V_S30 and NZS 1170.5 site class maps of New Zealand

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ABSTRACT: Two parameters required in earthquake ground-motion prediction equations (GMPEs) commonly used in New Zealand are V_S30, the average shear-wave velocity to 30 m depth, and NZS 1170.5 Site Class. Nationwide maps of these parameters have been developed using GIS from the GNS Science 1:250,000 scale (“QMAP”) seamless geological map data. The two maps use shear-wave velocity estimates for various geological units derived from site-specific measurements, established correlations with strength and density parameters from site investigations (Borcherdt, 1994), and extrapolation based on geological unit and topography. Where they are not known, depths of valley sediments are determined by extrapolation from digital elevation data. Results indicate that the youngest Tertiary-age sedimentary sandstones having shear-wave velocities (V_S) less than 1 km/s should not be taken as NZS 1170.5 class B rock, even though they might strictly satisfy the Class B definition. Conversely, at depths greater than a few hundred metres, very dense and deeply buried glacial outwash and lahar gravels exceed V_S=1 km/s and should be considered to be class B rock, allowing the calculation of site period based on shear-wave travel times down to the depth where such material is encountered. Further calibration has been undertaken using spectral inversions and H/V ratios from earthquake strong-motion records, some of which reveal significant 2D/3D amplification effects. Because of the compilation scale of the data, these maps should not be used site-specifically, but are valid for wider-scale modelling and planning. A map of depth to V_S=1 km/s is also under development.

1 INTRODUCTION

GNS Science produced NZS 1170.5 site class, site period and V_s30 maps for the Wellington Region in 2010 in the course of the “It’s Our Fault” study (Semmens et al. 2010), using a compilation of subsurface geological and geophysical data, including any available shear-wave velocity measurements or estimates. This work followed on from compilations of site conditions at GeoNet Strong Motion network stations (Cousins et al. 1996), and was conducted in parallel with current efforts to refine and update this database to include site period, V_s30, depth to V_s=1 km/s and NZS 1170.5 site class determinations for Strong Motion Network stations.

To assist with rapid production of isoseismal maps after an earthquake, GeoNet commissioned the production of a V_s30 map of New Zealand to provide the necessary ground condition parameters, one of which is V_s30. To achieve this it was decided to take the New Zealand 1:250,000 scale digital geological map as a base, and establish ranges of shear-wave velocity values for the various geological formations, based on direct measurements in boreholes or derived from geophysical methods coupled with the best available subsurface data.

After completion of the V_s30 map, the NZS 1170.5 site class map was compiled from the same data set, and a map of depth to V_s=1 km/s is currently being compiled.

It is impractical to present the entire V_s30 and NZS 1170.5 site class maps here because of their complexity and the limitations of page size, but it is expected that digital copies will be made available either for GIS usage or in the form of Google Earth .kmz files. In this paper, for illustrative purposes, we present examples of only that part of the mapped area covering the Wellington region.

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Because of the compilation scale of these maps, they must not be used for site- specific purposes, i.e. to adopt definitive site parameters at a given point location. However, they are expected to be sufficiently accurate for generalised modelling, and can provide a guide for likely site-specific conditions which must be then be refined through subsequent targeted site-specific evaluation or investigation. The maps should also be considered to be interim productions that may be improved as more measured data becomes available.

2 METHODOLOGY

2.1 Map base

The USGS Global V_s30 map generator (Allen and Wald 2007a and b) was considered as a potential method, which uses slope angles as a proxy for outlining basins of recent sediments. However, the results are unsatisfactory because of the poor resolution of the digital terrain model available in the on-line map generator, and the fact that the map generator uses a uniform rate of basin depth increasing with distance across basins from the toes of the surrounding slopes. This methodology does not reliably represent faulted basin boundaries, as demonstrated in Figure 1. It should also be noted that no areas of V_s<180m/s have been shown, even though these have been proven to be present in the area of the map. There are also problems with the resolution of the on-line map generator.

Figure 1 was generated for part of the Wellington area from the USGS Global V_s30 map server, and indicates that the lowest V_s30 class (proxy from the deepest part of the basin) is centred between the hills to the east and west, but the presence of the Wellington fault along the western margin means that the deepest part of the basin is much closer to the fault. (The classes B to E are NEHRP not NZS 1170.5)

It was therefore decided that the digital geological map would provide a better base for the V_s30 map than the slope-angle concept adopted in the USGS method. (However, the map of depth to V_s=1 km/s currently under preparation will use the slope-angle concept as a default except where basin depth morphology is well-established). But most importantly, the digital geological map has much higher resolution than the slope-angle based map from USGS.

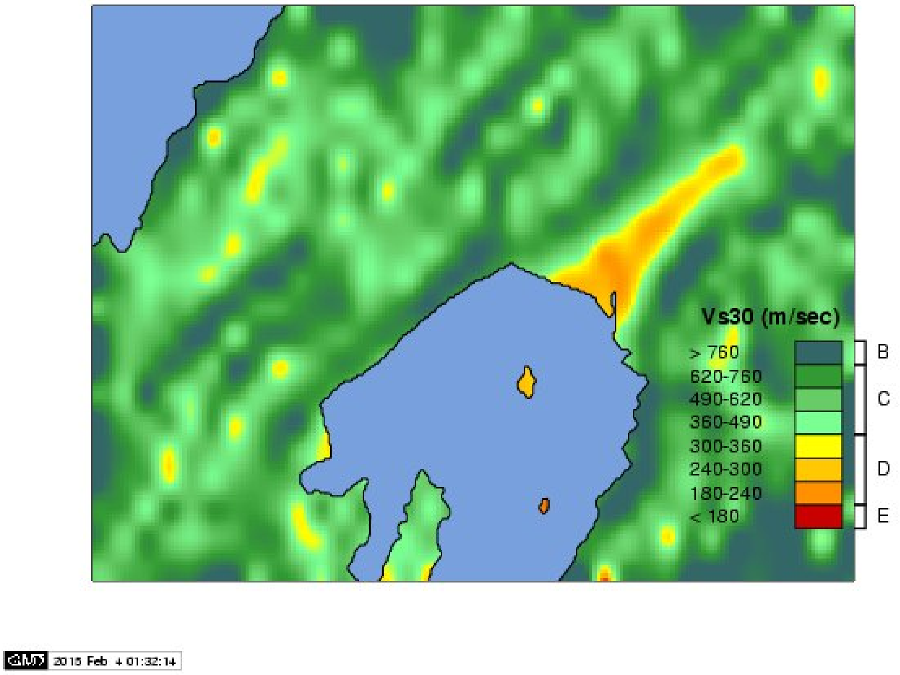

Figure 1. V_s30 map of part of Welllington area derived from USGS Global V_s30 map server.

2.2 **Assigning shear-wave velocity ranges to geological units**

2.2.1 *Basement (geological units classed as rock)*

The basic principle for assigning shear-wave velocity ranges to the mapped geological formations was to take all mapped basement rock units (as shown on Figure 2 in a simplified form) as having V_s30 values >760 m/s (the lower-velocity boundary of NEHRP class B rock) and calling them Class A/B in terms of NZS 1170.5. (Where a very deep weathered zone is present, class C is appropriate depending on the thickness to V_s>1km/s.)

2.2.2 *Paleogene to Neogene units (geological units intermediate between rock and soil)*

Generally shear-wave velocities in Paleogene to Neogene sediments as shown on Figure 2 (formerly referred to as “Tertiary rocks” and commonly known as “Papa”) exceed 1 km/s, and can be classified as class B rock, except for the younger Neogene units, which have been found to have V_s and strength too low to be classified as rock, at least in in their upper portions, which are therefore classified as soil.

2.2.3 *Quaternary units (geological units classed as soil)*

All Quaternary mapped units (excluding recent volcanics) were assigned V_s30 values of <760m/s, the particular range being assigned on the basis of the nature of the unit (e.g. sand, gravel, clay). Quaternary volcanic geological units are considered to be basement if they are lava flows or welded ignimbrites (and not underlain by materials with V_s<360 m/s), and treated as fine or coarse grained sediments in the cases of breccias and tephras. From various assessments made by GNS Science, V_s in earliest Quaternary glacial outwash deposits and early to late Quaternary lahar deposits may commonly exceed 1 km/s, especially where they are at depths of over a few hundreds of metres, and should therefore be considered as class B rock materials.

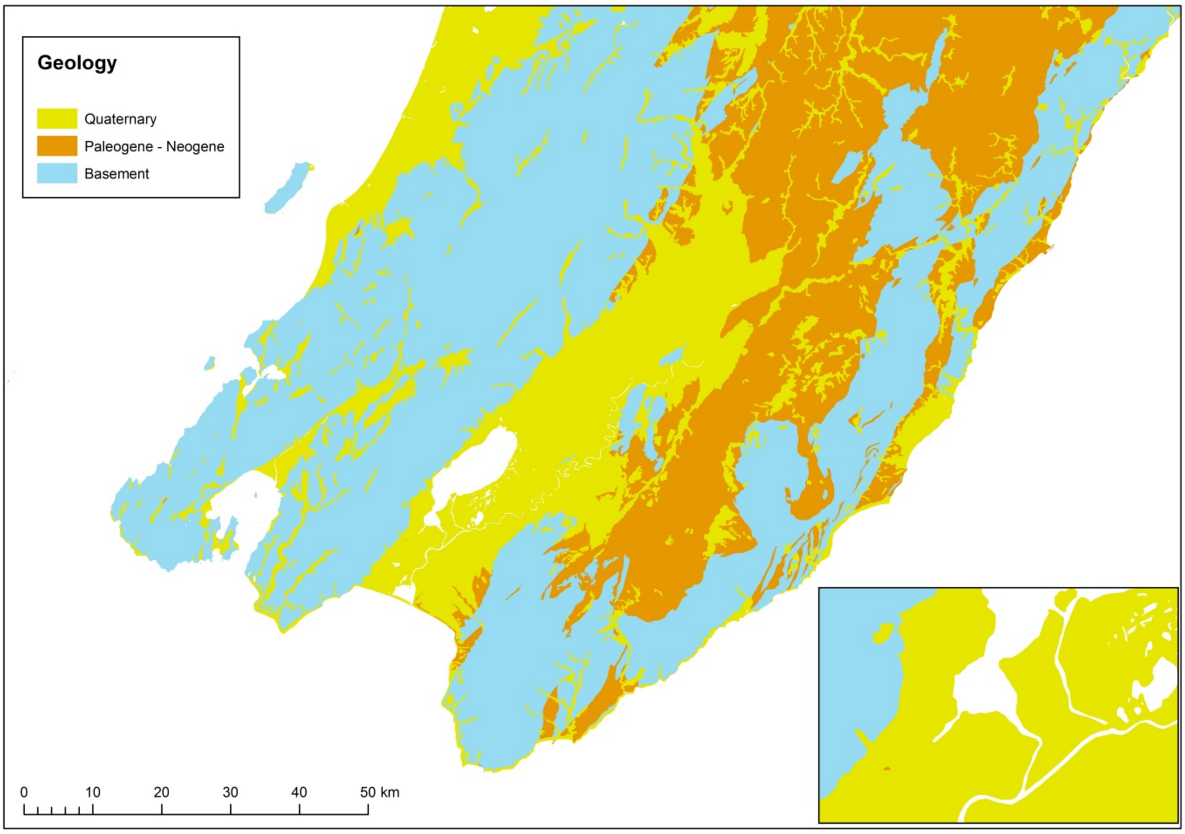

Figure 2. Geological base map covering Wellington region with inset of southeast Wairarapa.

2.3 Validation of the V_s assignments for geological units

Each geological unit was assigned shear-wave velocity ranges by calibration with available downhole measurements as well as velocities derived from various geophysical techniques that have been used where these are consistent with the known three dimensional geological models. Where there is insufficient information, the methods outlined by Borcherdt (1994) have been used.

This available downhole geological and geophysical information has been collated from previous commercial and research work by GNS Science as well as other agencies who kindly shared their information, or which was publicly available. The techniques used by GNS Science Ltd were mainly based on seismic cone penetration tests, microtremor measurements, e.g. Spatial Autocorrelation (SPAC, Beetham et al. 2010), Refraction Microtremor (ReMi, Louie 2001), station cross-correlation (Fry et al. 2010) and other techniques as discussed in Larkin and Van Houtte (2014). Horizontal-to-vertical spectral ratios (HVSR, commonly known as "Nakamura Ratios") at many sites were made from both microtremor and earthquake recordings.

In total, site period, V_s30 and NZS 1170.5 site class determinations were made using data from 120 locations scattered all over New Zealand. These were mainly from the Wellington and Christchurch areas, and also from Strong Motion Network sites. These data were used to calibrate and validate the V_s ranges that were applied to each of the 261 mapped Quaternary geological formations. Additionally, V_s ranges were assigned to very weathered or weak soft rocks (that have V_s and strength too low to be considered to be rock in terms of NZS 1170.5), and also to "basement" rocks.

In general the velocity ranges assigned to the various geological units based on available New Zealand measurements were consistent with the velocities assigned to units using Borcherdt's (1994) correlations.

2.4 Final validation and "sanity check"

A final stage in the production of these maps was to compare the modelled site class and natural period derived from the V_s layer model with site amplification observed during earthquakes recorded at a selection of Strong Motion Network stations. Observed site amplification was quantified using both site-to-reference spectral ratios derived from spectral inversions (Kaiser et al. 2013) and horizontal to vertical spectral ratio (HVSR) methods where available. This served as a double check and reconciliation for both the production of these nation-wide maps and a parallel project to improve the accuracy of key site parameters at the Strong Motion Network sites.

Examples of typical HVSR plots for a station on deep or soft sediment (TEPS) and another on rock (OPZ) are shown on Figure 3. The left hand plot is Te Papa in Wellington (soil site), and the right hand plot is Otago Peninsula (rock site). The station TEPS shows a clear and strong peak at ~1s which corresponds well to the classification of Site Class D and estimated site period based on the layered V_s geological model dataset used to derive the maps. In contrast, station OPZ shows a 'flat' response typical of a non-amplified rock station in keeping with its classification as Site Class B.

In many cases spectral ratio amplification peaks revealed a likely site period that was able to validate or somewhat refine Site Class assignment based solely on site periods derived from the V_s layer models underpinning the models presented here. In some cases, differences in observed (spectral ratio) and inferred site period were observed at basin margins or in areas of complex 2D/3D structure. This result highlights the importance of assessing site parameters on a site-specific basis, particularly for geologically or topographically complex areas.

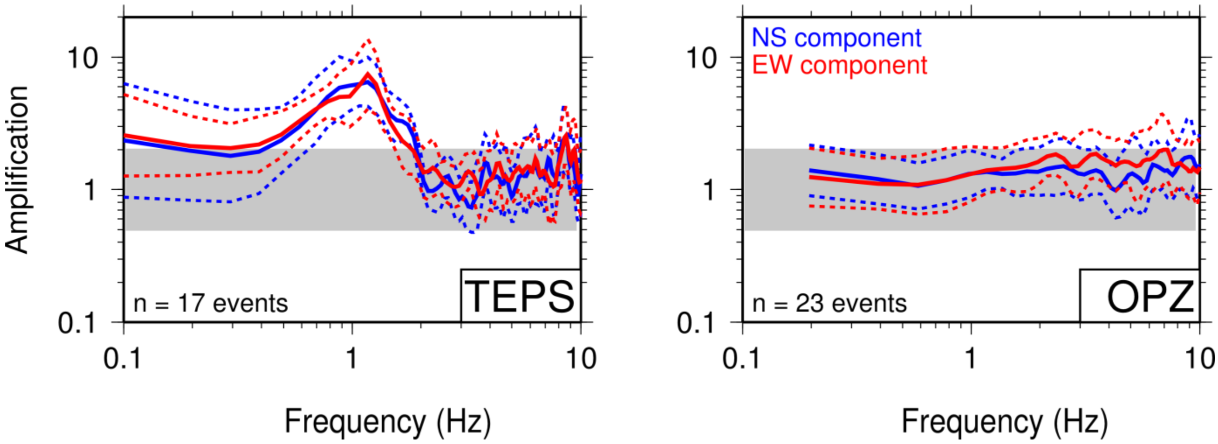

Figure 3. HVSR plots for two selected GeoNet strong motion sites. Solid lines are average of *n* events, dashed lines are the log-normally distributed standard deviations. Shaded area indicates values within a factor of two of that expected for an idealised non-amplified site (i.e. standard reference value of 1). It is generally a good indicator that the amplification is real, if the HVSR peak exceeds this measure and lies above the shaded area.

3 CONSTRUCTION OF V_S30 MAP

At the 120 previously-assessed locations where quality data were available values of V_s30 were assigned to surface mapped units based on an assigned V_s for that unit plus that of any underlying units within the top 30 m. Where no data existed, extrapolation was made to surface units of similar material type and topographic setting to those for which quality data existed.

Further refinement was made to the geological unit polygons, achieved using site investigation data and historical records of liquefaction and other related ground damage that we assume might indicate $V_s30<180$ m/s in certain areas that were not differentiated as geological unit polygons within the geological model in their own right, new model polygons reflecting lower V_s30 values were constructed.

For Quaternary units adjacent to rock (e.g. basin edges), the depth to bedrock is usually less than 30 m below the ground surface, which therefore increases the V_s30 value assigned to the given Quaternary unit. This means that it was not just a simple case of taking a geological unit and assigning a V_s30 range to it.

Draft V_s30 maps derived by the method outlined above were then assessed for consistency. Minor modifications were made as considered necessary for the reason that the same lithological description or soil classification of sediments in one sedimentary basin could have significantly different properties in another basin depending on source material and depositional environment (e.g. source rock strength, glacial or non-glacial depositional environment).

Once these adjustments had been made, the final map (as shown in part in Figure 4) was produced in digital form. These maps have been used over the last 12 months for isoseismal modelling of ground shaking intensity during real-world and scenario earthquakes.

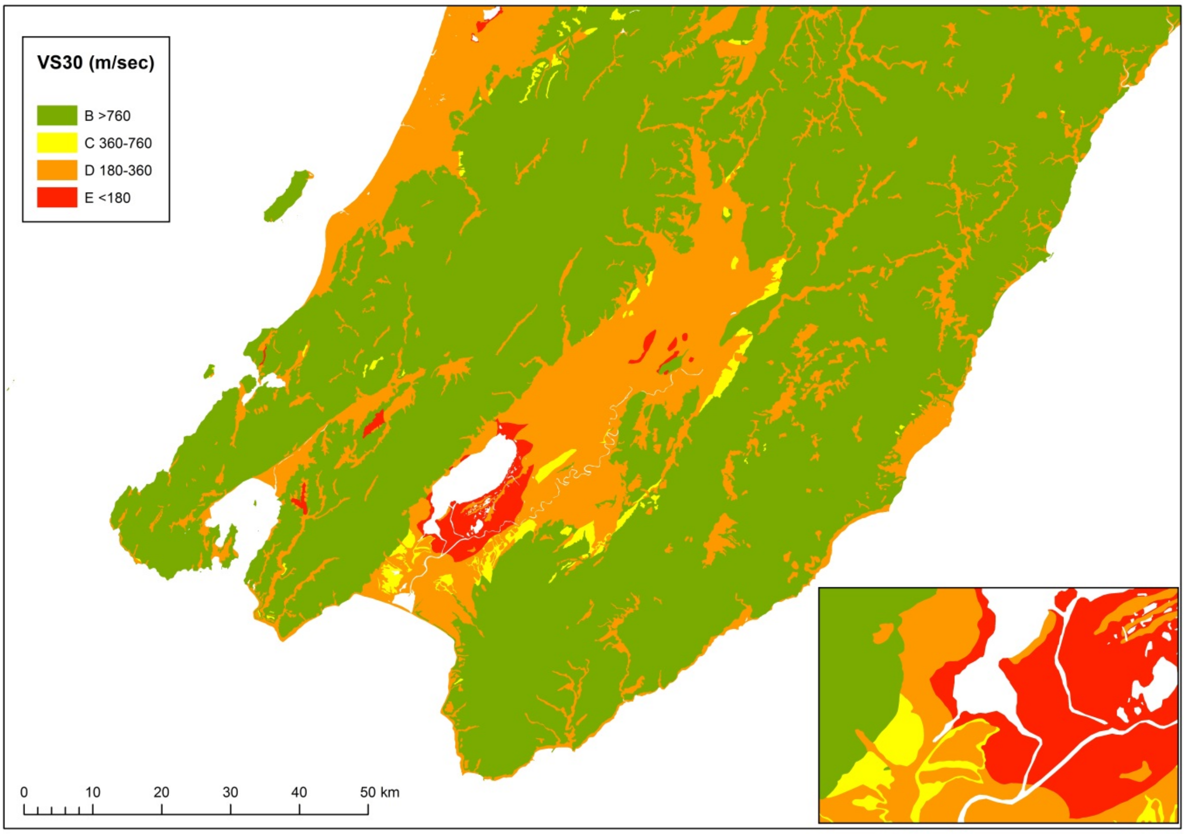

Figure 4. Portion of New Zealand V_s30 Map.

4 CONSTRUCTION OF NZS 1170.5 SITE CLASS MAP

A site class map of New Zealand (a portion of which is shown on Figure 5) was compiled using the same dataset as the V_s30 map, but reinterpreted under the NZS 1170.5:2004 criteria, the most important of which in practical terms is the Class C/D boundary, defined as being at a low amplitude natural period of 0.6 s. (Site period is defined as four times the travel time from rock to surface, so 0.15 s yields a 0.6 s period).

All mapped basement bedrock and most of the Paleogene-Neogene bedrock were taken as Class B (Rock). Class A (strong rock) was not differentiated because it is generally of quite limited distribution because of near-surface stress relief and weathering which reduces its V_s.

Class C (shallow soil) was assigned for some soft rock (Neogene) units, or where deep weathering of otherwise class B rock units was indicated. Also, a 150 m wide buffer zone of Class C outside the Class B rock polygons was developed to accommodate the fact that bedrock dipping under basin sediments will yield site periods that increase with increasing depth to rock up to the 0.6 s threshold between Classes C and D. A nominal 50 m depth to rock has been assigned for this boundary on the basis that an average V_s of around 300 m/s in alluvial sediments (including medium dense sandy gravels and stiff soils) produces a 0.15 s shear-wave travel time from rock to surface. A range of 250 to 400 m/s is typical for such materials near the surface, and conservative in terms of measured values of V_s at depths of a few tens of metres.

An arbitrary dip of the rock surface below sedimentary basins has been taken as 18.4 degrees (150 m step out from rock at the surface to achieve a 50 m depth). Often the dip of the bedrock surface is known to be much steeper than this, but 18.4 degrees is taken arbitrarily, because anything steeper would reduce the width of the zone to less than the resolution of the map. It was considered that it was more important to indicate on the map that such an effect exists at basin edges than to attempt any greater accuracy. (The inset on Figure 5 demonstrates the narrowness of the 150 m Class B buffer zone that is designated as Class C.)

Class D (deep or soft soil sites) have been outlined as anything not classed as B or C above. Although some of the site-specific dataset used to compile these maps indicates Class D site periods of between 0.6 and >2 s, no attempt has been made to extrapolate these through the entire country because of limited coverage leaving large areas with no relevant information.

The NZS 1170.5 criterion for Class E includes more than 10 m depth of very soft or very loose material with $V_s<150$ m/s. It is conceivable that just over 10 metres of such materials might overlie rock at shallow depth, yielding a site period well below 0.6 s (in fact, the extreme would be 0.27 s), which would otherwise indicate a Class C designation. However, it is considered that such situations would be very rare, and that most Class E areas will be a subset within Class D areas.

Class E (very soft soil sites) were established from geological map units designated as swamp deposits with other areas established from site investigation data in the GNS Science collection added manually where an existing geological polygon was not present. Such areas include hydraulic reclamations in Wellington, estuarine sediments of some major rivers, such is in the Hutt Valley and Firth of Thames, and areas where liquefaction and related ground damage had been recorded in past earthquakes.

As was done for the V_s30 map, a draft print of the site class map was examined for consistency, and where necessary, adjustments were made manually. The digital version has been provided for risk modelling, and it is expected that it will be made available in the form of a Google Earth .kmz file for others to make use of it.

It is expected that on-going refinement and corrections where necessary will lead to continuous improvement of the present product.

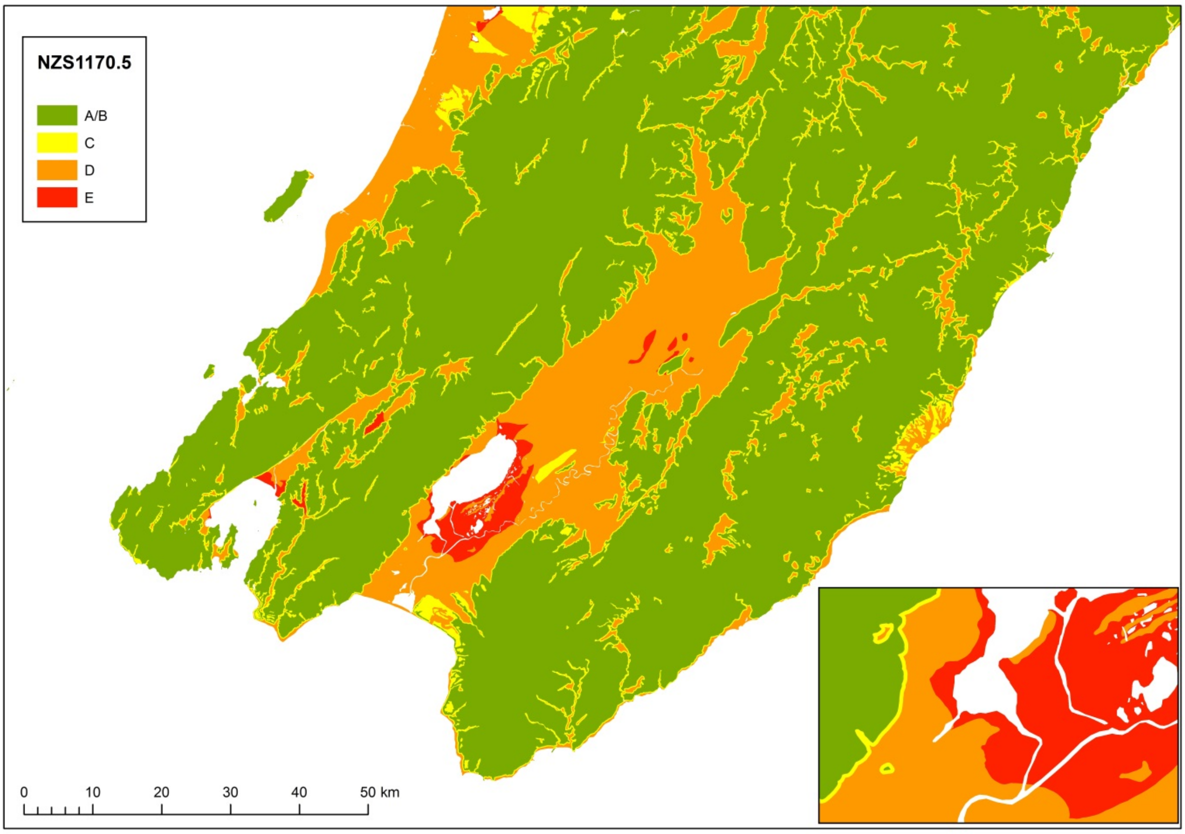

Figure 5. Portion of NZS 1170.5 Site class map of New Zealand.

5 CONCLUSIONS

We present new nationwide maps of V_s30 and site classification according to the New Zealand Design Standards NZS 1170.5. The maps have been generated based on mapped geological units of the GNS Science “QMAP” geological model at 1:250,000 and available geological and geophysical measurements allowing assignment of geological unit properties.

While the GNS Science “QMAP” seamless geological map in digital form provides an excellent base map for conversion into V_s30 and NZS 1170.5 site class maps, it should be noted that the compilation scale of the map was mainly at the 1:50,000 scale and simplified for representation at 1:250,000 scale. The data accuracy is not considered to be better than ±250 m, which precludes the maps from being used site-specifically.

The paucity of real data of relevance to the aims of these maps (particularly in terms of geographical distribution) means that a number of assumptions have had to be made. So while it is believed that the maps are useful for broad-scale modelling and for planning purposes, they are not sufficiently detailed for site-specific use. However, they could be used as a guide to what would be required to establish site class, site period and V_s30 for a particular site.

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