. The Eden Fault Scarp from Mount Osmond looking northeast.

No major landslips or rockfalls were reported after the earthquake except for a mudflow, caused by a loosening of the soil on the hillsides combined with the advent of winter rains. A similar landslip has recently taken place along the Gorge Road on the edge of the Kangaroo Creek Reservoir (Fig. 6). Although this was not due to seismic disturbance, it is clear that incipient slides of this type could be set off by a seismic shock.

There is also considerable potential for rockfalls in the Adelaide Hills, mostly as a result of quarrying or civil engineering activity. Figures 7 and 8 show slab and wedge failure slides in a major road cutting south of Adelaide.

Most proposed hills subdivisions are now inspected by geologists of the S.A. Dept of Mines and assessed for foundation conditions and landslip potential. Abandoned quarries within subdivisions are backfilled or stabilized by the developer, and farm earth dams are inspected for stability by engineers of the Engineering and Water Supply Department.

The Recent St Kilda Formation north and west of Adelaide (Fig. 1), mentioned earlier in this paper, consists of a series of loosely consolidated silty organic sands with irregular lenticular peat layers. Figure 9 shows an engineering geological log of this material, whose low in-situ density is clearly demonstrated by the Standard Penetration Test results and by the Static Cone Penetrometer graphs. Areas underlain by this formation are currently being developed as domestic housing sites with suitable civil engineering treatment, but the possible effects of liquefaction under a sustained earthquake shock are difficult to assess.

CONCLUSIONS

There is a need for more reliable methods of predicting major earthquakes based on seismic data currently being collected. A unified Code on Earthquake Engineering is also urgently required. The S.A. Building Code leaves the decision on requirements for earthquake building design to local Councils; government engineers have adopted a horizontal acceleration of 0.08g for all major civil engineering structures, and all multi-storey blocks are located away from fault lines.

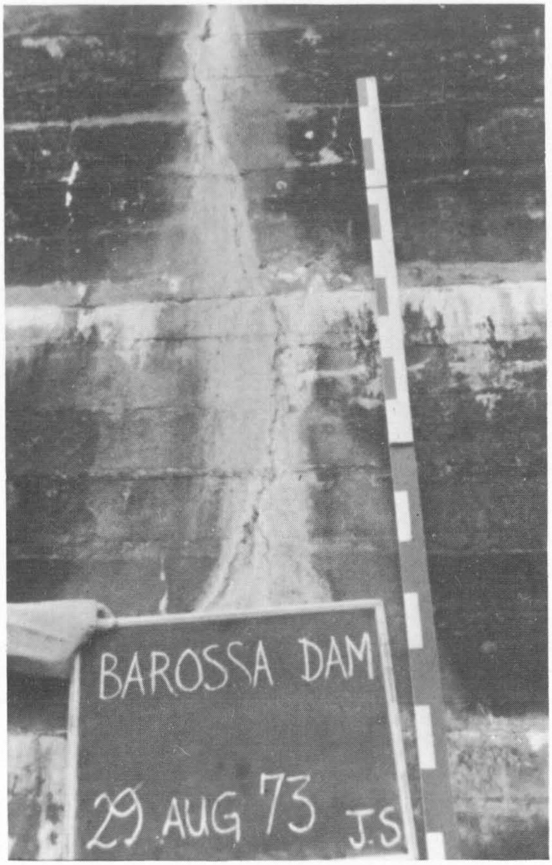


Fig. 5. Vertical crack in wall of arch dam probably caused by 1954 earthquake.

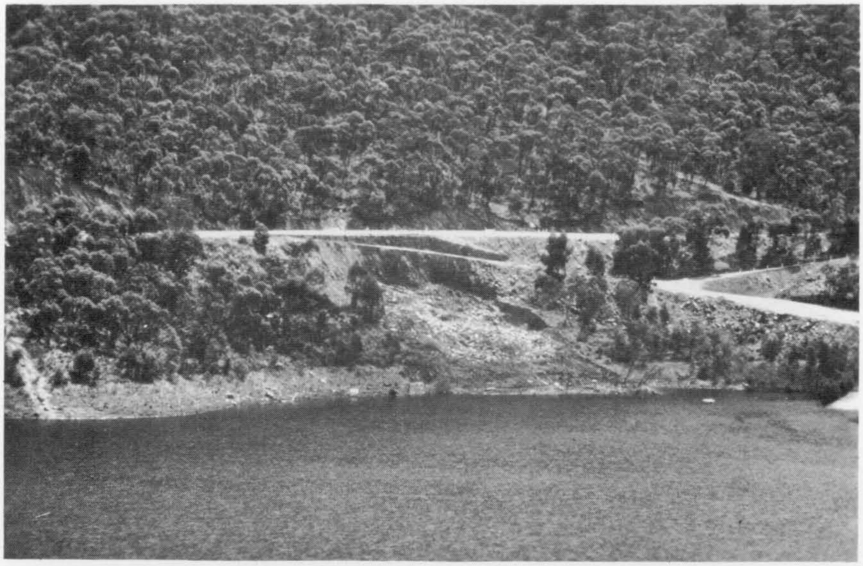


Fig. 6. Recent landslip on edge of Kangaroo Creek Reservoir.

Fig. 7. Slab slide in road cutting south of Adelaide.

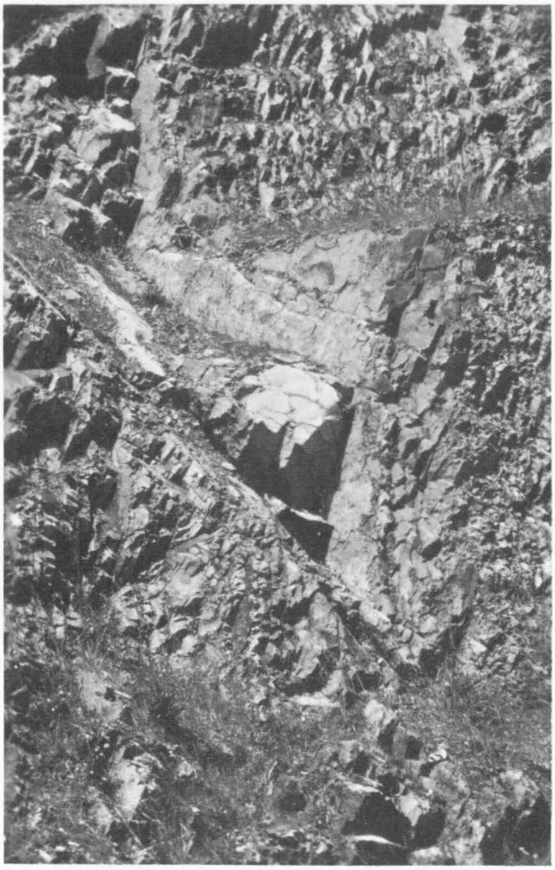


Fig. 8. Wedge slide in road cutting south of Adelaide.

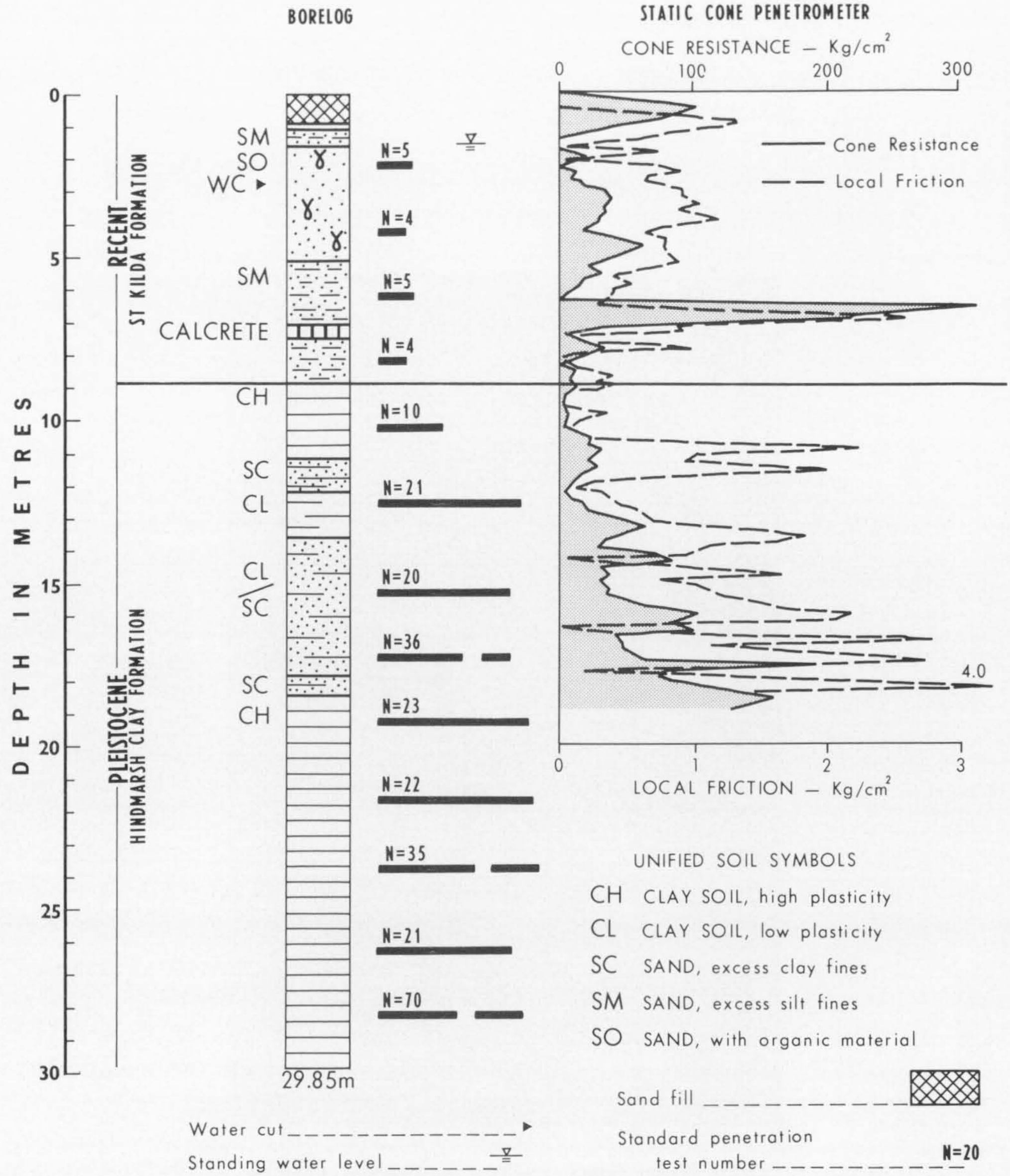


Fig. 9. In situ engineering properties of St Kilda Formation.

REFERENCES

BOLT, B. A., 1956—The epicentre of the Adelaide Earthquake of 1954, March 1. *J. Proc. R. Soc. N.S.W.* 40(II).

COPPIN, R. J., 1964—Gravimetric investigation of the Eden Fault-Burnside Fault zone. *S.A. Dept Mines Min. Review*, 120.

KERR GRANT, C., 1956—The Adelaide Earthquake of 1 March 1954. *Trans. Roy. Soc. S.A.*, May 1956.

PROGRESS REPORT ON SEISMIC ZONING IN AUSTRALIA

by R. Underwood
Hydro-Electric Commission,
Tasmania

SUMMARY

Seismic zoning is an attempt to compress all available information about seismic hazard into a single quantity which varies broadly over the country. A main use is in conjunction with an earthquake-resistant design code. Australia is *de facto* zone zero as ordinary design ignores earthquake effects, and our attempt at zoning amounts to pointing out the (probably few, small) areas where some resistance ought to be built into ordinary designs.

We propose to zone on the basis of seismic risk maps. Risk is a relation between some characteristic of strong shaking and return period. Shaking increases with earthquake size, but large events may have return periods longer than the design life of ordinary structures. We propose to map 50-year peak acceleration, velocity, and intensity, as well as studying the gradients of the risk calculation. Risk maps, like seismicity maps, peak where there are lots of earthquakes, but shaking which extends to some distance is also important. For example, Darwin will have a risk value due to big Banda Sea events.

Loss of precise knowledge of structural behaviour in return for the simplicity of a single zone number is no more important than the lack of precision in the empirical correlations between ground motion and magnitude, distance, and depth. In Australia there is a need for observations on which to base our own correlations, but simply gathering seismicity into catalogues is also valuable. Catalogues are even shorter than the lives of structures, so we must make questionable extrapolations to the return periods of interest. Catalogues are biased because they miss little events but seldom miss big ones; therefore estimates of shaking at long periods are biased high.

Two methods for estimating risk are being used in Australia. Cornell's offers an analytic passage from seismicity to risk and is adapted for detailed site studies. Assumptions and geology are easily inserted but it is easy to lose sight of the deficiencies of catalogues. For mapping at a grid of sites, Milne and Davenport's method is more convenient. Ground motion for every event is calculated and the statistical distribution of this quantity is studied. The trouble is that there is no direct way to incorporate any data beyond the catalogue. As is to be expected, the required extrapolation to longer return periods is obviously unreliable.

INTRODUCTION

Seismic zoning is an attempt to compress all available information about seismic hazard into a single quantity which varies broadly over the country. A main use is in conjunction with an earthquake-resistant design code. Special structures deserve special consideration of risk, and different users will use the same basic seismicity data to produce different zone maps. The Australian National Committee on Earthquake Engineering is preparing a code for earthquake-resistant construction, and Sub-committee 2 is to provide the zoning recommendations for this. David Denham of the Bureau of Mineral Resources and I have concerned ourselves with the zoning project.

It should be noted that Australia is *de facto* zone zero, as ordinary design practice in Australia ignores earthquake effects, and our attempt at zoning amounts to pointing out the (probably few, small) areas where some resistance ought to be built into ordinary designs.

ZONING

Our zoning is based on the idea that sites which have similar risk relations ought to be in the same zone. Examples of seismic risk relations are given in each of references 1 to 9; the concept is simply that the larger the shaking, the longer on the average will be the time between occurrences. This time is the return period, and its reciprocal is the probability that the severity of shaking will exceed the given figure once per year. For a given design life, there will be a high probability of the shaking exceeding some given figure, but a lower probability of more violent shaking. Risk is the quantitative expression of this idea, and two opposing influences act to determine it: the fact that the ground shaking increases with earthquake size is countered by the decrease in probability of occurrence of large events.

Although the designer's attention will be focused on the larger shaking to be expected with low probability of occurrence, which is to say with return period several times the design life, we have initially produced estimates of expected ground motion characterized by peak ground acceleration, peak velocity, and peak intensity for a 50-year return period, and we plan next to provide means to extend this to other return periods. The risk relation is first evaluated at each site on a grid one degree (sometimes ½ degree) square. The 50-year ground motion is determined and the site values are contoured. The contour levels appropriate to zone boundaries have not yet been adopted; they depend largely on engineering considerations. Risk maps, like seismicity maps, peak where there are lots of earthquakes, but shaking which extends to some distance is also important. For example, Darwin can be expected to have a risk value that arises from the seismicity of the Banda Sea.

LIMITATIONS OF ZONING

The simplicity of expressing seismic risk by a single zone number is appropriate for code work, but the advantage of this simplicity must be weighed against the more precise knowledge of structural behaviour which comes from dynamic analysis and 'design earthquake' methods as described in C. T. J. Bubb's contribution to this symposium. A more important loss of precision comes from ignorance of the correlation between ground motion and magnitude, distance, and depth. In Australia there are few observations to establish the relevant correlations, but my impression is that Esteva & Rosenblueth's constants (Underwood, 1969) given in equations 3 and 3a, and which are commonly adopted elsewhere, are decidedly conservative. This is a field ripe for research.

The effect of ground is left out of this discussion. It forms the subject of micro-zonation, which should be considered when deciding whether a building ought to be code-designated or given special treatment.

Gathering seismic data into catalogues, ideally one catalogue, is also a necessary and worthwhile task. From the catalogue, statistics have to be extracted and extrapolated to predict the rare events (larger than any in the catalogue) which are expected to occur at the 50 to 500 year return periods which are of interest. Two arguments indicate that simple straight-line extrapolation of cumulative distribution of magnitudes on a log-log plot is always conservative. The tectonic argument has to do with the finite amount of strain energy that may be stored in a region, and the finite rate at which it may be released, while the statistical argument is that the catalogue is inevitably incomplete at low magnitudes. If the number is underestimated at low magnitudes but correctly estimated at middle magnitudes, a straight-line extrapolation will overestimate the number of high-magnitude events. A check for completeness can and should be made with 'second-order' statistical methods. To strengthen these questionable extrapolations, geological data have to be incorporated, but we do not have a formal technique for this at present. We would be inclined to put more weight on evidence that can be demonstrated in the field than on evidence derived from tectonic theories.

METHODS

Two methods for risk are being used in Australia. The most widely used is Cornell's method (Underwood, 1969), which offers an analytic passage from seismicity to risk and is adapted for detailed site studies. It has the advantage that assumptions and geological information are easily inserted, but there is always a danger of losing sight of the deficiencies of the catalogues.

For mapping at a grid of sites, the probability plotting method of Milne & Davenport is more convenient. The familiar cumulative distribution of magnitude is an example of a probability plot. For seismic risk not magnitude but calculated peak ground motion is plotted. One plot is generated for each characteristic of the motion, and for each site. The required extrapolation to longer return periods sometimes produces values that are obviously implausible. There is no direct way of incorporating any data beyond the catalogue.

Either method leads to a risk relation which is linear on log-log paper, and can be written as a function of the form

$$T = a\,Y^{1/m} \qquad (1)$$

where T is the return period, a and m are constants, and Y is a symbol which can stand for peak ground acceleration, peak ground velocity, or a function of intensity, according to context.

RESULTS

Because each risk relation is a line in the T-Y field, comparison of risk relations at different sites leads to cluttered diagrams. Simplicity is achieved by recasting equation (1) in the form

$$Y = Y_{(T\,=\,50)}(T/50)^m \qquad (2)$$

where $Y_{(T\,=\,50)}$, the peak ground motion for 50-year return period, is the quantity being used for the initial zoning maps. Each risk line in the T-Y field can now be represented by a point of ordinate Y_{50} and abscissa m in a rectilinear co-ordinate system.

Figures 1 and 2 show these simplified plots of acceleration and velocity, respectively, for all Australian results available. The plotted symbols (e.g. J12) refer to Table 1, which

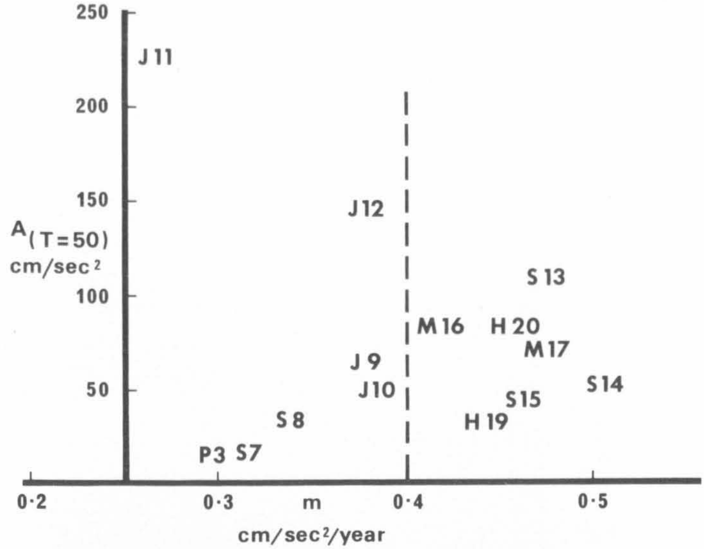


Fig. 1. Acceleration risk relations for Australian sites. The ordinate is the peak horizontal acceleration calculated for a 50-year return period, the abscissa is the gradient of the risk relation. Numbers refer to the cases listed in Table 1. Risk increases to the right and towards the top. For details of codes refer to Table 1.

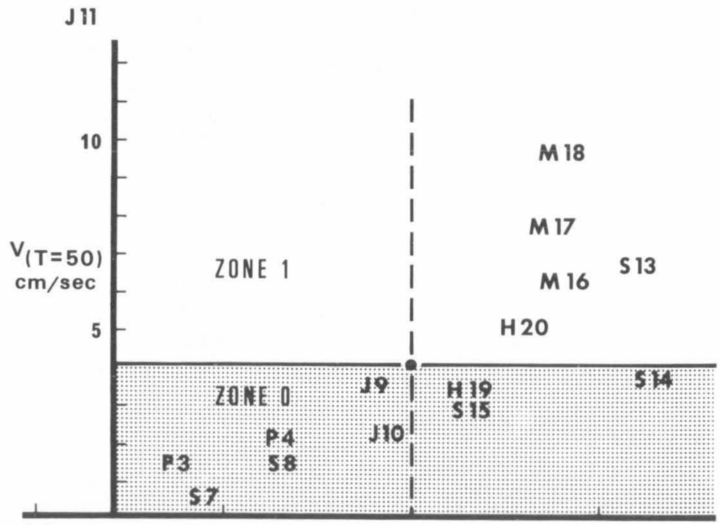


Fig. 2. Velocity risk relations for Australian sites in the intercept-gradient field. Points falling in the screened region are in the zero zone proposed by Bubb (1971). Points $m > 0.5$ may run into a higher zone at longer return periods.

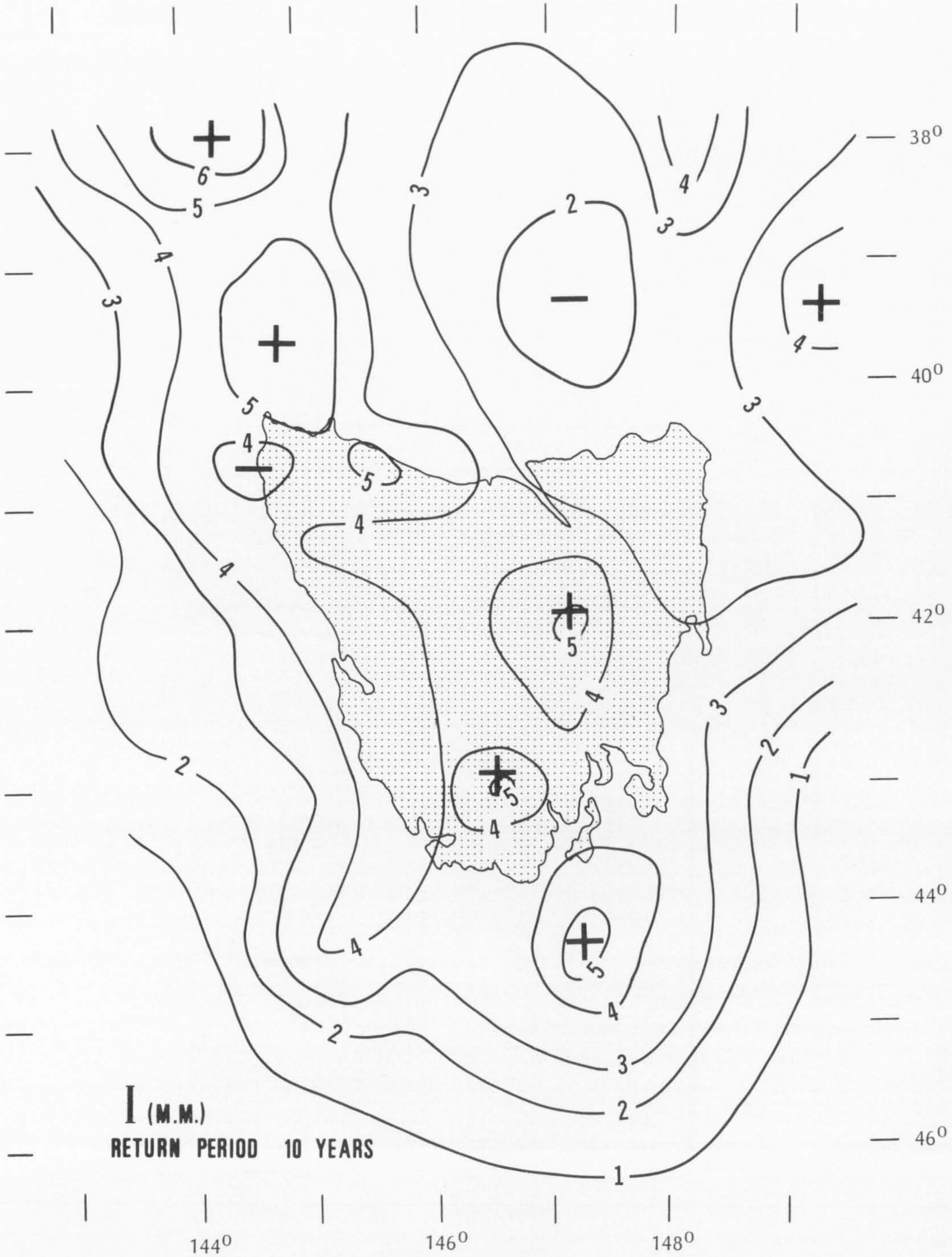


Fig. 3. Intensity at 10-year return period for Tasmania.

TABLE 1. AUSTRALIAN SEISMIC RISK CALCULATIONS

The codes in the left hand column refer to Figs 1 and 2

Code	*Site*	*Seismic Source Description*	*Ref.*	*V (T=50)*	*m_V*	*A (T=50)*	*m_A*
P 3	Perth, WA	Sources localized, no background b = 1.16; Preferred solution	1, 8	1.6	.37	20	.30
P 4	Perth, WA	Sources localized, no background b = 1.0; Conservative solution	1	2.2	.43	—	—
S 7	Savage River, Tas	Uniform background, no localized sources b = 1.0	9	0.6	.39	20	.31
S 8	Savage River, Tas	Uniform background, no localized sources b = 1.1	9	1.7	.43	35	.34
J 9	Jervis Bay, NSW	Uniform background	4	3.6	.48	65	.38
J 10	Jervis Bay, NSW	Weak background, main activity in discrete sources	4	2.3	.49	40	.38
J 11	Jervis Bay, NSW	Weak background, main activity in discrete sources + 'Pt Perpendicular Fault'	4	13.0	.32	220	.26
J 12	Lucas Heights, NSW	Weak background, main activity in discrete sources	3	—	—	145	.38
S 13	Eucumbene-Jindabyne Tunnel, Snowy Mtns, NSW	All Southeast Australian activity, localized in discrete sources	5	6.7	.62	110	.48
S 14	M1, Snowy Mtns, NSW	All Southeast Australian activity, localized in discrete sources	5	3.8	.63	55	.51
S 15	T3, Snowy Mtns, NSW	All Southeast Australian activity, localized in discrete sources	5	3.0	.53	45	.46
M 16	Modbury, SA	All activity in a uniform background	7	6.3	.59	85	.41
M 17	Modbury, SA	Activity localized in discrete sources, but Eden Fault inactive	7	7.7	.58	75	.47
M 18	Modbury, SA	Activity localized in discrete sources, but Eden Fault moderately active	7	9.6	.58	125	.47
H 19	Hastings, Vic	Activity localized in discrete sources	6	3.4	.53	50	.44
H 20	Hastings, Vic	Activity localized in discrete sources + additional activity on the Tyabb Fault	6	5.0	.56	85	.44

contains details of the sites and the assumptions made in the calculations.

A typical seismic risk map is given in Figure 3. It is contoured from the 10-year intensity calculated at a grid of sites at one-degree (some parts half-degree) spacing across Tasmania. Here, the Modified Mercalli Intensity was treated as a metrical quantity I, calculable from a knowledge of the magnitude ML, depth H, and epicentral distance Δ:

$$\exp I = 2981 \exp (1.45\, ML)\, R^{-2.64} \quad (3)$$

$$R^2 = \Delta^2 + H^2 + 20^2 \quad (3a)$$

The constants in these equations are the ones advocated for California and, as mentioned above, seem to be conservative for Australia. The seismicity data base was Tasmanian catalogue '1973A', containing 113 events in the 10.5 years up to mid-1973. At the first site, intensity from each event was calculated; values of intensity less than I were culled out and the remaining values were sorted into order from largest to smallest. Noting that the first entry in this ordered list gives the intensity that has been reached precisely once, the second gives the intensity reached or exceeded precisely two times in the catalogue period, and so on, the return period on the i-th entry was estimated as:

$$Ti = \frac{\text{number of years in the catalogue} + 1}{i}$$

The intensity values were graphed against the logarithm of Ti to produce a probability plot sufficiently straight when the data were good to enable the estimation of the 10-year intensity. This procedure was repeated at each site.

Maps like Figure 3, and similar maps of peak acceleration and of peak ground velocity, provide the basis on which the final decisions on zones have to be made.

The foregoing emphasizes the amount of assumption and decision which underlines the seemingly simple zone number on the final map.

REFERENCES

(Numbers reference Table 1)

1. McCue, K. F., n.d.—Report on the seismicity of Western Australia, part 1: Seismicity of Zone A and its effects on Perth and environs. *Report, Imperial College, London.*
2. McCue, K. F., 1973—Report on the seismicity of Western Australia, part 2: Relative seismicity of Western Australia. *Report, Imperial College, London.*
3. Mumme, I., A.A.E.C. private communication, 1974.
4. Underwood, R., 1970: Modelling of seismic risk at Jervis Bay. Unpublished Report to A.A.E.C.
5. Underwood, R., 1970—Unpublished work reported to S.M.A.
6. Underwood, R., 1969—Numerical Seismic Risk. *Earthquake Engineering Symposium, Melbourne.*
7. Underwood, R., 1970—Unpublished work.
8. Underwood, R., 1973—Unpublished recomputation from Ref. 1.
9. Underwood, R., 1973—The seismic risk at Savage River. Unpublished Report 644-SE1-2 of Geology Section, H.E.C.

DYNAMIC RESPONSE OF BLACK MOUNTAIN TOWER TO ESTIMATED GROUND MOTIONS

by C. T. J. Bubb

Australian Department of Housing and Construction

SUMMARY

Procedures involved in the check analysis of the Black Mountain Tower, Canberra, which is a tall steel and concrete telecommunications tower situated in a region of minor seismicity, are described. The tower, dimensioned on the basis of a static wind analysis, was checked to ensure satisfactory performance if a significant seismic event did occur. The procedures used to select the location and magnitudes of suitable earthquakes, considering the seismic activity of the region, and also the scaling of digitized earthquake accelerograms to achieve the desired intensity, are described. Time history dynamic analyses of the structure were performed assuming a viscously damped elastic structure for a number of scaled accelerograms. Adopting a damping factor of three percent of critical for the structure, the results indicate satisfactory performance with stresses in the reinforced concrete shaft well below yield. Whilst significant yielding is predicted for the uppermost portion of the steel mast this was considered acceptable for reasons given in the paper.

INTRODUCTION

To replace the existing facilities at Canberra and to provide for the expected future growth of telecommunications traffic in and out of Canberra, the Parliamentary Standing Committee on Public Works in 1972 recommended the construction of a telecommunications tower on Black Mountain in the A.C.T.

The structure, shown in Figure 1, consists of a tapered reinforced concrete tower, rising 132 m from ground level, housing the stair well, lift shafts, PMG ducts, and services. Two 'drums' are constructed on this tower—the lower houses telecommunications equipment, whilst the upper drum and the annulus immediately above provide visitors with a restaurant and lookout. To the top of this tower is attached a steel mast 70 m high which is to support antennae for the various telecommunications services.

Since the Black mountain site is in a region of minor seismicity, an important phase in the design process was to ensure that the structure would perform satisfactorily in the event of an earthquake. This paper gives a summary of the approach employed and the results obtained.

SEISMIC ACTIVITY

The records of the Bureau of Mineral Resources, Geology & Geophysics for the Canberra Region, Lat. 34°S-37°S, Long. 147°E-150°E (based mainly on earthquake hypocentres provided by the Australian National University) indicate consistent seismic activity surrounding the Black Mountain site. Although most of the events recorded have magnitudes well below 3.5, there have been some above 4 and several in the Gunning-Dalton region of magnitude above 5. The depths of most events are shallow, generally within the upper 10 km of the crust (Cleary, 1967); hence the severity of motions may be greater than would be expected from magnitude alone.

A map of epicentre locations for the Canberra area for 23 years of record (Fig. 2) indicates the extent of this activity and shows a distinct concentration of events in several regions to the north, particularly in the Gunning-Dalton region. In this figure are also marked the locations of known faults taken from the standard geological maps. The Lake George Fault is the most extensive one, and seismic activity has been associated with it in the past. Now, however, it appears relatively inactive, because most of the strain in the region is being released by earthquakes in the Gunning-Dalton region (Cleary, 1967).

Nevertheless, for the purposes of this engineering assessment it was assumed that the Lake George Fault was active; this may have led to an over-estimate of likely ground motion—i.e. on the safe side. Since the results of the response study, as discussed later, did not disclose a critical design situation, this assumption seemed acceptable and refinements were not considered. The results should not be applied directly to other projects or to Canberra generally as they may be too conservative.

SELECTION OF REPRESENTATIVE EARTHQUAKES

There are two possible ways of estimating the magnitude of future earthquakes: a probability approach based on magnitude/frequency

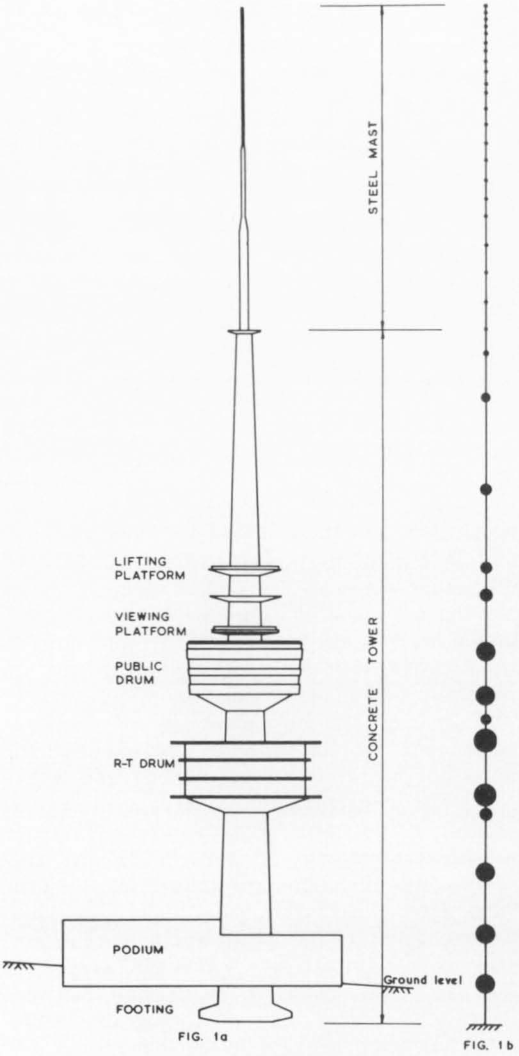


Fig. 1. Black Mountain tower and its lumped mass representation.

relations, and a maximum credible magnitude based on energy release. Since time did not permit reduction of the data to homogeneous sets and the development of magnitude/frequency relations, the latter approach was adopted. This method is based on the assumption that no single future earthquake will release more energy than the total energy released by known past earthquakes; it tends to over-estimate energy release and thus favours conservative design.

The energy released by an earthquake may be assessed by a formula such as the one given by Richter (1958).

$$\text{Log}\, E = 9.9 + 1.9\, ML - 0{\cdot}024\, ML^2$$

Where E is energy in ergs

ML is Richter magnitude

By applying this relation to each significant event (say greater than magnitude 2) for the whole 23 years of the earthquake record, the total amount of energy released in the areas A and B in Figure 2 has been estimated as of the order of 2.1×10^{20} ergs. The magnitude of a single earthquake that would release this energy is found to be $ML = 5.85$. Therefore it would seem that close shocks larger than ML 6 need not be anticipated.

On the basis of this argument and the information on the relative seismic activity of the region it was decided to investigate the response of the tower to earthquakes in the following locations designated in Figure 2.

(i) AREA C. Ground motion due to an event of magnitude with source 32 km away on the Lake George Fault.

(ii) AREA B. Ground motion due to an event of magnitude 6.5 with its source 40 km away in the southern region of area B. Also ground motion due to an event of magnitude 7 with its source 65 km away, in the northern part of area B.

(iii) AREA A. Ground motion due to an event of magnitude 7 with source 120 km away from site.

It seems unreasonably conservative to postulate events of magnitudes greater than these as having a significant possibility of occurrence within the lifetime of the structure. As a check on this assertion a rough magnitude/frequency/area relation was developed for the region; when applied to the earthquakes described above, this relation suggests return periods of at least 250 years and 1000 years for the earthquakes in Areas B and C respectively. When using this relation it was not considered worthwhile to extrapolate too far; hence no return period for the event of magnitude 7 is quoted.

SCALING OF EARTHQUAKES

Analysis of a structure's response to earthquake excitation involves the application of a digitized accelerogram to the base of the numerical model of the structure. Since the severity of an earthquake is modified with distance, a means of relating the ground motion at the site of the structure to the magnitude of the earthquake and the distance to its epicentre is required; one such relation, proposed by Esteva (1969), is

$$V = 15\, e^{M}\, (R + 0.17\, e^{0.59M})^{-1.7}$$

which relates the peak ground velocity V at the

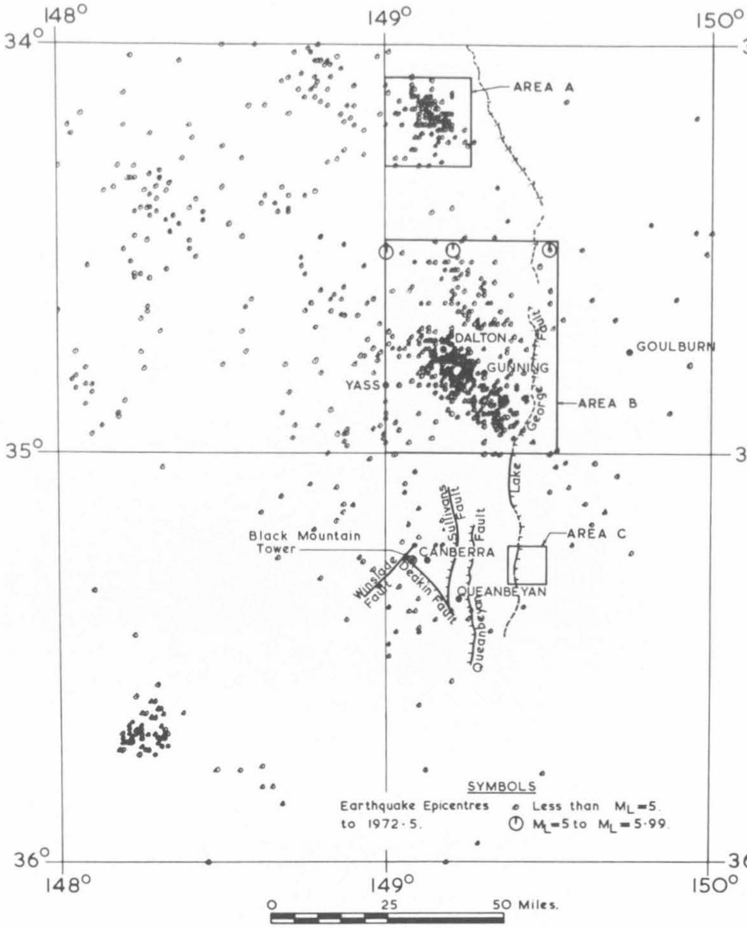


Fig. 2. Locations of epicentres for Canberra and surrounding areas.

site to the magnitude M and epicentral distance R of the earthquake. Using the data on the proposed earthquakes, the required peak velocities of the accelerograms to which the structure will be subjected can be estimated and hence the ordinates of the accelerogram can be scaled to achieve these values.

Both simulated and actual digitized accelerograms selected from the 'CALTEC' library (Jennings et al., 1968) were used to represent the characteristics expected of the ground motions. E.g. for the earthquake in Area C, simulated earthquake D_1, which models the shaking close to a fault of a shallow earthquake of magnitude 4.5 to 5.5, has been selected. The other accelerograms chosen were the simulated earthquake C_1, and the actual accelerograms for events at Taft (July 1952) and San Francisco (March 1957). A table of pertinent values regarding the scaling process is included as Table 1.

DYNAMIC ANALYSIS

The dynamic analysis of the structure for the earthquake motions indicated above was performed using the program DYFRAM.* This program uses the method of modal superposition to determine the response of a viscously damped elastic structure with masses lumped at discrete intervals as shown in Figure 1.

Output from the program consists of the basic dynamic properties of the structure; i.e. mode shapes and corresponding natural periods.

* DYFRAM was originally obtained from University of California, Berkeley, as FRMDYN was written by E. Wilson.

TABLE 1. SCALING OF EARTHQUAKES

Source area	*Earthquake*	*Estimated magnitude* (Richter)	*Epicentral distance* (km)	*Estimated maximum site velocity* (cm/s)	*Max. velocity of digitized accel.* (cm/s)	*Scale factor to produce estimated site motion*
C	D_1	6	32	12.5	27.9	0.46
B	C_1	6.5	40	14	7.0	2.01
	San Francisco (1957)	6.5	40	14	4.9	2.86
B	Taft (1952)	7.0	65	10.6	13.8	0.77
A	Taft (1952)	7.0	120	4.2	13.8	0.30

TABLE 2. NATURAL PERIODS OF THE FIRST FIVE MODES OF THE STRUCTURE

Mode	1	2	3	4	5
Period, seconds	2.95	1.24	0.83	0.61	0.37

The periods of the first five modes are noted in Table 2.

Initially the structure was divided into 22 elements (7 in the steel mast and 15 in the concrete shaft); however, when it was determined that some yielding of the steel mast would occur it was decided to increase the number of elements in the steel mast to 21 to define the response better, at least to the extent of ensuring that yielding was actually occurring. Since the program performs an elastic response analysis the predicted deflections are only approximate, once yielding occurs.

The damping assumed in the first computer run was 5 percent of critical; however, when examination of the response showed that the stress ranges under dynamic excitation for most of the steel mast and all of the concrete tower were not more than half of the yield stress, the damping assumed in the later runs was reduced to 3 percent of critical (Newmark & Rosenblueth, 1971). This decrease in damping in turn increased the stress range slightly and hence also the length of the portion over which yielding occurred.

The results of these earthquake analyses are summarized in Figure 3 for both 3 and 5 percent of critical damping, in terms of the ratio maximum dynamic moment to the yield moment at that section. From this figure it can be seen that on the basis of the elastic calculations a maximum ductility ratio of almost 5 is called upon in the top of the steel mast. That yield does occur in the steel mast, however, is not considered critical for the following reasons—

(i) The steel used will have appreciable ductility even at low temperatures.

(ii) Only a few yielding cycles can be expected since the earthquake itself will not be of long duration (in this region).

(iii) The design of the mast is such that, in the unlikely event of extensive permanent deformation, replacement of the upper part of the mast would be relatively easy.

Finally it will be noted that the maximum moments at various parts of the structure are caused by different earthquakes—demonstrating the necessity for earthquake response studies to use a variety of earthquake inputs.*

LATERAL FORCE ANALYSIS

There were two phases in the lateral force analysis of the tower. The first phase, on which the structure was actually designed, was to calculate that the structure would satisfactorily resist the expected wind forces. The structure was dimensioned to remain within normal working stresses under a 100-year-return-period wind and to just reach its ultimate strength under an estimated 5000-year-return-period wind. The second phase was to check that the tower as designed would satisfactorily resist the maximum credible earthquake forces due to seismic activity in the region.

In addition to the dynamic analysis described previously, a comparison was made with the earthquake force provisions of the Uniform Building Code (1970) to the tower. The results indicate that for this long-period structure the UBC forces for a seismic zone 2 correspond roughly to the 100-year-return-period wind forces. (These results together with those for the wind and dynamic analysis of the tower are summarized in Table 3 for two tower levels).

* The coefficient of variation for base movements was approximately 10%.

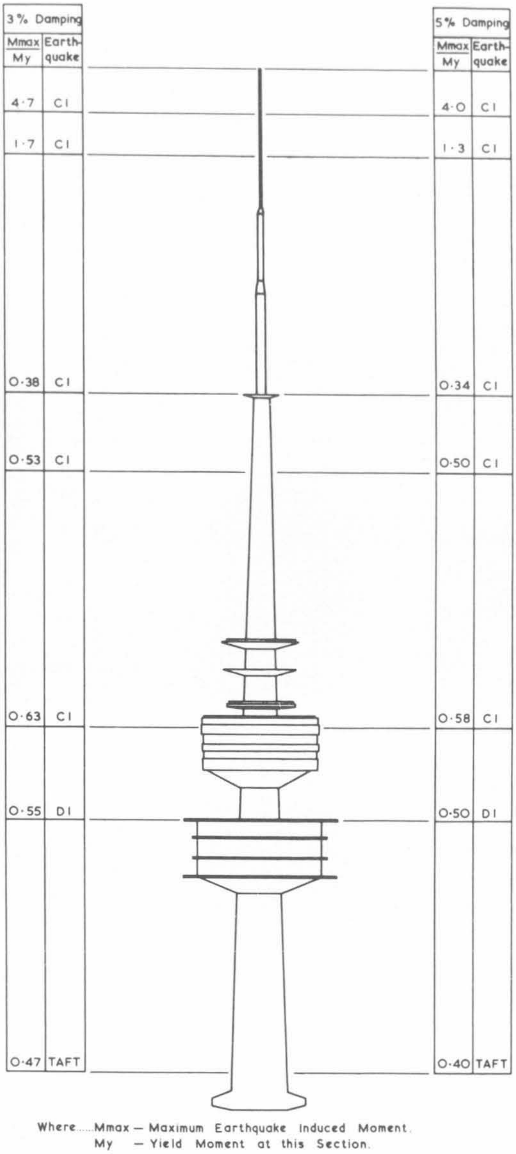


Fig. 3. Maximum moment ratios for Black Mountain Tower.

This kind of result is only to be expected for long-period structures. Quite a different result would be expected for a typical building structure of shorter period. In that case it would not be economical to attempt to remain within the elastic limit, and hence a simple elastic analysis would be quite misleading and overconservative.

ACKNOWLEDGEMENTS

The approval of the Secetary, Department of Housing and Construction, Mr A. S. Reiher, to present this paper is gratefully acknowledged. Structural Section staff including Engineers Messrs S. Vitteleschi and later G. Horoschun assisted in the preparation of data for the DYFRAM computer runs and in the analysis of the results. The Chief Structural Engineer, Mr N. Sneath, is responsible for the overall structural design of the Tower.

TABLE 3

Level	*Force*	*Earthquake forces* (3% Damp.) Dynamic anal.	*Earthquake forces* UBC Code (Zone 2)	*Wind forces (100 year return period)*
Base (—11 m)	Moment (kN.M)	160 000	269 800	257 200
	Shear (kN)	3 630	2 880	2 950
Appendage platform (132 m)	Moment (kN.M)	11 000	31 600	14 500
	Shear (kN)	410	476	600

REFERENCES

CLEARY, J. R., 1967—The seismicity of the Gunning and surrounding areas, 1958-1961. *J. Geol. Soc. Aust.*, 14(1), 23-29.

ESTEVA, L., 1969—Seismic risk and seismic design decisions. *Seminar on Seismic Design of Nuclear Power Plants, Camb., Mass.*: Massachusetts Inst. of Tech. Press; quoted by Newmark & Rosenblueth (1971).

JENNINGS, P. C., HOUSNER, G. W., & TSAL, N. C., 1968—Simulated earthquake motions. *Earthquake Eng. Research Lab., Pasadena*: California Inst. of Technology, April 1968.

NEWMARK, N. M., & ROSENBLUETH, E., 1971—FUNDAMENTALS OF EARTHQUAKE ENGINEERING. Prentice Hall, p. 422.

RICHTER, C. F., 1958—ELEMENTARY SEISMOLOGY. W. H. Freeman & Co.

UNIFORM BUILDING CODE, *U.S.A.* International Conference of Building Officials, Calif., 1970, Vol. 1.

SEISMIC CONSIDERATIONS AFFECTING THE SAFETY OF NUCLEAR PLANT

by D. J. Higson

Australian Atomic Energy Commission

SUMMARY

The safety of nuclear power stations is ensured primarily by the inherently stable characteristics of the reactors which are used and the very high standards which have been adopted for the design and construction of the plant. The reactor core is made up from ceramic oxide fuel which is capable of withstanding very high temperatures (well above those of normal operation) without serious damage.

Additional safety features are engineered into the designs to provide further lines of defence in case of accidents:

(i) Auxiliary systems would prevent any unsafe conditions from developing in consequence of a fault in the process plant. These devices include automatic shut-down and emergency core cooling systems, and guaranteed power supplies to essential services.

(ii) A leak-tight containment building completely encloses the reactor and would prevent the spread of any radioactive contamination which might be released from the reactor core in a hypothetical accident.

The importance of an earthquake in this context is that it is potentially a common cause of damage to all three lines of defence simultaneously: the process plant, the protective systems, and the containment. The corresponding design requirements for components and structures depend upon their relative importance to public safety. For the unlikely event (in Eastern Australia) of a severe earthquake it might be economical to accept the possibility of damage to the station, but this damage must not lead to an uncontrolled release of radioactivity; i.e. at least one line of defence should remain effective.

For construction of nuclear power plant on a given site, an estimate of the likelihood of severe seismic effects at that site is therefore required in order to specify the design basis earthquake. The most useful form of information is the relation between earthquake intensities and frequencies.

Page 74 is blank.

THE ROLE OF LOCAL GEOLOGY IN SEISMIC INTENSITY PREDICTIONS

by I. A. Mumme

Australian Atomic Energy Research Establishment

SUMMARY

This report describes earthquake risk factors in preliminary site evaluation for nuclear power reactors.

Starting from a knowledge of the seismic and geotectonic environment of the site in question, the likely ground motion during earthquakes is assessed in four steps. Firstly, estimation of the magnitude of the 'design basis earthquake' that might occur at an adjacent causative fault which is considered to be the most important source of seismicity in the surrounding region. Secondly, attenuation of the ground motions between the causative fault and the site under consideration. Thirdly, the effect of local soil and underlying geological conditions. Finally, the selection of an appropriate ground motion spectrum from an observed earthquake motion where the site and source conditions match those for the site in question.

Using such information, structural analysis can then design earthquake resistant structures.

INTRODUCTION

Although the maximum ground motions that are likely to occur at a particular site can be strongly influenced by local geology, little attention has been given to this aspect of engineering seismology.

This has been due partly to lack of concern amongst engineers for including local geological effects in design considerations for fossil fuel plants, oil refineries, storage tanks, high-rise buildings, and dams.

The purpose of this paper is to outline recently developed procedures for incorporating such geological site factors as site impedance and thickness of soil in the evaluation of seismic threat to a nuclear power plant. Problems relating to the occurrence of rock faulting beneath the plant, foundation instability due to liquefaction, seismically induced floods, and tsunamis are not considered here although they are important considerations in the siting of some nuclear power plants.

SITE EVALUATION METHODOLOGY BASED ON CONCEPT OF DESIGN BASIS EARTHQUAKE

Many different approaches have been proposed and used in recent years by various Atomic Energy Authorities for evaluating the seismic hazard at a site, but the methods described in this paper are based on the concept of a 'design basis earthquake' (DBE), which is linked with a detailed study of the 'active faults' that occur within 320 km of the proposed site. This treatment of the problem is in accordance with the present state of the art for evaluating the safety of reactor systems, particularly in earthquake-prone areas (Matthiesen, Howard & Smith, 1973).

Another important reason for evaluating seismic threat by the DBE approach is that once the causative fault is identified, it is easy to determine where the most severe earthquake is likely to occur. However, it is first necessary to identify the causative fault that could give rise to the severest earthquake motion that can reasonably be expected at the site.

First, the investigator should prepare a tectonic map delineating fault zones and other seismo-tectonic features (e.g. thrusts), folds and other geological structures, lithology, and known earth movements in recent times. Distinctions should then be made between 'active', extrapolated, and inferred faults, and detailed maps should be prepared of the dips, strikes, and lengths of the various faults. The history of the different 'active faults' should be studied in detail.

To aid the identification of 'active faults' or 'potentially active faults', the following definition is recommended by licensing authorities in America (USAEC, 1971):

'An "active fault" is a fault which has exhibited one or more of the following characteritics:

(1) Movement at or near the ground surface at least once in the past 35 000 years, or more than once in the past 500 000 years. Where there is an absence of data permitting absolute dating of a subsurface fault, perceptible geological or topographical evidence of surface rupture, surface warping or offset of other geomorphic features may be used to classify a fault as active, or

(2) A fault is considered active if it has exhibited creep movement along the fault plane or

has exhibited instrumentally well-determined macroseismicity, or

(3) It is related to another fault that is considered active in such a manner that movement on one could be reasonably expected to be accompanied by movement on the other.

'In cases where geological evidence of past activity at or near the ground surface along a particular fault may be obscured at a particular site, for example, at a site having a deep alluvial overburden, other valid geological reasons have to be sought to demonstrate whether the fault is active or not.

'Active faults of lesser length than those indicated in Table 1 need not be considered in determining the safe shutdown earthquake (DBE) except where unusual circumstances indicate such consideration is appropriate.'

TABLE 1

(After USAEC, 1971, Table 1; distances have been converted from miles to kilometres)

Distance from site in kilometres	*Minimum length of fault (kilometres) to be considered in establishing safe shut-down earthquake (DBE)*
0-30	1.6
greater than 30 to 80	8
greater than 80 to 160	16
greater than 160 to 240	32
greater than 240 to 320	76

To aid in the above interpretation of 'active faults', as recommended by the USAEC, attention should be given to the seismicity of the surrounding area; epicentres should be plotted on the geological map and correlated not only with the mapped faults but with other known tectonic features. Epicentres that cannot reasonably be correlated with tectonic structures should be identified with seismotectonic provinces.

Particular attention must be given to areas that have a relatively scarce earthquake history for in such areas the determination of the design basis earthquake (DBE) becomes difficult. Not only should geological and microseismological studies be carried out, but also regional geophysical investigations (e.g. gravity and magnetic surveys) to attempt to locate active fault zones and other possible sources of earthquakes.

In regions where earthquake epicentres cannot be associated readily with surface faulting or where faults have not been extensively mapped, other criteria must be used; for example, the intensity at the site from the strongest earthquake ever recorded near the site may be determined from isoseismal maps. If such data are lacking then an artificial map can be drawn using observed intensity information based on the amount of damage and felt motion that was recorded during the occurrence of historic earthquakes in the general area.

Assuming that the causative fault can be identified, we can use the DBE approach. To do this, however, it is necessary to characterize the DBE that poses the threat to the site by a peak value of ground acceleration, an accelerogram or acceleration response spectrum, and a duration time for this hypothetical earthquake. This information can be obtained by carrying out the procedures outlined in the following sections.

DETERMINATION OF THE MAGNITUDE OF THE DBE USING THE 'ACTIVE FAULT' INFORMATION DERIVED FROM A GEOLOGICAL STUDY OF THE SURROUNDING REGION

No strong-motion earthquake data have been recorded in Australia, but experimental results given in Figure 1 may be used to estimate the maximum magnitude of an earthquake which is likely to occur along any particular 'active fault'. This graph was taken

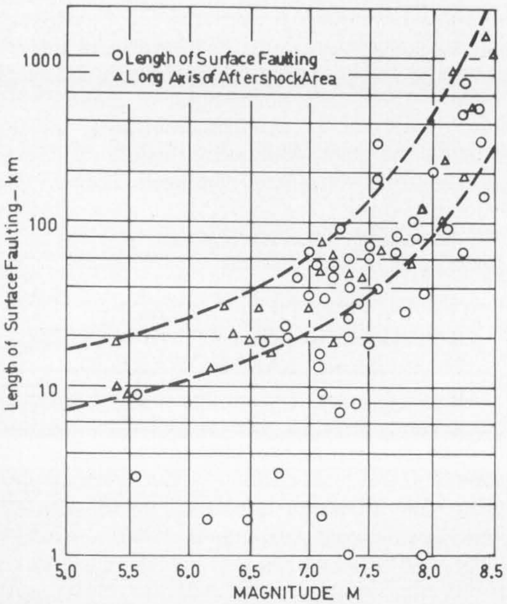


Fig. 1. Relation between earthquake magnitude and length of fault (after Albee & Smith, 1966).

from a paper by Albee & Smith (1966), and is based on comprehensive reviews of the important characteristics of earthquakes in California, where, as in Australia, earthquakes take place in the crust at relatively shallow depths.

This graph shows the relation of earthquake magnitude to the length of surface faulting or the long axis of the aftershock area. (It is important to consider the latter values as well since some earthquakes with magnitudes as high as 7 have not exhibited surface rupture effects.)

For this discussion, the upper curve in the figure is accepted as defining the minimum fault length required before an earthquake of a given magnitude is to be expected along the fault. From a knowledge of the lengths of faults in the region, therefore, we can determine the magnitude of the DBE for a site under investigation.

CORRELATION OF THE DESIGN BASIS EARTHQUAKE MOTION WITH MAGNITUDE AND DISTANCE FROM THE CAUSATIVE FAULT

As the ground motion at a particular site is a function of many variables belonging to several disciplines, namely seismology, geology, and foundation engineering, it is not surprising that until recently some correlations of the expected amplitude of ground motion (e.g. peak acceleration) involved only earthquake magnitude, epicentral distance, and sometimes focal depth. For example a set of curves (Fig. 2) developed by Housner (1965), relating maximum ground acceleration to epicentral distance and earthquake magnitude, has been in general use for many years for estimating maximum ground acceleration.

Although such a set of curves is quite suitable for predicting ground acceleration on firm soil or soft rock at distances greater than 50 km from an earthquake epicentre, recent data obtained from the San Fernando earthquake of 9 February 1971 raise serious doubts of their reliability within 30 km of the epicentre. The revised curves shown in Figure 3 were derived by Matthiesen et al. (1973) from recent information that includes earthquakes closer than 30 km, and they are preferred to Housner's curves.

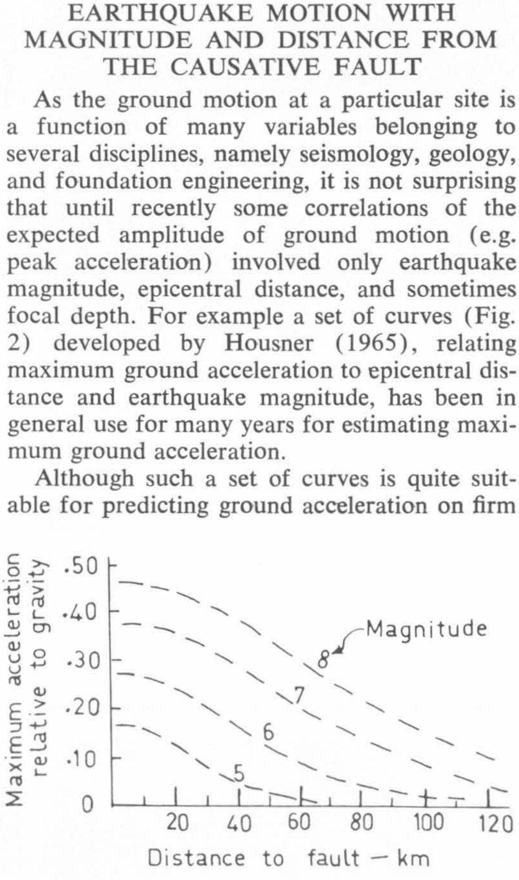


Fig. 2. Maximum acceleration versus distance from epicentre (after Housner, 1965).

Figure 3 expresses ground motion in terms of acceleration. Figures 4 and 5, also derived by Matthiesen et al. (1973), show the corresponding ground velocity and displacement.

Except for sites in the epicentral region, it is believed that these correlations are strongly influenced by site conditions. Thus they should be used only for firm soil or soft rock. But approximate rules proposed by Newmark & Hall (1969) can be used to modify the curves

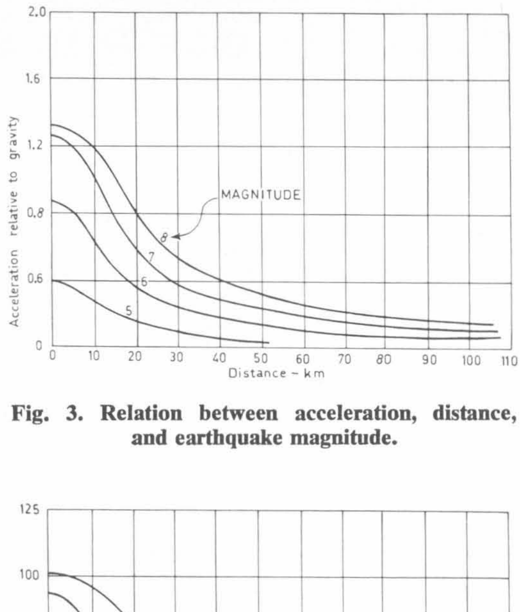


Fig. 3. Relation between acceleration, distance, and earthquake magnitude.

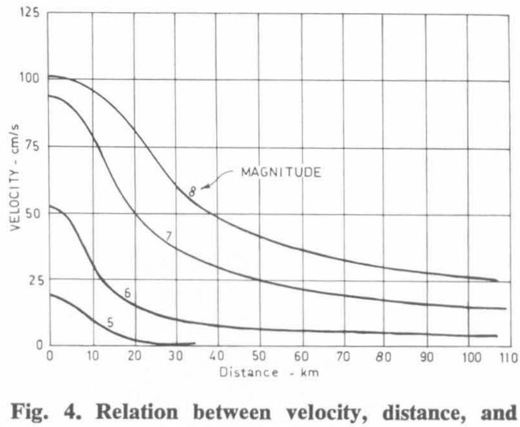


Fig. 4. Relation between velocity, distance, and earthquake magnitude.

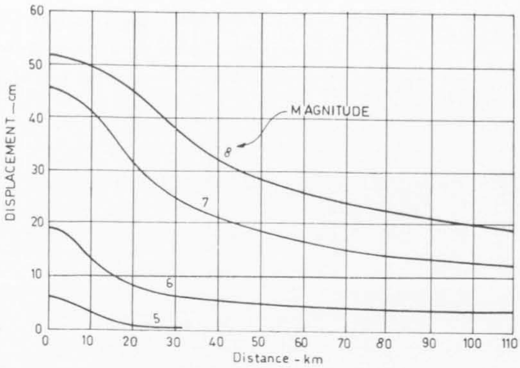


Fig. 5. Relation between displacement, distance, and earthquake magnitude.

to make them apply to either very soft ground or hard rock at the site (see Table 2).

TABLE 2

Rock type	*Multiplier*
Soft ground	1.5
Firm soil—soft rock	1.0
Hard rock	0.67

These methods should be used only for the preliminary investigation of a site. For a more accurate evaluation, a detailed knowledge of the physical properties at the site is required. This can be obtained either from field tests or from laboratory investigations of representative samples of the foundation rocks.

RELATION BETWEEN EARTHQUAKE MOTION, MAGNITUDE, DISTANCE, AND LOCAL SITE PROPERTIES

Blume's Method (Blume, 1967)

For sites well away from the causative fault, Blume's method can be applied; it assumes that the ground motion is due to a vertically propagated plane front of shear waves moving upward through uniformly stratified layers. (The energy from a distant earthquake does reach the surface by a near-vertical path because of refraction in layers of progressively decreasing velocity toward the surface).

In Blume's method for assessing the maximum ground acceleration at a site, use is made of the concept of site impedance expressed in terms of the product of specific soil density and seismic shear velocity, i.e. D_sV_s. The density (D_s) and shear wave velocity (V_s) values for a specific site can be determined from laboratory tests on representative foundation materials, and from field surveys using geophysical techniques.

The procedure adopted by Blume to relate earthquake magnitude, acceleration at the site, and particular site characteristics is as follows. The maximum ground acceleration to be expected is derived from recorded motions of past earthquakes. These records are modified by applying a local site amplification factor to account for differences between the site where the recording was made and the site where the estimate is required. The site factor b used in this method is calculated from Gutenberg & Richter's (1956) data and the site characteristics at the US Coast & Geodetic Survey strong-motion recording stations. It is obtained from an empirical curve (c.f. Fig. 6). Having obtained b, one can then use Figure 7 to obtain a hypothetical epicentral acceleration. This value can then be reduced to allow for depth and epicentral distance. For example, use could

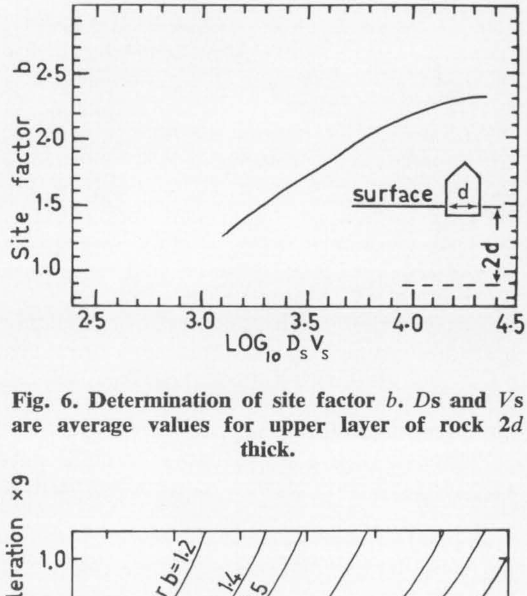


Fig. 6. Determination of site factor b. Ds and Vs are average values for upper layer of rock $2d$ thick.

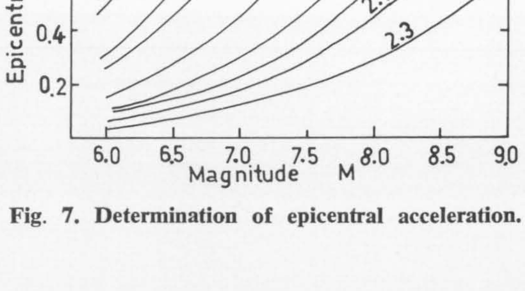


Fig. 7. Determination of epicentral acceleration.

be made of the graph presented in Figure 8 after Gutenberg & Richter (1956).

Wiggins' Method (Blume, 1967)

This method also establishes a means of relating earthquake magnitude, site acceleration, and the site characteristics; it also uses recorded motions of past earthquakes. These studies lead to the following relationship for scaling distance and earthquake size for the sites studied.

$$V_{max} = \frac{9.71 \times 10^{-5} E^{1/3}}{(D_s V_s)^{\frac{1}{4}} R^{1.37}} \qquad (1)$$

where D_s = specific density of soil
V_s = shear velocity of soil (km/s)
E = total kinetic energy released by the design basis earthquake (ergs)
R = hypocentral distance (km)
V_{max} = maximum particle velocity (cm/s)

Using the Gutenberg & Richter magnitude energy relationship, namely

$$\log_{10} E = 9.4 + 2.14M - 0.054M^2 \qquad (2)$$

where M = magnitude of the design basis earthquake, Wiggins showed that

$$A_{max} = (82.6 - 7.59M - 0.0022R) \times \frac{3.75 \times 10^{-5} E^{1/3}}{(D_s V_s)^{\frac{1}{4}} R^{1.37}} \qquad (3)$$

where A_{max} = maximum ground acceleration at the site (in cm/s).

Thus by taking into account the magnitude M of the DBE and its hypocentral distance R, the maximum ground acceleration at the site can be calculated.

At sites located in the epicentral region the available strong-motion data suggest that the local geology has little effect on ground motion (Bernreuter & Tokarz, 1972). The probable explanation of this is that much of the seismic energy there is derived from a complex pattern of many waves, some caused by refractions and reflections, some by scattering through the ground layer, and some emitted from different parts of the fault plane surface. This probably also explains why the epicentral ground motion can be slightly higher in hard-rock areas than in deep alluvial areas, whereas an opposite and more marked effect is true at sites distant from the epicentre. Another explanation for increased epicentral ground motion in hard-rock areas is that hard rock can withstand greater accelerations before the elastic limit is reached. As stated above, however, the effect of local geology on epicentral ground motion is only small, and therefore the curves of Matthiesen et al. presented in Figure 3 can

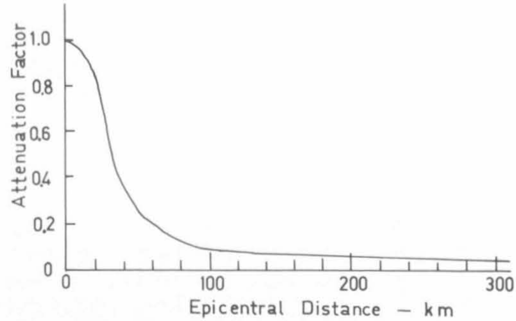


Fig. 8. Attenuation of maximum rock acceleration with distance from epicentre.

confidently be used to estimate the peak ground acceleration at a site close to a causative fault.

Of course detailed geological and geophysical investigations should again be carried out at the site to reveal any unusual conditions, e.g. a deep saturated soil column, which could have an undesirable response to seismic events.

ESTIMATION OF THE GROUND MOTION AND USE OF RESPONSE SPECTRUM AT THE SITE

Once the DBE maximum ground acceleration has been estimated for the site, the next step is to predict the expected ground motion there from such a hypothetical earthquake. This can be done by using strong-motion accelerograms recorded during earthquakes.

Strong-motion earthquake data that have been used for this purpose include those recorded from earthquakes at El Centro (1940), Taft (1952), San Francisco Golden Gate Park (1957), Koyna, Lima, Parkfield (1966), and Matsushiro. An accelerogram resulting from the Taft earthquake is illustrated in Figure 9 as an example of a strong-motion record.

Such accelerograms should be studied and one or more selected and modified if necessary to take regional conditions and epicentral distance into account. The time-history of ground motion accepted for the site can then be normalized to the peak acceleration already estimated there. By this means one can obtain a suitable evaluation of the rock motion at the site for use in the design of the power plant.

The information contained in the chosen accelerogram can also be expressed in the form of a ground motion spectrum. (The desired ground motion spectrum is defined as a plot of the vibratory ground movement against the frequency of the components of the motion.)

Because of the difficulty, however, of computing maximum stresses and strains directly from the transient response of the proposed structure to the complicated earthquake-induced ground motions, it is worth mentioning another approach originally proposed by M. A. Biot in 1932, as it has gained much popularity amongst design engineers in recent years (Blume, 1967). The predicted ground motions are represented in the form of response spectra which indicate the estimated response of the power plant when subjected to vibratory ground motions due to an earthquake. The response spectra represent the maximum amplitude of the vibratory motions over a range of frequencies corresponding to the natural frequencies of the structures or their various elements for various degrees of assumed damping.

Thus, by using the DBE ground motions expressed as an accelerogram, as ground motion spectra, or as response spectra, design engineers are then able to estimate the nuclear plant's response to the DBE ground motions, and the likelihood of structural damage.

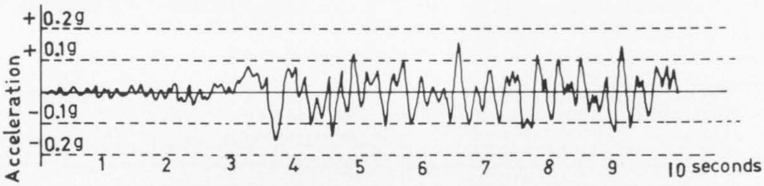


Fig. 9. Accelerogram of Taft earthquake.

REFERENCES

ALBEE, A. L., & SMITH, J. L., 1966—Earthquake characteristics and fault activity in southern California. *In* ENGINEERING GEOLOGY IN SOUTHERN CALIFORNIA (R. Lung & R. Proctor Eds). *Assoc. of Engr. Geol. Spec. Pub.*, October 1966.

BERNREUTER, D. L., & TOKARZ, F. J., 1972—Design Basis Earthquakes for the Lawrence Livermore Laboratory site. *Lawrence Livermore Laboratory, University of California, Livermore*. Report UCRL—51193.

BLUME, J. A., 1967—Summary of current seismic design practice for nuclear reactor facilities. *John A. Blume & Assoc., Engineers, San Francisco,* Report TID 25021.

GUTENBERG, B., & RICHTER, C., 1956—Earthquake magnitude, intensity, energy, and acceleration. *Bull. Seism. Soc. Am.,* 46, 105-143.

HOUSNER, G. W., 1965—Intensity of shaking near the causative fault. *Proc. Third World Conference on Earthquake Eng.,* Vol. 1, Auckland, New Zealand.

MATTHIESEN, R. B., HOWARD, G., & SMITH, C. B., 1973—Seismic considerations in siting and design. *Nuclear Engineering and Design,* 25, 1-2, North Holland Publishing Co.

NEWMARK, W. M., & HALL, W. J., 1969—Seismic design criteria for nuclear reactor facilities. *Proc. Fourth World Conference on Earthquake Eng.,* Santiago, Chile.

USAEC, 1971—Nuclear power plants, seismic and geological siting criteria. *U.S. Atomic Energy Commission Federal Register.* Vol. 36, No. 228, 10 CFR 100, No. 25.

SEISMIC EFFECTS ON NUCLEAR POWER PLANTS

by A. L. Borea and J. L. Meek

Queensland University

SUMMARY

This paper sets out to discuss the problems related to the design of the nuclear power plant structure for transient loads that may be imposed by ground motions. It recognizes that ground motion may be experienced from several sources such as nearby explosion, forced vibration, machinery, or earthquake.

For the case of explosion, there is a need to study the basic wave propagation problem and to obtain expressions for ground motion and acceleration at a distance from the disturbing force. In this the importance of foundation material is stressed. The natural phenomena of the earthquake are also considered. Features associated with attempts to define a suitable basic earthquake—its magnitude, probability of occurrence, etc.—are discussed.

Speculation is made as to the probability of earthquakes in Australia. The end product of all such investigation is the study of the power plant structures, under the influence of the dynamic forces. This may be undertaken on the crude basis of spectral analysis or by more refined finite element models using a specified earthquake as input. Here emphasis is placed on the necessity to include the interaction between foundation and structure as well as accurate modelling of the structure itself.

THE EFFECT OF LARGE DAMS ON EARTHQUAKE RISK

by K. J. MUIRHEAD

Australian National University

SUMMARY

In the last decade a number of instances of local earthquake activity have been attributed to the filling of reservoirs. Some have reached magnitude 6 and have caused considerable damage.

Why a reservoir should induce seismic activity is still largly unknown. It is believed, however, that it is due to crustal loading or an increase in pore pressure (or both) triggering the release of stored tectonic stresses.

In Australia, induced activity can be attributed to only one reservoir, Talbingo, where a large number of small events occurred after filling commenced. Earthquakes near other reservoirs cannot be positively attributed because of the lack of seismic observations before the water was impounded.

R75/538