Appendix A - MODIFIED MERCALLI (MM) SCALE OF EARTHQUAKE INTENSITY (AFTER DOWRICK, 1996)

A.1 MM I

People

Not felt except by a very few people under exceptionally favourable circumstances.

A.2 MM II

People

Felt by persons at rest, on upper floors or favourably placed.

A.3 MM III

People

Felt indoors; hanging objects may swing, vibrations may be similar to passing of light trucks, duration may be estimated, may not be recognised as an earthquake.

A.4 MM IV

People

Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration may be likened to the passing of heavy traffic, or to the jolt of a heavy object falling or striking the building.

Fittings

Doors and windows rattle. Glassware and crockery rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock.

Structures

Walls and frame of building are heard to creak, and partitions and suspended ceilings in commercial buildings may be heard to creak.

A.5 MM V

People

Generally felt outside, and by almost everyone indoors. Most sleepers awakened. A few people alarmed.

Fittings

Small unstable objects are displaced or upset. Some glassware and crockery may be broken. Hanging pictures knock against the wall. Open doors may swing. Cupboard doors secured by magnetic catches may open. Pendulum clocks stop, start, or change rate.

Structures

Some windows Type I cracked. A few earthenware toilet fixtures cracked.

A.6 MM VI

People

Felt by all. People and animals alarmed. Many run outside. Difficulty experienced in walking steadily.

Fittings

Objects fall from shelves. Pictures fall from walls. Some furniture moved on smooth floors, some unsecured free-standing fireplaces moved. Glassware and crockery broken. Very unstable furniture overturned. Small church and school bells ring. Appliances move on bench or table tops. Filing cabinets or “easy glide” drawers may open (or shut).

Structures

Slight damage to Buildings Type I. Some stucco or cement plaster falls. Windows Type I broken. Damage to a few weak domestic chimneys, some may fall.

Environment

Trees and bushes shake, or are heard to rustle. Loose material may be dislodged from sloping ground, e.g. existing slides, talus slopes, shingle slides.

A.7 MM VII

People

General alarm. Difficulty experienced in standing. Noticed by drivers of motorcars who may stop.

Fittings

Large bells ring. Furniture moves on smooth floors, may move on carpeted floors. Substantial damage to fragile contents of buildings.

Structures

Unreinforced stone and brick walls cracked. Buildings Type I cracked with some minor masonry falls. A few instances of damage to Buildings Type II. Unbraced parapets, unbraced brick gables, and architectural ornaments fall. Roofing tiles, especially ridge tiles, may be dislodged. Many unreinforced chimneys damaged, often falling from roof-line. Water tanks Type I burst. A few instances of damage to brick veneers and plaster or cement-based linings. Unrestrained water cylinders (Water Tanks Type II) may move and leak. Some windows Type II cracked. Suspended ceilings damaged.

Environment

Water made turbid by stirred up mud. Small slides such as falls of sand and gravel banks, and small rock-falls from steep slopes and cuttings. Instances of settlement of unconsolidated or wet, or weak soils. Some fine cracks appear in sloping ground. A few instances of liquefaction (i.e. small water and sand ejections).

A.8 MM VIII

People

Alarm may approach panic. Steering of motor cars greatly affected.

Structures

Buildings Type I, heavily damaged, some collapse. Buildings Type II damaged, some with partial collapse. Buildings Type III damaged in some cases. A few instances of damage to Structures Type IV. Monuments and pre-1976 elevated tanks and factory stacks twisted or brought down. Some pre-1965 infill masonry panels damaged. A few post-1980 brick veneers damaged. Decayed timber piles of houses damaged. Houses not secured to foundation may move. Most unreinforced domestic chimneys damaged, some below roof-line, many brought down.

Environment

Cracks appear on steep slopes and in wet ground. Small to moderate slides in roadside cuttings and unsupported excavations. Small water and sand ejections and localised lateral spreading adjacent to streams, canals, lakes, etc.

A.9 MM IX

Structures

Many buildings Type I destroyed. Buildings Type II heavily damaged, some collapse. Buildings Type III damaged, some with partial collapse. Structures Type IV damaged in some cases, some with flexible frames seriously damaged. Damage or permanent distortion to some Structures Type V. Houses not secured to foundations shifted off. Brick veneers fall and expose frames.

Environment

Cracking of the ground conspicuous. Landsliding general on steep slopes. Liquefaction effects intensified and more widespread, with large lateral spreading and flow sliding adjacent to streams, canals, lakes, etc.

A.10 MM X

Structures

Most Buildings Type I destroyed. Many Buildings Type II destroyed. Buildings Type III heavily damaged, some collapse. Structures Type IV damaged, some with partial collapse. Structures Type V moderately damaged, but few partial collapses. A few instances of damage to Structures Type VI. Some well-built timber buildings moderately damaged (excluding damage from falling chimneys). Dams, dykes, and embankments seriously damaged. Railway lines slightly bent. Cement and asphalt roads and pavements badly cracked or thrown into waves.

Environment

Landsliding very widespread in susceptible terrain, with very large rock masses displaced on steep slopes. Landslide dams may be formed. Liquefaction effects widespread and severe.

A.11 MM XI

Structures

Most Buildings Type II destroyed. Many Buildings Type III destroyed. Structures Type IV heavily damaged, some collapse. Structures Type V damaged, some with partial collapse. Structures Type VI suffer minor damage, a few moderately damaged.

A.12 MM XII

Structures

Most Buildings Type III destroyed. Many Structures Type IV destroyed. Structures Type V heavily damaged, some with partial collapse. Structures Type VI moderately damaged.

A.13 Construction types

Buildings Type I Buildings with low standard of workmanship, poor mortar, or constructed of weak materials like mud brick or rammed earth. Soft storey structures (e.g. shops) made of masonry, weak reinforced concrete, or composite materials (e.g. some walls timber, some brick) not well tied together. Masonry buildings otherwise conforming to Buildings Type I–III, but also having heavy unreinforced masonry towers. (Buildings constructed entirely of timber must be of extremely low quality to be Type I).

Buildings Type II Buildings of ordinary workmanship, with mortar of average quality. No extreme weakness, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces. Such buildings not having heavy unreinforced masonry towers.

Buildings Type III Reinforced masonry or concrete buildings of good workmanship and with sound mortar, but not formally designed in detail to resist earthquake forces.

Structures Type IV Buildings and bridges designed and built to resist earthquakes to normal use standards, i.e. no special collapse or damage limiting measures taken (mid 1930s to c. 1970 for concrete and to c. 1980 for other materials).

Structures Type V Buildings and bridges designed and built to resist earthquakes to normal use standards, i.e. no special damage limiting measures taken, other than code requirements, dating from since c. 1970 for concrete and c. 1980 for other materials.

Structures Type VI Structures dating from c. 1980 with well defined foundation behaviour, which have been especially designed for minimal damage, e.g. seismically isolated emergency facilities, some structures with dangerous or high (value) contents, or new generation low damage structures.

Windows

Type I – Large display windows, especially shop windows.

Type II – Ordinary sash or casement windows.

Water tanks

Type I – External, stand mounted, corrugated iron water tanks.

Type II – domestic hot-water cylinders unrestrained except by supply and delivery pipes.

Appendix B - REGIONAL SEISMICITY

B.1 List of Earthquakes with ML ≥ 3.0 in the Investigated Region

To estimate rates of occurrence, dependent events (foreshocks and aftershocks) were removed from the catalogue. To decluster the earthquake data set, the identifiable foreshocks and aftershocks were removed according to the procedure described by (McFadden et al., 2000). An event was considered to be a foreshock or an aftershock if it was within a distance, d km, of the main shock, defined below and, if it occurred within 10 years of a mainshock of magnitude 7, within 1 year of a magnitude 6 event, within 3 months of a magnitude 5 event, and within 10 days of a magnitude 4 event.

$$d = 10^{\frac{M_L - 4.11}{1.65}} \text{ km}$$

Geoscience Australia’s QUAKES Database retrieval parameters:

preferred solutions
date between 18410101 and 20010101
lat between -34.9 and -30.9
long between 149.75 and 153.75
depth between 0 and 33 km
Magnitude between 3 and 9

Source	Date	UTC	Lat	Long	Depth	Ms	ML	auth unsp
AUST	18410127	215500	-32.8	151.6	10		4.9	MCCU
AUST	18421027	193000	-32.6	151.6	10		5.3	MCCU
AUST	18680618	140000	-32.8	151.6	10		5.3	MCCU
AUST	18721018	185000	-33.7	150	15		5.3	MCCU
AUST	19020228	122000	-34.3	150.8	5		4.1	
AUST	19160610	1751	-32.25	152.5	0		4.6	
BURKE	19190815	102121	-33.5	150.7	0		4.6	RIV
MCCUE	19251218	104710	-33	151.6	10	4.5	5.3	MCCU
BURKE	19341110	234740	-34.9	150	0	4.2	4.8	RIV
BURKE	19341111	104632	-34.9	150	0		3.5	RIV
BURKE	19351208	30807	-34.5	150.5	33		3	RIV
DESU	19591012	212340	-31	151.5	0		4.7	RIV
CAN	19600717	255	-34	150.25	10		3	
CAN	19610521	214003	-34.547	150.503	19		5.6	RIV

Source	Date	UTC	Lat	Long	Depth	Ms	ML	auth unsp
CAN	19620208	52548.8	-34.55	150.51	4		3.3	CAN
CAN	19620502	135355	-33.9	150.1	8		3	CAN
CAN	19620710	64405.6	-34.2	150.43	8		3.2	CAN
CAN	19620928	204717	-34.47	150.01	27		3	CAN
CAN	19620929	13134.5	-34.48	150.03	26		4.2	RIV
CAN	19680708	115013.5	-34.57	150.51	13		4.5	CAN
CAN	19681018	175112.4	-34.52	150.45	13		3.1	ISC
CAN	19700309	121617	-32.8	152.42	0		3	CAN
AUST	19720430	171123.9	-31.01	150.15	0		3.9	CAN
CAN	19730301	321	-33.57	151.95	0		3	CAN
CAN	19730301	424	-33.78	152.12	0		3.4	CAN
CAN	19730309	190914.7	-34.17	150.32	21	5.3	5.5	CAN
CAN	19730309	192159.1	-34.15	150.37	38		3.7	CAN
CAN	19730309	192750.3	-34.18	150.34	16		3.2	CAN
CAN	19730309	192848.5	-34.14	150.28	13		3.1	CAN
CAN	19730309	193221.6	-34.18	150.35	15		3.4	CAN
CAN	19730309	195347.5	-34.17	150.33	13		3	CAN
CAN	19730309	200628.7	-34.15	150.32	12		3	CAN
CAN	19730309	201212	-34.13	150.35	9		3.2	CAN
CAN	19730309	204146.6	-34.16	150.32	12		3.5	CAN
CAN	19730309	205418.1	-34.17	150.36	4		3.3	CAN
CAN	19730309	210110.8	-34.19	150.37	25		3.4	CAN
CAN	19730310	41137.2	-34.18	150.34	26		3.5	CAN
CAN	19730310	81450.9	-34.19	150.34	20		3	CAN
CAN	19730310	124705.6	-34.17	150.35	26		3.2	CAN
CAN	19730310	125310.2	-34.17	150.35	25		3.3	CAN
CAN	19730310	125354.4	-34.16	150.34	26		3.6	CAN
CAN	19730310	132947.1	-34.18	150.34	22		3.1	CAN
CAN	19730310	180412.1	-34.18	150.35	24		3.1	CAN
CAN	19730311	30922.8	-34.18	150.37	13		3.1	CAN
CAN	19730312	144202.5	-34.18	150.35	12		3.1	CAN
CAN	19730313	61445	-34.16	150.34	24		3.5	CAN
CAN	19730314	60602.4	-34.2	150.33	22		3.9	CAN
CAN	19730314	95534.6	-34.18	150.32	21		3.2	CAN
CAN	19730315	214849.4	-34.17	150.34	18		3	CAN
CAN	19730316	14802.2	-34.17	150.34	27		3.7	CAN

Source	Date	UTC	Lat	Long	Depth	Ms	ML	auth unsp
CAN	19730317	170529.9	-34.16	150.36	24		3.4	CAN
CAN	19730319	25610.3	-34.19	150.33	16		3.5	CAN
CAN	19730321	143959.1	-34.18	150.33	12		3.4	CAN
CAN	19730325	12546.6	-34.18	150.34	14		3.2	CAN
CAN	19730327	105210	-34.18	150.35	15		3	CAN
CAN	19730328	165913.3	-34.17	150.32	17		3	CAN
CAN	19730414	210602.6	-34.18	150.31	12		3.4	CAN
CAN	19730507	115753	-34.17	150.4	0		3	CAN
CAN	19760109	43028.9	-34.21	150.63	7		3	CAN
CAN	19770413	215742.5	-33.51	150.17	20		3.4	CAN
AUST	19780123	71222.3	-33.62	151.17	30		4	CAN
CAN	19780822	103732.3	-32.87	151.42	20		3.4	CAN
CAN	19781211	23111.3	-33.89	151.69	21		3.3	CAN
CAN	19790204	132604.1	-33	151.4	29		3.2	CAN
CAN	19790226	82123	-34.58	151.77	0		3.2	CAN
CAN	19790302	180512.2	-32.99	151.41	13		3	CAN
CAN	19790413	152414.5	-32.99	149.85	7		3	CAN
CAN	19790416	13416.7	-33.94	150.53	18		3	CAN
CAN	19790506	130922	-32.1	149.83	0		3.3	CAN
CAN	19800424	41701	-33.76	150.09	19		3	CAN
ISC	19800907	95539.8	-34.155	150.698	18		3.3	CAN
CAN	19801215	150614.1	-32.76	151.41	16		3.4	CAN
CAN	19810222	131233.5	-32.98	150.51	10		3.4	CAN
CAN	19810225	52902.3	-32.78	151.46	21		3.6	CAN
CAN	19810907	24514	-32.46	150.99	19		4.2	CAN
AUST	19811115	165810.8	-34.249	150.897	14	3.9	4.6	AUST
ASC	19811119	121852.8	-34.227	150.886	12		3.3	ASC
CAN	19820713	93019	-34.25	152	0		3	CAN
CAN	19820909	42823	-33.6	151.96	15		4.1	AUST 4.3
CAN	19820915	43042	-34.75	150.87	0		3	CAN
CAN	19820915	43349.9	-34.75	150.87	26		3.3	CAN
CAN	19821225	164840	-33	151.9	0		3.5	CAN
CAN	19830206	231351.5	-31.08	151.33	25		4.6	CAN
CAN	19830209	42930	-33.83	151.76	0		3	
CAN	19830322	133935.3	-34.35	150.4	19		3.5	
CAN	19830414	151636.2	-33.46	150.6	29		3	

Source	Date	UTC	Lat	Long	Depth	Ms	ML	auth unsp
CAN	19830429	165104.8	-32.56	151.39	10		3.6	
CAN	19830518	84252.1	-33.98	150.65	22		3.5	
CAN	19830617	25940.3	-32.44	150.92	20		3.5	
CAN	19830924	72551.9	-33.6	150.13	16		3.6	
CAN	19831101	5009	-33.9	150.45	0		3.1	
CAN	19840720	215620.2	-32.52	151.37	21		3.9	
AUST	19850213	80122.8	-33.49	150.18	7		4.3	AUST
CAN	19850213	115944.4	-33.38	150.14	12		3.2	CAN
AUST	19850510	2544.8	-33.63	150.13	0		3	AUST
CAN	19850713	214655.2	-33.56	150.08	14		3.2	CAN
CAN	19850713	230624	-33.63	150.11	0		3.1	CAN
AUST	19850822	141618	-32.6	152.4	0		3.1	AUST
AUST	19860220	214355.3	-33.33	150.604	2		4	AUST
AUST	19870624	145319.2	-33.47	150.17	0		3.1	AUST
AUST	19870624	150455.2	-33.432	150.149	5		4.3	AUST
AUST	19870624	153236	-33.41	150.1	13		3.4	AUST
AUST	19870624	154706.8	-33.46	150.18	0		3.5	AUST
AUST	19870826	13833.9	-32.732	151.168	0		3	
AUST	19870904	71535.9	-32.09	152.58	0		3.4	AUST
AUST	19880430	170012.4	-33.5	150.15	1		3.2	AUST
AUST	19891216	2856.1	-34.7	150.67	23		2	
AUST	19891227	232657	-32.946	151.607	11	4.6	5.5	AUST
MEL	19900330	113300	-34.25	150.83	0		3	
MEL	19900522	63928	-32.026	150.332	10		3.4	
AUST	19910717	23411.1	-32.54	150.9	3		3.2	AUST
AUST	19931023	123241.5	-32.914	151.299	7		3	AUST
AUST	19940806	110351.6	-32.924	151.288	2		5.3	AUST
AUST	19950503	42423	-33.17	150.24	14		3.2	AUST
AUST	19950520	112911.8	-33.86	150.07	6		3.6	AUST
AUST	19950528	231258.4	-32.518	151.408	4		3.5	AUST
AUST	19950707	65324.5	-32.928	151.318	1		3.2	AUST
AUST	19951121	170214.1	-32.884	151.269	2		3.1	AUST
AUST	19961001	214222	-33.819	150.405	5		3.4	AUST
AUST	19961210	125426.1	-34.158	150.53	5		3.3	AUST
AUST	19961210	125835.4	-34.141	150.503	6		3.2	AUST
AUST	19970708	100122.4	-31.594	153.06	10		3.7	AUST

Source	Date	UTC	Lat	Long	Depth	Ms	ML	auth unsp
AUST	19980309	124042.9	-32.143	150.003	3		3.1	AUST
AUST	19990317	15810.6	-34.234	150.77	8		4.8	AUST
ASC	19990818	1451.1	-33.888	152.302	2		3.3	
ASC	19990818	1915.9	-33.901	152.175	0		3	

Seismic Parameters:

Source: contributing agency

Date: date of earthquake

UTC: Universal Coordinated Time

Lat: decimal latitude

Long: decimal longitude

Depth: focal depth in km

Mb: body wave magnitude

Ms: surface wave magnitude

MD: duration magnitude

MN: Nuttli magnitude

ML: local magnitude

Auth: agency that assigned the magnitude

- MCCU
- RIV
- CAN
- ISC
- AUST
- ASC
- AUST 4.3

Unsp: unspecified magnitude

Mw: moment magnitude

Obs: number of observations

Stat: number of stations

B.2 List of Significant Earthquakes in the Study Region

Date	Time (UTC[22])	Lat (°S)	Long (°E)	Place	M_L[23]	I_{max}[24]	Comments	Source
02/07/1837	12:20	(33.0)	(152.0)	Near Newcastle	(5.0)	V	Felt in Newcastle MM V	Hunter, 1991
27/01/1841	21:55	32.8	151.6	Near Newcastle	4.9	V	Felt in Newcastle MM V	McCue, 1995
27/10/1842	19:30	32.6	151.6	Near Paterson	5.3	V	Felt in Newcastle MM V	McCue, 1995
18/06/1868	14:00	32.8	151.6	Maitland	5.3	VI	Felt in Newcastle MM V - VI; Damage reported	McCue, 1995
18/10/1872	18:50	33.7	149.8	Jenolan Caves	5.3	VI	Felt in Newcastle MM IV - V	McCue, 1995
10/06/1916	00:17	32.25	152.5	Seal Rocks	4.6	VI-VII	Felt in Newcastle MM IV-V	McCue, 1995
15/08/1919	10:21	33.5	150.7	Kurrajong	4.6	V	Felt in Newcastle MM II-III	Everingham et al, 1982
18/12/1925	10:47	33	151.6	Boolaroo	5.3	VI	Felt in Newcastle MM VI; Damage reported	Rynn et al., 1987
21/05/1961	21:40	34.55	150.503	Robertson-Bowral	5.6	VII	Felt in Newcastle MM III - IV	Everingham et al, 1982
09/03/1973	19:09	34.17	150.32	Picton	5.5	VII	Felt in Newcastle MM III	Everingham et al, 1982
15/11/1981	16:58	34.25	150.9	Appin	4.6	V	Felt in Newcastle MM III	Everingham et al, 1982
13/02/1985	08:01	33.49	150.18	Lithgow	4.3	VI	Felt in Newcastle MM III	McCue, 1995
20/02/1986	21:43	33.33	150.604	Upper Colo	4.0	IV	Felt in Newcastle MM II	McCue, 1995
24/06/1987	15:04	33.43	150.149	Lithgow	4.3	VII	Not felt in Newcastle	McCue, 1995
27/12/1989	23:26	32.95	151.607	Newcastle	5.6	VIII	Felt in Newcastle MM VIII; Damage	McCue, 1995
08/06/1994	11:03	32.92	151.288	Ellalong	5.4	VII	Felt in Newcastle MM IV - VI	Jones et al., 1994
17/03/1999	01:58	34.23	150.77	Appin	4.8	V	Not felt, Newcastle	McCue et al., in press

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[22] *UTC = Universal Coordinated Time = Australian Eastern Standard Time minus 10 hrs*

[23] M_L *= Richter (or local) magnitude*

[24] I_{max} *= maximum seismic intensity measured on the Modified Mercalli Scale*

B.3 Isoseimal Maps

Isoseismal maps show the distribution of the shaking effects of earthquakes, and provide valuable information for estimates of earthquake risk. They are of particular significance in Australia, where instrumental strong-motion data are scarce and difficult to obtain.

The reports of damage and other "felt" effects are quantified in terms of assigned intensities (MM values) and the compiled isoseismal maps for each earthquake and are presented as a contour map of the individual intensities. Isoseismal maps were published in three BMR/AGSO Atlases (Everingham et al., 1982; McCue, 1995; Rynn et al., 1987). The Modified Mercalli (MM) scale, the basis of modern intensity estimates, is described in Appendix A.

The results have been obtained from the files and computer data lists of Geoscience Australia (GA) formerly known as the Australian Geological Survey Organisation, Canberra. Geoscience Australia maintains the Australian National Earthquake Data Centre, where information on all located earthquakes occurring in the Australian region is recorded and updated.

The details of five earthquakes for which isoseismal maps are shown in Figure B - 1 to Figure B - 6 are listed in the following table: These details were taken from GA's earthquake database, which contains earthquake parameters obtained from all sources. The selection of hypocentres and magnitudes for the atlas earthquakes is based on a careful examination of all available data and an appraisal of published information on the earthquakes.

Table B - 1: List of earthquakes with magnitude 5 or greater in the Study Region

Source	Date	UTC	Lat	Long	Depth	M_b	M_s	M_L	auth	M_w	stat
AUST	18421027	193000	-32.6	151.6	10			5.3	MCCU		
AUST	18680618	140000	-32.8	151.6	10			5.3	MCCU		0
MCCUE	19251218	104710	-33	151.6	10		4.5	5.3	MCCU		2
AUST	19891227	232657	-32.946	151.607	11	5.7	4.6	5.5	AUST	5.6	17
AUST	19940806	110351.6	-32.924	151.288	2	5.3		5.3	AUST		

For earthquakes that occurred before 1958, instrumentally determined hypocentres are either not available or have been inaccurately determined because instrumental recordings were rare and timing was inaccurate by modern standards. In fact, until the mid-1950s only five recording stations (Brisbane, Adelaide, Perth, Melbourne, and Sydney) were in continuous operation on the Australian continent. Hence, most of the early earthquake maps show epicentres that have been determined from macroseismic observations; the epicentres are plotted in the zones of highest intensities.

Determinations of epicentres and depths for earthquakes after the late 1950s are more accurate than for earlier earthquakes and their accuracy can vary less. By the end of 1983, many more seismographic stations had been installed but there were still significant gaps in the coverage of northern New South Wales. The most accurate results have been obtained for those earthquakes with epicentres located within networks of stations, and those which have been closely studied because they were felt over a wide area. The focal depths of some earthquakes have been determined by using local network results or reliable depth phases recorded as teleseisms.

Each magnitude was investigated to ensure that it was reliably determined from instrumental data because earthquake lists frequently record magnitudes that have been determined from intensity data or have been determined by non-standard methods. Local magnitude (M_L) was the most commonly determined magnitude, and therefore generally preferred by researchers. Reliable magnitude values for several of the earlier earthquakes could not be determined instrumentally from seismograms, so their magnitudes were calculated according to the following formula for macroseismic data (McCue, 1980):

$M_L (I) = 1.01 \ln Rp (111) + 0.13$,

where Rp(l11) is the radius or perceptibility to the MM III contour and ln is the natural logarithm. Magnitudes determined by this method should be treated as approximate values which may be revised as a result of further research.

These isoseismals maps are smoothed versions because they enclose all intensity observations equal to or greater than a given intensity, but ignore some intensity reports which did not fit the general pattern. Because of the sparseness of instruments to record strong ground motion in Australia we will have to continue to rely on the careful analysis of felt intensities to assess earthquake risk. Therefore it is essential that a comprehensive and reliable source of these data is maintained. New isoseismal maps of future earthquakes and possible revisions of existing isoseismal maps will be included.

A significant event which occurred in the study region within the last 100 years occurred on 18 December 1925 and had a magnitude of ML 5.0 determined from the Mainka seismograms recorded at Riverview, whilst that derived from the radius of perceptibility was ML(I)=5.3. The isoseimal map was compiled from newspapers reports in the Sydney Morning Herald, Northern Daily Leader, Lithgow Mercury, Queanbeyan Age and Goulburn Herald. At Newcastle two severe shocks were felt and there was panic in a picture theatre. In Sydney a sharp shock was felt. The earthquake was also felt by a miner 600 feet below the surface in West Maitland.

Figure B - 1: Isoseismal map for the Newcastle earthquake, 27 October 1842

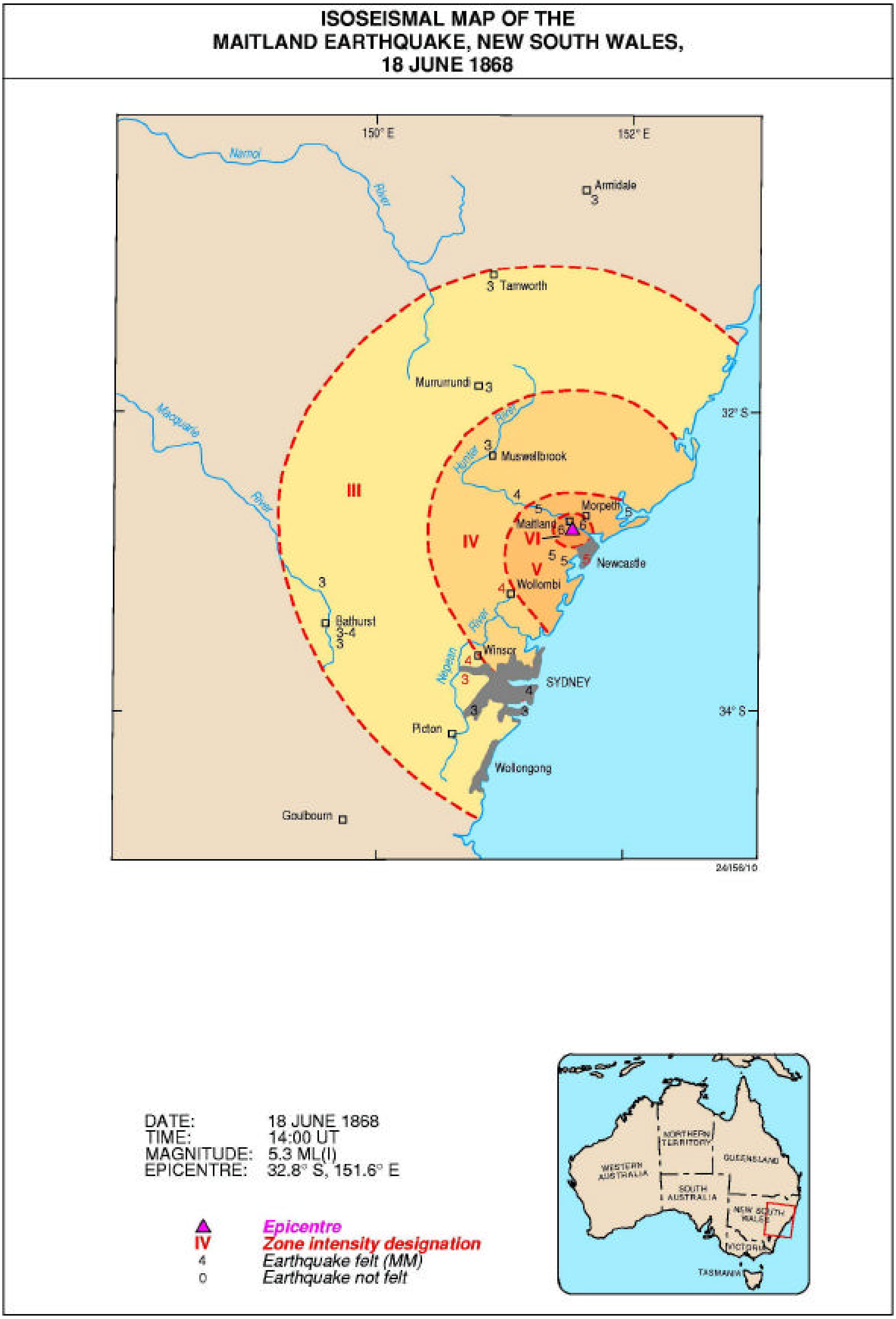


Figure B - 2: Isoseismal map for the Maitland earthquake, 18 June 1868

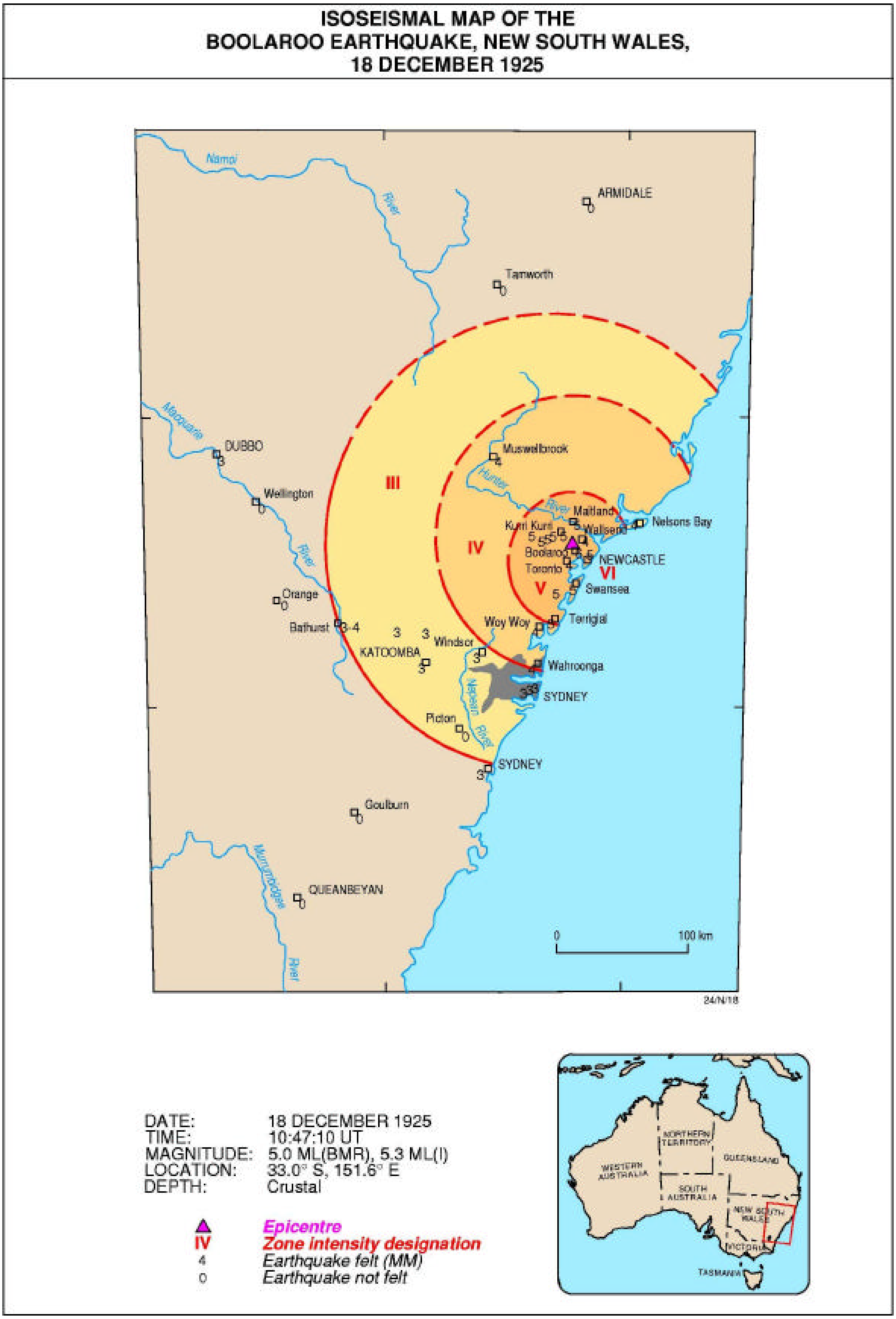


Figure B - 3: Isoseismal map for the Boolaroo earthquake, 18 December 1925

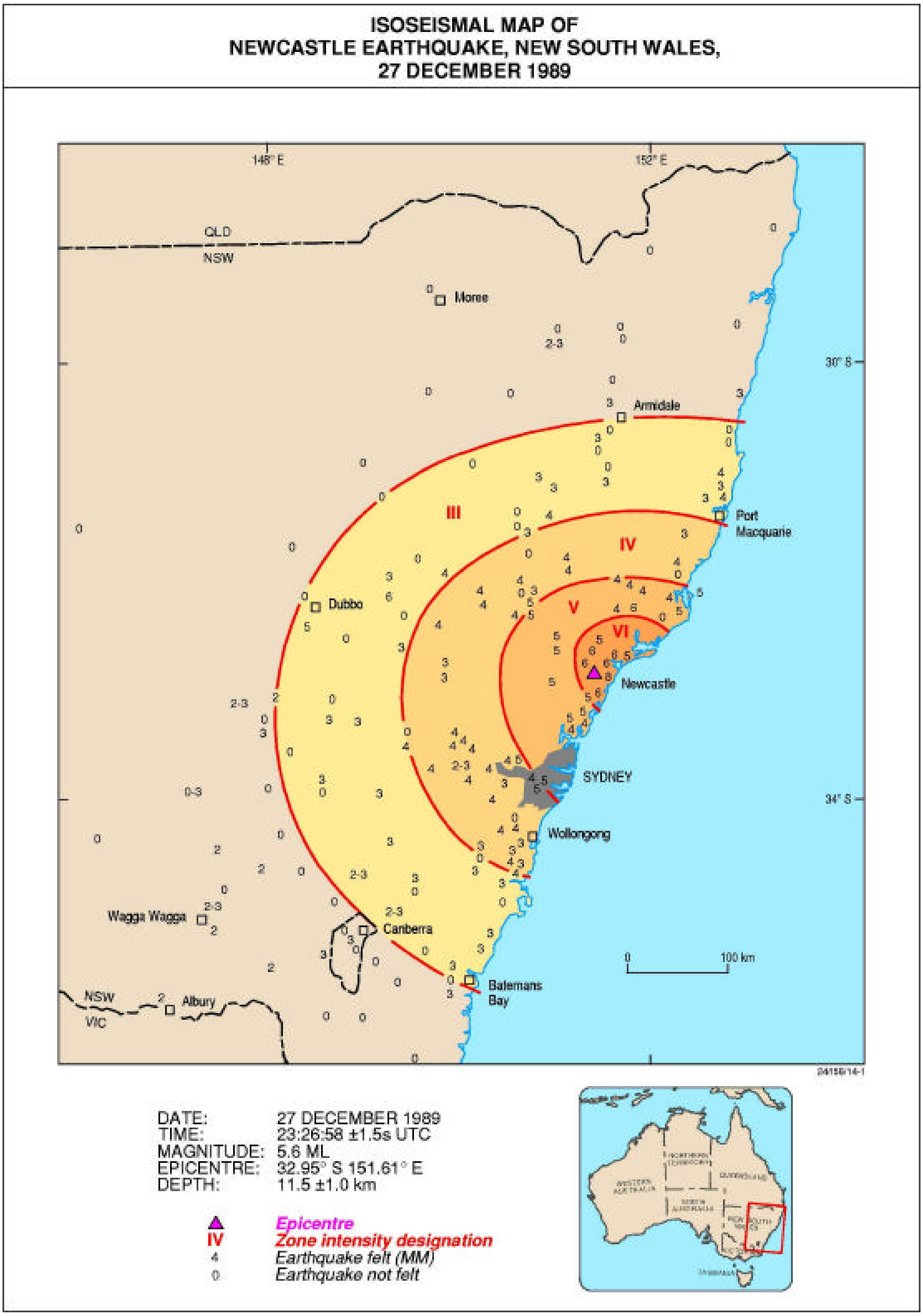


Figure B - 4: Isoseismal map for the Newcastle earthquake, 27 December 1989

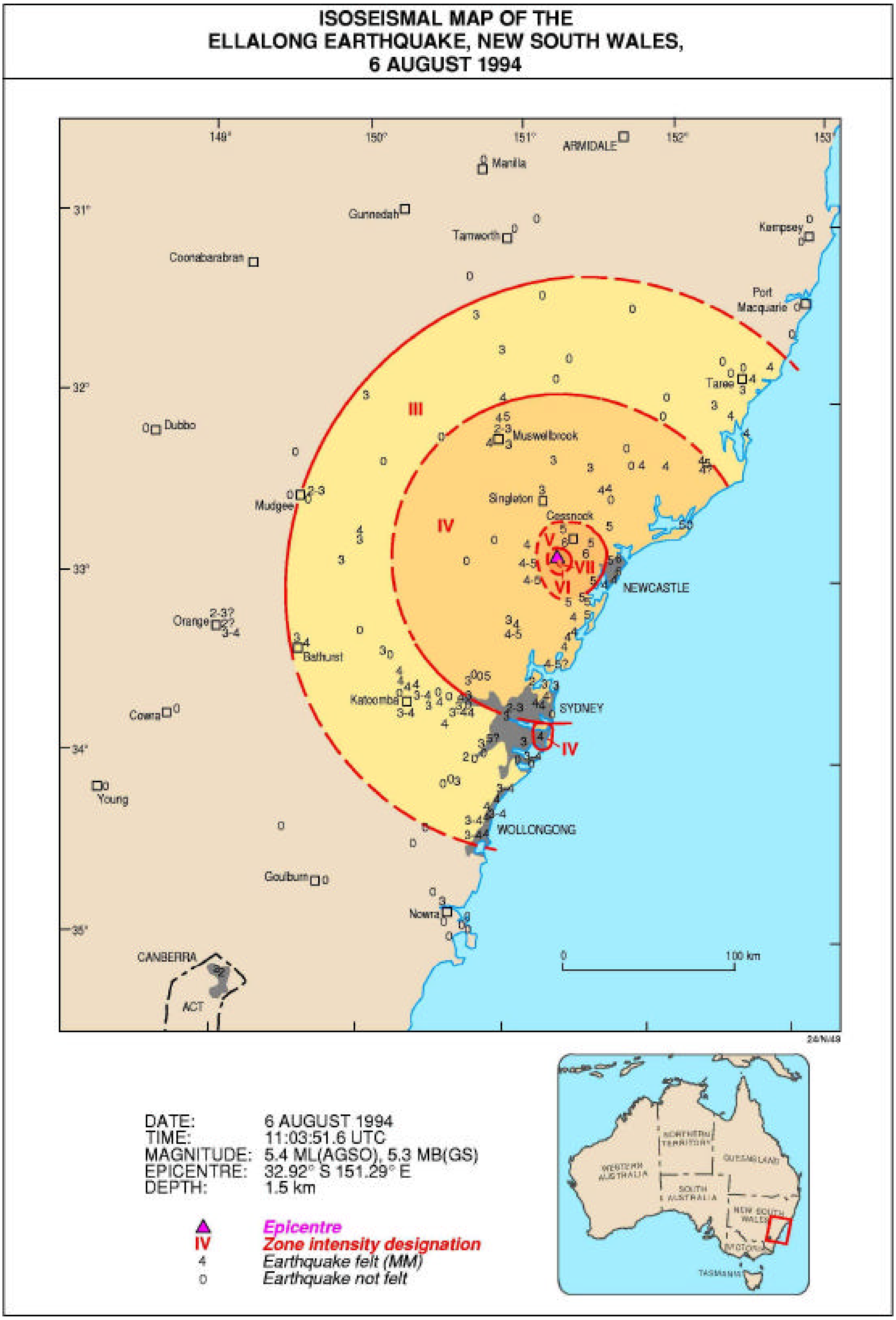
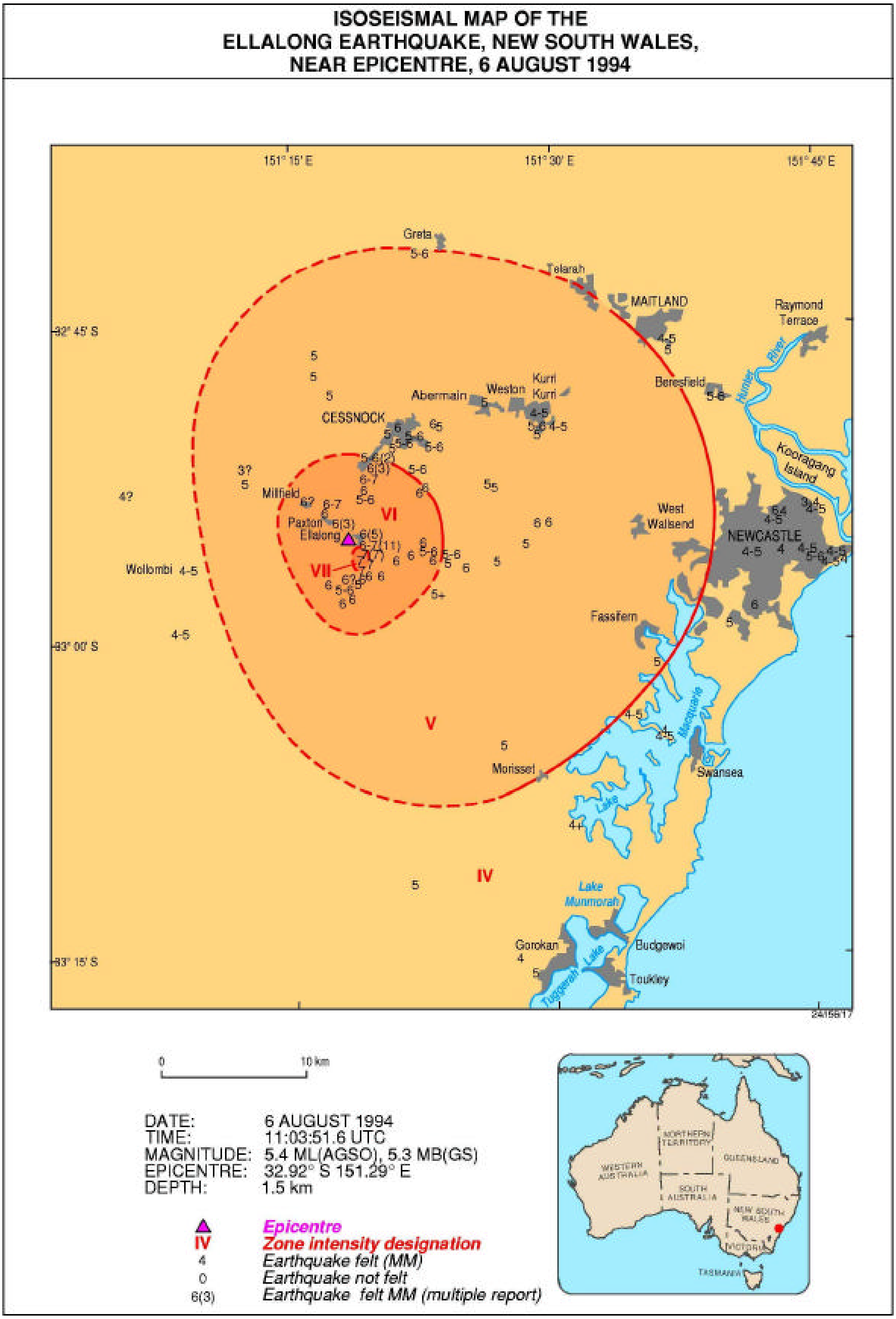


Figure B - 5: Isoseismal map for the Ellalong earthquake, 6 August 1994



ISOSEISMAL MAP OF THE
ELLALONG EARTHQUAKE, NEW SOUTH WALES,
NEAR EPICENTRE, 6 AUGUST 1994

DATE:	6 AUGUST 1994
TIME:	11:03:51.6 UTC
MAGNITUDE:	5.4 ML(AGSO), 5.3 MB(GS)
EPICENTRE:	32.92° S 151.29° E
DEPTH:	1.5 km

▲	Epicentre
IV	Zone intensity designation
4	Earthquake felt (MM)
0	Earthquake not felt
6(3)	Earthquake felt MM (multiple report)

Figure B - 6: Local isoseismal map for the Ellalong earthquake, 6 August 1994

Appendix C - EARTHQUAKE HAZARD IN THE LOWER HUNTER REGION OF NSW

C.1 The Workshop

The following is a draft report on a workshop held in Sydney on 19 December 2000 attended by a group of scientists experienced in the geological and tectonic structures of the Hunter Region. Geoscience Australia has used the outcomes from the workshop to refine the analytical processes for estimating seismic hazard. This appendix is presented as a short technical note followed by informal notes from the meeting.

C.2 Part A - Regional Earthquake Hazard Models

C.2.1 The Cities Project

The Cities Project is examining risk to Australian urban communities from a range of geohazards. The Newcastle part of this project is particularly looking at risk from seismic hazards. Risk is defined in a quasi mathematical form as:

$$\text{RISK} = f\left\{ \text{ Hazard, Elements Exposed, Vulnerability } \right\}$$

Risk contains both time and magnitude elements and is an expression of the cumulative or compendium probability of events occurring. This cumulative dimension is particularly important in considering massively impacting events such as earthquakes or tsunamis for which the estimate of recurrence interval is stated in hundred or thousand year periods.

C.2.1.1 Geological Structures and Seismic Hazard Workshop

One of the main tasks of the project is development of an earthquake hazard model for the Newcastle and Lake Macquarie region. The earthquake hazard model formed the basis from which ground-shaking scenarios with associated likelihood of occurrence were generated, for Newcastle and Lake Macquarie. The ground shaking scenarios, suitably modified by amplification factors that account for local ground conditions, were be used to assess earthquake risk in the Newcastle/Lake Macquarie study area.

Geoscience Australia (GA) sought the most knowledgeable experience available of tectonic structures and of possible active fault zones in the project region to refine this model. A workshop was convened as a part of the Cities Project following formal and informal discussions within the geological and seismological community.

The objective for GA was to develop a model for the occurrence of earthquakes for the study region, based on a consensus of expert opinion on the likelihood, magnitude and location of events. Wave propagation and ground shaking were not considered in this part of the process. The Risk Assessment process being used for this project required an estimate of the seismic hazard of the Study Region. The two specific outputs which GA wished to take away from the workshop were:

- A description of seismic occurrence models for the Newcastle and Lake Macquarie region, specifically focused on recurrence intervals, locations and magnitudes of events, and;
- Estimation of specific parameters for the model

An informal meeting with the several most experienced and knowledgeable geologists and seismologists available, was convened in Sydney on Tuesday 19 December 2000 to assist with this task. At the commencement of the workshop the group considered that it could reach a consensus and should aim to do so, rather than be pressed to voting on points.

C.2.1.2 Terminology used

Hazard can be defined as the probability of occurrence, within a specified period of time in a given area, of a potentially damaging natural phenomenon (earthquakes in this case).

Models are the theoretical constructs which are used to describe the tectonic structures and seismic behaviour, past and possible future, for the Lower Hunter region. Two sets of these models, accepted as providing feasible representations of the geology and tectonics of the Lower Hunter Region, were considered. Area Source models assume that probability of seismic events exists uniformly across a defined zone and Fault Source models assume that seismic activity will occur on specified faults.

C.2.2 Definition of Earthquake Source Zones

C.2.2.1 Area Source Seismic Zones

Earthquake source zones which have a random distribution of earthquake epicentres within a given geographic area are termed Area Source Seismic Zones. Earthquakes of given magnitudes have an equal probability of occurrence anywhere in each zone. The EQ magnitude/return period function is calculated for events of all magnitudes to estimate the seismic hazard faced by communities in the Study Area according from these zones. Those accepted were:

Tasman Sea Margin Zone (or TSMZ)

This zone is defined as a single, uniform hazard earthquake source zone that extends from northern Tasmania into Queensland as far north as the southern extremity of the Great Barrier Reef. The western margin of the TSMZ corresponds approximately with the 350 m AHD topographic contour west of the Great Dividing Range, and its eastern margin is located approximately along the eastern Australian continental shelf margin. The TSMZ is associated with the opening of the Tasman Sea and the separation of the New Zealand and Australian land masses. A square zone of side 300km centred on the Newcastle/Lake Macquarie study area is a subset of the Tasman Sea Margin Zone with uniform seismic probability derived from the larger zone and is termed the Newcastle Study Zone for the subject work. The boundaries of this zone are based on the assumption that no geological features can be identified which might change the probability of EQ occurrence in any part of the zone, such as the Hunter Region, from the overall TSMZ statistical averages. The TSMZ is shown in Figure 1.

Newcastle Triangle Zone

This zone has been specified on the hypothesis that the geological structures of the Lower Hunter region are well defined and have sufficiently clear tectonic inter-action to determine local seismic activity which is different from that in the wider field Tasman Sea Margin Zone. This comprises a triangular zone of approximately 3,000 km^2 defined by the geological structures of the Lower Hunter Region and is assumed to have uniform earthquake occurrence.

The triangle is bounded by the coastline, a north-west – south-east line through Port Stephens representing the edge of the New England Fold Belt and a north-west - south-east line through Wyong and Singleton (Figure 2). Seismic activity outside this triangle zone would be derived from the Tasman Sea Margin Zone. Coordinates of the Newcastle Triangle Zone are: near Nelson Bay (32^{*} 45’, 152^{*} 10’), near Wyong (33^{*} 15’, 151^{*} 30’), and near Singleton (32^{*} 30’, 151^{*} 15’). The south-west side of this triangle does not well represent a geo-tectonic feature and at this stage the Newcastle Triangle Zone is only a first approximation of a local zone of heightened seismic activity.

This zone is based on the assumption that the occurrence of EQs within it is more conditioned by the geological structures of the Hunter Region than by the average occurrence over the whole Tasman Sea Margin Zone. Although a triangular shaped zone has been adopted at this stage of the analysis, further work is proceeding on specifying the boundaries as they represent actual deep geological features with tectonic significance.

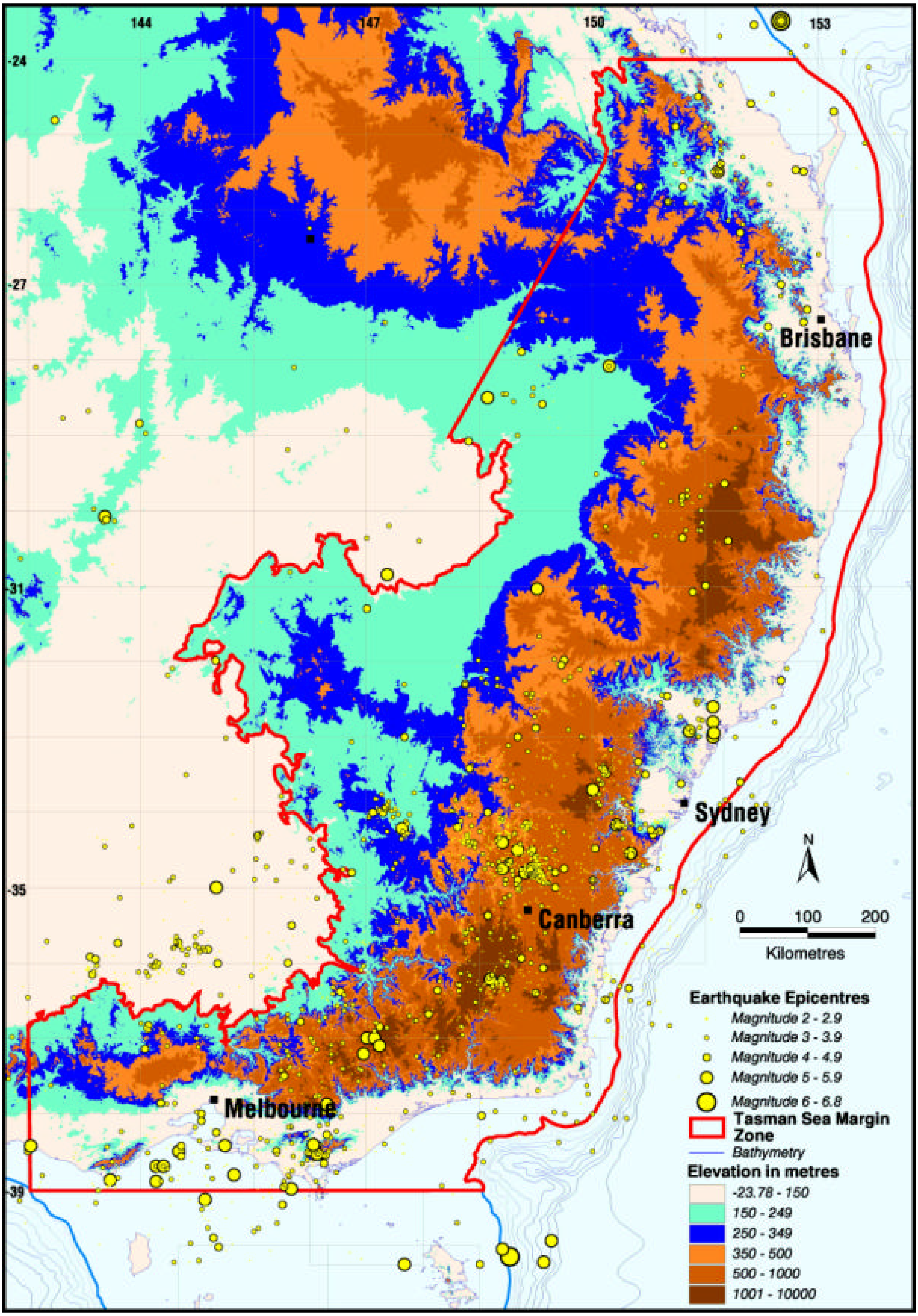
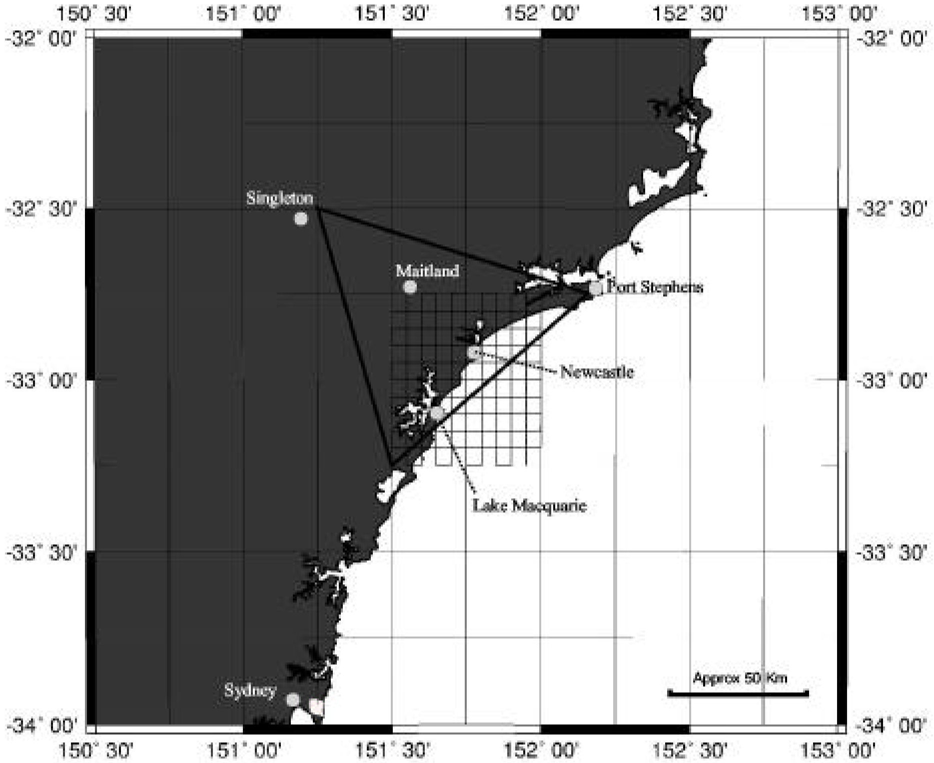
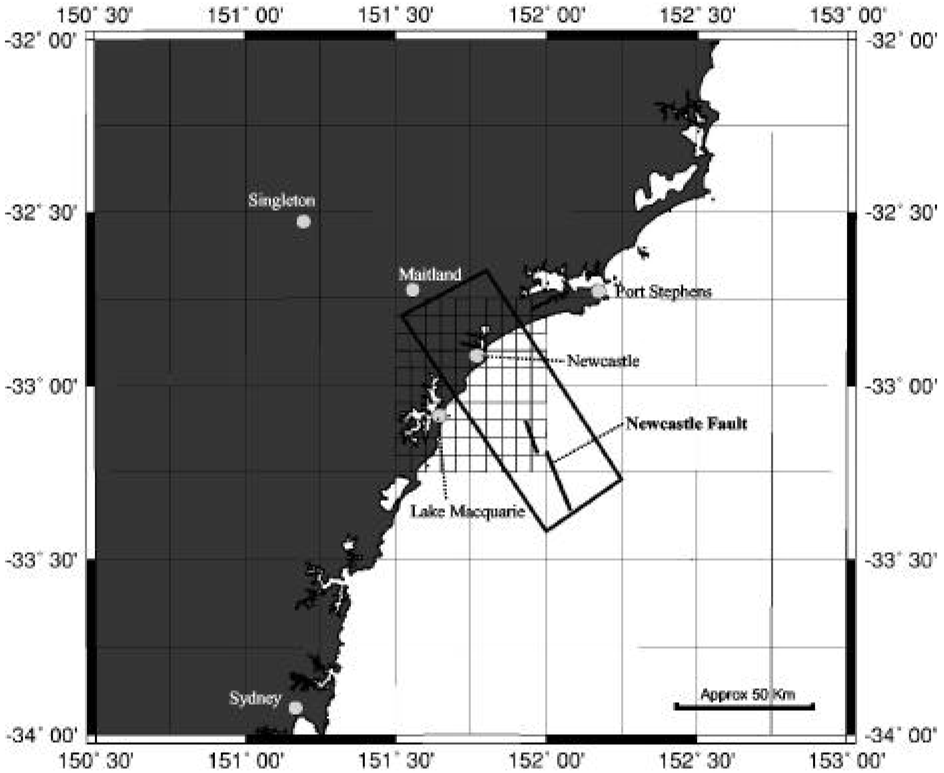


Figure 1: Tasman Sea Margin earthquake source Zone (TSMZ)



Newcastle Triangle Zone



Newcastle Onshore/Offshore Polygon Zone

Figure 2:Part 1 - Newcastle Triangle Zone, Part 2: - Newcastle Onshore/Offshore Polygon Zone. Its boundaries also correspond to the Newcastle/Hunter River Cross Fault Zone

Newcastle Onshore/Offshore Polygon Zone

This is a polygon zone defined to include the fault structures on- and off- shore in the Lower Hunter Region. The faults considered to be potentially active are the Newcastle Fault, offshore from Newcastle and reported by G Huftile in the literature, and a feature between the end of the Mooki Thrust near Maitland and the coastline near the city of Newcastle. This zone of uniform EQ hazard is a rectangle 20 to 30 km wide, aligned north-west - south-east, centred on a line approximately through Nobbys Head, bounded by a NE/SW line through Maitland and a line approximately 50 to 60 km parallel to it and off the shore (Figure 2).

C.2.2.2 Fault Source Zones

Only one fault system was accepted by the workshop. It is termed the *Newcastle/Hunter River Cross Fault Zone* and is a coupled fault system comprising: It is described in more detail in Appendix C.

The *Newcastle Fault* (offshore, but possibly also onshore) being the structure described by Huftile et al. (1999), lying 20 to 50 km south-east of Newcastle.

The *Hunter River Cross Fault* lies in the *Hunter River Transverse Zone* being a zone from the eastern extremity of the Hunter Mooki Thrust Zone near Maitland to the coast at Newcastle. This fault has uncertain location and was accepted by the workshop as being equivalent to the onshore component of the Newcastle Fault suggested above.

The *Newcastle/Hunter River Cross Fault Zone* is shown in Figure 2. The only other major fault was the Hunter Mooki Thrust which was not considered by the workshop to be an active fault structure.

C.2.3 Conclusions & Recommendations

Workshop delegates agreed to an Areal Source Zone earthquake hazard model, a Fault Zone earthquake hazard model, and an ultimate Earthquake Hazard Model that combines the areal zone and fault zone models in a probabilistic form.

C.2.3.1 Area Source Zone Model

In and near the study area, the model assigns equal (ie., 50%) weighting to the Newcastle Triangle Zone and to the Newcastle Onshore/Offshore Polygon Zone. Outside of this area, earthquakes are generated with likelihood of occurrence determined by the seismicity parameters of the Tasman Sea Margin Zone.

In practice, GA decided to use an Area Source Zone Model with 100% weighting applied to the Newcastle Triangle Zone within the Tasman Sea Margin Zone. That is, the Newcastle Onshore/Offshore Polygon Zone was not included in the Area Source Zone Model. The reason for this move is that estimates of earthquake hazard from a Newcastle Onshore/Offshore Polygon Zone are essentially the same as estimates of earthquake hazard from a Fault Source Zone Model, as we describe below. Its inclusion in both the Area Source Zone Model and the Fault Source Zone Model would have led to an overweighting on the Newcastle Onshore/Offshore Polygon Zone in comparison to other possible Lower Hunter earthquake source zones.

C.2.3.2 Fault Source Zone Model

The Newcastle/Hunter River Cross Fault Zone, a coupled fault system, was accepted as a fault model. The model assumes that earthquakes will be located on the Newcastle Fault or its on-shore extension. Earthquakes of equal magnitudes will be located with equal probability along the fault. Earthquakes can also occur in the region beyond the fault zone with a likelihood of occurrence given by the seismicity parameters of the *Tasman Sea Margin Zone*.

In practice, the Newcastle/Hunter River Cross Fault Zone has boundaries that correspond closely to the Newcastle Onshore/Offshore Polygon Zone. GA decided that the modelled ground motions in the study area resulting from earthquake occurrence on a distributed system of sub-parallel, north-west trending faults in the Newcastle/Hunter River Cross Fault Zone would be little different from modelled ground motions resulting from the random occurrence of earthquakes in the Newcastle Onshore/Offshore Polygon Zone.

C.2.4 Earthquake Hazard Model for the Lower Hunter

The probabilistic Earthquake Hazard Model for the Lower Hunter assigns weighting to the likelihood of occurrence of earthquakes as follows:

Event Magnitude	***Area Source Zone Model***	***Fault Source Zone Model***
Small earthquakes (M< 5.5)	75%	25%
Large earthquakes (M5.5 to 6.5)	25%	75%

The maximum earthquake magnitude considered possible in the study region is M6.5 plus or minus M0.5.

C.3 Part B - Notes From the Workshop

C.3.1 Hazard Models Framework

C.3.1.1 Introduction

At the commencement of the workshop the group considered that it could reach a consensus and should aim to do so, rather than be pressed to a vote on conclusions, which would raise the issue of the weighting of votes.

The following notes were prepared by GA and circulated to all participants for comment, addition and correction. They are abbreviated and intended to capture the principal statements and conclusions of all participants, but they are neither a full record of all discussion nor are they minutes of the workshop. They attempt to include all significant points made by all participants.

C.3.1.2 Seismic Incidence Science

Geoscience Australia presented the principles of seismic incidence science covering: the Guttenberg/Richter curve with the “a & b” parameters and the characteristic “bump” at maximum magnitude; the occurrence of ground shaking at a location, affected by decay and attenuation of the energy wave as it travels from its source; and the site factors at a location which can amplify the amplitude of shaking and bring frequency into proximity to that of the surface soil layer and structures on the surface. The probability analysis for seismic response at a location is obtained by integrating all possible seismic events received at that location. In summary, the seismic experience at a location is comprised of:

* the location, frequency and magnitude of rock mass rupture events,
* attenuation as energy travels from these events to the specified location of concern, and
* site amplification within surface layers at the location.

A very big uncertainty for GA’s cities project is information on probable locations of earthquake events within the region, being the three spatial coordinates of a seismic rupture event, the direction and the nature of the rock mass movement of this event. There are two types of this uncertainty, randomness in nature, and human knowledge of activity on existing faults.

C.3.1.3 Decision Making Process

The fault logic tree template which GA will adopt was discussed.

C.3.2 Regional Earthquake Catalogue

It was noted that the GA catalogue contains, for the Lower Hunter Region, seventy five (75) EQs of magnitude >2.0ML.

Depths range from 0 to 21 km with error of +- 5 km.

The Newcastle EQ1989 was at depth 11 km and its location has been ascribed accuracy of +- 5 km in all x, y ,z coordinates.

The Ellalong EQ1994 was at depth 2 km (it may have been mining related though this hypothesis is rejected by GA).

The Newcastle EQ1989 occurred over a fault face of about 5 km square. The participants agreed that it resulted from a reverse thrust mechanism.

The catalogue is complete offshore.

Instrumentation has been normalised so that all events >3.2M are included for the last 20 years, >4.0M for the last 100 years.

Events have not been stratified by depth.

Mine activity, blasts and collapses have been removed from the catalogue.

C.3.3 Tectonic Framework

Participants briefly outlined the tectonic structure of the Lower Hunter:

The Hunter Thrust has an end about 10 km west of the coast and then roughly follows the Hunter River inland in a WNW direction.

The Sydney Basin in this region is underlain by the Lachlan Fold Belt at a depth of about 6 km.

The Hunter River Transverse (Cross Fault) Zone (HRTZ) is an indicator of old structure in continental formation, with a NW orientation.

If EQs are occurring at depths much greater than 6 km (as is indicated) this may indicate re-activation of old stress fields and faults in the older HRTZ.

A discussion followed on the location of possible activity and age of structures involved:

The stress field in the Sydney Basin is variable with strong NW but some NS measurements. Work by Dr J Enver of CSIRO is a reference. There is a strong NE trending signal close to Newcastle.

There may be old blocks which have rotated with the stress field unrelieved, leading to an array of observed stress orientations.

What is the relevance of the question of depth? There are modern day stresses and there is re-activation of structures. Whether the EQ events are in the Sydney Basin or deeper there are two fracture planes, whether these are Sydney Basin or deeper in the Lachlan is an unknown.

A M5.5 EQ would be expected to rupture on 25-35 km^2 of fault and the aftershock, which was measured, would probably be on the edge of the main fault. This could put the depth as deep as 14km.

If the events are deep in the Lachlan then we are looking at Lachlan seismic events which occur as far south as Goulbourn and Canberra. This would influence the EQ catalogue used to estimate return periods.

The on-shore off-shore differences were noted. Geology offshore is not necessarily the same as geology onshore eg. Currarong Oregon is different and it is poorly known in the Sydney-Newcastle area. There is evidence of faulting offshore. Events in this medium may not be related to Lachlan based events.

The relationship between surface geology, tectonic structures and zones of varying seismic activity were considered. Field research over recent years has shown no sign to indicate the Hunter Thrust is active.

The seismic activity polygons developed by Gibson and others, based on the Gibson EQ catalogue and used in other studies in the Sydney Basin were discussed. The Gibson work produced a zone around Newcastle which included most of the observed EQ Events.

It was noted that caution is needed when laying seismic activity polygons over the surface geology. The size of events and whether mine shocks were included was an issue. Is it possible to plot energy released rather than just events? Are aftershocks from larger events removed?

If there is a re-activation of old rift faults, the currently observed surface features and zone boundaries may be less relevant.

C.3.4 Source Models

Geoscience Australia staff then described the three seismic source model types which GA was proposing: zone models, area source models, and fault models. The three parameters in these models are ‘a’ the y intercept of frequency, ‘b’ the slope of occurrence against magnitude and ‘M_{MAX}’ the maximum magnitude. M_{MAX} cannot be calculated from the earthquake catalogue but must come from the geology and palaeontology of a zone. All EQs occur on faults; large EQs occur on faults with an area large enough.

The sampling and analysis problem of dealing with errors in small numbers was questioned because the scientific record in Australia is very short. [This point did not raise sufficient debate during the workshop, considering its significance in the work of EQ forecasting.]

C.3.4.1 Zone Models

A new tri-polygon model which includes the majority of EQ events on the continental plate has previously been proposed by GA. One of the polygons includes most of eastern Australia, from north Queensland to Tasmania.

This tri-polygon model, including most of eastern Australia in large zone, was rejected by the workshop as irrelevant – the stress patterns at the north end are quite different from at the south end. A revised zone was proposed, termed the Tasman Sea Margin Zone (TSMZ) which includes the majority of seismic events in eastern Australia, extending from Fraser Island in SE Queensland to Melbourne. This was agreed to be a very significant tectonic structure in the continental plate [inclusion of north-eastern Tasmania was uncertain in the workshop, and it was excluded later by GA because of tectonic differences].

The continental shelf is 40-60 km offshore at Newcastle with a depth change from 200m on the shelf down to 2000 to 5000m over the edge. It is a passive margin but deeper than world average passive margins.

A discussion ensued on very large earthquakes, the scale of fault movement and energy needed to generate them and the likely maximum EQ Event in the Lower Hunter Region. Later discussion put this as a maximum M6.5 +- 0.5 Event. It was noted that bigger EQs were typically at 15km depth. It was noted that different geo-structures exist at different depths.

Geoscience Australia noted that the catalogue enabled EQs down to M3.0 to be analysed in this TSMZ ‘though it excluded the two large M6 events near Gladstone in Queensland. John Schneider commented that only parameter ‘a’ was taken from the zone analysis and that maximum magnitude would come from the geological context. However more large EQ events decrease the error in “b” and hence have an effect on the hinge point of the curve.

Tasman Sea Margin Zone (TSMZ)

This model assumes uniform EQ hazard on the coastal zone extending from north-east Tasmania to south-east Queensland. This model is statistically reduced through analysis of the catalogue to a square zone of 100,000 km2 of uniform seismic probability centred on the Newcastle/Lake Macquarie study area. This is termed the Newcastle Study Zone and is a subset of the Tasman Sea Margin Model.

C.3.4.2 Area Source Models

The Gibson Mooki Polygon which was discussed earlier under Tectonic Structures was reviewed and adjusted by an appraisal of geological structures.

A large triangle was drawn with a SW/NE side along the coast from near Terrigal to Birubi Point (Anna Bay), a NW/SE side from Birubi Point to just north of Singleton, and an uncertain NW/SE side from Singleton to Terrigal. This was termed the “Newcastle Triangle Zone”. The north and east sides were considered to have geological significance; the south-west side had uncertain significance and/or location. It was agreed that this triangle represented a zone of stress build up squeezed in the Sydney Basin. The corners of this triangle were at 32:50S/151:50E, 33:20S/151:30E, 32:10S/150:50E drawn very, very approximately.

The seabed between the coast and a line parallel to the coast and about 100km offshore (edge of continental shelf) may be of New England Fold Belt origins. The offshore continental shelf also has geological significance in consideration of tectonic structures and seismic events.

Newcastle Triangle Zone

This comprises the Newcastle Triangle Polygon. Seismic activity outside this zone would be represented by the Tasman Sea Margin Zone model. The Newcastle Triangle Polygon Model assumes uniform EQ hazard for a smaller triangular zone bounded by the coastline, a north-west – south-east line through Port Stephens and a north-west - south-east line through Wyong and Singleton (Figure 1).

C.3.5 Fault Sources

C.3.5.1 Newcastle Fault

Recent research was presented.

The Offshore Newcastle fault is west dipping, shows at least 30m of uplift and a minimum area of 1000 km2 , with incomplete mapping so the area is bigger than this.

- The estimated dip is 39°+-3°.

If Newcastle EQ 1989 was typical it would take 30,000 such events to generate this fault; if these had occurred over 3 million years this gives a return period of 100 years.

The surface shows as a monocline with no surface rupture. World experience is that EQs with magnitude M6.0 to M6.5 will break the surface so it is hypothesised that the Newcastle Fault has experienced no events of magnitude greater than M6.0 over the last one million years.

The next stage of investigation would be drilling and careful logging to determine materials, age, source etc in the top of the offshore Quaternary. The PROD device at Sydney University may be appropriate and can drill to depths of 250m. “Swath” mapping and side-scan sonar would also be good investigation tools. Such research is needed to substantiate hypotheses of seismic activity on this fault.

A discussion followed on relationship between the Newcastle Fault and the nominated EQ1989 epicentre at Boolaroo.

The Newcastle fault can fit the epicentre well; the strike is well defined from several lines.

The Newcastle Fault could extend inshore but would not necessarily be seen closer inshore.

As the surface layers are soft they would not rupture but be deformed by plastic strain; does this affect the maximum magnitude?

If the fault moved in one event on the mapped section (30 km length at 40° dip to a depth of 15 km) then a M7.2 event would have occurred; this would rupture the surface.

The maximum possible magnitude on this fault may be > M6.0< M7.0 and this would not rupture the whole length in one event.

The average rate of movement could be 30 metres over about 5 million years.

C.3.5.2 Hunter-Mooki Thrust and Hunter Transverse Zone

As stated earlier field research over recent years has shown no evidence which indicates that the Hunter Thrust (HMT) is active. What is the meaning if the Hunter-Mooki Thrust is not active and the Newcastle Fault is?

The Hunter-Mooki Thrust has an easterly end near Maitland. There may be a link between the Newcastle Fault offshore and the HMT ie. a continuity of structure and fracture. At this point it was proposed that the current term for the HR Transverse Zone should be used; this is Hunter River Cross Fault (HRCF).

Geoscience Australia has shown that the Ellalong EQ 1994 could not have occurred on the onshore extension of the Newcastle Fault. This is relevant in justifying the adoption of the dual model.

Geoscience Australia noted that the seismic budget for the zone seemed to exceed the supply available from the Newcastle Fault capacity. Does this mean that return periods will be less than calculated earlier or that another source of seismic budget exists, such as in the HR Cross Fault Zone?

One estimate showed that if 50 metres of fault slip occurred over 5 million years this would indicate a M7.0 event approximately every 200,000 years, or a M5.5 event every 2,000 to 3,000 years. One researcher favoured a series of M5.0 to M5.5 events.

C.3.6 Conclusions

Comments were then made on Earthquake hazard models for the Hunter Region. Zones which were not considered significant and which were rejected for more detailed analysis were the NSW Microzone Model after Gibson and the east Australian polygon model after GA. A poll was taken on Hunter Region earthquake models and considerable consensus achieved. No participants disagreed with the following table of possible models.

The maximum possible magnitude for an earthquake in the Lower Hunter Region was considered with full agreement to be M6.5 +- 0.5.

Agreed weights for seismicity models

	Random model	**Fault model**
Earthquakes M<5.5	75%	25%
Earthquakes M5.5 to M6.5	25%	75%

Agreed models	Comments	Active or accepted Y/N	% weight of total
Random earthquake models			
Newcastle onshore triangle (Blue Triangle)	Equal weight 50% with Newcastle onshore/offshore model	Y	Combined 50/50
Newcastle offshore/onshore polygon (Red Polygon)	Equal weight 50% with Newcastle onshore triangle model	Y	
Tasman Sea Margin Zone	Preferred to Large Quadrilateral As uniform model - 100%, or as background seismicity	Y	100% or background
Gibson Mooki microzone model	Not accepted.	N	Nil
Large east Australian rectangle (the GA model)	Not accepted; replaced by Tasman Sea Margin Zone	N	Nil
Fault models			
6 Newcastle Fault, offshore and onshore	Onshore occurrence uncertain. Modelling coupled with Hunter River Cross Fault	Y	Coupled fault structures
7 Hunter River Cross Fault	Location uncertain Modelling coupled with Newcastle Fault	Y	
8 Hunter-Mooki Thrust	Not supported	N	

C.4 Part C - Workshop Participants

Assoc Prof Ron Boyd	University of Newcastle
John Brunton	Department of Mineral Resources, NSW
Prof Stephen Cox	Australian National University
Dr Dick Glen	Department of Mineral Resources, NSW
Dr Gary Huftile	Queensland University of Technology
Michael Neville	Department of Public Works & Services, NSW
Dr Albert Brakel	Geoscience Australia
Dr John Schneider	Geoscience Australia
Trevor Jones	Geoscience Australia
Dr Mark Leonard	Geoscience Australia
Dr Cvetan Sinadinovski	Geoscience Australia
David Stewart	Geoscience Australia

Appendix D - GEOLOGY AND TECTONIC FRAMEWORK

D.1 Introduction

The geology of the Newcastle and Lake Macquarie municipalities described in this appendix, forms the framework for ground shaking assessment modelling. As alluvial sediments are the major geological amplifier of seismic energy, the Quaternary geology is the primary focus of this paper. The underlying Permian basement and associated structural elements are also discussed to provide geological context.

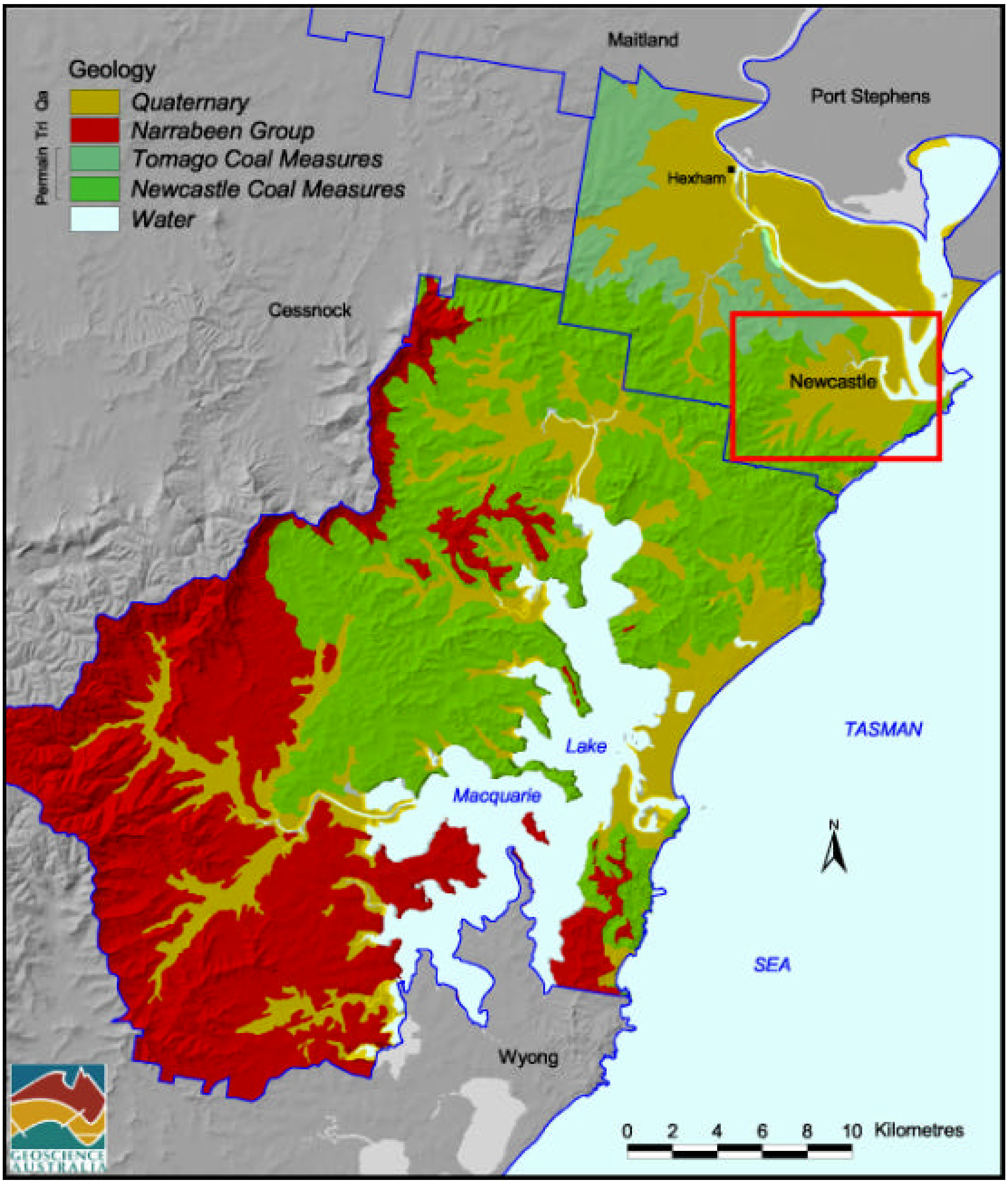


Figure D - 1: Geology of the Newcastle and Lake Macquarie regions. The Quaternary sediments within the red box outlined above are referred to as the Newcastle Basin.

Detailed facies and depositional interpretations based on a detailed subsurface dataset are presented for the Quaternary succession in the area directly to the south of the Newcastle municipality, hereafter referred to as the Newcastle Basin ('study area' in Figure D - 1). In the area to the north of Newcastle City and around Lake Macquarie, interpretations are based primarily on the work of others (Roy et al. 1995) and surface geophysical data, and thus these interpretations are broader in scope.

D.1.1 Regional Geology

D.1.1.1 Tectonics

This Section briefly outlines the tectonic setting of the study area, as a basic understanding of this tectonic context is critical when considering the underlying structures that may be responsible for earthquakes in the region.

The Newcastle region is situated in the north-eastern portion of the Sydney Basin (Figure D - 2). The Sydney Basin is the southern component of the composite Sydney-Gunnedah-Bowen Basin, a Permo-Triassic sedimentary basin extending from near Batemans Bay in the south to Collinsville in the north (Bembrick et al., 1980).

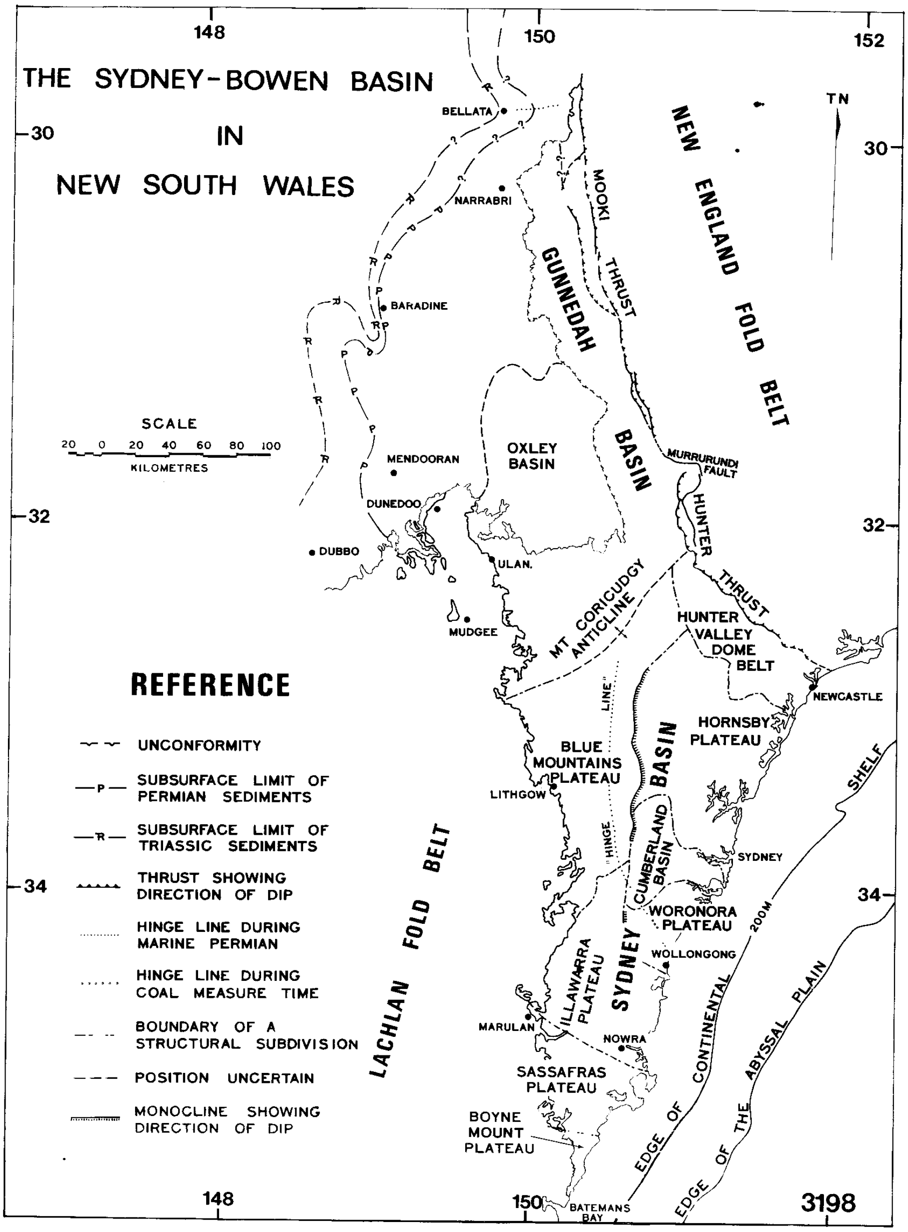


Figure D - 2: Tectonic elements of the Sydney-Bowen Basin in New South Wales (Bembrick et al., 1980)

The Sydney Basin is separated from the New England fold-belt in the north-east by the Hunter-Mooki Thrust system. The basin unconformably overlies the Lachlan foldbelt, to the south-west. It is essentially continuous with the Gunnedah Basin to the north, but a boundary between the two is drawn along the Mount Coricudgy Anticline. Sydney Basin sediments appear to extend out under the continental shelf in the region between 32º and 35ºS and may be exposed in canyon systems (Kamerling, 1966; Mayne et al., 1978).

On a regional scale, two morpho-tectonic divisions have been described within the Newcastle region (Bembrick et al., 1973; Bembrick et al., 1980). The northern element is the Hunter Valley Dome Belt, and the southern element is the Hornsby Plateau. The Hunter Valley Dome Belt is an area of Permian sedimentary and volcanic rocks, generally of low relief, characterised by low amplitude folds with short axial traces, and north-west – south-east trending faults. The municipality of Newcastle and the northern half of Lake Macquarie are located within the Hunter Valley Dome Belt. The southern half of Lake Macquarie is situated on the Triassic sedimentary rocks of the Hornsby Plateau, which is of relatively higher relief, and is characterised by large scale low amplitude folds and only minor faults. The plateau forms the southern boundary of the Hunter Valley and is marked by an escarpment of Triassic age rocks (Lohe and Dean-Jones, 1995).

D.2 Structural Geology

D.2.1 Offshore Structural Geology

The major offshore structural elements are a series of coast parallel folds, which comprise a coastline-marginal anticline, the Offshore Syncline and the Offshore Uplift, and the coast perpendicular extension of the Newcastle Syncline (Crouse and McGuire, 1993).

In recent years seismic surveys have delineated a monocline in near surface sediments which trends NW-SE with the south-west side up (Figure D - 3). This monocline is interpreted to be the result of movement on a shallowly south-west dipping reverse fault (Figure D - 4). The fault terminates approximately 20km south-east of Newcastle (Figure D - 5), and is assumed to have formed relatively recently due to the Cainozoic age of the pre-growth and growth strata (Huftile et al., 1999).

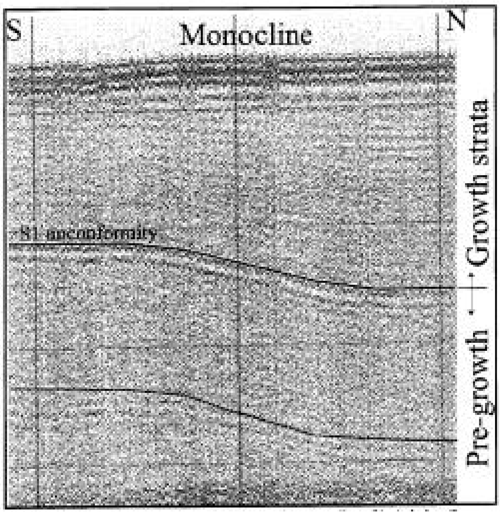


Figure D - 3: Seismic survey showing monocline in sediments offshore from Newcastle (Boyd et al., 1988)

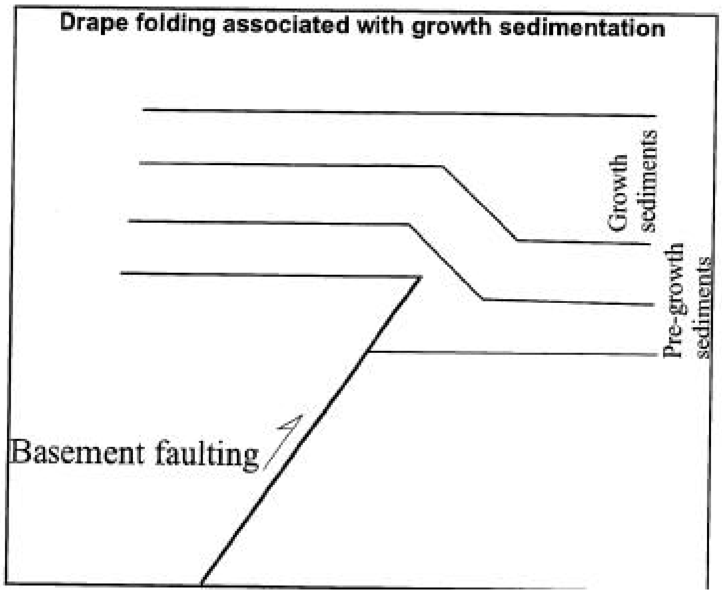


Figure D - 4: Schematic showing the fault interpreted to have formed the monocline in the sediments offshore from Newcastle (Boyd et al., 1988)

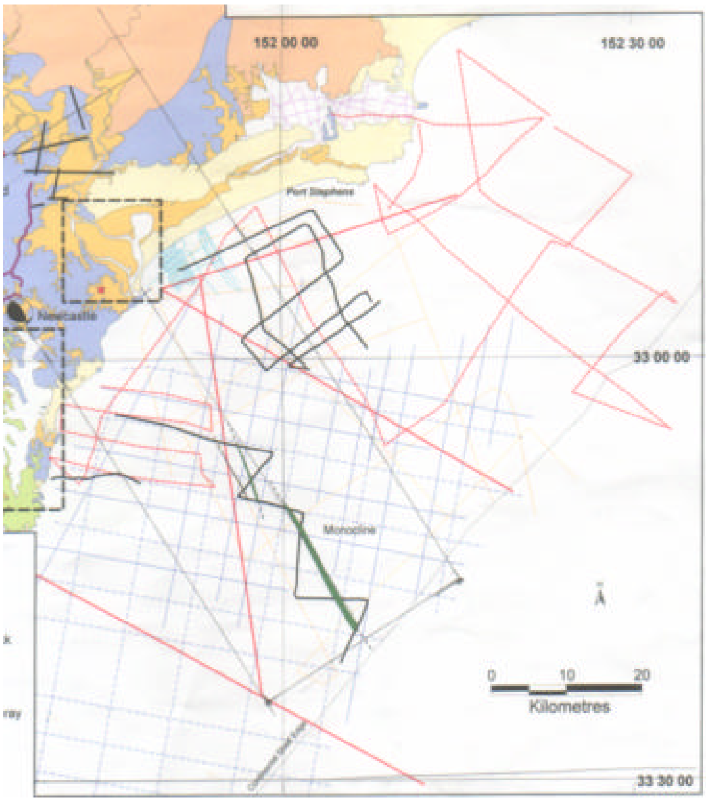
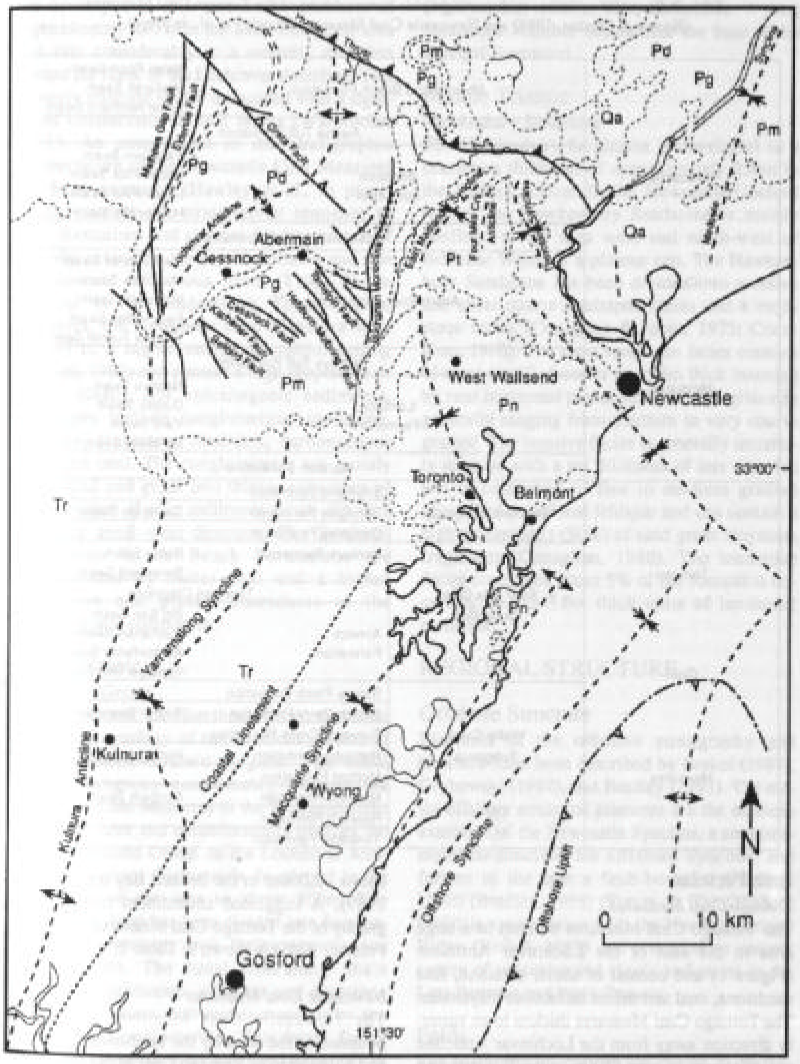


Figure D - 5: Position on the Newcastle fault offshore from the study area. The green lines running NW-SE delineate the position of the fault

D.2.2 Onshore Structure

D.2.2.1 Folds

The Newcastle-Gosford region is characterised by a series of north-east to north-west trending open folds with curvilinear traces. These folds are broad open structures plunging shallowly to the south. From west to east the main fold structures are the Lochinvar-Kulnura Anticline, Yarramalong Syncline, and Macquarie Syncline (Figure D - 6).



Regional structural elements of the Newcastle Coalfield. Pd Dalwood Group; Pg Greta Coal Measures; Pm Maitland Group; Pt Tomago Coal Measures; Pn Newcastle Coal Measures; Tr Triassic; Qa Quarternary alluvium.

Figure D - 6: Regional structural elements of the Newcastle-Gosford area (Lohe and Dean-Jones, 1995)

As a lower order feature, there are a number of small east-west cross folds that post date the meridional folds. One major monoclinal feature, the Buchanan Monocline occurs in the northern central part of the region (Figure D - 6).

D.2.2.2 Faults

Normal Faults

Normal faults are the most obvious and dominant brittle deformation style in the region. Normal fault planes generally dip between 55-75 degrees and have a curved (listric) cross-sectional profile that flattens out at depth

(Lohe and Dean-Jones, 1995). North-west to north-north-west trending normal faults are the dominant style in the Newcastle region. They typically have a vertical displacement of less than 6m (Crapp and Nolan, 1975).

Thrust and Reverse Faults

The major thrust fault system in the area is the Hunter-Mooki Thrust, which consists of a series of generally north-west trending ramps dipping north-east at approximately 14 degrees (Figure D - 6). Displacements associated with the Hunter-Mooki Thrust have propagated well into the Sydney Basin affecting both Permian and Triassic strata, but no recent activity has been recorded on the fault system (Lower Hunter Geological Structures Working Group, 2000).

It is thought that an onshore extension of the offshore Newcastle fault may exist. This structure, termed the Hunter River Cross Fault continues inland across the northern part of the Sydney Basin. It lies south of the Hunter-Mooki Thrust and has been suggested to extend east-south-east through older rocks to the Narromine area (Glen and Walshe, 1999).

High angle reverse thrusts also occur in the region in association with the dominant north-west trending normal faults and represents compressional reactivation of these faults (Williams, 1979).

Strike-slip faults

Strike-slip displacements are probably relatively common in the region but are difficult to positively identify because stratiform markers are not offset (Lohe and Dean-Jones, 1995).

D.2.2.3 Basement Geology

The stratigraphy of the Sydney Basin is shown in Figure D - 7. Within the study area the sedimentary rocks of the Late Permian Tomago Coal Measures (TCM) and Newcastle Coal Measures (NCM) form the basement for the Quaternary basin fill.

The TCM underlie the majority of the Quaternary basin fill to the north of Newcastle City, with the greatest proportion of outcrop occurring to the west of Hexham. These predominantly fine-grained sedimentary rocks consist of shale, siltstone, fine sandstone, coal, and minor tuffaceous claystones. The TCM thicken eastward away from the Lochinvar Anticline, to a thickness of over 1200 m in the Williamtown area (Lohe and Dean-Jones, 1995). Sedimentary structures suggest deposition took place on tidal mud flats under marine to brackish conditions (Diessel, 1980).

The NCM outcrop to the south and west of Newcastle City. The unit underlies the southern portion of the Newcastle area Quaternary basin fill and the Quaternary sediments preserved around the northern end of Lake Macquarie. In contrast to the older TCM, the NCM contain a greater proportion of coarse sedimentary rocks, including conglomerate and sandstone. Siltstone, claystone, laminites, carbonaceous shale, and coal are also major constituents. The NCM are developed to their maximum thickness of approximately 450m in the Lake Macquarie area, and thin considerably in a westerly direction toward the flank of the Lochinvar Anticline (Lohe and Dean-Jones, 1995). The lower part of the NCM was deposited in a beach or shoreface environment (Moelle and Dean-Jones, 1995), but the majority of the unit was deposited by deltaic and fluvial processes on an alluvial plain (Diessel, 1980).

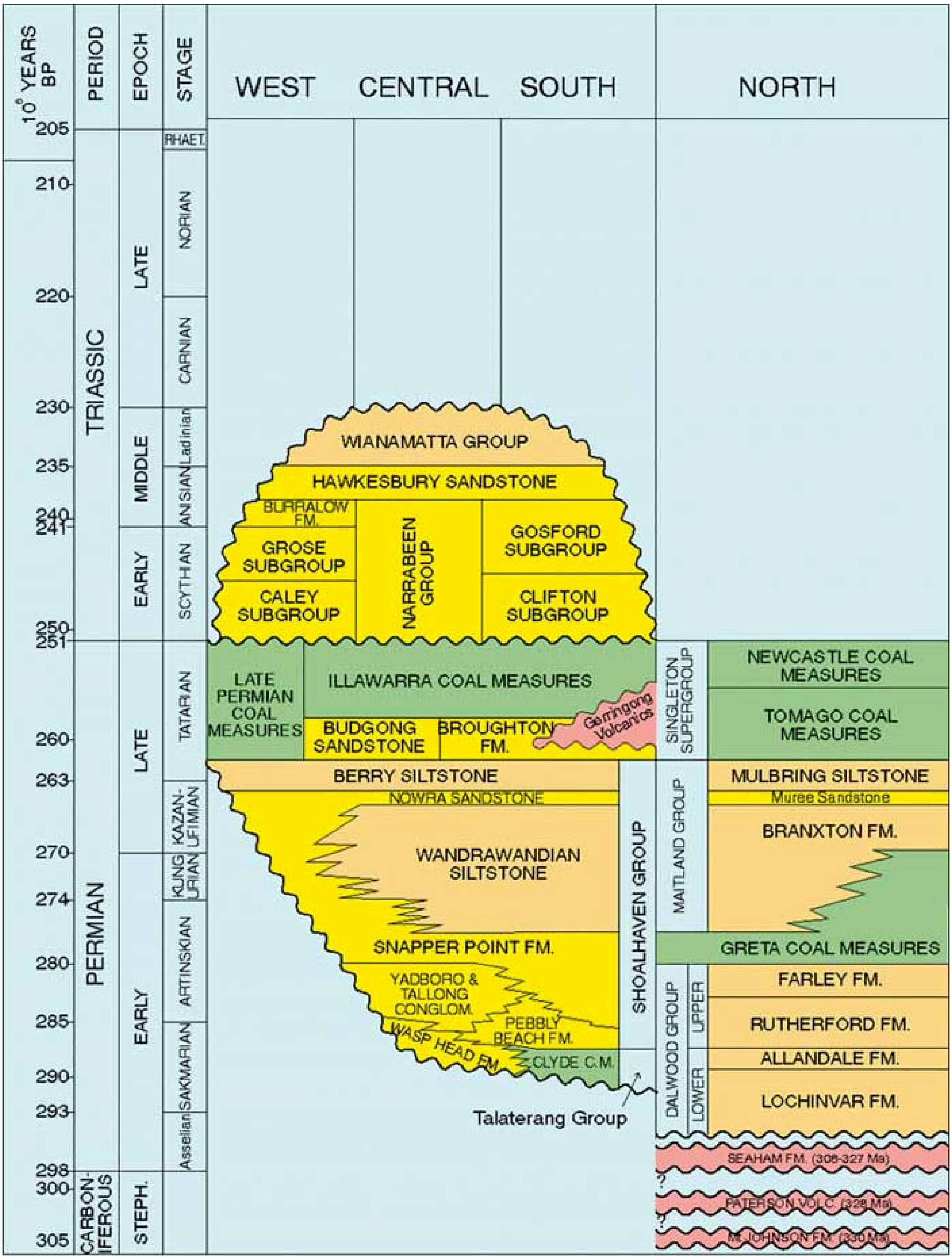


Figure D - 7: Stratigraphy of the Sydney Basin[25]

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[25] *NSW Department of Mineral Resources, www.minerals.nsw.gov.au/petrol/offstrat.htm*

D.3 Quaternary Geology

D.3.1 Previous Work

The Quaternary sediments of the Newcastle and Lake Macquarie region have been studied for over a century, with papers describing the geology of the lower Hunter Delta published in the 19th century and early 20th century(David and Etheridge, 1890; David and Guthrie, 1904). More detailed studies of the Central Coast region were presented over the last 50 years {(Thom, 1965){(Roy, 1980){(Roy and Crawford, 1980){(Thom et al., 1981){(Thom and Murray-Wallace, 1988).

In recent years, a comprehensive geological analysis of the Hunter Delta described the lithofacies in the area to the north of Newcastle city, and outlined the depositional history for the region in the Holocene (Roy et al. 1995). This study supplements that work, in that the main focus is a detailed description of the area to the south of Newcastle.

A small number of studies have been undertaken on the Quaternary geology of Lake Macquarie (Roy and Peat, 1973). Conclusions regarding facies or depositional history presented in this study for the Lake Macquarie region are based primarily on this previous work, with minor input from subsurface data collected to the east if Lake Macquarie.

D.3.2 New Data and Methodology

The detailed geological interpretations presented in this study for the Newcastle and eastern Lake Macquarie area are based primarily on approximately 100 lithological logs (Figure D - 8) derived from a cone penetration test (CPT) data-set acquired by the Engineering Department at the University of Newcastle. In the CPT, a conical penetrometer tip is pushed slowly into the ground and monitored. The device contains electrical transducers to measure both tip (Qc) and side (Fs) resistances as the instrument is advanced. A friction ratio is calculated by relating the sleeve friction to the tip resistance ($^{Fs}/_{Qc}$). Coarse grained sediments such as sands and gravels tend to resist penetration at the tip, whereas finer grained sediments such as clays and silts resist penetration along the sleeve, therefore there is a direct relationship between the friction ratio and lithology. The higher the friction ratio the finer the sediment grain size.

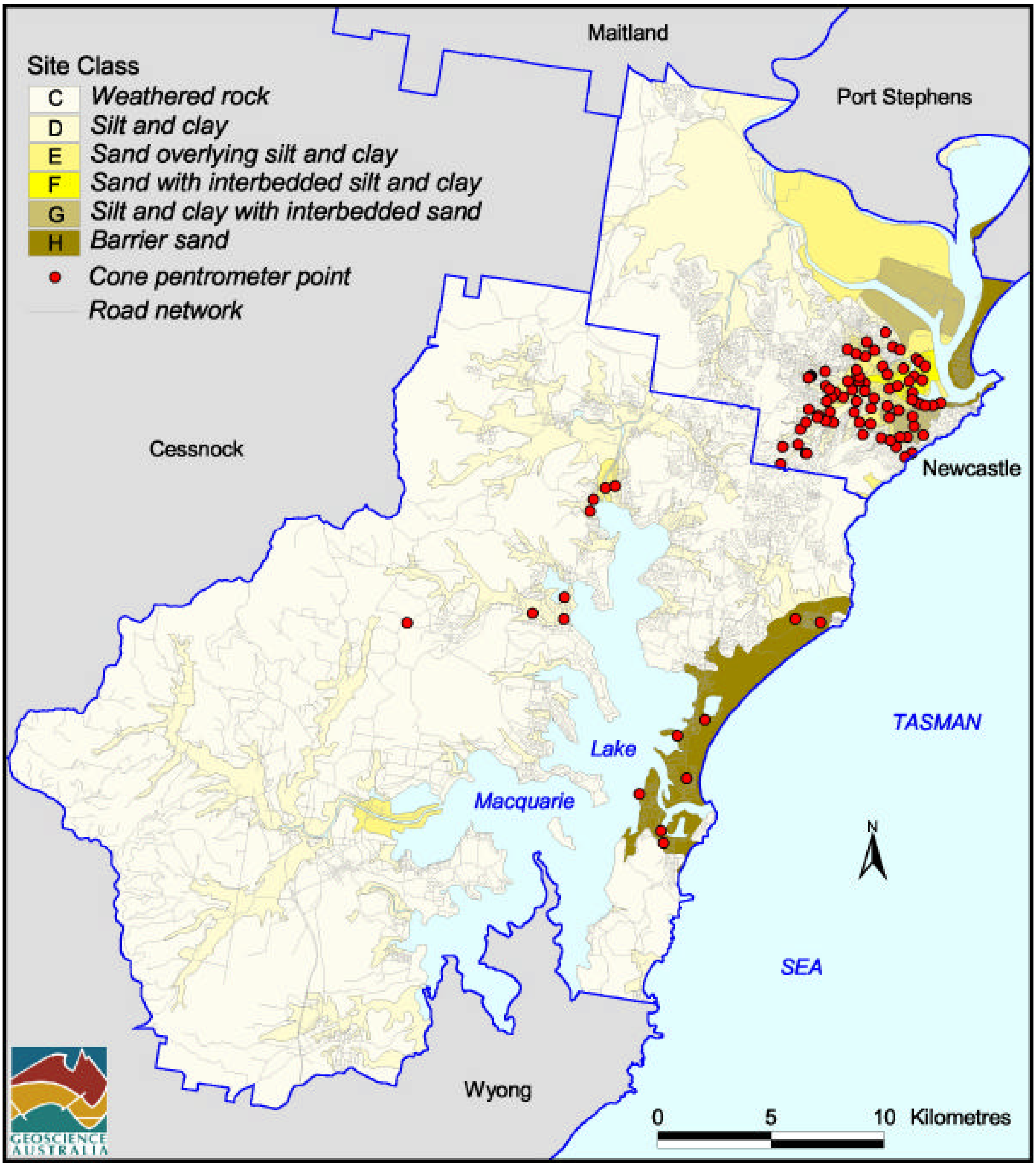

Figure D - 8: Locations of cone penetration tests undertaken by the University of Newcastle Engineering Department

Beyond the Newcastle basin the only data-set with moderate spatial coverage is a series of natural period measurements obtained through a microtremor investigation. This dataset was used to make minor, broad interpretations, but the inherent assumptions involved in the microtremor analysis prevent more than the most cursory analysis. A detailed description of the methodology involved in the microtremor study is presented in Appendix E.

D.3.3 Newcastle Basin Quaternary Succession

The sediments of the Newcastle Basin are discussed here in some detail as this is the first documented analysis for this section of the Quaternary alluvium in the Newcastle district, based on a series of highly detail sedimentary logs obtained through a cone penetration test. The Quaternary geology to the north of Newcastle city is not discussed in this study as it is addressed in detail by Roy et al. (1995).

Five sedimentary facies are identified in the Newcastle Basin on the basis of CPT log analysis. Sedimentary facies are aerially confined parts of an assigned stratigraphic unit that show characteristics clearly distinct from those of other parts of the unit.

D.3.3.1 Sedimentary Facies

Estuarine silts and clays

Silt and clay of this facies characteristically forms the lowermost unit across the majority of the Newcastle Basin. In addition to being the most widespread of the facies it is also the thickest, with a maximum thickness of approximately 28m in hole Wik-01. In some localities a clear fining upward succession is preserved, from sandy silt to clay (Figure D - 9); elsewhere the silt and clay is interlayered and intermixed.

This facies is commonly overlain by tidal delta sands, and occasionally by other facies. In some localities in the western part of the basin this facies contains estuarine delta or colluvial lobe sands.

The fine grained nature of this facies indicates it was deposited in a low energy environment. The Newcastle basin lies directly adjacent to the junction of the Hunter River and the ocean, therefore these silts and clays appear to comprise fine terrigenous material that has been carried into a near-shore system by the Hunter River and floodwaters. The most likely depositional environments are estuarine or lagoonal systems. This interpretation is consistent with previous work (Roy et al. 1995) which displays estuarine basin mud as the most geographically widespread facies towards the mouth of the Hunter River.

The characterisation of this facies as estuarine muds, is also supported by the interpretation of the overlying sand body as a tidal delta. Wave dominated estuarine systems typically comprise a wedge of littoral sand prograding landward into muddy estuarine sediments (Reinson, 1992). The Newcastle Basin is an excellent example of this estuarine morphology.

The fining upward succession preserved in a number of CPT holes is interpreted to be a function of the rise in global sea levels associated with the termination of the last glaciation approximately 20 thousand years ago. The global sea level rise resulted in a post-glacial marine transgression, which inundated coastal valleys (Roy and Thom, 1981). The progressively finer sediments were deposited in the progressively deeper water as the lower energy conditions in deep water are favourable for the deposition of fine sediment.

Tidal delta sands

The sand of this facies characteristically forms one of the upper horizons in the sediment column across the eastern half of the basin. The sand unit is distinctly wedge shaped, thinning from a maximum thickness of 8-9m in Car-01 (Figure D - 10) and Ham-04 towards the outlet of the Hunter River, to a sharp or gradational boundary with the estuarine and tidal delta silts and clays towards the middle of the Newcastle Basin. From the CPT data, the sand appears to be homogenous in grain size to the extent that it does not fine into silt or coarsen into gravel.

The upper and lower boundaries of the sand unit are generally sharp. In the majority of localities this facies overlies the estuarine silts and clays, and it commonly underlies floodplain silts and clays or is preserved to the surface.

The homogenous nature and sharp boundaries of this facies indicates that it was not deposited due to a gradual change in the nature or intensity of a depositional process which was already occurring in the basin. The wedge-like cross-sectional shape of the unit indicates deposition must have taken place through the incursion of the sand unit from the east. This indicates that the sand body was not introduced as part of a deltaic system associated with the Hunter River, as this would have deposited a wedge which thickens to the north. The most likely candidate for deltaic deposition from the east is a tidal delta, which is forming through the back-stepping of sand from the coastal barrier system as a result of tidal action and storm surges. This interpretation is consistent with the work of Roy et al. (1995), who displays extensive deposition of sand by tidal deltas in this part of the Newcastle Basin.

Where the lateral boundary with silts and clays is gradational, this is interpreted to be a function of mixing with estuarine silts and clays at the delta front.

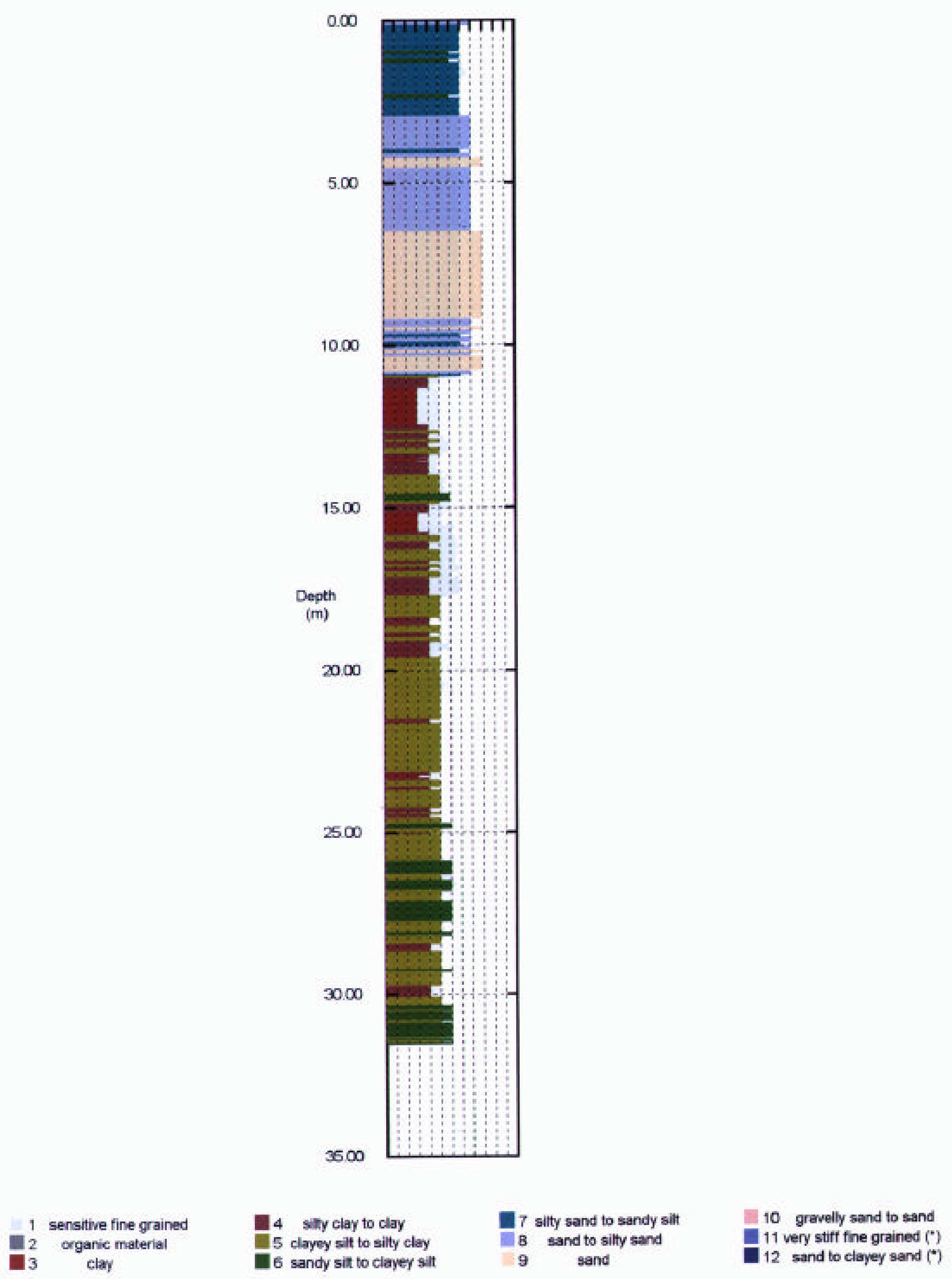

Figure D - 9: The CPT log from Ham-a3 showing a fining upward succession from silt to clay in the lower section

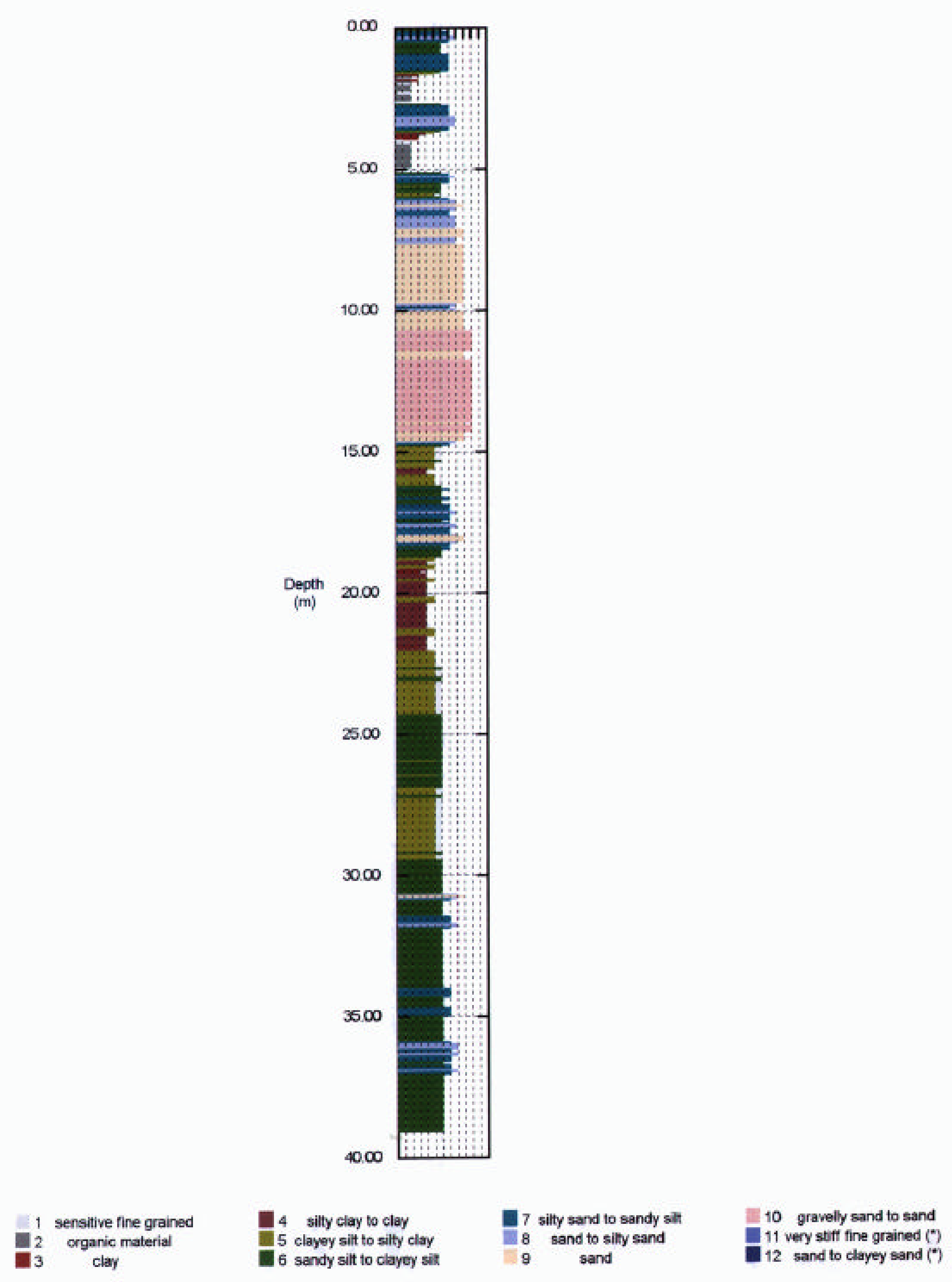

Figure D - 10: The CPT log from Car-01 showing a thick sand body overlying silts and clays

Estuarine delta or colluvial lobe sands

A number of thin lens-shaped sand units are preserved within the estuarine silts and clays around the western, southern, and northern edges of the Newcastle Basin (Figure D - 11). The maximum thickness for this facies is preserved in Brd-03, which contains two units, both of which are approximately 2m thick. They appear to preserve a lobate geometry, and like the tidal delta sands these sand units tend to have sharp boundaries.

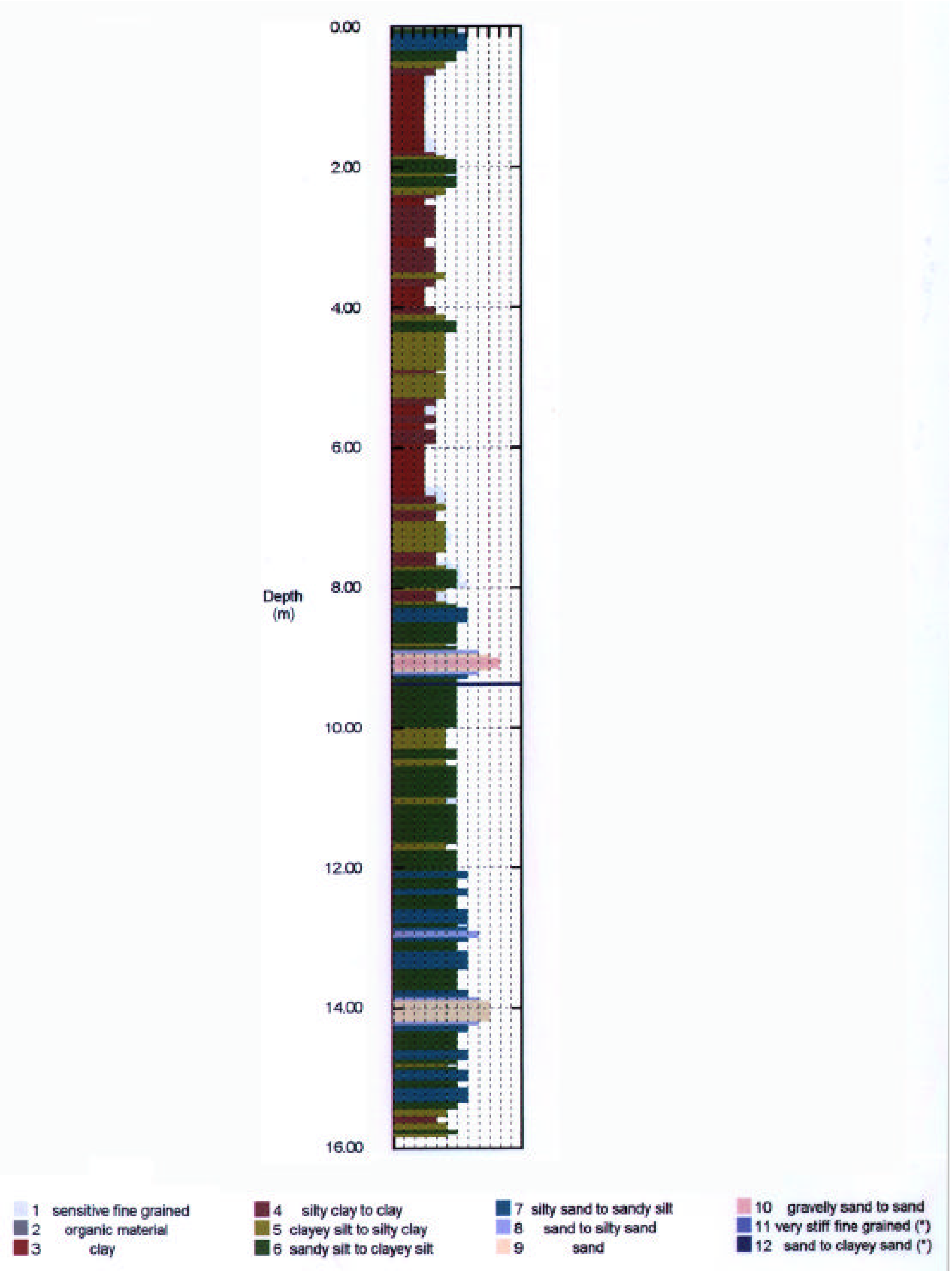

Figure D - 11: The CPT log from Adm-01 showing thin sand horizons within slits and clays

The relatively sparse distribution of this facies, both spatially and stratigraphically, makes interpretation difficult. Minor fluvial deltas exist around the Newcastle basin where tributaries of the Hunter River enter the basin (Roy et al. 1995). These thin lenses of sand may have been deposited through this process but an alternative hypothesis is that they are the preserved remains of colluvial lobes, which entered the basin as gravity flows.

This facies is not considered to have been deposited as crevasse splays for two reasons. Firstly the lobes of sand appear to have been sourced from the edges of the basin away from the Hunter River channel, and secondly they are deposited within estuarine muds, as opposed to floodplain muds which commonly preserve crevasse splays.

Floodplain silts and clays

In a number of localities across the eastern portion of the Newcastle Basin, silts and clays are preserved overlying the tidal delta sand facies (Figure D - 12). The silts and clays tend to be interlayered and intermixed, with no clear trends in grain size. Preserved within this facies, at a small number of localities, are thin lens-shaped units of organic clay. Away from the tidal delta sands, it can be assumed that these silts and clays overlie the estuarine silts and clays, but with only CPT data it is impossible to distinguish between the two.

There is no direct evidence to suggest that these muds were deposited on a floodplain as opposed to within an estuarine system, but they differ from the estuarine silts and clays outlined above, in a number of aspects. Firstly these overlie the tidal delta sands, secondly they are the only facies to preserve organic clays, and finally they do not preserve any thin sand units. Therefore this facies is described as floodplain silts and clays, primarily to distinguish it from the stratigraphically lower muds.

Interpreting this facies as being deposited on a floodplain is somewhat supported by the work of Douglas (1995) who states that floodplain alluvium forms a superficial veneer on top of estuarine muds and extends from upstream of the delta region to about 4km downstream of Hexham. These silts and clays may therefore represent the southernmost extension of those floodplain muds.

Floodplain organic clays

As noted above, thin lens-shaped units of organic clay are preserved within the floodplain silts and clays (Figure D - 13). The maximum thickness is slightly less than 2m in Kot-02. The boundaries appear to be gradational for the most part, with clays increasing in organic content up section.

The fact that this facies is preserved entirely within the floodplain silts and clays indicates that it was also deposited on a floodplain. The depositional environment is envisioned to be one in which, following a flooding event, the floodplain was infilled to the point that a swamp was formed. This swamp added a large proportion of organic material to terrigenous muds, which resulted in the deposition of organic clay.

D.3.4 Lake Macquarie Quaternary Succession

Due lack of geological data in the western Lake Macquarie area, only the broadest assumptions are made in regards to the geology of this region.

The relatively few CPT holes pushed into the Quaternary sediment to the west of Lake Macquarie indicate that they are comprised of a relatively thin succession of silts and clays. Additionally, the geographic morphology of the alluvial units preserved around the north, west and south edges of the lake are very similar to the shape of the Newcastle Basin towards its extreme western end (Figure D - 1). The period at which the sediment naturally vibrates due to ambient seismic energy around these parts of the lake, as recorded through a microtremor study, are also similar to those for the western end of Newcastle Basin. These similarities, and the absence of a major fluvial system which would facilitate the formation of a major estuary, indicate that the alluvium around Lake Macquarie, except to the east, is primarily of floodplain origin, either from the Hunter River to the north or the smaller fluvial systems which enter Lake Macquarie from the west. The sediments are thus likely to be silts and clays, with minor input of sands through the erosion for the lake foreshore (Roy and Peat, 1973).

A small number of geotechnical boreholes have been drilled through the Quaternary alluvium to the east of Lake Macquarie, around the Swansea area (Douglas, 1995). These boreholes penetrated through an average of 30m of sand. The small number of CPT holes pushed into this region, and approximately 10km to the north adjacent to the coast, also intersected intermediate thicknesses of predominantly sand. The sediments in this area are not represented by any of the facies documented above for the Newcastle Basin, because they are closest to the tidal delta sands in lithology, but the two sand units differ in a number of aspects. Firstly they differ in thickness, as this sand unit is at least three times thicker than the tidal delta sands. They also in geometry as the tidal delta sands are lobate, whereas this sand body appears to be elongate, running parallel with the coast. Finally the tidal delta sands are wedge shaped in cross section, and this sand unit appear consistently thick over at least five kilometres.

High microtremor values are recorded in the Swansea area, extending up the coast along the elongate sedimentary body that separates Lake Macquarie from the ocean, indicating the presence of this sand unit throughout. The thick sandy nature of the sediments and the elongate geographic morphology indicates that this section of sediment is represented by a barrier sand system. This interpretation is consistent with previous work which identifies barrier sand bodies along the central coast of New South Wales (Roy et al., 1995).

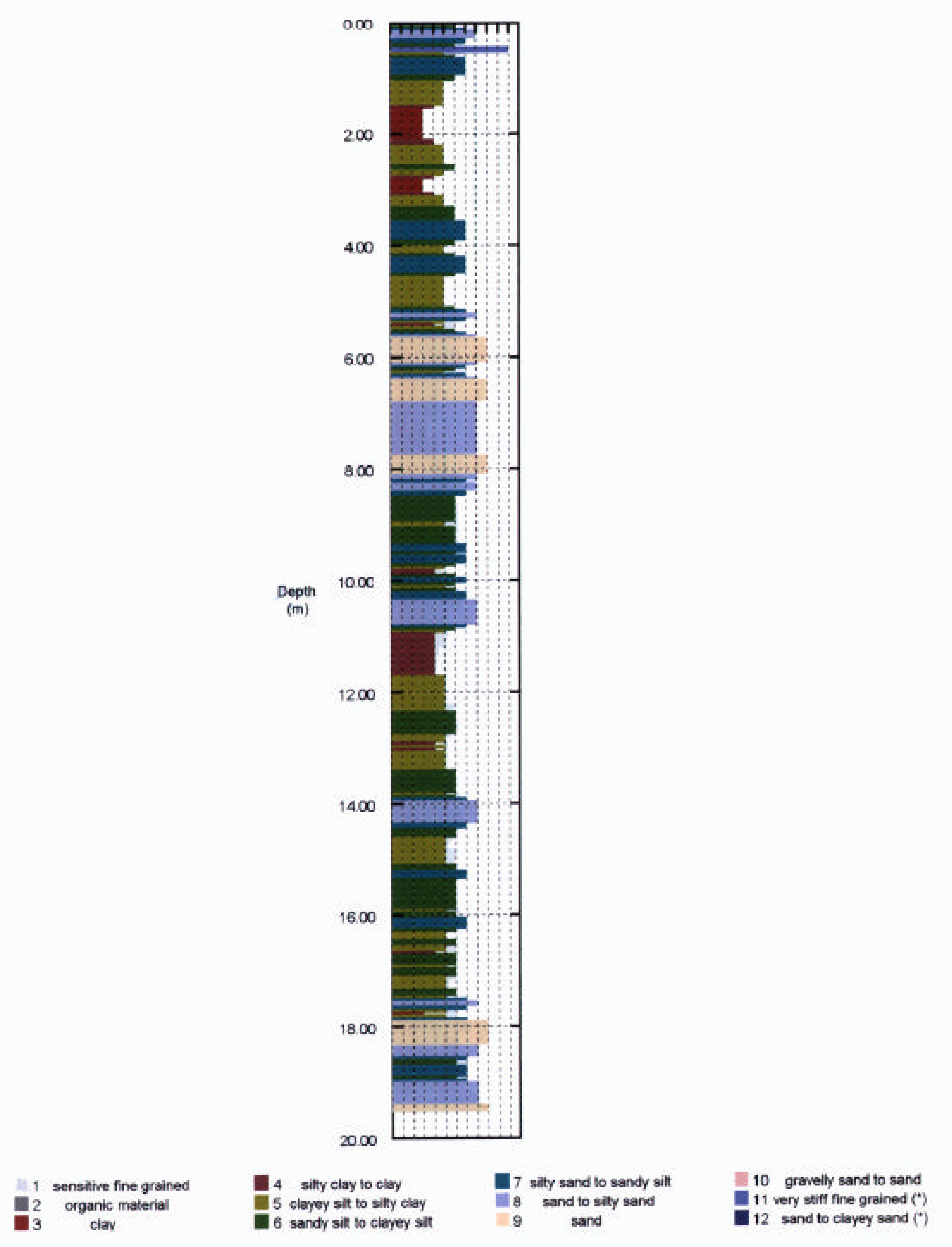

Figure D - 12: The CPT log from Nlt-08 showing silts and clays overlying a thick sand body

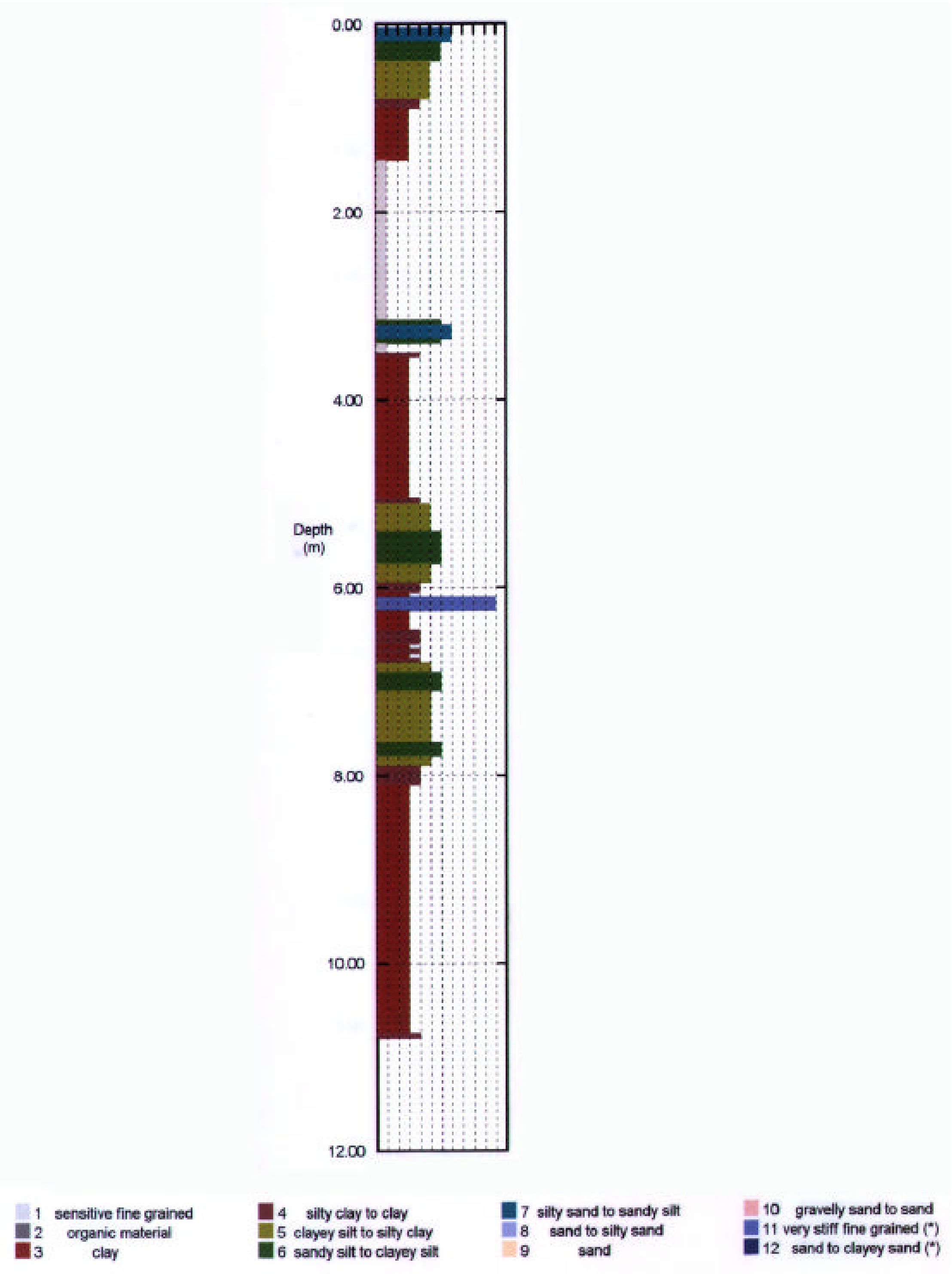

Figure D - 13: The CPT log from Kot-02 showing a thin horizon of organic clay

D.3.5 Depositional History

This depositional history is based primarily on the sedimentary facies identified by CPT in the Newcastle Basin. Application to the Lake Macquarie area is less reliable, because of the sparsity of the data, noted above. The Newcastle Basin and Lake Macquarie were probably formed due to the incising of fluvial systems, the Hunter River in the case of Newcastle Basin, through the Permian and Triassic sedimentary rocks in the area at the onset of the last glaciation, about 30ka. Following the termination of glaciation, a marine transgression infilled the palaeovalleys with estuarine silts and clays. During sea level highstand barrier systems formed along the mouths of the palaeovalleys, then tidal deltas formed through the backwashing of barrier sands by tidal and storm surge processes. Eventually the estuarine environments were buried by floodplain silts and clays, which occasionally developed into swamps and facilitated the deposition of organic clays.

D.4 Characterisation of Site Classes Based on Local Geology

The local geology of Newcastle and Lake Macquarie, as outlined above, was used to construct a series of site classes for the regolith of the region. These site classes represent regions that are considered to have a similar response when exposed to an earthquake.

D.4.1 Weathered Rock

All regions of the study area that do not preserve sediments overlying the bedrock were categorised as site class C. The bedrock within this class, which also underlies the Quaternary sediments, was assumed to have a 10 - 15 m thick weathering profile. This assumed thickness of weathering was based on the expert opinion of staff from the NSW Department of Public Works and Services, who referred to weathering profiles of a similar thickness in nearby parts of the state (NSW Department of Public Works and Services, 1998).

D.4.2 Quaternary Sediments

The semi- to unconsolidated Quaternary sediments overlying the bedrock are the primary geological amplifier of earthquake energy and therefore these are the major focus in defining site classes.

The lithology and structure of the sedimentary succession in the vicinity of Newcastle city and eastern Lake Macquarie was outlined in detail by a series of cone penetrometer (CPT) logs which were assembled and analysed by the Engineering Department at the University of Newcastle. Due to the spatial distribution of this detailed data set, and a lack of subsurface geological data for the remainder of the study area, site classes were defined for the Newcastle Basin and eastern Lake Macquarie and then extrapolated across the study area.

The CPT logs in the Newcastle region revealed a sedimentary succession dominated by silt and clay, overlain in the deeper part of the basin by a thick sand unit, with rare, thin lenses of organic clay and sand. These predominantly comprise estuarine silts and clays, overlain in places by tidal delta sands, with minor input from estuarine delta or colluvial sands. Four site classes were therefore characterised for the Newcastle region and are shown as site classes D - G in Figure D - 14. Site class D comprises estuarine silts and clays overlying weathered rock, possibly with some input from floodplain silts and clays. Site Class E comprises estuarine silts and clays overlain by a relatively thin bed of tidal delta sand. Site Class F comprises estuarine silts and clays, with an estuarine delta or colluvial sand interbed, overlain by a relatively thick bed of tidal delta sand. Site class G comprises estuarine silts and clays overlain by either tidal delta, estuarine delta or colluvial sand, which in turn is overlain by floodplain silts and clays. A sixth site class, H, was defined to characterise the thick barrier sand body to the east of Lake Macquarie and to the north of Newcastle city.

D.4.3 Extrapolation of Site Classes to Broader Newcastle and Lake Macquarie Region

An extensive microtremor survey was carried out across the broader Newcastle and Lake Macquarie regions to supplement the limited subsurface geological data outside the Newcastle basin area. Microtremor data is used to measure of the natural period of vibration for subsurface sediments. A detailed description of microtremor theory and sampling methodology is outlined in Appendix E. A combination of microtremor and CPT data as well as inferences regarding depositional processes was used to characterise the isolated alluvial deposits to the north, west and south of Lake Macquarie. The natural periods of these deposits, as measured through the microtremor survey, were exclusively low, which indicates that the deposits are shallow but does not allow for further classification.

Each of the CPT holes pushed into the isolated deposits north of Lake Macquarie penetrated approximately 15m of sediment, comprising predominantly silts and clays. Thus, the majority of these CPT holes were pushed into regolith corresponding to Site Class D. The exception in terms of the CPT holes in this area is Bol-1, which preserves a significant proportion of sand, and thus the area surrounding this hole was characterised as Site Class E. Bol-1 is located directly adjacent to Cockle Creek, therefore the most likely explanation for the presence of sand within this hole is that it was introduced into the system as fluvial outwash forming an estuarine delta sand body. There is only one other significant fluvial system entering Lake Macquarie, that being Dora Creek which flows from the west. The section of the alluvial deposit that underlies the downstream terminus of Dora Creek, was classified as Site Class E due to its similarity with the region around Bol-1, and the probability that this fluvial system is also introducing some sand into the lake. With the exception of these two areas, the isolated alluvial deposits were interpreted to represent Site Class D, due to the predominance of silts and clays in the CPT points to the north of Lake Macquarie, and the lack of fluvial influence throughout the region.

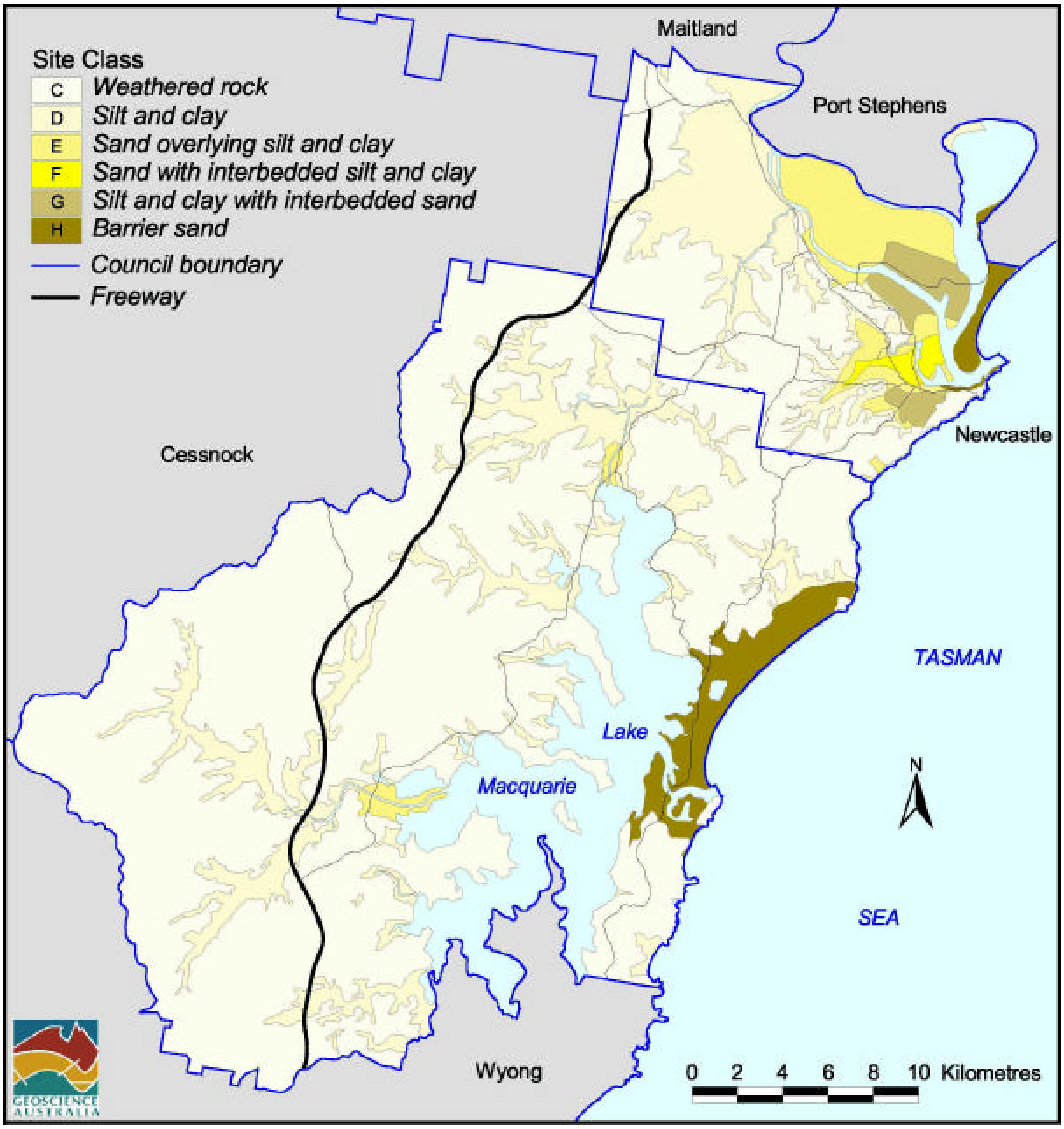

Figure D - 14: Regolith site classification of the Newcastle and Lake Macquarie region

Appendix E - MICROTREMOR SURVEY

Microtremor data provides an invaluable tool for estimating the natural period of vibration for soils. Microtremor data is especially useful in regions where there is little or no detailed geological or geotechnical data available. Whilst microtremor data by itself does not allow for confident estimations of the amount of ground shaking amplification likely to be experienced in a region, it can provide valuable insight into which periods of motion are most likely to be amplified. In addition to this, microtremor data is quickly and easily obtained, and is perhaps the least expensive form of data available that can provide insight into the amplification of ground shaking.

E.1 Methodology

Within the course of this project, Geoscience Australia (GA) seismologists used portable, digital seismographs to record microtremors at about 450 sites in Newcastle and Lake Macquarie in 2000 (Figure E - 1). Sensors were a triaxial, passive type with a natural period of 1 s and used a sampling rate of 100 Hz. The sites had a nominal 250 m spacing within the Newcastle CBD, and 500 m spacing for the remainder of the survey region, and were located primarily on sediments. Two recordings, each of 200 s duration, were made at each site.

The single site, H/V, or 'Nakamura' method was used in order to obtain measurements of natural period from microtremor data. In this method the horizontal, spectral, ground shaking is divided by the vertical, spectral, ground shaking to produce H/V spectral ratio plots. A resonant peak may be observed in the spectral ratio plot for a site, and that peak is interpreted to occur at the fundamental period of vibration of the sediment column. A large body of theoretical and empirical research from the past decade has analysed the H/V method and compared its prediction of the fundamental ground period with, for example, assessments made from earthquake recordings (Nakamura, 1989; Lachet and Bard, 1994; Field and Jacob, 1995; Nakamura, 2000). The results generally indicate that the method is robust in revealing the natural period of sediment vibration excited by vertically propagating seismic shear waves.

The recordings were divided into time series of 40 s duration each with 10 s overlap. Each of these smaller time series was Fourier transformed via a FFT algorithm, and then smoothed. The smoothed horizontal spectrum was then divided by the smoothed vertical spectrum for each of the time series, to produce a set of spectral ratios. These spectral ratios were then averaged, and standard deviations were calculated, in order to produce spectral ratio plots. The FFT computer programs written by Cvetan Sinadinovski and other programs written by Vic Dent and Long Cao, all of GA, were used to process the data. Denis Hackney processed and analysed the microtremor data.

E.2 Natural Period Results

A comparison of contours of natural period with the site classes for the Newcastle region demonstrates that there is a good correlation between these two models (Figure E - 2). The general shape of the contours matches the shape of the site classes very well everywhere but in the region towards the north of Newcastle. In this region there is a distinct difference between the two models. This discrepancy between geological model and natural period could be due to a number of factors. However, given the close proximity of bedrock, the most likely reason appears to be basin-edge effects.

Figure E - 2 also demonstrates that there is a good correlation between the thickness of sediment and the calculated natural period, with an increase in thickness being associated with an increase in natural period. If the thickness of the alluvium, H, is well constrained, then the equation:

$$Vs = 4H/T,$$

can be used to determine the shear wave velocity, Vs, from the natural period T. This method does assume that the alluvium beneath the microtremor point is acting as a single homogenous unit. Nevertheless, this method could be used to gain valuable insight into subsurface velocities where there is no available information from boreholes etc.

Whilst microtremor data was not used to create the main site class models used in this report, it has demonstrated it's effectiveness at detecting changes in the amplification properties of soils. The method has also been used within this study as an invaluable aid in the mapping of site classes away from regions where the geology is well constrained. In addition to this, the main reasons for the detailed study of amplification factors presented in Chapter 4 was to understand and quantify any amplification of ground shaking in the Newcastle and Lake Macquarie region, and to help explain the damage caused by the 1989 Newcastle earthquake. Whilst detailed geotechnical data was available for this study, unfortunately this is not the norm. Given the inexpensiveness and ease of acquisition of microtremor data, it is imperative that more work be carried out to understand the full potential of this data for ground shaking amplification studies.

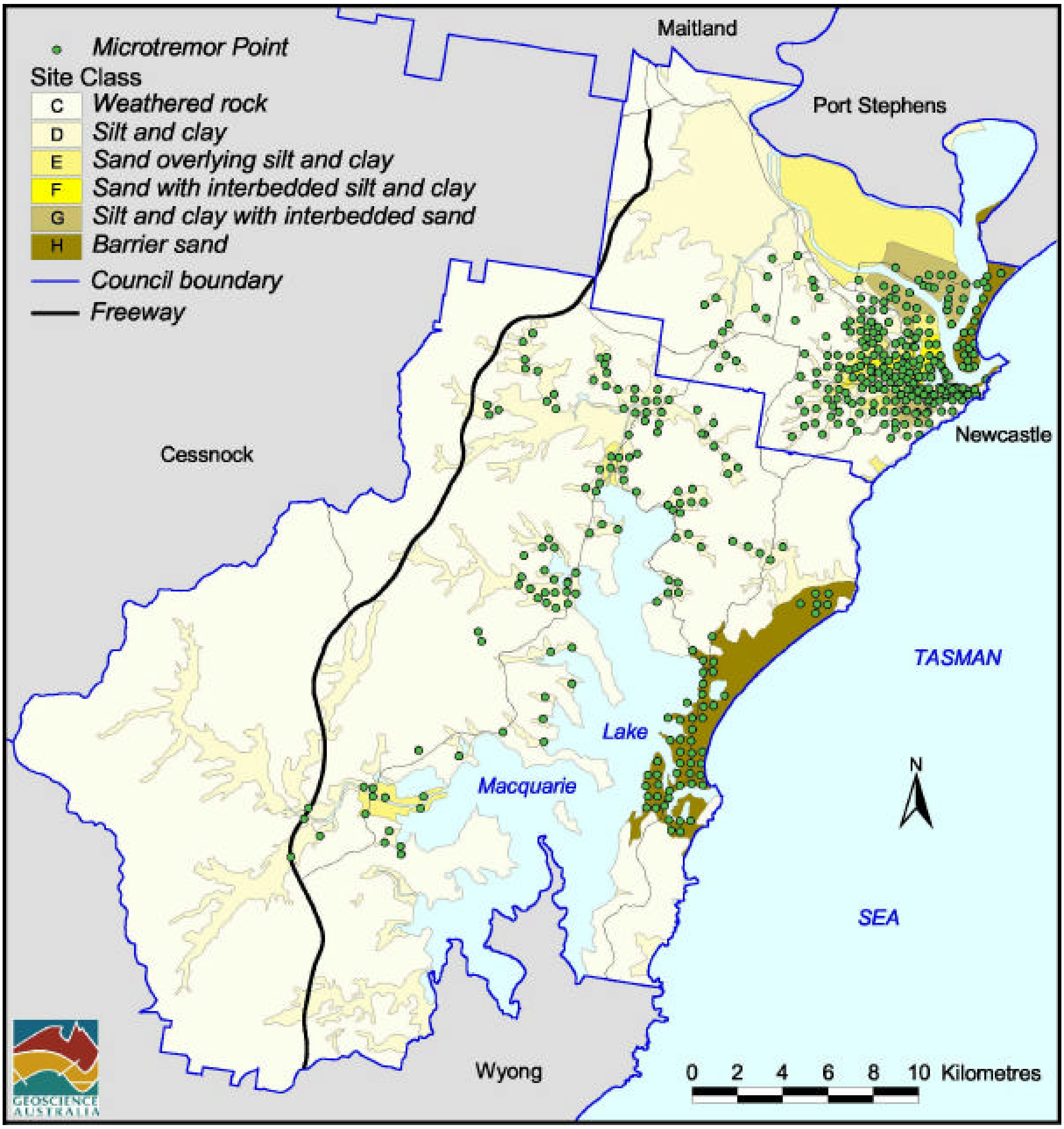

Figure E - 1: Location of Newcastle and Lake Macquarie microtremor readings

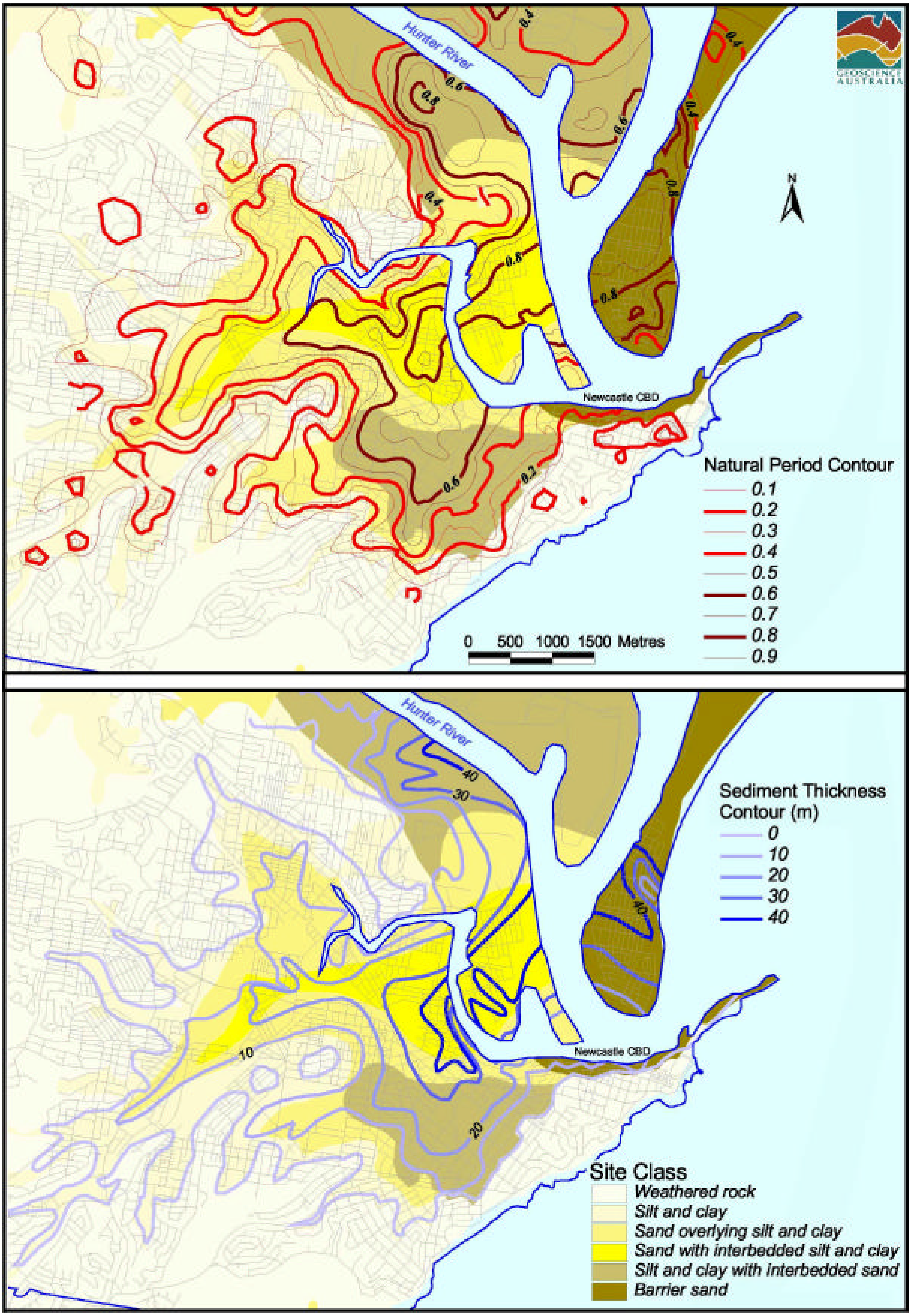

Figure E - 2: Comparison of natural period contours, Newcastle site classes and sediment thickness

Appendix F - GEOTECHNICAL PROPERTIES OF NEWCASTLE AND LAKE MACQUARIE REGOLITH SITE CLASSES

The following Sections describe how the velocities and densities used in Chapter 4 were obtained.

F.1 Shear Wave Velocity

The University of Newcastle has undertaken a significant program of seismic cone penetration testing (SCPT) throughout the Newcastle municipality. Each SCPT provides a measure of shear wave velocity for each 1.5 m interval down the cone penetrometer hole. The locations of the SCPTs used are shown in Figure F - 1. In order to develop a characteristic shear wave velocity profile for each site class, the SCPTs in each site class were grouped together. For any given depth all of the available velocities at that depth were averaged to produce a mean shear wave velocity profile. This mean profile was then used as the characteristic velocity profile for that site class. The velocity data for site classes D through H are shown in Figure F - 2 - Figure F - 6

Unfortunately little information was available about the velocities of both the unweathered and weathered basement within the region. Consequently, velocities were extracted from a NSW Department of Public Works and Services publication (NSW Department of Public Works and Services, 1998). These velocities were P wave, velocities, so a Poisson's ratio of 0.3 was used to obtain the shear wave velocities used in Chapter 4.

F.2 Densities

The density values used within this work were taken primarily from published values, and discussions with geological experts in the region. Table F - 1 describes all of the density values used within this work, as well as the source of each density.

Table F - 1: Density values and their sources for the Newcastle Lake Macquarie region

Material / Class	Density (gcm^{-3})	Source
Sand (Class E/J, F/K and G/L)	1.78	Published densities on Page 2-18 of (Kulhawy and Mayne, 1990)
Clay (Class E/J and F/K)	1.82	
Silt (Class E/J and F/K)	1.98	
Clay (Class D/I)	1.3	
Silt (Class D/I)	1.56	
Weathered Bedrock (All Classes)	2.14	Expert opinions from staff of NSW Department of Mineral Resources and Coffey Geosciences
Unweathered Bedrock	2.39	

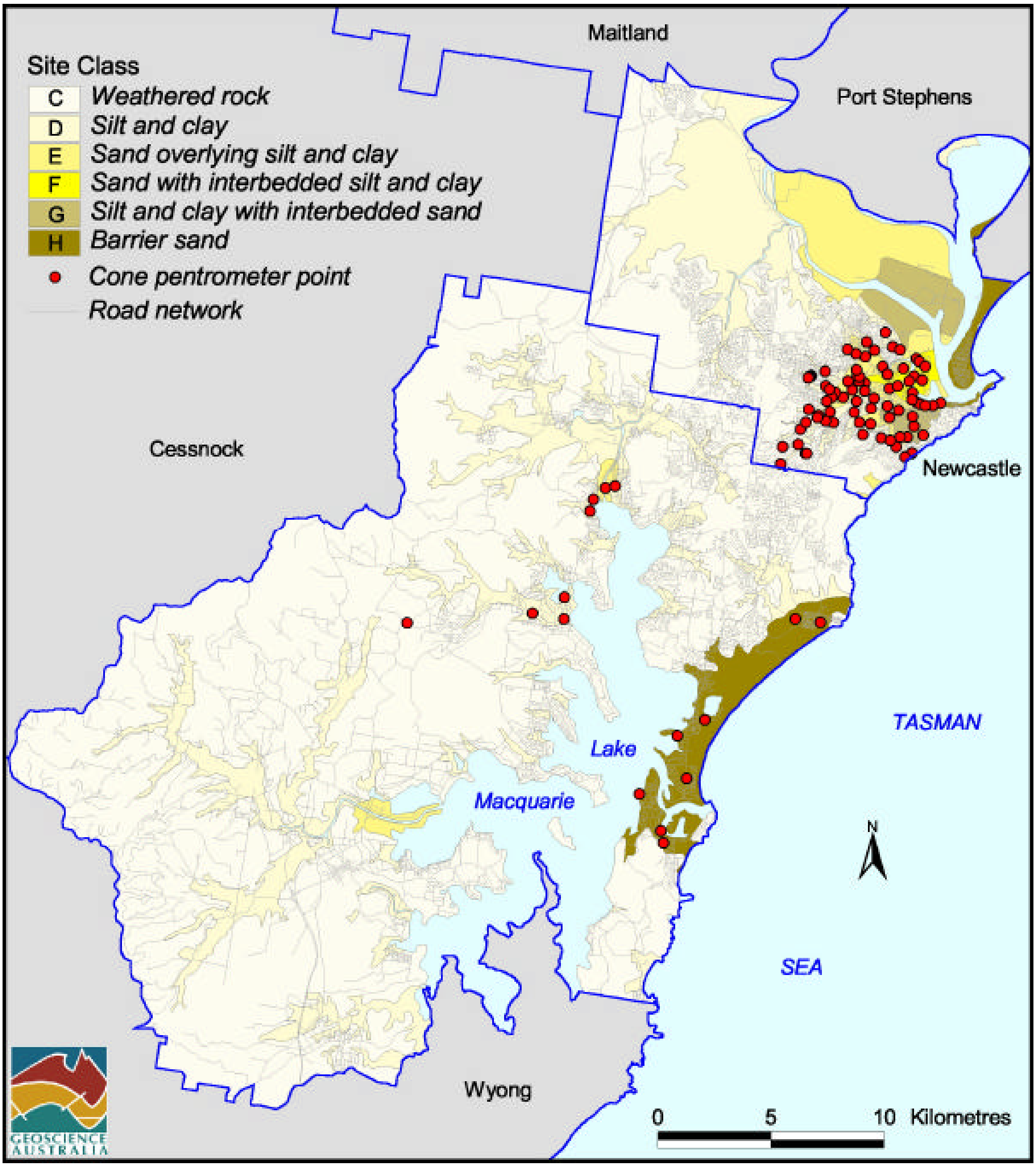

Figure F - 1: Location of SCPT holes used to determine the velocities used within this study

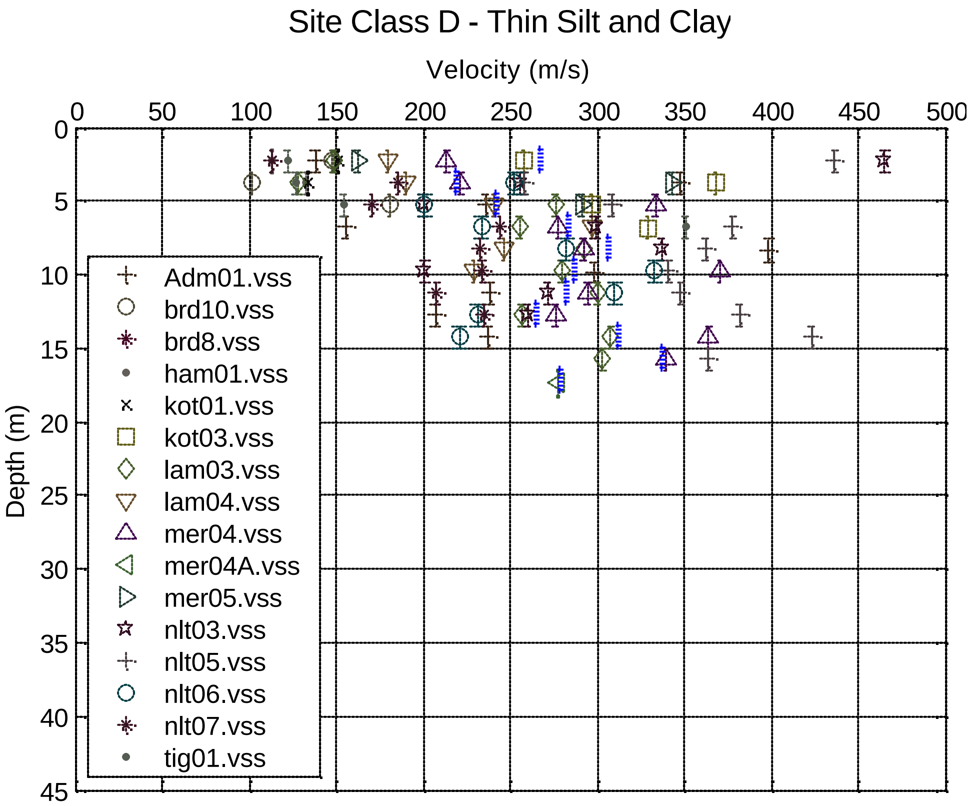

Figure F - 2: Shear wave velocity data for regolith site class D. Note that the thick blue line is the mean shear wave velocity for a given depth, and is used as the characteristic velocity model for the site class

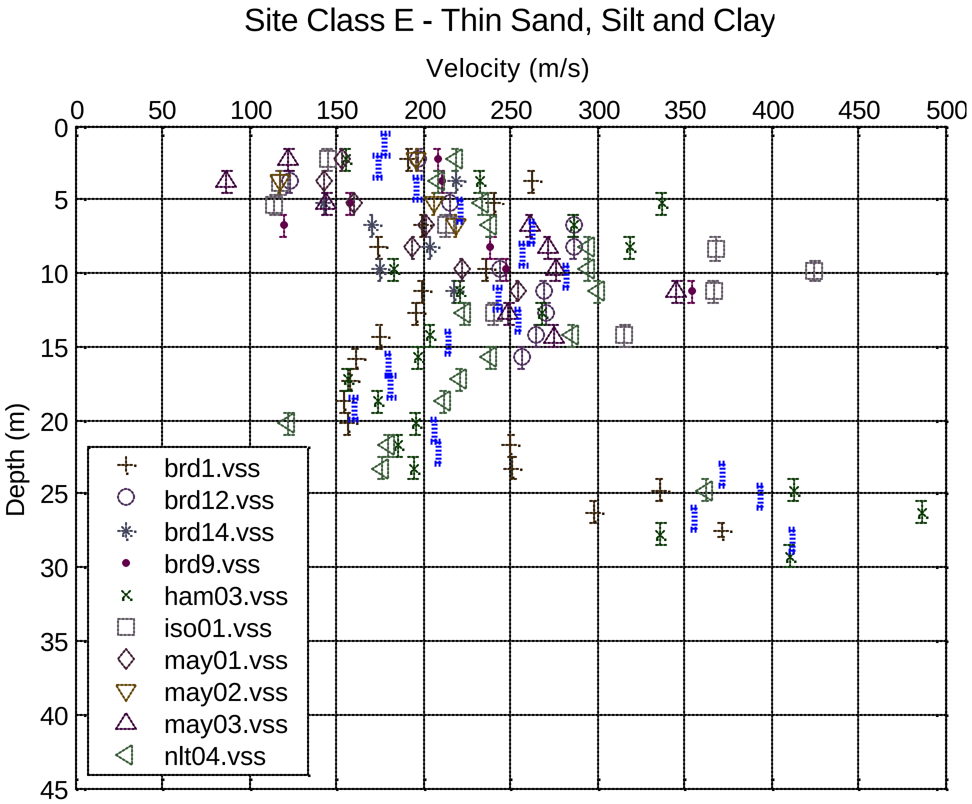

Figure F - 3: Shear wave velocity data for regolith site class E. Note that the thick blue line is the mean shear wave velocity for a given depth, and is used as the characteristic velocity model for the site class

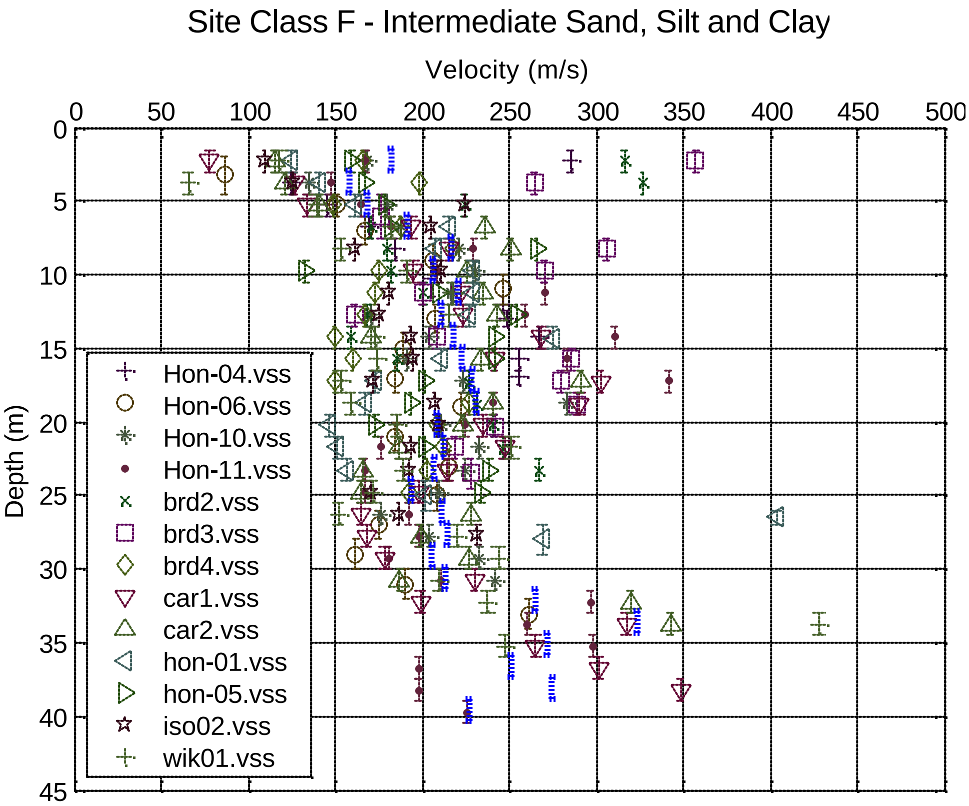

Figure F - 4: Shear wave velocity data for regolith site class F. Note that the thick blue line is the mean shear wave velocity for a given depth, and is used as the characteristic velocity model for the site class

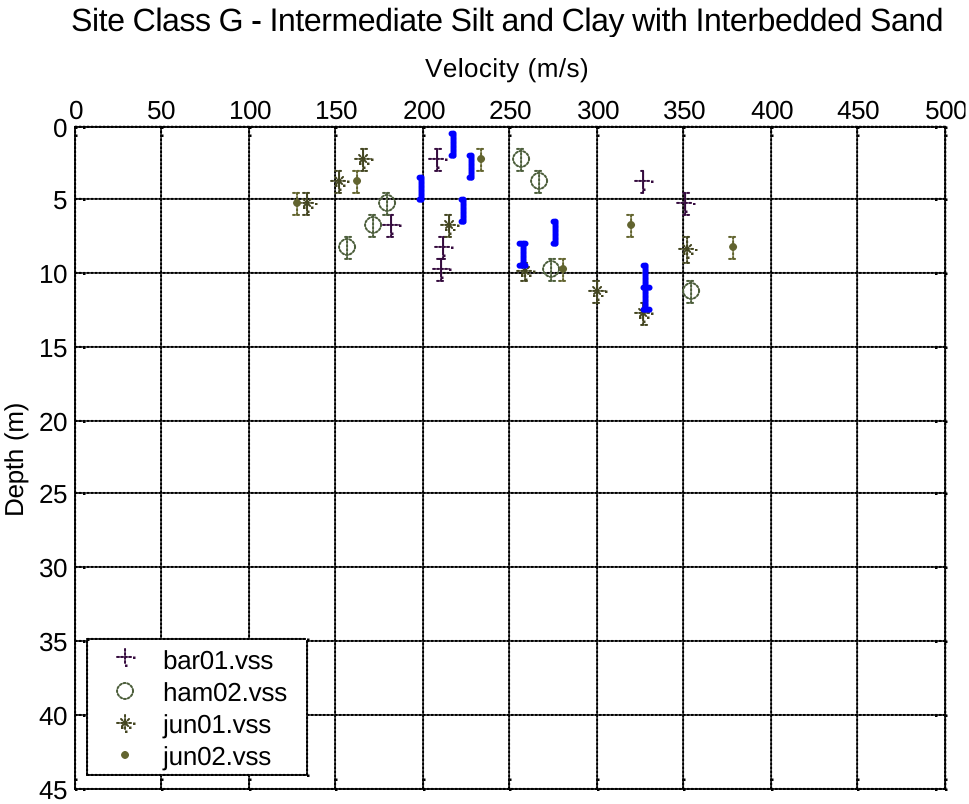

Figure F - 5: Shear wave velocity data for regolith site class G. Note that the thick blue line is the mean shear wave velocity for a given depth, and is used as the characteristic velocity model for the site class

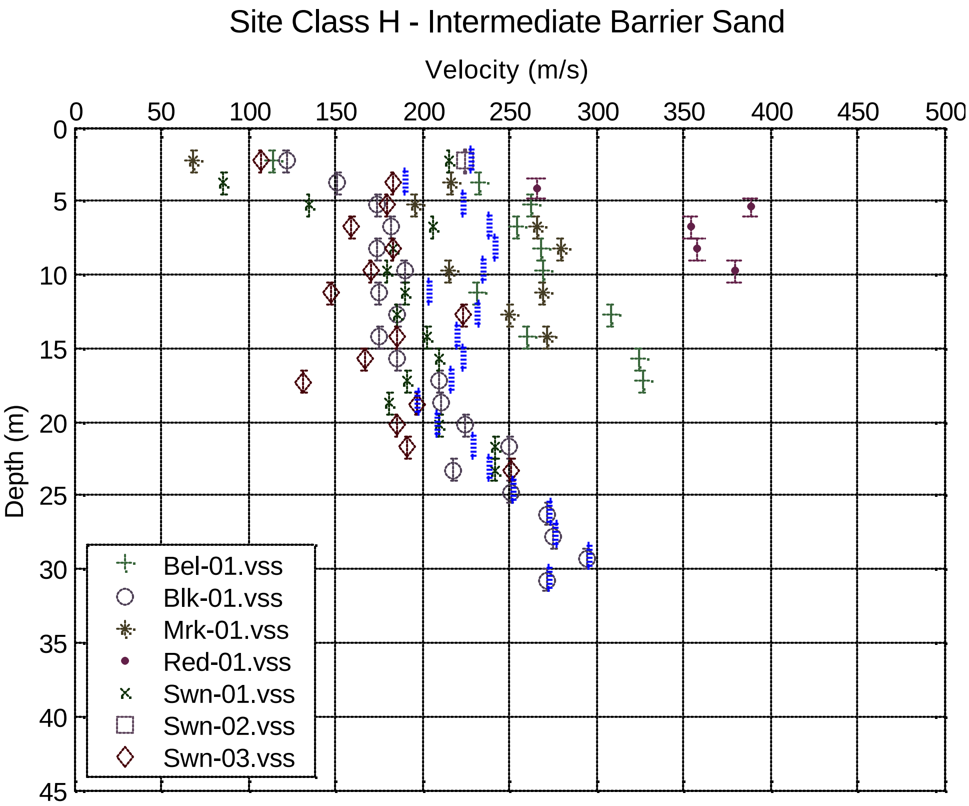

Figure F - 6: Shear wave velocity data for regolith site class H. Note that the thick blue line is the mean shear wave velocity for a given depth, and is used as the characteristic velocity model for the site class