Appendix D: PERTH BASIN GEOLOGY REVIEW and SITE CLASS ASSESSMENT

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Introduction

The presence of soils, sediments and weathered rock, which are collectively referred to as regolith, can affect earthquake ground shaking, and so influence local earthquake hazard in a region. In order to quantify localised changes in earthquake hazard due to variations in the regolith, the Perth metropolitan area was divided into a series of site classes. The site classes encompass regions that are considered to have a similar response to earthquake ground shaking.

This appendix details the background information, datasets, and procedures utilised in developing these site classes. The first section briefly reviews the regional geologic and geomorphic setting. The geology of this part of the Perth Basin is then described in more detail, in particular the Late Tertiary and Quaternary units, as it is these parts of the basin succession that comprises the majority of the regolith. These sections of the report are almost exclusively taken from the literature, particularly the studies of Playford *et al.* (1976) and Davidson (1995). The subsequent section details the development of site classes for the region and describes the geotechnical properties of each class. The final section discusses the site classes in the light of previous geotechnical investigations for the area.

Included within this report is a brief summary of the site conditions at Northam, one of Western Australia's largest inland towns, which is located 98 km northeast of Perth on the Avon River (see Chapter 1, Figure 1.2). The information on Northam is provided as a basis for comparison of potential earthquake hazard between 'rock' sites of the Yilgarn Block and 'soil' sites in the Perth Basin.

Regional Setting – Perth Basin

The following Basin summary, unless otherwise indicated, is taken from the study of Playford *et al.* (1976).

The Perth Basin is a deep trough nearly 1,000 km long that averages about 65 km in width, filled with sedimentary rocks. The total thickness of the Phanerozoic succession may exceed 15,000 m. The eastern margin of the basin is defined throughout most of its length by the Darling Fault, which generally marks the contact between the Perth Basin and the Archaean Yilgarn Block. The northern part of the basin is bordered by a ridge of relatively shallow basement rocks (The Northampton Complex – Iasky and Mory, 1993) that extend from the north. The western and southern offshore margins of the Perth Basin have not been precisely defined. The southwestern corner of the basin is bounded by a narrow belt of Proterozoic granulite and gneiss in the Leeuwin Block.

Structure

The Perth Basin is a faulted trough filled with sediments, the dominant structural feature being the Darling Fault. The fault itself is obscured by sediments, and is presently located approximately 1–3 km west of the fault's surface expression – the Darling Scarp (Janssen *et al.*, 2003). The Darling Fault is nearly 1,000 km long, and its maximum throw may exceed 15,000 m. The Perth Basin is generally intensely faulted, with most faults having north to northwest trends and throwing both to the east and west. There are a number of moderately large cross-faults trending approximately east–west.

A number of structurally controlled sub-divisions are recognised in the Perth Basin, but the Perth metropolitan region under investigation lies exclusively over the Dandaragan Trough (Figure D.1).

Stratigraphy

Pre-Mesozoic stratigraphy includes Proterozoic siliciclastic sedimentary rocks, the Silurian Tumblagooda Sandstone, and a well-developed Permian succession that comprises nine formations over at least 2,600 m. Within the Mesozoic, the Triassic succession varies between continental and marine, and is of a similar thickness to the Permian sequence. The mainly continental Jurassic sediments are widespread throughout the basin, and are believed to be at least 4,200 m thick. The Perth Basin Cretaceous succession, which may be as thick as 12,000 m, comprises a lower continental unit, a mixed continental, paralic and marine unit, and a lower marine unit, which are separated by unconformities. A well-marked unconformity occurs within the continental to paralic sequence of the Lower Cretaceous. Tertiary marine sediments up to 600 m thick occur beneath the Perth area and over much of the continental shelf. Quaternary deposits blanket much of the Perth Basin (Playford *et al.*, 1976), and these are outlined in detail in the following section. Thicknesses of Tertiary/Quaternary deposits in the region generally increase to the west and north.

Geomorphology

An excellent summary of the geomorphology of the Swan Coastal Plain in the vicinity of Perth is provided by Davidson (1995), and reproduced below. Wyrwoll (2003) presents a succinct account of the Perth region geomorphology.

In the Perth region, the Swan Coastal Plain is about 34 km wide in the north, 23 km in the south, and is bounded to the east by the Gingin and Darling Fault Scarps, which rise to over 200 m above sea level. The scarps represent the eastern boundary of Tertiary and Quaternary marine erosion. The Swan Coastal Plain consists of a series of distinct landforms (McArthur and Bettenay 1960), roughly parallel to the coast (Figure D.2). The most easterly landform comprises the colluvial slopes which form the foothills of the Darling and Dandaragan Plateaus and which represent dissected remnants of a sand-covered, wave-cut platform known as the Ridge Hill Shelf. To the west of the colluvial slopes lies the Pinjarra Plain, a piedmont and valley-flat alluvial plain consisting predominantly of clayey alluvium that has been transported by rivers and streams from the Darling and Dandaragan Plateaus. The plain is generally about 5 km wide west of the colluvial slopes, but along the Serpentine River it is about 15 km wide in an east–west direction.

To the west of the Pinjarra Plain, the Bassendean Dune System forms a gently undulating aeolian sand plain about 20 km wide with the dunes to the north of Perth generally having greater topographic relief than those to the south. The dunes probably accumulated as shoreline deposits and coastal dunes during interglacial periods of high sea level and originally consisted of mostly lime (calcareous) sand with quartz sand and minor fine-grained, black, heavy-mineral concentrations. Apart from a small local area to the south of Perth, the carbonate material has been completely leached leaving dunes consisting entirely of quartz sand.

West of the Bassendean Dune System are two systems of dunes which fringe the coastline. The most easterly of these is the Spearwood Dune System, which consists of slightly calcareous aeolian sand remnant from leaching of the underlying Pleistocene Tamala limestone. The most westerly dune system, which flanks the ocean, is the Quindalup Dune System, consisting of wind-blown lime and quartz beach sand forming dunes or ridges that are generally oriented parallel to the present coast, but which may also occupy blowouts within the Spearwood Dune System.
The rivers crossing the coastal plain are flanked by clayey floodplains and river terraces of recent origin. Other wetlands, consisting of swamps and lakes, have formed in the inter-dunal swales of the Bassendean Dune System, in the inter-barrier depressions between the Spearwood and Bassendean Dune Systems, and within the Spearwood Dune System.
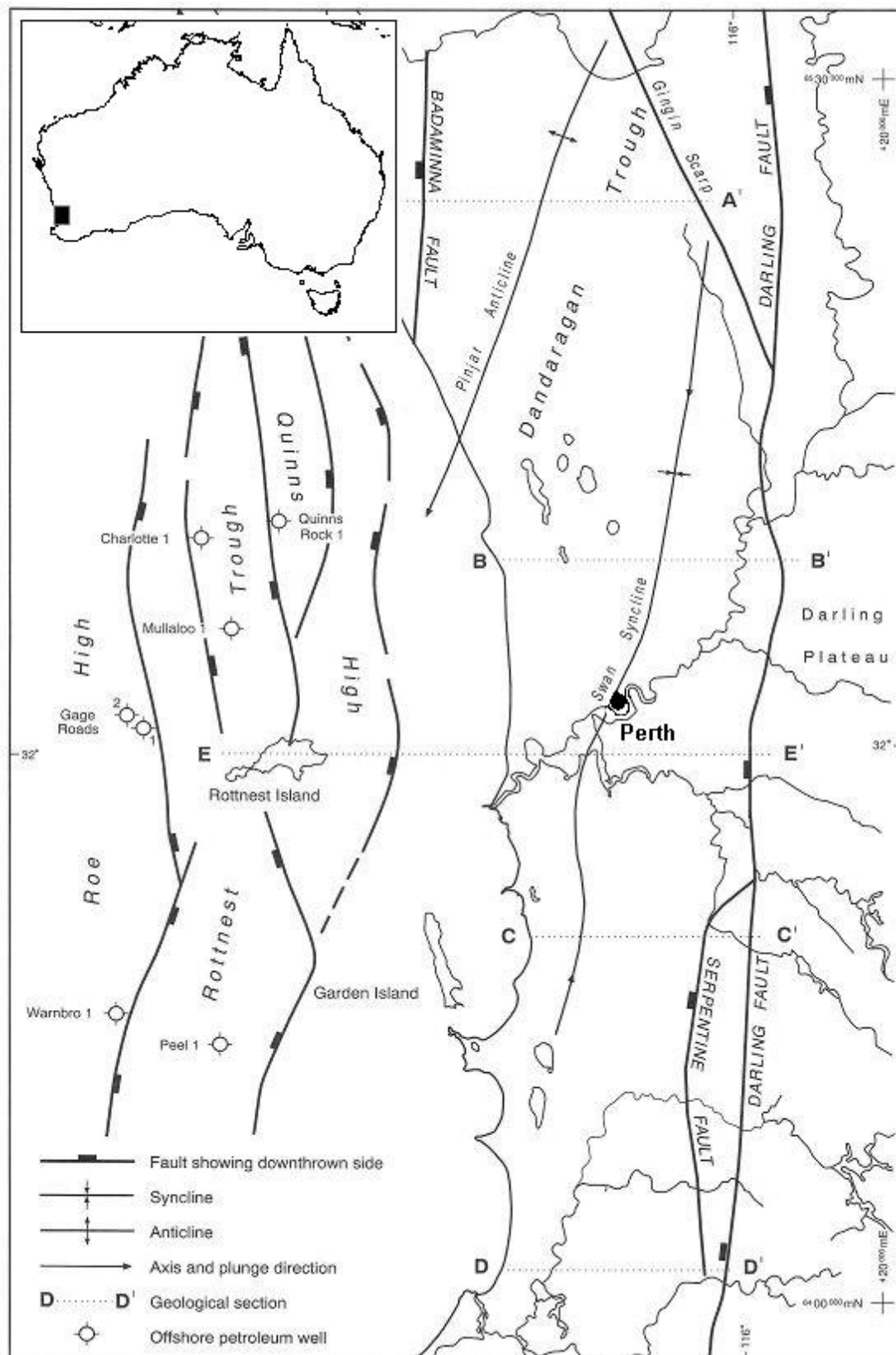
Figure D.1: Structural geology of the Perth region (from Davidson, 1995)
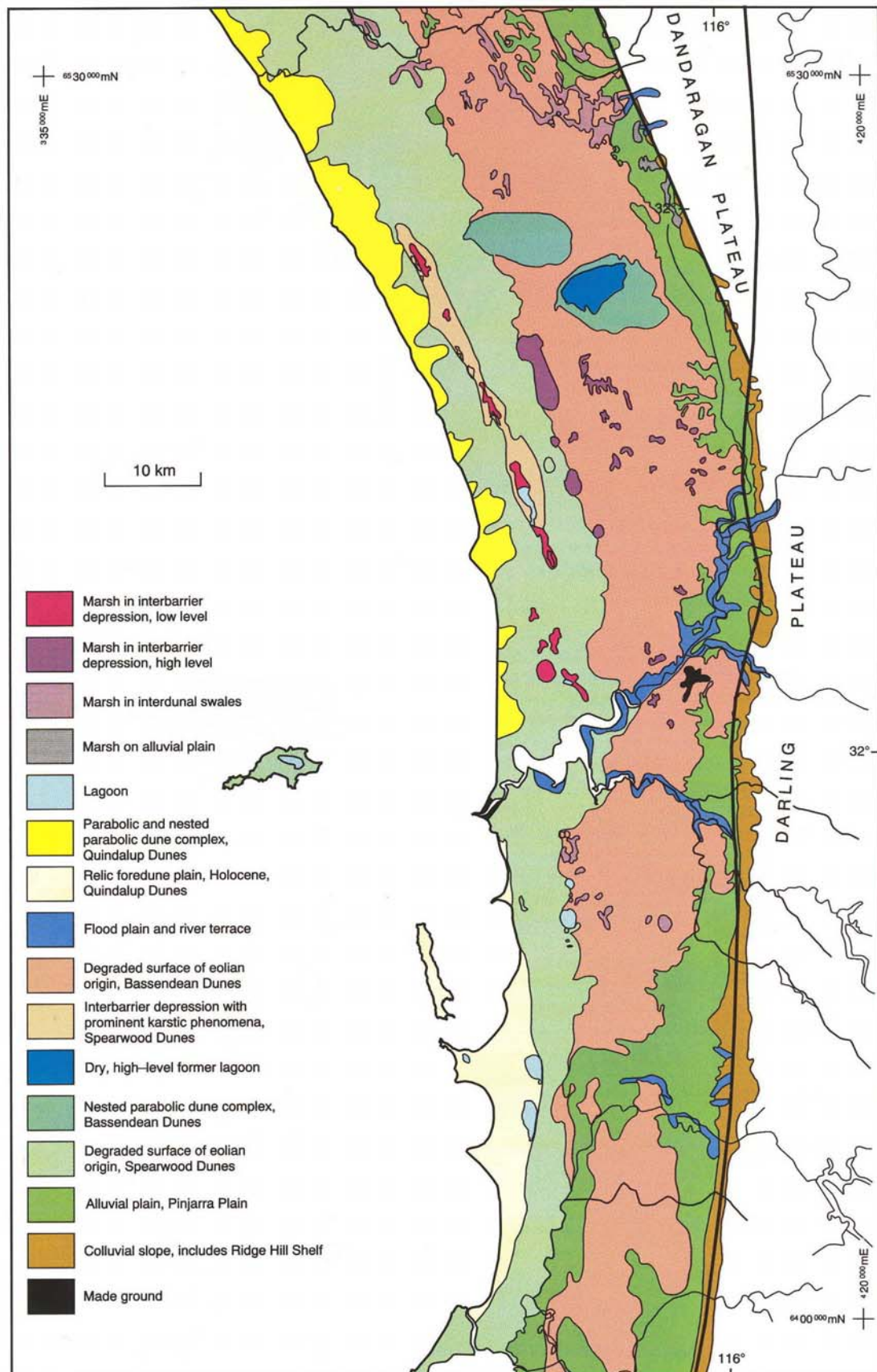
Figure D.2: Geomorphology of the Perth region (from Davidson 1995)

Geology

The character, distribution and depositional history of the geological units outlined in this section have previously been described by Playford *et al*. (1976), and are summarised by Davidson (1995). A succinct outline of the Perth region geology is given by Commander (2003). The sequence stratigraphy for the major Mesozoic and Cainozoic units are presented in Figure D.3. Unless otherwise indicated, the following summaries are taken from Davidson (1995).

Figure D.3: Stratigraphic column of Perth Basin sediments in the Perth region (from Davidson 1995) [continues over]

AGE		Cockbain (1990), Playford et al. (1976)		Davidson (1995)	

Figure D.3: Stratigraphic column of Perth Basin sediments in the Perth region (from Davidson 1995)

Underlying Cretaceous–Tertiary formations

The Late Tertiary–Quaternary formations that cover the area under investigation predominantly overlie one or more Cretaceous–Tertiary units, namely the Osborne Formation, the Molecap and Poison Hill Greensands, and the Kings Park Formation (see Figure D.3). Henceforth these underlying units are collectively referred to as 'basement', as it is the overlying regolith that is of most relevance to this site class study.

Osborne Formation

The Osborne Formation (McWhae *et al*., 1958) comprises a basal sandstone unit (Henley Sandstone Member), a middle shale unit (Kardinya Shale Member), and an upper, interbedded sandstone and shale succession (Mirrabooka Member). The majority of the southern part of the study area is underlain by the Mirrabooka Member. The Osborne Formation is of shallow marine origin, has a maximum thickness of about 180 m, and is Early Cretaceous (~114 Ma) in age.

Molecap Greensand

The Molecap Greensand (Fairbridge, 1953) consists of fine to medium-grained, yellowish-brown to greenish-grey, glauconitic, silty and locally clayey sandstone. It underlies the superficial formations in sections of the northern study area. The Molecap Greensand is of shallow marine origin, has a maximum thickness of about 80 m, and is Late Cretaceous (98 Ma) in age.

Poison Hill Greensand

The Poison Hill Greensand (Fairbridge, 1953) consists of unconsolidated pale yellow to dark green, fine to very coarse-grained, richly glauconitic, silty and locally clayey sand. It underlies the superficial formations in the north of the study area. The Poison Hill Greensand was deposited locally through erosion of the Osborne Formation. This unit was originally thought to be a channel infill deposit of Quaternary age (Morgan, 1964; Allen, 1977; Barnes, 1977), but extensive palynological investigation has been unable to confirm this. It is currently considered to be Cretaceous–Tertiary (~80 Ma) in age. The unit has a maximum thickness of about 90 m).

Kings Park Formation

The Kings Park Formation (Quilty, 1974) occupies a deep channel incised through the Cretaceous sedimentary succession. The valley in which it is preserved may once have been connected with the Perth canyon, which cuts the continental slope west of Rottnest Island (Playford *et al*., 1976). The formation predominantly comprises grey, calcareous, glauconitic siltstone and shale of shallow marine to estuarine origin. It has a maximum onshore thickness of about 530 m and is Early to Mid-Tertiary (~54 Ma) in age (Playford *et al*., 1976).

Superficial formations

A thin veneer of Late Tertiary and (primarily) Quaternary regolith comprise the surficial cover over much of the Perth Basin (Playford *et al*., 1976) (Figure D.4, see also D.3). These 'superficial' formations (a collective term coined by Allen, 1976) consist mainly of sand, silt, clay and limestone in varying proportions. Along the eastern margin of the Swan Coastal Plain materials are dominated by silts and clays (muds), while those in the central area of the Plain are predominantly sandy. To the west, the sandy materials pass laterally into limestone, which borders the coastal strip. Formal stratigraphic names have not been given to many Quaternary units (Playford *et al*., 1976): where they are formally named, the distribution of the units has not been clearly defined.

This section outlines the material characteristics of the superficial units that comprise the majority of the Swan Coastal Plain, which were utilised in reconstructing the three-dimensional regolith architecture of the Perth region.

Ascot Formation

Originally defined as the Ascots Beds by Playford *et al.* (1976), the Ascot Formation (Cockbain and Hocking, 1989) consists of hard to friable, grey to fawn calcarenite with thinly interbedded sand commonly containing shell fragments, glauconite and phosphatic nodules near the base of the formation. The fine to coarse sand is very poorly sorted, angular to rounded, and contains a rich assemblage of bivalves and gastropods. Where present, the Ascot Formation lies unconformably on the Leederville Formation, Osborne Formation, Molecap Greensand, or Poison Hill Greensand. The formation was deposited as a prograding shoreline (Kendrick *et al.*, 1991). It has a maximum thickness of 25 m in the southern and northern Perth areas, and is widespread as a basal unit of the superficial formations.

Yoganup Formation

The Yoganup Formation, defined by Low (1971), comprises white to yellowish-brown, unconsolidated, poorly sorted sand, gravel and pebbles, with local subordinate clay, ferruginised grains and heavy minerals. It occurs sporadically along the eastern margin of the Perth region and westwards (as sub-crop) about 5 km from the foothills of the Darling Scarp, and is generally about 10 m thick. The Yoganup Formation unconformably overlies the Osborne Formation and/or the Leederville Formation, and is unconformably overlain by the Guildford Formation. It may inter-finger with the Ascot Formation at the base of the superficial formations. The unit is a buried pro-graded shoreline deposit, with dunes, beach ridge, and deltaic facies (Baxter, 1982). In the Perth region, it has a maximum known thickness of about 10 m and has been extensively eroded prior to deposition of the Guildford Formation.

Guildford Formation

The Guildford Formation, raised to formation status by Low (1971) from the Guildford Clay (Aurousseau and Budge, 1921), consists of pale-grey, blue, but predominantly brown silty and slightly sandy clay. The unit is up to 35 m thick and commonly contains lenses of fine to coarse-grained, very poorly sorted, conglomeratic and (in places) shelly sand at its base, particularly in the type area of the Swan Valley. The Guildford formation outcrops over much of the eastern Perth region, unconformably overlies Jurassic and Cretaceous rocks, Kings Park Formation, Ascot Formation or Yoganup Formation. It is essentially a fluvial mud deposit.

Bassendean Sand

The Bassendean Sand, defined by Playford and Low (1972) from the type area in the Perth suburb of Bassendean, is present over much of the central Perth region, with a maximum thickness of about 80 m (Davidson, 1995). It is pale grey to white and includes fine to coarse, but is predominantly medium-grained. It comprises moderately sorted, sub-rounded to rounded quartz sand, and commonly exhibits fining upward textures. A layer of friable, limonite-cemented sand, colloquially called 'coffee rock', occurs throughout most of the area near the watertable. The Bassendean Sand unconformably overlies the Cretaceous and Tertiary strata, and inter-fingers to the east with the Guildford Formation. To the west, it is unconformably overlain by the Tamala Limestone. The depositional mechanism for this unit is unclear; it was likely deposited in a variety of fluvial, estuarine, and shallow-marine environments.

Tamala Limestone

The Tamala Limestone, defined by Playford *et al.* (1976), extends along the coastal strip of the Perth region. It consists of a creamy-white to yellow, or light-grey, calcareous aeolianite, which by definition suggests deposition as coastal dunes (Nidagal and Davidson, 1991). The Tamala Limestone contains various proportions of quartz sand, fine- to medium-grained shell fragments, and minor clayey lenses. The quartz sand varies from fine to coarse-grained, but is predominantly medium-grained, moderately sorted, sub-angular to rounded, frosted, and commonly stained with limonite. The limestone contains numerous solution channels and cavities, particularly in the zone of watertable fluctuation, and in some areas exhibits karst structures. Its upper surface is exposed and leached to the extent that the upper part of the unit comprises unconsolidated sand. Depending on the location, this unit unconformably overlies the Leederville Formation, Osborne Formation or the Bassendean Sand, and has a maximum known thickness of 110 m in the Perth area, but may be up to 150 m thick outside

the Perth area (eg, Hutt River). Along the coastal margin it is unconformably overlain by the Becher Sand or the Safety Bay Sand.
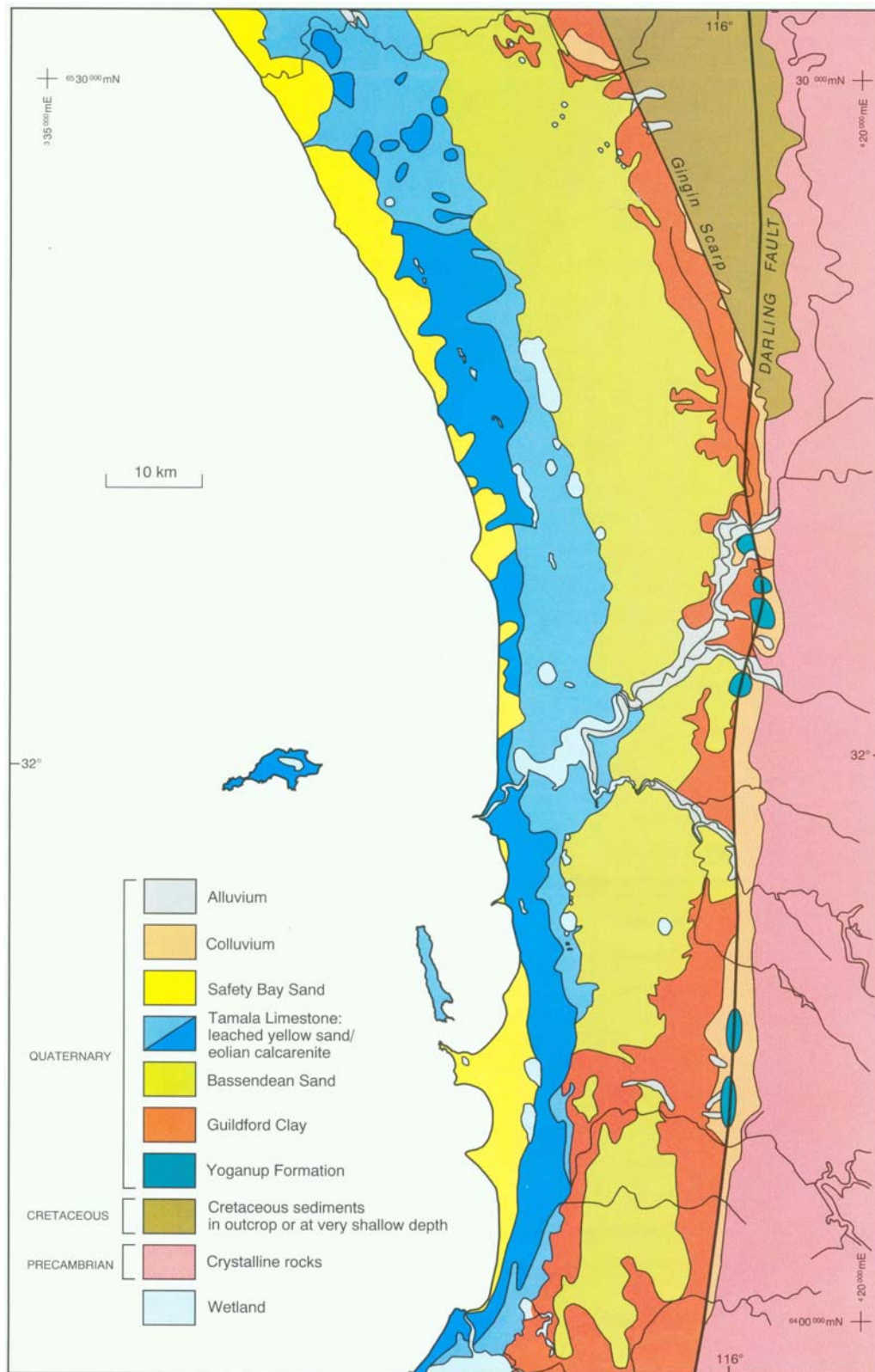

Figure D.4: Generalised surface geology of the Perth region (from Davidson 1995)

Becher Sand
The Becher Sand, defined by Semeniuk and Searle (1985), extends along the coastal margin of the Perth region, and consists of fine to medium-grained quartz and skeletal sand that is mostly structureless and bioturbated. Although it has not been extensively studied, the Becher Sand is typically 10–15 m thick (Semeniuk and Searle, 1985) with a maximum thickness of 20 m in the Rockingham area. It unconformably overlies the Tamala Limestone and is unconformably overlain by the Safety Bay Sand. The Becher Sand was previously referred to as the Safety Bay Sand but, because it is of nearshore marine origin and not aeolian, it is genetically distinct from the Safety Bay Sand.

Safety Bay Sand
The Safety Bay Sand, defined by Passmore (1967, 1970) and Playford and Low (1972), comprises white, unlithified, calcareous fine to medium-grained quartz sand and shell fragments with traces of fine-grained, black, heavy minerals. It occurs along the coastal margin as stable and mobile aeolian dunes, which overlie the Tamala Limestone and Becher Sand (Davidson, 1995). The type section at Rockingham is 24 m thick, but may be upwards of 100 m in other parts of the Perth Basin (Playford *et al.*, 1976).

Northam

Northam is located in the western Yilgarn Craton, adjacent to the Perth Basin (see Chapter 1, Figure 1.2). The western margin of the craton is defined by the Darling Fault (Figure D.1). The Yilgarn Craton is dominated by ancient granitic rocks of the Precambrian Western Shield. This block is comprised of Archaean rocks that have essentially remained tectonically stable since the Late Carboniferous–Early Permian glaciation (BMR Palaeogeographical Group, 1990), an event considered responsible for removing much of the pre-existing regolith (Ollier, 1978). The oldest dated sediments are Late Tertiary (early to mid-Eocene, 55–40 Ma) marine sediments found primarily as palaeo-drainage channel fill (Ollier, 1988).

The Atlas of Australian Soils (Northcote *et al.*, 1967) shows the Northam area as being dominated by rolling to hilly or river terrace type geomorphology. The primary soil types are red clayey subsoils, which may set hard during the dry season. The Western Australian Department of Agriculture's catchment hydrogeologist in Northam states the regolith in the area comprises 6–10 m of silt/clay alluvium, overlying approximately 30 m of weathered granite bedrock (Shahzad Ghauri, pers. comm., 2003). The absence of any significant sand component in these sediments is interesting given the presence of granitic bedrock. One excavation within the town intersected bedrock at less than 3 m, which was likely a basement high. This is consistent with the findings of Anand and Paine (2002), who, despite reporting regolith thicknesses of up to 150 m on the Yilgarn Craton, consider average values to be closer to 30–50 m, including 5–10 m of transported overburden. Johnston and McArthur (1981) report similar results for regolith profiles north of Narrogin, some 100 km southeast of Northam.

D.3   Key Datasets

This section outlines a number of the datasets that were critical to the development of site classes for the Perth region. A number of other secondary datasets used (e.g. digital elevation models) are not outlined in this section.

Water and Rivers Commision boreholes

The Water and Rivers Commision (WRC), an agency of the Western Australian State Government, provided Perth Cities Project with the locations of approximately 28,000 boreholes distributed throughout the Perth study area. In addition to the locations, WRC supplied a spreadsheet of accompanying drillers/geologists records (ie, geological and regolith information) for a proportion of the boreholes (over 80,000 records). A subset of 2,717 bores with their associated descriptive records

(12,199 records in total) were extracted from the larger WRC dataset on the basis of spatial location within or in proximity to the Perth study area (Figure D.5).

The descriptions of the boreholes are highly variable in terms of their detail and the context in which they were logged. However, it is reasonable to assume that the majority were drilled with the aim of exploring for aquifers across the Swan Coastal Plain. In most cases broad descriptions of grain size are documented for relatively coarse intervals, and there is poor differentiation between consolidated and unconsolidated sections: for example, weathered shales and siltstones are often described as mud or clay. The borehole records are rarely described in terms of Perth Basin stratigraphy and where they are, the Cainozoic section is usually described as a single unit. Another limiting factor of this dataset is that the holes were drilled with the primary aim of delineating aquifers. In many places along the coast it was only necessary to drill to the top of the Tamala Limestone, given that the overlying Safety Bay Sand comprises the primary superficial aquifer. Consequently many of the logs that have an associated description do not penetrate to sufficient depths to assist in the reconstruction of the complete regolith architecture (therefore in the majority of cases regolith thicknesses can only be considered as *minimums*).

Seismic Cone Penetrometer Test data

Seismic Cone Penetrometer Test (SCPT) survey involves monitoring a conical penetrometer tip that is pushed slowly into the ground. The device contains electrical transducers to measure both tip (Q_c) and side (F_s) 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 a direct relationship between the friction ratio and regolith material can be inferred (in general, the higher the friction ratio the finer the grain size). In addition to providing an estimate of regolith material type, the seismic velocity of the sediment was measured every 1.5 m during the SCPT.

The maximum depth to which a SCPT can penetrate is approximately 30 m, and discontinuation of a SCPT (the completion of a successful test) can be due to a combination of circumstances, primarily:

- excessive pressure at the probe tip due to coarse sand, rock or highly consolidated material;
- excessive friction along the probe sleeve due to fine-grained sediments;
- over-inclination of the probe due to skewing of the bore path.

This is significant as an SCPT does not necessarily provide an accurate measurement of the thickness and character of regolith at a site. If the regolith within the region is thicker than 30 m, or has a thin competent layer such as a limestone lens at a relatively shallow depth, the results will not reflect the true nature of the regolith.

For the Perth study, three SCPT surveys were completed, constituting a total of 57 sites. The distribution of SCPT sites in the Perth study area is shown in Figure D.6.

Microtremor data

One of the primary datasets collected to assist in the assessment of Perth's vulnerability to earthquake hazard was a series of natural period estimates calculated from microtremor measurements. An extensive microtremor field survey was undertaken in October and November of 2001 by Geoscience Australia in the Perth metropolitan area (and Northam). Readings were taken at over 3,000 locations in the Perth metropolitan area at a nominal grid spacing of 500 m (Figure D.7). The survey involved using a ground seismometer and measuring the resonant vibration of unconsolidated regolith (T), as generated by phenomena such as wind, waves and anthropogenic influences (eg, traffic). The method used for the analysis was the Nakamura Method (Nakamura, 1989), which is used to identify the fundamental natural period of vibration of the upper layer of sediments.

The results of the microtremor survey were utilised by Brian Gaull of Guria Consulting in the development of shear wave velocity estimates for the region (Gaull, 2003). He utilised the measured natural periods in conjunction with regolith thickness determined from the WRC boreholes to calculate estimates of seismic shear wave velocity for isolated regions within the Perth metropolitan area. Comparison of the Gaull shear wave velocity measurements and the shear wave velocities in the context of the site classes produced as part of this study is outlined in the discussion.

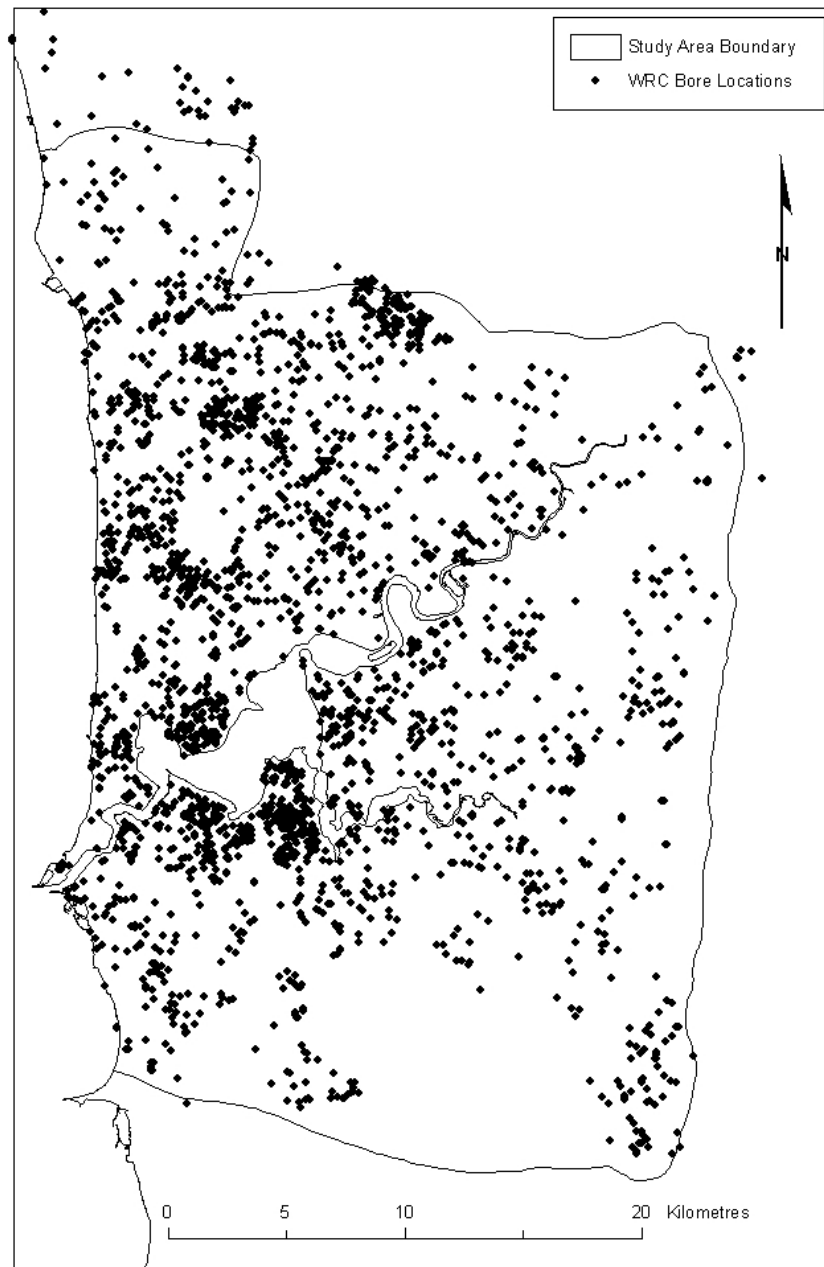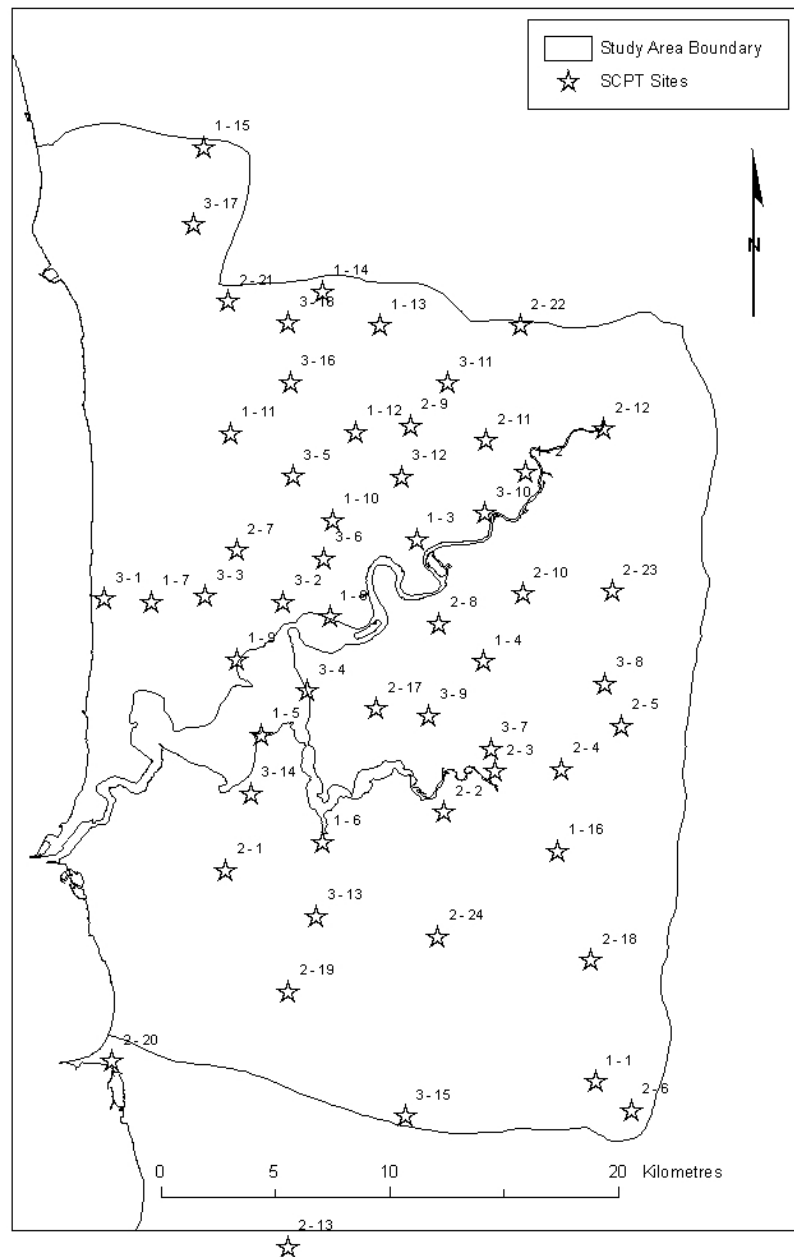**Figure D.5**: Borehole locations for the Perth study area

Figure D.6: SCPT site locations for the Perth study area
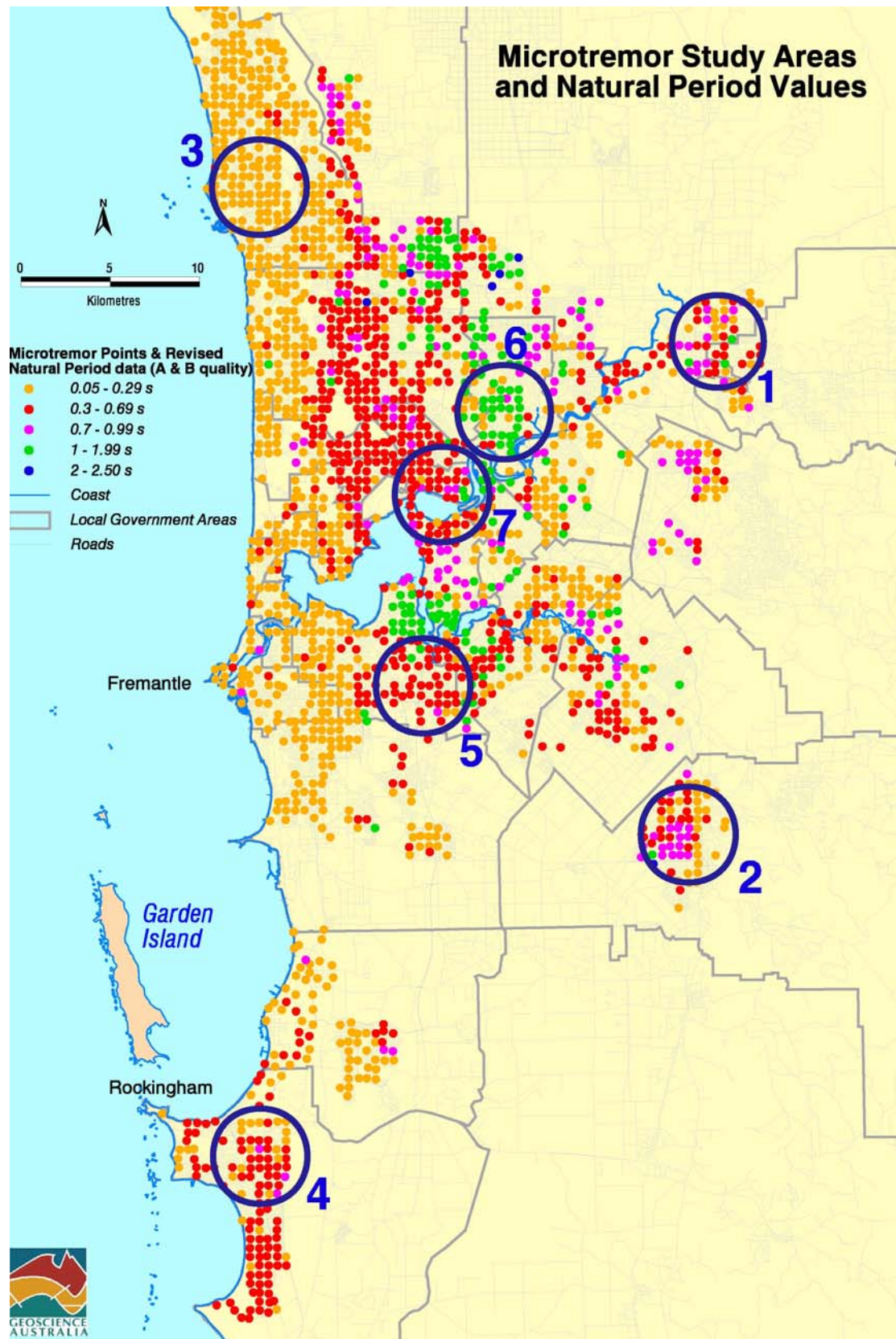
Figure D.7: Microtremor measurement locations for the Perth study area. Gaull's measurement zones are shown as blue circles

D.4   site class Development

The environmental geology maps produced by the Geological Survey of Western Australia (Gozzard, 1982a–b, 1983a–b, 1985, 1986; Jordan, 1986a–c, Smurthwaite, 1989) provide a valuable starting point for site class studies as they show the spatial distribution of Quaternary units at the surface. However, to accurately characterise site classes it is necessary to describe the distribution of the regolith in three dimensions. This process has primarily involved analysis of the geotechnical borehole data provided by the Western Australian Water and Rivers Commission.

In developing site classes for the Perth study area, it was necessary to consider the dominant regolith factors that influence the attenuation and amplification of earthquake ground motion, namely regolith thickness and regolith material type.

Regolith thickness plays a major role in determining the shear wave velocity of an earthquake energy wave as demonstrated by the quarter wavelength theory equation:

$$V_s = 4H \, / \, T \hspace{5cm} \textbf{Equation D.1}$$

where V_s = shear wave velocity (m/s), H = thickness of material or layer (m) and T = period (s). Hence, for a given period in a given material, as the value of H decreases (ie, the regolith gets shallower) the shear wave velocity is reduced, and the damping of the energy is increased.

Regolith material type also exerts a major control on the degree of amplification or attenuation experienced by travelling waves. The properties of regolith materials are represented by cyclic stress–strain curves, which describe the shear modulus and damping effects on energy applied to a material under strain. These relationships are a key component of modelling earthquake site response. In most instances, for a given period and magnitude, coarse-grained regolith materials (eg, sand or gravel) tend to amplify ground motion by virtue of low internal friction and particle movement which dissipates earthquake energy and increases the energy wave amplitude. Finer-grained, denser regolith materials (such as silt or clay) will have a slightly weaker amplification effect due to a higher internal friction and lower shear modulus which permit more effective energy transfer. Consolidated or cemented regolith materials tend to behave more like bedrock, attenuating earthquake energy and generally causing little or no amplification.

Regolith thickness assessment

The first step in analysing the WRC borehole data was to assess which holes were useful in characterising the three-dimensional architecture of the regolith, as many holes only penetrated the uppermost layers. Preliminary assessment in this context was achieved through comparison of borehole depth and published isopach maps of regolith thickness (Davidson, 1995) in a GIS environment. Holes that penetrated to depths greater than that indicated by the regolith isopachs were included in the preliminary investigation. Unfortunately, at the majority of localities, the depths to basement in the selected boreholes were significantly different to the depths indicated at those localities by the isopach map. The primary implication of this was that the only known isopach map of regolith thickness in the Perth region (that by Davidson 1995) was not sufficiently accurate to be included in any site class analysis.

Automatic selection of basement depths was attempted for each hole using keywords in a Microsoft Excel querying procedure. This was largely unsuccessful as depths to basement may be either:

- Underestimated due to boulders, rock/limestone floaters, indurated (cemented) or gravel layers that cause drill refusal; or

- Overestimated as there is no clear differentiation between consolidated and unconsolidated sediments, as mentioned previously.

As such, it became necessary to manually check through the borehole database and interpret the lithological strata and thickness of the superficial formations in the context of published descriptions of the Cainozoic stratigraphy (outlined previously). This stage of the analysis was very labour-intensive and time-consuming due to the size of the database. It was further complicated as the critical step in this process, identifying the basement, was very difficult for the most part due to the lack of distinction between consolidated and unconsolidated sediments.

Of the 2,717 boreholes selected, 604 are interpreted as having intercepted the basement/superficial boundary, with some or all of their regolith materials belonging to defined superficial formations. The most common basement formations encountered throughout the region (where identifiable) are the grey to black clays or shales of the Kings Park Formation, and the Kardinya Shale Member of the Osborne Formation. The isopach map of regolith thickness produced through this borehole interpretation and analysis is presented in Figure D.8. It should be noted that these regolith isopachs include both the Tamala Limestone (despite the fact that it is predominantly consolidated regolith) and the Poison Hill Greensand (as this unit is unconsolidated and consequently will have an impact on earthquake energy amplification). The inclusion of the Poison Hill Greensand is the main reason for the deeper regolith contours in the north of the study area (Figure D.8), and by way of example, the borehole at this anomalously deep locality penetrated 57 m of Poison Hill Greensand.

Statistics for the 604 manually interpreted bore logs show an average thickness for the superficial regolith of 29 m, with a distribution indicating that the majority of profiles are <50 m deep (Figure D.9). Statistics for borehole depths (as opposed to interpreted regolith thicknesses) in all 2,717 bores across the region show an average of 26 m, and present a similar distribution (Figure D.10). These average thickness values are in good agreement with each other, although they are slightly at odds with Playford *et al.*'s (1976, p. 206) assertion that the majority of the Quaternary deposits overlying the Swan Coastal Plain are <20 m thick. However, as mentioned previously, the inability to readily differentiate the base of the Quaternary deposits from the underlying basement materials means that several metres of weathered basement could potentially have been included in the borehole depth values. The inclusion of this 'extra' material in the averaged thickness estimates is considered justifiable, particularly given that their physical weathering state is likely to be similar to those of materials in the superficial formations above, and that the materials behaviour in response to an earthquake ground motion will also be similar.

Regolith data reclassification

Recognising the massive task involved in manually interpreting the remaining 2,100 bore logs with respect to discriminating the basement/superficial boundary and formation type, the decision was taken to develop a simplified material classification for all of the Perth study area WRC bore data (Table D.1). Given the degree of variability and inconsistency in the borehole database records, it was considered that a simplified classification would:

- capture the majority of regolith material information at a level of detail suitable for use in site class assessment, and;

- provide a 'cleaner', more consistent dataset for interpreting regolith material distribution across the Perth study area.

This re-classified data was produced and analysed to provide a broader spatial assessment of dominant regolith material distribution, and was used to develop the final site classes in conjunction with the previous detailed interpretation undertaken on regolith information from 604 bores.
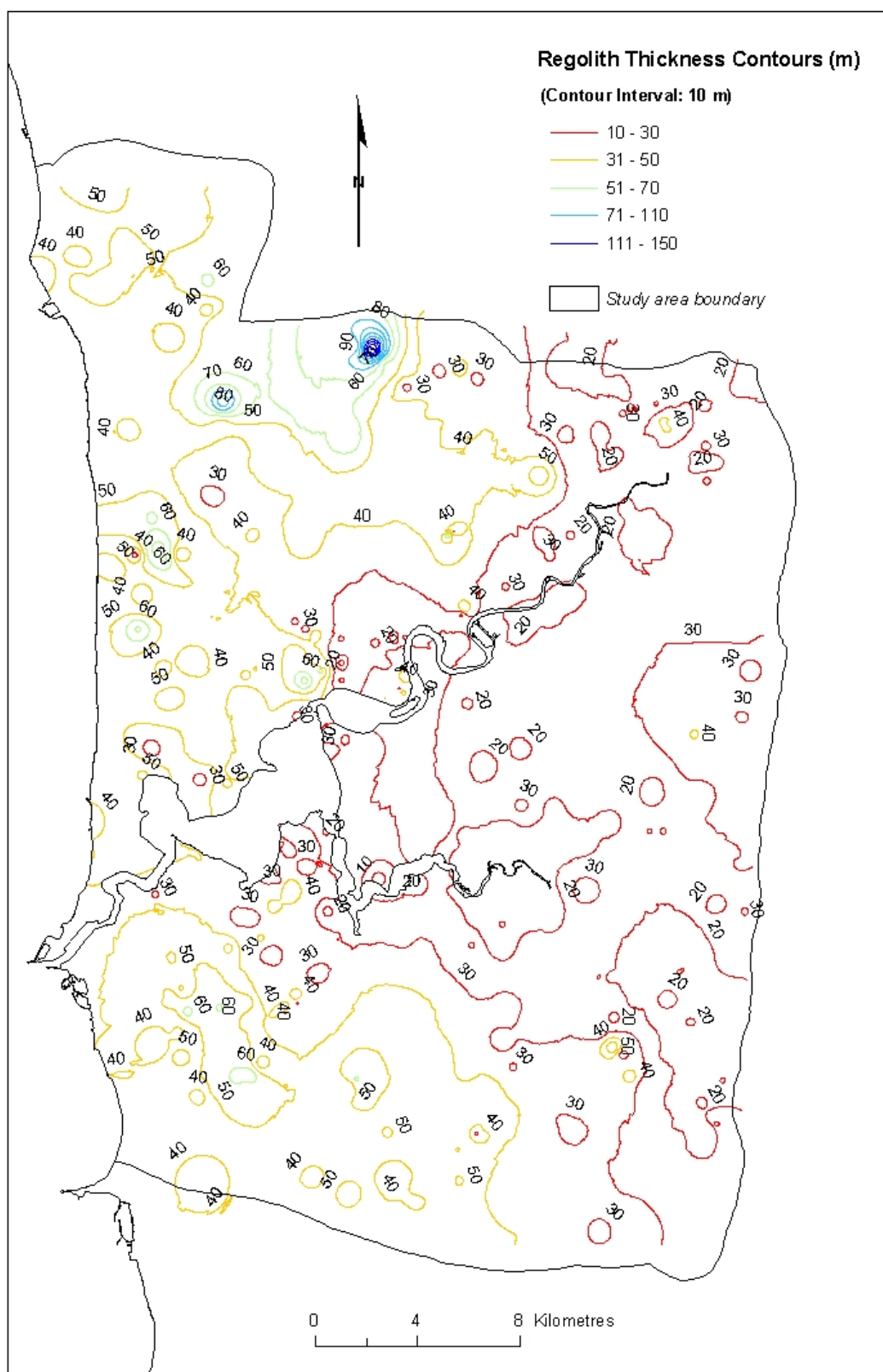
Figure D.8: Perth study area regolith thickness contours. Thicknesses include the (consolidated) Tamala Limestone and the Cretaceous (unconsolidated) Poison Hill Greensand
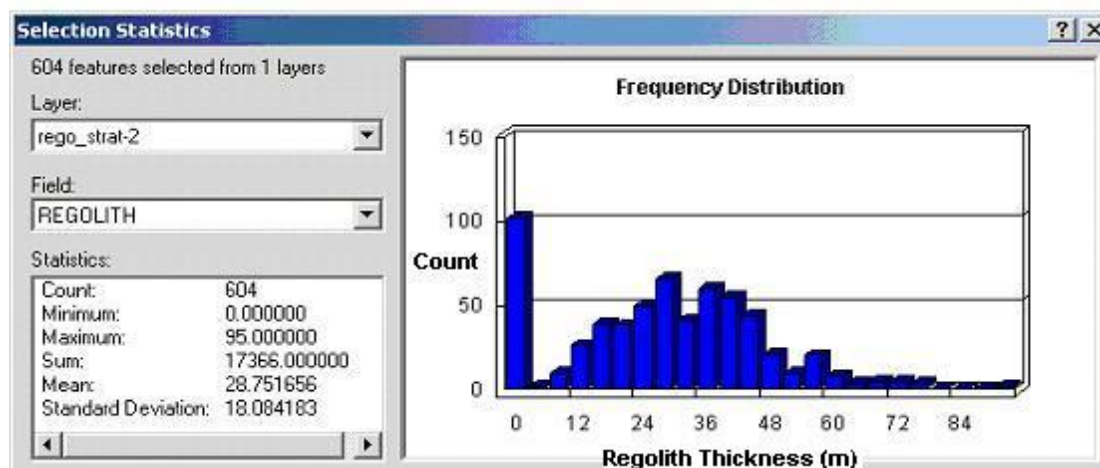
Figure D.9. Regolith thickness statistics for the 604 reinterpreted Water and Rivers Commission bores in the Perth study area.
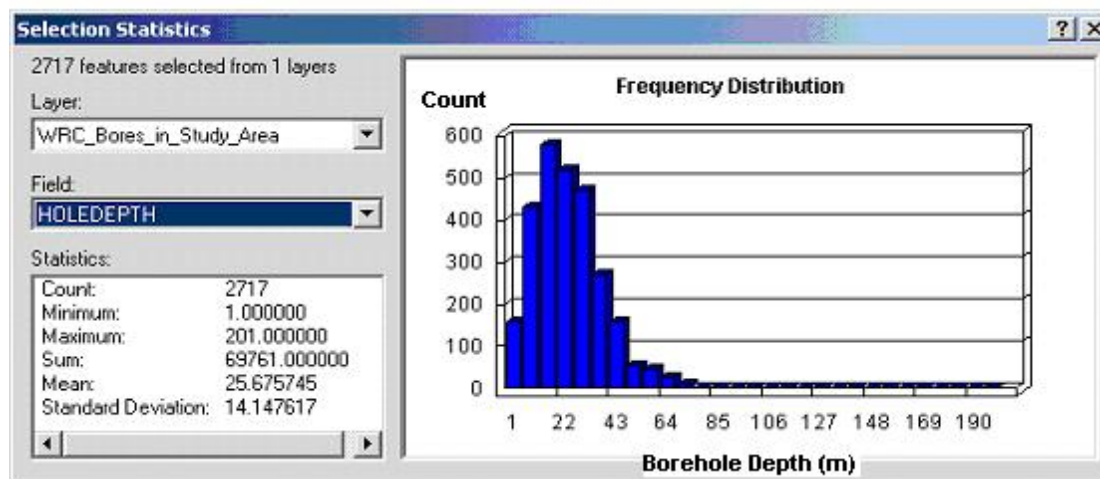

Figure D.10: Borehole depth statistics for the 2,717 Water and Rivers Commission bores across the Perth study area

Regolith material type

Having already developed a regolith thickness map for the Perth study area based on the initial 604 interpreted bores, the reclassified regolith data was used to cross-check the thicknesses and assess the spatial distribution of the dominant regolith material types.

The regolith materials of the Swan Coastal Plain are dominated by sands and calcareous deposits (limestone and secondarily cemented calcareous sands), with areas in the east closer to the Darling Range characterised by significant deposits of mud (silts and clays) (Figure D.11; Table D.2a–b). Given the general dominance of these broad regolith material types across the Perth study area, classification of bore records on the basis of material dominance within each profile was undertaken to refine this distribution. Of the logged bores (2,717) in the study area, the total thickness of material in any given profile is classified as containing >50% sand, mud or limestone for 97% (2,622) of profiles (Table D.2a). Seventy percent of profiles (1,891) are classified as containing >75% of one or other of these materials (Figure D.11; Table D.2b).

Table D.1: Summary of simplified regolith classes, dominant materials and number of records attributable to each class from the Perth study dataset

Material class	Identifier	Description	No. of records	% of records
Not logged	0	No record for the materials in the specified depth range.	54	0.5
Sand	1	Sand; silty sand; gravel; other coarse unconsolidated materials.	7 692	63.1
Mud	2	Silt; sandy silt; clay; sandy clay; mud.	1 611	13.2
Limestone	3	Limestone and any materials indurated by calcareous cements, including secondarily cemented calcareous sands.	2 030	16.6
Consolidated	4	Materials indurated by non-calcareous cements such as secondarily silicified sands; iron-oxide indurated materials (ferricrete); bedrock.	554	4.5
Coffee rock	5	Generally sands (occasionally muds) partly or completely indurated by organic complexes and iron-oxides.	203	1.6
Other	6	Rubble, fill and construction materials; refuse; organic matter (e.g. peat); other 'items' from the drillers logs not readily attributable to any other material class (e.g. slime, soup, seaweed).	55	0.5

Table D.2: Regolith materials (**a**) >50% and (**b**) >75% of total hole depth for the 2,717 logged profiles in the Perth study area

(a)

Dominant material	Profiles of >50% of material	% of profiles	Material thickness (m) Minimum	Material thickness (m) Maximum	Material thickness (m) Average
Limestone	464	53	5	87	35
Mud	227	30	1	45	18
Sand	1 931	73	1	201	24
TOTAL	**2 622**	**96.5**			

(b)

Dominant material	Profiles of >75% of material	% of profiles	Material thickness (m) Minimum	Material thickness (m) Maximum	Material thickness (m) Average
Limestone	230	26	5	87	36
Mud	81	11	4	45	19
Sand	1 580	60	1	78	23
TOTAL	**1 891**	**69.6**			

5.   Perth Site Classes

The classification of regolith materials on the basis of the methods presented above permits distinct spatial groupings to be identified, both in terms of material type and thickness. Using this information four separate site classes have been established for the Perth study area (Figure D.12).

For areas where a given regolith material comprises >75% of the profile in a majority of profiles, the site class is represented by a single geotechnical profile for that regolith material. However, there is overlap between areas in the distribution of materials (eg, there are appreciable numbers of sand-dominated profiles within the limestone area in the west – see Figure D.11). Furthermore, the use of a single geotechnical profile accounting for only one material type can not always be considered representative across all areas. For example, in the west the limestone is commonly covered with a layer of sand. Given this heterogeneity, any one site class is modelled as one or more geotechnical profiles for a representative regolith profile overlying 15 m of weathered basement (an averaged figure for the Perth study area) which in turn is overlying 'bedrock'. Where more than one profile (or material within a profile) is necessary, a proportional weighting is applied to the quantity of each material within the geotechnical profile, and also to the proportion of the site class represented by that particular geotechnical profile.

The incorporation of information on multiple regolith material types within a site class accounts for the variation in spatial distribution of these materials. As it is potentially misleading to represent all of the regolith within a defined area on the basis of one standard geotechnical profile, multiple profiles for the dominant regolith materials were incorporated into the regolith amplification model, where applicable. By applying a weighting to account for the proportion of each geotechnical profile type within the site class, the variability in amplification due to differences in regolith material type and thickness is captured.

In the following section each of the four site classes outlined above (Figure D.12) is described in terms of its lithology, regolith thickness, geotechnical profiles and natural period. Each class is then classified into some of the widely used generic site classification schemes:

- current Australian Loading Standard (Standards Australia, 1993);
- draft Australia/NZ Loading Standard (in prep.);
- NEHRP (Building Seismic Safety Council, 2000a; 2000b); and
- International Building Code (International Code Council, 2003).

Classification into the current Australian Loading Standard was based on thickness and lithology, classification into the new draft Australia/NZ standard was based on natural period, and classification into the NEHRP and International Building Codes was based on shear wave velocity.

Shallow Sand site class

Lithology
This class is dominated by fine to very coarse, but predominantly medium-grained, moderately sorted, sub-angular to rounded quartz sand, yellow to pale grey and white in colour. Shell fragments, heavy minerals, and clay and rare limestone lenses and horizons are found throughout the section.

Regolith thickness
The 145 boreholes within this site class have an interpreted regolith thickness varying from 4–61 m, with an average thickness of 20 m (standard deviation = 13 m).

Geotechnical profiles
The entire Shallow Sand site class is represented by a sand profile 10–40 m thick. Profile averaged shear wave velocities for the 14 SCPTs undertaken within this site class ranged from 237 m/s to

382 m/s, with an average profile value of 294 m/s (standard deviation = 43 m/s). Figure D.13 shows the distribution of shear wave velocity profiles for the Shallow Sand site class.
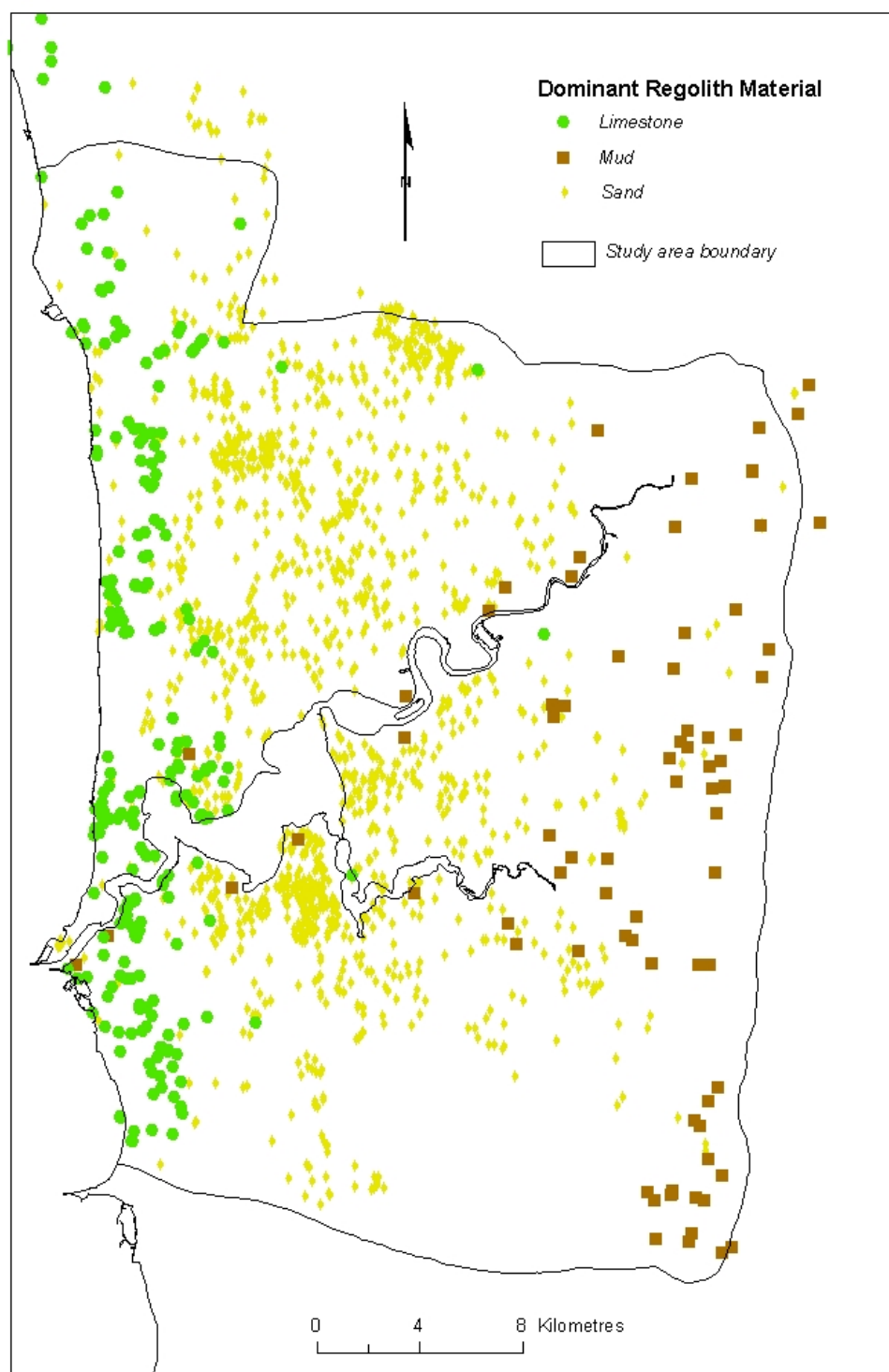

Figure D.11: Distribution of dominant regolith materials (>75% of total hole depth) across the Perth study area
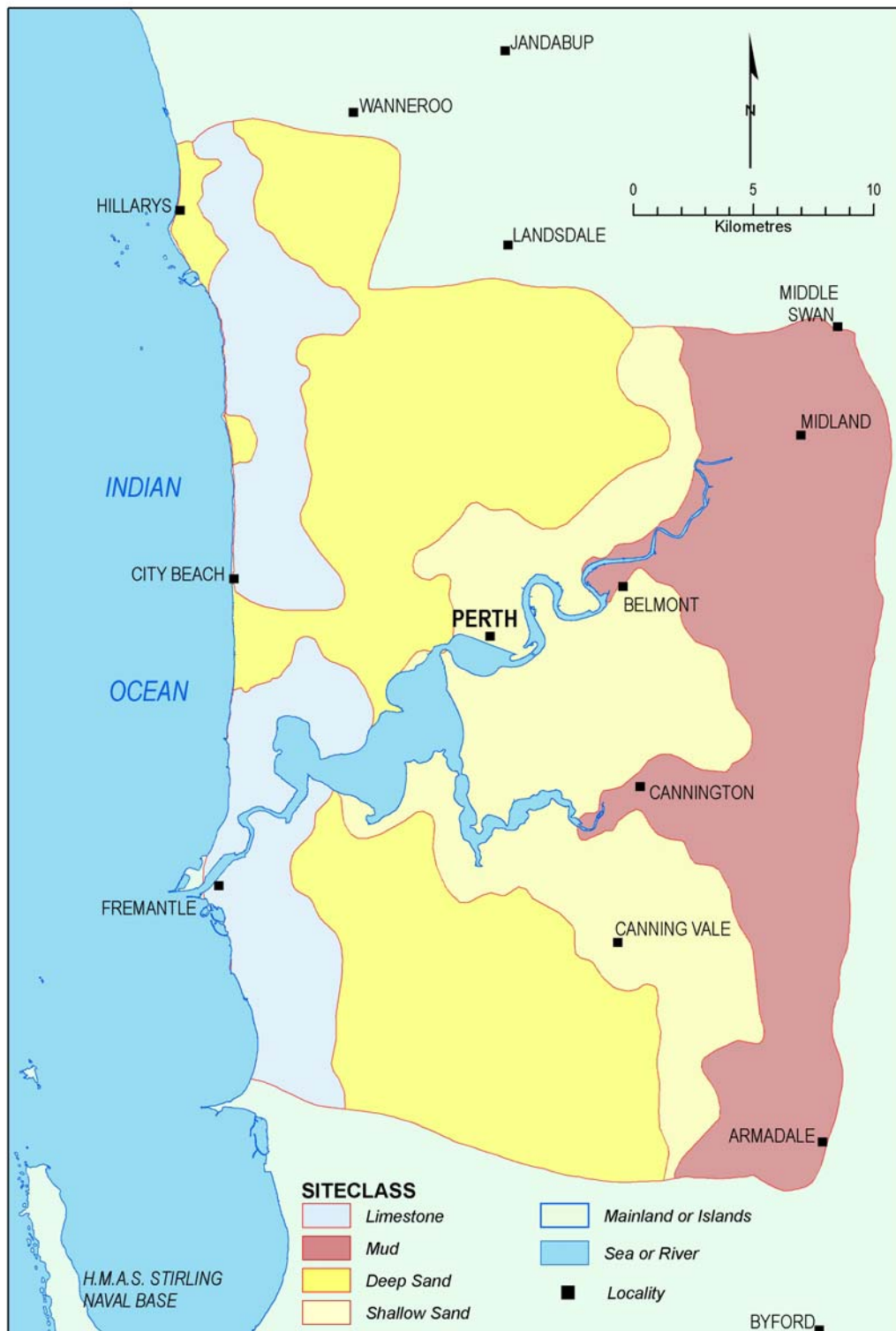
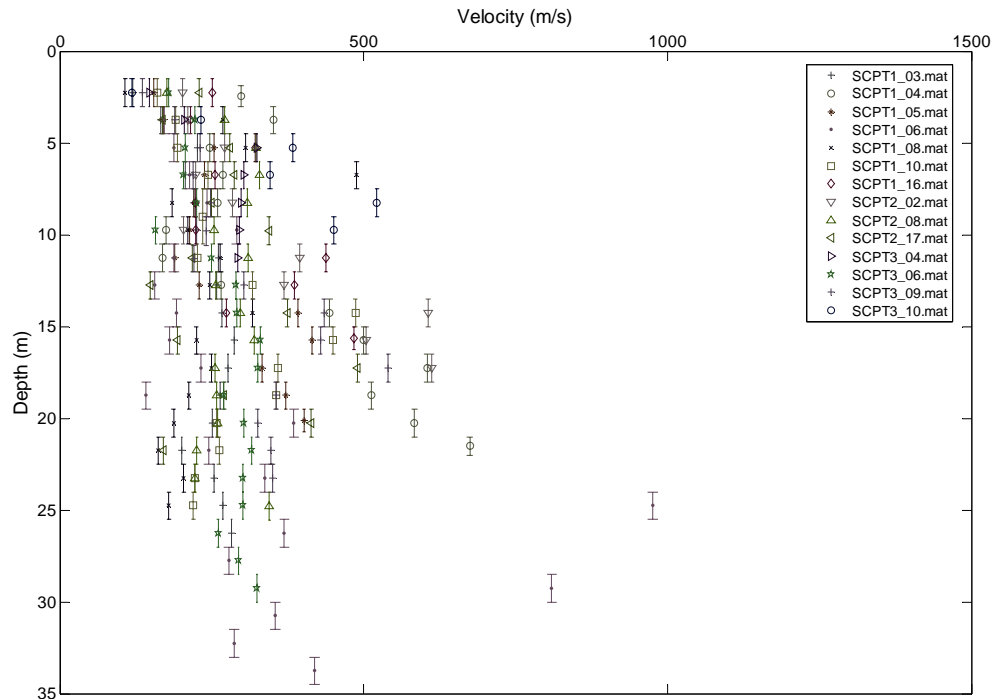**Figure D.12**: Site classes defined for the Perth study area

Figure D.13: Shear wave velocity data for the Shallow Sand site class

Natural period
Microtremor survey measurements across this class comprise 687 sites, with an average natural period of 0.65 seconds and a standard deviation of 0.46.

Classification in generic site class schemes

- Australian Loading Standard: *Soil profile with more than 12 m of very loose or loose sands*, as this class comprises an average of 20 m of sand.

- New Australia/NZ Loading Standard: *Class D – Deep or Soft Soil Sites*, as the average natural period for the class is greater than 0.6 s. However, the standard deviation for the microtremor measurements may force values below 0.6 and hence shift the site class into *Class C – Shallow Soil Sites*.

- NEHRP: *Class D – Stiff Soil*, as the majority of measured shear wave velocities are greater than 180 m/s and less than 360 m/s.

- International Building Code: *Class D – Stiff Soil Profile*, as the shear wave velocity of this class is between 200 m/s and 400 m/s (600-1,200 ft/s).

Deep Sand site class

Lithology
The materials in this class are essentially identical to those of the Shallow Sand class.

Regolith thickness
The 193 boreholes within this site class have an interpreted regolith thickness varying from 0–95 m, with an average thickness of 42 m (standard deviation = 14 m).

Geotechnical profiles
The entire Deep Sand site class is represented by a sand profile 30–60 m thick. Profile averaged shear wave velocities for the 26 SCPTs undertaken within this site class ranged from 129 m/s to 539 m/s, with an average profile value of 300 m/s (standard deviation = 82 m/s). Figure D.14 shows the distribution of shear wave velocity profiles for the Deep Sand site class.
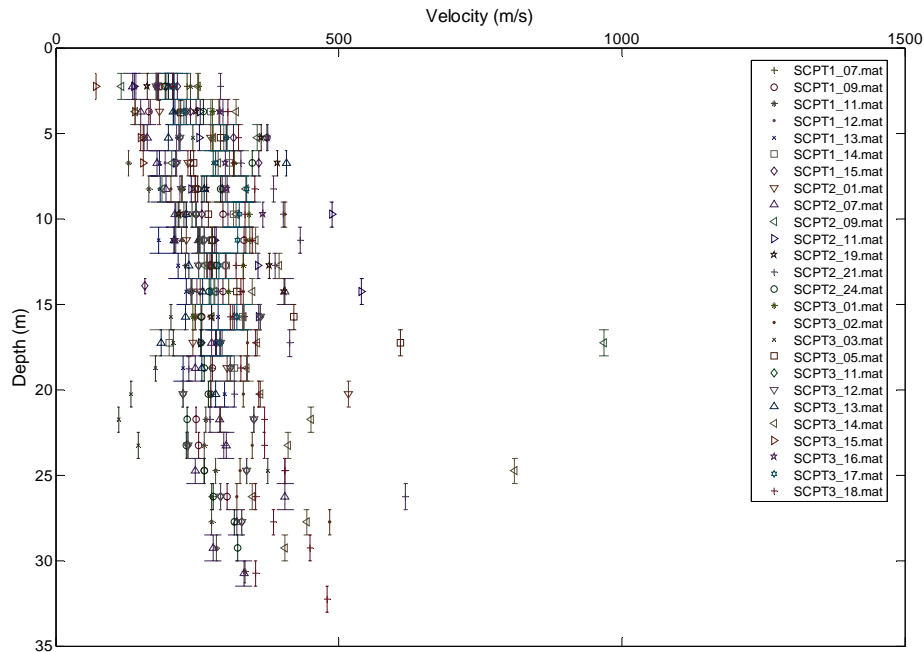
Figure D.14: Shear wave velocity data for the Deep Sand site class

Natural period

Microtremor survey measurements across this class comprise 928 sites, with an average natural period of 0.5 s and a standard deviation of 0.50.

Classification in generic site class schemes

- Australian Loading Standard: *Soil profile with a total depth of 20 m or more, and containing 6–12 m of very loose or loose sands*, as this class comprises an average of 42 m of sand.

- New Australia/NZ Loading *Standard: Class D – Deep or Soft Soil Sites*, as the average natural period for the class is greater than 0.6 seconds. The large standard deviation for the microtremor measurements gives potential values below 0.6, suggesting a shift into Class C – Shallow Soil Sites, although the significant regolith thickness values should preclude this.

- NEHRP: *Class D – Stiff Soil*, as the majority of measured shear wave velocities are greater than 180 m/s and less than 360 m/s, although spread on the distribution may move some sites into *Class C – Very Dense Soil/Soft Rock*.

- International Building Code: *Class D – Stiff Soil Profile*, as the shear wave velocity of this class is between 200 m/s and 400 m/s (600-1,200 ft/s).

Mud-dominated site class

Lithology

This class is characterised by mud-dominated regolith profiles containing variegated, but predominantly brown clays, silts, silty clays, and less commonly sandy clays and silts. Sandy lenses and horizons, occasionally shell-bearing towards the lower part of the succession, are distributed throughout. The class also contains some sand-dominated regolith profiles with materials similar to those of Shallow Sand class.

Regolith thickness

The 191 boreholes within this site class have an interpreted regolith thickness varying from 0–4 m, with an average thickness of 18 m (standard deviation = 13 m).

Geotechnical profiles

Approximately 80% of the mud-dominated site class is represented by a mud profile 10–30 m thick, while the remaining 20% is represented by a shallow sand profile (10–30 m thick) as per the Shallow Sand class. Profile averaged shear wave velocities for the 13 SCPTs undertaken within this site class ranged from 178 m/s to 895 m/s, with an average profile value of 330 m/s (standard deviation = 179 m/s). If the anomalous maximum value of 895 m/s (associated with Site 2-23, which intercepts a consolidated conglomeratic layer) is removed, the 12 remaining profiles give an average of 283 m/s (standard deviation = 60 m/s). Figure D.15 shows the distribution of shear wave velocity profiles for the Mud-dominated site class.

Natural period

Microtremor survey measurements across this class comprise 410 sites, with an average natural period of 0.5 s and a standard deviation of 0.35.
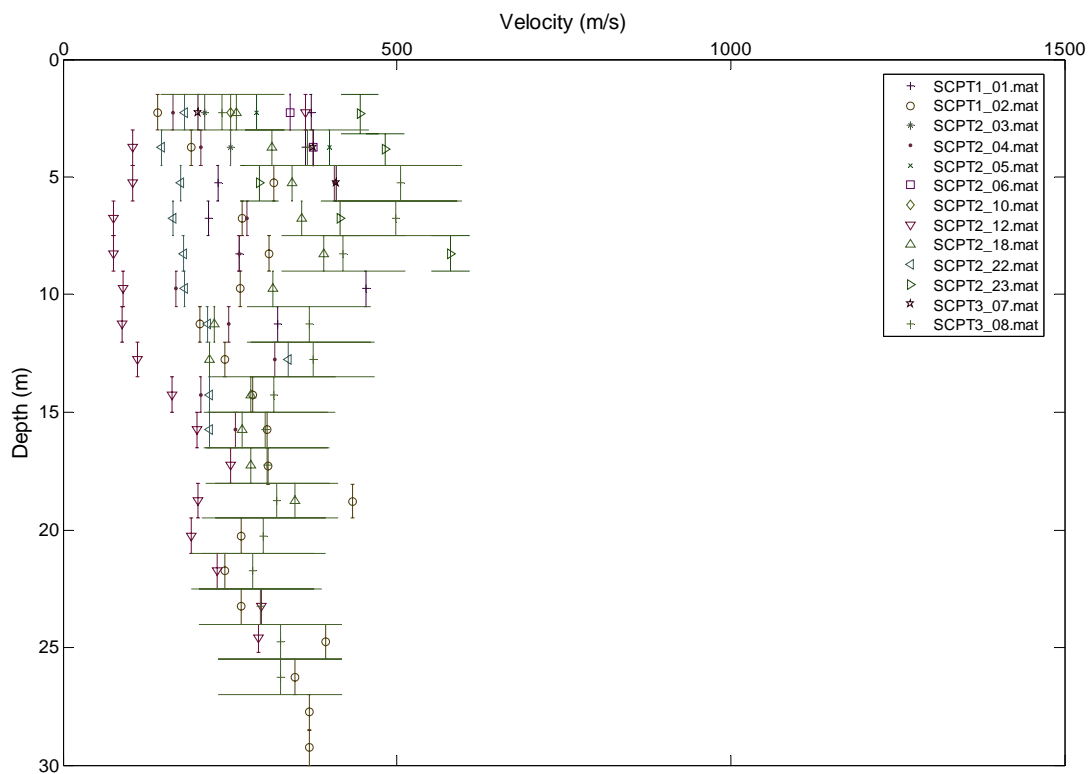

Figure D.15: Shear wave velocity data for the Mud-dominated site class.

Classification in generic site class schemes

- Australian Loading Standard: *Soil profile with more than 12 m of silts*, as this class comprises an average of 18 m of mud. However, it should be noted that this site class is not characterised by shear wave velocities less than 150 m/s, as suggested by the code, and therefore it may be more appropriate to identify this class in a S*oil profile with not more than 30 m of firm, stiff or hard clays*.

- New Australia/NZ Loading Standard: *Class C – Shallow Soil*, as the average natural period for the class is less than 0.6 s. However, the standard deviation for the microtremor measurements may force values above 0.6 and hence shift the site class into *Class D – Deep or Soft Soil*.

- NEHRP: *Class D – Stiff Soil*, as the majority of measured shear wave velocities (minus the anomalous value) are greater than 180 m/s and less than 360 m/s.

- International Building Code: *Class D – Stiff Soil Profile*, as the shear wave velocity of this class is between 200 m/s and 400 m/s (600–1,200 ft/s).

Limestone-dominated site class

Lithology
The sands within this class are identical to those in the Shallow Sand class. The limestone is composed of hard to friable calcareous aeolianite, commonly containing shells and shell fragments. Thin sand interbeds are preserved throughout the succession. It is creamy-white to yellow, or more commonly light-grey to fawn coloured at depth. The limestone contains numerous solution cavities.

Regolith thickness
The 74 boreholes within this site class have an interpreted regolith thickness varying from 0-79 m, with an average thickness of 40 m (standard deviation = 18 m).

Geotechnical profiles
Approximately 80% of the Limestone-dominated site class is represented by a geotechnical profile 15–60 m thick, composed of 10 m of sand overlying 30 m of limestone. The remaining 20% of the class is represented by a deep sand profile (30–60 m thick) as per the Deep Sand site class. Profile averaged shear wave velocities are unavailable for the limestone in this class, as SCPTs failed to penetrate the substrate. Wilkens *et al*. (1992) suggest shear wave velocities for limestone in the range 700–1,100 m/s, with an average of about 900 m/s. In the absence of real data for limestone in the Perth study area, this average figure has been adopted. Shear wave velocities for the sand profiles are as per the Deep Sand class.

Natural period
Microtremor survey measurements across this class comprise 504 sites, with an average natural period of 0.22 s and a standard deviation of 0.38.

Classification in generic site class schemes
- Australian Loading Standard: *Soil profile with a total depth of 20 m or more, and containing 6–12 m of very loose or loose sands*, as this class comprises an average of 42 m of sand.
- New Australia/NZ Loading Standard: *Class C – Shallow Soil Sites*, as the average natural period for the class is less than 0.6 s. The low average value for the microtremor measurements suggests that *Class B – Rock* may be more appropriate for this site class, however, the Standard specifies a 3 m maximum thickness of the overlying soil, and as such precludes this classification.
- NEHRP: *Class B – Rock*, as the shear wave velocity range of Wilkens *et al.* (1992) suggests a range between 760 m/s and 1,500 m/s.
- International Building Code: *Class B – Roc*k, as the suggested shear wave velocity of this class is between 800 m/s and 1,300 m/s (2,500–5,000 ft/s).

Site classification in Northham

The regolith in the Northam area comprises 6–10 m of silt/clay alluvium, so based purely on regolith material type and thickness, its most appropriate classification is into the Mud-dominated class. Microtremor survey data from the area show an average natural period of 0.39 s across 20 sites. This figure is quite low when compared to the average figures for all defined sites classes in the Perth Basin. However, given the large standard deviations associated with these figures, the average for Northam is within the range of one standard deviation for the Mud-dominated site class.

D.6. Discussion

Site class distribution

The distribution of site classes defined for the Perth study area (see Fig. D.12) strongly reflects the occurrence and distribution of regolith materials, whose type and thickness influence the potential

amplification of earthquake ground motion. Despite the complex geomorphic history of the Swan Coastal Plain, the regolith materials of the superficial formations (and hence the defined site classes) can be generalised and effectively separated into three spatially distinct zones.

Eastern Zone

Mud-dominated materials found in association with the Pinjarra Alluvial Plain and colluvial slopes of the Ridge Hill Shelf (Davidson, 1995). Materials consist of fluvial mud deposits of the Guildford Formation and more recent alluvial and colluvial materials, with minor contributions of sand, gravel and minor clays from palaeo-shoreline deposits of the Yoganup Formation. Regolith thicknesses are <50 m, and average ~20 m. The distribution of regolith materials in Figure D.8 highlights the fact that small areas of mud-dominated materials can be expected to be found in association with present drainage (for example, along the Swan River) outside the mapped site class boundary.

Central Zone

Shallow and deep sand-dominated profiles related to multiple generations of prograding shoreline deposits and aeolian reworking. Materials are primarily associated with the degraded surfaces of the Bassendean and Spearwood Dune Systems (McArthur and Bettenay, 1960). Regolith thicknesses average ~20 m in the shallower areas in the east, while generally increasing to the west where averages are closer to 40 m. Local variability is encountered, particularly where underlying unconsolidated Cretaceous–Tertiary units such as the Poison Hill and Molecap Greensands are present.

Western Zone

Limestone-dominated materials underlying the degraded surface of the western Spearwood Dune System, and foredune plains/dune complexes of the Quindalup Dune System (McArthur and Bettenay, 1960). The limestone has formed primarily as a result of solution of calcareous dune sands and re-precipitation of carbonate material further down the sequence. The occurrence of quartz sand deposits overlying (and interspersed with) the limestone can be attributed partly to this solution process, which has chemically 'winnowed' the quartz sands. However, the primary mechanisms for the occurrence of the sand deposits are near-shore marine sand deposition of the Becher Sand, and more recent aeolian deposition of the Safety Bay Sand unit (coincident with the Quindalup Dune System – McArthur and Bettenay 1960). Regolith thicknesses tend to be <80 m, with an average of approximately 40 m for both Limestone-dominated and interspersed Deep Sand profiles.

Liquefaction potential

Liquefaction is a phenomenon in which the strength and stiffness of a soil is reduced by earthquake shaking or other rapid loading. Liquefaction and related phenomena have been responsible for tremendous amounts of damage in historical earthquakes around the world (Yanagisawa, 1983; Borchardt, 1991; Morales et al., 1995). Liquefaction occurs in saturated soils, that is, soils in which the space between individual particles is completely filled with water. This water exerts a pressure on the soil particles, thereby influencing how tightly the particles themselves are pressed together. Prior to an earthquake, the water pressure is generally relatively low. However, earthquake shaking can cause the water pressure to increase to the point where the soil particles can readily move with respect to each other. Because liquefaction only occurs in saturated soil, its effects are most commonly observed in low-lying areas near bodies of water such as rivers, lakes, bays, and oceans (University of Washington 2005).

There are a number of different ways to evaluate the liquefaction susceptibility of a soil deposit (Kramer, 1996).

1. Historical Criteria: Soils that have liquefied in the past can liquefy again in future earthquakes.

2. Geological Criteria: Saturated soil deposits that have been created by sedimentation in rivers and lakes, deposition of debris or eroded material, or deposits formed by wind action can be very liquefaction susceptible.

3. Compositional Criteria: Liquefaction susceptibility depends on the soil type. Soils composed of particles that are all about the same size are more susceptible to liquefaction than soils with a wide range of particle sizes.

4. State Criteria: At a given effective stress level, looser soils are more susceptible to liquefaction than dense soils. For a given density, soils at high effective stresses are generally more susceptible to liquefaction than soils at low effective stresses.

Andrus and Stokoe (2000) compiled 225 liquefaction case histories from the United States, Taiwan, Japan and China. Of these case history sites 90% of the liquefied horizons had a critical layer thickness of less than 7 m, an average depth below land surface of less than 8 m, and a standing water level (water table) less than 4 m.

There does not appear to be any record of liquefaction in the Perth area, therefore there are no soils that fulfil Kramer's (1996) criteria 1. Sediments deposited by rivers or lakes (criteria 2) and well-sorted sand layers (criteria 3) are widely distributed throughout the study area. However, the water table is generally close to the surface only in close proximity to the Swan and Canning Rivers, therefore potentially liquefiable saturated sediments are likely to be confined to this region. To test which, if any, of these layers have the potential to liquefy, the shear wave velocities from five SCPT sites were modelled.

Of the five SCPT sites assessed, three sites (1-5, 1-6 and 2-12, see Figure D.5) were considered to have some potential for liquefaction. Site 1-6 contains a single thin (~1 m) sand horizon at approximately 14 m depth, capped by mud layers. Site 2-12 has two potentially liquefiable layers, which consist of sand to silty-sand horizons approximately 2 m thick at depths of about 15 m and 18 m. The water table depths at these two sites are about 5 m and 8 m respectively (Davidson, 1995). In light of the case history database presented by Andrus and Stokoe (2000), it is unlikely that these layers will liquefy as each of these horizons is considerably deeper than 8 m, and the water table is deeper than 4 m.

Site 1-5 contains a sand and gravel sequence approximately 15 m thick extending from a depth of 5 m down to nearly 20 m, with a 5 m overlying (confining) layer of silt and a water table at approximately 1 m (Davidson, 1995). Despite having the correct material type under a confining layer coupled with a shallow water table, the significant thickness of the sand/gravel sequence and the occurrence of the majority of the sequence at a depth of greater than 8 m below the land surface make it unlikely that this sequence will liquefy.

On the basis of these test cases there is a very low liquefaction potential in the Perth region, a conclusion similar to that reached by Cocks *et al*. (2003).

Guria Consulting Report

The results presented by Brian Gaull in his report on the 2001 microzonation study of the Perth region (Gaull, 2002; 2003) are based on a series of shear wave velocities for seven zones in the greater Perth metropolitan region (Figure D.6). Shear wave velocities were estimated by relating the natural period and thickness of the regolith in each zone. A mean depth and mean natural period, and the gradient of depth-natural period plots were used to calculate shear wave velocities for each zone. As outlined above, one of the datasets collected during the site class study was a series of seismic cone penetrometer tests. These tests were undertaken within or very close to Gaull's seven zones, allowing for direct comparison between measured shear wave velocities and Gaull's (2002) velocity estimates derived from microtremor data. This comparison is presented below by site (or 'target' – Gaull, 2003).

Site 1: Midland
Estimated shear wave velocity for this zone of approximately 235 m/s based on the total depth and natural period data, and 200 m/s based on a mean depth and mean period.

SCPT site 2-12 is located within this zone. The test pushed to a depth of 25.2 m, the upper 12 m of which was predominantly organic clays with lesser clay to clayey silt, while the lower 13 m was predominantly sandy silt to sand. The shear wave velocity of the upper 12 m varies around 100 m/s. The shear wave velocity of the lower sandier section increases down-hole from approximately 200 m/s to 250 m/s.

Site 2: Kelmscott
Estimated shear wave velocity for this zone is approximately 220 m/s based on the total depth and natural period data, and 190 m/s based on a mean depth and mean period.

SCPT site 1-1 is located within this zone. The test pushed through to 12.0 m, the upper 6.5 m of which was a fining down sequence of sand to clay, while the lower 5.5 m was predominantly gravelly sand. The shear wave velocity of the upper section decreases down-hole from approximately 350 m/s to 225 m/s. The shear wave velocity of the lower sandy section varies significantly around 275 m/s.

Site 3: Hillarys
Estimated shear wave velocity for this zone is approximately 450 m/s based on the total depth and natural period data, and 285 m/s based on a mean depth and mean period.

SCPT site 3-17 is located within this zone. The test pushed through 19.85 m of silty sand to sand. The velocity plots show the shear wave velocity varies slightly around a value of approximately 300 m/s.

Site 4: Rockingham
Estimated shear wave velocity for this zone is approximately 190 m/s based on the total depth and natural period data, and 200 m/s based on a mean depth and mean period.

SCPT site 3-14 is located within this zone. The test pushed through 33.05 m of predominantly silty sand to sand. The velocity plots show the shear wave velocity varies slightly around a value of approximately 350 m/s for the majority of the profile.

Site 5: Bateman
Estimated shear wave velocity for this zone is approximately 250 m/s based on the total depth and natural period data, and 180 m/s based on a mean depth and mean period.

SCPT site 1-6 is located within this zone. The test pushed through 34.5 m of predominantly silty sand to sand, with lesser clay and clayey silt layers. The velocity plots show the shear wave velocity in the upper half of the test varies slightly around a value of approximately 200 m/s. The shear wave velocity in the lower half of the test varies slightly around a value of approximately 300 m/s, with the exception of two distinct layers with shear wave velocities between 900 m/s and 1,000 m/s.

Site 6: Bayswater
Estimated shear wave velocity for this zone is approximately 220 m/s based on the total depth and natural period data, and at least 185 m/s based on a mean depth and mean period.

SCPT site 3-12 is located within this zone. This test penetrated 29.25 m of regolith, the upper 20 m of which was predominantly sand, while the lower 10 m was dominated by clayey silt to silty sand. The shear wave velocity of the upper sandy section increases down-test from 220 m/s to 250 m/s. The shear wave velocity of the lower sandy section varies around a value of approximately 300 m/s.

Site 7: Perth
Estimated shear wave velocity for this zone is approximately 265 m/s based on the total depth and natural period data, and 230 m/s based on a mean depth and mean period.

SCPT site 1-8 is located within this zone. The test penetrated 25.5 m, the upper half of which was predominantly clay with silty bands, while the lower half is dominated by sandy silt to clayey silt. The shear wave velocity in the test decreases down-hole from approximately 250 m/s to 200 m/s.

Discussion

Overall the shear wave velocity estimates presented by Gaull (2002) do not compare favourably with the measured shear wave velocities. At most sites the calculated shear wave velocity values based on either the total or mean natural period and depth data can only be considered comparable to the measured SCPT value in a small percentage (generally <50%) of the profile. For example, the estimate of 220 m/s (based on the total data) for Site 6 agrees with the measured shear wave velocity values near the top of the profile for SCPT site 3-12. However, the SCPT data demonstrate an increase in shear wave velocity with depth, with values in the lower profile averaging 300 m/s – significantly higher than either of the calculated values. Overall, the calculated shear wave velocity data tend to either underestimate (eg, Sites, 2, 4 and 6) or overestimate (eg, Site 3) the actual (measured) shear wave velocities in almost the entire profile.

There does not appear to be any trend in the reliability of the estimates calculated from the total data as opposed to the mean data. That is, in some cases the total data estimate was closer to the measured shear wave velocity value, while in others it was the average data estimate that was more accurate. For example, the total data estimate for Site 2 (220 m/s) is closer to the measured shear wave velocity, but at Site 3 the average data estimate (285 m/s) is more accurate.

Estimated shear wave velocity values presented by Gaull also do not appear to account for the presence of very high or low velocity layers, as we would expect from an assessment of the capabilities of the methods available to Gaull. A good example of this is seen at Site 5, where estimated values are 3–4 times lower than measured values for high velocity layers.

Overall, the method applied and results presented by Gaull (2002) should be used with caution in relation to earthquake studies. Conversion of microtremor-derived natural periods into shear wave velocities through depth relations should be confined to areas in which the regolith comprises a low variability (preferably homogeneous) sequence of material with well constrained thickness information. As the Quaternary geology of the Perth Basin fulfils neither of these criteria, the results of Gaull's (2002) report should be appraised carefully.

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