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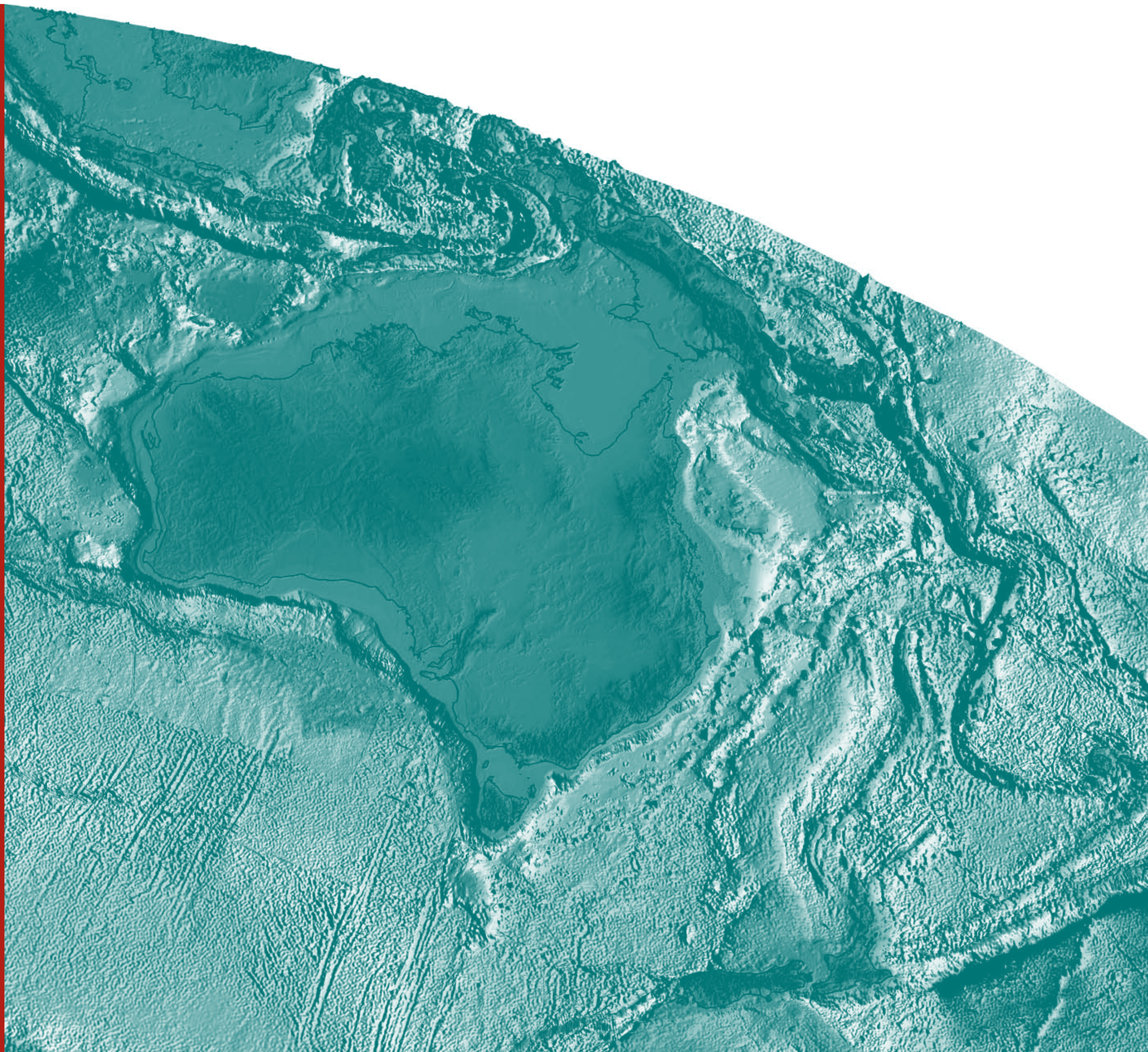

SPATIAL INFORMATION FOR THE NATION

Development of the Australian National Regolith Site Classification Map

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RMS™

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Contents

Executive Summary

A key recommendation of the Council of Australian Governments review into natural disaster management arrangements in Australia is that a five-year national program of systematic and rigorous disaster risk assessments be developed and implemented. This process requires the construction of national databases and standardised methods and models that allow objective comparison of risks between regions and across hazards. A significant component of this process is the completion and delivery of a series of national earthquake risk assessments.

The need for an improved understanding of earthquake ground shaking in Australia was recognised following the 1989 Newcastle earthquake, which resulted in 13 fatalities and $4.5 billion in estimated losses. An enhanced capability to anticipate the impacts of such events will facilitate improved earthquake disaster mitigation and planning for Australian communities, and influence the development of relevant engineering codes and standards. To achieve this it is necessary to model earthquake events, the mechanisms by which earthquake energy dissipates, and the potential influence of variation in geological materials on the ground shaking.

At present, national scale earthquake hazard products for Australia do not included the effect of regolith site response on ground shaking, and as such may provide inconsistent or inaccurate estimates of ground shaking in some areas. The development of the National Regolith Site Classification Map represents a significant advance in our ability to model the potential influence of near-surface geological materials on earthquake ground shaking, and therefore to assess earthquake hazard and risk in Australia.

The National Regolith Site Classification Map presented here has been developed through the application of a pre-existing methodology which has been modified to suit Australian conditions. The changes include the development and application of an innovative method to account for weathering in bedrock geological units. To the extent that the data permits, site classification takes into account the age and physical properties of the geological materials and relates them to key geophysical parameters that most accurately represent the behaviour of these materials under the influence of earthquake ground motion. The compilation of data at both national and regional scales has led to the development of a multi-resolution tool that provides more detailed information in and around the major population centres. This same variation in spatial resolution does, however, make map sheet edge mismatches unavoidable.

The National Regolith Site Classification Map provides a tool for estimating the regolith site response to ground shaking at any location in Australia. This product has potential implications for revision of earthquake-related Standards and Building Codes in Australia, particularly regarding the criteria used to classify sites according to ground shaking potential. When implemented within Geoscience Australia’s National Earthquake Risk Model (EQRM) the National Regolith Site Classification Map and associated amplification factors represent fundamental components of the most rigorous available method for assessing earthquake risk in Australia.

Introduction

MOTIVATION

In implementing the recommendations from the Council of Australian Governments review into natural disaster management arrangements in Australia (Council of Australian Governments, 2004) the Risk Research Group at Geoscience Australia initiated several projects contributing to a national program of systematic and rigorous disaster risk assessments. Geoscience Australia's Earthquake Risk Model (EQRM) (Robinson *et al.*, 2005) is fundamental to these projects, and is underpinned by a number of key input datasets, including the National Regolith Site Classification Map. The map also represents a significant complementary dataset to the Australian National Earthquake Hazard Map, which is currently under revision.

SEISMIC HAZARD IN AUSTRALIA

Despite its intra-plate setting, roughly 70 earthquakes have caused damage to populated areas in Australia since 1788 (McCue, 1990). The most deadly and damaging of these is the M 5.6, 1989 Newcastle earthquake (McCue *et al*., 1990), which resulted in the deaths of thirteen people and estimated losses of AUS$4.5 billion (BTE, 2001). The largest recorded historic event in Australia is the 1941 M_S 6.8 Meeberrie earthquake (Everingham *et al*., 1982). Maximum ground shaking (Modified Mercalli) intensities of MMI VIII were reported near the epicenter, while the city of Perth (600 km to the south) experienced intensities of IV to V. Given the demonstrated significance of events such as Newcastle, and the possibility of events approaching M 7.0, an improved understanding of earthquake hazard and risk is essential, particularly in high exposure areas.

The earthquake hazard in a region can be described in terms of *the level of ground shaking that has a certain chance of being exceeded in a given amount of time*. For example, it is common to describe earthquake hazard in terms of the level of ground shaking that has a 10% chance of being exceeded in 50 years. In order to calculate the earthquake hazard, three key models are needed, specifically:

1) **regional seismicity model**, which describes the earthquake sources according to the rate and magnitude of event activity;
2) **ground motion attenuation model**, which describes generally how earthquake ground shaking or intensity decreases with distance away from the earthquake source; and
3) **regolith site response model**, which describes how local regolith (soils, sediments and weathered rock) will affect the ground shaking experienced during an earthquake.

The *regional seismicity model* is composed of seismicity source zones, which may be defined using historical activity rates and an understanding of the underlying geological structures. The level of earthquake activity is generally assumed to be uniform throughout each source zone, but differs from one zone to the next. Several different source zone models currently exist for Australia (e.g. Gaull *et al*., 1990; Brown & Gibson, 2004; Leonard, 2007).

Attenuation models modify the seismic waves with distance from the earthquake source to estimate the characteristics of the earthquake vibrations below a site at bedrock level. As crustal properties may vary significantly between tectonic environments, attenuation models are generally region specific. However, most attenuation models applied in Australia have been developed elsewhere; primarily in North America (e.g. Atkinson & Boore, 1995; Sadigh *et al*., 1997; Toro *et al*., 1997). This is due to a paucity of local data and a perceived similarity in regional attenuation characteristics. A southeast Australian attenuation model is currently under development (Allen *et al*., in prep.), and preliminary comparisons against eastern North American models show that attenuation differences are only significant at distances greater than 100 km (Allen & Atkinson, 2006).

The *regolith site response model* modifies earthquake ground shaking at a site according to the expected influence of regolith (weathered rock and overlying sediments and soils) on the propagating seismic waves (Idriss & Seed, 1968). Local site conditions can significantly alter the amplitude, frequency and duration of earthquake ground motions, and thereby influence the occurrence and degree of damage to buildings and other structures (Seed & Idriss, 1969; Idriss, 1990). This is demonstrated by the strong spatial correlation between building damage and site conditions observed for the 1989 Newcastle earthquake (Chandler *et al*., 1991), and for events elsewhere around the world (e.g. Meremonte *et al*., 1996; Higashi & Sasatani, 2000; Andrus *et al*., 2006).

Current national scale earthquake hazard products for Australia do not include the effect of regolith site response, and so may produce inconsistent or inaccurate estimates of the potential impact of ground shaking. The development and incorporation of the National Regolith Site Classification Map and associated amplification factors into the National Earthquake Risk Model therefore represents a fundamental improvement critical to the rigorous assessment of earthquake risk in Australia.

Development of the Australian National Regolith Site Classification Map

The primary aim of the Australian National Regolith Site Classification Map is to provide a broad scale data layer representing the likely physical response to earthquake ground shaking of all major occurrences of surficial geological materials across the country. This data layer underpins the national site response model and represents a key input into the national earthquake risk model (Robinson *et al.*, 2005).

The National Regolith Site Classification Map groups regolith materials on the basis of their likely response to earthquake ground shaking. It has been developed by applying an Australia-specific site classification scheme based on a number of national and regional scale geological and geotechnical datasets, combined with more detailed local data where available.

Development of the regolith site classes was undertaken collaboratively with Risk Management Solutions Inc. (RMS), an international risk management company based in Newark, California. RMS had a pre-existing 'geotechnical' site classification model for Australia which they were interested in updating. A formal agreement was reached between RMS and Geoscience Australia (GA), by which GA would identify and supply appropriate geological and geotechnical datasets for incorporation into the RMS model and provide expertise in interpreting this data. In return GA was granted a conditional licence to utilise and modify this dataset for the purpose of earthquake risk modelling.

REGOLITH SITE CLASSIFICATION

Factors in Site Response

Local site conditions can significantly alter the amplitude and frequency content of earthquake ground motion. In particular, the physical properties of regolith, such as shear-wave velocity, density, particle size and plasticity, exert a major control on the degree of amplification or attenuation experienced by travelling waves. The degree to which this modification occurs is heavily influenced by three key phenomena, namely *impedance*, *damping* and *resonance*.

Impedance is the ability of a material to resist particle motion and can be defined as the product of shear-wave velocity (V_s) and density. As a seismic wave passes from one material into another with a lower V_s (and hence decreasing impedance), the amplitude of the seismic wave increases in order to conserve energy (Borcherdt, 1994; Fig. 1).

The increase in amplitude with decreasing V_s is counteracted by the ability of poorly consolidated or highly weathered materials to absorb more seismic energy, *damping* the ground motion. Cyclic stress-strain curves, which are highly specific to the material type (e.g. sand, silt, clay), are used to describe the shear modulus and damping effects on energy applied to a material under strain (e.g. Seed & Idriss, 1969; Seed *et al*., 1986; Vucetic & Dobry, 1991; Kramer, 1996).

The configuration of the underlying material also affects the amplitude of the seismic wave. Sharp contrasts in rock properties, and hence impedance, may result in internal reflection of the wave energy. In such cases *resonance* may occur as a portion of the seismic waves become trapped within the discrete layers and begin to reverberate. This effect is maximised when the frequency of the seismic wave is in phase with the natural period of the geological unit. In the simplest case, shear-waves are amplified most at frequencies equal to $V_s/4H$, where H is the thickness of the geological layer (Reiter, 1991). In general, resonance primarily affects lower frequency (longer period) ground motions.

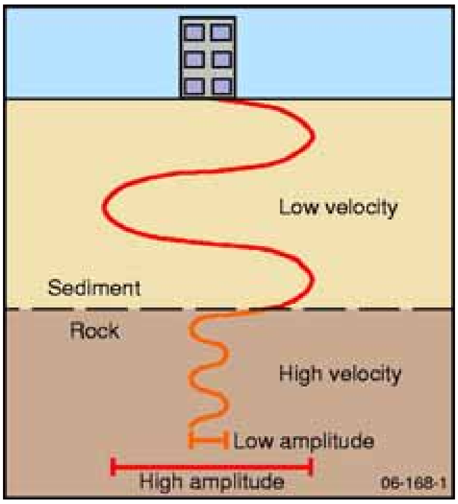

Figure 1. Diagram illustrating the effect of impedance on earthquake shear-wave energy. An increase in wave amplitude coincides with the transition from higher velocity rock (high impedance) to lower velocity (low impedance) sediment.

The overall effects of local site conditions on an input ground motion are illustrated by the example response spectra in Figure 2. These represent the ground motion at different periods for different geological material types normalised to the peak ground acceleration. Finer-grained regolith materials (e.g. silt, clay) exhibit much lower V_s values than typical rock and generally cause significant amplification of earthquake energy at natural periods similar to typical buildings (0.2 to 1 s). Stiff soils and coarser-grained regolith materials have V_s values intermediate between bedrock and fine grained sediments. This translates into reduced damping of the earthquake energy, but also less amplification.

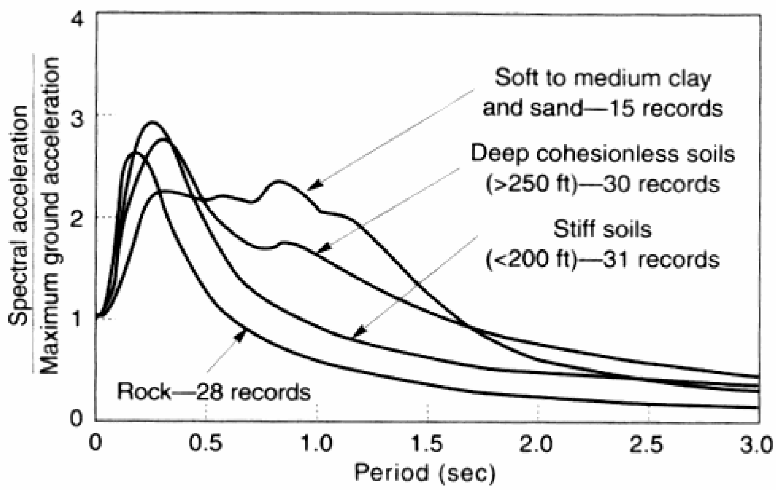

Figure 2. Examples of average normalised response spectra for different site conditions (5% damping) (after Seed *et al.*, 1976).

Site Class Evaluation

Geological materials that are considered likely to exhibit a similar physical response to a given earthquake ground motion may be grouped into a *site class*. Correct site class definition is essential to reduce uncertainty in assessments of the potential response of structures to earthquake ground motion. The previous section outlines a range of factors that may significantly influence the amplitude and frequency of ground motion. However, for less detailed or regional scale site assessment studies it may not be practical to assign site classes based on a comprehensive list of parameters due to a paucity of relevant data.

A simpler approach is to consider the ground motion amplification effect of impedance alone. The preferred and mostly widely applied method for defining site classes based upon impedance utilises the shear-wave velocity of the upper 30 m below ground surface (V_s^{30}), assuming constant density (e.g. Borcherdt, 1994; Anderson *et al*., 1996; Wills & Silva, 1998; Dobry *et al*., 2000; Wills *et al*., 2000; Boore, 2004; Choi & Stewart, 2005; Holzer *et al*., 2005). Empirical studies have demonstrated a consistent relationship between earthquake site response and V_s^{30} (e.g. Borcherdt 1994), even in situations where available models of shallow shear-wave velocity require extrapolation to 30 m (Boore, 2004).

Although V_s^{30} is best determined by direct measurement, such data are sparse. Many seismic hazard assessments employ geology as a proxy for shear-wave velocity, based upon extensive testing by numerous workers characterising strong ground motion sites in the USA, particularly in California (Fumal & Tinsley, 1985; Park & Elrick, 1998; Wills & Silva, 1998; Wills *et al*., 2000; Wills & Clahan, 2006).

Wills *et al*. (2000) initially attempted to assign all mapped geological units for California to the pre-existing National Earthquake Hazard Reduction Program (NEHRP) site classes (Table 1) (Building Seismic Safety Council, 2001; 2004). However, the Californian shear-wave velocity data demonstrate that many geological units have ranges of V_s^{30} values that cross the boundaries between NEHRP classes. Consequently, Wills *et al*. (2000) developed intermediate classes to account for such variability (Table 2).

Table 1. NEHRP site class definitions (Building Seismic Safety Council, 2001; 2004).

NEHRP Site Class	V_s^{30} (m/s)	Material
A	> 1500	Hard rock
B	760 - 1500	Firm to hard rock
C	360 - 760	Very dense soil / soft rock
D	180 - 360	Stiff soil
E	< 180	Soft soil
F	-	Soils requiring site-specific testing and evaluation

Table 2. Modified NEHRP site classes, associated V_s^{30} values and general groupings of geologic materials associated with each class, based on 556 measured profiles from California (Wills *et al*., 2000).

Modified NEHRP Site Class	V_s^{30} (m/s)	Geological Materials
B	> 760	Plutonic & metamorphic rocks; most volcanic rocks; coarse-grained sedimentary rocks Cretaceous & older
BC	555 - 1000	Franciscan Complex rocks except 'melange' and serpentine; crystalline rocks of the Transverse Ranges which tend to be more sheared; Cretaceous siltstones or mudstone
C	360 - 760	Franciscan melange and serpentine; sedimentary rocks of Oligocene to Cretaceous age, or younger coarse-grained sedimentary rocks
CD	270 - 555	Sedimentary rocks of Miocene and younger age, unless formation is notably coarse-grained; Plio-Pleistocene alluvial units; older (Pleistocene) alluvium; some areas of coarse younger alluvium
D	180 - 360	Younger (Holocene) alluvium
DE	90 - 270	Fill over bay mud in the San Francisco Bay area; fine-grained alluvial and estuarine deposits elsewhere along the coast
E	< 180	Bay mud and similar intertidal mud

This modified NEHRP classification uses correlations between V_s^{30} from 556 measured profiles and mapped 1:250,000 scale geology from California. V_s^{30} is assigned to geological units based on the age and physical properties of each unit. The modified classification excludes the original NEHRP classes A and F due to the general difficulty in discriminating significant areas of truly 'hard' unweathered rock or materials requiring site-specific investigation at the mapping scale defined.

SITE CLASS ASSIGNMENT IN AUSTRALIA

In Australia our understanding of the relationship between regolith materials and their response to earthquake ground shaking is generally poor. This is due to both a paucity of ground motion data and a lack of available geotechnical and geophysical data (particularly shear-wave velocity data) that could be used to define typical V_s^{30} ranges for different near-surface regolith materials.

Accordingly, the site classes applied to the Australian National Regolith Site Classification Map are the modified NEHRP classes (Building Seismic Safety Council, 2004) defined by Wills *et al*. (2000). However, Australia's stable continental setting means that a variety of regolith types are present which may not be accurately classified by the Californian-based scheme, in particular *in situ* weathered bedrock materials. Consequently, it was necessary to adjust the site class definitions to account for these differences.

Site Classification for Weathered Bedrock

Significant areas of the Australian landscape are underlain by Mesozoic and older bedrock units, many of which exhibiting substantial weathering (Fig. 3). The presence of these weathered materials can have a major impact on calculated earthquake site response (Davis, 1995; Steidl *et al*., 1996). Average acceleration response spectra on weathered rock sites can be up to 20% higher than those at competent rock sites (Idriss & Silva in Rodriguez-Marek *et al*., 2001).

Under the Wills *et al*. (2000) classification scheme, site class B encompasses all hard rock materials (e.g. plutonic & metamorphic rocks; most volcanic rocks; coarse-grained sedimentary rocks Cretaceous & older). However, in many parts of Australia there are appreciable thicknesses of *in situ* weathered material overlying these types of geological units. For example, weathering profiles in the Yilgarn Craton of Western Australia can exceed 70 m (Anand & Paine, 2002), while profiles developed in Tertiary basalts in Queensland can be up to 40 m thick (Willey, 2003). Clearly the direct application of a California-derived site classification to such materials is inappropriate.

Weathering profile development and thickness is highly variable. Heterogeneities in the rock, such as fractures and faults, play an important role in determining the depth of the weathering front. Local and regional ground water systems may also leave a weathering overprint, while surface reworking of regolith material can introduce further complexity. High spatial variability and a lack of geophysical or geological data with which to characterise the third dimension further restrict our ability to accurately predict weathering profile characteristics. Despite this local scale variability, data which describe the typical weathering state of bedrock on a regional scale are available (e.g. Chan *et al*, 1986; Table 3). This information is used to refine the site classification of hard rock units (units classed as B using the modified NEHRP classification), by taking into consideration the potential impact of weathering on near surface rock properties.

Table 3. Description of the weathering states and associated properties used to assign weathered bedrock units to site classes (simplified from Eggleton, 2001).

Weathering State	Field Criteria	Alteration / composition
Extremely weathered	Only major parent rock features discernable, such as lithological changes or resistant veins; resistate minerals may remain in a matrix of secondary minerals. Material crumbles.	Quartz is the only remaining primary mineral.
Very highly weathered	Retains structures from the original rock but is composed completely of secondary and resistate minerals from the parent material. Core-stones, if present, are rare and rounded. Material can easily be broken by hand.	All feldspars are weathered; mineralogy is dominated by kaolin ± goethite ± hematite with or without residual quartz; other primary minerals in low abundance or absent.
Highly weathered	Strong iron staining, and more than 50% secondary minerals; core-stones are free and rounded, and there are numerous microfractures. The material can be broken apart in the hands with difficulty.	Nearly all feldspars are weathered; appreciable silica has been lost; mineralogy includes kaolin ± goethite ± hematite with significant amounts of primary minerals.
Moderately weathered	Marked iron staining common; up to 50% secondary minerals; core-stones rectangular and interlocked. Larger particles have thick weathering skins. Can be broken by a kick (with boots on) or a light hammer tap, but not by hand.	Most feldspars in larger particles are weathered; primary minerals still dominant with smectite, kaolin ± iron oxides present.
Slightly weathered	Core-stones, if present, are interlocked with few microfractures; material can be broken with a hammer; sediments have traces of weathering on the surfaces of sedimentary particles.	Weak iron staining; slight weathering of feldspars; primary minerals very prominent.
Fresh	Having no visible signs of weathering.	None.

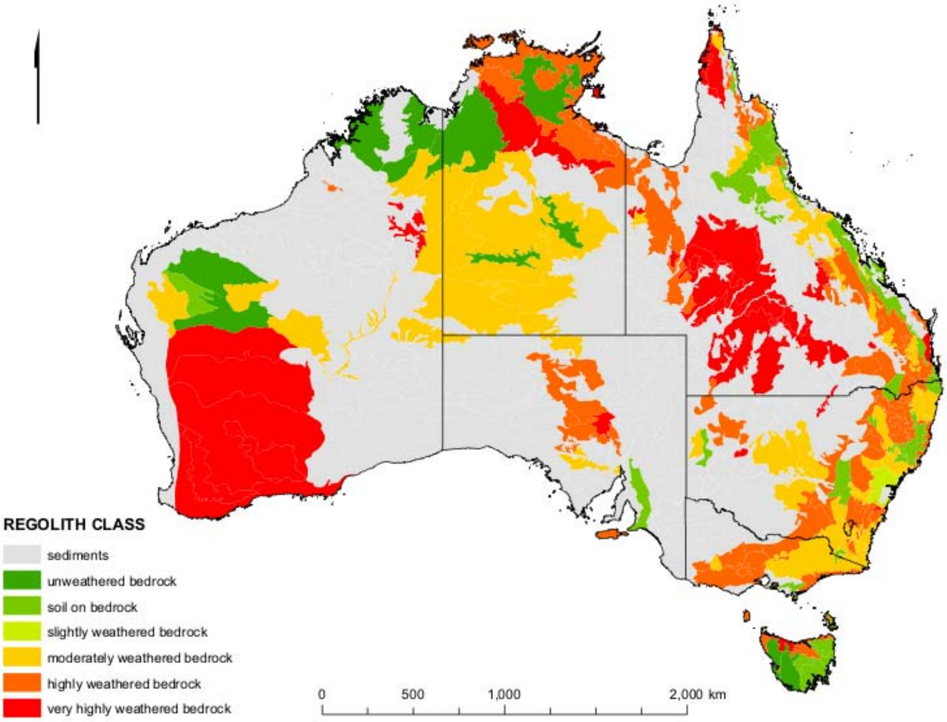

Figure 3. Generalised spatial distribution of weathered bedrock units across Australia (derived from Chan *et al*., 1986).

A generalised relationship was developed between the weathering state of hard rock units and the associated V_s values and weathering profile thicknesses.

Shear-wave velocity estimates for different rock weathering states are not widely published. Tables 4, 5 and 6 contain examples of the limited information available to relate rock weathering to shear-wave velocity in Australia. As the majority of seismic velocities found in the literature are represented by P-wave velocity (V_p), the relation $V_p/V_s = 1.87$ is applied in order to estimate V_s, assuming a Poisson's ratio of 0.3 (Kramer, 1996).

Table 4. Seismic velocities for variously weathered bedrock types in the Canberra region (Henderson, 1986). Shear-wave velocities have been estimated from P-wave data assuming a Poisson value of 0.3.

Weathering State	Measured V_p (m/s)	Estimated V_s (m/s)
Highly to extremely weathered rock	< 800	< 430
Moderately to highly weathered rock	800 - 1500	430 - 800
Slightly to moderately weathered rock	1500 - 3000	800 - 1600
Fresh to slightly weathered rock	> 3000	> 1600

Table 5. Seismic velocities for variously weathered rocks in the Terrigal Formation, north of Sydney (Awad & Peck, 1976; McNally, 1993). Shear-wave velocities have been estimated from P-wave data assuming a Poisson value of 0.3.

Weathering State	Measured V_p (m/s)	Estimated V_s (m/s)
Residual soil	355	190
Extremely weathered rock	925	490
Highly weathered rock	1295	690
Moderately weathered rock	2150	1150
Slightly weathered rock	3150	1670
Fresh	3600	1925

Table 6. Measured vertical seismic shear-wave velocity profiles on Hawkesbury Sandstone, Sydney (adapted from Coffey Partners International Pty Ltd., 1998a & b).

Weathering State	Depth range (m)	Measured V_s range (m/s)
Residual soil – highly weathered rock	0 - 3	250 - 380
Slightly – extremely weathered rock	3 - 6	800 - 1450
Slightly weathered – fresh rock	6 - 14	1200 - 1450

Despite significant variability, rock weathering states may also be correlated with typical weathering profile thicknesses. Such a relationship is defined here using Australia-specific examples from the literature (see Appendix 1). Published work suggests that very highly weathered units have profiles which extend, on average, to depths greater than 30 m. Highly weathered units also have deep profiles which generally extend to depths of 5-20 m thick and are underlain by more moderately weathered material. In units exhibiting slight to moderate weathering the thickness is significantly reduced, and is generally less than 10 m.

The compiled shear-wave velocities and profile thicknesses for each weathering state are then used to estimate an appropriate site class adjustment for hard rock units (Table 7), where necessary. For example, if a rock unit is described as fresh to slightly weathered, the unit will remain as site class B. If the unit is highly or extremely weathered, it will be adjusted to a site class BC or C respectively.

Table 7. Bedrock weathering classes with average V_s (estimated from V_p), thickness and adjusted site class.

Hard Rock Weathering State	Estimated V_s (m/s)	Thickness (m)	Site Class
Extremely weathered	490	> 30	C
Highly weathered	690	> 20	BC
Moderately weathered	1150	< 15	B
Slightly weathered	1670	< 15	B
Fresh	1925	-	B

Defining Australia-Specific Site Classes

The weathered bedrock classification scheme described previously and the site class assignments defined in Wills *et al*. (2000) have been combined and adapted for the Australian environment, and are presented in Table 8.

Table 8. Modified Wills *et al*. (2000) site classification scheme as applicable to Australian regolith conditions.

Site Class	V_s^{30} (m/s)	Geological Materials
B	> 760	Fresh to moderately weathered hard rock units (Plutonic & metamorphic rocks, most volcanic rocks, coarse-grained sedimentary rocks Cretaceous & older)
BC	555 - 1000	Highly weathered hard rock; some Tertiary volcanics
C	360 - 760	Sedimentary rocks of Oligocene to Cretaceous age; coarse-grained sedimentary rocks of younger age; extremely weathered hard rock units
CD	270 - 555	Sedimentary rocks of Miocene and younger age, unless formation is notably coarse-grained; Plio-Pleistocene alluvial units; older (Pleistocene) alluvium; some areas of coarse younger alluvium
D	180 - 360	Younger (Holocene to Late Pleistocene) alluvium
DE	90 - 270	Fine-grained alluvial, deltaic, lacustrine and estuarine deposits
E	< 180	Intertidal and back-barrier swamp deposits

SPATIAL DATA INPUT AND PROCESSING

Data Compilation

Over 40 geospatial datasets were combined to create an Australia-wide coverage of regolith properties, from which a site classification map could be produced. Figure 4 illustrates the general distribution of the geospatial data used. A background 1:2,500,000 scale national dataset ensures nationwide data coverage. In more heavily populated areas, higher resolution regional- to local-scale geological data were used to refine this national layer. Most major cities are covered by data at a scale of at least 1:100,000, with many areas covered at much higher resolution.

Assignment of site classes on the basis of V_s^{30} requires information on the properties of the regolith from the ground surface down to a depth of 30 m. However, most available geological datasets have not been compiled with this purpose in mind, so they do not always explicitly capture all the information required for V_s^{30} determination. For example a geological map may provide detailed distinctions between Quaternary sediment types, but give no information regarding the weathering state of older bedrock.

Several sets of information are of fundamental importance when assigning site classes on a regional scale: unit age, unit description (with clear inter-unit distinction between Quaternary sedimentary units) and weathering state. For more detailed analysis, regolith thickness is also important. Consequently, for some regions it is necessary to combine several data layers to more accurately classify the Australian regolith with respect to all the required attribute information.

Details of all input datasets and related spatial analyses are presented in the following sections.

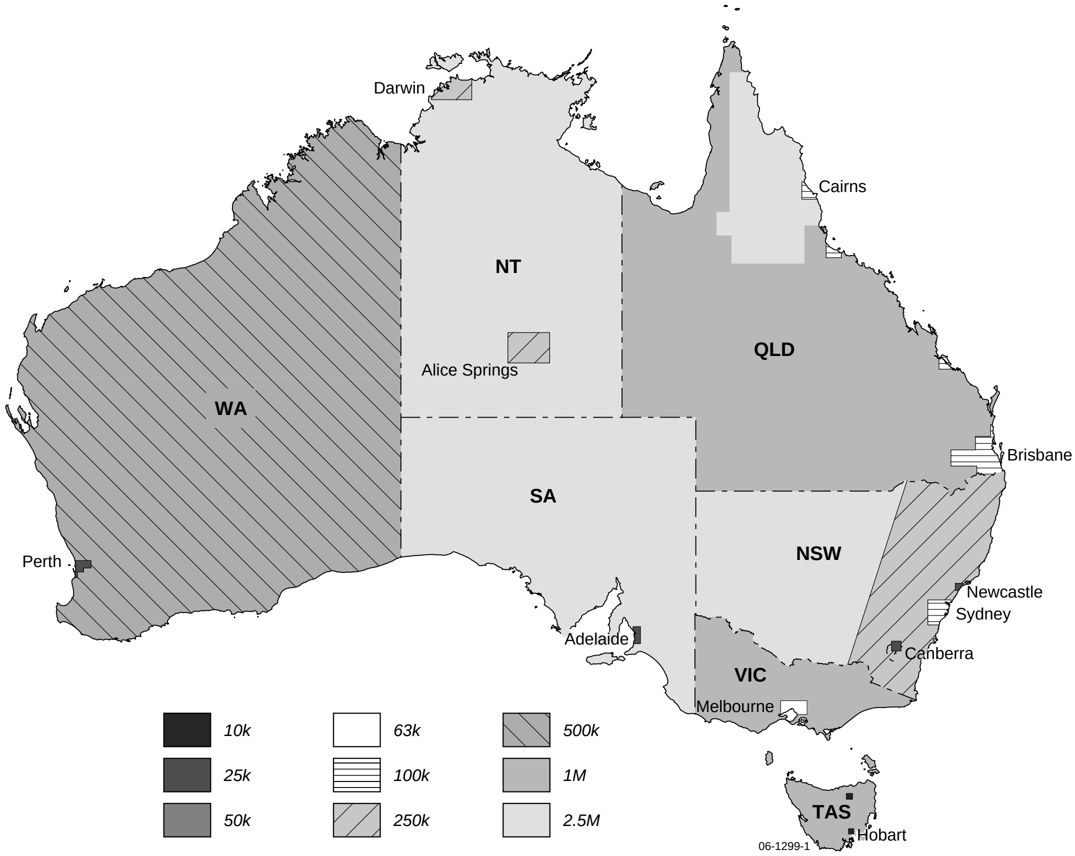

Figure 4. Distribution and scale of geological datasets incorporated in the National Regolith Site Classification Map.

National Scale Data

A number of national scale geological datasets were included as input data layers in the development of the Australian National Regolith Site Classification Map (Table 9). These national scale data layers were united to produce a national scale 'combined geoscience map' upon which a site classification scheme could then be imposed.

Table 9. National scale datasets used in the development of the National Regolith Site Classification Map.

Dataset	Scale	Reference
Digital Atlas of Australian Soils	1:2,000,000	(Bureau of Rural Sciences, 1991)
Bedrock Geology of Australia	1:2,500,000	(Bureau of Mineral Resources, 1986)
Surficial Geology of Australia	1:2,500,000	(Bureau of Mineral Resources, 1986)
Regolith Terrain Map of Australia	1:5,000,000	(Chan *et al*., 1986)
Geotechnical Landscape Map of Australia	1:5,000,000	(Grant *et al*., 1984)

The key datasets were the Surficial Geology of Australia and the Regolith Terrain Map of Australia. Both datasets assist in discriminating bedrock-dominated areas from those with significant transported regolith cover. The Surficial Geology dataset also provides general lithological information about the surficial materials. The Regolith Terrain Map provides information on landform (topographic) and regolith material types, and importantly, an indication as to the weathering state of the bedrock, a potentially significant factor in assigning geologic units to site classes.

A re-classified version of the Bedrock Geology of Australia was used primarily to cross-reference the Regolith Terrain Map to estimate the likely extent of weathering in various bedrock units (e.g. matching Tertiary volcanic units with degrees of weathering for basalt units along the Great Dividing Range); a process repeated in the analysis of higher resolution datasets (see next section).

The Digital Atlas of Australian Soils was used only to provide guidance on the likely surficial material types in areas where geological information was too ambiguous to permit a decision to be made regarding the dominant lithology. Similarly the Geotechnical Landscape Map of Australia was used only for cross-checking dominant lithologies and geomorphic types in some areas, and on occasion to verify the presence of secondary lithologic features such as cemented duricrusts (e.g. silcrete, ferricrete).

Spatial data and associated attribute information from the Surficial Geology, Bedrock Geology and Regolith Terrain maps were combined to create a national 1:2,500,000 scale combined geoscience map. The spatial processing steps undertaken in the creation of this underpinning dataset are as follows.

1. Union of the Surficial Geology and Regolith Terrain maps to produce a coverage that captures the higher spatial resolution of the surficial geology polygons and the more detailed attribute data provided by the Regolith Terrain map.
2. As a result of the above, areas characterised by exposed bedrock are defined, and the properties of the units underlying these need to be accounted for. Age information in the Bedrock Geology map is heavily biased towards units older than Cainozoic, i.e. there is only one age class for Cainozoic units but multiple distinctions for Mesozoic and older sequences. As detailed information is not required for these older sequences, the age units and rock types for this layer are re-sampled to provide a simplified ‘bedrock type’ layer with only two classes: (i) Cainozoic sedimentary units and (ii) other.
3. The combined Surficial Geology and Regolith Terrain coverage (1) is unioned with the simplified Bedrock layer (2).
4. A new attribute field is created by combining the following data:
    a. the Surficial Geology ‘TEXT’ attribute, which describes the dominant lithology (i.e. bedrock or other lithological type);
    b. the Regolith Terrain ‘REGO_CLASS’ attribute, which describes the regolith class and provides information on bedrock weathering state; and
    c. the simplified Bedrock layer (see 2).

Regional Scale Data

Details of the higher resolution regional- to local-scale datasets used to further refine the classification and provide more detailed information for key population centres in all States and Territories are given in Appendix 2. Datasets for the Northern Territory, South Australia and the Australian Capital Territory required no additional spatial analysis. However, several other datasets did require further analysis, and a commentary regarding this is given below.

- The New South Wales 1:250,000 scale geological data was only integrated for the high exposure eastern section of the state due to computing limitations. A weakness of this dataset is that it provides only a limited breakdown of Quaternary sediment types. In particular, no distinction is made between fine-grained marine deposits and coarser-grained alluvial sediments, which may exhibit significantly different site response. To ensure discrimination between these materials within the site classification, Quaternary alluvial units were spilt into two classes depending on distance from the coast. Units less than 10 km from coastal or estuarine waters were assumed to be of marine origin; those greater than 10 km from coastal waters were assumed to be alluvial deposits.

- The 1:1,000,000 scale geological maps of northwest and southern Queensland provided detailed information on Cainozoic and younger units, however little information was available on the thickness and type of weathering in older bedrock units and volcanic deposits. Similar short-comings were also identified in the Tasmanian and Victorian datasets at this scale. In an effort to refine the classification, all bedrock units were intersected with the national Regolith Terrain map (Chan *et al.*, 1986), and subsequently attributed with a field characterising the regolith weathering state of the unit.

- The state-wide 1:500,000 scale regolith map of Western Australia (Marnham & Morris, 2003) provides detailed information on the state of regolith weathering, but contains only limited information on rock type and age. A new state-wide dataset was therefore created by combining the state regolith map with the national Surficial Geology map, using processing steps similar to those outlined in the previous section on National Scale Data.

DATA CLASSIFICATION

The relationships between regolith properties and site classes defined for Australia were then used to assign site classifications to each geological unit defined in the spatial database.

In most instances, geological units derived from the higher resolution datasets contain sufficiently detailed information to allow direct application of the site classification scheme. Class assignments were refined using additional information from a variety of supplementary data sources, as presented in Table 10.

Table 10. Supplementary data sources used to refine site class assignments.

State / Territory	Reference(s)
NSW / ACT	Haworth (2003); Jones & Neville (1996); New South Wales Department of Mineral Resources (1994)
NT	Nott (2003a); Vanden Broek (1980)
QLD	Nott (2003b); Hicks *et al.* (1999) ; Murphy *et al.* (1989); Trezise *et al.* (1989); Willey (2003)
SA	Sheard & Bowman (1994); Lintern (2004)
VIC	Garrett (1975); Vandenberg (1971); Victorian Department of Natural Resources & Environment (1997); Williams (1992)
WA	Anon (1976); Anon (1977a); Anon (1988b); Anon (1978); Gozzard (1985)

The classification procedure for units associated with the national scale 1:2,500,000 coverage is more complex due to the variety of attribute data present. The initial site classification for this dataset is based upon the surficial geology attributes shown in Table 11. Site class values are then adjusted up or down by an intermediate class step depending on the average regolith characteristics of that region. For example, if a region is generally characterised by bedrock exposure it would be classed as B. However, if the available regolith information suggested that the landscape was dominated by overlying sand sheets then the classification would be increased by an intermediate class step (e.g. BC) to reflect the potential increase in ground shaking response resulting from the overlying sediment. In the case of units found in bedrock-dominated areas the degree of weathering is taken into account using the weathering state classification scheme described previously.

Table 11. Classification scheme showing the major surficial geology units and their assigned modified site class (see also Table 8).

Surficial Geology Unit	Site Class
Bedrock (Cainozoic)	B
Clay, silt, minor sand: residual, some alluvium	CD
Ferruginous, aluminous, siliceous duricrust; +/- minor quartz sand	C
Limestone: terrestrial; minor sand and clay	C
Quartz sand: aeolian and residual; +/- minor Fe, Al & Si duricrusts	CD
Sand, silt, clay and gravel: alluvial, lacustrine, colluvial +/- marine	CD

INTERPRETATION

The National Regolith Site Classification Map for the whole of the Australian continent is shown in Figure 5. The general distribution of site classes is, as expected, consistent with the distribution of major geological features. It is important to recognise that a proportion of the base geoscience data included in this product is derived from datasets representing mapped outcrop geology rather than regolith geology *per se*. In these, generally *older*, outcrop geology datasets the quantity and quality of regolith information recorded varies significantly, and in most cases is insufficient to provide a reasonable estimate of regolith properties directly. However, in bedrock-dominated areas the outcrop datasets offer a more detailed sub-division of the geological materials present. In circumstances where the higher resolution outcrop geology provides the best scale data for assessing the geological materials present, the units are populated with regolith information from the broader scale national regolith terrain map (or State equivalents), and their site classes adjusted accordingly.

The regolith site classification scheme itself is suitable for application at almost any scale. However, the highest spatial resolution at which it can be validly applied in any given area is limited by:

i) the resolution of the underpinning geological/regolith data for that area;
ii) mapping errors inherent in these input data sets; and
iii) availability of data with which to constrain the variation in rock properties with depth (i.e. control on the third dimension).

For example, the Perth metropolitan region has geological data at 1:50,000 scale and accompanying borehole and geotechnical to constrain the third dimension. As such, the classification may be accurate when mapping at sub-kilometre scales. In contrast, in an area like Alice Springs the classification is applied to units derived from 1:250,000 scale geological data, with no constraint on the variation in rock properties with depth, and as such provides less confidence at a similar scale.

National Scale

Regions of slightly weathered bedrock overlain by thin regolith profiles are represented by site classes B and BC, associated with areas such as the Great Dividing Range, which runs north-south down the length of eastern Australia, Mt. Lofty Ranges (Figure 5, grid ref. H54-I54), McDonnell Ranges (F52-G53), Pilbara and Hamersley (F50-G50) and Kimberley (D51-E52) regions, and most of Tasmania.

Areas of shallow sedimentary cover where bedrock has been extensively weathered, such as the Yilgarn Craton (G50-I51), are dominated by site classes C and CD. These classes also identify soft rock and very dense soils as represented by the more recently deposited carbonate-dominated Nullarbor Plain (H51-H53), significant areas of the Northern Territory, and many of the erosional and depositional environments on the western side of the Great Diving Range.

Site class D delineates areas of stiff soils, many of which show a close spatial association with major sedimentary basins, most notably the Eromanga Basin (F53-G54, H54), Murray Basin (I54-I55), Karumba Basin (E54), and the Officer (G52-H52), Carnarvon (G50-H50) and Canning Basins (F51-G51).

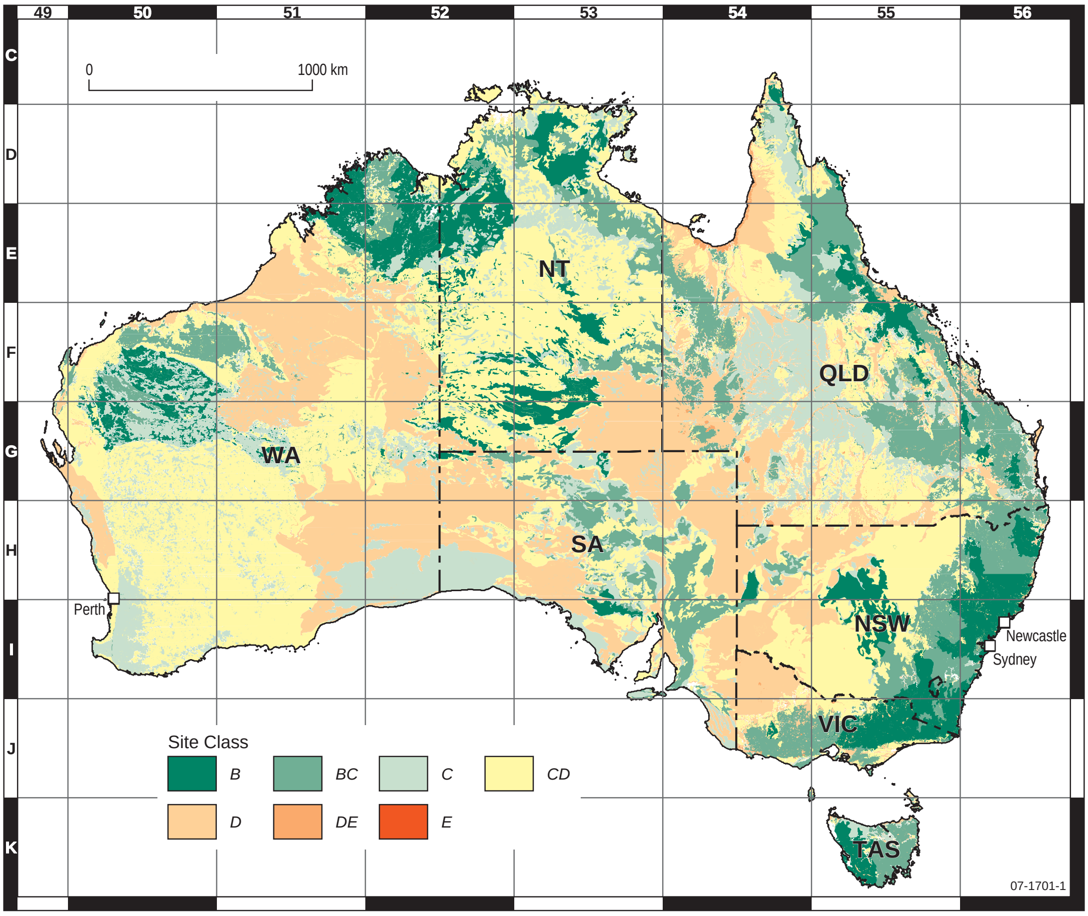

Figure 5. Australian National Regolith Site Classification Map.

The softer soil sites in classes DE and E are almost exclusively restricted to depositional environments, with the inland areas represented by playa lake systems (e.g. Lake Eyre Basin, G53-G54) and other areas of restricted drainage such as marshlands, some floodplain and lacustrine sediments and larger dune/swale systems in more humid (higher rainfall) zones. In the coastal regions they are predominantly represented by intertidal zones (e.g. mangroves and saturated intertidal mud), such as around the margins of the Gulf of Carpentaria (D53-E54) and north of Adelaide (I54), and softer alluvial, lacustrine and marine deposits, such as along the Swan Coastal Plain (H50) and the east coast of Queensland (e.g. Stradbroke Island, G56). While site classes DE and E represent only a small fraction of the overall land mass of Australia, these areas have the greatest potential to amplify earthquake ground motion.

Regional Scale

Site classification maps for the Australian cities of Sydney, Perth and Melbourne are shown in Figures 6, 7 and 8 respectively. Note that vertical and horizontal boundary discontinuities in these maps represent variation in input data spatial resolution and associated attribute data.

Sydney

In the Sydney region (Fig. 6) site class BC differentiates the softer sedimentary rock units of the Triassic Wianamatta Group from more resistant surrounding (unconformable) units (site class B), primarily the Hawkesbury Sandstone.

Site classes C and CD are predominantly associated with Tertiary landforms of the Hawkesbury-Nepean River System to the west of the Greater Sydney metropolitan area, and are not visible in Figure 6. The majority of areas characterised as site class D relate to Quaternary alluvial deposits of the present drainage networks, as well as marine and aeolian deposits along the present coastline. There are appreciable areas mapped as site class D immediately south of the Sydney CBD in association with the Botany sub-basin, as well as surficial deposits around the shores of Botany Bay itself, particularly in the west and south.

It is these same areas, along with intertidal and alluvial deposits in the upper middle reaches of the Parramatta River and its tributaries, as well as those of Port Jackson (i.e. Sydney Harbour), that constitute the soft materials of site classes DE and E.

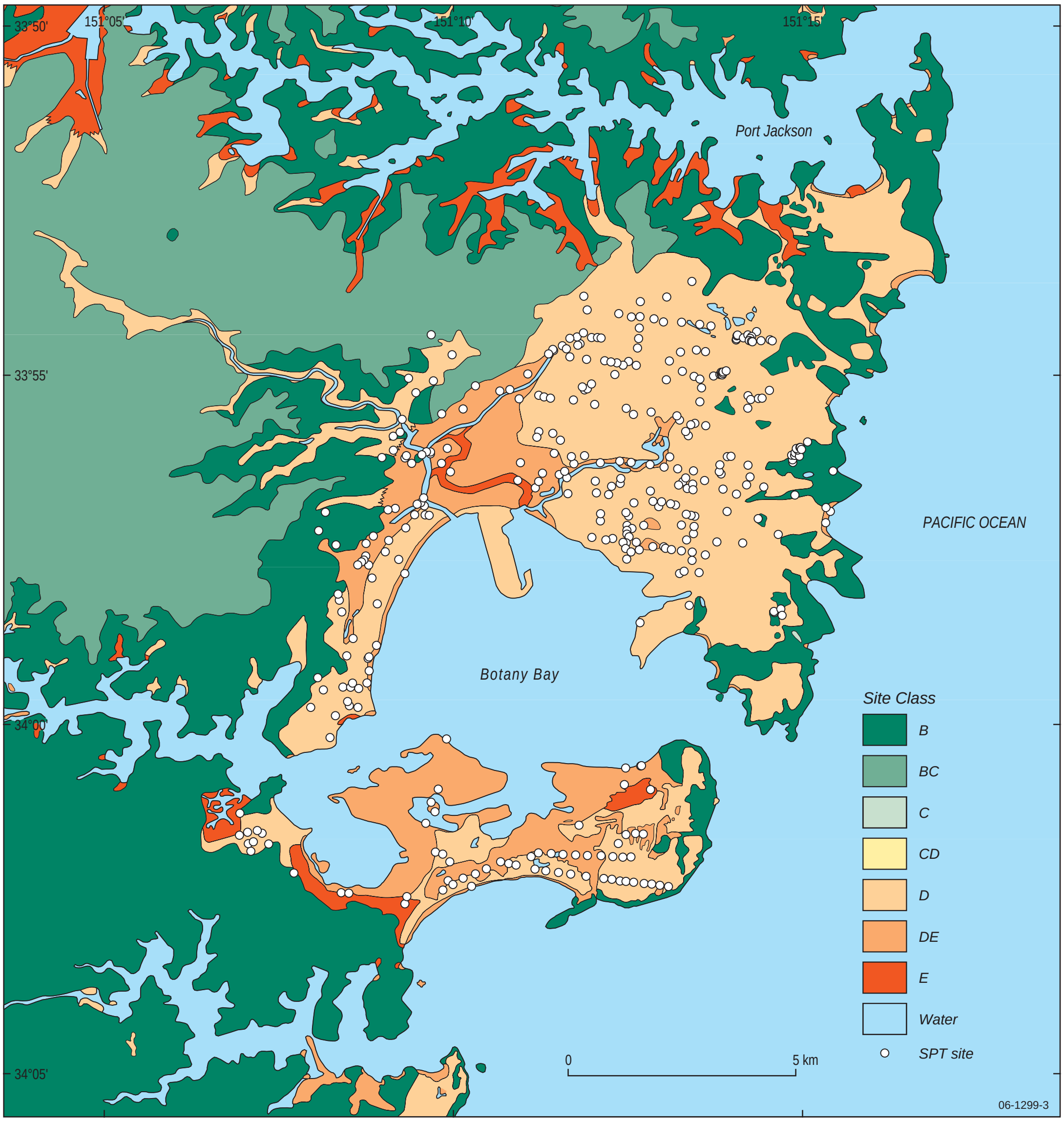

Figure 6. Site classification map of the Sydney region differentiating higher velocity bedrock (green) from lower velocity sediments of the Botany Basin (red/orange).

Perth

One of the most striking features of the Perth region is the several-hundred metre-high Darling Escarpment. This linear structural feature trends north-south and separates the primarily depositional Swan Coastal Plain from the erosional Darling Range (Fig. 7). In contrast to the Sydney region, there is a lowering of site class within the drainage system east of the Darling Escarpment as harder, less weathered Archaean granitic materials characteristic of the Yilgarn Craton (site class B) are exposed by incision through the extremely weathered overlying regolith (site class C).

To the west of the Darling Fault on the Swan Coastal Plain the landscape is dominated by stiff, predominantly sandy soils (site classes CD and D) associated with Pleistocene to Holocene marine and aeolian deposits. Areas of secondary carbonate cementation within the calcareous dune systems along the coastal fringe result in the presence of harder limestone substrates, and as such locally the site class may be lower. However, significant thicknesses of unconsolidated sands interspersed with the limestone generally resulted in a higher site classification. This highlights the difficulty in classifying for site response at such small scales, and reinforces the importance of acquiring detailed local scale data.

Site classes DE and E are restricted to finer-grained alluvial deposits along the Swan River and swamp and lacustrine deposits associated with areas of occluded drainage on the coastal plain.

Figure 7 also demonstrates the application of a site classification scheme based on broad scale geological information. Comparison of the broader scale site classes to the north and south of the Perth metropolitan area (CD and D in the west; C in the east), where less detailed data is available, reflect the general dominance of these site classes within the areas where more detailed data is available.

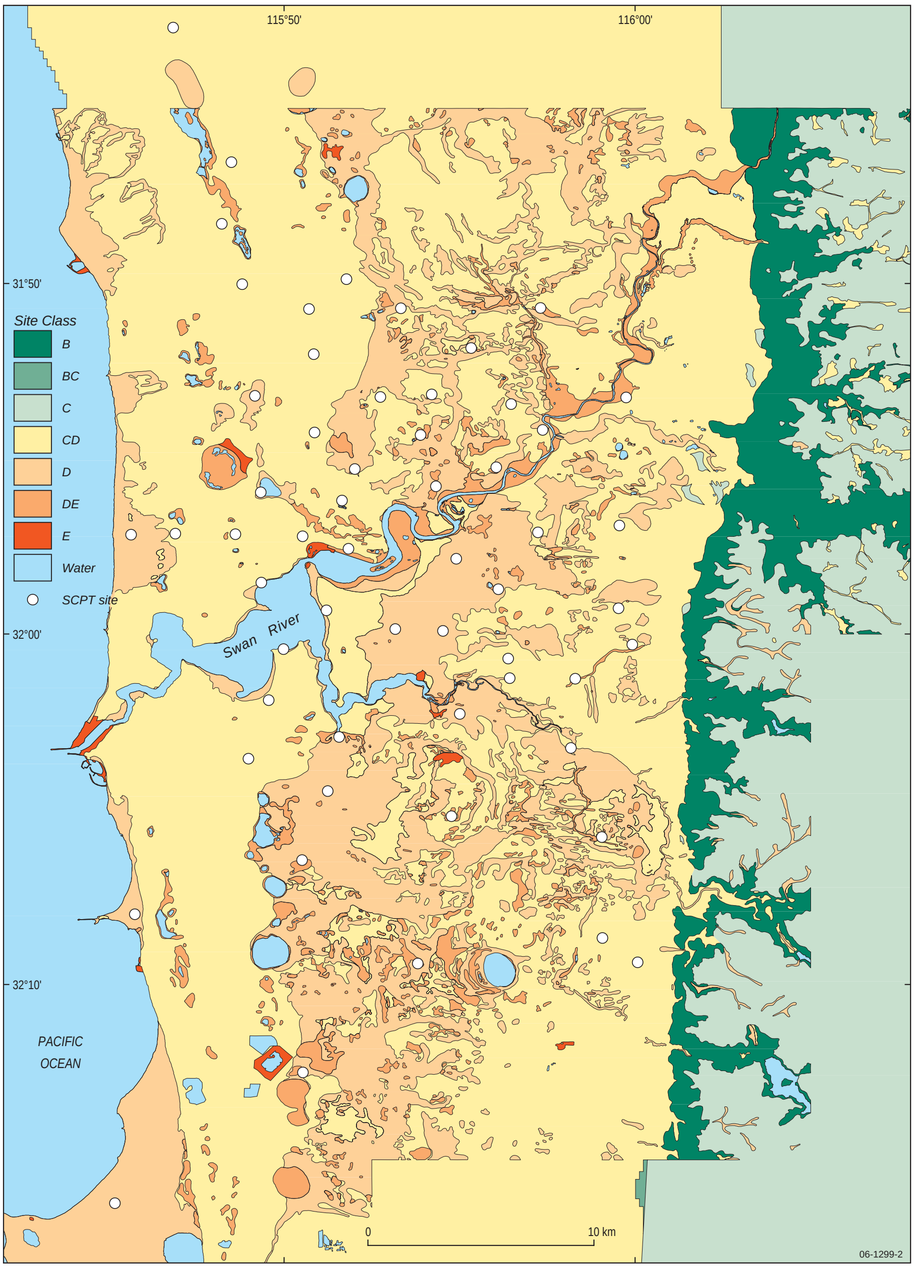

Figure 7. Site classification map of the Perth region showing strong contrast between higher velocity weathered Yilgarn Craton bedrock (green) in the east and lower velocity unconsolidated sediments on the Swan Coastal Plain in the west (yellow/orange).

Melbourne

In the Melbourne region (Fig. 8) site class BC differentiates the lava plains of the Pleistocene Newer Volcanics from the Siluro-Devonian Lachlan Fold Belt metasediments and granites that form the southern end of the Great Dividing Range to the east (site class B).

Similar to Sydney, dense/stiff soils of site classes CD and D are primarily associated with Quaternary alluvial deposits of the present drainage networks, as well as marine and aeolian deposits along the present coastline.

Deltaic sediments of the Yarra and Werribee Rivers and shoreline sand deposits along the northern edge of Port Philip Bay represent the most significant occurrences of site class DE. Higher resolution data delineate an appreciable area of swamp and lagoonal deposits to the southeast of Melbourne which also fall into this site class. This latter area highlights a scale discrepancy between the base geological datasets, with the more detailed data discriminating a mixture of site classes CD and D, associated with Pliocene sands, effectively separated from the materials of site class DE (mentioned above). To the south of this area, the availability of only small scale data results in classification as site class D. This underlines the importance of acquiring detailed local scale data for accurate site class assessment.

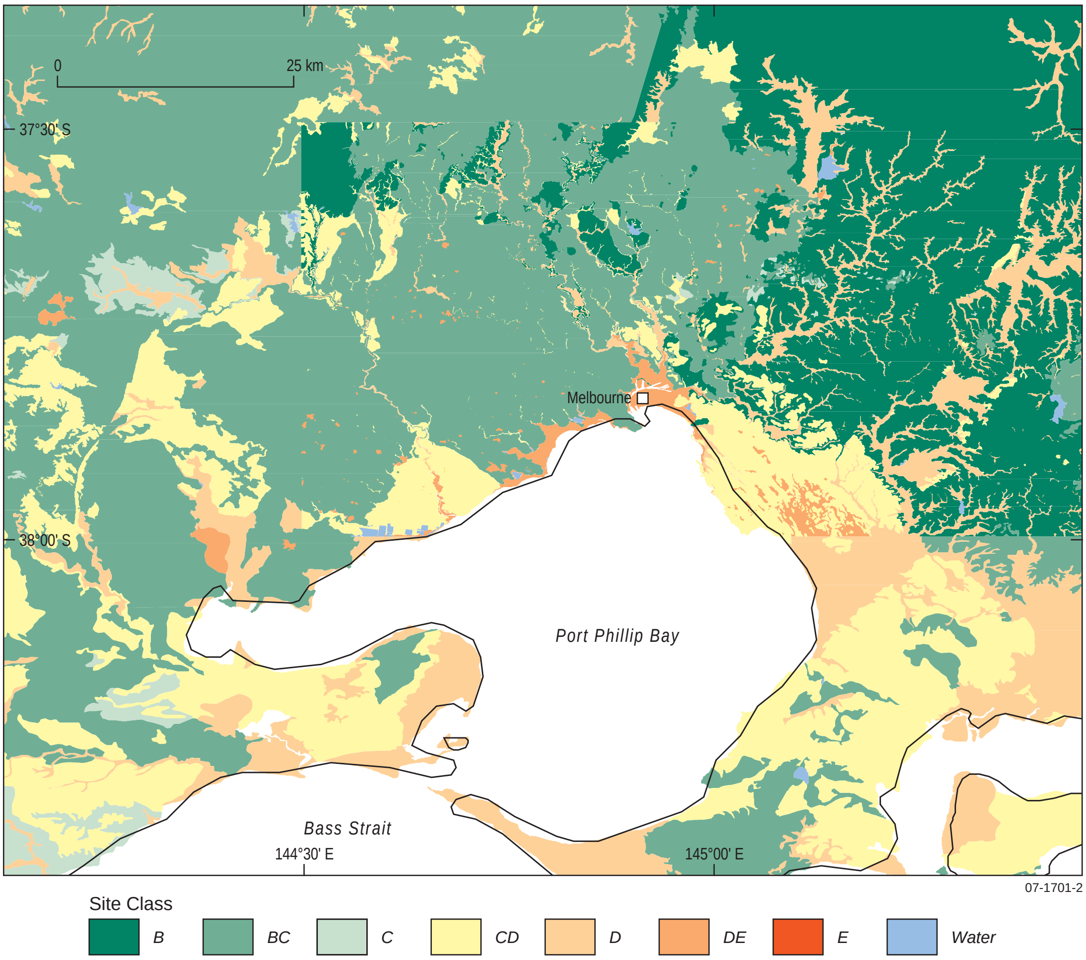

Figure 8. Site classification map of the Melbourne region differentiating lower velocity recent coastal and alluvial deposits (yellow/orange) from higher velocity bedrock materials (green).

VALIDATION

The development of the National Regolith Site Classification Map has resulted in a product with a host of potential applications. However, prior to implementing this product in a modelling framework, a validation process was required to ensure the accuracy and consistency of the classification. To this end a series of validation exercises were completed to test the ability of the map, and therefore the methodology, to consistently and accurately (within the limits of the input data) classify materials into an appropriate site class.

Geological and down-hole geophysical data from several urban centres were used to test the classification in a variety of Quaternary environments. Although this validation process is the subject of another paper (McPherson & Hall, in review), the results for Perth and Sydney are discussed below.

Perth

Shear wave velocity profiles have been measured at 57 seismic cone penetrometer testing (SCPT) sites around the Perth urban area (McPherson and Jones, 2005). These data were correlated with 1:50,000 scale mapped geology in order to cross check the relationships between geological unit descriptions and recorded material properties. V_s^{30} values were calculated for each borehole greater than 15 m deep. Where borehole depth is less than 30 m, shear wave velocities were linearly extrapolated using the method of Boore (2004). The application of this technique is considered valid since the depth of the sediment column across the majority of the region is significantly greater than 30 m, and therefore a major contrast in regolith properties within 30 m of the surface is unlikely.

To test the variation in typical regolith behaviour with sediment age and texture, V_s^{30} statistics and median velocity profiles are calculated for the dominant material types (Figures 9a&b; Table 12). An individual profile shows the median shear-wave velocity for all boreholes of similar rock type, at 2 m depth intervals. Although there is minimal variation in V_s^{30} on a regional scale, a subtle yet clear correlation is evident between V_s^{30}, sediment texture and age. Medium- to coarse-grained Pleistocene sands and silts have a median V_s^{30} of 302 m/s, while fine- to medium-grained materials of a similar age show consistently slower site conditions, with a median V_s^{30} of 253 m/s. A similar relationship is observed for Holocene aged sediments, where fine-grained silts and clays have a median V_s^{30} of 230 m/s, and sands a median value of 287 m/s. All material descriptions and behaviours are consistent with the relationships defined in the Wills *et al*. (2000) classification (Table 2).

This analysis demonstrates that, when applied to broad scale analysis, the scheme of Wills *et al.* (2000) is appropriate for classifying Quaternary sediments in the Perth region. However, the variability in sediment type and subtle differences in material properties highlight the difficulty in developing site classifications at such local scales, and reinforces the importance of acquiring detailed directly measured data for local investigations.

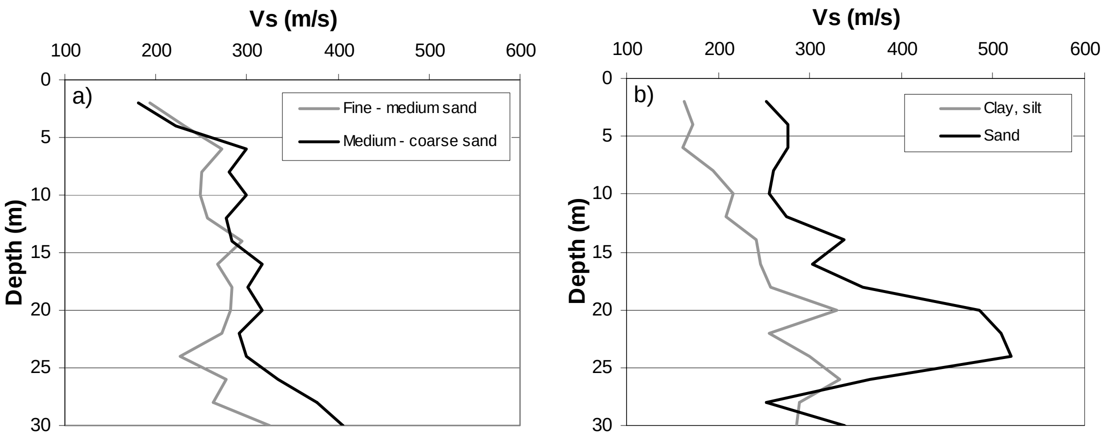

Figure 9. Median V_s profiles for selected sediment types in the Perth urban area. (a) Pleistocene sand; (b) Holocene sand and silt.

Table 12. Statistics for geological units in the Perth region showing differences in median V_s^{30} as a function of age and material texture (grain size). Data from seismic cone penetration test holes with a 15 m minimum depth.

		V_s^{30} (m/s)			
Age	**Material Type**	**Median**	**16th percentile**	**84th percentile**	**No. of Sites**
Holocene	Silts / clays	230	155	262	5
	Mixed sand	297	236	363	4
Pleistocene	Fine - medium sand	253	215	303	16
	Medium - coarse sand	302	228	379	13

Sydney

No directly measured shear wave velocities are publicly available for the Sydney region. However, shear wave velocities calculated from standard penetration test blow count data assist in quantifying the variation in shear wave velocity and basement depths for over 300 locations across the basin (Burg, 1996). The calculated V_s profiles were correlated with 1:100,000 scale mapped geology to test the site classifications for the Sydney region.

Profiles of median shear wave velocity calculated for key rock types are shown in Figure 10. Despite local variability, shear wave velocity profiles for the different geological units are remarkably consistent. For many of the units this result is not unexpected, as they are of comparable age and have similar material properties. However, velocity profile variations due to grain size differences, similar to those observed in the Perth profiles, are not resolved here, demonstrating the advantage of direct V_s measurements over calculated values.

Median V_s^{30} statistics calculated for each sediment type using data from boreholes greater than 25 m depth show values varying from 269-369 m/s, depending on the unit composition (Table 13). Although these ranges are broadly consistent with the Wills *et al.* (2000) classification, the most significant factor impacting the V_s^{30} statistics is the variation in depth to basement. Where the sediment thickness exceeds 30 m, calculated V_s^{30} ranges from 200-250 m/s, equivalent to site class D. The underlying Hawkesbury Sandstone has V_s^{30} values in the range of 1200-2500 m/s (NEHRP A/B) depending on the degree of weathering and thickness of overburden. Where depth to basement is less than 30 m, V_s^{30} values are higher and site classes change accordingly.

Figure 7 shows the direct relationship between calculated V_s^{30} and depth to basement for each borehole. This clearly illustrates the importance of regolith thickness in determining site class assignments, in agreement with the observations of Wills and Clahan (2006). The lack of regolith thickness data across much of Australia is consistent with the situation in many parts of the world, and represents a major limitation in the implementation of this type of methodology. Given the importance of the third dimension in determining site response it has to be recognised that this product provides only a two-dimensional representation of a three-, and some might argue, four-dimensional entity.

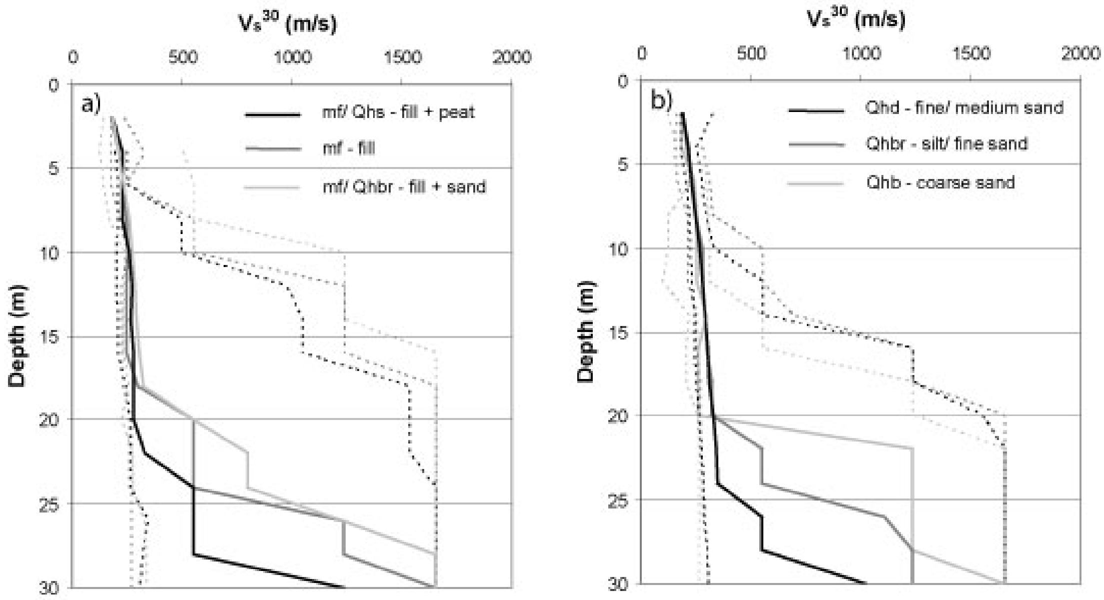

Figure 10. Median V_s^{30} profiles for Holocene units in the Botany Bay area, Sydney, dominated by (a) artificial fill; and (b) beach and dune sands. Solid lines represent median calculated V_s^{30} with dashed lines marking the 16th and 84th percentiles.

Table 13. Statistics for geological units in the Sydney region showing differences in median V_s^{30} as a function of age and material texture (grain size).

			V_s^{30} (m/s)			
Age	**Material**	**Map Unit**	**Median**	**16th percentile**	**84th percentile**	**No. of Sites**
Holocene	fill	mf	339	250	538	5
Holocene	fill + sand	mf/ Qhbr	317	251	670	19
Holocene	fill + peat	mf/ Qhs	269	255	565	7
Holocene	coarse sand	Qhb	312	194	485	5
Holocene	silt/ fine sand	Qhbr	296	250	474	29
Holocene	fine-med. sand	Qhd	283.5	256	461	214
Holocene	peat/ mud	Qhs	369	272	502	28

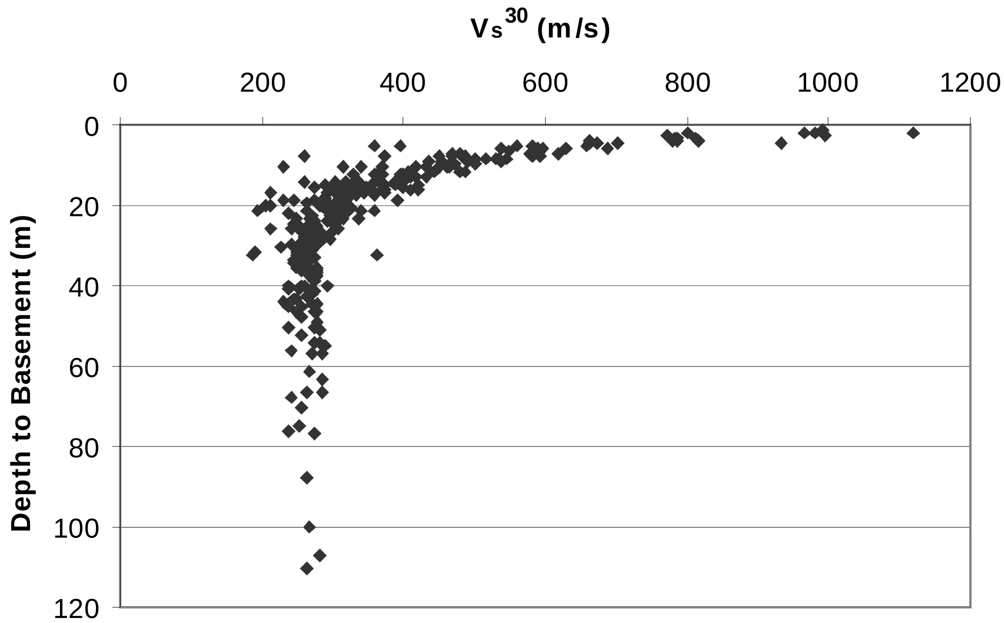

Figure 14. Depth to basement plotted against calculated V_s^{30} for boreholes in the Botany Bay area, Sydney. Results show a trend of decreasing velocity with increasing regolith thickness.

The validation analyses conducted for Perth and Sydney illustrate that average site class conditions are generally captured accurately. It also supports the idea that in these regions the map may be employed in earthquake risk assessments at the city scale and finer. However, the Sydney example also demonstrates the limited accuracy of this method at high spatial resolution, reinforcing the importance of collecting as much detailed geophysical and geotechnical data as practical when conducting site response assessments at very localised or site-specific scales.

APPLICATIONS OF THE NATIONAL REGOLITH SITE CLASSIFICATION MAP

Standards and Building Codes

The National Regolith Site Classification Map, with associated amplification factors, has a potential role to play in future revisions of the Australian Earthquake Loading Standard (Standards Australia, 1993). The current Standard requires the determination of a site factor based on substantiated geotechnical data in order to attain an appropriate earthquake design category for a structure. Only two of the current site classes use any geophysical measure (V_s) to estimate potential ground shaking response, with no requirement to estimate this parameter over a standardised depth range (e.g. the top 30 metres of material - V_s^{30}). The current International Building Code (International Codes Council, 2000) employs a NEHRP-based site classification system similar to that implemented in the National Regolith Site Classification Map, whereby site classes are delineated on the basis of geophysical measurements adjusted to a standard depth range (V_s^{30}) and/or geotechnical data.

Revision of the Australian Earthquake Loading Standard to adopt a NEHRP-type site classification, similar to that applied in the National Regolith Site Classification Map, would provide greater flexibility in terms of the methods and data by which site classification could be achieved. It would also promote the more accurate direct physical measurement of material response to potential earthquake ground shaking.

Earthquake Hazard and Risk Assessment

The application of the National Regolith Site Classification Map to earthquake hazard and risk modelling involves the assignment of amplification factors to each site class to create a regolith site response model. Amplification factors represent the ratio of predicted ground shaking on bedrock to that on ‘soil’ (i.e. at the surface of the regolith), with this ratio being used to adjust the earthquake ground shaking at a site. Using generalised profiles based on averages of measured geophysical (V_s) data for relevant materials, amplification factors for each site class are modelled relative to the bedrock response for a given earthquake event. In the Australian circumstance there are insufficient numbers of measured geophysical profiles available to develop these generic profiles, so data from elsewhere must be utilised, in this case from the western United States (Silva, 2005).

Previous national scale earthquake hazard map products for Australia have not included the influence of regolith site response, and so may significantly underestimate ground motion at any given location. The incorporation of the National Regolith Site Classification Map and associated amplification factors into the National Earthquake Risk Model (EQRM) is therefore essential for the rigorous assessment of earthquake hazard and risk in Australia.

CONCLUSION

The National Regolith Site Classification Map presented here represents the first publicly funded national scale earthquake site classification product for Australia, which is, for reasons of confidentiality, not yet publicly available. It is appropriate for national to regional scale earthquake hazard and risk assessment. Calibration with limited available geotechnical, geophysical and borehole geological data indicates that average geophysical conditions are captured accurately, although local variability in regolith properties means that this data is inappropriate for local to site-specific analyses. The product also demonstrates that the site classification methodology of Wills *et al*. (2000) can be successfully applied to other tectonic settings, with some modifications.

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APPENDICES

Appendix 1: Regolith Profile Thickness Values

Examples of regolith weathering thickness values for selected areas of Australia, as used to provide estimates for different weathering classes (SW = slightly weathered, MW = moderately weathered, HW = highly weathered, EW = extremely weathered, RS = residual soil).

Location	Age	Thickness (m)	Description	Weathering State	Reference
Yilgarn Craton, WA	Proterozoic	avg 50, max 100	very deeply weathered granitoids	HW-EW	Anand & Paine (2002); Brand & Butt (2001); Scott (2001)
Darwin, NT	Cretaceous	5-20	deep weathering profiles	HW-EW	Nott (2003a)
Brisbane, QLD	Mesozoic +	< 5	shallow weathering on Bunya phyllite	SW	Koppi (1981)
Southwest QLD	Cretaceous	40-90	deeply weathered bedrock	HW-EW	Senior & Mabbutt (1979)
Newcastle, NSW	Permian	10-15	weathered bedrock	MW	Dhu & Jones (2002)
Sydney, NSW	Triassic	6-10	weathered Wianamatta Group	SW-MW+RS	Herbert (1979)
Monaro Plains, NSW	Tertiary	1-7	weathered basalts	MW-HW	Taylor *et al*. (1992)
Canberra, ACT	Silurian - Ordovician	1-70	highly variable; greater depths relating to shear structures	HW	Henderson (1981,1986)
TAS	Ordovician - Devonian	avg < 10 max 30	deeply weathered Mathinna Beds; Bell Shale	MW-EW	Leaman (2002)
Hobart, TAS	Triassic	< 5	sandstone and mudstone; susceptible to local deep weathering	SW-HW	Hofto (1990)
	Permian	< 2	shallow weathering	SW	
Toowoomba, QLD	Tertiary	20-40	deep weathering profiles on Main Range Volcanics	HW-EW+RS	Willey (2003)
SA (various locations)	Various	20-50		MW-EW+RS	Lintern (2004)

Appendix 2: Refinement Data

Table detailing regional to local scale datasets used for refinement of the Australia National Regolith Site Classification Map (by State/Territory).

MAP	SCALE	REFERENCE
AUSTRALIAN CAPITAL TERRITORY (ACT)		
Central Canberra	1:10,000	Henderson (1986)
Coppins Crossing	1:10,000	Henderson (1980)
Canberra, Queanbeyan and Environs	1:50,000	Henderson (1981)
NEW SOUTH WALES (NSW)		
Botany Bay	1:33,333	Jones & Neville (1996)
Penrith	1:100,000	Jones & Clark (1991)
Sydney	1:100,000	Herbert (1983)
Wollongong – Port Hacking	1:100,000	Geological Survey of New South Wales (1985)
Newcastle Coalfield Geology	1:100,000	Hawley & Brunton (1995); Hawley *et al*. (1995)
Newcastle	1:250,000	Engel (1966)
New South Wales	1:250,000	New South Wales Department of Mineral Resources (1994)
NORTHERN TERRITORY (NT)		
Darwin East	1:8,333	Vanden Broek (1980)
Bynoe	1:100,000	Pietsch (1986)
Darwin	1:100,000	Pietsch (1983)
Koolpinyah	1:100,000	Pietsch (1985)
Alice Springs	1:250,000	Shaw & Wells (1983)
Darwin	1:250,000	Pietsch & Stuart-Smith (1987)

MAP	SCALE	REFERENCE
QUEENSLAND (QLD)		
Beenleigh	1:100,000	Geological Survey of Queensland (1985)
Brisbane	1:100,000	Queensland Department of Mines (1986)
Caboolture	1:100,000	Murphy *et al*. (1989); Geological Survey of Queensland (1979a)
Cairns	1:100,000	Willmott (1988)
Caloundra	1:100,000	Geological Survey of Queensland (1976)
Gladstone	1:100,000	Queensland Department of Mines (1988)
Helidon	1:100,000	Geological Survey of Queensland (2001)
Ipswich	1:100,000	Geological Survey of Queensland (1981)
Mount Lindesay	1:100,000	Department of Natural Resources and Mines (2003)
Murwillumbah	1:100,000	Geological Survey of Queensland (1978)
Toowoomba	1:100,000	Geological Survey of Queensland (1979b)
Townsville	1:100,000	Geological Survey of Queensland (1986); Tresize *et al*. (1989)
Surface Geology of Australia – NW Queensland, W Cape York and Torres Strait	1:1,000,000	Whitaker & Hanna (2004)
Surface Geology of Australia – S Queensland	1:1,000,000	Whitaker *et al*. (2004)
SOUTH AUSTRALIA (SA)		
Adelaide	1:50,000	Forbes (1980)
Echunga	1:50,000	Belperio (1985)
Gawler	1:50,000	Belperio (1988)
Noarlunga	1:50,000	Forbes (1983)
Onkaparinga	1:50,000	Forbes (1979)
Soils, stratigraphy and engineering geology - Adelaide Plains	1:50,000	Sheard & Bowman (1994)

MAP	SCALE	REFERENCE
TASMANIA (TAS)		
Launceston	1:10,000	Geological Survey of Tasmania (1996)
Hobart	1:25,000	Hofto (1990)
Surface Geology of Australia - Tasmania	1:1,000,000	Liu *et al*. (2005a)
VICTORIA (VIC)		
Melbourne	1:63,360	Geological Survey of Victoria (1974)
Ringwood	1:63,360	Vandenberg (1971); Geological Survey of Victoria (1981)
Sunbury	1:63,360	Geological Survey of Victoria (1973)
Yan Yean	1:63,360	Garrett (1975); Geological Survey of Victoria (1981)
Queenscliff	1:250,000	Geological Survey of Victoria (1985)
Melbourne	1:250,000	Victorian Department of Natural Resources and Environment (1997)
Surface Geology of Australia - Victoria	1:1,000,000	Liu *et al*. (2005b)
WESTERN AUSTRALIA (WA)		
Armadale	1:50,000	Jordan (1986a)
Fremantle	1:50,000	Gozzard (1983a)
Gingin	1:50,000	Anon (1976)
Gleneagle	1:50,000	Smurthwaite (1989)
Mandurah	1:50,000	Anon (1977a)
Moore River – Cape Leschenault	1:50,000	Anon (1977b)
Muchea	1:50,000	Gozzard (1982a)
Mundaring	1:50,000	Jordan (1986b)
Perth	1:50,000	Gozzard (1985, 1986)
Pinjarra	1:50,000	Anon (1978)
Rockingham	1:50,000	Gozzard (1983b)
Serpentine	1:50,000	Jordan (1986c)
Yanchep	1:50,000	Gozzard (1982b)
Regolith of Western Australia	1:500,000	Marnham & Morris (2003)