Eurocode 8 seismic hazard zoning maps for the UK

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Foreword

This report provides national seismic hazard maps compiled by the BGS for the purposes of seismic zoning within the Eurocode 8 context. It was commissioned to assist the drafting of the UK National Annexes to the structural Eurocode BS EN1998: Design of structures for earthquake resistance (EC8). The hazard maps this study produced are contained in the British Standards Institution Published Document PD6698:2007: Background paper to the UK National Annexes to BS EN 1998-1, 1998-4, 1998-5 and 1998-6.

The use of values on the maps as design coefficients, replacing site-specific studies, is not generally considered best practice. The values are intended to give a general indication of the expected hazard level. Two maps are provided, with return periods of 475 years and 2,500 years, both showing horizontal peak ground acceleration (PGA) for rock site conditions. PGA is here defined as the geometric mean of the two horizontal components (and not the larger component as was frequently the case in previous studies). Values were computed over an area bounded by 49 - 59^{o} N and 8^{o} W - 2^{o} E. The computations were made for points distributed on a grid at approximately 15 km intervals in both directions, and this defines the spatial resolution of the maps.

Key decisions respecting the modelling decisions for the study were taken by a panel of experts convened at the Institute of Civil Engineers (ICE) on 26 April 2007; thus the model takes into account, to a large degree, a consensus of opinion of the informed seismic hazard community in the UK.

Issue 2.0 of this report incorporates some clarifications and extra text (including Appendix 2) following a meeting at BSI on 7 September 2007, at which Issue 1.0 was discussed.

Issue 2.01 clarifies the status of this report in relationship to the UK National Annexe, and adds a new concluding section to Appendix 1.

Issue 2.02 updates the reference to the PD cited above.

Issue 3.0 corrects some errors in calculations found in previous issues, which distorted the results. The new maps give somewhat higher hazard values. Sections 6.3 and 7 and 7.1 have been modified in places.

Acknowledgements

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1 Introduction

The earliest attempt to map seismic activity, and hence hazard, in the UK was made by O'Reilly (1884), and the (perhaps better known) map of Ballore (1896) does show a division of the British Isles into distinct zones. However, at this early date, hazard could only be expressed in terms of simple distinctions between levels of frequency of earthquake occurrence, usually subjectively assessed, and not as ground motion, which is how seismic hazard is expressed today.

The first true hazard map (in the modern understanding of the word) for Great Britain was thus that of Lilwall (1976), which expressed hazard in terms of intensity with a 200-year return period, using an extreme-value technique based on the work of Milne and Davenport (1969). A subsequent study by Ove Arup (1993) used true probabilistic seismic hazard assessment (PSHA) to calculate hazard at selected points in the UK, but these points were too few to be contoured. The first contour maps of hazard on the UK territory produced using PSHA were therefore those of Musson and Winter (1996), prepared for the then Department of Trade and Industry (DTI).

The UK was, of course, also covered in two major international seismic hazard mapping projects, the Global Seismic Hazard Assessment Programme (GSHAP) and SESAME (Grünthal et al 1996, Jiménez et al 2001). Both these studies used a common source model for the UK, which was derived from a simplified version of the Musson and Winter (1996) model. The results are in conformity with those of Musson and Winter (1996), although different ground motion models were used.

An updated hazard map for the UK was published by Jackson (2004), but only for intensity. This is described in Musson (2004a).

A specific zoning map for the UK was produced for a report on dam safety for the UK, and has since been widely circulated (Halcrow 1990). This map assesses hazard in a completely subjective way into high, medium and low classes, which are to be understood as entirely relative terms. Despite its informal nature, it proved to be a reasonable depiction of relative hazard levels when compared to later quantitative maps.

The maps in the present report are therefore the first UK national seismic hazard maps to be issued specifically in connection with an earthquake building code. They are based on a new seismic source model, elaborated from that of Musson (2004a) and based rather heavily on neotectonic considerations described by Chadwick et al (1996). The work also takes advantage of very recent advances in the modelling of strong ground motion. The underlying earthquake catalogue is that of Musson (1994) with minor unpublished revisions and extended up to the beginning of June 2007.

All magnitude values in this report can be taken to be moment magnitudes (Mw) unless otherwise specified. This is in contrast to most writing on UK seismicity, where local magnitude (ML) is generally used. Conversions from ML to Mw have been made following Grünthal and Wahlström (2003).

The results of the study are expressed as peak horizontal bedrock acceleration values (PGA). In this study, PGA is defined as the geometric mean of the two horizontal components (and not the larger component as was frequently the case in previous UK studies). How PGA is to be defined is a matter of convention, and current practice is tending towards the geometric mean in some form or another as opposed to larger component (or vector sum, which is the largest possible expression, seldom if ever used). The difference between PGA (largest component) and PGA (geometric mean) is a factor about 1.15, following Bommer et al. (2005). PGA values in this report should therefore be multiplied by 1.15 to obtain the equivalent larger-component values.

Because of inherent differences between hazard mapping and site-specific hazard studies (Musson and Henni 2001; see also Appendix 1), the practice of always taking conservative decisions, normal in site-specific work, has not been followed. Thus the values in the maps are intended to be realistic best-estimate values, not conservative design values.

As part of this project, a meeting was convened at the Institute of Civil Engineers on 26 April 2007, attended by leading experts of the UK seismic hazard community, to discuss the key decisions influencing the construction of the hazard model (Booth 2007). Consensus was achieved on all the major issues. This study can therefore be considered as meeting the requirements for Level 3 in the classification of seismic hazard studies proposed by the Senior Seismic Hazard Assessment Committee (SSHAC) in the USA (Budnitz et al. 1997), in terms of expressing the general views of the informed community of experts, outside the immediate authorship of this report.

2 Seismicity of the UK

As stated in the previous section, the basis for this study is the UK earthquake database maintained by BGS. Parameters for historical earthquakes were derived by Musson (1994), taking into consideration the results of a variety of studies on historical seismicity in the UK, as detailed in the references cited by Musson (1994). Parameters for events after 1970 are almost entirely derived from instrumental monitoring, first by LOWNET and latterly using the entire BGS UK seismic monitoring network of around 140 stations (Baptie 2005). The few exceptions are some events in the early 1970s that were too far from LOWNET to be recorded, but which can be assessed from macroseismic data. The UK earthquake database has been kept using local magnitude (ML) as the expression of an earthquake's size. Historically, this was a convenient decision for any monitoring agency in northern Europe. Pending the results of a current project to reassess earthquake magnitudes for the UK in terms of moment magnitude (Mw), for the purposes of the present study all magnitudes were converted to Mw using a formula from Grünthal and Wahlström (2003), based on a large data set of north-west European earthquakes.

The general characteristics of UK seismicity in terms of frequency and distribution (Figure 1) have been discussed by Musson (1996a, 2002, 2007a) and the discussion will not be repeated here.

Catalogue completeness varies with time. Although there is a considerable amount of information relating to earthquakes in the UK before 1700, the completeness is hard to establish. It has been shown by Musson (1994, 2005) that earthquakes ~ 4 Mw can certainly be missing from the historical record in southern Scotland and northern England as late as the latter half of the 17th Century. Offshore, the situation is obviously worse. It is suggested by Musson (2007b) that it would be quite possible for a large passive margin earthquake comparable to the 1929 Grand Banks (Newfoundland) event to have occurred in historical times on the UK continental margin without it being recognised. In fact, an earthquake in 1508 may even have been such an earthquake (Musson 2004a, 2007b).

A related problem is that for most medieval earthquakes, even when the dates are known, the locations are not. Assigning epicentral co-ordinates on very weak information is very unreliable, especially when that information concerns damage to single, anomalous structures. Thus the reported damage to St David's cathedral in 1247 does not necessarily indicate a Pembrokeshire earthquake, and the destruction of St Michael's church, perched on the steep and narrow eminence of Glastonbury Tor, does not make the earthquake of 1275 a Somerset event.

Thus, as far as consistent reporting of British seismicity is concerned, the key date is 1700, when newspapers started. This watershed is important, because before newspapers, no-one was under any obligation to record the occurrence of an earthquake. A chronicler might or might not, depending on circumstances and inclination. But it is the *job* of a newspaperman to report what happens, and to do so continually and in a timely fashion. Thus the absence of a report of an earthquake in a manuscript chronicle is of doubtful significance, whereas far more can be read into the absence of a report in a local newspaper.

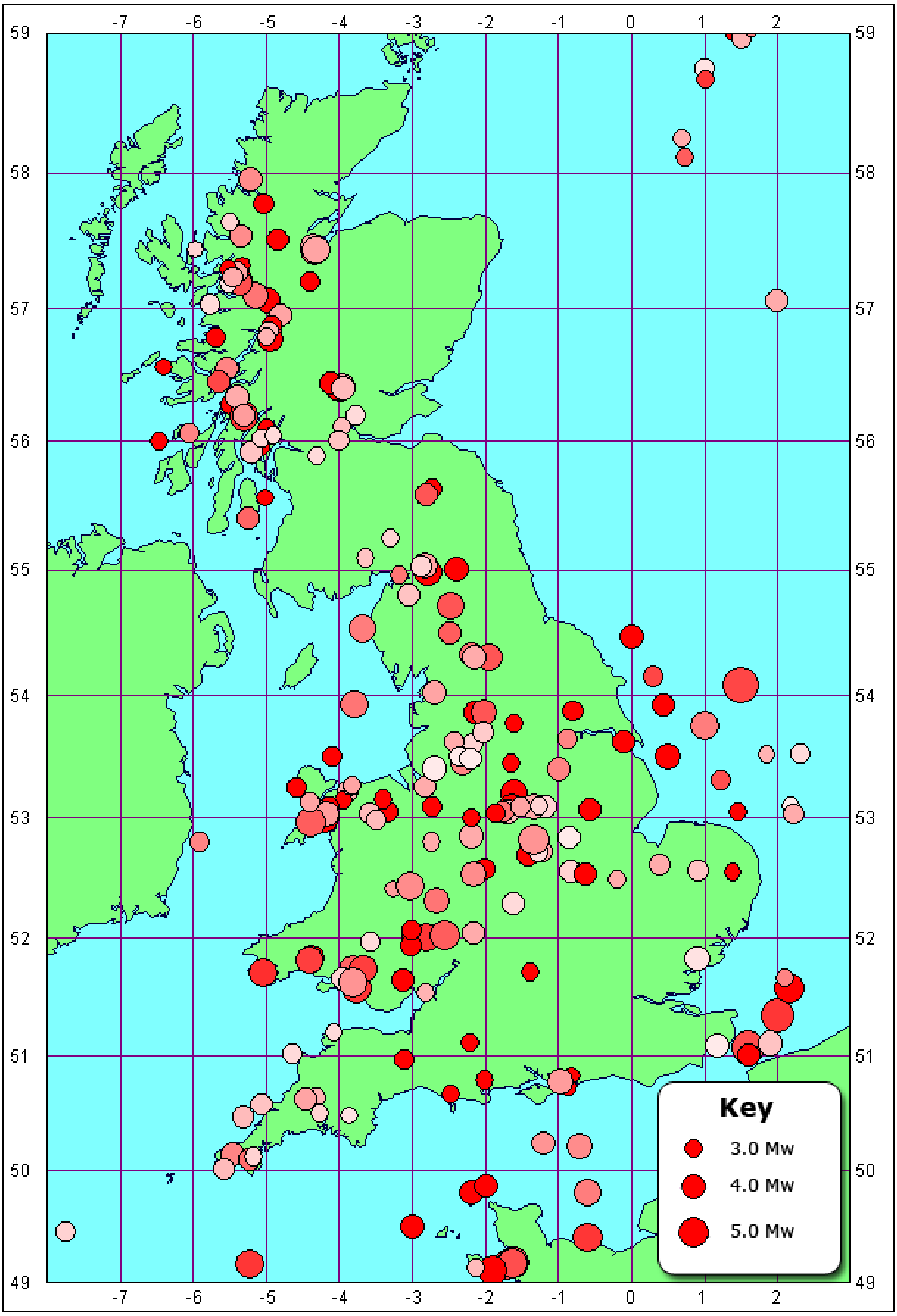

Figure 1 - Seismicity of the UK (all events ≥ 3.0 Mw). Lighter colouring indicates shallower events.

Completeness of an earthquake catalogue can be estimated either statistically, using one of a variety of methods ultimately derived from the work of Stepp (1972), or using expert judgement with respect to the nature of historical sources. It was found by Musson and Winter (1996) that the two approaches tended to give similar answers for the UK. For the purposes of the present study, a simple statistical analysis was made for the whole of the UK mainland, using a method described in Musson (1996a). This computes the annual earthquake rate for sub-catalogues concluding in 2005: 2000-2005, 1995-2005, 1990-2005 … etc. When the sub-catalogues are short, the average rates will be unstable and influenced very much by short-term fluctuations. As the lengths of the sub-catalogues increase, they become a more stable representation of the long-term average, so long as they are complete. When extended into the incomplete period, the average rate will drop further and further as more earthquakes are missed. The breakpoint indicates the start of the incomplete period (Figure 2).

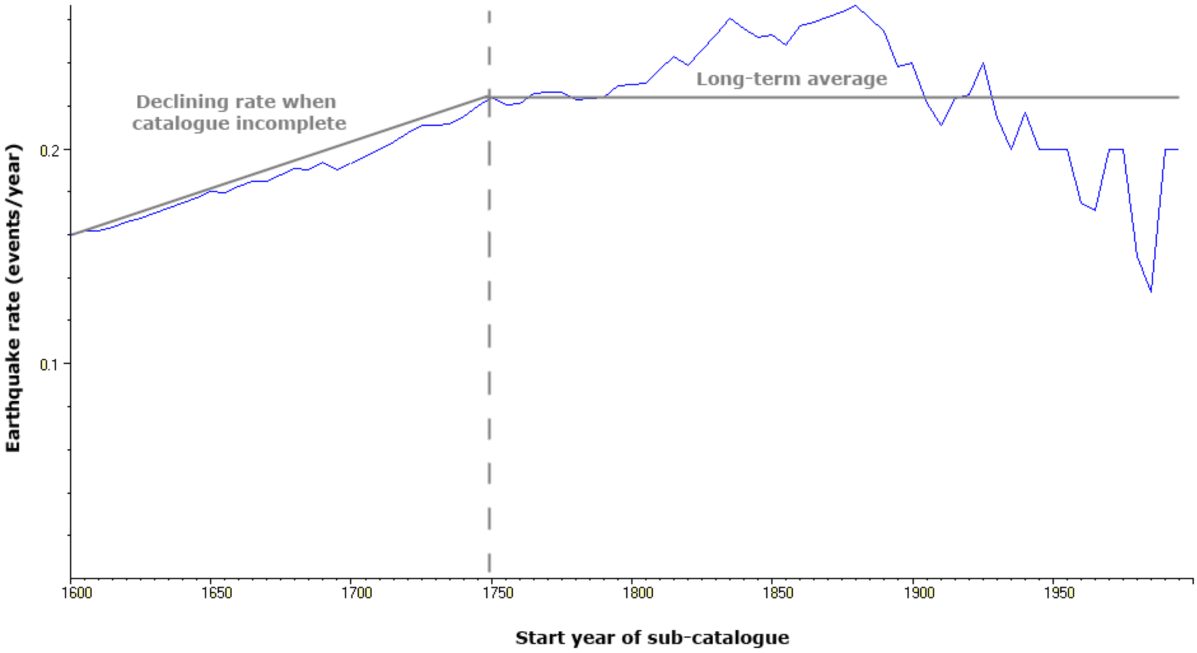

Figure 2 - Example of catalogue completeness analysis for 4.0 Mw.

The data are sufficient to give robust results for magnitudes up to 4.5 Mw. Completeness for higher magnitudes is required for analytical purposes (see Section 5), and the values given below for magnitudes 5.0 and 6.5 Mw are subjective estimates. These values are also assumed to apply to coastal waters. The seismicity of the Viking Graben is a different case. Statistical analysis confirms the expectation that the instrumental catalogue is probably complete after 1970 for magnitudes above 3.0 Mw, but the dates given for higher magnitudes are estimates.

Magnitude	UK	SE England	Dogger	Viking Graben
3.0	1970	1970	1970	1970
3.5	1850	1850		
4.0	1750	1750	1850	
4.5	1700	1700	1750	1900
5.0	1650	1650	1650	
5.5		1300		
6.5	1000	1000	1000	1700

Table 1 - Catalogue completeness

The results are shown in Table 1. An additional completeness level has been added for south-east England, and also for the offshore area between Lincolnshire and the Dogger Bank.

For purposes of analysis, the catalogue was purged of aftershocks and foreshocks by hand.

3 Methodological background of seismic hazard analysis

The earliest beginnings of seismic hazard research were in the 19th century, with attempts to distinguish, in a simple way, those areas that are more affected by earthquakes from those that are relatively untroubled (e.g. Ballore, 1896). For this purpose, it was sufficient to plot the effects of earthquakes from historical observations. At this stage there was no desire to express hazard in a quantitative manner. Considering the time scales on which earthquakes occur (larger events may have recurrence intervals of several hundred years) a reliable quantitative evaluation of hazard cannot usually be obtained from observational data alone.

3.1 DETERMINISM

The next step from observational methods was to a deterministic approach to the subject. This involved focusing attention on geological data and the search for active faults. The basic principle is that if you can identify the nearest active fault to a particular site, and calculate the largest earthquake that could possibly occur on that fault, then you can calculate the largest possible ground shaking at that site. While this method is attractively simple even today (Winter et al., 1994; Krinitzsky, 1995), it has two significant problems.

The first is that dangerous faults can easily go unidentified until an earthquake actually occurs on them - as was the case with the Northridge earthquake (Los Angeles) in 1994.

The second is that the method lacks any probabilistic dimension. The use of the largest possible event without consideration of what the likelihood of its occurrence is, tends towards resulting seismic hazard figures which can be severely over-conservative, especially in areas of low to moderate hazard. This is particularly the case when one is driven by the problem of unidentified faults to allow “floating” earthquakes which can happen anywhere in a region – including directly under the site of interest. This is likely to be a particular problem in intraplate areas where the relationship between faulting and seismicity is often obscure.

The implications of determinism and their place in modern hazard assessment are discussed very well in a paper by McGuire (1999). He argues that in cases of high hazard, especially where hazard is controlled by a few well-understood fault sources, then the worst case is actually so likely to occur within the typical lifetime of a structure, that one might as well accept the inevitable and design for it. As one considers cases of progressively lesser hazard, deterministic procedures increasingly tend to result in unreasonably pessimistic forecasts.

It is possible to propose methods, which are deterministic in nature but which avoid over-conservatism by not considering the worst possible case, but merely some selected scenario (e.g. “the largest earthquake that can reasonably be expected” – whatever “reasonably” means – as in Krinitzsky, 2003). The problem here is that hazard values simply become arbitrary choices. It is difficult to defend the choice of one scenario over another.

3.2 STATISTICAL METHODS

One approach, which has been tried quite widely (e.g. Burton, 1979; Gruppo di Lavoro, 1979), is a purely statistical analysis of earthquake occurrence data using extreme value (Gumbel) statistics to quantify likely levels of future ground shaking. The theory behind this is that extreme events (which are the best-documented ones in the past and the most important ones in the future) follow a certain statistical distribution. By applying this distribution to the largest earthquakes in the past one should be able to obtain good evaluations of seismic hazard. Many seismologists have been sceptical of the idea that one can get better results if one starts the analysis by throwing away 90% of one's data, and practical tests have generally not obtained good results from this method (Knopoff and Kagan, 1977), although attempts have been made to improve on the technique (Kijko and Sellevoll, 1989).

In practice the estimates made by extreme value methods tend to be very poorly constrained as soon as the return period begins to approach the length of the earthquake catalogue. It is also difficult to find any way to take into account the inherent uncertainties that need to be considered in seismic hazard analysis, especially the intrinsic aleatoric nature of ground motion.

For these reasons, hazard analyses based on extreme value analysis are not often encountered nowadays, and especially not for studies related to earthquake engineering and design.

3.3 PROBABILISTIC HAZARD ANALYSIS

Since the early 1970s the most prominent method used for seismic hazard analysis has been the probabilistic method (usually referred to as PSHA - probabilistic seismic hazard analysis). This method was first introduced by Cornell (1968) and since then widely adopted and modified (McGuire, 1978; Bender and Perkins, 1987). The PSHA technique uses the widest possible amount of data, combining seismological, geological and geophysical data to build up a model of the earthquake-producing processes. The aim is to understand the nature of the features in the earth's crust that are actually causing earthquakes in a region, and to be able to produce a numerical model of these features. Any area in which earthquakes might occur can be divided up into sub-regions that behave in a consistent way with regard to producing earthquakes. These smaller regions are called seismic source zones; a collection of source zones covering a whole region is called a seismic source zone model. The seismologist undertaking a PSHA study constructs a seismic source zone model from investigations of earthquakes, faulting, and other crustal properties, and then seeks to quantify the rate of occurrence in each seismic source zone. From this, and with some assumptions about the way in which earthquakes occur with respect to time (e.g. that the time of the next earthquake is not affected by the time elapsed since the previous one), it is possible to calculate the probability that any degree of ground shaking will be exceeded.

Early uses of the PSHA method suffered from one important drawback - they required perfect information on all parameters of the earthquake process, which was usually not available. Considering the few hundred years for which earthquake data are available, there is insufficient information to calculate some of the parameters required precisely. There is therefore an element of uncertainty in what is known about the properties of any seismic source zone, which really needs to be factored in to the calculations of hazard. Modern PSHA studies, following ideas proposed by Coppersmith and Youngs (1986) are usually able to deal with this problem by incorporating into the model what is known as a "logic tree", in which certain parameters are given a range of possible values with guesses as to the probability of each. So, for example, the maximum earthquake in any area might be described as 7.0 (50% chance), 7.5 (30% chance) or 8.0 (20% chance).

A further development in PSHA methodology is the increasing use of smoothing processes, which, applied to the seismicity, obviate any need to draw up a seismic source model. One of the criticisms of standard PSHA methods is that, in the absence of clear procedures for constructing seismic source zones, widely differing interpretations can be produced from expert to expert, which result in large variations in computed hazard and a consequent uncertainty in what results are believable. In a well-known study by Bernreuter et al. (1989), several different experts produced incompatible source models of the Eastern USA (see the polemic discussion by Krinitzsky, 1993a, b). To try and remove this subjectivity in the modelling process, a number of authors have attempted to do away with discrete source zones in favour of applying some smoothing factor to the observed seismicity. An early developer of this idea was Perkins, who saw the smoothed seismicity as a way of obtaining a first approximation of hazard with the minimum of work (D Perkins pers. comm., 1993). So far as we can trace, this approach was first used in practice by Jacob et al. (1994) in New York. It was subsequently promoted by Frankel et al. (1996), Woo (1996) and Lapajne et al. (1997) among others.

The disadvantage of this approach is that one loses all the insights into the seismogenic process that may be gained from a study of local tectonics. In some parts of the world especially, understanding these processes is critical in evaluating the hazard, and applying a smoothing process blurs important local distinctions in the seismogenic structure. However, as long as one understands that the zoneless estimation of hazard is to be viewed as a first approximation rather than a final verdict, this method can be a useful technique, especially for hazard maps where specific local values are not critical, and especially for areas where tectonic processes are not well understood in any case.

3.4 MONTE CARLO METHODS

One of the reasons that the PSHA method has been so popular is that it enables the widest possible amount of data to be taken into consideration in building the model. However, it is possible to use such models in another seismic hazard technique: Monte Carlo simulation. Since the seismic source zone model is a complete description of the way in which earthquakes occur in a region, it is a fairly straightforward matter to use the model to generate artificial earthquake catalogues using a Monte Carlo process (controlled use of random numbers). Each catalogue represents a version of what could occur in the way of earthquakes in that region in the next 50 or 100 years that would be consistent with past behaviour. From direct observation of the effects of a very large number of simulations, probabilities can be calculated with ease. This method allows uncertainties in the input parameters to be dealt with in a very powerful way - parameters can be entered as distribution functions with observed means and standard deviations. A different value can be sampled from the distribution for each simulation. Alternatively, a logic tree approach can be used.

Monte Carlo approaches of one form or another have been used in a number of seismic hazard studies in different parts of the world, as in studies by Rosenhauer (1983), Shapira (1983), Johnson and Koyanagi (1988), Ahorner and Rosenhauer (1993), Cramer et al. (1996), Ebel and Kafka (1999) etc., although, in view of its many advantages, it is surprisingly under-utilised as a technique. It should be noted, however, that the term “Monte Carlo” is used in seismic hazard studies with respect to at least three distinctly different approaches. One application is to use a Monte Carlo approach to sample branches of a large logic tree representing diverse parameters expressing the uncertainty; each branch is still evaluated using a classic Cornell (1968) approach. The second approach is to take the historical earthquake catalogue and redistribute it using Monte Carlo methods, e.g. by selecting a magnitude at random and associating it with a randomly chosen epicentre. The third method is the one that is followed in this study. It relies on the formulation of a seismic source model in the same way as a conventional probabilistic study, but computes the hazard in a totally different way, i.e. by generation of synthetic earthquake catalogues and simple observation of the results. Unlike the other approaches, this method is completely compatible with conventional PSHA studies, and gives the same output given the same input (Musson, 1998).

The advantages of this approach are several. In the first case, it is very flexible, and can be adapted easily to many variations as the need arises. Secondly, it is much less of a “black box” than the standard PSHA method. The synthetic catalogues generated can be inspected as a check on the realism of the model. Thirdly, the process is rather clearer to the layman. It is not hard to understand the idea that the future seismic history has been simulated 10,000 times and only once did the shaking at site exceed such-and-such a value.

That this is essentially an observation-based approach (albeit synthetic) is shown by the way in which the actual hazard probabilities are calculated. The method in conventional PSHA is essentially analytic, based on the integration of the probability functions describing seismicity and attenuation. In the Monte Carlo approach, the steps are as follows:

(1) Generate a synthetic earthquake catalogue of N years in length.

(2) For each event in this catalogue, simulate the ground motion at site (using the attenuation function with a random scatter).

(3) Note the highest ground motion value obtained in each year.

(4) Repeat steps (1)-(3) R times, such that R x N is at least 10^3 times greater than the return period of interest. Thus, if one were concerned about hazard with annual probability of 10^{-4}, one could use 100,000 catalogues of 100 years, or 200,000 of 50 years.

(5) In the above case, one now has 10,000,000 values for the annual maximum ground motion at site. To find the ground motion that has an annual probability of being exceeded of 1 in 10,000, simply sort the values in order of decreasing severity and pick the 1001st value. This has been exceeded 1,000 times out of 10,000,000 and therefore has a 1 in 10,000 probability.

This process is summed up in Figure 3.

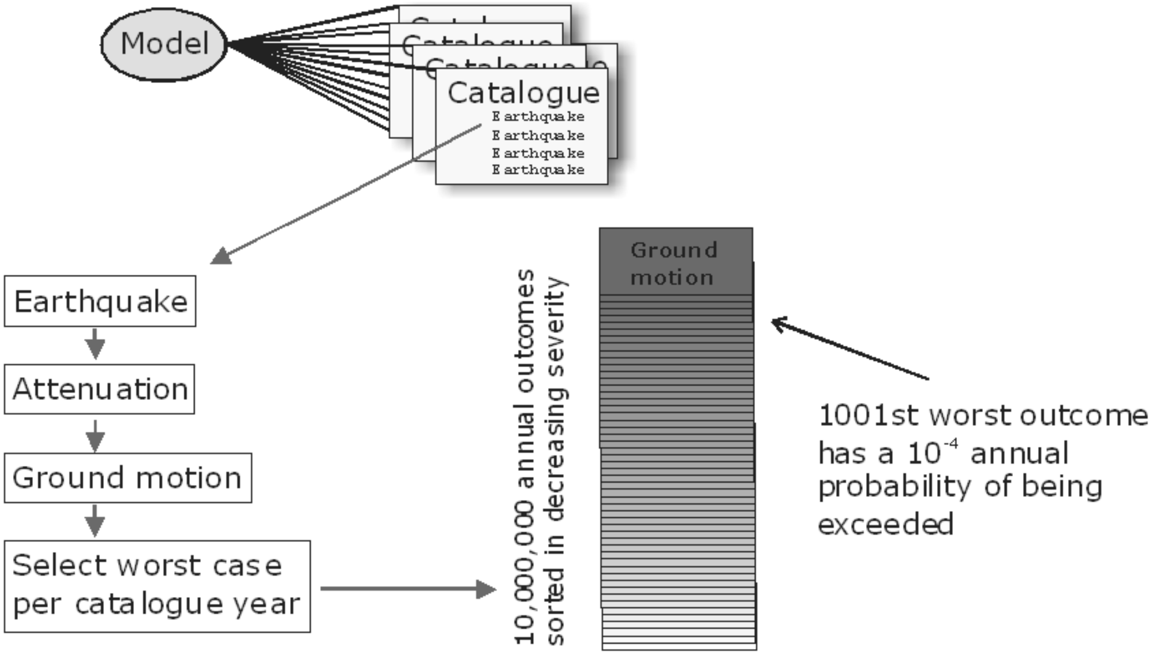

Figure 3 - The elements of the Monte Carlo simulation approach to probabilistic seismic hazard assessment.

This is extremely simple and requires no complex mathematics. Accordingly, the process is very transparent. It is very easy to halt the simulation process at any point and examine the data that are being generated. This is very useful for checking the model. It also means that the hazard can be interrogated in all sorts of ways: one can very easily determine what sort of earthquakes are causing high ground motions simply by printing them out as they occur. The method is rooted in actuality, since one is dealing always with discrete events, the credibility of which can be checked. The danger with many PSHA analyses is that the process is something of a black box; the Monte Carlo calculation process is very much more open and accountable.

What needs to be stressed carefully is that the method above is completely compatible with conventional PSHA calculations of expected hazard. The conventional PSHA study can be reduced to the proposition: IF the seismicity is as expressed in this seismic model, THEN the probability of ground motion at site is X. The Monte Carlo simulation study reduces to exactly the same proposition with the same value of X. Although the internal workings are totally different to the conventional methodology, from the same initial model one obtains exactly the same result (usually to a tolerance of about 0.001 g). It is not necessary, therefore, to discuss in a special way whether the results of the Monte Carlo seismic hazard modelling are valid. If the results of a conventional PSHA can be considered valid, then the equivalent Monte Carlo results are equally valid, because they are the same results, just obtained using a different process.

It can be noted in passing that the use of this method avoids any questions about "mean" and "median" hazard values (e.g. Abrahamson and Bommer 2005). The probability of ground motion is expressed as the directly observed, frequency-based probability. It is not the mean of anything, nor the median of anything.

3.5 SEISMIC HAZARD AND SEISMIC HAZARD MAPS

The above discussion summarises the basic methodology of seismic hazard assessment in general, it remains to say something about the use of seismic hazard techniques to produce maps (as in the present study) compared to other types of study, in particular, site hazard studies.

The production of maps of seismic hazard can be thought of as a first stage towards taking counter measures against the earthquake threat. It should be understood that these are indeed a first stage and not a final one. The aim of seismic hazard maps is twofold: firstly, to show clearly the variation in seismic hazard within a region, and the relative levels. Secondly, to provide guidance as to the expected levels of ground motion. It should be understood that the values on any seismic hazard map are for guidance and are not generally recommended to be taken as design values. The basic outline of a probabilistic seismic hazard study, whether for mapping purposes, or for the production of a site-specific hazard curve, is the same. But there are differences in procedure, particularly with regard to the way in which the underlying seismotectonic models are constructed.

The matter is put succinctly by Page and Basham (1985) in the context of hazard mapping for offshore hydrocarbon exploration:

> *Seismotectonic models may be formulated in various ways, depending on the purpose of the hazard assessment in which they are to be used. Different levels of knowledge concerning geologic hazards are needed at different stages and by different parties in the development of offshore petroleum resources. In deciding whether to hold a lease sale, a governmental body may want a national or broad regional overview of the relative geologic hazards among various proposed lease areas. For selecting tracts to be offered in a lease sale and for bidding in tracts in the sale, more detailed knowledge is required to identify the potential hazards associated with individual tracts. Finally, for the siting and design of offshore production facilities and for the governmental regulation of operations, highly detailed knowledge of the specific hazards affecting a given site is needed.*
>
> *The seismotectonic model prepared for a large region generally does not have the same degree of information and specificity needed for detailed application to a specific site or small area. For example, evaluation of the relative ground-shaking hazard for a continental shelf requires ground-motion estimates to be derived on a gross regional basis, so as to provide information applicable to typical sites throughout the entire shelf region. For such a broad-scale evaluation, not all potential earthquake sources that may affect any site throughout the region can be investigated in the same degree of detail that is required for assessing hazards to a critical facility at a specific site. Thus, for regional evaluations, seismotectonic models will be generalised, as a rule.*

There is a further and related point, which turns on the issue of conservatism. This is simply that the model for a hazard map must address all possible places, whereas that for a site study can be sensitised to that site. One can investigate, for a site, the effect of possible interpretations of the seismicity and tectonics and ensure that an adequately conservative solution is adopted for design purposes. But one cannot determine a model that is conservative for all possible sites. A demonstration of this point is given by Musson and Henni (2001).

This subject is discussed in more detail in Appendix 1 to this report.

4 Tectonics of the UK

The UK is located in the north-western sector of the Eurasia plate, far from any plate boundaries. The two closest boundaries are the Mid Atlantic Ridge to the west and the collision zone between Africa and Eurasia to the south. It is an intraplate area and as such, levels of seismicity are characteristically low.

Baptie (2007) determined fault plane solutions for 75 UK earthquakes in order to investigate the driving forces behind earthquakes in the UK. The best constrained focal mechanisms (see Figure 4) are mainly strike-slip with north-west – south-east compression and north-east – south-west tension, or vice versa. The orientation of P (compression) axes clusters between north and north-west, in line with ridge-push originating in the Mid Atlantic. This orientation varies spatially: there is a preferred near north direction in Scotland and a more north-west orientation in England and Wales (Baptie, 2007). Thus north-south and east-west trending faults are more likely to be reactivated in the current prevailing stress regime.

Broadly, the crust of Britain and Ireland consists of three blocks: Laurentian crust north of the Highland Boundary Fault, Avalonian crust south of the Iapetus Suture Zone and an intervening zone of accreted terranes that form a complex suture zone separating the Laurentian and Avalonian blocks (Figure 5). The tectonic development of the region has been complex. Rifting of Avalonia (including southern Britain and Ireland) from Gondwana in the early Ordovician (c. 475 Ma ago) initiated the closure of the Iapetus Ocean to the north and the opening of the Rheic Ocean to the south (Cocks et al., 1997). The closure of Iapetus occurred between 460 and 420 Ma ago. The Iapetus Suture Zone is the line along which Laurentia and Avalonia fused. The Caledonian Orogeny, a result of collision between Laurentia and Avalonia and other former fragments of Gondwana following the closure of Iapetus, affected an area extending from the Moine Thrust in the north to the Welsh Borderland Fault System in the south (Woodcock and Strachan, 2000).

The English and Welsh Caledonides extend from the Iapetus Suture Zone in the north to the Variscan Front (VF) in the south. Many of the seismotectonic zones as defined by Chadwick et al. (1996) within the English and Welsh parts of the Caledonides are perpendicular to the direction of maximum compressive stress. The central part of the English-Welsh Caledonides is a north-north-west – south-south-east-trending linear seismotectonic zone between the Midlands Microcraton in the south and the Iapetus Suture in the north (Chadwick et al., 1996). This follows the Pennine Line/Pennine Fault. The Scottish parts of the Caledonian Orogenic Belt lie to the north of the Iapetus Suture Zone and the seismotectonic zones within the Scottish Caledonides also trend north-east – south-west.

The VF delineates the northern extent of deformation associated with the Variscan Orogeny. All of England south of the VF is part of the Variscan Orogenic Belt. The belt is cut by east-west-trending thrusts and is also compartmentalised by north-west-trending transcurrent faults (Chadwick et al., 1996).

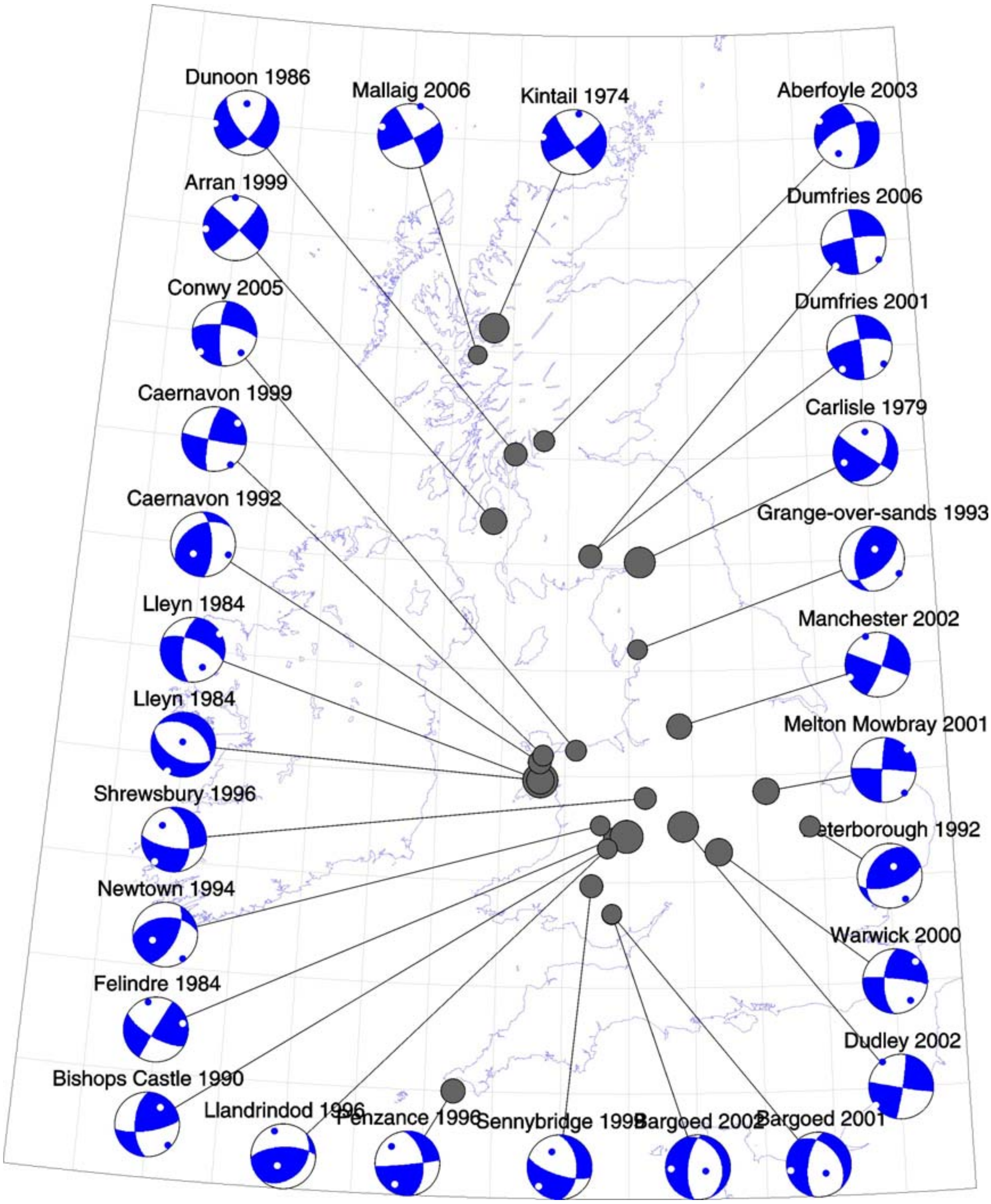

Figure 4 - Focal mechanisms for UK earthquakes (from Baptie, 2007).

In Section 6 of Chadwick et al. (1996), a proposal is made for a seismotectonic zonation of the UK, intended to represent the surface projections of subsurface volumes of characteristic upper crustal geological structure. The model begins by dividing the country into a series of basement provinces, according to a simplified system based on Palaeozoic orogenic episodes.

CF – Caledonian Foreland
SC – Scottish Caledonides
EC – English and Welsh Caledonides
M – Midlands Microcraton
V – Variscan orogenic belt

Each of these provinces is then further divided into seismotectonic zones based on subsurface geological criteria so as to present areas that have, more or less, uniform structural characteristics, and which can thus be used as the basis for seismic source modelling. These zones are shown in Figure 6, which is a simplified redrawing of Figure 6.2 in Chadwick et al. (1996). The basement provinces are shown in different coloured shading to differentiate them. The full explanation of this system can be found in Chadwick et al. (1996) and is not given here.

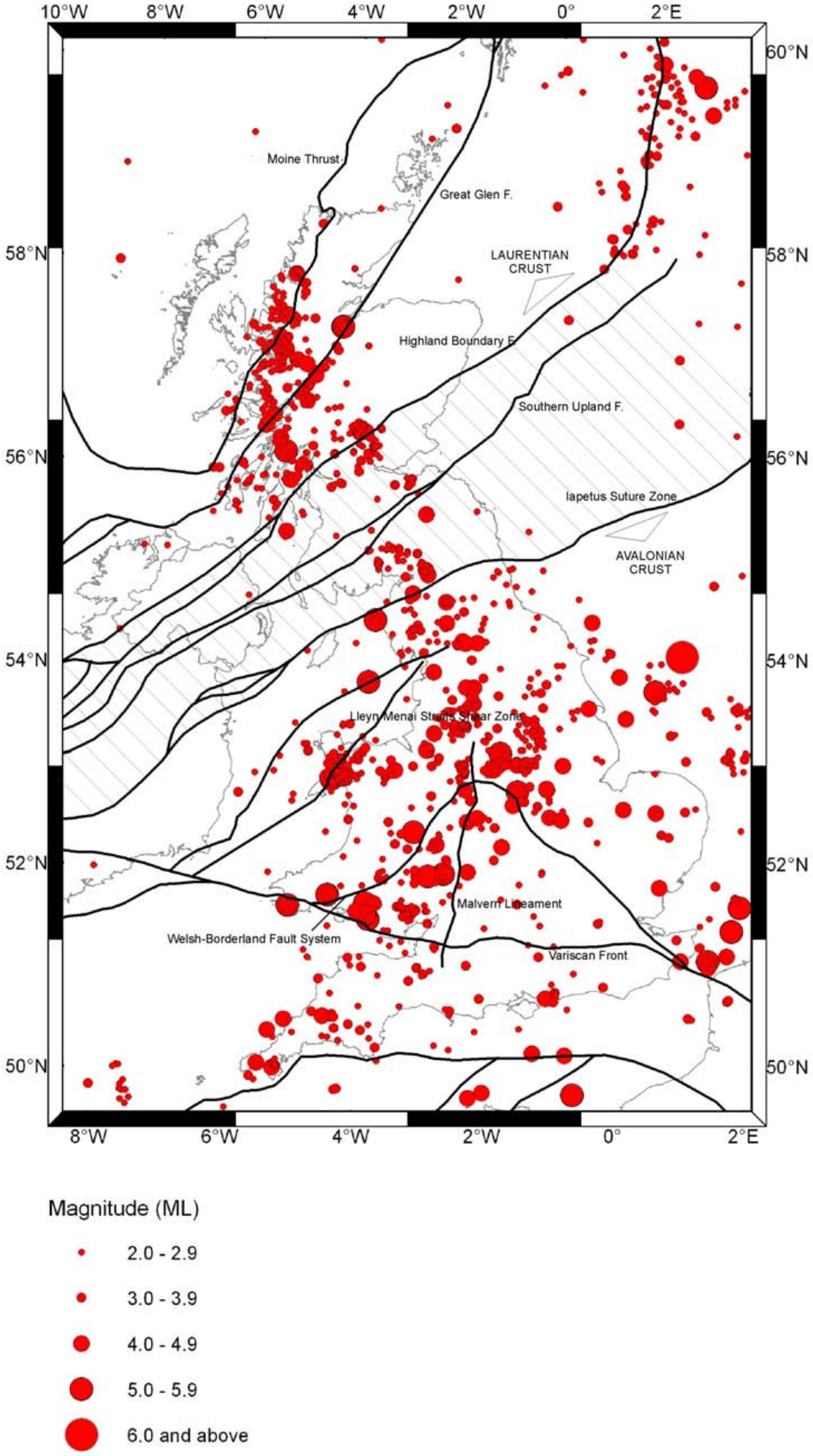

Figure 5 - Crustal terranes of the British Isles.

Statistical tests reveal that the distribution of seismicity across the UK is non-random (Musson, 2000b) but it is apparent from Figure 5 that there is no correlation between the configuration of tectonic terranes and seismicity. Several competing theories seek to explain the distribution of earthquakes in the UK, which are summarised here (see also Musson, 2007a). None fully account for the distribution of seismicity that is observed.

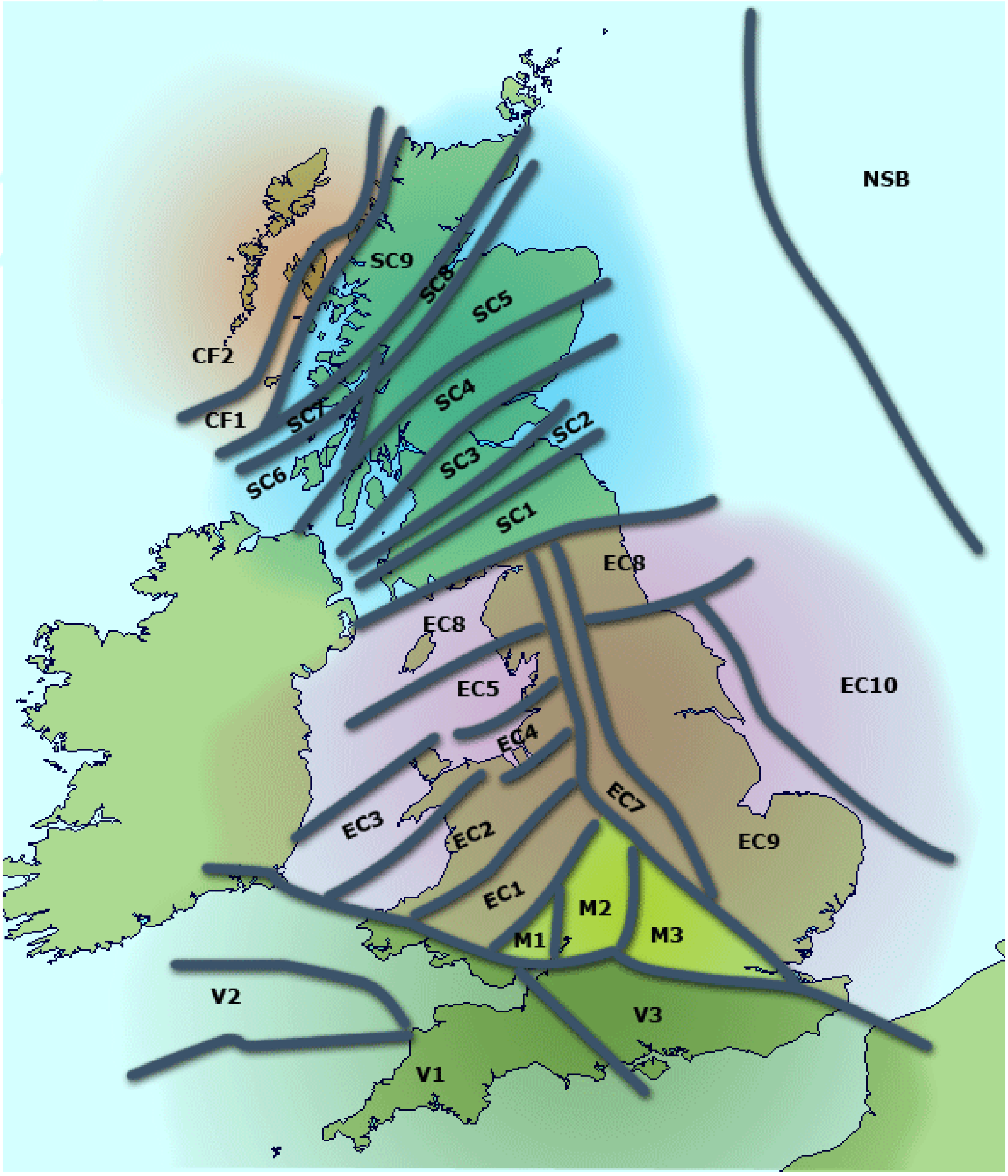

Figure 6 - Seismotectonic model of the UK, after Chadwick et al. (1996).

4.1 PALAEOGENE-NEOGENE DEFORMATION

Muir Wood (1989) proposes that the distribution of earthquakes in the UK is related to four phases of intraplate deformation concentrated along linear zones stretching from the Mediterranean to the Mid-Atlantic Ridge. Muir Wood (1989) considers that these zones acted as sub-plate boundaries within the Eurasia plate and resulted in significant deformation in the British Isles. Whilst this hypothesis does explain why levels of seismicity in eastern Scotland and north-eastern England are low, it fails to explain the absence of earthquakes in Ireland or south-western Scotland. Furthermore, Musson (2007a) shows that the most activated areas of the UK do not correspond with the most seismically active areas.

4.2 GLACIAL REBOUND

Musson (1996a) notes the correlation between the distribution of seismicity in Scotland and the distribution of ice cover during the last glacial advance see, for instance, Dawson (1992). Muir Wood (2000) extended the concept of deglaciation tectonics by proposing a pattern of stress interference between radial stress fields due to post-glacial rebound and forebulge collapse, and the general tectonic maximum horizontal stress. However, despite its ingenuity, the model fails to sufficiently account for the distribution of epicentres that is observed.

4.3 MAJOR FAULT SYSTEMS

There is a tendency for larger British earthquakes to occur in the footwall blocks of major fault systems. In some cases, such as the Lleyn Shear Zone, this is because the earthquakes occur at relatively large depths, and are therefore beneath the hanging wall. Earthquakes also tend to cluster around fault intersections, such as the Iapetus Thrust with the Pennine Fault, and the Variscan Front Thrust with north-west-trending transcurrent faults (Chadwick et al., 1996). There are also cases where earthquakes seem to cluster between converging faults, for example, the Moine Thrust and Great Glen Fault, the Moine Thrust and the Highland Boundary Fault, Church Stretton Fault and the Variscan Front (Chadwick et al., 1996). Musson (2007a) shows that the presence of major faults is not a good predictor of seismicity by itself but that it may be a contributory factor.

As is typical in intraplate areas, the relationship between seismicity and geological structure is unclear and attributing earthquakes to specific faults is very difficult. However, due to the gentle inclination of many upper crustal faults and shear zones, when placed under strong compressive or tensile stresses they are reactivated in a specific manner, involving earthquake generation at considerable depth on the faults/shear-zones themselves and at shallower depths, in their hanging wall blocks (Chadwick et al., 1996). What follows is a distillation of the discussion presented by Chadwick et al. (1996) of the main faults and shear zones of the UK and how they appear to be related to seismic activity (see Figure 5).

Outer Isles Thrust (OIT) – A north-north-east-trending thrust that dips gently to the east-south-east and forms one of the largest and most clearly mappable deep structures in the UK. Although two or three earthquakes have occurred offshore in this area, the OIT does not appear to be seismically active.

Moine Thrust – This structure is sub-parallel to the OIT. It is a major crustal structure dipping east-south-east. Although it is not as prominent as the OIT on seismic reflection data, it is associated spatially with considerably more activity, with earthquakes ranging in size from < 2.0 ML to ML > 4.0. Earthquakes are particularly numerous between the converging Moine Thrust and Great Glen Fault.

Great Glen Fault – This fault is believed to constitute a north-east-trending sub-vertical transcurrent fault system penetrating to lower crustal depths. Significant seismicity is associated with certain segments of the fault and several large earthquakes have been located within a few kilometres of the fault. Interaction between the Great Glen Fault and the Moine Thrust at seismogenic depth (15-18 km) may be related to the occurrence of two relatively large earthquakes near Oban.

Highland Boundary Fault - This follows the Caledonian structural trend (north-east – south-west) and delineates the southern edge of the Laurentian terranes. This structure has behaved both as a strike-slip feature and a collisional suture during the development of the British Isles (Woodcock and Strachan, 2000). Deep seismic reflection data offshore suggest that it dips gently towards the north-west. If this is also true onshore, the Comrie swarms lie in its hanging wall block and are possibly associated genetically with the fault (Chadwick et al., 1996).

Southern Uplands Fault – The sub-surface geometry of this structure is uncertain but it is thought to dip gently to the north-west in a similar fashion to the Highland Boundary Fault. Minor earthquakes lie in the postulated hanging wall block but whether these are directly related to the Southern Uplands Fault is unclear and probably doubtful.

Iapetus Thrust – This is arguably the most fundamental structural lineament of Britain and Ireland (Beamish and Smythe, 1986). It dips gently north-north-west and penetrates to considerable depths (possible to the Moho). There is significant seismicity in its hanging wall with several large events (ML > 4.0), which lie roughly along the intersection of the suture zone/thrust and the Pennine Fault.

Pennine Line – This is a north-south-trending complex of faults and folds that links northward to the Pennine Fault. It seems to be an important influence on earthquake distribution in this area but due to a paucity of seismic reflection data, the structures in this area are mostly poorly understood.

Lleyn Shear Zone (LSZ) and the Menai Straits Fault System – These probably correspond to a prominent north-west-dipping upper crustal thrust seen on offshore seismic reflection data. The area around the Lleyn Peninsula is characterised by major seismicity, with numerous large events occurring in both historical and more recent times.

Welsh Borderland Fault System – This includes the Church Stretton Fault Zone and other related structures such as the Pontesford-Linley Fault. It lies at the north-western margin of the Midlands Microcraton, separating it from the Caledonian Orogen to the west. The sub-surface geometry of these faults is poorly understood. However, considerable seismicity seems to be associated with these faults with epicentres generally lying in their hanging wall blocks.

Malvern Lineament – This is an ancient basement fault structure. Its deep subsurface geometry is uncertain. A similar parallel structure lies 50 km to the east, likely dipping west and linking with the Malvern Lineament at depth. Both of these structures appear to be associated with the seismicity in this region.

Variscan Front Thrust (VFT) – The VFT extends from southern Ireland to northern France and marks the northern edge of the Variscan Orogenic Belt. The VFT dips roughly southwards and it is intersected along its length by north-west-trending near-vertical transcurrent faults, which divide it into structurally distinct segments. In south Wales and the Bristol Channel, the VFT is associated with considerable activity and there are particular concentrations of activity close to the intersections of the transcurrent faults.

4.4 MANTLE PROCESSES

Seismic tomography studies (e.g. Goes et al., 2000; Arrowsmith et al., 2005) have investigated the role of the upper mantle in the distribution of seismicity in Britain. Goes et al. (2000) show that there is an anomalously hot, low-density region beneath Britain that extends down to at least 200 km. Bott and Bott (2004) remark that the combined anomaly zones determined by Goes et al. (2000) cover most of the seismicity of mainland Britain and propose that the distribution of seismicity is associated with thermally weakened crust and associated uplift. Arrowsmith et al. (2005) present higher resolution tomographic images of the mantle anomaly but it does not confirm Bott and Bott's (2004) speculation that the distribution of earthquakes is a good guide to the shape of the anomaly. Assertions by Arrowsmith et al. (2005) that seismicity is related to the anomaly, specifically that earthquakes are concentrated around its edges, are not fully borne out by the distribution of events.

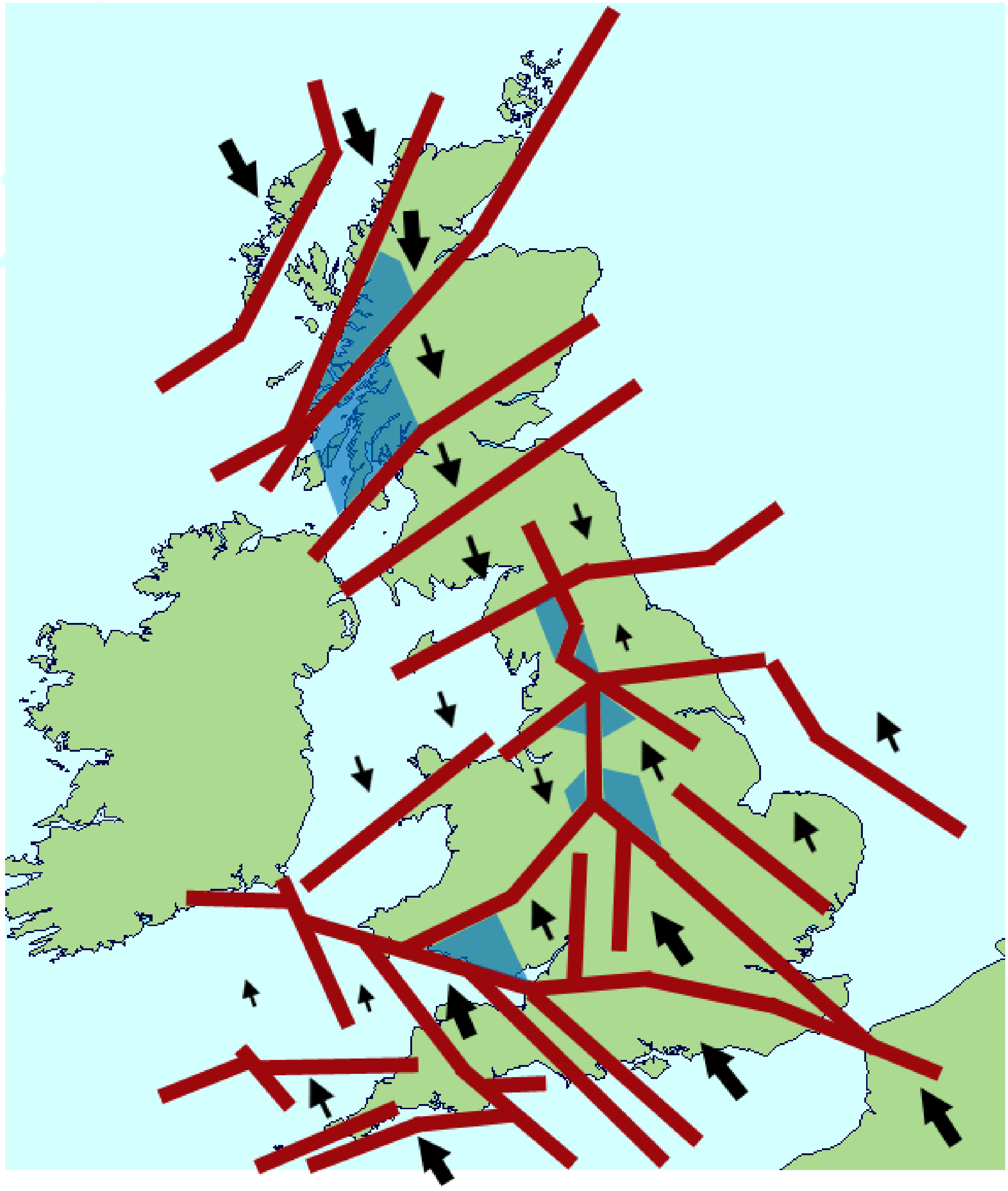

Figure 7 - Kinematic model, after Chadwick et al. (1996). Red lines: major fault zones; arrows: incipient block motion (relative); blue shading: area of high strain rate.

4.5 KINEMATIC BLOCK INTERACTIONS

Chadwick et al. (1996) present a model illustrating the types of province interaction and fault displacements that may be being driven by present-day crustal stresses (see Figure 7). This model assumes an overall north-west – south-east direction of maximum compressive stress, swinging round to a more north-south direction in Scotland. Western Scotland, central northern England and south Wales, which are all areas of relatively high seismicity, are subject to relatively high strain rates. These should be considered as minor ‘jostlings’ or slight rotational adjustments between blocks that are being pressed together (Chadwick et al., 1996), rather than significant deformational processes. One can think of the overall process as being related to geometry as much as geology. The interactions between blocks of differing rigidity in a compressive environment will set up patterns of stress which will be controlled by the spatial configuration of the different blocks. The concept of the rigid indenter is one example of this type of process, which is discussed in more detail by Musson (2007a).

5 Hazard model for this study

In this section, the translation of the preceding discussion into a formal model is described.

5.1 THE SEISMIC SOURCE MODEL

Most of the study area is divided into a series of seismic source zones in which it is presumed that seismicity is homogeneous in character, such that earthquakes have an equal probability of occurring at any point in the zone.

The source model attempts to express both the tectonics and seismicity of the study area. The basic outlines of the model are based on the crustal divisions, especially with respect to overall kinematic processes that can be expected to play a controlling part in determining the distribution of seismicity. The detailed geometry reflects both geological features, where these seem to be relevant, and the seismicity itself.

In contrast to earlier seismic hazard software such as SEISRISK III (Bender and Perkins, 1987), the software used by BGS models earthquakes that occur within defined seismic source zones not as point sources, but as finite ruptures. This means that the spatial extent of faulting in any earthquake is taken into account in the hazard calculations, even though it is modelled as occurring within a source zone. The lengths of ruptures are estimated from the study of Wells and Coppersmith (1994). Of course, in the UK this is not likely to be critical, since seismic sources are generally very small. Each zone in the model is defined according to these parameters:

i) The geometry
ii) The magnitude-frequency parameters of the seismicity
iii) The maximum magnitude
iv) The depth distribution
v) The expected orientations of faulting (which can be random)

Uncertainties in these parameters were expressed using a logic tree structure.

There are 23 source zones in the model, as shown in Figure 8. For convenience, each zone is identified by a code, based on the seismotectonic model of Chadwick et al. (1996), as discussed in the previous section. Unlike many previous source models for the UK, the model used here is strongly based on tectonics and kinematics, and is less influenced by the seismicity distribution, though this is important too. The zones can be thought of as being grouped into four major classes according to basement province: the Scottish Caledonides (SC), English Caledonides (EC), Midland Microcraton (M), and Variscides (V). The coding system used here for source zones uses these four prefixes, followed by a number corresponding to the individual zones in Chadwick et al. (1996) and Figure 6. A number on its own means that the source corresponds more or less to the geometry in Figure 6. A number followed by L, M or H means that the source

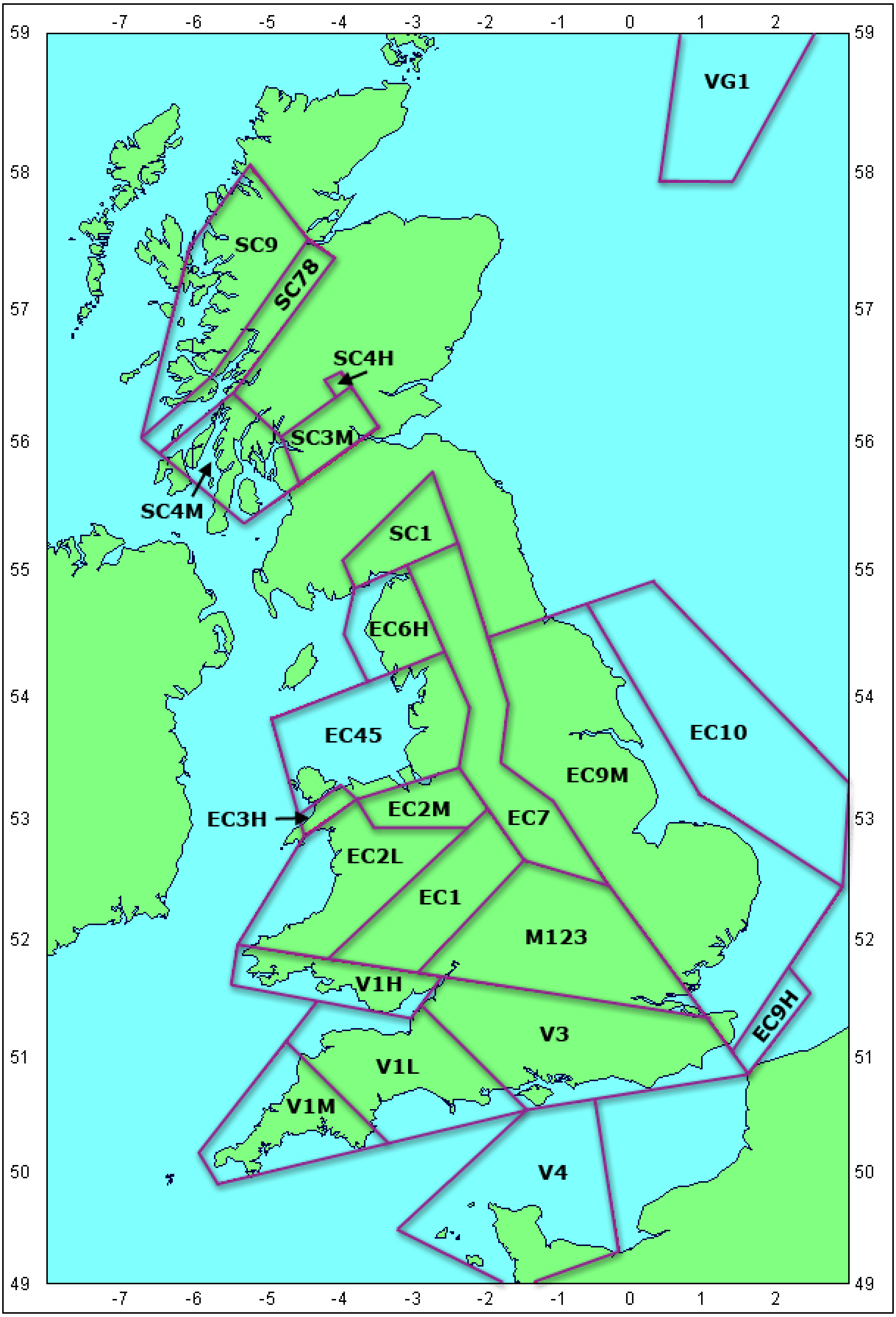

Figure 8 - Zone model for this study.

corresponds to that part of the seismotectonic zone with relatively low, medium or high seismicity (in many cases the low seismicity parts are not actually modelled). Two numbers indicate that two zones have been amalgamated.

In addition, a single zone, VG1, has been added to represent seismicity in the Viking Graben and associated structures.

The source model does not completely tessellate over the whole of the UK; some parts of Scotland with very low seismicity have been excluded, together with the extreme north-east of

England, the Isle of Man, Northern Ireland and much of the offshore waters around the UK. These areas are of such low seismicity that they can be disregarded for hazard mapping purposes (in studying seismic hazard for sensitive structures it might be worthwhile looking at these areas, but not for the present study).

The model will now be discussed on a source-by-source basis.

5.1.1 Scottish Caledonides

SC1M – The Southern Uplands of Scotland are an area of generally low seismicity except for a notable concentration of earthquakes in the Dumfries-Johnstonebridge-Eskdalemuir area. This corresponds to the location of a series of Permian basins, the boundary faults of which could be responsible for some of these events (Baptie 2007). Alternatively, the fact that this area is over the Iapetus Suture directly opposite the northern end of the Pennine Chain may be significant. Historically, none of these events has exceeded 3.2 Mw, so their hazard significance is questionable. The zone has been extended as far as Galashiels to include events there, notably the 1728 earthquake, which is the largest known event in southern Scotland.

SC3M – SC3 represents the Midland Valley of Scotland. This is inactive east of the Ochil Hills. The seismicity has been well reported because of its proximity to urban centres, and includes swarm activity, but is historically all below 3.5 Mw.

SC4H – This is a small zone around Comrie, Perthshire, and is an active source, subject to repeated swarm activity, with events up to 4.4 Mw historically. How to treat this activity in the model is a difficult decision. In the GSHAP model this activity was merged with the Midland Valley seismicity (Grunthal et al. 1996); however, the characteristics of the Comrie seismicity are very different as regards both the tectonic situation and the earthquakes themselves, compared to the Midland Valley activity. One could treat the seismicity as associated with the Highland Boundary Fault (HBF); this would distribute the hazard along the line of the HBF at least to the west towards Aberfeldy (where some recent small earthquakes have occurred, Ottemöller and Thomas, 2007) and perhaps to the east as well, but this may not be realistic – the historical evidence is consistent with a very localised source, perhaps at the intersection of two structures. The option followed here is to treat the seismicity as uniquely located; this follows historical experience, but tends to produce locally high hazard values because of the spatial concentration. (There is also a fourth option of merging all the seismicity of the Scottish Highlands into a single zone; see the discussion in Section 7.1).

SC4M – This is an amalgam of the western part of zone SC4 plus SC6. Together they comprise the southern part of the West Scottish high strain rate area in Figure 6.1 of Chadwick et al. (1996), south of the Great Glen.

SC78 – This is an amalgam of zones SC7 and SC8, with the exception of the part of SC8 north of Inverness. The source corresponds to the Great Glen fault zone (GGF). This is not to say that the GGF is considered to be “active”, as is often claimed in popular works on geology. Rather, it is conjectured that this major fault zone acts as a zone of weakness, promoting seismicity either side of it; this seems to be borne out by the distribution of earthquakes. Many events are clearly close to the GGF but not on it. The source has been extended quite far to the west in accordance with Figure 6, although the western part (SC7) is less seismic active (perhaps partly due to poorer reporting).

SC9 – This source represents the northern part of the West Scottish high strain rate area in Figure 6.1 of Chadwick et al. (1996) and Figure 7, north of the Great Glen, and also the bulk of zone SC9. Arguably the inner part of this source zone, around Kintail, is more active than the outer part, but at the level of events > 4 Mw the disparity is not significant.

5.1.2 English Caledonides

EC1 – This follows zone EC1 fairly accurately. In previous models (Musson and Winter 1996, Grünthal et al. 1996, Jackson 2004) the seismicity of the Welsh Marches has been joined in with that of South Wales, which it resembles to some degree. Here it is separated out due to the seismotectonic difference.

EC2L – The zone EC2 in Chadwick et al. (1996) covers mid Wales and north-east Wales. Since the latter is more seismically active, it is treated separately here. EC2L is a low seismicity source, and not very important to the hazard.

EC2M – This source comprises the northern, more active, part of the EC2 zone.

EC3H – The area around Snowdonia is very strongly active in terms of seismicity, producing some of the largest onshore events to have affected the UK. It is not obvious why this should be so, unless due to stress concentrations on the margins of a P-wave anomaly beneath the Snowdonian Massif, recently revealed by tomographic studies (Hardwick et al. 2007). The rest of EC3 is of very low seismicity and is not modelled.

EC45 – This is the East Irish Sea Basin, and corresponds to EC4 and EC5 merged. There doesn't seem to be enough difference in the seismicity between these two zones to make it necessary to treat them separately.

EC6H – This source is the Lake District Dome, and corresponds to the eastern part of EC6 – the western part is much less seismic.

EC7 – This important source corresponds more or less to zone EC7. Previous models for the UK have not extended seismicity associated with the Pennines as far south as is done here. However, it joins up the high strain rate areas in Figure 7.

EC9H – Another problematic modelling decision is posed by the seismicity of the Dover Straits. This area is prone to earthquakes of magnitude between 5.0 and 5.5 Mw, but since the principal events are both historical and offshore, there is considerable uncertainty as to the source details of this activity. The most recent investigation (Melville et al. 1996) of the historical seismicity here has led to relocations of some of the events north-eastwards, leading to a source extending further to the north-east than the equivalent source in Musson and Winter (1996) or the GSHAP model. Arguably, this view is supported by recent seismicity in the southern North Sea. The 2007 Folkestone event, interestingly, does not fall in the EC9 zone at all, but in V3. If the EC-V divide is meaningful here, it may be that the Folkestone earthquake has no structural connection to the large earthquakes of 1382 and 1580.

EC9M – This source encompasses the rest of zone EC9, covering eastern England and East Anglia. It is of moderate seismicity.

EC10 – This is an offshore source zone covering a number of significant NW-SE trending geological structures such as the Sole Pit Trough, the Dowsing Fault Zone, and the Silver Pit Fault. It has hosted a number of important earthquakes, including the largest known UK earthquake (7 June 1931, 5.8 Mw). The eastern edge of EC10 is unclear in Chadwick et al. (1996); the boundary drawn here is defined by the seismicity.

5.1.3 Midland Microcraton

M123 – In Chadwick et al. (1996) the Midland Microcraton is split into three zones, M1, M2 and M3. There is little to distinguish them seismically, and they are taken together here.

5.1.4 Variscides

V1H – South Wales is grouped with the Cornubian Peninsula in Chadwick et al. (1996) in zone V1, but seismically it is very different, being subject to characteristic earthquakes around 4.5-5.0 Mw in magnitude, whereas earthquakes in Cornwall and Devon seldom reach 4.0 Mw. Source V1H is constructed as a strip along the South Wales coast. As mentioned above, previous models tended to join this to the seismicity of Herefordshire and Shropshire.

V1L – This is another part of V1, of low seismicity, covering Devon, Somerset and Dorset.

V1M – This source more or less corresponds to Cornwall. The boundaries of the source are drawn not far offshore, and reflect chiefly the seismicity.

V3 – This is more or less as drawn in Chadwick et al. (1996), except that a southern border has been added just offshore.

V4 – This source has no counterpart in Chadwick et al. (1996); it is an area of the Central English Channel, including the Channel Islands and the Cotentin Peninsula, and approaching the Isle of Wight to the north. This area has seen a number of significant earthquakes in the past, including events above 5.0 Mw.

5.1.5 North Sea

VG1 – This source is not treated in great detail, and reflects the high seismicity of the Viking Graben and related structures. Because of its distance from land, it is not very important for studies of onshore hazard. It has been drawn so as to include some seismicity associated with the Witch Ground Graben to the south, and also some other structures adjacent to the Viking Graben itself, while avoiding the East Shetland Basin and Horda Platform, which seem to be relatively inactive. The northern and eastern limits have been arbitrarily truncated at 62° N and 4° E. The north-western corner has been extended over to the Magnus Trough on account of the 7 January 2007 earthquake (4.8 Mw) (Lars Ottemöller, pers. comm.).

5.2 RECURRENCE PARAMETERS

The seismicity parameters (*a* and *b* of the Gutenberg-Richter relationship) for each zone were determined using a maximum likelihood procedure according to the method proposed by Veneziano and Van Dycke (1985), and given also in Johnston et al. (1994). This method computes a matrix of possible values, expressing the uncertainty in these two parameters while also taking into account the correlation between them.

It also allows for the maximum possible use of the historical earthquake catalogue, considering that the data will be complete for different periods at different magnitude ranges, as discussed in Section 2 (and shown in Table 1).

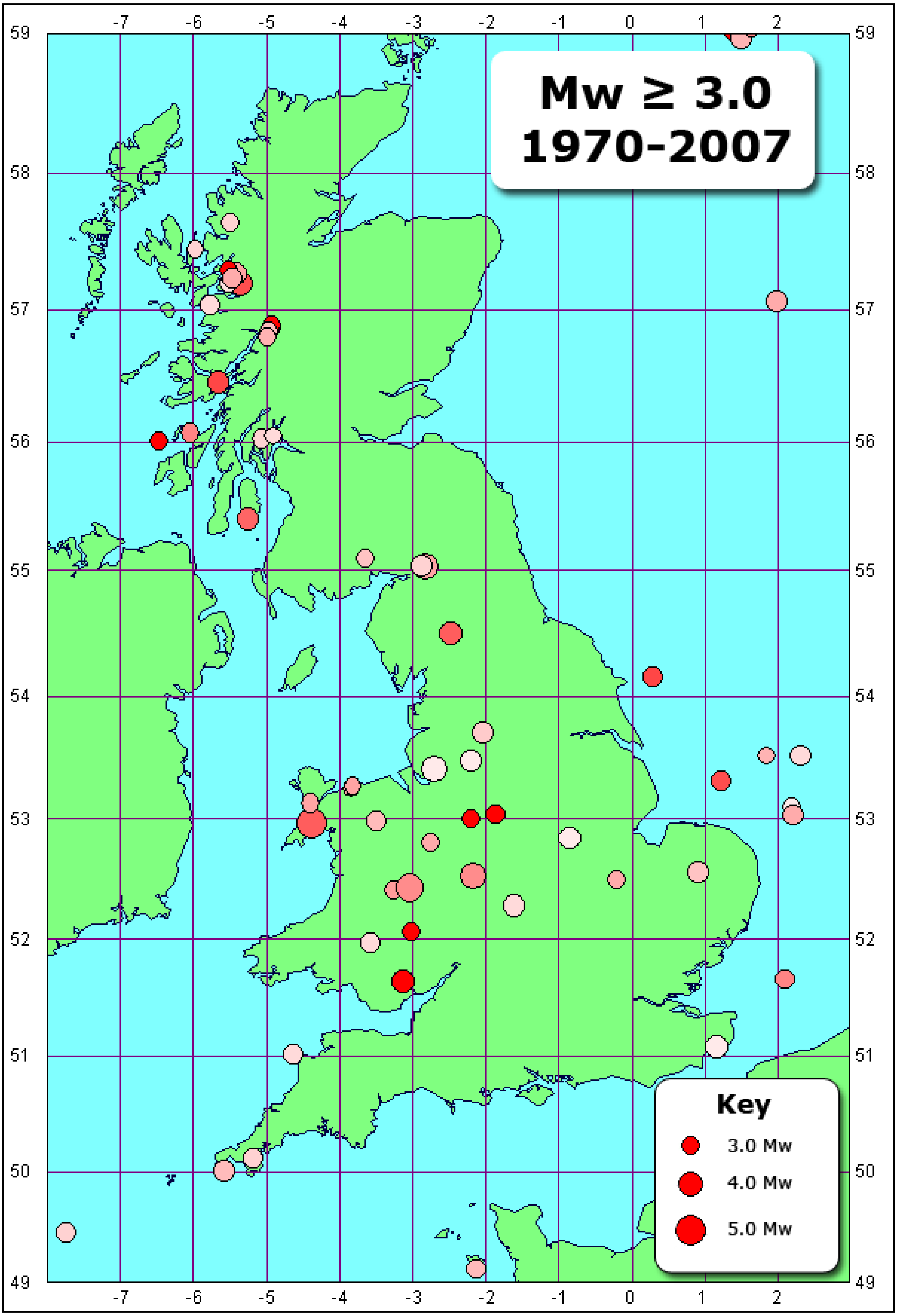

Figure 9 - Seismicity above 3.0 Mw since 1970.

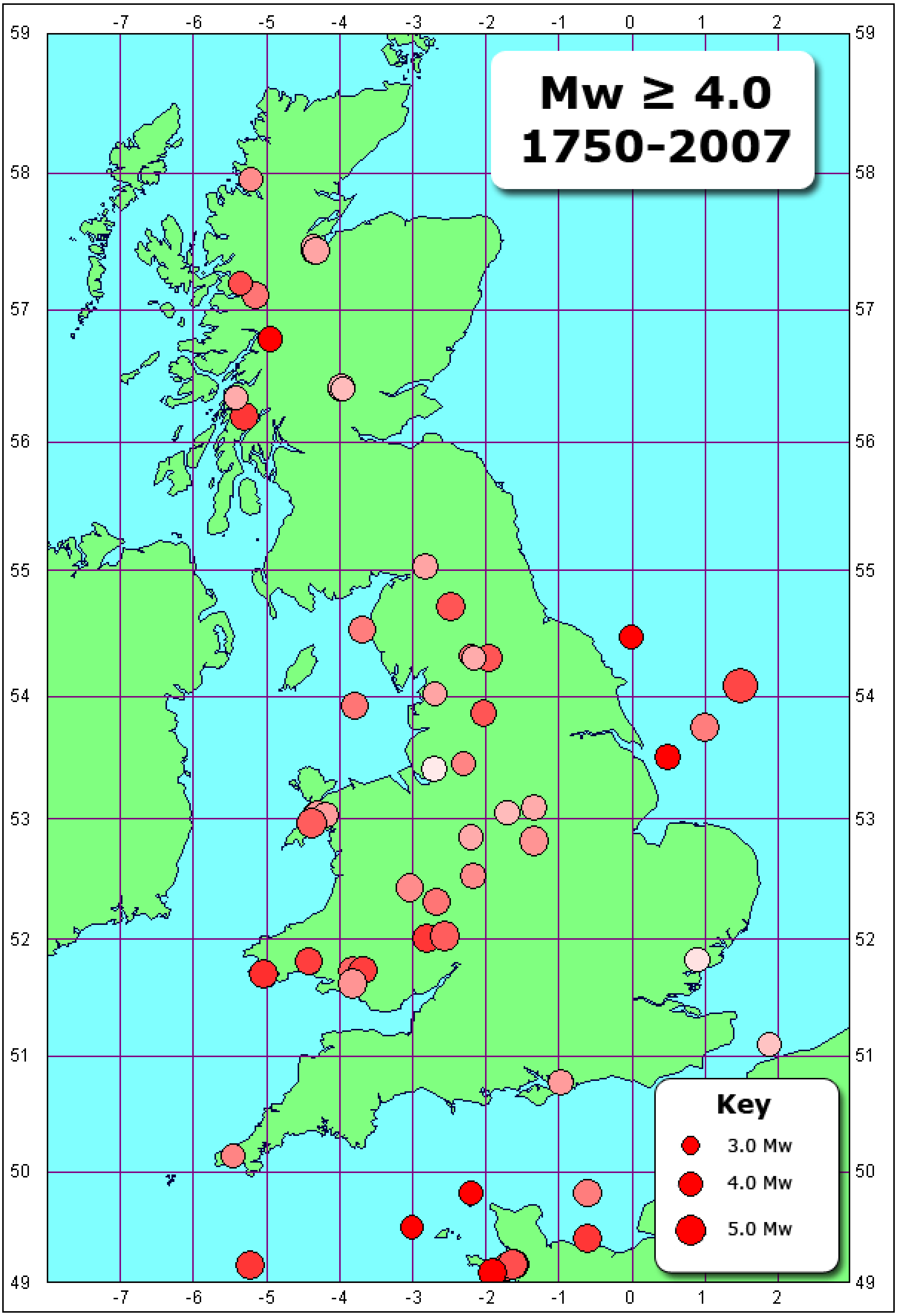

Figure 10 - Seismicity above 4.0 Mw since 1750.

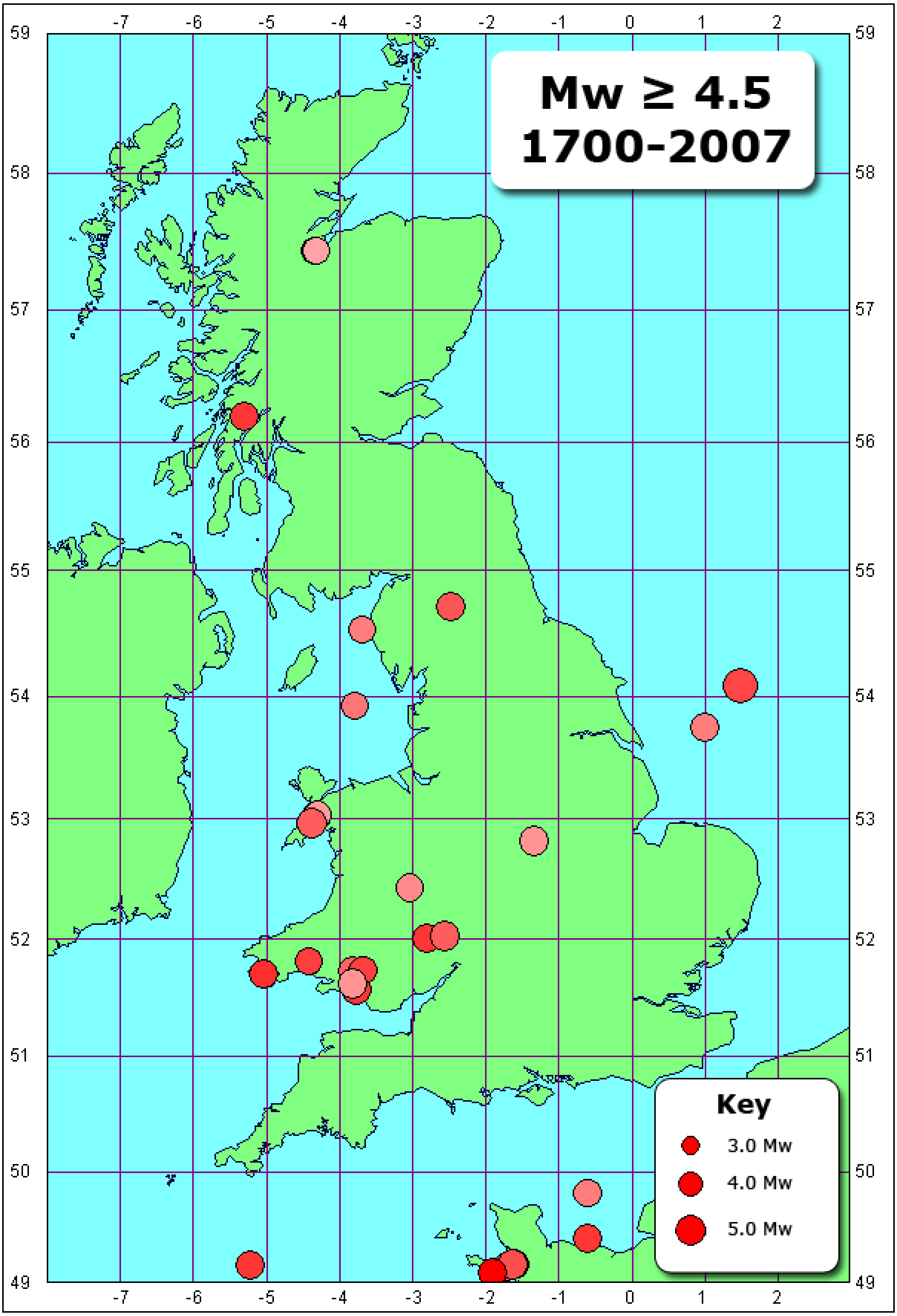

Figure 11 - Seismicity above 4.5 Mw since 1700.

The precise application of the method was as follows.

Essentially, Table 1 defines a series of complete data sets (Figures 9-11). So for a typical zone, recurrence can be assessed on the number of earthquakes with Mw ≥ 3.0 since 1970, *plus* the number of earthquakes with Mw ≥ 3.5 1850-1969, *plus* the number of earthquakes with Mw ≥ 4.0 1750-1849, *plus* the number of earthquakes with Mw ≥ 4.5 1700-1749, *plus* the number of earthquakes with Mw ≥ 5.0 1650-1699 (or usually, the absence of them), *plus* the absence of earthquakes larger than 6.5 Mw since 1000. (The fact that the analysis includes events down to 3.0 Mw is unconnected with the minimum magnitude for the hazard analysis, which is a totally separate issue – see Section 5.4 below. Confining the analysis to larger-magnitude events would give too few data to constrain the results adequately. There is no reason to suppose there is any discontinuity in magnitude recurrence in this part of the magnitude range.) From this information, a 5×5 matrix of correlated *a/b* values is obtained, with the weights on each combination.

However, clearly when there are few events in a zone, the *b* value will be poorly constrained or even indeterminable. Experience shows that around 100 events are needed to obtain good b-value estimates. From the modern instrumental part of the catalogue we obtain equation (1).

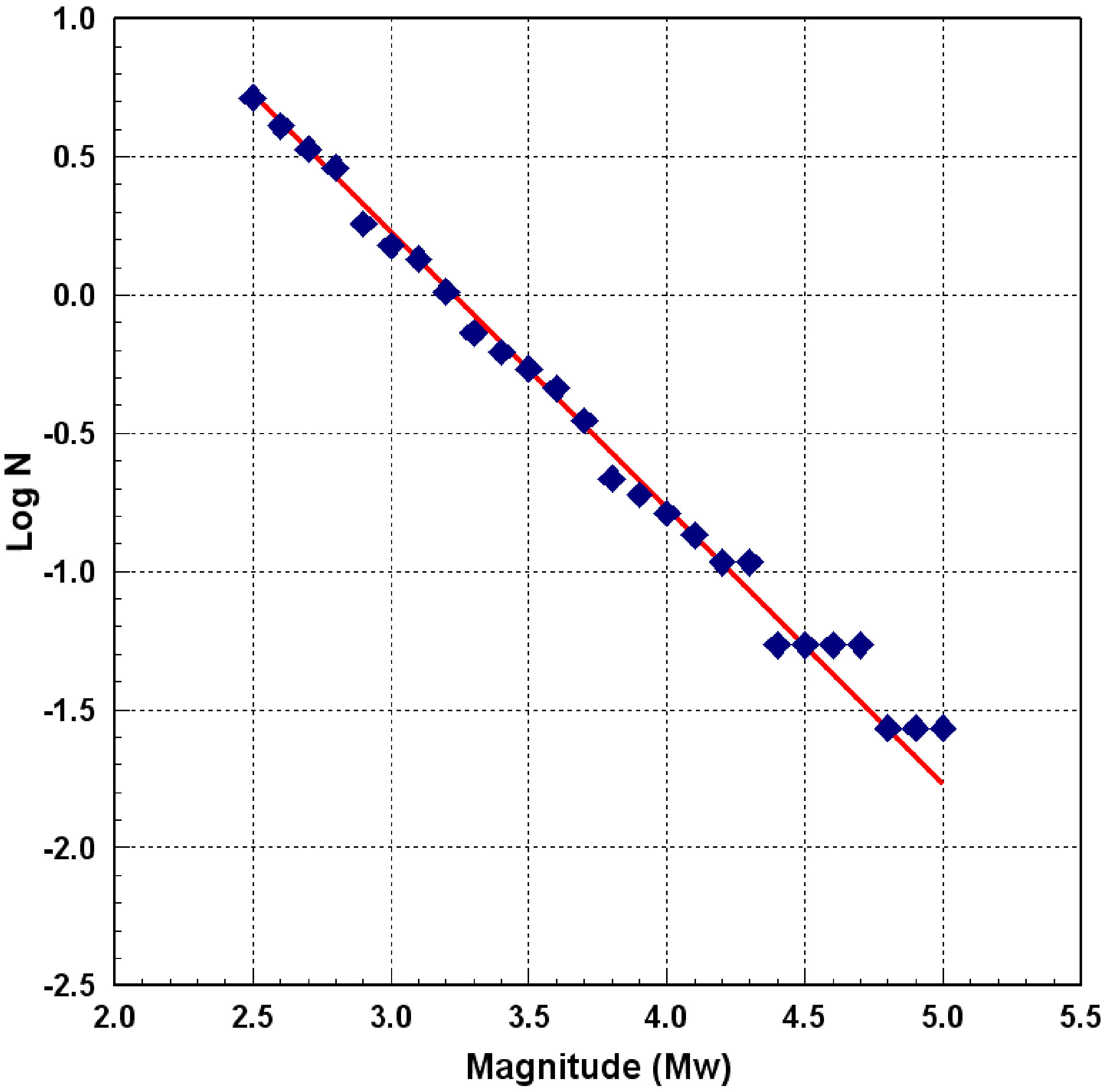

Figure 12 - Gutenberg-Richter plot for post 1970 UK seismicity. The red line shows Equation (1).

$$\text{Log N} = 3.23 - 1.00 \text{ Mw} \qquad (1)$$

This well-constrained *b* value is assumed to gave some general validity over the whole study area, and is used as a weighted prior in the maximum likelihood analysis (weight of 50) for all zones (Figure 12). The weighting system is defined in such a way that a weight of 100 will force all *b* values to the prior, and a weight of 0 will have no effect at all.

The slight variation in catalogue completeness for south-east England in Table 1 was applied to zones EC9M, EC9H, M123 and V3. The Viking Graben completeness values were used for zone VG1.

This procedure could not be used for the zones SC3M and V1L, as there are no earthquakes at all matching any of the completeness thresholds in those zones. Both these zones were given a single *b* value of -1.00 and activity rate of 1.11 (expressed with respect to zero magnitude).

When the resulting model was tested, it was found to underpredict the number of earthquakes with magnitude ≥ 4.5 Mw quite significantly. Excluding VG1, but including V4, in the completeness period for 4.5 Mw (about 300 years), the historical record amounts to 27 events. The average number of events per 300 years given by the model was only 17. While one could argue that this could be a chance effect, analysis of 1,000 synthetic catalogues showed that only 25 catalogues had 27 or more earthquakes.

Furthermore, detailed analysis showed that the effect could be isolated to four zones: EC1, EC3H, V1H and V4. These zones have a proclivity to produce more events in the magnitude range 4.5-5.0 Mw than events in the range 3.5-4.5 Mw, in defiance of expected magnitude-recurrence behaviour. This has been commented on before (Musson 2005, 2007a). While one hesitates to use the phrase “characteristic earthquake” in a discussion not concerned with actual faults, it does seem that in these zones the magnitude range 4.5-5.0 Mw is particularly favoured.

In order to improve the ability of the model to reflect historical experience, these four zones were entered twice into the model. The second entry was constructed so as to increase seismicity in the favoured range, according to the observed shortfall in the predictions made by the main model. These duplicate zones were given a semi-arbitrary *b* value of -1.0 and a maximum magnitude of 5.0 Mw (so the potential for large earthquakes is not increased). The activity rates were set so as to generate the missing number of events, on average, compared to the historical experience, with some scatter (a standard deviation of 0.5 events). The missing numbers were considered to be: EC1, one event, EC3H, two events, V1H, four events, V4, four events. (This is a total of eleven additional events despite the fact that the shortfall on average was ten events. This is due to the fact that the extent of the deficit in the four zones was slightly compensated for by the rest of the model, e.g. a zone with no events ≥ 4.5 Mw historically having an average of, say, 0.5 events per 300 years in the simulations.)

A similar situation applies to zone EC9H, where historically two earthquakes around 5.5 Mw have occurred, and one 4.9 Mw, in the last 700 years. The expected rate of occurrence of magnitude 5 events in the model is 0.55 events in 700 years. A duplicate of EC9H was added to the model, producing extra events in the range 5.0-5.5 Mw only, at a rate of roughly one every 500 years, with a very flat distribution (*b* = -0.1, implying that these “semi-characteristic” earthquakes are almost as likely to be 5.5 as 5.0 Mw).

The complete values obtained by the maximum likelihood method are tabulated in Appendix 2.

5.3 MAXIMUM MAGNITUDE

Maximum magnitude (Mmax) is an essentially unknowable parameter that sets a limit on the largest possible earthquakes to be considered in the hazard analysis. In a broad sense, maximum magnitude can be constrained by fault length – any large earthquake requires a sufficiently large structure to host it, and this certainly limits the locations where great earthquakes (M>8) can occur. However, an approach to Mmax based on fault length runs up against two problems. In the first case, relationships between fault length and magnitude are subject to scatter. According to the values used in this study from Wells and Coppersmith (1994), a subsurface fault length of 50 km is required for a magnitude 7 earthquake. However, this is just a mean value, and one cannot exclude the possibility of a magnitude 7 event occurring on a 40 km long fault. Added to that is uncertainty as to what proportion of a fault can rupture at once. It can be hypothesised that no more than half of a fault will rupture in a single event, but this cannot be demonstrated to be the case.

In an area like the UK, maximum magnitude is a particularly contentious issue, since there is little to go on. In any low seismicity area, the length of the seismic cycle is such that it is quite likely that the historical time window may not capture the largest possible event. Also, considering intraplate seismicity from a global perspective, there are many instances of strong (~7 Mw) events occurring in virtually aseismic areas (Johnston et al 1994).

Nevertheless, there may still be restrictions on what is likely in the UK. The occurrence of large intraplate events in cratonic crust (Ungava, Tennant’s Creek) or on passive margins (Grand Banks) or failed rifts (New Madrid) does not mean that such events can occur anywhere in an intraplate setting. It is interesting to note that throughout recorded history, the largest earthquakes to have occurred in the UK have all been offshore. Events with onshore epicentres have never gone above 5 Mw. This appears to be statistically significant (Musson 2007a); but on the other hand, it is clearly not the case just across the Channel in Belgium where the 1692 Verviers earthquake had a magnitude between 6.0-6.5 Mw (Camelbeeck et al 1999, 2001).

Macroseismic magnitudes of the larger historical earthquakes are also not always well-constrained. There have been considerable doubts about the magnitude of the New Madrid events of 1811-1812 (Hough 2004), for instance. The largest historical earthquake in transalpine Europe is believed to be the 1356 Basel event; the most recent magnitude determination of this, at 6.9 Mw (ECOS 2002), is not accepted by all.

There is also palaeoseismic evidence from Belgium for prehistoric earthquakes between 6.5 and 7.0 in magnitude (Camelbeeck and Megrahoui 1996, Camelbeeck 1999, etc). Additionally, there is a possibility of large passive margin events on the continental slope (Musson 2007b), but this is outside the spatial limits of this study, and in any case would be of such low probability, and at such distance, not to materially affect the hazard calculations.

However, experience shows that for probabilistic hazard analysis in areas of low to moderate seismicity, maximum magnitude is not a critically sensitive parameter. We therefore define two maximum magnitude distributions using a logic tree as follows:

Mmax (Mw)	*Weight (Onshore)*	*Weight (Offshore)*
5.5	0.2	
6.0	0.5	0.6
6.5	0.3	0.4

Table 2 - Maximum magnitude distribution

5.4 MINIMUM MAGNITUDE

It is a requirement of probabilistic seismic hazard assessment that frequency-magnitude relationships have a lower bound as well as an upper bound. This is conventionally deemed to be the smallest earthquake considered to be of engineering significance. Small earthquakes can generate high acceleration values, but because of short duration and high frequency content, these are not likely to result in damage. Informed opinion (see Benjamin, 1989) is that for engineered structures such as dams and power stations, earthquakes less than magnitude 5 Mw can be discounted, but for other applications, a lower bound of 4 Mw is appropriate. This issue was discussed at a project review meeting of interested parties in the UK hazard community (Booth 2007). It was agreed that a compromise value of 4.5 Mw was suitable.

In this study we therefore use 4.5 Mw as the smallest magnitude to be considered in the hazard analysis.

5.5 DEPTH DISTRIBUTION

A study by Baptie (2002) divided the UK into six areas, and found differences in depth distribution between these areas, with north-west Scotland and Cornwall having generally shallower seismicity. This study used mostly small magnitude events (< 4 ML), and it is questionable whether these conclusions also apply to larger magnitude events. It is suggested by Musson (2007a) that larger British earthquakes are generally deeper. Analysing the events with magnitude ≥ 4.5 Mw in the catalogue, the shallowest event is at 11 km and the mean depth is 20 km. Of course, some of these depth values are rather uncertain. It is not possible to see any significant regional variation. Thus, a single depth distribution was used for all zones, as shown in Table 3.

Depth (km)	*Weighting*
5	0.10
10	0.25
15	0.40
20	0.25

Table 3 - Depth distribution for all zones

This is actually a shallower distribution than shown by the data, to allow for the possibility that some of the depths of historical earthquakes may be overestimated.

5.6 FAULTING

The effect of style of faulting, fault orientation and rupture dimensions is taken into account in the hazard calculations, though the physical extension of earthquake ruptures has next to no effect on hazard because source dimensions are very small for the UK. We consider that the UK experience in the last 30 years as regards focal mechanisms of the larger events is most likely typical, and future earthquakes are expected to be predominantly strike-slip events on north-south or east-west trending structures. Thus, for all zones in the model, we define a faulting distribution of 100% strike-slip events, 50% with north-south orientation and 50% with east-west orientation. This is certainly sufficient for hazard mapping purposes; for site studies it would be possible to investigate the sensitivity of the results to other potential faulting models.

6 Ground Motion Model

Choice of ground motion model is an important factor in seismic hazard analysis. This is the equation that predicts what ground motion value will be observed at site as a function of magnitude and distance (and possibly other factors). The uncertainty (scatter) in this prediction (usually referred to as sigma) is itself an important factor.

6.1 STRONG GROUND MOTION MODELLING IN INTRAPLATE AREAS

Ideally, it is preferable to use a ground motion prediction relation derived from local data, but this is seldom possible except in regions of dense station coverage and high seismicity such as Japan and California. Otherwise, one must adopt either (a) a relationship in which local data is augmented with data from a broader region, or another region altogether, or (b) a relationship from anywhere in the world considered to be tectonically similar. It can also be argued, though, that a model based on a large amount of data from a variety of sources is likely to be more robust than a model using less data, but only from more local sources (Ambraseys 1995). In actual use in hazard analysis, a ground motion model will be called upon to predict accelerations from the complete spectrum of magnitude and distance. A model that is derived from a dataset that does not cover this full spectrum may not be reliable. This is a particular problem in that datasets frequently tend to be biased towards small earthquakes at short distances and large earthquakes at long distances (and generally, the largest earthquakes are severely under-represented). This can lead to scaling problems when ground motions must be calculated for parts of the magnitude-distance domain not well represented in the dataset.

This has important repercussions for areas like the UK. A number of studies in the past have attempted to use what local data exist in the UK to derive locally-validated models (Musson et al 1994, Winter et al 1996, Free et al 1998), and found strong inconsistencies between local data (mostly from small earthquakes and at quite considerable distances) and published models that have been used for UK hazard studies (Joyner and Boore 1981, Principia 1982, Ambraseys and Bommer 1991). It is now considered that it is really not reliable to scale up weak ground motions to strong ground motions – but this implies the converse, that one cannot reliably estimate weak motions from strong ones. Thus a ground motion model in which the scaling is derived principally from large earthquakes may be particularly poor at predicting ground motions from relatively small events – which may actually dominate the hazard in low seismicity areas. One possible option, which was seriously considered for this project, would be to use a composite model in which a weak motion model such as Free et al (1998) would be used for events less that a threshold magnitude value (5.0 or 5.5) and a strong motion model (such as Ambraseys et al 1996) for larger events. However, careful inspection of weak motion models suggests that they are too weakly constrained even for this application.

As it happens, the development of ground motion models is currently in a state of flux. On the one hand, theoretical debate has been advanced by a series of methodological discussion papers such as Bommer and Scherbaum (2005), Bommer et al. (2005), etc, covering several important issues. These are concerned especially with handling uncertainty in ground motion predictions, both epistemic (relating to lack of knowledge about expected ground motions) and aleatory (relating to chance fluctuations). This is a critical issue. It is shown by Abrahamson and Bommer (2006) that a tendency of recent hazard results to be systematically much higher than older ones is due to more accurate treatment of uncertainty in ground motion modelling. On the other hand, it is argued by Brune (1999) that the current treatment of uncertainty, regardless of whether it is methodologically correct or not, may be demonstrably overestimating hazard.

At the same time, new ground motion models are being produced with some frequency. In Europe, a series of models based on European and south-west Asian data, that began with Ambraseys and Bommer (1991), has continued with Ambraseys et al (2005), Akkar and Bommer (2007), and Bommer et al. (2007). Also, a model published by Berge-Thierry et al (2003) for use in France, is clearly of interest to the UK as well. At the same time, in the United States, the Next Generation Attenuation (NGA) project has sought to take ground motion modelling to a new level of complexity hitherto not seen (Power et al. 2006).

A full discussion of all these developments is beyond the scope of this report, so we confine ourselves to what is most important regarding decision making in the present project.

6.2 SELECTION OF GROUND MOTION MODELS FOR THIS STUDY

The models of Ambraseys and Bommer (1991), Ambraseys (1995) and Ambraseys et al (1996) have been widely used in Europe, and to some extent represent a conceptual anchoring point with past studies. These are all more or less compatible, and differ only slightly in the results derived from them. In contrast, the Ambraseys et al (2005) model is incompatible with them and predicts higher hazard levels that appear unrealistic (see Section 6.3 below). This is due to a combination of an insensitive magnitude scaling system with a magnitude-dependent uncertainty that gives very high uncertainties on ground motions from smaller earthquakes (which are dominant in the UK). Thus, although the median predicted ground motions predicted by Ambraseys et al (2005) are similar to those of Ambraseys et al (1996), the predicted hazard levels are very dissimilar. Given that the magnitude-dependence of the uncertainty may very likely be an artefact of data selection or poor metadata (Campbell and Bozorgnia 2006a) it is undesirable to have the hazard increased dramatically for what may not be a good reason. As a result, it was decided not to use Ambraseys et al. (2005) in this study.

Turning to consideration of the NGA project: in this, five teams were asked to produce empirical ground motion models for use in active shallow crustal regions, from a common database of worldwide strong-motion recordings (Power et al 2006, Campbell and Bozorgnia 2006b). Models were required to be valid for magnitudes up to 8.0 Mw (8.5 for strike-slip events), for distances up to 200 km, and spectral periods up to 10 s. Such a requirement forced the teams to develop elaborate functional forms to enable the models to scale effectively across the entire domain. As a result, the models produced by the teams are more complex than any previous models. Some of these complexities are introduced to handle factors not greatly relevant to the UK, such as detailed modelling of hanging wall effects in large thrust earthquakes. However, others are very relevant. For instance, the model of Campbell and Bozorgnia (2006a) uses a trilinear approach to magnitude scaling, in contrast to the linear approach used by Ambraseys et al (2005) and Berge-Thierry et al (2003). This means that magnitude scaling at both the high and low ends of the magnitude domain are handled independently, and thus likely to be rather more accurate in the modelling of ground motions from relatively small earthquakes in places like the UK.

The far greater degree of sophistication in the NGA models, especially with regards to magnitude and distance scaling, makes the use of NGA models in the present study a compelling choice, provided one can justify the use in the UK of models designed for “active” crustal regions. Clearly, the UK is not an active seismic area in the normal sense of the term, but equally, neither is it a stable shield area. The limited experience in dealing with ground motion from earthquakes in north-west Europe has suggested that models based on Californian data are more appropriate for the UK than models intended for use in Eastern North America. Also, any purely empirical model is likely to be based mostly on data from active regions, so any tectonic argument against applying NGA models is equally valid against Principia (1982), Ambraseys et al (1996) and any other of the main models that have been used in UK PSHA studies in the past.

The NGA models are also viewed as updates of well-established previous models. Thus Campbell and Bozorgnia (2006a) is stated to be an update on Campbell (1997) and Campbell and Bozorgnia (2003), and to be sufficiently scientifically superior that it can be considered to completely supersede those earlier models. Similarly with Chiou and Youngs (2006) with regard to Sadigh et al. (1997), and so on.

Akkar and Bommer (2007) and Bommer et al. (2007) represent an intermediary situation between the relatively simple models such as Ambraseys et al. (2005) and the NGA models. Akkar and Bommer (2007) use a very similar data set to Ambraseys et al. (2005), of European-Mediterranean data, but a more complex functional form, though not so elaborate as the NGA models. Of special interest to the present study is Bommer et al. (2007), which extended the Akkar and Bommer (2007) dataset downwards to include events as low as 3.0 Mw. They found that ground motions for smaller events were significantly over-predicted by Akkar and Bommer

(2007). Furthermore (and this is highly significant, if perhaps not wholly unexpected), they demonstrated that, not only are models such as Akkar and Bommer (2007) unreliable when projected outside the margins of their ranges of applicability, they are also unreliable *at or close to* the margins.

The question, then, is exactly which models to pick. Harmsen (2006) has shown that the five NGA models actually agree with one another rather well, considerably better than the antecedent models that they replace. This consensus would seem to be a good sign. Although the models are ultimately based on the same data resource, the modelling teams were allowed to make their own selections from the data, using whatever criteria they chose. It seems unnecessary, therefore, to implement all five models. Campbell and Bozorgnia (2006a) seems from Harmsen (2006) to be perhaps the most representative (i.e. least outlying) model for intraplate sites, and the trilinear approach to magnitude scaling is attractive.

We combine this with the Bommer et al. (2007) model, which is clearly of great interest for the UK. Bommer et al. (2007) include a discussion as to whether uncertainty should be magnitude-dependent or not. Their initial findings supported a magnitude dependency (in line with Akkar and Bommer 2007), but they acknowledge the weight of the arguments in Campbell and Bozorgnia (2006a) and elsewhere, that this may be an artefact. They thus provide a second model (their Tables 4 and 5) in which aleatoric variability is treated as independent of magnitude. Inevitably, though, this results in rather high values of sigma. However, if the apparent magnitude dependence of sigma is due to uncertainties in the metadata, these uncertainties are not expunged in the second model from Bommer et al. (2007), and undoubtedly are inflating the final values for sigma.

There would be some justification, therefore, in simply taking a "generic" sigma value (i.e. a value frequently reported by other studies) and using it in place of that from Table 5 of Bommer et al. (2007), while using coefficients from Table 4 of Bommer et al. (2007). Such a procedure would be analogous to that followed in non-empirical ground motion models (for example, Toro et al. 1997). This would also combat to some degree the fact that when ground motions from small earthquakes do scatter to high values, these are generally in high-frequency spikes of no engineering significance; thus the high scatter, while observed in data sets, should not be allowed to over-influence the hazard results for engineering purposes.

However, in this study we avoid these issues and simply apply the primary model from Bommer et al. (2007), i.e. Tables 2 and 3, with no modification. It is, however, assumed that the maximum value of aleatory uncertainty is the value for 5.0 Mw, following a pers. comm. suggestion by John Douglas. This gives an intra-event variability of 0.546-0.060 Mw and an inter-event variability of 0.326-0.032 Mw for PGA, in base 10 logarithms, where Mw is considered never to be less than 5. For Mw = 5, this works out to a sigma of 0.297, or 0.683 in natural log units, which is significantly higher than the value of 0.526 obtained by Campbell and Bozorgnia (2006a).

The two models, Campbell and Bozorgnia (2006a) and Bommer et al. (2007), are equally weighted in our logic tree, following the principle of indifference.

It may be noted in passing that Campbell and Bozorgnia (2006a) and Bommer et al. (2007) take a different approach to the measurement of source-site distance. The latter uses Joyner-Boore distance (distance to the surface projection of the coseismic rupture), while the former uses a mixture of measures, but predominantly rupture distance (which is arguably the better measure for UK earthquakes which have small source dimensions). A merit of the M3C hazard software is that it can handle the combination of different distance metrics with complete accuracy, since each component ground motion model is encapsulated in its own independent subroutine, using its own approach to distance measurement. The problems discussed by Scherbaum et al. (2005) thus never arise, since it is never necessary to convert one distance measure to another.

6.3 SENSITIVITY TEST

As a test of the sensitivity of the results to the choice of ground motion model, a series of hazard curves is presented for a "typical" UK location (actually a point in south-east Wales). Figure 13 compares the results obtained from Campbell and Bozorgnia (2006a) alone, Bommer et al. (2007) alone, and the weighted combination. Additionally, Figure 14 compares the preferred model with what would be obtained from some other studies: Ambraseys et al. (1996), which has been used in the past for a number of routine UK seismic hazard studies, Berge-Thierry et al. (2003), intended to be applicable to France, Ambraseys et al. (2005), considered to be an update on Ambraseys et al. (1996), and Chiou and Youngs (2006), which is probably the most conservative of the NGA models for intraplate usage. In Figure 14, the results have all been standardised with respect to definition of PGA, so the curves are exactly comparable. Only the two Ambraseys et al. studies define PGA as the larger of two components; all the other studies discussed in this section use a definition that is either the geometric mean or is more or less equivalent.

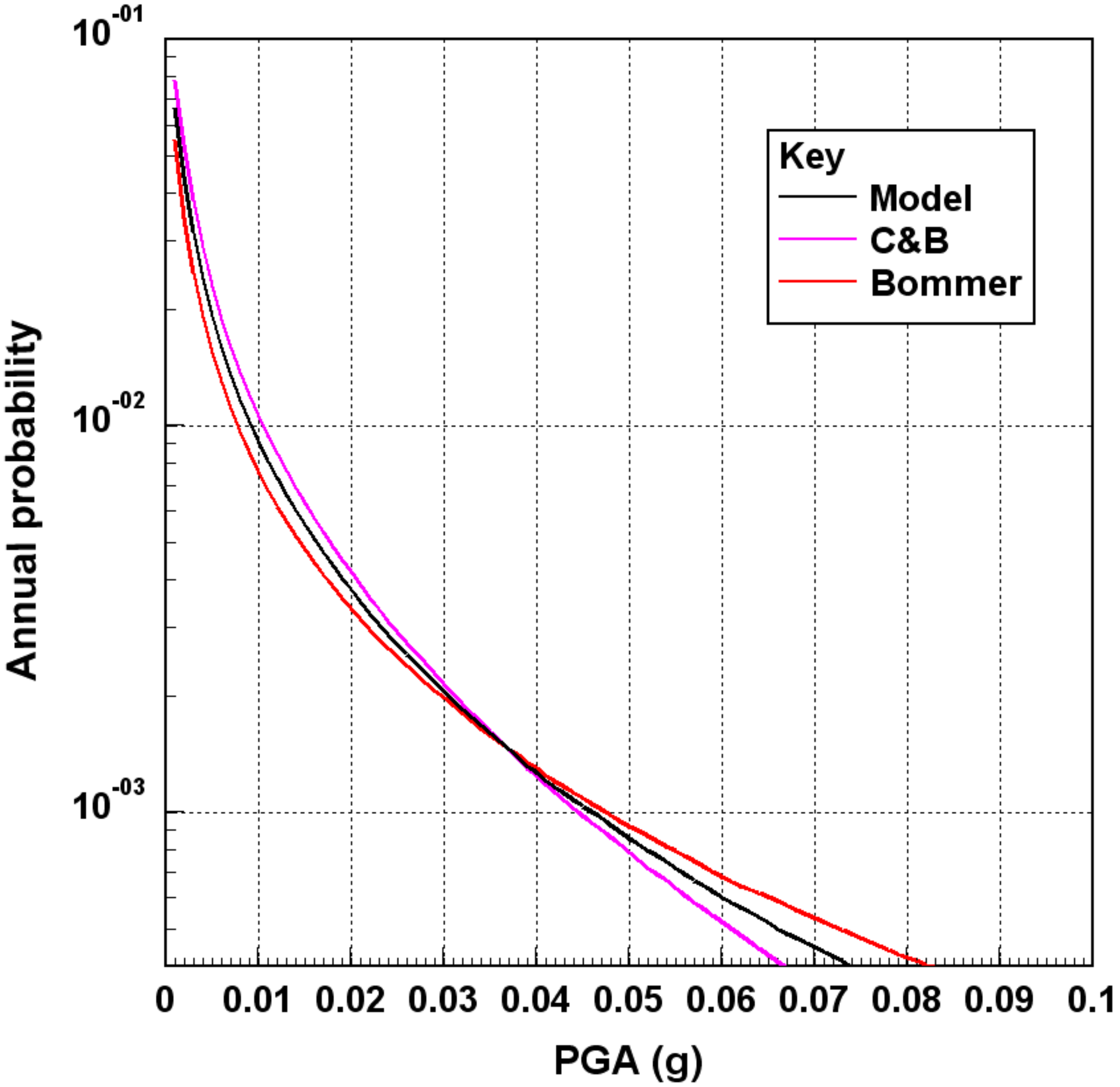

Figure 13 - Comparison of the two SGM models used in this study (and the two combined). These are hazard curves for a site in south-east Wales. C&B = Campbell and Bozorgnia (2006a); Bommer = Bommer et al. (2007).

The curves are only shown to an annual probability of 1 in 2,500, since this is the probability limit for this study. The two models selected for this study are in rather good agreement. For probabilities higher than 0.00105 per annum (1 in 950) Campbell and Bozorgnia (2006a) gives higher results, due to the influence of the smaller magnitude events in the Bommer et al. (2007) data set on the median predictions. At lower probabilities, the higher sigma values in Bommer et al. (2007) become more influential.

Figure 14 shows that sensitivity to choice of ground motion model increases with increasing return period. The comparison with Berge-Thierry et al. (2003) and Ambraseys et al. (1996) is complicated by the need to convert Mw to Ms; views on this conversion differ (see, for instance, Grünthal and Wahlström 2003).

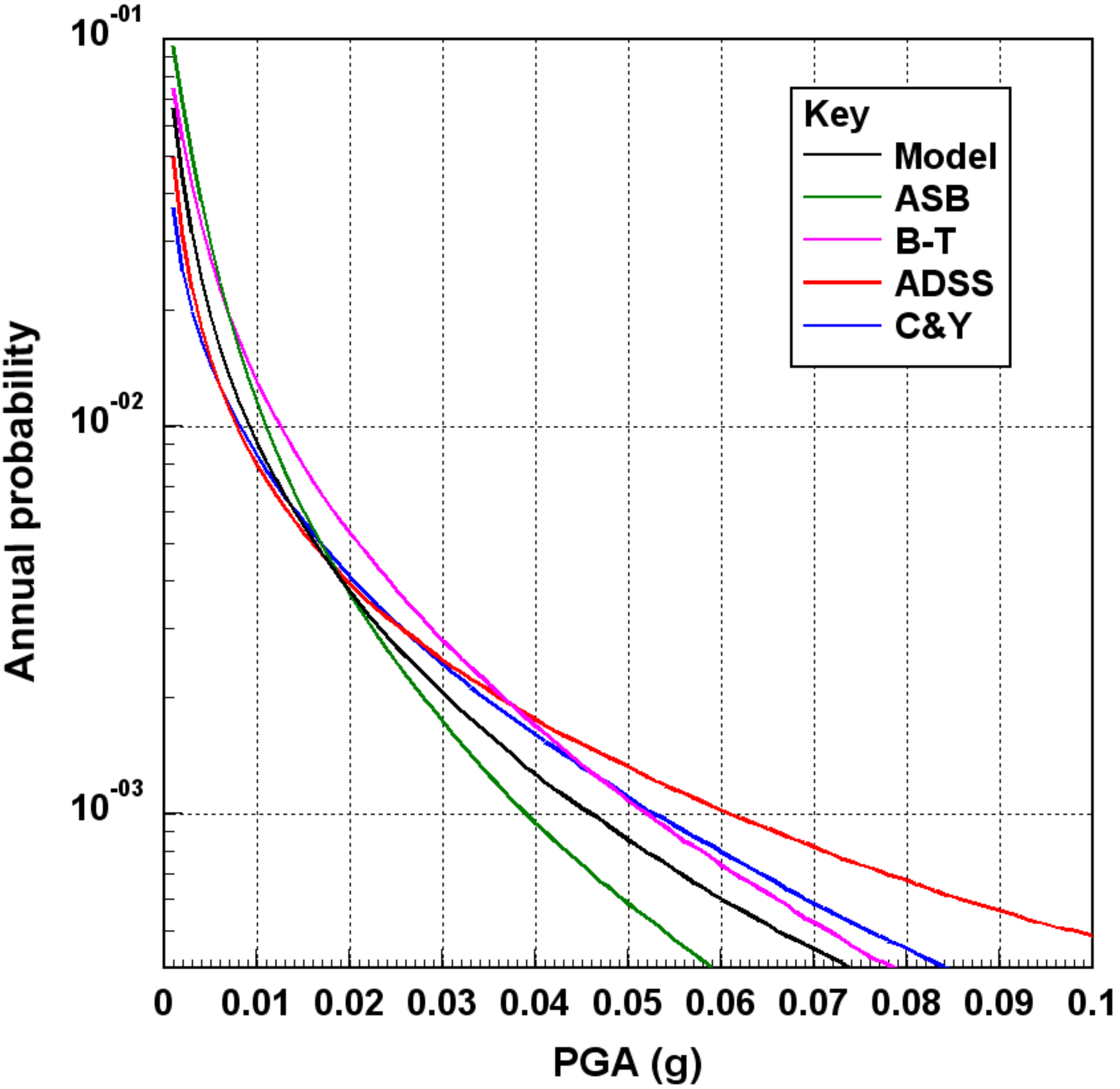

Figure 14 - Comparison of the SGM model used in this study with some other models; hazard curves for the same site as the previous figure. ASB = Ambraseys et al. (1996); B-T = Berge-Thierry et al. (2003); ADSS = Ambraseys et al. (2005); C&Y = Chiou and Youngs (2006).

Ambraseys et al. (2005) give markedly higher values; it appears as an outlier in the distribution due to the high sigma values given. The contrast with Ambraseys et al. (1996) is very marked. Thus, although Ambraseys et al. (2005) is a recent study, it does not seem to be recommendable for practical use in hazard analysis. The high sigma values in Bommer et al. (2007) could also be an issue in studies examining longer return periods than looked at in the present study. It would be worth examining whether these could improved, e.g. by varying the distance measure used. Joyner-Boore distance may not be appropriate for smaller magnitude events.

7 Results

The hazard calculations are based on running the model for 100 years 25,000 times, for an effective 2.5 million observation-years. This is sufficient to give good resolution of the hazard down to the 2,500-year return period level.

The maps are presented as Figures 15 and 16. Values were computed over an area bounded by 49 - 59° N and 8° W - 2° E. The computations were made for points distributed on a grid at

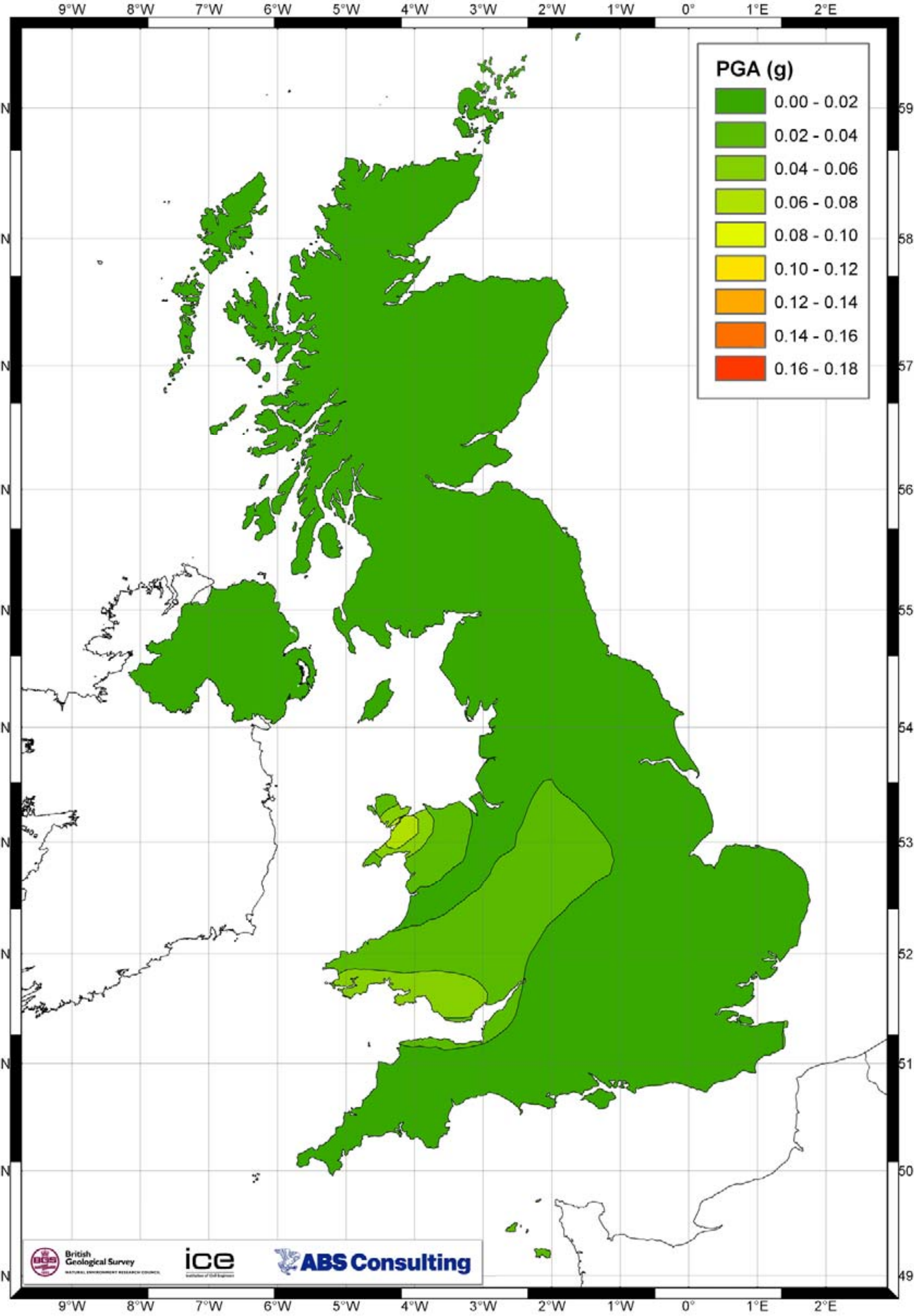

Figure 15 - PGA hazard map for 475 year return period.

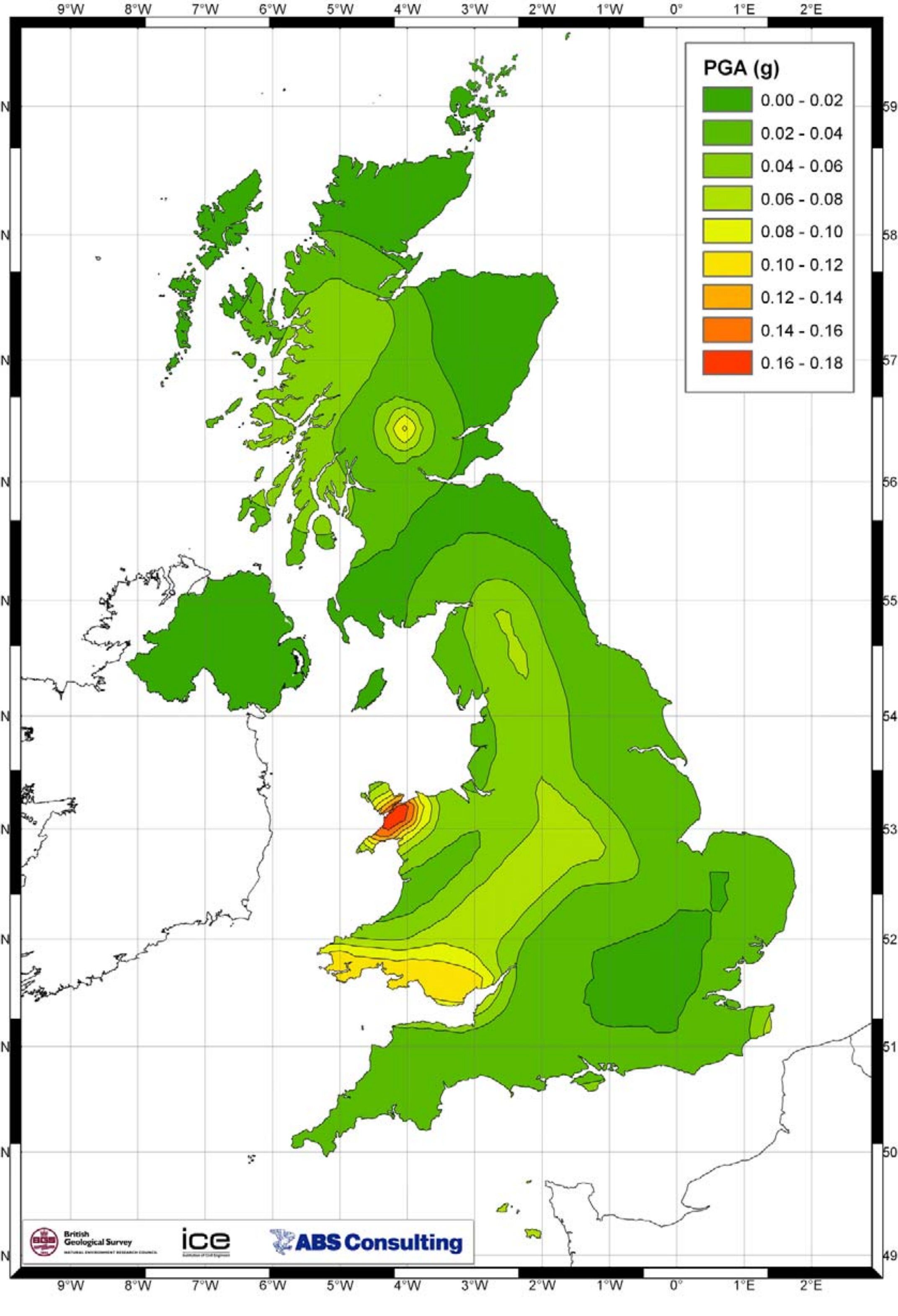

Figure 16 - PGA hazard map for 2,500 year return period.

approximately 15 km intervals in both directions, and this defines the spatial resolution of the maps. The contours were generated using a regularised spline technique based on twelve-point samples. (This was chosen to avoid smoothing away peaks in the hazard.)

The map (Figure 15) of PGA values with 10% probability of being exceeded in 50 years (475 year return period) shows that for most of the country values are less than 0.02 g, the exceptions being north-west Wales, south Wales, and a belt extending through the Welsh Marches to the Peak District. This contour also includes the Channel Islands, and just clips the coast of east Kent. The figure of 0.04 g is reached in a small part of north-west Wales and along the south

Wales coast. Figure 16 shows ground motion values at the 2,500 year return period and is more expressive of the spatial distribution of hazard; again, the highest amplitudes are in north-west Wales, reaching 0.16 g. A PGA value of 0.10 g is shown over most of south Wales, and is also reached at Comrie, in Perthshire.

It should be re-iterated that the values shown on these maps are not necessarily a good guide to the results that would be obtained from site studies (see Appendix 1). This is likely to be particularly true for sites close to the epicentre of a significant past earthquake. In the compilation of a hazard map, it is sufficient to assume that a recurrence of this earthquake could occur anywhere within its source zone, in the absence of any evidence to the contrary. In a site study it is likely that one would wish to examine the hypothesis that the earthquake in question might repeat itself in more or less the same location, and possibly with a large magnitude. This leads to a localisation of the hazard, which can significantly increase the ground motions to be expected, especially at longer return periods.

7.1 DISCUSSION AND VALIDATION

The results shown in this study are rather low, even given the understanding that the UK is a low seismicity area. The results shown in Figure 15 are, for instance, lower than those obtained in the European map of seismic hazard prepared in the SESAME project (Jiménez et al. 2001) and its global predecessor, GSHAP (Grünthal et al. 1996). In both these maps of hazard for the 475 year return period, almost all of Great Britain fell within the 0.02 g contour, and most of western Scotland, western England and Wales within the 0.04 g contour, with a substantial area rising above 0.06 g. It is useful, therefore, to consider what factors may influence this contrast.

Firstly, it can be reiterated here that many previous UK studies have used the definition of PGA as the larger of two horizontal components, whereas this study uses the definition more generally followed in recent strong ground motion models as the geometric mean of the two components. This immediately reduces the results by a factor of 1.15.

While it is a commonplace in the seismic hazard community that results tend to be dominated by decisions made about the ground motion model, here it is not apparent that this is primarily the case. As was seen in Section 6.3 above, the selection of ground motion model is not highly critical for this study. (This would be less true at longer return periods.)

A further contributing issue is the minimum magnitude bound of 4.5 Mw. This corresponds, according to the conversion formula used, to a magnitude of 4.9 ML, and such events are not common in the UK, especially not on the UK mainland. In the last 300 years, there have been only eighteen such events with onshore epicentres, a rate of about one event per seventeen years. (The last 34 years have been true to this rate, with two such events in 1984 and 1990; the 1979 Carlisle earthquake just missing the cut). Figure 15 shows the ground motion with 10% chance of being exceeded in 50 years – but for any 50 year period, the average number of onshore events is only three – and these might occur anywhere in Britain. So the overall likelihood of one of these events occurring sufficiently close to a site to be damaging is rather low.

Previous studies have used lower minimum magnitude thresholds (as low as 4.0 ML in Musson and Winter 1996), increasing the amount of seismicity contributing to the hazard. As a test, comparison was made between the results obtained and those that would be obtained using a minimum magnitude of 4.0 Mw. Using a minimum magnitude of 4.5 Mw, the simulations produced a mean of 12.82 events per 100 years (including the offshore parts of the model). Changing the minimum to 4.0 Mw increased this to 32.02 events per 100 years.

The effect of this on the hazard is, however, damped, especially in some parts of the country, such as South Wales. Where seismicity is concentrated in the magnitude range 4.5-5.0 Mw, reducing the minimum magnitude to 4.0 Mw makes little difference. The hazard is controlled by events around 4.5 Mw in magnitude. Taking an area like the Scottish Highlands, where this characteristic magnitude range is not an issue, reducing the minimum magnitude to 4.0 Mw would increase the hazard by a factor of around 1.35 for a 475 year return period and 1.15 for a 2,500 year return period.

Since these factors are not sufficient to explain the differences between our results and, for instance, the SESAME results, it would appear that a mixture of factors are at work, including, probably, differences in the magnitude-frequency analysis.

An important question, therefore, is whether the current model adequately expresses the seismicity of the UK above 4.5 Mw. For this, it is easier to remove the Viking Graben from the discussion, since completeness is so much less for this zone. For the rest of the model, the number of events this size in the last 300 years is 27. Whether this is true to the long-term average, one cannot know – this is epistemic uncertainty that needs to be incorporated in the model.

But there is an issue, that one also cannot tell whether the last 300 years were relatively active or relatively inactive as regards the true long-term rate. What can be said, though, is that likely things are inherently more probable than unlikely things. This may seem a tautology, but it means that, by implication, it is more probable that the historical record was a likely outcome (with respect to long-term averages) than that it was an unlikely outcome. If it was a likely outcome, then the uncertainty with respect to the true rates should be a distribution more or less symmetrical about the observed distribution.

This returns us to the issue of the duplicate zones added to the model to account for “semi-characteristic” earthquakes. Testing the initial model showed that the historical result was so much of an outlier to the probability distribution of possible model outcomes that the predictive power of the model was questionable.

While the use of these zones means that the statistics of the model depart from the pure objectivity of the maximum likelihood method, they do provide a corrective, such that it becomes possible to “close the loop” and certify that the output of the model is compatible with the input (Musson 2004c).

One can now repeat the validation exercise. It is suggested by Musson and Winter (2007) that a useful measure is provided by the distribution of number of events and mean magnitude of a population of simulations of N years of earthquakes according to a model, and the historical values for N years of observation. (Mean magnitude is a crude estimator of *b* value).

For this purpose, the model (excluding the Viking Graben) was used to generate 1,000 simulations of 300 years length. For each simulation the number of events ≥ 4.5 Mw was counted, and the mean magnitude of events ≥ 4.5 Mw. These were then plotted as a smoothed contour plot of the probability distribution of the various combinations. This is shown as Figure 17 (contour value is number of simulations out of 1,000). The historical result is shown as a star; it plots acceptably within the distribution. The model is shown to be slightly conservative, insofar as it predicts slightly more large earthquakes (mean magnitude of 4.9 as against observed 4.8) and slightly more earthquakes (28 per 300 years against observed 27), but these are minor differences. One can therefore conclude that the model, overall, gives an accurate representation of the seismicity of the UK when tested against the last 300 years of observation.

The same is also true when the zones are analysed individually. While Figure 17 shows that the model overall is producing the correct level of seismic activity, one wishes to know also that earthquakes in the synthetic observations have the correct spatial distribution vis a vis the zone model.

To this end, Table 4 is presented, which shows the expected number of events ≥ 4.5 Mw per zone in 300 years according to the model (from the simulation results), and the observed number in the earthquake catalogue.

Zone	Predicted	Observed
SC1M	0.12	0
SC3M	0.06	0
SC4H	0.51	0
SC4M	0.84	1
SC78	1.26	2
SC9	1.05	0
EC1	2.58	3
EC2L	0.24	0
EC2M	0.30	0
EC3H	2.76	3
EC45	0.78	1
EC6H	0.27	1
EC7	2.55	2
EC9H	1.26	0
EC9M	0.69	0
EC10	1.47	2
M123	0.15	0
V1H	5.37	6
V1L	0.06	0
V1M	0.84	0
V3	0.27	0
V4	6.09	6

Table 4 - Earthquakes per 300 years, by zone

Overall, this is a good match. Some of the larger disparities are due to the selection of Mw ≥ 4.5 in 300 years as the yardstick, which does not represent, for instance, the historical seismicity of zone SC4H at magnitudes slightly less than 4.5 Mw, nor the earthquakes > 4.5 Mw in zone EC9H in a time window longer than 300 years.

There is therefore no possibility that the model in this study misestimates the hazard compared to other studies because of an inadequate representation of UK seismicity data. Figure 17 and Table 4 demonstrate that the model depicts what is known about UK seismicity accurately, and even slightly conservatively. Such validation exercises are extremely useful; they provide a transparency that is often lacking from seismic hazard studies (Musson 2004c). One can be confident that the model is correctly depicting seismicity, since one can see that this is so.

Even so, there are certainly some possible points of discussion with regard to the construction of the model.

The most obvious issue is the number and size of the zones. Given the size of the UK, a model of 23 zones might be considered to be over-detailed, and much simpler zonations could undoubtedly be proposed (which would have the advantage that each larger zone would have more earthquakes to analyse to determine recurrence rates). The question is one of whether the seismicity in the UK has such a strong stationarity that small zones are necessary to represent a stable pattern of localised seismicity?

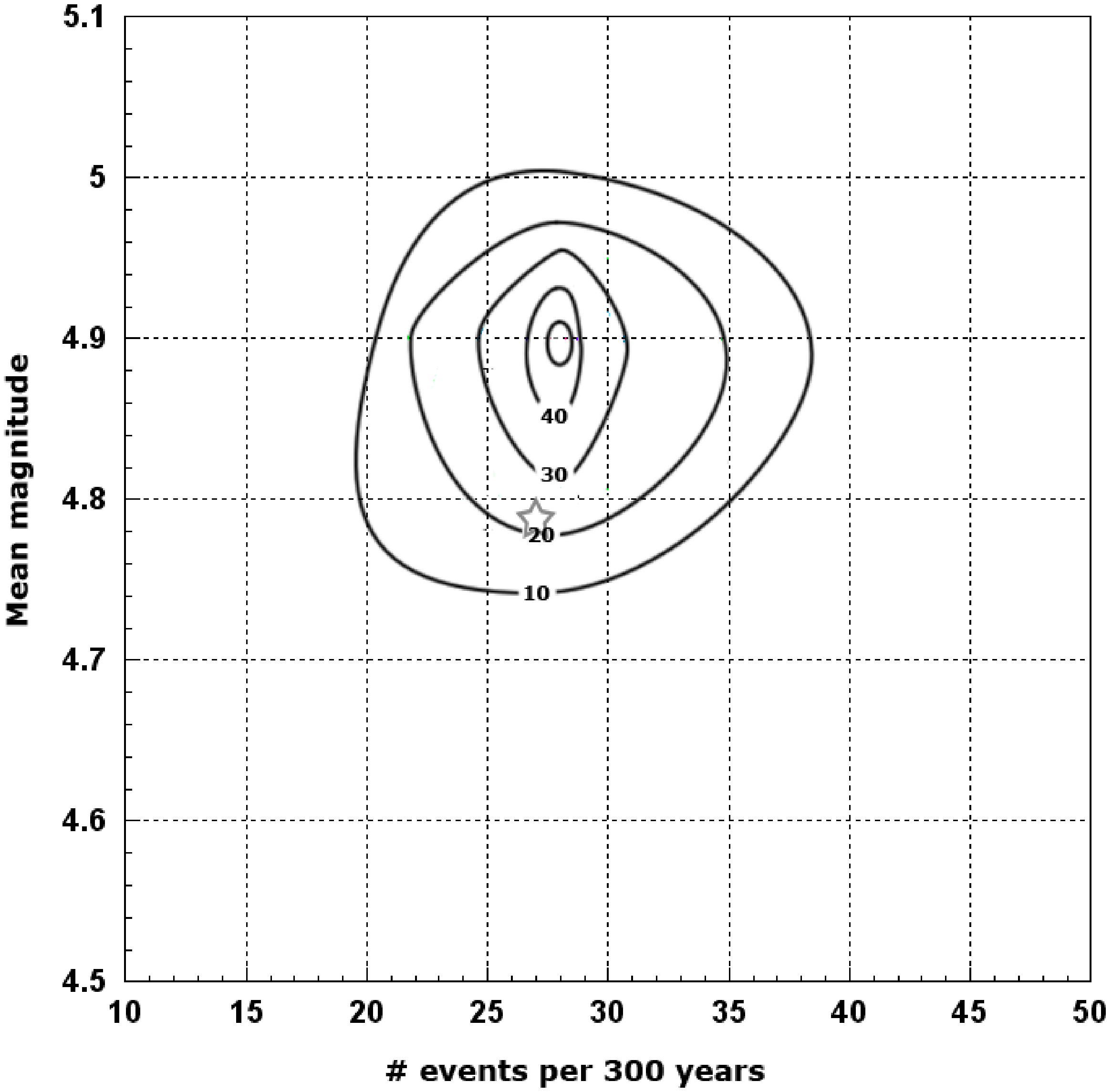

Figure 17 - Distribution of catalogue statistics from 1,000 trials from the model (contoured) compared to the historical observation (star).

So far as one can answer that question at all, the answer would seem to be yes. North-west Wales is a good case in point. Within the period of the last 350 years, there have been three large earthquakes with magnitudes close to 5.0 Mw, which have struck more or less in the same place. So whatever “seismogenic unit” is responsible for these events, the recurrence interval is substantially less than the historical period. It would therefore be rather strange, supposing the ideally “correct” zone to be large, that these three earthquakes should strike in almost exactly the same spot (to say nothing of smaller events in the 4.0-4.5 Mw range). Thus any attempt to define a large zone that included the Snowdonian seismicity along with either the rest of North Wales or with a large amount of the Irish Sea, would create a problem in that a consistent spatial behaviour observable over the last few centuries would be lost. And there is no good reason to suppose that something consistently observable over the last 350 years should suddenly change in the next 50 years. Hazard maps, whatever the assigned return period, are intended to be a guide to the hazard in the immediate future, and it is more likely than not that the immediate future will be similar to the historical past.

A similar argument can be raised in respect of the seismicity of Comrie, represented by the very small zone SC4H. The model maker has four main choices. Firstly, one can draw a small zone local to Comrie, as done here. Secondly, one can make a leap of faith and assume that the activity is associated with the Highland Boundary Fault, and extend the zone into the aseismic areas to the north-east and south-west. Thirdly, one can merge the Comrie seismicity with that of the Central Valley, which would mean in this model joining SC4H and SC3M. Or lastly, one could put all the seismicity of the Scottish Highlands, from Ullapool to Comrie and from Oban to Inverness into one large zone. In the case of Comrie, one is not just dealing with seismicity with a distinct local focus, but also of a distinct character, since the activity at Comrie takes the form of intense earthquake swarms lasting several years, of which the two swarms of 1795-1801 and 1839-1846 are well documented. One has to ask the question as to whether, if another six-year earthquake swarm were to occur in the near future, one would find it more credible that it should centre on Comrie again (first option), Kirriemuir (second option), Glasgow (third option) or Aviemore (fourth option).

Arguably this epistemic uncertainty should be handled with a logic tree of alternative zonations, but this was deemed to be outside the scope of the present project. The net effect of preserving localisation is that hazard becomes markedly concentrated near small zones, resulting in the bulls-eye contours around Comrie (and Snowdonia) in Figure 16. This becomes more exaggerated at longer return periods, and especially with SGM models with high sigma, since the model effectively holds the earthquakes in place near to the site, and thus the effects of upward scattering ground motions are not ameliorated by variations in source-to-site distance.

One could alternatively argue that the model is not localised enough, since it does not specifically reflect repeating earthquake locations close to Inverness and Swansea. However, both these places are already located within relatively high seismicity zones, so the model is probably adequate in both cases, at least for a mapping study.

An additional justification for the numerous zones is that such a model does respect tectonic considerations, rather than just being made on the basis of epicentres. The structural complexity of the British Isles argues against oversimplifying the model.

Also, it should be mentioned that simplifying the model would not obviate the problem of the “semi-characteristic” seismicity. If one took all of Britain south of 54^{o} North as a single zone, the same problem of modelling the seismicity adequately would still occur. A similar solution was adopted in a previous hazard mapping model (Jackson 2004), but for South Wales and Herefordshire only. Such an approach cannot be avoided if one wishes realistic results, unless one supposes that historical experience is an extreme outlier amongst all possible outcomes.

A small question mark still hangs over the SGM model. Although the NGA models and Bommer et al. (2007), as argued previously, should be better at representing ground motions from smaller magnitude earthquakes (5 Mw or less), the latter study uses Joyner-Boore distance as the measure of source to site distance. It is questionable whether this is appropriate for earthquakes with small source dimensions. For events with small sources it is reasonable to assume that ground motions will be higher for shallow events. One only has to contrast the effects of shallow British earthquakes like the recent 28 April 2007 Folkestone earthquake with those from larger but deeper events such as the 19 July 1984 Lleyn Peninsula earthquake. Any SGM model using Joyner-Boore distance removes focal depth from consideration. This suggests that the hazard shown here may be slightly exaggerated given that the mean depth of events ≥ 4.5 Mw in the catalogue is 20 km, compared to the h0 term in Bommer et al. (2007) of 8 km. (Of course, it is also true that the depths, many of them assessed from macroseismic data, are subject to some uncertainty). It is also likely that the lack of inclusion of focal depth of smaller events in models such as Bommer et al. (2007) contributes to the higher sigma value, due to metadata issues for smaller magnitude earthquakes. The effect of this is lessened by the balancing effect of including Campbell and Bozorgnia (2006a). However, as previously discussed, this is likely to be more of an issue when dealing with longer return periods.

Lastly, one possible other contentious issue is the maximum magnitude distribution. The distribution used here for the UK mainland could be considered conservative, given the lack of events even >5.0 Mw in quite a long period of historical observation (see, for instance, Ambraseys and Jackson 1985). Thus, although the aim of this study was to portray the seismic hazard of the UK realistically and without conservatism, it is still possible that the results veer on the conservative side.

Overall, the results presented here confirm what might be supposed from general and historical experience, that the seismic hazard of the UK can be considered as very low.

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Appendix 1 Seismic hazard mapping issues

The purpose of this Appendix is to discuss the production of maps of seismic hazard in terms of the issues that distinguish mapping studies from site-specific studies, with special relevance to the production of zoning maps in a regulatory/standards environment.

Seismic hazard is the branch of seismology in which many aspects of the science are combined into a product which can act to improve society's defences against the danger of earthquake damage. It forms a bridge between the subjects of seismology and earthquake engineering. Seismic hazard studies concerned with specific engineering projects are a common task. Such studies are usually concerned with determining design values in terms of peak or spectral acceleration at one or several sites.

However, engineers are not the only people concerned about the hazard from earthquakes. Politicians and planners are likely to be concerned about levels of hazard over a national territory, or even over a larger region. Thus some representation of variations in seismic hazard with respect to space are needed. The application of methods for assessing hazard over an area are not necessarily the same as those used for determining point hazard values. The literature on seismic hazard maps is large, and often obscure. It is not possible in this paper to give a complete overview, or mention all the techniques that have been used at different times in different countries to create maps of seismic hazard. An overview of the situation as it was in different parts of the world a little over a decade ago is given by McGuire (1993), and while methodology has advanced greatly in the intervening years, it is still interesting to note the different approaches that have been followed.

TYPES OF MAP

What is a seismic hazard map? The term "seismic hazard" has come to acquire a narrow definition as the probability of observing some level of earthquake ground shaking within a specified time interval. Ground shaking is defined in terms of some parameter, usually peak ground acceleration (PGA), spectral acceleration, or macroseismic intensity (e.g. EMS-98 – European Macroseismic Scale). Thus, the most common type of hazard map takes a return period and plots contours of associated PGA amplitudes (e.g. Giardini 1999). There is no reason why the process cannot be inverted – for a given ground motion value one can plot contours of equal probability. Thus Mouroux et al (1993) plot contours of the annual probability of observing intensity 7 or higher. For regulatory purposes, where a specific return period is laid down in law, maps of ground motion for a given probability are required, but for other purposes, the inverted approach may be more meaningful. Intensity 7 (MSK – Medvedev-Sponheuer-Karník or EMS) is the level at which damage becomes more than slight. Thus a map such as that in Mouroux et al (1993) allows one to see at once how probable damage is at any location. The same approach is applied in the recent Aftershock Forecast Maps for California (http://pasadena.wr.usgs.gov/step/) which indicate the daily probability of observing intensity 6 (Modified Mercalli) taking into account both background hazard and the possibility of aftershocks from recent seismicity.

However, there are many parameters of seismicity that are capable of being mapped, and some of them can also be considered to be indicators of hazard in some sense. Even a straightforward epicentre plot gives a visual impression of which areas are more dangerous than others. A very simplistic map can at least distinguish areas where seismicity is so low that it can be disregarded for engineering purposes for low-consequence construction.

Some maps of this sort use more or less subjective criteria. Mallet and Mallet (1858) produced the first world seismicity map, in which bands of progressively darker colour represented increasing seismicity rates, according to Mallet's assessment of frequency and severity of events. The result is impressive for its period, and the plate boundaries, where onshore, can be seen clearly. In some sense, this could also be considered to be the first seismic hazard map. An example of a more modern implementation of a similar approach is to be found in Swiss Re (1977), where the world is contoured in shades of brown according to "low exposure", "moderate exposure", "heavy exposure" and "very heavy exposure", where these categories are undefined quantitatively, but are intended to represent "the combined effect of event probability and loss caused".

One type of map commonly encountered is that of historically observed maximum intensity (e.g. Radu, 1983 for Europe). Such maps are of interest, but can be misleading. Maximum intensity is a rather unstable parameter; one new earthquake in a relatively low seismicity area can suddenly change many of the values. A "bulls-eye" effect where an isolated earthquake has occurred in the past may not be a good indicator of where the next analogous event is going to occur.

USES OF SEISMIC HAZARD MAPS

Seismic hazard maps can also be divided according to intended use, and here one can make a division into two broad categories: maps for regulatory purposes, and maps for informational purposes. In this report, the former category only will be considered.

In most earthquake-prone countries there should exist an official earthquake zoning map that will divide the national territory into regions of approximately equal hazard. The national building code will then specify the regulations that apply to construction within that zone, in terms of required antiseismic measures. The zoning map will be based on a national hazard map, with some system for converting ground motion hazard values into a classification scheme. For example, the Greek building code that existed in 1990 used four zones defined according to the PGA value with 20% probability of being exceeded in 50 years, the defining contour lines being those for 0.17 g, 0.23 g and 0.39 g (Makropoulos 1993).

More commonly, such maps take as standard the 10% probability of being exceeded in 50 years (475 years return period), following Algermissen and Perkins (1976), often without any clear rationale for doing so (Bommer and Pinho 2006).

Because of the legal status of such national maps, seismic hazard studies become to some extent politicised. The publication of a new hazard map that contradicts the old one presents some institutional difficulties (see, for instance, the discussion in section 13 of Giardini, 1999). One should not lose sight of the potential danger that a hazard map, produced entirely from scientific motivation, may be seized upon by local special interest groups as a weapon in controversial issues.

Leyendecker et al (2000) discuss some of the issues in producing regulatory maps, considering the need to reflect reasonably consistent margins of safety against the collapse of structures. For large areas (such as the United States) there is a considerable difference in the extent to which one can characterise seismicity in terms of known properties of faults. In places like California, where the hazard is high and can be reasonably well understood in terms of large earthquakes on major structures, there are advantages in pursuing a deterministic approach to hazard (McGuire 1999); elsewhere this is much less appropriate. The seismic hazard maps for use in the 1997 NEHRP (National Earthquake Hazards Reduction Program) Provisions were therefore based on a hybrid of deterministic and probabilistic procedures (Leyendecker et al 2000).

An important issue here is the topic of conservatism. It is common usage in hazard studies that are intended to produce design values for a construction project to tend towards making conservative decisions (i.e. pessimistic ones) when confronted with choices where no objective decision is possible, so as to "err on the safe side". For instance, maximum magnitude is a necessary parameter in seismic hazard assessment, but is inherently unknowable. For a seismic source, even if one was convinced that the largest historically observed earthquake was in fact the practical maximum event, it would be normal practice to add on something extra as a safety margin.

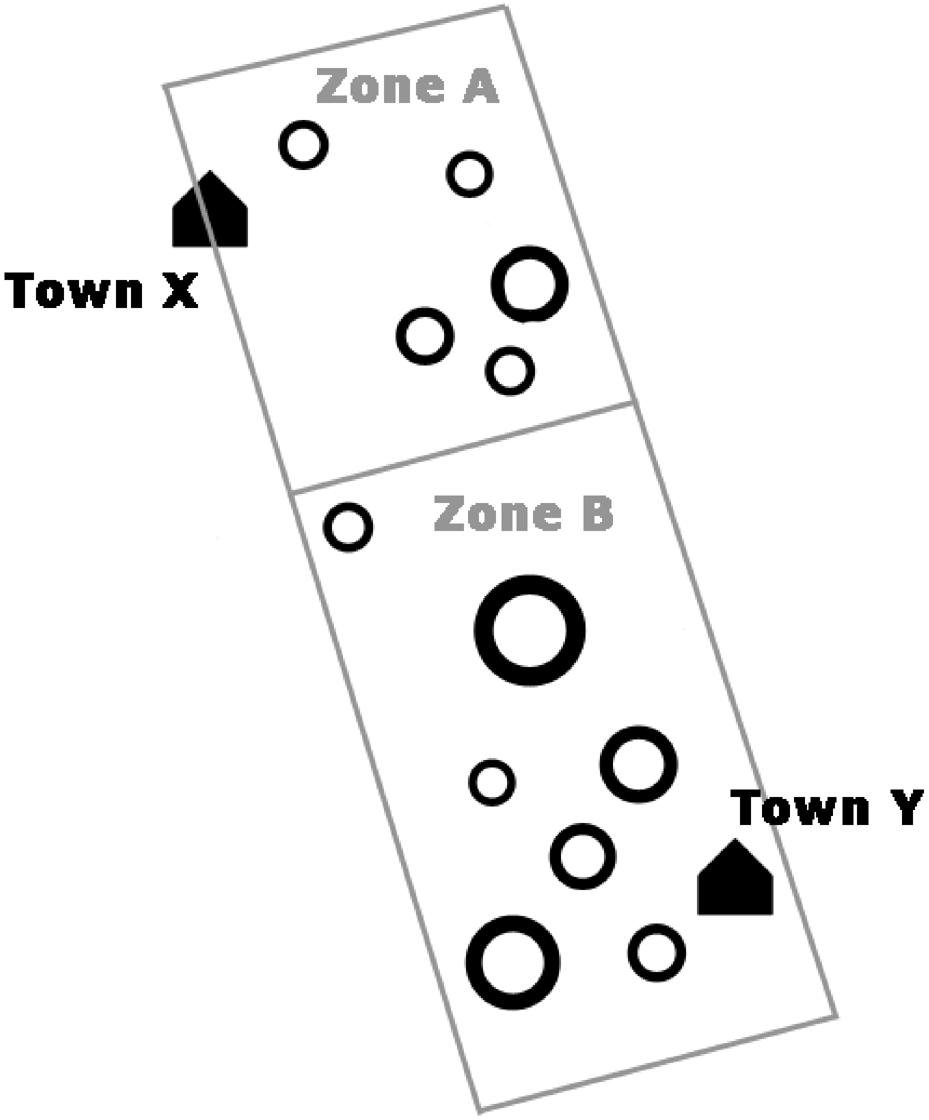

Figure A1 - Hypothetical illustration of a typical problem in source zonation: are Zones A and B to be kept separate or merged? The decision taken has different effects on the conservatism of the hazard at X and Y.

In a seismic hazard map, one cannot have equal conservatism over the whole map. Consider the case in Figure A1. Is the seismicity here better represented as one source zone or two? From the earthquake catalogue, it appears that zone B is more active than zone A, but the catalogue is not very complete, and geologically and tectonically both zones are similar. In this region there are two towns, X and Y. If the hazard analyst elects to merge the two zones, the hazard at X will increase and the hazard at Y will decrease, as some of the seismicity from zone B is spread into zone A. Therefore, for a site at X, a single zone is the more conservative decision; for a site at Y, keeping the zones separate is more conservative. There is no solution that is equally conservative for both; and for a hazard map one needs to make a single decision for the whole map. Putting both alternatives into a logic tree doesn't solve the case – the resulting hybrid is fully conservative at neither site. Nor can one escape the problem by turning to smoothed seismicity methods (discussed further below), though one can, perhaps, conceal it. In practice, therefore, one needs to abandon attempts at conservatism when producing hazard maps and seek instead to take decisions based on best judgement.

As a result, it is considered bad practice to try and read engineering design parameters from a seismic hazard map (see also the discussion in Page and Basham, 1985, quoted in section 3 of this report). The value one reads is a first approximation to the hazard at a given point. For design purposes, what is needed is a specific study that takes decisions entirely with respect to the site of interest, and can therefore be conservative with respect to that site. The degree of conservatism can be expected to vary with the importance of the structure.

It follows that one may expect a tendency for design values to be slightly higher than those shown on a national hazard map, though the extent of the difference may not be very large. In fact, it is also possible for design values to be lower, particularly for the following reason. Decisions made in hazard studies can also be affected by the type of structure under consideration. For instance, in Benjamin (1989) it is recommended that the minimum magnitude to be considered in a seismic hazard study for an engineered structure can be around 5 Mw, since ground motions from smaller events are not likely to damage steel/RC construction. However, if ordinary masonry buildings are being considered, then all earthquakes over 4 Mw should be taken account of. Raising the minimum magnitude has the effect of lowering the hazard, which may offset the effect of other conservatisms introduced when dealing with critical structures.

Thus a hazard map for zoning purposes can be considered as best-judgement values for application to ordinary building stock. This is in line with the fact that Eurocode 8 does not apply to special structures (such as nuclear facilities).

HAZARD MODELS FOR MAPPING PURPOSES

It follows, therefore, that constructing a seismic source model according to standard probabilistic seismic hazard (PSHA) procedures is not quite the same for producing a hazard map as it would be for a site study. In the discussion that follows, a familiarity with standard PSHA methodology is assumed. Reiter (1990) and McGuire (2004) provide useful monographs on the subject.

As already discussed, one cannot be perfectly conservative when producing a seismic hazard map; with the result that the final map becomes more of a "best estimate" of hazard, rather than something with built-in safety margins.

A further difference is that, for a single site, although it is normal to consider seismicity within an area out to 300 km radius around the site, it is really the part of the model within 100 km of the site (or less) that is crucial. As a matter of practice, one tends to treat seismicity in the far field of a site with greater abstraction in a model. For a hazard map, the far field becomes the area surrounding the region to be contoured, and the area to be modelled in detail is therefore much larger.

Thirdly, modelling uncertainty is of less concern when preparing a hazard map. In cases where there is little to go on in estimating a poorly constrained parameter there is no particular reason to suppose that the true value is either higher or lower than the best estimate. It is shown by Musson (2006) that the net effect of taking higher and lower values of the seismicity parameters to reflect uncertainty is that the options tend to cancel each other out in their overall effect.

One issue that needs to be considered when defining the geometry of seismic source zones is that the shape of the map will be strongly influenced by how zones are defined. It is common practice in regions of discontinuous seismicity to draw seismic source zones as simple boxes around groups of epicentres. Bhatia et al (1999) is an example; their source zone model for Peninsular India is a series of small separated rectangles. The result is a hazard map in which contours appear as rectangular boxes around each zone. It does not look very realistic. Another example can be found in the section of the model in Jiménez et al (1999) for Algeria, which, in contrast to the Tunisian section of the same model, produces a boxy and unrealistic-looking contour map. This model was improved in Jiménez et al (2001) with much better results. This is not simply a matter of cosmetic appearance; it is not likely that hazard in reality follows such rectilinear patterns.

A similar issue is the avoidance of cliff-edges to the hazard contours where a high hazard zone abuts a low one. This was a problem with early seismic hazard programs; since 1983 the problem has been obviated by allowing some sort of jitter to seismicity at the edges of zones to smooth out cliffs (Bender and Perkins 1982). When using this, one should be aware that the reduction in hazard amplitudes within high seismicity zones is significantly greater than the increase in hazard amplitudes in low seismicity zones. This is because estimates of seismic hazard are sensitive to the concentration of seismicity. Redistributing some seismicity to outside an active zone adds the seismicity to a larger net area than the area it is removed from, in a manner analogous to geometric spreading. In site studies, the objective of the study is to derive appropriately safe design values for the site in question, and thus the actual shape of the zone geometry is less important. For a hazard map the prime objective is to show the spatial variation in hazard, so something that is obviously improbable because of boxiness or sharp edges will not be ideal.

One way to circumvent these problems is not to use any source zone geometry, but to rely instead on methods of spatial smoothing of seismicity. This was tried by Jacob (1994) but is more commonly associated with Frankel et al (1996). Spatial smoothing methods have become increasingly popular since then, but in truth, the approach has been over-sold, and its benefits are to some extent illusory. It is certainly more appropriate to use such methods for hazard maps than for site studies, though.

The principle involved is to replace the source zone model, which would be constructed by the hazard analyst in an attempt to partition an area into zones of equal earthquake probability, with a smoothing of the historical earthquake catalogue using either a Gaussian function (Frankel et al 1996) or a kernel method (Woo 1996).

The first effect of this, of course, is that the hazard results now rely entirely on the historical catalogue, whereas a constructed zone model can also be informed by considerations of geology and tectonics. An important source of relevant information has simply been discarded. It is argued sometimes that this is appropriate because the underlying tectonics are too obscure to be helpful (Woo 1996), but one still sees the method applied in areas where there are strong and obvious tectonic controls on seismicity, as for instance in the Caribbean (Shepherd et al 1999). This can be handled to some degree by the use of hybrid models, where, for instance (as in Frankel et al, 1996) major faults are treated as sources that are superimposed over spatially smoothed background seismicity.

It is commonly claimed (e.g. Lapajne 2000) that using a spatial smoothing approach overcomes problems of subjectivity in preparing a seismic source model. This is untrue; nor does the fact that one no longer has the possibility of different zone models proposed by different analysts mean that one has removed uncertainty. It is more accurate to say that using a smoothing approach conceals the subjectivity and uncertainty from the user. It would obviously be insufficient to write up a hazard study by saying “a zoned approach to seismicity was used” with no mention of what the zones were. A good hazard model is a realisation of a conceptual model based on an interpretation of kinematic processes driving seismicity (e.g. Meletti et al 2000).

Equally, it is insufficient to write “a smoothed approach to seismicity was used” without explanation of the parameters controlling the smoothing. The detail is what matters. The danger is that in electing to circumvent the chore of preparing a zone model by applying a smoothed

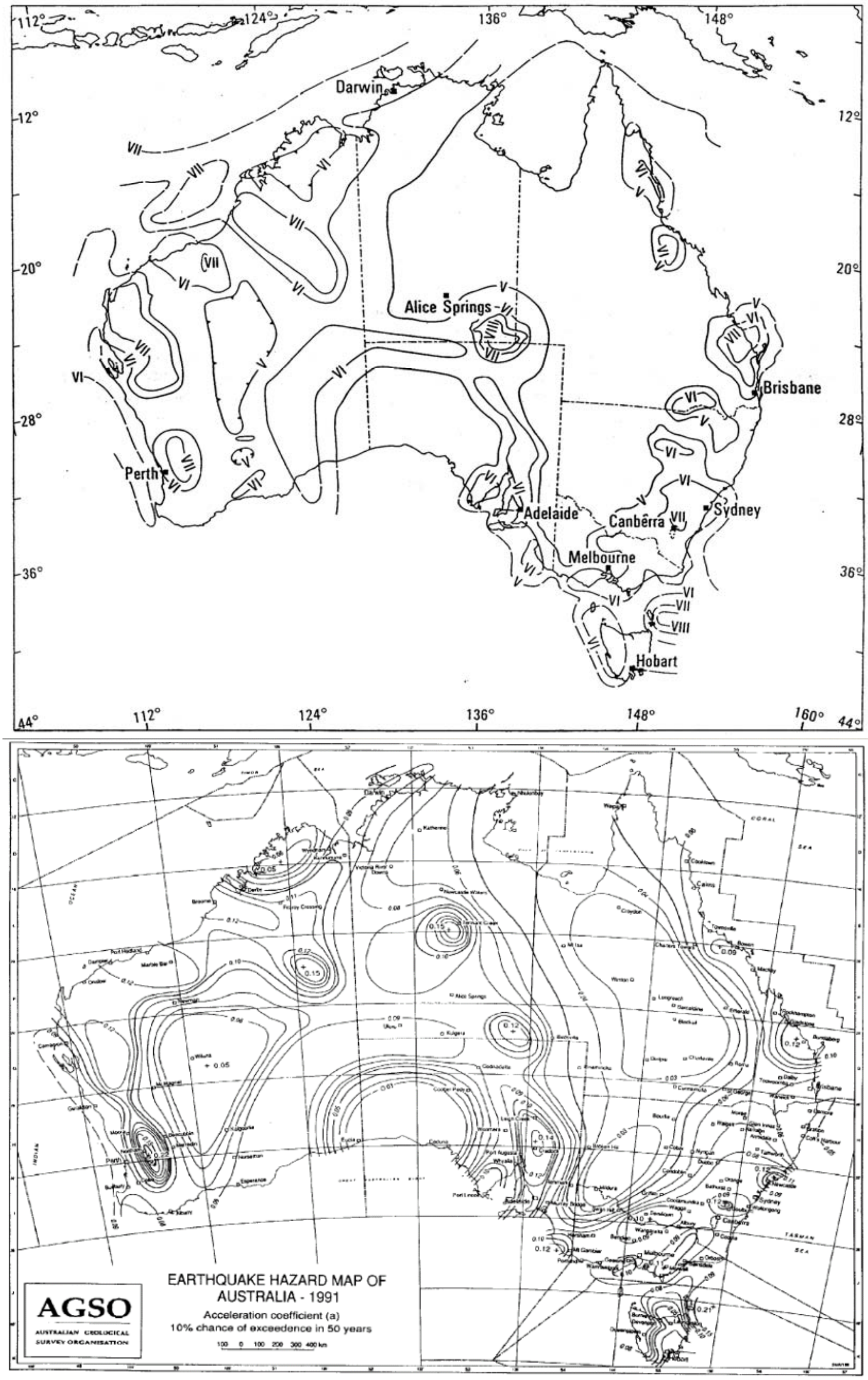

Figure A2 - Two hazard maps for Australia: A (top) from Gaull et al (1990) shows intensity hazard with 475 year return period; B (bottom) is PGA for the same return period. A was produced before the Tenant Creek earthquakes in Northern Territory; B after it.

approach, will choose the one smoothing parameters without any reference to any conceptual model, in a somewhat arbitrary manner.

A limitation of the spatially smoothed method can be seen in a recent paper by Peláez et al (2005). An earlier study of seismic hazard in Algeria (Peláez et al, 2003) using the smoothed seismicity approach gave low hazard results in the area heavily damaged by the 21 May 2003 Boumerdes earthquake, because previously there was no seismicity in this area. Recomputing the hazard map with the inclusion of the 2003 earthquake significantly altered the estimated hazard. It is questionable whether it is a good thing that a hazard map should be so unstable that the occurrence of one earthquake changes the values significantly, as occurs in Peláez et al (2005). This is not by any means a problem exclusive to maps produced by the spatial smoothing process. The history of seismic hazard maps in Australia is a case in point. Figure 2 shows two iterations of Australian seismic hazard maps. Figure 2a is from Gaull et al (1990); the hazard in Northern Territory is considered very low, except for a bulls-eye of hazard around a cluster of earthquakes in the Simpson Desert (two 6.5 Ms events on 28 October 1937 and 27 June 1941, and a further 6.2 Ms on 28 August 1972). Figure 2b, from McCue et al (1993), is a revision of the map after the three strong (>6 Ms) earthquakes at Tennant Creek on 7 January 1988. A new bulls-eye has been added at Tennant Creek. But does the occurrence of Tennant Creek events really alter the hazard in such a way? It can easily be argued that the hazard at Tennant Creek is certainly no higher now than in the 1980s, and possibly less, as the next strong intraplate event is more likely now to occur somewhere else (R. Adams, pers. comm.). A further revision to the model has now been proposed in which seismicity is related to broad structural shear zones, thus eliminating very localised peaks of hazard (McCue et al 1998), though there does not as yet exist a map based on this new model (K.F. McCue, pers. comm.).

MEAN AND MEDIAN HAZARD

One issue recently come into focus is whether hazard maps (or other hazard studies) should present the mean or median hazard value (Abrahamson and Bommer 2005, Musson 2005, McGuire et al. 2005). This problem needs to be explained briefly. Conventional modern PSHA methodology uses a logic tree to express epistemic uncertainty in the model parameters as weighted branches. Most PSHA programs evaluate each branch in turn according to the standard Cornell-McGuire method to obtain the complete set of end-members of all the branches. From these a weighted mean is obtained as the final hazard value. Alternatively, one end member can be selected: the median (50-percentile), 84-percentile, or any other fractile. According to Abrahamson and Bommer (2005) the median is preferable to the mean because it is less sensitive to extreme values in the logic tree. They also argue that the use of the mean value is incorrect because it conflates probabilities and uncertainties. A full refutation of this is beyond the scope of this Annexe; see Musson (2005, 2007). The following points can be made. Firstly, choosing the median is an arbitrary decision. There is no particular reason to prefer the 50-percentile to the 55-percentile, 60-percentile or any other value. Secondly, extreme values in a logic tree either shouldn't be there (if they are unrealistic) or they should be given their correct weight. To include something in the model and then take steps to disable it is logically inconsistent. Thirdly, to insist that uncertainties are not probabilities and have to be treated differently, is to take a narrow and misguided view of probability theory that is ultimately unsustainable.

There is, in fact, an alternative method of calculating PSHA besides the analytic method introduced by Cornell (1968); this is the stochastic modelling approach described in section 3.4 of the present report. This provides an extremely direct, observational approach to computing seismic hazard. Although a logic tree is used, the end members are never evaluated individually, and the hazard is computed empirically in the manner shown in Figure 3 of the main report. The ground motion with annual probability $1/n$ is simply the value that is exceeded 1000 times in n x 1000 annual outcomes. It is not the mean or the median of anything; it is a directly observed numerical probability. However, the value corresponds to the mean hazard value as computed using the Cornell-McGuire method, demonstrating that the mean hazard actually uniquely corresponds to the probability of a given outcome as implied by the model. Thus it is incorrect to say that any ground motion corresponds to the 84-percentile value of the hazard with annual probability of 0.001. One is, in effect, stating the ground motion that has some other probability of occurrence than 0.001 per year.

Therefore, for hazard results to correctly reflect the probability level assigned to them, they must correspond to the weighted mean of the end members of the logic tree and not the median. The directly observational approach to seismic hazard made possible through the use of Monte Carlo modelling demonstrates the truth of this. Clearly, any map that is intended to have regulatory status needs to show probabilities correctly, and therefore must necessarily correspond to mean hazard when a Cornell-McGuire approach is used.

HAZARD, PROBABILITIES AND AREA

In assessing the values depicted on a hazard map, and especially with respect to subsequent experience, care is needed in the interpretation of probability. It might seem strange if, immediately following the publication of a hazard map, an earthquake occurred within the national territory that exceeded the 2,500-year ground motion for some locality. In fact, such an occurrence is quite likely. One can imagine a case where, for the sake of argument, a hazard map shows a uniform PGA of 0.1 g with annual probability of 0.0004 over the whole territory. This means that the probability of exceeding 0.1 g *at one particular spot* is 0.0004 annually. The annual probability of exceeding 0.1 g *somewhere* is different, and considerably higher. If one could consider the territory as comprising 1,000 cells, within which the seismic exposure was independent of all other cells, then the chance within one cell of the 2,500 year PGA being exceeded in the coming year is 0.9996. The chance that none of the cells will exceed 0.1 g is therefore 0.9996^{1000}, or ~0.67. There is therefore roughly a one-third chance that the 2,500 year PGA will be exceeded somewhere in any given year. The exact probabilities will depend on the extent to which the experiences at different localities are independent from one another, which depends on the characteristics of the seismicity.

A further distinction is made by Malhotra (2007) between “site-specific hazard” (at a point) and “aggregate hazard” (the experience over an area). The latter is little investigated. From a societal point of view, there is a difference between a high ground motion observed only at one point, and the same ground motion observed simultaneously over a large area, and thus causing a greater amount of loss. One might expect different results depending on whether hazard was influenced more by frequent small earthquakes (affecting small areas only) or rarer larger earthquakes (affecting larger areas together). The issue is further complicated by the aleatory variability of ground motion over fairly small distances.

This can be expected to be a subject of future research. It might be useful, for instance, for a local authority to know the probability of a given ground motion value occurring somewhere within its area of responsibility, rather than just the probability of it occurring at a given point.

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Appendix 2 Values of magnitude-frequency for the model used in this study

The following table gives the complete magnitude-frequency statistics determined by the maximum likelihood procedure. For each zone (except two low seismicity zones), 25 lines are provided, each one giving an activity rate/*b* value combination, and the weighting for that combination. Activity rates are given as the logarithm of the number of events per year above 3.0 Mw. This magnitude was used as the baseline for the calculations, and it is not a requirement of the software that this should also be the minimum magnitude in the hazard calculations, which is something quite different. The *b* values are presented without minus signs.

SC1M

a	*b*	*wt*
-2.62	0.72	0.007
-2.62	0.86	0.033
-2.62	1.00	0.058
-2.62	1.14	0.040
-2.62	1.28	0.011
-2.15	0.72	0.013
-2.15	0.86	0.064
-2.15	1.00	0.118
-2.15	1.14	0.085
-2.15	1.28	0.024
-1.93	0.72	0.012
-1.93	0.86	0.065
-1.93	1.00	0.138
-1.93	1.14	0.096
-1.93	1.28	0.028
-1.48	0.72	0.004
-1.48	0.86	0.026
-1.48	1.00	0.062
-1.48	1.14	0.054
-1.48	1.28	0.018
-1.26	0.72	0.000
-1.26	0.86	0.005
-1.26	1.00	0.016
-1.26	1.14	0.017
-1.26	1.28	0.006

SC4H

a	*b*	*wt*
-1.87	0.68	0.009
-1.87	0.82	0.031
-1.87	0.96	0.039
-1.87	1.10	0.018
-1.87	1.24	0.003
-1.55	0.68	0.019
-1.55	0.82	0.081
-1.55	0.96	0.117
-1.55	1.10	0.061
-1.55	1.24	0.012
-1.37	0.68	0.016
-1.37	0.82	0.082
-1.37	0.96	0.153
-1.37	1.10	0.088
-1.37	1.24	0.019
-1.10	0.68	0.004
-1.10	0.82	0.032
-1.10	0.96	0.078
-1.10	1.10	0.063
-1.10	1.24	0.017
-0.94	0.68	0.000
-0.94	0.82	0.006
-0.94	0.96	0.021
-0.94	1.10	0.023
-0.94	1.24	0.008

SC4M

a	*b*	*wt*
-1.33	0.77	0.009
-1.33	0.90	0.029
-1.33	1.03	0.033
-1.33	1.16	0.014
-1.33	1.30	0.002
-1.15	0.77	0.018
-1.15	0.90	0.079
-1.15	1.03	0.111
-1.15	1.16	0.055
-1.15	1.30	0.010
-1.02	0.77	0.015
-1.02	0.90	0.084
-1.02	1.03	0.158
-1.02	1.16	0.089
-1.02	1.30	0.019
-0.86	0.77	0.004
-0.86	0.90	0.035
-0.86	1.03	0.087
-0.86	1.16	0.068
-0.86	1.30	0.018
-0.75	0.77	0.000
-0.75	0.90	0.006
-0.75	1.03	0.024
-0.75	1.16	0.025
-0.75	1.30	0.008

SC78

a	*b*	*wt*
-1.09	0.77	0.009
-1.09	0.90	0.031
-1.09	1.03	0.033
-1.09	1.16	0.012
-1.09	1.28	0.001
-0.95	0.77	0.017
-0.95	0.90	0.080
-0.95	1.03	0.111
-0.95	1.16	0.050
-0.95	1.28	0.008
-0.84	0.77	0.012
-0.84	0.90	0.082
-0.84	1.03	0.164
-0.84	1.16	0.088
-0.84	1.28	0.017
-0.71	0.77	0.003
-0.71	0.90	0.033
-0.71	1.03	0.091
-0.71	1.16	0.072
-0.71	1.28	0.018
-0.62	0.77	0.000
-0.62	0.90	0.006
-0.62	1.03	0.025
-0.62	1.16	0.028
-0.62	1.28	0.009

SC9

a	*b*	*wt*
-1.08	0.83	0.009
-1.08	0.96	0.030
-1.08	1.09	0.033
-1.08	1.22	0.012
-1.08	1.35	0.001
-0.94	0.83	0.018
-0.94	0.96	0.079
-0.94	1.09	0.110
-0.94	1.22	0.052
-0.94	1.35	0.008
-0.83	0.83	0.013
-0.83	0.96	0.083
-0.83	1.09	0.162
-0.83	1.22	0.088
-0.83	1.35	0.018
-0.70	0.83	0.003
-0.70	0.96	0.035
-0.70	1.09	0.090
-0.70	1.22	0.071
-0.70	1.35	0.018
-0.60	0.83	0.000
-0.60	0.96	0.006
-0.60	1.09	0.025
-0.60	1.22	0.027
-0.60	1.35	0.009

EC1

a	*b*	*wt*
-1.19	0.66	0.009
-1.19	0.79	0.031
-1.19	0.92	0.033
-1.19	1.05	0.012
-1.19	1.18	0.001
-1.03	0.66	0.017
-1.03	0.79	0.080
-1.03	0.92	0.112
-1.03	1.05	0.050
-1.03	1.18	0.007
-0.92	0.66	0.012
-0.92	0.79	0.081
-0.92	0.92	0.164
-0.92	1.05	0.088
-0.92	1.18	0.017
-0.79	0.66	0.003
-0.79	0.79	0.032
-0.79	0.92	0.090
-0.79	1.05	0.073
-0.79	1.18	0.018
-0.69	0.66	0.000
-0.69	0.79	0.006
-0.69	0.92	0.025
-0.69	1.05	0.029
-0.69	1.18	0.010

EC2L

a	*b*	*wt*
-2.20	0.72	0.004
-2.20	0.86	0.020
-2.20	1.00	0.040
-2.20	1.14	0.031
-2.20	1.28	0.009
-1.82	0.72	0.009
-1.82	0.86	0.051
-1.82	1.00	0.109
-1.82	1.14	0.090
-1.82	1.28	0.029
-1.62	0.72	0.008
-1.62	0.86	0.053
-1.62	1.00	0.140
-1.62	1.14	0.116
-1.62	1.28	0.040
-1.29	0.72	0.002
-1.29	0.86	0.022
-1.29	1.00	0.067
-1.29	1.14	0.073
-1.29	1.28	0.029
-1.11	0.72	0.000
-1.11	0.86	0.004
-1.11	1.00	0.018
-1.11	1.14	0.024
-1.11	1.28	0.012

EC2M

a	*b*	*wt*
-1.93	0.78	0.008
-1.93	0.92	0.029
-1.93	1.06	0.038
-1.93	1.19	0.019
-1.93	1.33	0.004
-1.61	0.78	0.019
-1.61	0.92	0.078
-1.61	1.06	0.115
-1.61	1.19	0.064
-1.61	1.33	0.014
-1.43	0.78	0.018
-1.43	0.92	0.084
-1.43	1.06	0.157
-1.43	1.19	0.088
-1.43	1.33	0.021
-1.17	0.78	0.005
-1.17	0.92	0.036
-1.17	1.06	0.077
-1.17	1.19	0.058
-1.17	1.33	0.016
-1.01	0.78	0.000
-1.01	0.92	0.007
-1.01	1.06	0.020
-1.01	1.19	0.019
-1.01	1.33	0.006

EC3H

a	*b*	*wt*
-1.80	0.58	0.008
-1.80	0.71	0.030
-1.80	0.85	0.037
-1.80	0.99	0.016
-1.80	1.13	0.002
-1.53	0.58	0.019
-1.53	0.71	0.080
-1.53	0.85	0.115
-1.53	0.99	0.059
-1.53	1.13	0.011
-1.36	0.58	0.015
-1.36	0.71	0.083
-1.36	0.85	0.159
-1.36	0.99	0.088
-1.36	1.13	0.019
-1.14	0.58	0.004
-1.14	0.71	0.033
-1.14	0.85	0.081
-1.14	0.99	0.064
-1.14	1.13	0.017
-0.99	0.58	0.000
-0.99	0.71	0.006
-0.99	0.85	0.022
-0.99	0.99	0.024
-0.99	1.13	0.008

EC45

a	*b*	*wt*
-1.42	0.74	0.008
-1.42	0.87	0.029
-1.42	1.01	0.034
-1.42	1.14	0.014
-1.42	1.28	0.002
-1.22	0.74	0.018
-1.22	0.87	0.079
-1.22	1.01	0.111
-1.22	1.14	0.056
-1.22	1.28	0.010
-1.09	0.74	0.015
-1.09	0.87	0.084
-1.09	1.01	0.158
-1.09	1.14	0.089
-1.09	1.28	0.019
-0.92	0.74	0.004
-0.92	0.87	0.035
-0.92	1.01	0.086
-0.92	1.14	0.067
-0.92	1.28	0.018
-0.80	0.74	0.000
-0.80	0.87	0.007
-0.80	1.01	0.024
-0.80	1.14	0.025
-0.80	1.28	0.008

EC6H

a	*b*	*wt*
-2.23	0.69	0.009
-2.23	0.83	0.032
-2.23	0.97	0.044
-2.23	1.10	0.023
-2.23	1.24	0.005
-1.85	0.69	0.020
-1.85	0.83	0.079
-1.85	0.97	0.118
-1.85	1.10	0.068
-1.85	1.24	0.015
-1.65	0.69	0.018
-1.65	0.83	0.083
-1.65	0.97	0.147
-1.65	1.10	0.087
-1.65	1.24	0.021
-1.32	0.69	0.005
-1.32	0.83	0.034
-1.32	0.97	0.072
-1.32	1.10	0.055
-1.32	1.24	0.015
-1.14	0.69	0.000
-1.14	0.83	0.007
-1.14	0.97	0.019
-1.14	1.10	0.018
-1.14	1.24	0.006

EC7

a	*b*	*wt*
-0.91	0.66	0.009
-0.91	0.78	0.035
-0.91	0.90	0.034
-0.91	1.02	0.010
-0.91	1.15	0.000
-0.80	0.66	0.015
-0.80	0.78	0.082
-0.80	0.90	0.113
-0.80	1.02	0.045
-0.80	1.15	0.005
-0.71	0.66	0.009
-0.71	0.78	0.078
-0.71	0.90	0.168
-0.71	1.02	0.085
-0.71	1.15	0.013
-0.61	0.66	0.001
-0.61	0.78	0.030
-0.61	0.90	0.096
-0.61	1.02	0.078
-0.61	1.15	0.017
-0.52	0.66	0.000
-0.52	0.78	0.005
-0.52	0.90	0.027
-0.52	1.02	0.034
-0.52	1.15	0.011

EC9H

a	*b*	*wt*
-1.84	0.58	0.009
-1.84	0.72	0.030
-1.84	0.85	0.037
-1.84	0.99	0.016
-1.84	1.12	0.002
-1.57	0.58	0.019
-1.57	0.72	0.080
-1.57	0.85	0.115
-1.57	0.99	0.060
-1.57	1.12	0.011
-1.41	0.58	0.015
-1.41	0.72	0.083
-1.41	0.85	0.158
-1.41	0.99	0.089
-1.41	1.12	0.019
-1.18	0.58	0.003
-1.18	0.72	0.032
-1.18	0.85	0.081
-1.18	0.99	0.064
-1.18	1.12	0.017
-1.03	0.58	0.000
-1.03	0.72	0.006
-1.03	0.85	0.022
-1.03	0.99	0.024
-1.03	1.12	0.008

EC9M

a	*b*	*wt*
-1.51	0.73	0.008
-1.51	0.86	0.028
-1.51	1.00	0.034
-1.51	1.14	0.015
-1.51	1.27	0.002
-1.29	0.73	0.019
-1.29	0.86	0.078
-1.29	1.00	0.111
-1.29	1.14	0.057
-1.29	1.27	0.010
-1.15	0.73	0.016
-1.15	0.86	0.084
-1.15	1.00	0.158
-1.15	1.14	0.088
-1.15	1.27	0.019
-0.97	0.73	0.005
-0.97	0.86	0.036
-0.97	1.00	0.085
-0.97	1.14	0.066
-0.97	1.27	0.018
-0.84	0.73	0.000
-0.84	0.86	0.007
-0.84	1.00	0.024
-0.84	1.14	0.024
-0.84	1.27	0.008

EC10

a	*b*	*wt*
-1.13	0.75	0.009
-1.13	0.88	0.029
-1.13	1.01	0.033
-1.13	1.13	0.015
-1.13	1.26	0.002
-0.95	0.75	0.018
-0.95	0.88	0.078
-0.95	1.01	0.110
-0.95	1.13	0.057
-0.95	1.26	0.011
-0.82	0.75	0.015
-0.82	0.88	0.084
-0.82	1.01	0.159
-0.82	1.13	0.090
-0.82	1.26	0.020
-0.66	0.75	0.004
-0.66	0.88	0.035
-0.66	1.01	0.086
-0.66	1.13	0.066
-0.66	1.26	0.018
-0.55	0.75	0.000
-0.55	0.88	0.007
-0.55	1.01	0.024
-0.55	1.13	0.023
-0.55	1.26	0.007

M123

a	*b*	*wt*
-2.58	0.72	0.010
-2.58	0.86	0.040
-2.58	1.00	0.059
-2.58	1.15	0.034
-2.58	1.29	0.007
-2.12	0.72	0.020
-2.12	0.86	0.079
-2.12	1.00	0.121
-2.12	1.15	0.072
-2.12	1.29	0.017
-1.90	0.72	0.018
-1.90	0.86	0.079
-1.90	1.00	0.143
-1.90	1.15	0.082
-1.90	1.29	0.020
-1.44	0.72	0.005
-1.44	0.86	0.031
-1.44	1.00	0.063
-1.44	1.15	0.046
-1.44	1.29	0.013
-1.22	0.72	0.000
-1.22	0.86	0.006
-1.22	1.00	0.016
-1.22	1.15	0.015
-1.22	1.29	0.004

V1H

a	*b*	*wt*
-1.48	0.55	0.009
-1.48	0.68	0.031
-1.48	0.81	0.034
-1.48	0.94	0.013
-1.48	1.08	0.001
-1.28	0.55	0.017
-1.28	0.68	0.080
-1.28	0.81	0.113
-1.28	0.94	0.053
-1.28	1.08	0.008
-1.15	0.55	0.013
-1.15	0.68	0.082
-1.15	0.81	0.164
-1.15	0.94	0.088
-1.15	1.08	0.017
-0.98	0.55	0.003
-0.98	0.68	0.032
-0.98	0.81	0.087
-0.98	0.94	0.071
-0.98	1.08	0.018
-0.86	0.55	0.000
-0.86	0.68	0.005
-0.86	0.81	0.024
-0.86	0.94	0.028
-0.86	1.08	0.009

V1M

a	*b*	*wt*
-1.29	0.79	0.009
-1.29	0.92	0.030
-1.29	1.06	0.033
-1.29	1.19	0.013
-1.29	1.32	0.002
-1.11	0.79	0.018
-1.11	0.92	0.079
-1.11	1.06	0.111
-1.11	1.19	0.054
-1.11	1.32	0.009
-0.98	0.79	0.014
-0.98	0.92	0.083
-0.98	1.06	0.163
-0.98	1.19	0.088
-0.98	1.32	0.018
-0.83	0.79	0.003
-0.83	0.92	0.034
-0.83	1.06	0.087
-0.83	1.19	0.069
-0.83	1.32	0.018
-0.71	0.79	0.000
-0.71	0.92	0.006
-0.71	1.06	0.024
-0.71	1.19	0.026
-0.71	1.32	0.009

V3

a	*b*	*wt*
-2.23	0.71	0.008
-2.23	0.85	0.031
-2.23	0.98	0.043
-2.23	1.12	0.023
-2.23	1.26	0.005
-1.84	0.71	0.020
-1.84	0.85	0.079
-1.84	0.98	0.118
-1.84	1.12	0.068
-1.84	1.26	0.015
-1.64	0.71	0.019
-1.64	0.85	0.083
-1.64	0.98	0.150
-1.64	1.12	0.087
-1.64	1.26	0.021
-1.32	0.71	0.006
-1.32	0.85	0.035
-1.32	0.98	0.072
-1.32	1.12	0.054
-1.32	1.26	0.015
-1.13	0.71	0.000
-1.13	0.85	0.007
-1.13	0.98	0.019
-1.13	1.12	0.017
-1.13	1.26	0.005

V4

a	*b*	*wt*
-1.29	0.51	0.009
-1.29	0.64	0.033
-1.29	0.77	0.034
-1.29	0.90	0.011
-1.29	1.03	0.001
-1.13	0.51	0.016
-1.13	0.64	0.082
-1.13	0.77	0.114
-1.13	0.90	0.049
-1.13	1.03	0.006
-1.01	0.51	0.010
-1.01	0.64	0.080
-1.01	0.77	0.166
-1.01	0.90	0.086
-1.01	1.03	0.015
-0.87	0.51	0.002
-0.87	0.64	0.030
-0.87	0.77	0.091
-0.87	0.90	0.075
-0.87	1.03	0.018
-0.77	0.51	0.000
-0.77	0.64	0.005
-0.77	0.77	0.026
-0.77	0.90	0.031
-0.77	1.03	0.010

VG1

a	*b*	*wt*
-0.06	0.85	0.005
-0.06	0.96	0.021
-0.06	1.07	0.029
-0.06	1.18	0.016
-0.06	1.29	0.004
0.01	0.85	0.015
0.01	0.96	0.067
0.01	1.07	0.100
0.01	1.18	0.060
0.01	1.29	0.015
0.07	0.85	0.017
0.07	0.96	0.087
0.07	1.07	0.156
0.07	1.18	0.092
0.07	1.29	0.025
0.13	0.85	0.008
0.13	0.96	0.049
0.13	1.07	0.090
0.13	1.18	0.063
0.13	1.29	0.018
0.18	0.85	0.001
0.18	0.96	0.012
0.18	1.07	0.025
0.18	1.18	0.019
0.18	1.29	0.006