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Seismic hazard: UK continental shelf

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for the Health and Safety Executive

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Seismic hazard: UK continental shelf

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FOREWORD

This report on seismic hazard mapping of offshore Britain is a summary of work carried out by EQE International Limited for the Health and Safety Executive (HSE). This work was undertaken in conjunction with NORSAR, Oslo, who have at the same time been working on the seismic zonation for Norway, on behalf of the Norwegian Council for Building Standardization (NBR).

Through the coordination and synchronization of the British and Norwegian seismic hazard mapping projects:- a degree of harmonization which has not previously been achieved, the results of these studies provide an internationally consistent basis for offshore seismic loading in the most seismically active area offshore Britain.

The contents of the report are the work of EQE International Limited, and do not necessarily reflect the policies of the HSE.

EXECUTIVE SUMMARY

This report documents an investigation of seismic hazard in UK offshore waters, which has been conducted by EQE with the scientific collaboration of the Norwegian Seismic Array (NORSAR). The results are expressed probabilistically, and displayed graphically in a series of contour maps of peak ground acceleration for return periods of 100 years, 200 years, 495 years, 1000 years, and 10,000 years.

The northern North Sea region has the highest level of seismic hazard in UK offshore waters. Whereas previous seismic hazard maps for the North Sea have shown discontinuities in hazard levels across the boundary separating the British and Norwegian sectors, the hazard maps produced in this joint Anglo-Norwegian study satisfy the condition of continuity across the sector boundary. This consistency is achieved through agreement on unified seismic source and ground motion attenuation models in the northern North Sea, and represents a major advance in seismic hazard assessment across international frontiers.

The harmonized Anglo-Norwegian seismic hazard maps show that the highest peak ground acceleration hazard in UK offshore waters is attained in the northern North Sea. Close to the sector boundary, the 10^{-4}/yr exceedance peak ground acceleration can reach values of 30%g. The seismic hazard is somewhat less in the southern North Sea, where the 10^{-4}/yr exceedance peak ground acceleration can reach values of almost 25%g. Outside these two specific regions, the hazard is lower near the Western UK coast, typically about 20%g offshore Wales and Northwest England; and the hazard is smaller elsewhere.

For the specification of bedrock earthquake loading at any offshore site, a common EQE-NORSAR approach has been formulated. This involves the specification of a single seismic response spectral shape, which is anchored at 40Hz to the relevant site-specific peak ground acceleration for the requisite return period.

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1. INTRODUCTION

1.1 CROSS-FRONTIER COLLABORATION

The methodologies adopted to evaluate seismic hazard may vary significantly from country to country, even where the countries share a common border and the regional seismic zones overlap. Apart from methodological differences, the underlying seismological and geological databases maintained in neighbouring countries may also differ substantially in scope, reliability and interpretation, and thus cause further international disparities in the conduct and output of seismic hazard assessment. For reasons both technical and administrative, it is rare for a collaborative industrial venture to be established, involving independent organizations from several countries, which is aimed at joint probabilistic seismic hazard mapping for a region spanning a common international border. All too often, hazard contour maps display a discontinuity across frontiers, which is explained by an international breakdown in human communication rather than being attributable to any natural geological fracture.

The comparative study reported herein was a collaborative and cooperative endeavour combining the seismic hazard expertise available to EQE and NORSAR, and involved a transparent exchange programme of knowledge, information and expert judgement. This has been made contractually feasible through the synchronization of the work done for offshore Britain, under contract to the Health and Safety Executive (HSE), with that carried out by NORSAR for offshore Norway, under a contract to the Norwegian Council for Building Standardization (NBR).

This latter project (NORSAR, 1998), has been sponsored by various Norwegian government and petroleum organizations: The National Fund for Natural Disaster Assistance; The National Office of Building Technology and Administration; Norwegian Water Resources and Energy Administration; A/S Norske Shell; Norsk Hydro; Saga Petroleum; and Statoil A/S. This Norwegian project has also involved technical cooperation with NGI, who collaborated with EQE and NORSAR on the joint study of Earthquake Loading on the Norwegian Continental Shelf (Bungum and Selnes, 1988). This study was fully documented in fifteen specialized technical reports. Broader in geographical perspective than ELOCS, the prime goal of the current Norwegian project has been the development of a seismic zonation for Norway, resulting in the production of seismic hazard maps for Norwegian onland and offshore areas that can form part of the Norwegian National Application Document under Eurocode 8.

The benefits of a cross-frontier collaboration for seismic hazard assessment are manifold: rationalisation of scientific databases; reconciliation of hazard evaluation procedures; pooling of expert judgement; sharing of internal documentation; independent international validation of hazard computation etc.. Although this is more than a decade away from being the first UK study of North Sea seismic hazard, (see e.g. Woo and Muir Wood, 1986), this is the first study to which these important benefits accrue.

Given the substantial amount of common work shared between EQE and NORSAR, and the open publication of the extensively detailed NORSAR (1998) report, some of the common documentation is not duplicated here. Instead, copious reference is made to the NORSAR report, which is publically available, and which is recommended to readers wishing to gain a more complete international picture of technical aspects of this Anglo-Norwegian collaboration.

Apart from transcending international frontiers, another original facet of this study, which sets it apart from predecessors, is that this is the first study of UK offshore seismic hazard which incorporates the logic-tree methodology (Kulkarni et al., 1984) for representing parametric uncertainty. Traditionally, single best-estimate values are assigned to input model parameters. However, due to incomplete earthquake data and imperfect understanding of seismicity, there is uncertainty in the choice of seismic area zonation, in estimating zonal activity rates, b-values and maximum magnitudes, as well as in defining ground motion attenuation. Through assigning a probabilistic weight to alternative plausible parameterisations, quantitative account is taken of uncertainty in hazard input variables, and the propagation of uncertainty in the hazard computation..

This more elaborate and expansive treatment of uncertainty has now become standard in probabilistic seismic hazard assessment; in particular, the logic-tree methodology has been applied in site-specific studies for most of the nuclear installations in Britain. Compared with best-estimate analyses, logic-tree analyses have the virtue of greater statistical robustness against change in modelling parameters, and hence are more appropriate for practical engineering applications.

1.2 GEOLOGICAL BACKGROUND

Prior to undertaking a quantitative assessment of regional seismic hazard, a qualitative geological perspective is lent by a review of the underlying geological background. The emphasis below is placed on the North Sea, since this is the region of offshore Britain where the level of seismicity is highest, and where geological structure might be most informative. In most parts of Northwest Europe (SHWP, 1993), the correlation between seismicity and geological structure is very poor. This reflects the large scale over which tectonic forces operate within the western part of the Eurasian plate, and the myriad faults over which a moderate quantity of seismic energy might be dissipated. For example, to the Northwest of Scotland, there is very scant seismicity associated with the principal structures such as the Rockall Trough, the Rockall-Hatton Basin and the Faeroe-Shetland Channel.

A map of the structural framework of the UK and Norwegian North Sea is shown in Fig.1.1. The twenty two structural elements are listed as follows: (1) Møre Basin; (2) Magnus Embayment; (3) East Shetland Sub-basin; (4) Unst Sub-basin; (5) Vestland Arch; (6) Horda Platform; (7) East Orkney Sub-basin; (8) Fair Isle Sub-basin; (9) Fladen Ground Spur; (10) Outer Moray Firth Basin; (11) Halibut Horst; (12) Forties-Montrose High; (13) Norwegian-Danish Basin; (14) Egersund High; (15) Forth Approaches Basin; (16) Offshore Durham and North Dogger Shelf; (17) Cleveland Sub-basin; (18) Silver Pit Sub-basin; (19) East Midlands Shelf; (20) Cleaver Bank High; (21) Sole Pit Sub-basin; (22) South Hewitt Shelf.

In the geological history of the North Sea area, tectonics and sedimentation were controlled by four evolutionary events (Schmitz, 1994): the Late Caledonian Orogeny in Late Silurian/ Early Devonian times; the Variscan Orogeny in Late Carboniferous times; the Cimmerian Rift Phases in Late Triassic to Early Cretaceous times; and the Alpine Orogeny in Late Cretaceous to Mid-Tertiary times. Those events which have moulded the North Sea's major structural elements are of interest for establishing the geological background for current crustal deformation, and a summary is presented below, along with references to the geological background of other UK offshore areas.

The Late Caledonian Orogeny completed a basic change in plate geometry. On closure of the Iapetus Ocean and the Tornquist Sea, the Caledonian fold belt, which covered most of the North Sea area, came into existence. In the Southwest, the London-Brabant Massif became the dominating tectonic element. Following the orogeny, compressional and extensional movements, associated with horizontal displacements, modified the area, creating grabens and pull-apart basins. During the Early Carboniferous, tectonic movements which were dominantly extensional, continued in breaking up the basin area into grabens and horsts.

The English Channel may be postulated (Smith, 1992) to have tectonized and metamorphosed Marine Devonian and carboniferous rocks at depth. Marine Devonian rocks lie in the western part of the Western Approaches as the basin extended. During Late Devonian times, parts of the Western Approaches were a high part of the Bretonic uplift. Off SW England and westwards, the Cornubian Platform extends to the continental margin.

The Variscan Orogeny resulted from the collision of the southerly Gondwana continent and Laurussia, which rearranged the regional setting such that North of the Central European subduction zone a foredeep developed. This extended far into the Southern North Sea. Late Variscan movements modified the area, particulary East of the London-Brabant Platform. Reconstruction of the general area started as two major W-E trending Permian basins came into existence: the North and South Permian Basins which encompass the Mid North Sea (Ringkøbing) High. Among the driving forces were an overall E-W oriented extension and the collapse of the Variscan Mountains. In parallel with the destruction of the Variscan fold belt, the Variscan foreland was deformed as a result of NW-SE directed transtension. Additionally, it was dissected by NW-SE and NE-SW oriented conjugate shear faults and suffered from transpressive movements, particularly in the Sole Pit area and surroundings. Resulting from the above, grabens and horsts formed in both the foreland and Variscan mountain area, and widespread magmatism was triggered. The main areas of occurrence of this volcanism were the Mid North Sea High and its surroundings.

The Mesozoic era of the North Sea was dominated by rifting. The North Sea structural pattern changed during the Triassic, when extensional movements were accentuated, leading to a set of mainly N-S oriented rift grabens, which cut across the W-E oriented Permo-Triassic mega-basins. The main grabens are the Viking, Central and Moray Firth Grabens, and the Horda Half-Graben. The evolution of the grabens is related to the southward propagation of a major rift system separating Fennoscandia from Laurentia.

In Triassic times, fault movements occurred in the Western Approaches Basin and in the Celtic Sea basins and their northern and eastern extensions. The western part of the Western Approaches, the Cornubian Platform and Armorica underwent uplift associated with major tectonic developments at what was to be the margin of the European continent. In addition, there were other smaller sources linked to more local faulting and to halokinesis.

The Cimmerian Rifting Phase is associated with the opening of the Central Atlantic and the Western Tethys. The Mid-Cimmerian break represents a fundamental reorganization of the palaeographic pattern, and is associated with the uplift of the Central North Sea Dome, which covers the triple junction area where the Viking, Central and Moray Firth Grabens meet. From the Kimmeridgian to the Valanginian, crustal extension obviously accelerated, culminating in the Late Cimmerian rift phase that affected the main grabens, in particular the Viking Graben. The Cimmerian rifting was followed by the period of Mid-Cretaceous thermal relaxation, which led to subsidence of the general area.

The Alpine Orogeny, which was a result of the Africa-Europe collision, engendered a NW oriented stress regime, as evident in the Central and Southern North Sea. The resulting inversion of basinal areas induced transpressional deformation that affected the Mesozoic basins and grabens South of the Mid North Sea High, i.e. the Sole Pit and Cleveland Sub-basins and part of the Central Graben, as well as the Egersund and Stord Basins. In parallel with these structure-forming events in the South, plate divergence in the Atlantic domain continued. Being linked with the onset of the sea-floor spreading in the North Atlantic, the North Sea grabens ended as abortive rifts. Thermal relaxation caused major basinal parts of the North Sea area to steadily subside, with only minor faults involved. By the end of the Alpine Orogeny, all basinal areas subsided. Subsidence was not uniform, yet its main axis followed the N-S graben trends. The regional downwarping of the North Sea area lasted into Quaternary times, although with varying rates of sedimentation.

2. THE SPATIAL PATTERN OF SEISMICITY

2.1 HISTORICAL EARTHQUAKES

Because of the long time scales over which seismic activity is manifested, it is important for all studies of seismic hazard that the maximal information is gleaned from historical and even archaeological sources. This is especially important for intraplate regions of sparse seismicity, where the twentieth century instrumental record may itself provide a rather pale impression of the spatial pattern of seismicity, which may be more fully delineated by the historical catalogue, notwithstanding errors in epicentre location and magnitude estimation.

The acquisition of historical information on earthquakes in Northwest Europe is a cumulative process, which follows the Pareto distribution in volume of data capture per library research day. In the early 1980’s when historical earthquake research was burgeoning, hundreds of pages of primary documentary information could be retrieved with a modest newspaper library effort. The Scandinavian Earthquake Archive, which was created as part of a 1980’s assessment of North Sea seismicity (Woo and Muir Wood, 1986), comprised no less than ten large tomes. Much of this archival information is derived from local newspapers, which flourished from the nineteenth century, but there are regional historical chronicles dating back to earlier centuries.

In the late 1990’s, a saturation level is near approaching, where any additional primary information of seismological importance would probably require an investment of weeks of trawling patiently and meticulously through arcane journals and diaries. Such effort might be rewarded by the acquisition of information enlarging the arc of coverage for a known historical event, which would help refine the macroseismic felt area. Less often and more fortuitously, there might be a discovery of evidence of a small unknown tremor.

This level of effort is best justified and most readily sustained in the context of site-specific seismic hazard investigation. Since the early North Sea historical researches, conducted a decade ago, and reported in OTH 86 219 (Woo and Muir Wood, 1986) and ELOCS Report 2-1 (Muir Wood and Woo, 1987), there have been supplementary researches conducted by NORSAR for the oil industry in Norway, and by the UK Seismic Hazard Working Party (SHWP) for the nuclear industry in Britain and Continental Europe. Particularly relevant for UK offshore waters have been the exhaustive historical earthquake studies undertaken for UK and French coastal nuclear installations: Hartlepool; Sizewell; Bradwell; Dungeness; Gravelines (France); Devenport; Hinkley Point; Wylfa; Heysham; Sellafield; Chapelcross; Hunterston; Torness and Dounreay.

Collectively, these SHWP site-specific hazard studies cover almost all UK coastal waters, as well as most of the continental North Sea coast. While the archive of historical information has been increased gradually over the years, the basic procedure for quantifying the size of a historical earthquake remains that developed previously (Principia, 1982):

[1] interpreting historical accounts in terms of macroseismic Intensity;

[2] plotting Intensities at locations where the earthquake was felt;

[3] drawing an isoseismal map for the event;

[4] estimating the area within the outer isoseismals;

[5] calculating a macroseismic surface wave magnitude (M_S) via a correlation between felt area and instrumentally measured M_S.

Accumulating all the surface wave assignments, a catalogue has been produced of all regional earthquakes of engineering interest, namely those having a surface wave magnitude of 4 or more. Fig.2.1 shows a plot of all known Northwest European epicentres which have a surface wave magnitude of 4 M_S or more.

2.2 INSTRUMENTAL SEISMOLOGICAL DATA

With the twentieth century development of sensitive seismic instrumentation for measuring small ground movements, the concept of earthquake magnitude was introduced by Richter (1935) as a way of quantifying the sizes of local Southern Californian earthquakes. Since its inception, various types of magnitude have been defined, which have the same basic generic form, being logarithmically dependent on ground displacement or velocity measured by a seismometer.

Because amplitudes of seismic ground motion diminish with distance from the earthquake source to the location of the seismometer, it is necessary to make a correction for this distance, so that magnitudes calculated by seismologists at varying site-source distances are self-consistent. In order to characterize spectral differences attributable to regional seismic wave propagation effects, a synoptic analysis of selected high-quality long period seismograms recorded in Europe was undertaken by NORSAR (1997). This involved a substantial programme of historical seismogram compilation, focused mainly on Uppsala, Sweden, and the German seismological stations. The seismograms in the dataset were digitized at NORSAR, using both conventional digitizing table methods and also modern scanning technology; the former being capable of handling more complex analogue recordings. These were then analyzed, using the corresponding system response functions, to provide a synoptic assessment of long period seismic wave characteristics. Among the seismological findings, a new set of seismic moments and moment magnitudes have been estimated, which have been utilized in determining new magnitude-moment relations, which are referred to below.

The EQE catalogue of twentieth century instrumental data has been compiled from the comprehensive International Seismological Centre (ISC) catalogue covering the period 1904 to 1990, which includes data from all world-wide reporting seismological agencies. In particular, the catalogue includes the contributions from the Fennoscandian agencies based in Oslo, Bergen, Uppsala, Copenhagen and Helsinki. In addition, this ISC catalogue has been supplemented by the NORSAR and British Geological Survey catalogues for the most recent recording period from 1990 to 1996 inclusive.

Fig.2.2 shows a plot of all Northwest European epicentres reported by the ISC from 1904 to 1990, which have a magnitude of 3 or more. To gauge the extent of UK offshore seismicity, Fig.2.3 shows a plot of BGS offshore earthquake epicentres from 1990 to 1996 inclusive, having a local magnitude of 2 or more. Based on comparisons over several decades, local magnitude values estimated by BGS tend to be somewhat larger than the corresponding surface wave magnitudes.

For consistency with the treatment of the historical catalogue, which accounts for the bulk of earthquake knowledge for the British Isles, surface wave magnitude values are retained for use in the characterization of activity rates of UK onland and offshore seismic sources. Given the archive of primary historical earthquake information, and the databank of regional isoseismal maps, the potential in principle exists for moment magnitude (M_w) values to be assigned to each historical event, provided there is a well-defined instrumental calibration of macroseismic data. However, for British earthquakes, there are comparatively few events for which seismic moment determinations have been made, in contrast with events for which surface wave magnitudes have been measured. Hence, for Britain, M_s remains the preferred earthquake magnitude type.

This contrasts with the circumstances prevailing in Norway, where moment magnitudes may be better constrained than surface wave magnitudes, which are subject to a degree of volatility due to the blocking of L_g waves in traverses across the North Sea. Apart from this geophysical merit, moment magnitude has the virtue of a direct association with seismic energy release. Using the definition of seismic moment introduced by Aki (1966): $M_0 = \mu AD$, where μ is the fault rigidity modulus, A is the fault area, and D is the displacement across the fault, seismic energy released in an earthquake can be related to the seismic moment and the stress drop σ according to the relation: $E = (\sigma/2\mu) M_0$.

M_w can be defined in terms of seismic moment M_0 (dyne-cm), via the Hanks and Kanamori (1979) relation, as follows:

$$M_w = (2/3) \operatorname{Log} M_0 - 10.7$$

Because seismic moment is proportional to fault area and fault displacement, it is equivalent to seismic energy, up to a stress drop factor.

As it turns out, regression analysis of the relation between moment magnitude and EQE surface wave magnitude reveals that, within the size range of historical events (which is the range contributing most to seismic hazard), the difference is minor. NORSAR (1998) have derived the following regression relation, combining results for M_S values obtained from all felt area information:

$$M_w = 1.233\, M_s - 1.183$$

There is near equality of the two magnitudes around 5.0, and for any M_s between 4.0 and 6.0, the largest difference between moment magnitude and surface wave magnitude is 0.25.

2.3 SEISMOTECTONICS

Seismotectonics is an Earth Science discipline which seeks a basic understanding of the underlying geophysical processes, and a scientific explanation for the geological controls of regional seismicity. The contribution seismotectonics can make to seismic hazard assessment is a function of the breadth and depth of this understanding, which supplements seismological and geological data in informing judgement on the selection and parameterisation of a seismic source and attenuation model. In regions of the world, such as California, where tectonics are active and the study of seismotectonics is advanced, this contribution inevitably has been more influential than in less seismic areas such as Britain.

Although British seismicity is comparatively sparse, sufficient data exist to demonstrate unequivocally that the spatial pattern of British earthquakes is not random, and thus the British Isles cannot be treated as a single homogeneous seismic zone. For the earthquakes of engineering interest (magnitude 4 M_S or more), the localization of seismicity is such that events tend not to occur where they have not occurred before: there remain large areas of Britain which have not fallen within the epicentral region of a significant historical earthquake.

Where major events seem to have occurred in areas without apparent historical precedent, uncertainty in epicentre location or catalogue incompleteness may provide a plausible explanation. The magnitude 5 M_S 1185 Lincoln earthquake, for example, is poorly located. Even though the stone vault of the cathedral collapsed, (an event famous in the annals of British earthquake history), the free-field site ground motion need not necessarily have been particularly high. Structural vulnerability would have been exacerbated by the replacement of the original wooden vault by one built from stone. Furthermore the ground motion at the cathedral would have been amplified by its topographical location on a ridge. Thus it is conceivable that this event might not have been local, but might have been epicentred offshore near the epicentre of the 1931 Dogger Bank event.

The marked zonation of historical British earthquakes is an important observation which demands, and can be given, a seismotectonic explanation. The respective positions of the British postglacial rebound dome and forebulge, in relation to the underlying tectonic stress field, would be expected to engender a pattern of alternating regions of higher and lower seismicity, of a kind which seems to be approximately replicated in the historical catalogue. A precise elaboration of this pattern awaits numerical modelling of the sensitivity to lateral variations in lithospheric and mantle properties, which are known to exist under the British region. The geographical stability of seismic zonation cannot be explained in terms of crustal loading alone, but must also reflect variations in the regional capacity of the brittle crust to sustain this loading. The seismological evidence appears to indicate a preference for certain zones to be exploited repeatedly in the release of seismic energy. The delineation of the preferred seismic zones tends to be reinforced with the repetition of similar-sized regional earthquakes.

Through analysis of the effect of the superposition of crustal uplift and tectonic forces, allowing for variations in capacity, a more precise quantitative spatial image of seismogenesis should emerge. But in the current absence of such numerical computation, other candidate theories merit exploration. One such is the theory of ridge-push. By cross-correlating annual cumulative seismic energy release, Skordas (1992) has suggested a causal relation between seismicity along the North Atlantic Ridge and the intraplate seismicity in Fennoscandia. Physical models, simulating ridge-push, might support the hypothesis of a tectonic relation between the opening of the Atlantic Ocean and the strain regime in the oceanic lithosphere and the continental margin.

According to Skordas, these models predict low levels of strain in the continental interior, which is consistent with the low activity around Britain and Fennoscandia. However, taking the ridge-push theory as the controlling mechanism for earthquake occurrence, it is difficult to explain a number of obvious features of regional seismicity, not least being the manifest asymmetry of seismicity on opposing continental margins.

Another candidate theory of seismotectonics stresses the influence of the Alpine Orogeny, encompassing all deformation post-dating the major Mesozoic phases of rifting. This theory was developed by Whittaker and Long (1989), who proposed that, in southern England, the thrust driven inversion which has been in operation over the last ten million years may still be operating. The idea that the continuing effects of the Alpine Orogeny are important for contemporary seismicity found support in the late 19th century, and encouraged the siting of Milne's seismological observatory on the Isle of Wight. However, advocates of the influence of the Alpine Orogeny have difficulty in explaining the lack of a significant correlation between seismicity and the principal faults involved in the localisation of compressional deformation in southern England. In assessing the significance of the spatial correlation between major historical earthquake epicentres and any set of geological features, it has to be demonstrated through rigorous methods of stochastic geometry that this correlation is clearly superior to that which would arise from a merely random distribution of epicentres. Given the small number of major earthquakes in and around Britain, robust demonstration of this statistical requirement is not trivial.

Notwithstanding this difficulty, attempts have been made to correlate seismicity with a wide range of geological characteristics. These attempts have been unsuccessful in matching UK seismicity with bulk crustal properties such as crustal thickness, and only marginally more successful with upper crustal structural provinces and deep crustal shear-zones. However, it is in the match of UK seismicity with certain major existing faults, that some apparent correlations are easier to find. But even this evidence has to be treated with circumspection: the fact that all historical earthquakes are small enough to have occurred on small faults of no more than 6km length implies that the population of seismogenic faults is largely unobserved.

A spatial plot of earthquake epicentres in a seismic source zone can suggest to the naked eye the underlying presence of linear seismogenic structures. The approximate collinearity of three, or perhaps more, epicentral locations can be taken as putative evidence. However, before any seismotectonic inferences are drawn from the spatial disposition of zonal epicentres, apparent collinearity should be suspected as an artefact of stochastic geometry, arising from the random distribution of the epicentres within the zone. Statistical analysis of earthquake epicentres shows that a surprisingly large number of near-perfect alignments are accountable by chance alone (Kendall and Kendall, 1980). This complicates any attempt at associating seismicity with faulting, especially where, as over much of the southern North Sea, salt mobilization obscures the connection between Plio-Quaternary faulting and basement displacement.

Recognizing this caveat, in offshore UK waters there are discernible some well-defined geological controls on seismic activity. One such is the western boundary of the Viking Graben, which is a major complex of westerly dipping fault-zones, and marks the eastern boundary of the Shetland Platform. The earthquake of 24th January 1927 was relocated by ISC to the western boundary of the Viking Graben, using European seismological data provided by Principia (Woo and Muir Wood, 1986). The pattern of displacement on this western boundary has been reconstructed, using geophysical as well as geological data, and reveals various notable sequences of Tertiary and post-Palaeocene fault activation.

In the North Sea, the offshore activity is especially associated with the graben structures and the shelf edge. Another seismically active area is west of Jutland in the Norwegian-Danish Basin, possibly related to the Tornquist Zone. Between 59 N and 63 N, the Norwegian coastal areas have a high level of seismicity, even though the Horda Platform and Shetland Platform - Tampen Spur areas are practically devoid of earthquakes.

2.4 NEOTECTONICS

The millenial period of regional historical seismological observations can be extended backwards into the past through the archaeoseismic and palaeoseismic records. Negative archaeoseismic evidence against large earthquakes since the Iron Age is seen in the survival of seismically highly vulnerable neolithic structures, such as dry-stone construction broch towers, which date from the later centuries B.C.. Classic examples include Gurness and Midhowe in Orkney, Mousa in Shetland, and Dun Carloway, Lewis (Armit and Ralston, 1997).

As with archaeological findings, palaeoseismic evidence also tends to be negative, or else equivocal. As with any scientific study where direct empirical observation is mostly precluded, the investigation of recent active faulting is a painstaking labour, complicated by the subterranean nature of earthquake sources. Geological and geophysical investigation constitutes a spatial sampling process, to which every trench dug and seismic line shot makes a contribution. This sampling process is only partially systematic and methodical, with specific faults targeted on the basis of their perceived likelihood for revealing neotectonic evidence.

An uncertainty audit of neotectonic investigation would catalogue the deficiencies in empirical data imposed by observational constraints (Atakan, 1997). In respect of data acquisition from seismic profiles, the very existence and extent of apparent fault offsets can be misleadingly asserted if the geophysical data are poor. In common with trenching data, further uncertainties abound because observed displacements need not necessarily be neotectonic, but may have a superficial origin. And even if displacements are properly identified as neotectonic, interpretation of offset information in terms of event occurrences and magnitudes is beset with ambiguities as to the proportion of non-coseismic deformation; as to the number of individual events; and as to the stability of the magnitude/offset relation.

The weighing of uncertain evidence is a crucial stage in the evaluation of neotectonics. A common error made in weighing evidence of all kinds is known as ***the fallacy of the transposed conditional*** (Aitken, 1995). If the evidence is denoted as E, and the proposition to be established (e.g. a fault being active) is denoted as G, then Pr(E|G), the conditional probability of the evidence given G, is often erroneously and unknowingly substituted for Pr(G|E), which is the conditional probability of G given the evidence E. Confusion over this transposition can lead to the scientific elevation of dubious claims for neotectonics, their unhindered proliferation, and a consequent apparent escalation in the inferred level of palaeoseismicity (Woo, 1997).

The more meticulous and intensive a neotectonics investigation is, the greater opportunity there exists for alternative explanations for circumstantial evidence to be systematically formulated and scientifically aired: e.g. artefacts of seismic data processing; halokinesis; or ice collapse. Indeed, these three particular alternative explanations have been suggested in Cumbria, Northwest England. At Sellafield in Cumbria, where the most concentrated effort in UK has been expended in searching for the evidence of neotectonic structures (NIREX, 1997), no conclusive geomorphological evidence for neotectonic faulting in Cumbria could be found in the form of scarps, disrupted terraces or offsets.

Reference to specific individual claims for neotectonics is cited in the Appendices, in the context of the choice of seismic zonation of the overall UK offshore region. The degree to which neotectonic arguments influence zonation varies according to the empirical strength and geological credibility of these claims.

3. SEISMIC HAZARD SOURCE MODEL

3.1 SEISMIC HAZARD COMPUTATION

The model for the occurrence of ground motions at a site in excess of a specified level is assumed to be that of a Poisson process. This is valid if the occurrence of earthquakes is a Poisson process, and if the probability that any one event will produce site ground motions in excess of a specified level is independent of other events. The probability that a ground motion level z is exceeded at a site in unit time is thus expressed as:

$$P\ (Z \geq z) = 1 - \exp(-\nu(\ z)\ )$$

where $\nu(z)$ is the mean number of events per unit time in which Z exceeds z.

According to convention (McGuire, 1976) in probabilistic hazard analysis, the region around a site is partitioned into disjoint polygonal area seismic zones, which constitute a set of seismic area sources. The basic principle underlying a zonal partition is that, whereas significant differences may exist between zones, the characteristics of seismicity within each zone are supposed to be sufficiently homogeneous, or the uncertainty over future spatial patterns of activity is perceived to be sufficiently great, for seismological parameters to be treated as uniform within the designated zones. As non-seismological criteria for delineating zones, geological data have been used with varying degrees of scientific conviction. Where there is a lack of correlation between geological structure and seismicity, as in many intraplate regions, it has been canonical practice to assume that earthquakes are equally likely to occur anywhere over the area.

With N seismic sources, and model parameters $\underline{S}_n$ for source n, the mean number of events per unit time in which ground motion level z is exceeded can be written as:

$$\nu(z) = \Sigma_n\ \nu_n(z|\underline{S}_n)$$

$$\text{where}\quad \nu_n(z|\underline{S}_n) = \Sigma_{i,j}\ \lambda_n(M_i|\underline{S}_n)\ P_n(r_j|M_i, \underline{S}_n)\ G_n(z|\ M_i, r_j, \underline{S}_n)$$

$\lambda_n(M_i|\underline{S}_n)$ = Mean number of events per unit time of magnitude M_i on source n, given parameters $\underline{S}_n$;

$P_n(r_j|M_i, \underline{S}_n)$ = Probability that the significant site-source distance is r_j , given an event of magnitude M_i on source n, having parameters $\underline{S}_n$;

$G_n(z|\ M_i, r_j, \underline{S}_n)$ = Probability that ground motion level z will be exceeded, given an event of magnitude M_i at a significant distance r_j from the site, and parameters $\underline{S}_n$.

The three functions $\lambda_n(M_i|\underline{S}_n)$, $P_n(r_j|M_i, \underline{S}_n)$, $G_n(z|\ M_i, r_j, \underline{S}_n)$, model the inherent stochastic uncertainty in the frequency of occurrence and location of earthquakes, and in the attenuation of seismic waves. Besides this natural uncertainty, there is also an element of uncertainty associated with the variability of the model parameters $\underline{S}_n$. This source of uncertainty is accounted for by regarding the parameters $\underline{S}_n$ as random variables, whose discrete values are assigned weights reflecting their likelihood.

These discrete values represent notional branches in an uncertainty logic-tree for the seismic hazard model. At each node, discrete probability weights are attached to the various branches, which are disjoint and exhaustive of possible choices; thus summing to unity. The values given to the weights are based predominantly on observational data, supplemented where necessary by expert judgement. The elicitation of expert judgement at EQE and NORSAR has been undertaken in accord with standard procedure for decision conferencing.

In the actual implementation of the logic-tree, discrete probability distributions are assigned for all the principal sources of modelling uncertainty: the zonal seismic source geometry; the maximum magnitude; the b-value; the activity rate; the choice of attenuation relations; and the aleatory (random) scatter in attenuation. Fig.3.1 shows the schematic form of the logic-tree, with its various separate branches. Computerized enumeration of the complete set of branches allows the probability distribution of $\nu(z)$ to be calculated.

SIGNIFICANCE OF FAULTING

The seismic sources constructed for a seismic source model are of two types: zonal area sources, and individual fault sources. The latter type of source is used to supplement a zonal source model where there is good geological and seismological evidence supporting fault activity, and where there is significant hazard sensitivity to the modelling of an active fault as a specific source. A major difficulty with the interpretation of geological data is that the majority of faults offshore are known only from their position in the sedimentary cover rocks, which may be decoupled from the underlying crystalline basement. Earthquakes of engineering interest often have hypocentres at greater depths in the crust than is revealed by geological or geophysical observations.

Apart from fault geometry, knowledge of geologically recent fault behaviour is fraught with uncertainty over activity rate, especially if information on slip rates is ambiguous, and if local historical seismicity is sparse. In general, the spatial correlation between epicentres of notable earthquakes and geological structures is, with some exceptions, rather unconvincing in the region around the British Isles. Even if the likelihood of the evidence, if the fault were not actually seismically active, may be considered small, this does not imply the converse, namely that the likelihood of the fault being active is high. Accordingly, in very instances are specific faults included in site-specific UK seismic hazard studies.

The modelling of individual faults within a seismic source model may be viewed as a procedure geared more towards sensitivity analysis; answering the hypothetical question of potential impact of the fault on local seismic hazard. Within the present study, the purpose of which is to map seismic hazard offshore UK, only area zone sources are used for seismic source modelling. The contribution of individual faults is thus subsumed within the activity of the various area zones which include them.

3.2 SEISMIC AREA ZONATION

Prior to the validation of plate tectonic concepts in the 1960’s, it was customary for earthquake catalogues to be taken at face value as representative empirical guides to the sources of hazard, future as well as past. However, given the lack of direct tectonic input, the sole reliance on historical earthquake data was deprecated by Cornell (1968) on the grounds that insufficient weight was given to known correlations between geological structure and most seismic activity. It still remains common practice in seismic hazard analysis to construct a source model of seismicity, which includes a geographical partition of the region around the site of engineering interest, into disjoint Euclidean seismic area zones, sometimes called tectonic provinces.

The basic principle underlying a zonal partition is that, whereas significant differences may exist between zones, the characteristics of seismicity within each zone are supposed to be sufficiently homogeneous for seismological parameters to be assigned adequately on a zonal basis. As non-seismological criteria for delineating zones, geological data have been used with varying degrees of scientific conviction. There are tectonic provinces defined either from causal relationships established between geological structures and earthquakes, or from faults which have been historically aseismic, but show recent geological displacement. Other than these, two more classes of zone can be defined. One is based on an association of seismicity with geology, which falls short of direct evidence of active faulting, and lacks development of a clear history relating contemporary seismic activity with geological structure. The other type of zone, is one constructed solely using the spatial distribution of historical seismicity. If there is an association with known geological structure, only a small portion may be currently active, and it may not be clear which of several possible structures could be active.

Ambiguity in the delineation of area seismic sources is a common predicament in intraplate regions of comparatively modest seismicity. Even if a zonation is established on the best cumulative scientific basis of seismotectonic, neotectonic, and seismological information, contrasting choices in zonation may be hard to differentiate on objective technical grounds. In this situation, the logic-tree formalism provides a resolution in terms of allowing several alternative distinct zonation schemes. In this study, use is made of this logic-tree facility in defining two alternative, equally-weighted, area zonations.

The starting point for the British zonation is the dual set of zonations (Nos. 1 and 2) constructed by NORSAR (1998) for the Norwegian sector of the North Sea. The first zonation is a detailed partition comprising 37 individual disjoint zones, developed specifically for the new seismic zonation for onland and offshore Norway. On the other hand, the second zonation corresponds to a coarser 24 zone regional partition which is essentially that developed for the Global Seismic Hazard Assessment Project: GSHAP (Grünthal, 1996).

Given the dual nature of the NORSAR zonations, which are accorded equal logic-tree weight, harmonization across the international sector boundary dictates that each be extended in a commensurate manner so as to cover the remaining British Isles area relevant to this study. The two resulting British zonations are henceforth labelled as [A] and [B]. As with their counterpart NORSAR zonations, these alternative zonations are assigned equal weight; there being plausible arguments to support both alternatives.

The manner in which the two NORSAR zonations have been extended has been based on the experience gained by EQE in participating in numerous site-specific seismic hazard studies in all the territories of interest: England, Scotland, Wales, Ireland, France, Belgium, Holland and Germany. It should be stated that the concept of a seismic zonation is, to some degree, site-specific in as much as the spatial resolution of a zonation may justifiably become progressively coarser with distance from the site, since the far-field approximation may be invoked. Thus the zonations constructed for individual sites within Northwest Europe would not be expected to be disjoint, as indeed they are not. However, the principal seismotectonic characterization of Northwest Europe can be established from the collective site-specific zonations, and this is the framework underlying the construction of the two EQE zonations [A] and [B] for the British Isles and surrounding territories.

The primary detailed EQE zonation with 38 area zones is [A]; this interfaces with the 37 source first NORSAR zonation, of which ten are sufficiently close as to be relevant to the computation of hazard in UK offshore waters. The secondary EQE zonation with 26 area zones is [B]; this interfaces with the 24 source second NORSAR zonation, of which eight are relevant to the computation of hazard in UK offshore waters. Maps of the EQE zonations, together with adjoining relevant NORSAR zones, are shown in Figs.3.2 and 3.3. Details about the individual mapped zones, including claims for neotectonics, are given in Appendices 1 and 2 for the two respective zonation models.

3.3 SEISMIC ACTIVITY RATE DISTRIBUTION

The non-equilibrium dynamics of the lithosphere have a sufficiently long time constant for there to have been little change in thermo-elastic state during the period of historical earthquake coverage. The comparatively stable rate of seismic energy release in Britain over the past nine centuries supports the use of historical seismicity as a guide to seismicity over the next 50 years. With the comprehensive evaluation of the historical seismicity of Britain and neighbouring regions, seismological parameterisations of all regional zones can be made using a methodology which assigns a probability distribution for activity rate.

Under the standard premise that earthquake occurrence is consistent with being a Poisson process, the maximum-likelihood procedure for calculating a zonal activity rate distribution within the EQE zones is described below. In contrast with deterministic procedures for estimating activity rate by fitting a log-linear magnitude-frequency relation, the probabilistic procedure adopted here recognizes the intrinsic uncertainty in estimating activity rate, due to the stochastic nature of earthquake occurrence. Where the mean activity rate is high, the probability distribution may well be quite narrow. However, where zonal seismicity is sparse, this distribution will be broadened so as to reflect the possibility that the apparent lull in activity may be merely a fleeting temporal fluctuation.

For a given zone, the time span of historical earthquake documentation can be divided into N time intervals of varying thresholds of completeness. Starting from the present day, these time intervals are labelled: D_1 ,D_2 , D_3 , . . .D_N . From historical and instrumental investigations, these time intervals are regionally associated with magnitude thresholds M_1 ,M_2 , M_3 , . . .M_N , so that in a general time interval D_i , all the events in the area zone having magnitude greater than or equal to M_i , have been recorded.

Let M_{max} be the area zone maximum magnitude, and let M_0 be the engineering threshold magnitude, defined as the smallest size of event of possible engineering concern (generally taken in the UK to be 4.0). Further, let a be the area zone activity rate, expressed as the annual number of exceedances of M_0 , and let the relative frequency of occurrence of events in the range M_i to M_{i+1} be defined as follows:

$$f_i = \{10^{**}(-bM_i) - 10^{**}(-bM_{i+1})\} / \{10^{**}(-bM_0) - 10^{**}(-bM_{max})\}$$

If n_i events are observed in the magnitude range M_i to M_{i+1} during the cumulative time period $D_1 + D_2 + D_3 +. . +D_i$, then the probability of occurrence, according to the Poisson distribution, is given by the expression: $x^{**}(n_i) \exp(-x)/n_i!$ where:

$$x = a\, f_i\ (D_1 + D_2 + D_3 +. . +D_i)$$

The dependence on activity rate a is contained in the reduced expression:

$$a^{n}{}_{i}\ \exp[-a\, f_i\ (D_1 + D_2 + D_3 +. . +D_i)]$$

As events are assumed to be independent under the Poisson hypothesis, their probabilities of occurrence may be combined multiplicatively to give the probability of occurrence of the joint sequence of events spanning the magnitude range of engineering interest. The dependence on activity rate a within this multiplicative product is as follows:

$$a^K \exp(-a D_{sum}), \quad \text{where } K = n_1 + n_2 + n_3 + .. + n_N ,$$

$$\text{and } D_{sum} = (D_1F_1 + D_2F_2 + D_3F_3 + .. + D_NF_N)$$

$$\text{with } F_i = f_i + f_{i+1} + ... f_N$$

The relative likelihood of different values of activity rate a may be inferred from this formula, and the fact that the expression has the form of the standard gamma distribution allows for convenient calculation of percentile values. For comparison, the general definition of the gamma distribution is:

$$f(x) = x^{\alpha-1} \exp(-x/\beta) / \beta^{\alpha}\, \mathrm{G}(\alpha) \qquad \text{for } x\ ^{3}\ 0$$

3.4 MAXIMUM MAGNITUDE DISTRIBUTION

The traditional statistical means of estimating maximum magnitude has been through recourse to Gumbel methods of extreme-value analysis (Gumbel, 1958). Following precedents in USA and elsewhere, applications to UK seismicity were undertaken by Lilwall (1976) and Burton (1978). The use of such extreme-value methods has been out of favour since a critical review by Knopoff and Kagan (1977), who recommended methods which make fuller use of seismicity data. To use Gumbel methods, the time span of a catalogue is divided up into arbitrary bins of perhaps five or ten years, and only the largest magnitude of an event occurring within each bin is noted. Other than the extreme event, information on major events within each bin is wasted. Furthermore, for some time bins, during which seismicity has been particularly low, the extreme event may be poorly known.

Rather than just retain data on extremes, a superior method would utilize all data above some high completeness threshold; if several large events occur in one time bin, a way should be found to use this information. A method based on all exceedances above a threshold would achieve maximum efficiency in the use of sparse data. Little progress towards this goal was possible until a crucial theoretical breakthrough was made by Pickands (1975) who introduced the generalized Pareto distribution, and proved its close connection with extreme value distributions. This seminal advance in probability theory is the most significant development since the pioneering work of Gumbel.

The generalized Pareto distribution has two free parameters: s is a scale parameter, and k is a shape parameter. The functional form of the distribution is as follows:

$$G(y; s,k) = (1 - (1 - ky/s)^{1/k})$$

Mathematically, Pickands showed that this equation arises as a limiting distribution for excesses over thresholds, if and only if the parent distribution is in the domain of attraction of one of the extreme value distributions. This means that whatever analysis of event statistics is possible using Gumbel modelling of extremes, can be replicated by Pareto modelling of exceedances. Furthermore, if events follow a Poisson process, then the maximum of the excesses has a generalized extreme value distribution. These results suggest that the generalized Pareto distribution is a logical choice for modelling the tails of hazard distributions, and already this new approach has been applied in environmental realms, such as storm and flood, where Gumbel methods had previously held sway.

The use of the generalized Pareto distribution is also appropriate for modelling the tails of complete earthquake distributions. The flexibility of the Pareto distribution means that longer tails can be modelled than with the standard negative exponential distribution. The choice of exceedance threshold level is catalogue dependent. For Britain, 4.0 M_S marks the threshold of engineering significance, and 4.5 marks the threshold for 'major' earthquakes. Beyond 4.5 M_S, the data are too sparse for statistical robustness. Thus, a natural choice for the limiting threshold for Pareto modelling would lie between 4.0 and 4.5 M_S.

Taking the threshold to be 4.0 M_S, the complete set of British events since 1800 has been used as a database for Pareto modelling. (A similar but earlier dataset post-1800 was previously used by Lilwall (1976) in his extreme value analysis of British earthquake data).

Using the method of moments to derive the two Pareto distribution parameters, k is found to be 0.153, and s is 0.372, and the maximum magnitude is 4.0 + (s/k) = 6.4. Reducing maximum magnitude values of 6.4, 6.0, 5.9, 5.3, 5.2, 5.1 are obtained as the threshold is raised from 4.0 to 4.5 in steps of 0.1. The downward trend is indicative of a diminishing limiting maximum magnitude figure. However, the sparseness of the data sample in the tail of the distribution has to be recognized in interpreting the results. From Pickand's theorem, the extreme maximum magnitude is the Pareto distribution maximum magnitude inferred from an event dataset with a limiting high threshold.

From the UK analysis, 6.4 would be regarded as a conservative estimate of maximum magnitude, corresponding to a very long tail in the distribution of exceedances. This underscores the conservatism of adopting, as a standard central M_{max}, the 6.5 M_S value of the 1356 Basel earthquake, which happens to be the largest known historical event in northwest Europe, north of the Alps. Because of its special place in European earthquake history, this event has achieved a status as a conservative maximum credible regional event.

This conservatism is recognized in assigning the logic-tree weights for maximum magnitude. In accord with NORSAR (1998) values for offshore Norwegian zones, defined using EPRI (1994) methodology, equal weights are assigned to values of 6.0 and 6.5, and a small residual weight of 0.2 is assigned to the extreme value of 7.0.

M_{max} :	6.0	6.5	7.0
Weight :	0.4	0.4	0.2

3.5 B-VALUE DISTRIBUTION

For individual regions of Britain, significant earthquakes may tend to cluster in size as well as in location, which implies that the log-linear Gutenberg-Richter magnitude-frequency relation may be a poor descriptor of local data. The validity of the log-linear relation only on a regional, rather than local scale, is in keeping with the contemporary notion of self-organized criticality (Bak et al, 1988) : power-law correlations are characteristic of the critical stress state of the region as a whole, rather than particular parts of it. Thus small stress fluctuations in one part of Britain may trigger a large earthquake in a distant county.

For UK as a whole, the Gutenberg-Richter relation can be fitted reasonably well from the complete catalogue of significant earthquakes with M_S greater or equal to 4.0. A maximum-likelihood value of 1.28 is obtained for the UK b-value, taking account of average UK historical thresholds of 1800 for 4.5 M_S; 1700 for 5.0 M_S; and 1600 for 5.5 M_S. The association of regions of minimal strain with high b-value has been observed by Westaway (1992).

For the North Sea, a state of diminished catalogue completeness detracts from the statistical robustness of b-value computation. However, the indications are that b-values may be somewhat lower, as judged by the magnitude-frequency analysis of NORSAR (1998). Recognizing the present geographical application of a b-value distribution to all UK offshore regions, equal weights of 0.5 are assigned to intermediate b-values of 1.1 and 1.2, as indicated below:

b-Value:	1.1	1.2
Weight :	0.5	0.5

4. SEISMIC GROUND MOTION

4.1 CHOICE OF ATTENUATION RELATIONS

Apart from the characterization of seismic sources, it is necessary to parameterize seismic ground motion at a given distance from an earthquake. The attenuation of seismic ground motion in and around the British Isles cannot, for the foreseeable future, be parameterised from local strong-motion data, because of the infrequency of events which might be capable of producing sufficient indigenous records. Given the comparatively low ambient level of seismicity, the magnitude-distance profile of a database of regional earthquake records is likely to be biased towards small magnitude near-field and moderate magnitude far-field data.

Where seismic networks are operational, local records of small events of magnitude 2 or less may accumulate in sufficient number to constitute a suitable ensemble for empirical Green’s Function representation. Although this approach has been tried with some measure of success in various onland European areas, including Roermond, (Holland), Corinth (Greece) as well as Hinkley Point (England), the logistical difficulties and costs of operating ocean-bottom seismometers rule out this method for offshore purposes.

Far-field data have accrued from a number of significant regional events, including several in the Norwegian Sea in the late 1980’s (Hansen et al., 1989), and the Bishop’s Castle earthquake of 2nd April 1990. At large distances, the effects of anelastic attenuation are particularly noticeable, and attenuation relations which have a logarithmic distance factor but not a linear distance factor are demonstrably conservative (Aspinall et al., 1991). While consistency with far-field moderate magnitude observations is in itself desirable, from a practical engineering perspective it is salutary to appreciate that, given the limiting maximum magnitude for the region, this is not a regime contributing as significantly to seismic hazard as the near or medium field.

The principal alternatives for attenuation relation prescription are twofold, involving reliance on empirical strong-motion data alone, or on various numerical modelling methods. In either case, there is a natural preference for recently developed attenuation relations, since both the observation of earthquake strong-motion and the theoretical underpinning of strong-motion seismology have witnessed major advances of late. In addition, for reasons of peer review and document transparency, there is a preference for attenuation relations which are published in the open scientific literature.

The main two choices available are:

[1] To use attenuation relations based empirically on regression analysis of strong-motion data recorded elsewhere in the world; but data which share the main characteristics expected of British records.

[2] To use attenuation relations based on numerical seismological models, calibrated and validated against actual strong-motion records.

Within the context of the logic-tree approach to seismic hazard assessment, where uncertainty in decision-making on parameterisation is systematically identified and quantified, the balance of argument supporting attenuation choice can be converted into a numerical probability weight.

In the present circumstances, the empirical attenuation relations of Ambraseys et al. (1996), and the stochastic model relations of Toro et al. (1997) can be viewed as representing contrasting but legitimate state-of-the-art alternatives. Each has its particular merits, and each is accorded equal recognition in weight assignment.

These two alternative attenuation models are detailed below. Random scatter in model predictions is a general feature of attenuation models. This scatter is represented statistically by a sigma value (standard deviation) for a lognormal distribution. To elaborate the attenuation logic-tree further, the variability in the random (aleatory) uncertainty sigma value needs to be specified. Recognizing the tendency for the range of sigma values to broaden with period, due to seismic wave dispersion and geotechnical effects, the following assignments are made:

Table 4.1
Logic-tree weights for alternative attenuation sigma values

Logic-Tree Weight	*P.G.A. Sigma*	*1 Hz -10 Hz Sigma*	*0.5 Hz Sigma*
0.3	0.5	0.5	0.5
0.4	0.6	0.65	0.7
0.3	0.7	0.8	0.9

4.2 THE ATTENUATION RELATIONS OF AMBRASEYS, SIMPSON AND BOMMER

In the early 1980's, a cooperative program on the acquisition and analysis of earthquake strong-motion data for engineering purposes was initiated by CEA, ENEA, ENEL and Imperial College, London. Apart from the retrieval of strong-motion data, there has been a strict emphasis on achieving a uniform determination of seismological and geophysical parameters associated with them (Ambraseys and Bommer, 1990).

In recent years, supplementary European Commission funding has been made available for the generation of a European strong-motion databank, which constitutes a valuable resource for the empirical analysis of seismic ground motion attenuation in Europe. Prior to these European initiatives, data from European earthquakes were widely fragmented and geographically dispersed, with restricted commercial access being granted to certain categories of data. Indeed, with the advantage of preferential access to Yugoslavian data, which were not widely available, Lee and Trifunac (1992) developed spectral attenuation relations specific to Yugoslavia.

In order to derive attenuation relations for general engineering application in Europe, Ambraseys et al. (1996) have assembled a large dataset of 422 triaxial records, generated by 157 earthquakes in Europe and adjacent regions. They range in surface wave magnitude from 4.0 to 7.9, and the event focal depth is less than or equal to 30 km. In this dataset, the focal depth and magnitude for each earthquake, the site geology for each recording station, and the site-source distance for each record were reviewed, and most were re-evaluated by Ambraseys et al.. In respect of the site-source distance, the convention has been to take the closest distance to the projection of fault rupture as the defining distance. For shallow moderate magnitude earthquakes, the epicentral distance is approximately equivalent.

For 5% damping, regression analysis of horizontal motion spectral attenuation has been performed to determine the following rock site attenuation relations:

Peak Accn. (cm/s^2): $\mathrm{Ln}\,A = 3.481 + 0.612\,M - 0.922\,\mathrm{Ln}\,[\sqrt{(r^2 + 3.5^2)}]$
0.5 Hz PSV (cm/s): $\mathrm{Ln}\,V = -2.980 + 1.160\,M - 0.728\,\mathrm{Ln}\,[\sqrt{(r^2 + 3.2^2)}]$
1.0 Hz PSV (cm/s): $\mathrm{Ln}\,V = -2.250 + 1.170\,M - 0.885\,\mathrm{Ln}\,[\sqrt{(r^2 + 4.3^2)}]$
2.0 Hz PSV (cm/s): $\mathrm{Ln}\,V = -0.823 + 0.967\,M - 0.913\,\mathrm{Ln}\,[\sqrt{(r^2 + 3.3^2)}]$
5.0 Hz PSV (cm/s): $\mathrm{Ln}\,V = 0.655 + 0.654\,M - 0.922\,\mathrm{Ln}\,[\sqrt{(r^2 + 4.2^2)}]$
10.0 Hz PSV (cm/s): $\mathrm{Ln}\,V = -0.814 + 0.504\,M - 0.954\,\mathrm{Ln}\,[\sqrt{(r^2 + 4.5^2)}]$

In choosing empirical attenuation relations, the following reasons can be given for using the equations developed by Ambraseys et al. (1996). The dataset on which they are based is concentrated within the distance, and magnitude range of predominant UK offshore interest. Thus the magnitude coverage broadens with distance in accord with hazard potential. With regard to the geographical origin of the database, the Southern European geographical origin of near-field data ought not to be unduly significant. Indeed, Martinez-Pereira and Bommer (1997) has recently undertaken a study of near-field ground motions, without distinguishing regional variations in the world-wide data sources. An additional virtue of the Ambraseys et al. database is that it favours surface wave magnitude, and indeed the surface wave magnitudes of the events have been recalculated. The uniformity of magnitude assignment in empirical attenuation relations is far from universal, because of the labour involved; in particular it is lacking in the strong-motion database previously compiled by Dahle et al. (1991).

With regard to other recent empirical attenuation relations, Spudich et al. (1997) have recently developed empirical strong-motion attenuation relations specifically for extensional tectonic regimes. Strong-motion data are taken from many different extensional tectonic areas, including Holland, New Zealand, Central America, Turkey as well as California. The distance measure used is that introduced by Joyner and Boore, namely the shortest distance from the station to the vertical projection of the fault rupture area onto the Earth’s surface. With this distance measure, all the records are within 105 km of the recording station. These attenuation relations are not used here for tectonic reasons; it is well recorded that reverse faulting earthquakes are prevalent in some areas offshore Norway. An additional disadvantage is their use of the geometric mean of the peak of the two horizontal components, rather than the larger of the two, which is required for probabilistic analysis, and which is the convention adopted by Ambraseys et al.(1996).

4.3 THE ATTENUATION RELATIONS OF TORO, ABRAHAMSON AND SCHNEIDER

Stochastic ground motion models have been considered as semi-theoretical alternatives to the purely empirical attenuation relations developed since the 1960’s. Stochastic models use simplified, yet physically based, representations of seismic energy release and wave propagation to obtain predictions of ground motion as a function of earthquake size, site distance, and model parameters. The source excitation; the stress drop; crustal velocity structure; crustal and near-site anelastic attenuation have been characterized by Toro et al. to fit the US Midcontinent seismotectonic environment, but are considered to be tectonically relevant to the intraplate environment of Northwest Europe.

The models are parameterised in terms of moment magnitude, which is similar to surface wave magnitude within the earthquake range of practical concern. The distance measure used is that introduced by Joyner and Boore, namely the shortest distance from the station to the vertical projection of the fault rupture area onto the Earth's surface. Because these are average predictions, an extra factor has to be introduced so that estimates can be made of the amplitude of the larger of the two horizontal components, which is more appropriate for seismic hazard assessments. According to Campbell (1981), this factor is estimated to be 13% for peak ground acceleration, and the same factor is assumed for spectral velocity. Leaving aside this factor, the rock site attenuation relations of Toro, Abrahamson and Schneider are listed below:

Peak Ground Acceleration (g's):
$\mathrm{Ln}\, A = 2.20 + 0.81\,(M\text{-}6) - 1.27\,\mathrm{Ln}\,[\sqrt{(r^2 + 9.3^2)}] - 0.0021\,\sqrt{(r^2 + 9.3^2)}$
Let $R = \sqrt{(r^2 + 9.3^2)}$; for $R > 100$, add : $0.11\,\mathrm{Ln}\,(R/100)$

0.5 Hz Pseudo-Velocity (cm/s):
$\mathrm{Ln}\, V = -0.74 + 1.86(M\text{-}6) - 0.31\,(M\text{-}6)^2 - 0.92\,\mathrm{Ln}\,[\sqrt{(r^2 + 6.9^2)}] - 0.0017\,\sqrt{(r^2 + 6.9^2)}$
Let $R = \sqrt{(r^2 + 6.9^2)}$; for $R > 100$, add : $0.46\,\mathrm{Ln}\,(R/100)$

1.0 Hz Pseudo-Velocity (cm/s):
$\mathrm{Ln}\, V = 0.09 + 1.42\,(M\text{-}6) - 0.20\,(M\text{-}6)^2 - 0.90\,\mathrm{Ln}\,[\sqrt{(r^2 + 6.8^2)}] - 0.0023\,\sqrt{(r^2 + 6.8^2)}$
Let $R = \sqrt{(r^2 + 6.8^2)}$; for $R > 100$, add : $0.41\,\mathrm{Ln}\,(R/100)$

2.5 Hz Pseudo-Velocity (cm/s):
$\mathrm{Ln}\, V = 1.07 + 1.05\,(M\text{-}6) - 0.10\,(M\text{-}6)^2 - 0.56\,\mathrm{Ln}\,[\sqrt{(r^2 + 6.8^2)}] - 0.0033\,\sqrt{(r^2 + 7.1^2)}$
Let $R = \sqrt{(r^2 + 7.1^2)}$; for $R > 100$, add : $0.37\,\mathrm{Ln}\,(R/100)$

5.0 Hz Pseudo-Velocity (cm/s):
$\mathrm{Ln}\, V = 1.73 + 0.84\,(M\text{-}6) - 0.98\,\mathrm{Ln}\,[\sqrt{(r^2 + 7.5^2)}] - 0.0042\,\sqrt{(r^2 + 7.5^2)}$
Let $R = \sqrt{(r^2 + 7.5^2)}$; for $R > 100$, add : $0.32\,\mathrm{Ln}\,(R/100)$

10.0 Hz Pseudo-Velocity (cm/s):
$\mathrm{Ln}\, V = 2.37 + 0.81\,(M\text{-}6) - 1.1\,\mathrm{Ln}\,[\sqrt{(r^2 + 8.3^2)}] - 0.0040\,\sqrt{(r^2 + 8.3^2)}$
Let $R = \sqrt{(r^2 + 8.3^2)}$; for $R > 100$, add : $0.08\,\mathrm{Ln}\,(R/100)$

5. SEISMIC HAZARD COMPUTATION

5.1 REGIONAL ACCELERATION HAZARD

In order to map seismic hazard offshore Britain, a seismic hazard computation has been carried out across a regular spatial grid of individual sites, spanning the geographical region of interest. For computational convenience of hazard mapping and contour smoothing, a grid mesh size has been taken of 0.5^o N by 1.0^o W, which approximates to 50km x 50km. The computation has been carried out using a logic-tree version of the standard programs EQRISK (McGuire, 1976) and FRISK (McGuire, 1978). This logic-tree program was developed for use offshore Norway as part of the ELOCS project. Whereas, in EQRISK, single parameter values are input into the hazard model, the logic-tree version allows multiple parameter values to be input, each weighted according to its relative likelihood.

Using the twin area zonation models described earlier, with their respective parameterizations, and the two peak acceleration attenuation relations cited above, the seismic hazard has been computed at each of the sites within the designated grid. For each grid site, expected peak ground acceleration values have been computed for annual exceedance probabilities of 10^{-2} , $5x10^{-3}$, $2.1x10^{-3}$, 10^{-3} and 10^{-4}. Inverting these annual exceedance probabilities yields the corresponding return periods: 100 years; 200 years; 475 years; 1000 years and 10,000 years. A spatial low pass filter has been applied to the grid output to smooth the results prior to contouring. The final results are displayed on four contour maps of peak ground acceleration, Figs.5.1, 5.2, 5.3, 5.4 and 5.5. The units of acceleration on these figures are m/s^2. On these contour maps, some closed contours include tick marks, which are either inward or outward facing. Inward-facing tick marks indicate falling values within the contour; outward-facing tick marks indicate falling values outside the contour.

Whereas previous seismic hazard maps for the North Sea have shown discontinuities in hazard levels across the boundary separating the British and Norwegian sectors, the hazard contour maps produced in this joint Anglo-Norwegian study satisfy the condition of continuity across the sector boundary. (Because the display of hazard results in the Norwegian sector lies outside the scope of this study, contours are not extended across the sector divide, so this continuity is not explicitly exhibited). This consistency, which is attained through agreement on unified models in the northern North Sea, is not commonly achieved in seismic hazard assessment across international frontiers.

The harmonized Anglo-Norwegian seismic hazard maps show that the highest peak ground acceleration hazard in UK offshore waters is attained in the northern North Sea, where the active status of the Viking Graben implies a sizeable local hazard contribution, attested by the 5.3 M_S earthquake of 24th January 1927. Close to the sector boundary, the 10^{-4}/yr exceedance peak ground acceleration can reach values of 30%g. The seismic hazard is somewhat less in the southern North Sea, where there is marked tectonic activity in the Sole Pit Basin. In the southern North Sea, the 10^{-4}/yr exceedance peak ground acceleration can reach values of almost 25%g. Outside these two specific regions, the hazard is lower near the western UK coast; and even smaller elsewhere.

5.2 BEDROCK SEISMIC RESPONSE SPECTRA

The engineering specification of earthquake loading requires definition of seismic ground motion across the frequency range of practical interest. This is traditionally implemented through prescription of seismic response spectra, which define the dynamic response of a single-degree-of-freedom oscillator subject to input seismic ground motion. The computation of this response is conventionally performed via Duhamel's integral:

$$u(t) = (1/w) \int_0^t h_g (t) \exp[-Vw (t-t)] \sin w(t-t)\, dt$$

where ω is the oscillator frequency, ς is the damping value, and η_g is the ground acceleration.

In order that the annual exceedance probability of spectral values should be frequency-independent, a uniform hazard computation has been carried out of spectral amplitudes across a range of frequencies: 0.5Hz, 1Hz, 2Hz, 5Hz, and 10Hz. In this computation, use has been made of the spectral attenuation relations of Ambraseys et al., and Toro et al., which have been equally weighted. Although the published ground motion attenuation relations are not given at 0.2Hz, the need for results at these low frequencies requires the adoption of some extrapolation procedure. In accord with the procedure followed by NORSAR (1998), it is assumed conservatively that the spectral value at 0.2Hz is the mean of that obtained by assuming constant spectral velocity below 0.5Hz and constant spectral displacement below 0.5Hz.

Anchoring the seismic response spectra at 40 Hz to peak ground acceleration yields a normalized spectral shape. In calculating the spectral shape for various sites offshore Norway, including the northern North Sea, a single spectral shape is found to represent the frequency-dependence of seismic ground motion reasonably well. This (5% damping) spectral shape also is observed to change little with return period. This is illustrated in Fig.5.6 for a northern North Sea site (58°N, 1.5°E), which shows closely-bunched spectra normalized to 1g corresponding to annual exceedance probabilities of 1E-2, 1E-3 and 1E-4. This single generic spectral shape is considered appropriate for any site and return period, so that the specification of ground motion at a designated site would involve anchoring this spectral shape by the site acceleration hazard at the given return period.

At 5% damping, the generic normalized spectral values are listed in Table 5.1, and plotted in Fig.5.7, in comparison with the Principia (1981) hard ground normalized spectra, which have been used widely in UK. The latter spectra are semi-deterministic conservative mean-plus-standard deviation spectra, which exhibit the influence of rare magnitude 6 earthquakes. By contrast, the generic spectral shape has been developed using the principles of uniform hazard spectra, so that the exceedance probability changes little with frequency, and the spectral amplitudes reflect the rarity of large magnitude earthquakes offshore UK. As might be expected, these generic spectra display in Fig.5.8 similar characteristics to the uniform hazard spectra developed for UK application by Principia (1988) within the range 1Hz to 40Hz.

Table 5.1
5% Damping Seismic Response Spectrum Normalized to 1g at 40 Hz

Frequency (Hz)	0.2	0.5	1.0	2.0	5.0	10.0	40.0
5% Damping Normalized Spectral Velocity (cm/s)	32.68	46.69	53.27	62.12	60.56	33.81	3.90

At other damping values ς, the spectra are modified by the following factor D, developed under the ELOCS project (Woo et al, 1988): $D = 1.48 - 0.30\,\mathrm{Ln}\varsigma$.

At low frequencies, the normalized generic seismic response spectra fall below the EUROCODE 8 spectra. This is as it should be, since the EUROCODE spectra are predominantly geared towards the larger events which occur in the much more seismically active regions of southern Europe. Earthquake-resistant building codes are written for general purposes to encompass all practical aspects of ground motion hazard to which structures and engineering systems may be subject. In particular, they usually implicitly cover shaking arising from long period motion: vibrations of 1 second period and more. The degree to which special consideration has been given to long period motion, and the conservatism with which it is treated, vary from one national code to another. In view of the fact that long period motion has not been studied extensively from a seismological perspective, and that the return period for observing severe long period motion from major earthquakes may be several generations or more, it should not be surprising that explicit reference to long period seismic risk mitigation is far from universal in the national codes (EQE, 1997).

5.3 EARTHQUAKE TIME HISTORIES

For the purpose of engineering dynamic analysis, there is a need for the specification of real time histories, which, when suitably scaled, match the generic response spectra defined above. To fulfill this need, three sets of 3-component recorded earthquake accelerograms have been selected as being appropriate, according to the criteria that the magnitude, distance and peak acceleration values of the records should be representative of a regional rare earthquake, allowing for a degree of parametric variation in spectral content and duration.

In keeping with the commonality of the bedrock response spectra, the same set of time histories are chosen here as by NORSAR (1998). All these records are in the public domain. The key parameters of the time histories are tabulated below:

Table 5.2
Key Parameters for the selected earthquake time histories

EARTHQUAKE	*Recording Site*	*Comp.*	*Dist. (km)*	*Mag.*	*PGA* (m/s^2)
Nahanni, Canada	Site 3	360 270 VT	29	6.9	1.53 1.61 1.26
Imperial Valley, California	Superstition Mountain	135 45 VT	24	5.7	2.01 0.93 0.81
Friuli, Italy	Tarcento	NS EW VT	19	5.2	2.16 0.80 0.69

5.4 SOIL RESPONSE EFFECTS

The presence of soil at a site alters the ground motion characteristics vis-B-vis bedrock. The seismic hazard maps described in section 5.1 relate to reference bedrock, and modification factors need to be applied to the bedrock response spectra in order to account for soil response effects. Although, in principle, a site-specific analysis of soil response might allow for precise information on site characteristics to be used in the determination of earthquake loading, a more efficient and practical approach is to classify sites generically according to a small number of soil types. Within the UK, this approach already pertains to nuclear installations (Principia, 1981), for which an empirical triple site classification is used; three being a standard minimal number, reflecting the much greater volume, quality and geotechnical range of strong-motion data needed to generate a meaningful higher classification.

Of course it is recognized that site amplification arises from a host of diverse geotechnical phenomena, the complexity of which can only broadly be captured with just three site categories. It is well understood, for example, that site amplification depends not only on soil stiffness and thickness, but also on soil damping, subsurface geometry, as well as bedrock stiffness. Thus, 24 classes could be defined by allowing for three soil stiffness categories: *rock, stiff and soft*; two soil thickness categories: *thin, thick*; two soil damping categories: *small (clay) and large (sand)*; and two bedrock stiffness categories: *hard and soft*. However, in the absence of an adequately large and geotechnically-differentiated database of strong-motion records, the parameterisation of this multiplicity of classes would require special reliance on numerical modelling and weak-motion observations; findings which are undoubtedly capable of affording considerable insight into site amplification, but which have yet to achieve equal standing with strong-motion data.

The sufficiency of three different classes of site, for onshore locations in Norway, has been demonstrated by NGI (1998) from a series of soil response analyses conducted for typical sites in major urban areas of Norway. For offshore sites, the Norwegian Petroleum Directorate (NPD, 1997) have made recommendations for soil response effects on sites on the Norwegian Continental Shelf. These are based on the ELOCS project results (Bungum and Selnes, 1988), and are expressed in terms of spectral ratios for soil/rock, for annual exceedance probabilities of 10^{-4} and 10^{-2}. The canonical number of site types is used, namely three, which are defined as: bedrock; stiff or dense soil; and soft ground.

The ELOCS study (Rognlien, 1987) demonstrated a sizeable degree of variation of amplification factors for different sites. Because of the site-specific nature of amplification factors, only period-dependent ranges of spectral ratios, rather than individual figures, are specified, and these ranges are shown as shaded areas in Fig.5.9a and 5.9b for exceedance probabilities of 10^{-4} and 10^{-2} respectively. If site-specific soil response analysis is not undertaken, then the uncertainty in soil response should be recognized by allowing for a range in soil amplification.

5.5 CONCLUSIONS

An evaluation of seismic hazard for offshore UK waters has been undertaken. Technical collaboration with NORSAR has ensured, for the first time, consistency of hazard mapping in the northern North Sea, which is the most seismically exposed offshore UK region. Peak acceleration hazard contour maps have been produced for return periods of 100, 200, 475, 1000 and 10,000 years.

The harmonized Anglo-Norwegian seismic hazard maps show that the highest peak ground acceleration hazard in UK offshore waters is attained in the northern North Sea. Close to the sector boundary, the 10^{-4}/yr exceedance peak ground acceleration can reach values of 30%g. The seismic hazard is somewhat less in the southern North Sea, where the 10^{-4}/yr exceedance peak ground acceleration can reach values of almost 25%g. Outside these two specific regions, the hazard is lower near the Western UK coast, typically about 20%g offshore Wales and Northwest England; and the hazard is smaller elsewhere.

For the specification of bedrock earthquake loading at any offshore site, a common EQE-NORSAR approach has been formulated. This involves the specification of a single seismic response spectral shape, which is anchored at 40Hz to the relevant site-specific peak ground acceleration for the requisite return period. This generic offshore spectral shape has been computed probabilistically, and it is similar to the hard ground uniform risk spectral shape derived previously for onland UK critical facilities. For stiff or soft soil sites, generic soil amplification factors are recommended.

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TECHNICAL GLOSSARY

ACCELEROGRAM	Time history record of ground acceleration
ACTIVE FAULT	A fault shown to have experienced geologically recent displacements.
ACTIVITY RATE	The annual number of earthquakes of a given magnitude.
ARCHAEOSEISMOLOGY	Evidence of seismic activity from archaeology.
ATTENUATION	The reduction in the amplitude of seismic ground motion with distance from the fault rupture.
BASINS	Regions which have shown long-term geological subsidence thereby accumulating great thicknesses of sediment.
B-VALUE	A parameter indicative of the ratio of small to large earthquakes.
COSEISMIC	Associated with earthquake occurrence.
CRUST	The outermost layer of the Earth, below which lies the mantle.
EPICENTRE	The epicentre of an earthquake is the point on the Earth's surface above the event origin.
EXTREME-VALUE STATISTICS	Analysis of the temporal sequence of the largest events in an earthquake catalogue.
FAULT RUPTURE	Displacement along a fracture with rupture length determining the size of the resulting earthquake.
FELT AREA	The felt area of an earthquake is the area over which felt effects of the event are observed.
FOCAL MECHANISM	The configuration of stress-release at the origin of an earthquake.
GRABEN	A downthrown block between two parallel faults.
GUTENBERG-RICHTER RELATION	Log-linear magnitude-frequency relation, indicating a trend for the cumulative number of earthquakes above a given magnitude to decrease in power-law fashion.
HALOKINESIS	The flow of thick buried sedimentary salt deposits.
HARD GROUND RESPONSE SPECTRA	Response spectra appropriate for sites (e.g. rock) where the natural soil frequency is greater than about 5Hz.

HYPOCENTRE	The place beneath the Earth’s surface where an earthquake is generated.
INTENSITY	A quantitative measure of the strength of earthquake ground motion at a given location.
INTRAPLATE	Region interior to a tectonic plate, on the boundaries of which most seismic activity occurs.
ISOSEISMAL	A contour line joining points of equal observed Intensity.
LITHOSPHERE	The effectively rigid crust and underlying outermost mantle.
LOGIC-TREE	A tiered hierarchy of alternative scenarios for input model parameterization.
MACROSEISMIC	A macroseismic observation is one based on descriptions of felt effects.
MAGNITUDE	A measure of earthquake size based on the amplitudes of seismic waves recorded instrumentally; surface wave magnitude is based on distant recordings of long period seismic waves; moment magnitude is based on measurements of seismic moment.
MAXIMUM MAGNITUDE	The largest credible earthquake for an active fault or other active seismic region.
NEOTECTONICS	The study of geologically recent crustal movements.
PALAEOSEISMOLOGY	The field investigation of geological evidence of past earthquake occurrence.
QUATERNARY	The most recent period of geological time, dominated by a succession of ice ages, beginning about 2 million years ago.
RESPONSE SPECTRUM	Frequency plot of the maximum response of a damped oscillator with a single degree of freedom.
RETURN PERIOD	Average time interval between events of a Poisson process.
RIFTS	Linear zones of subsidence defined by facing normal faults.
SEISMIC HAZARD	The annual probability of exceedance of earthquake ground motion.
SEISMIC MOMENT	The seismic moment of an earthquake is a measure of earthquake size based on the area and length of fault rupture.

SEISMIC REFLECTION	The investigation of the configuration of the subterranean geology through studying the echoes of near-surface explosive energy impulses.
SEISMOGRAM	The record produced by a instrumental seismograph.
SEISMOTECTONICS	The study of the inter-relation of crustal deformation and earthquake activity.
SLIP-RATE	The long term rate of movement along a fault.
SPECTRAL SHAPE	Seismic response spectrum normalized to 1g peak ground acceleration at 40 Hz.
STOCHASTIC GEOMETRY	The statistical study of spatial geometric patterns.
STOCHASTIC GROUND MOTION MODEL	A numerical model of seismic ground motion attenuation, involving some assumptions from random-vibration theory.
STRESS DROP	The reduction in stress across a fault plane during rupture.
STRONG-MOTION	Earthquake shaking capable of causing damage.
SURFACE WAVES	Seismic waves which travel along the surface of the earth.
TECTONICS	The geological study of the structural characteristics and development of the outer part of the Earth.
TERTIARY	The period from 2 million years before the present.
UNIFORM HAZARD SPECTRA	Response spectra with a frequency-independent annual exceedance probability.

APPENDIX 1: FIRST SEISMIC ZONATION

The first of the two seismic area zonations comprises the 37 zones for offshore Norway, constructed by NORSAR (1998) as part of the Norwegian seismic hazard mapping study, together with the 38 zones of EQE Model A, covering the region in and around the British Isles and neighbouring parts of continental Europe. With respect to seismic hazard mapping for UK offshore waters, ten of the NORSAR zones are sufficiently close as to be computationally relevant. A brief description of these NORSAR zones is given below, followed by a brief description of the 38 EQE Model A zones. The geography of these polygonal zones is shown on Fig.A.1.

A1.1 NORSAR ZONATION MODEL: [1]

[1] East of Shetland
Area zone Latitude and Longitude Vertices
57.7 -1.7; 58.0 0.7; 61.2 1.8; 61.6 0.2
The East Shetland Platform is a stable region of low seismicity,
which borders on its western edge the more active Viking Graben.

[2] West of Central Graben
Area zone Latitude and Longitude Vertices
53.3 4.0; 53.4 5.0; 55.7 3.5; 58.0 0.7; 57.7 -1.7
This is a seismically quiescent area of the North Sea bordering the Central Graben.

[3] Viking Graben
Area zone Latitude and Longitude Vertices
58.0 0.7; 58.2 2.8; 60.6 3.5; 61.2 1.8
The Viking Graben is a markedly active region of the North Sea.
The (5.3 M_S) 24th January 1927 earthquake was epicentred on the western boundary,
which is a major complex of westerly dipping fault zones.

[4] Central Graben
Area zone Latitude and Longitude Vertices
53.4 5.0; 53.8 6.7; 56.4 5.0; 58.2 2.8; 58.0 0.7; 55.7 3.5
Improved detection thresholds for the Central Graben have shown this area,
which is undergoing rapid subsidence, to be prone to moderate seismic activity.

[5] Horda Platform
Area zone Latitude and Longitude Vertices
56.4 5.0; 56.9 5.9; 57.9 5.8; 58.3 5.7; 58.8 5.2; 59.1 5.0; 60.6 4.9; 60.6 3.5; 58.2 2.8
The Horda Platform is a comparatively stable region separating the Viking Graben to the west from the θygarden Fault zone to the east.

[6] Sogn - Tampen
Area zone Latitude and Longitude Vertices
60.6 3.5; 60.6 4.9; 60.9 6.0; 61.4 6.0; 62.5 7.2; 62.4 1.5; 61.6 0.2; 61.2 1.8
This zone, which includes the major Tampen Spur fault system, displays quite intense seismic activity. One of the largest nearshore events in this zone was that of 15th May 1892, which was felt as far west as the Shetlands.

[7] Hordaland - Rogaland
Area zone Latitude and Longitude Vertices
58.8 5.2; 59.4 7.0; 60.4 6.9; 60.9 6.0; 60.6 4.9; 59.1 5.0
This is a zone of significant seismicity, which includes the offshore θygarden Fault zone, which is the most easterly coast-parallel N-S fault of the northern North Sea.

[8] Rogaland - Ryfylke
Area zone Latitude and Longitude Vertices_
57.9 5.8; 57.8 8.0; 58.5 9.0; 59.4 7.0; 58.8 5.2; 58.3 5.7
This is an onland zone of sporadic seismicity, which adjoins to the south the active Tornquist zone, which includes the prominent Fjerritslev Fault. One of the more notable Rogaland earthquakes occurred on 7th May 1857. This was felt over the whole of southern and western Norway.

[9] Norway-Denmark Basin
Area zone Latitude and Longitude Vertices_
56.9 5.9; 56.4 9.0; 58.5 9.0; 57.8 8.0; 57.9 5.8
This area incorporates the seismically active Tornquist zone, which is a very important continental fracture zone, passing towards the Northwest from southern Poland. The Tornquist zone marks the southern border of the Fennoscandian and East European cratons.

[10] Denmark Southwest
Area zone Latitude and Longitude Vertices_
53.8 6.7; 55.5 10.0; 56.4 9.0; 56.9 5.9; 56.4 5.0
This zone, which includes part of the Rinkϱbing Fyn High, has rather low seismicity. The Horn Graben which is the only significant structure south of the main axis of the Norwegian-Danish basin is not spatially correlated with observed seismicity.

A1.2 EQE ZONATION MODEL: [A]

A1 Faroes

Area zone Latitude and Longitude Vertices_

61.75 -1.0; 58.2 -7.2; 55.5 -8.5; 55.0 -10.0; 55 -11.75; 61.75 -11.75; 61.75 -1.0

Magnitude Observation Thresholds: 5M: 1900 4M:1985

This area west of the West Shetland Shelf, which extends to the Rockall Trough, lies well beyond the limits of Late Devensian glaciation in Scotland, and is seismically quiescent.

A2 Northern Isles

Area zone Latitude and Longitude Vertices_

61.75 -0.4; 61.6 0.2; 57.7 -1.7; 57.7 -3.7; 58.0 -5.8; 58.2 -7.2; 61.75 -1.0; 61.75 -0.4

Magnitude Observation Thresholds: 5M: 1900 4M:1970

This West Shetland Basin and Platform zone, which includes the Shetland Isles, is a seismically inactive area.

A3 Hebrides

Area zone Latitude and Longitude Vertices_

58.0 -5.8; 58.2 -7.2; 55.5 -8.5; 55.2 -6.7; 58 -5.8

Magnitude Observation Thresholds: 5M: 1700 4.5M:1800 4M:1900

On the western margin of the main Scottish area of post-glacial rebound, this Hebridean region, which includes part of the Outer Isles Thrust, has sparse seismicity.

A4 Scottish Highlands

Area zone Latitude and Longitude Vertices_

58.0 -5.8; 55.2 -6.7; 56.2 -2.7; 57.7 -3.7; 58 -5.8

Magnitude Observation Thresholds: 5M: 1700 4.5M:1750 4M:1800

This zone covers the centre of the dome of post-glacial rebound, as judged from isobases of the Main Postglacial Shoreline. In this zone is the main concentration of current Scottish seismicity. Correspondingly, in this zone the most effort has been directed towards compiling and describing evidence for fault movement and seismic activity during the late- and post-glacial epochs. The evidence comprised levelling surveys, remote sensing of lineaments, radiocarbon dating of Quaternary sediments, and detailed field examination of faults and fault-gouge material. This evidence indicates that Scotland has experienced substantially raised seismic activity during or closely following deglaciation.

A5 Mid-North Sea Platform

Area zone Latitude and Longitude Vertices_

57.7 -1.7; 57.7 -3.7; 56.2 -2.7; 55.8 -1.8; 55.0 -1.0; 54.3 2.7; 57.7 -1.7

Magnitude Observation Thresholds: 5M: 1800 4.5M:1900 4M:1960

This zone covers the seismically stable mid-North Sea Platform, and the similarly stable Grampian region of Northeast Scotland.

A6 Scottish Borders

Area zone Latitude and Longitude Vertices_

55.2 -6.7; 54.6 -5.75; 54.6 -4.9; 55.6 -2.4; 55.8 -1.8; 56.2 -2.7; 55.2 -6.7

Magnitude Observation Thresholds: 5M: 1700 4.5M:1750 4M:1800

This Midland Valley area is a rather aseismic region, lying south of the principal Scottish region of current postglacial uplift. Some borehole evidence has been accumulated suggesting possible movement on the Southern Uplands Fault, before the end of the Glacial period.

A7 Iapetus Suture

Area zone Latitude and Longitude Vertices_

55.6 -2.4; 54.6 -4.9; 54.1 -4.5; 54.25 -3.9; 54.6 -2.95; 54.9 -2.55; 55.6 -2.4

Magnitude Observation Thresholds: 5M: 1600 4.5M:1700 4M:1800

Throughout most of Lower Palaeozoic time, England was separated from Scotland by the Iapetus Ocean, which narrowed during the Ordovician. The Iapetus Suture is a significant region of current seismic activation, as witnessed by a series of earthquakes in the Carlisle area, most recently on 26th December 1979.

A8 Northeast England

Area zone Latitude and Longitude Vertices_

55.8 -1.8; 55.6 -2.4; 54.9 -2.55; 53.7 -1.5; 54.0 -0.6; 55.0 -1.0; 55.8 -1.8

Magnitude Observation Thresholds: 5M: 1600 4.5M:1700 4M:1800

This is one of the most notable quiescent zones of England, containing the Northumberland and Stainmore Troughs and the Alston Block, which adjoins the Pennine Fault.

A9 Pennines

Area zone Latitude and Longitude Vertices_

54.6 -2.95; 54.9 -2.55; 53.7 -1.5; 53.6 -2.0; 54.6 -2.95

Magnitude Observation Thresholds: 5M: 1600 4.5M:1700 4M:1800

The association of seismicity with the western boundary of the Pennines is a distinctive feature of the North of England. A specific NNW-trending West Pennines seismic zone encompasses the greatest concentration of earthquakes. The northern boundary of this zone is taken to follow the course of the Iapetus Suture zone. In the northern Pennines, there is some evidence that a number of faults have moved since the latest epigenetic mineralization.

A10 Lake District

Area zone Latitude and Longitude Vertices_

54.6 -2.95; 54.25 -3.9; 54.1 -4.5; 53.45 -3.6; 53.1 -3.3; 53.6 -2.0; 54.6 -2.95

Magnitude Observation Thresholds: 5M: 1600 4.5M:1700 4M:1800

The Lake District Zone is an active region bounded to the north by the Iapetus Suture zone, and includes the East Irish Sea Basin, the southern Lake District High, and the active Lake District Boundary Fault Zone. The East Irish Sea Basin is characterized by a number of half grabens controlled by N-S faults to the south, and by intersecting NE-SW and NW-SE faults to the north.

A11 Southern North Sea

Area zone Latitude and Longitude Vertices_

53.3 4.0; 52.8 2.0; 53.0 0.5; 53.2 0.2; 54.0 -0.6; 55.0 -1.0; 54.3 2.7; 53.3 4.0

Magnitude Observation Thresholds: 5M: 1900 4M:1950

This major seismic region of the southern North Sea includes the Sole Pit Basin. The major Dogger Bank earthquake of 7th June 1931 was epicentred in this zone. Within the zone lie the South Hewitt Fault, and the Indefatigible area, both of which exhibit evidence of neotectonics. On one BGS seismic line, passing NE-SW about 50km to the northeast of Norwich, the base Quaternary reflectors and other overlying intra-Quaternary reflectors can be seen to be downfaulted about 15m to the northeast along one strand of the South Hewitt Fault. Most of the layered Quaternary at this location is considered to be of Pre-Eemian age, and this sequence also appears to be displaced by the fault, although by less than the underlying unconformity. The post-Eemian deposits show little trace of displacement. There is evidence of some hangingwall flexure in the Quaternary sediments which dip towards the fault, suggesting that the displacement is not simply that of a normal fault. The fault can be observed as a major structure in the underlying Mesozoic bedrock, with an overall downthrow towards the southwest.

A12 Atlantic Offshore Ireland

Area zone Latitude and Longitude Vertices_

55.0 -11.75; 55.0 -10.0; 51.3 -10.0; 51.3 -11.75; 55.0 -11.75

Magnitude Observation Thresholds: 5M: 1900 4M:1970

The Atlantic area offshore Ireland has little observed seismicity, although there is tenuous evidence of Quaternary faulting in the northern part of the Slyne Trough, close to the margin of the Rockall trough.

A13 Ireland

Area zone Latitude and Longitude Vertices_

51.3 -10.0; 51.3 -5.75; 54.6 -5.75; 55.2 -6.7; 55.5 -8.5; 55.0 -10.0; 51.3 -10.0

Magnitude Observation Thresholds: 5M: 1800 4M:1900

This zone covers most of Ireland, which is seismically very stable, with no historical record of any notable tremors other than those caused by bogbursts. Some apparently young fault scarps have been mapped, but not yet trenched, in Connaught, in the west of Ireland.

A14 NW Irish Sea

Area zone Latitude and Longitude Vertices_

53.2 -4.9; 53.2 -5.75; 54.6 -5.75; 54.6 -4.9; 54.1 -4.5; 53.45 -3.6; 53.2 -4.9

Magnitude Observation Thresholds: 5M: 1600 4.5M:1700 4M:1800

The North Western Irish Sea is a comparatively aseismic area, adjoining the more active eastern Irish Sea region.

A15 North Wales

Area zone Latitude and Longitude Vertices_

53.45 -3.6; 53.1 -3.3; 52.6 -4.2; 52.7 -4.7; 53.2 -4.9; 53.45 -3.6

Magnitude Observation Thresholds: 5M: 1600 4.5M:1700 4M:1800

This seismically active corner of Britain includes the Menai Strait group of faults. The most recent event in this zone was the Lleyn earthquake of 19th July 1984. Discrepancies in geodetic levelling in the Menai Strait provide some circumstantial evidence for neotectonics.

A16 Mid-Wales

Area zone Latitude and Longitude Vertices_

52.3 -1.45; 51.65 -2.13; 52.0 -4.0; 52.6 -4.2; 53.1 -3.3; 52.8 -2.8; 52.3 -1.45

Magnitude Observation Thresholds: 5M: 1000 4.5M:1600 4M:1800

The mid-Wales zone is an active seismic region, which has a geological structure dominated by four NE-SW striking lineaments: the Bala Fault, the Severn Valley Fault, the Pontesford Lineament and the Church Stretton Fault. The most recent earthquake along the Welsh border occurred on 2nd April 1990, and caused light damage around Bishop's Castle, Clun and Shrewsbury.

A17 Central England

Area zone Latitude and Longitude Vertices_

53.1 -3.3; 53.6 -2.0; 53.7 -1.5; 54.0 -0.6; 53.2 0.2; 52.7 -1; 52.3 -1.45; 52.8 -2.8; 53.1 -3.3

Magnitude Observation Thresholds: 5M: 1000 4.5M:1600 4M:1800

This active zone includes South Yorkshire and Lancashire, Derbyshire and Nottinghamshire, which constitute a major seismic belt in north-central England. The most recent significant event was the (4.5 M_S) Derby earthquake of 11th February 1957. Not far from the epicentre, a number of unmineralized faults at Wirksworth, Derbyshire, have been labelled as comparatively recent.

A18 East Anglia & Lincolnshire

Area zone Latitude and Longitude Vertices_

53.0 0.5; 53.2 0.2; 52.7 -1.0; 52.2 0.2; 51.7 2.0; 52.8 2.0; 53.0 0.5

Magnitude Observation Thresholds: 5M: 1200 4.5M:1600 4M:1800

This area includes part of the Anglo-Brabant Platform. The level of seismicity is moderate, but several major earthquakes have occurred here, such as the Norwich earthquake of 28th December 1480. Within this zone, there are a number of claimed examples of possible neotectonics, including, close to Norwich, some apparent anomalies in the Bramertonian Crag deposits.

A19 Midland Microcraton

Area zone Latitude and Longitude Vertices_

51.3 -2.5; 52.7 -1; 52.2 0.2; 51.3 0.2; 51.3 -2.5

Magnitude Observation Thresholds: 5M: 1000 4.5M:1600 4M:1800

This area corresponds in the main to the Midland microcraton, which is a stable, rather aseismic, region of crust. The eastern past of the Midland microcraton is remarkable for being largely unfaulted.

A20 SW Irish Sea

Area zone Latitude and Longitude Vertices_

51.3 -5.75; 52.5 -5.75; 53.2 -5.75; 53.2 -4.9; 52.7 -4.7; 52.6 -4.2; 52.0 -4.0; 52.2 -5.7; 51.3 -5.75

Magnitude Observation Thresholds: 5M: 1600 4.5M:1700 4M:1800

This offshore area, which includes a large part of the St. Georges Channel Basin, shares with onland Ireland the characteristics of low historical seismicity. However, two apparent fault scarps, which might not necessarily be due to tidal currents, have been mapped in the St. George's Channel in the course of Admiralty hydrographic and sonar studies.

A21 South Wales

Area zone Latitude and Longitude Vertices_
52.2 -5.75; 52.0 -4.0; 51.65 -2.13; 51.3 -2.5; 51.3 -5.75; 52.2 -5.75
Magnitude Observation Thresholds: 5M: 1200 4.5M:1600 4M:1800

Along the northern margin of the Variscan overthrust belt, there is a distinctive South Wales zone of seismicity passing towards the ENE from offshore Pembrokeshire, through Swansea, which has witnessed a number of moderately damaging historical events. There have been claims for Plio-Quaternary displacements along the NE-trending Swansea Valley disturbance, which is one of four belts of faulting and folding which cross the northern limb of the South Wales coalfield syncline.

A22 London-Brabant

Area zone Latitude and Longitude Vertices_
52.2 0.2; 51.3 0.2; 50.3 3.7; 51.0 3.7; 51.4 2.6; 51.7 2.0; 52.2 0.2
Magnitude Observation Thresholds: 5M: 1000 4.5M:1600 4M:1800

This London-Brabant Massif zone extends from Belgium across the Channel through into East Anglia, and has witnessed some of the largest regional historical earthquakes. The most recent was the Brussels event of 11th June 1938, which was felt on tall London buildings.

A23 Offshore Low Countries

Area zone Latitude and Longitude Vertices_
53.3 4.0; 52.8 2.0; 51.7 2.0; 51.4 2.6; 52.0 3.9; 52.5 4.3; 52.7 5.1; 53.4 8.25; 54.5 8.25
53.8 6.7; 53.4 5.0; 53.3 4.0
Magnitude Observation Thresholds: 5M: 1200 4.5M:1800 4M:1960

This area of the south North Sea bordering Belgium and Holland is largely devoid of seismicity, with no substantive evidence of neotectonics.

A24 Cornubia

Area zone Latitude and Longitude Vertices_
49.6 -6.0; 50.8 -5.75; 50.8 -4.2; 50.2 -3.5; 49.6 -6.0
Magnitude Observation Thresholds: 5M: 1600 4.5M:1700 4M:1800

This zone occupies part of the Cornubian Platform, and has been subject historically to occasional moderate earthquakes. There is some tentative evidence of neotectonics near the Camel Estuary near Trebetherick.

A25 Wessex

Area zone Latitude and Longitude Vertices_
50.2 -3.5; 50.8 -4.2; 50.8 -5.75; 51.3 -5.75; 51.3 -2.5; 51.3 -1.5; 50.2 -3.5
Magnitude Observation Thresholds: 5M: 1000 4.5M:1600 4M:1800

The region to the north of the Bristol Channel almost all lies on the foreland below the Variscan Front. Within the Variscan overthrust belt of southern England, the largest historical earthquake in the Wessex zone is that of 1275, which caused damage in Glastonbury.   Possible evidence of prehistoric earthquake activity may be gleaned from the shattering of a stalagmite floor in the Joint Mitnor Cave, Devon.

A26 English Channel

Area zone Latitude and Longitude Vertices_

50.2 -3.5; 51.3 -1.5; 51.3 0.2; 50.3 3.7; 49.2 1.6; 50.0 -1.0; 50.2 -3.5

Magnitude Observation Thresholds: 5M: 1000 4.5M:1600 4M:1800

This zone is underlain by Variscan South-dipping low-angle overthrusts, and is a moderately active region. An apparent disparity between the elevations of mid-Quaternary sea-levels around the eastern Solent has given rise to speculations of neotectonics.

A27 Western Approaches

Area zone Latitude and Longitude Vertices_

51.3 -11.75; 51.3 -5.75; 50.8 -5.75; 49.6 -6.0; 47.75 -6.0; 47.75 -11.75; 51.3 -11.75

Magnitude Observation Thresholds: 5M: 1900 4.5M:1950 4.0M:1985

This area extends over the Western Approaches to the English Channel. This is a region of moderate historical seismicity, but evidence for neotectonics exists in the form of a WNW-ESE trending zone of flexure, some 2km wide, that extends for 75km from 8°17’W, 49° N to 9°15’W, 49° 12’N.

A28 Channel Offshore Plymouth

Area zone Latitude and Longitude Vertices_

49.0 -6.0; 49.6 -6.0; 50.2 -3.5; 50.0 -1.0; 49.0 -6.0

Magnitude Observation Thresholds: 5M: 1600 4.5M:1800 4M:1900

This zone is occupied by the mid-Channel suture, and has only sparse seismicity.

A29 Belgium-Meuse

Area zone Latitude and Longitude Vertices_

50.75 5.95; 51.15 5.50; 50.8 3.7; 50.3 3.7; 50.75 5.95

Magnitude Observation Thresholds: 5M: 1000 4.5M:1600 4M:1800

The Belgian earthquake zone is an important lateral branch of the Rhenish earthquake zone. The LiΠge earthquake of 8th November 1983 was the most recent significant event epicentred within this zone.

A30 Brittany

Area zone Latitude and Longitude Vertices_

49.0 -6.0; 50.0 -1.0; 49.2 1.6; 47.75 -1.0; 47.75 -6.0; 49.0 -6.0

Magnitude Observation Thresholds: 5M: 1000 4.5M:1600 4M:1800

This is an active zone containing Late-Variscan NW-SE wrench faults, bordered to the north by the Ouessant-Alderney Fault. Some notable Channel Islands earthquakes have occurred in this zone. On the Continental Shelf to the west of Brittany, seismic reflection profiles reveal evidence of fault zones with Pliocene/Quaternary movement.

A31 Paris Basin

Area zone Latitude and Longitude Vertices_

47.75 -1.0; 49.2 1.6; 50.3 3.7; 47.75 6.6; 47.75 -1.0

Magnitude Observation Thresholds: 5M: 1000 4.5M:1600 4M:1800

The part of the Paris Basin, which lies southwest of the Rhenish Massif, is a seismically quiescent part of France.

A32 Upper Rhine Graben
Area zone Latitude and Longitude Vertices_
47.75 6.6; 50.3 3.7; 50.6 5.15; 50.25 5.7; 50.5 6.2; 50.0 8.25; 47.75 8.25; 47.75 6.6
Magnitude Observation Thresholds: 5M: 900 4.5M:1600 4M:1800
This zone includes the corner of NE France bordering on the Upper Rhine Graben, which is the northern part of the Rhenish earthquake zone.

A33 Roer Valley Graben
Area zone Latitude and Longitude Vertices_
51.2 5.45; 51.4 6.3; 50.65 7.1; 50.5 6.2; 51.2 5.45
Magnitude Observation Thresholds: 5M: 900 4.5M:1600 4M:1800
The Roer Valley Graben is bounded on the northeast by the Peel fault, which ruptured in the (5.3 M_S) Roermond earthquake of 13th April 1992, and on the southwest by the Feldbiss Fault, along which palaeoseismic investigations have been undertaken.

A34 Ardennes
Area zone Latitude and Longitude Vertices_
50.60 5.15; 50.75 5.95; 50.5 6.2; 50.25 5.7; 50.60 5.15
Magnitude Observation Thresholds: 5M: 900 4.5M:1600 4M:1850
The Ardennes is an active seismic region adjoining the South Limburg Block. The most recent significant event occured on 21st December 1965.

A35 Erft Block
Area zone Latitude and Longitude Vertices_
50.0 8.25; 50.7 8.25; 51.0 6.68; 50.65 7.1; 50.5 6.2; 50.0 8.25
Magnitude Observation Thresholds: 5M: 900 4.5M:1600 4M:1800
The Erft-Sprung Fault has a large Quaternary vertical displacement of up to 80m. The current activity of this block is attested by a number of sizeable earthquakes this century.

A36 Lower Graben
Area zone Latitude and Longitude Vertices_
51.4 6.3; 52.7 5.1; 52.6 4.3; 51.2 5.45; 51.4 6.3
Magnitude Observation Thresholds: 5M: 900 4.5M:1600 4M:1800
The Lower Graben constitutes the northern part of the Rhenish earthquake zone, which is the most conspicuous seismological feature in the foreland of the Alps.

A37 Schelde Estuary
Area zone Latitude and Longitude Vertices_
52.5 4.3; 52.0 3.9; 51.4 2.6; 51.0 3.7; 50.8 3.7; 51.15 5.5; 52.5 4.3
Magnitude Observation Thresholds: 5M: 1000 4.5M:1600 4M:1800
As with the Dutch sector offshore North Sea region, this western part of Holland is rather aseismic.

A38 Northern Netherlands and Northwest Germany
Area zone Latitude and Longitude Vertices_
51.7 8.25; 53.4 8.25; 52.7 5.1; 51.0 6.68; 50.7 8.25; 51.7 8.25
Magnitude Observation Thresholds: 5M: 900 4.5M:1600 4M:1850
This northerly Dutch zone, which includes adjoining areas of Northwest Germany is comparatively aseismic.

APPENDIX 2: SECOND SEISMIC ZONATION

The second of the two seismic area zonations comprises the 24 zones for offshore Norway, constructed by NORSAR as part of GSHAP (Global Seismic Hazard Assessment Project), together with 26 EQE Model B zones covering the region in and around the British Isles and neighbouring parts of continental Europe. With respect to seismic hazard mapping for UK offshore waters, eight of the NORSAR zones are sufficiently close to be seismically relevant. A brief description of these NORSAR zones is given below, followed by a brief description of the 26 EQE Model B zones. The geography of all thezones is indicated in Fig.A.2.

A2.1 NORSAR ZONATION MODEL: [2]

[1] West of shelf areas
Area zone Latitude and Longitude Vertices_
57.8 -1.0; 57.8 0.5; 63.2 1.0; 64.0 -4.0
This area west of the Viking Graben, which includes parts of the West and East Shetland Platforms is comparatively quiescent.

[2] Viking Graben
Area zone Latitude and Longitude Vertices_
57.8 0.5; 58.0 3.0; 60.8 3.0; 63.0 3.5; 63.2 1.0
The Viking Graben is a markedly active region of the North Sea.
The (5.3 M_S) 24th January 1927 earthquake was epicentred on the western boundary, which is a major complex of westerly dipping fault zones.

[3] Central Graben
Area zone Latitude and Longitude Vertices_
54.5 3.8; 54.5 6.2; 55.5 5.9; 57.3 4.0; 58.0 3.0; 57.8 0.5; 55.5 3.2
Improved detection thresholds for the Central Graben have shown this area, which is undergoing rapid subsidence, to be prone to moderate seismic activity.

[4] Horda platform
Area zone Latitude and Longitude Vertices_
57.3 4.0 ; 58.7 5.5; 60.8 3.0; 58.0 3.0
The Horda Platform is a comparatively stable region separating the Viking Graben to the west from the θygarden Fault zone to the east.

[5] Sogn
Area zone Latitude and Longitude Vertices_
60.8 3.0; 60.5 7.0; 62.8 7.0 ; 63.0 3.5
This zone, which includes the major Tampen Spur fault system, displays quite intense seismic activity. One of the largest nearshore events in this zone was that of 15th May 1892, which was felt as far west as the Shetlands.

[6] Stord - Hordaland

Area zone Latitude and Longitude Vertices

58.7 5.5; 58.5 7.2; 60.5 7.0; 60.8 3.0

This is an onland zone of sporadic seismicity, which adjoins to the south the active Tornquist zone, which includes the prominent Fjerritslev Fault.

[7] Norway - Denmark Basin

Area zone Latitude and Longitude Vertices

57.3 4.0; 56.2 7.6; 58.1 10.0; 58.2 9.3; 58.5 7.2; 58.7 5.5

This area incorporates the seismically active Tornquist zone, which is a very important continental fracture zone, passing towards the Northwest from southern Poland. The Tornquist zone marks the southern border of the Fennoscandian and East European cratons.

[8] West of Jutland

Area zone Latitude and Longitude Vertices

54.5 6.2; 54.5 8.5; 56.2 7.6; 57.3 4.0; 55.5 5.9

This zone, which includes part of the Rinkϱbing Fyn High, has rather low seismicity. The Horn Graben which is the only significant structure south of the main axis of the Norwegian-Danish basin is not spatially correlated with observed seismicity.

A2.2 EQE ZONATION MODEL: [B]

B1 Faroes
Area zone Latitude and Longitude Vertices_
61.75 -3.0; 58.2 -7.2; 55.0 -8.0; 55.0 -11.75; 61.75 -11.75; 61.75 -3.0
Magnitude Observation Thresholds: 5M: 1900 4M:1985
This area west of the West Shetland Shelf, which extends to the Rockall Trough, lies well beyond the limits of Late Devensian glaciation in Scotland, and is seismically quiescent.

B2 Northern Isles
Area zone Latitude and Longitude Vertices_
61.75 -3.0; 57.8 -1.0; 57.7 -3.7; 58.0 -5.8; 58.2 -7.2 61.75 -3.0; 61.75 -3.0
Magnitude Observation Thresholds: 5M: 1900 4M:1965
This West Shetland Basin and Platform zone, which includes the Orkney Isles, is a seismically inactive area.

B3 Hebrides
Area zone Latitude and Longitude Vertices_
58.0 -5.8; 58.2 -7.2; 55.0 -8.0; 55.0 -6.5; 58.0 -5.8
Magnitude Observation Thresholds: 5M: 1700 4.5M:1800 4M:1900
On the western margin of the main Scottish area of post-glacial rebound, this Hebridean region, which includes part of the Outer Isles Thrust, has sparse seismicity.

B4 Scottish Highlands
Area zone Latitude and Longitude Vertices_
58.0 -5.8; 55.0 -6.5; 56.2 -2.7; 57.7 -3.7; 58.0 -5.8
Magnitude Observation Thresholds: 5M: 1700 4.5M:1750 4M:1800
This zone covers the centre of the dome of post-glacial rebound, as judged from isobases of the Main Postglacial Shoreline. In this zone is the main concentration of current Scottish seismicity. Correspondingly, in this zone the most effort has been directed towards compiling and describing evidence for fault movement and seismic activity during the late- and post-glacial epochs. The evidence comprised levelling surveys, remote sensing of lineaments, radiocarbon dating of Quaternary sediments, and detailed field examination of faults and fault-gouge material. This evidence indicates that Scotland has experienced substantially raised seismic activity during or closely following deglaciation.

B5 Forth-Central North Sea
Area zone Latitude and Longitude Vertices_
57.8 -1.0; 57.7 -3.7; 56.2 -2.7; 55.7 -1.73; 55.0 -1.0 ; 54.5 3.8; 55.5 3.2; 57.8 0.5; 57.8 -1.0
Magnitude Observation Thresholds: 5M: 1800 4.5M:1900 4M:1960
This zone covers the seismically stable mid-North Sea Platform, and the similarly stable Grampian region of Northeast Scotland, which has only sparse seismicity.

B6 Borders

Area zone Latitude and Longitude Vertices_

55.0 -6.5; 54.5 -5.75; 54.75 -3.5; 54.75 -3.5; 55.07 -2.78; 55.7 -1.73; 56.2 -2.7; 55.0 -6.5

Magnitude Observation Thresholds: 5M: 1700 4.5M:1750 4M:1800

This Midland Valley and Southern Uplands area is a rather aseismic region, lying south of the principal Scottish region of current postglacial uplift. Some borehole evidence has been accumulated suggesting possible movement on the Southern Uplands Fault, before the end of the Glacial period.

B7 NW Irish Sea

Area zone Latitude and Longitude Vertices_

53.7 -2.8; 53.2 -5.75; 54.5 -5.75; 54.75 -3.5; 53.7 -2.8

Magnitude Observation Thresholds: 5M: 1600 4.5M:1700 4M:1800

The North Irish Sea is a comparatively aseismic area, with somewhat higher activity in the eastern part, although scant geological evidence of recent fault movement.

B8 Pennines-Cumbria

Area zone Latitude and Longitude Vertices_

54.75 -3.5; 55.07 -2.78; 53.86 -1.7; 53.7 -2.8; 54.75 -3.5

Magnitude Observation Thresholds: 5M: 1600 4.5M:1700 4M:1800

The association of seismicity with the western boundary of the Pennines is a distinctive feature of the North of England. A specific NNW-trending West Pennines seismic zone encompasses the greatest concentration of earthquakes. The northern boundary of this zone is taken to follow the course of the Iapetus Suture zone. In the northern Pennines, there is some evidence that a number of faults have moved since the latest epigenetic mineralization.

B9 NE England

Area zone Latitude and Longitude Vertices_

55.7 -1.73; 55.07 -2.78; 53.86 -1.7; 54.2 -0.7; 55.0 -1.0; 55.7 -1.73

Magnitude Observation Thresholds: 5M: 1600 4.5M:1700 4M:1800

This is one of the most notable quiescent zones of England, containing the Northumberland and Stainmore Troughs and the Alston Block, which adjoins the Pennine Fault.

B10 Humber-North Sea

Area zone Latitude and Longitude Vertices_

53.3 4.0; 52.8 2.0; 53.0 0.5; 53.2 0.2; 54.2 -0.7; 55.0 -1.0; 54.5 3.8; 53.3 4.0

Magnitude Observation Thresholds: 5M: 1900 4M:1950

This major seismic region of the southern North Sea includes the Sole Pit Basin. The major Dogger Bank earthquake of 7th June 1931 was epicentred in this zone. Within the zone lie the South Hewitt Fault, and the Indefatigible area, both of which exhibit evidence of neotectonics. On one BGS seismic line, passing NE-SW about 50km to the northeast of Norwich, the base Quaternary reflectors and other overlying intra-Quaternary reflectors can be seen to be downfaulted about 15m to the northeast along one strand of the South Hewitt Fault. Most of the layered Quaternary at this location is considered to be of Pre-Eemian age, and this sequence also appears to be displaced by the fault, although by less than the underlying unconformity. The post-Eemian deposits show little trace of displacement. There is evidence of some hangingwall flexure in the Quaternary sediments which dip towards the fault, suggesting that the displacement is not simply that of a normal fault. The fault can be observed as a major structure in the underlying Mesozoic bedrock, with an overall downthrow towards the southwest.

B11 Ireland

Area zone Latitude and Longitude Vertices_
50.3 -11.75; 50.3-6.4; 51.0 -4.5; 51.3 -4.5; 51.3 -5.75; 54.5 -5.75
55.0 -6.5; 55.0 -8.0; 55.0 -11.75; 50.3 -11.75
Magnitude Observation Thresholds: 5M: 1900 4M:1960

This zone covers most of Ireland and western offshore area, which is seismically very stable, with no historical record of any notable tremors other than those caused by bogbursts. Some apparently young fault scarps have been mapped, but not yet trenched, in Connaught, in the west of Ireland.

B12 Wales-Central England

Area zone Latitude and Longitude Vertices_
51.3 -5.75; 52.5 -5.75; 53.2 -5.75; 53.7 -2.8; 53.7 -2.8; 53.86 -1.7; 54.2 -0.7;
53.2 0.2; 52.7 -1.0; 51.3 -2.5; 51.3 -5.75
Magnitude Observation Thresholds: 5M: 1000 4.5M:1600 4M:1800

The Wales/Central England zone is an active seismic region, which has a geological structure dominated by four NE-SW striking lineaments: the Bala Fault, the Severn Valley Fault, the Pontesford Lineament and the Church Stretton Fault. The most recent earthquake along the Welsh border occurred on 2nd April 1990, and caused light damage around the Welsh Borders and Shrewsbury.

B13 East Anglia & Lincs

Area zone Latitude and Longitude Vertices_
53.0 0.5; 53.2 0.2; 52.7 -1.0; 52.2 0.2; 51.7 2.0; 52.8 2.0; 53.0 0.5
Magnitude Observation Thresholds: 5M: 1200 4.5M:1600 4M:1800

This area includes part of the Anglo-Brabant Platform. The level of seismicity is moderate, but several major earthquakes have occurred here, such as the Norwich earthquake of 28th December 1480. Within this zone, there are a number of claimed examples of possible neotectonics, including, close to Norwich, some apparent anomalies in the Bramertonian Crag deposits.

B14 Southern North Sea/ Low Countries

Area zone Latitude and Longitude Vertices_
53.3 4.0; 52.8 2.0; 51.7 2.0; 51.2 3.0; 51.0 3.7; 51.8 5.6; 53.4 8.25; 54.5 8.25;
54.5 6.2; 54.5 3.8; 53.3 4.0
Magnitude Observation Thresholds: 5M: 1900 4M:1960

The offshore and western Holland areas are rather inactive, but the Lower Graben constitutes the northern part of the Rhenish earthquake zone, which is the most conspicuous seismological feature in the foreland of the Alps.

B15 Midland Microcraton

Area zone Latitude and Longitude Vertices_
51.3 -2.5; 52.7 -1.0; 52.2 0.2; 51.3 0.2; 51.3 -2.5
Magnitude Observation Thresholds: 5M: 1000 4.5M:1600 4M:1800

This area corresponds in the main to the Midland microcraton, which is a stable, rather aseismic, region of crust. The eastern past of the Midland microcraton is remarkable for being largely unfaulted.

B16 London-Brabant

Area zone Latitude and Longitude Vertices

52.2 0.2; 51.3 0.2; 50.3 3.7; 51.0 3.7; 51.2 3.0; 51.7 2.0; 52.2 0.2

Magnitude Observation Thresholds: 5M: 1000 4.5M:1600 4M:1800

This London-Brabant Massif zone extends from Belgium across the Channel through into East Anglia, and has witnessed some of the largest regional historical earthquakes. The most recent was the Brussels event of 11th June 1938, which was felt on tall London buildings.

B17 Wessex

Area zone Latitude and Longitude Vertices

50.2 -3.5; 51.0 -4.5; 51.3 -4.5; 51.3 -2.5; 51.3 -1.5; 50.2 -3.5

Magnitude Observation Thresholds: 5M: 1000 4.5M:1600 4M:1800

The region to the north of the Bristol Channel almost all lies on the foreland below the Variscan Front. Within the Variscan overthrust belt of southern England, the largest historical earthquake in the Wessex zone is that of 1275, which caused damage in Glastonbury. Possible evidence of prehistoric earthquake activity may be gleaned from the shattering of a stalagmite floor in the Joint Mitnor Cave, Devon.

B18 English Channel

Area zone Latitude and Longitude Vertices

50.2 -3.5; 51.3 -1.5; 51.3 0.2; 50.3 3.7; 49.2 1.6; 50.0 -1.0; 50.2 -3.5

Magnitude Observation Thresholds: 5M: 1000 4.5M:1600 4M:1800

This zone is underlain by Variscan South-dipping low-angle overthrusts, and is a moderately active region. An apparent disparity between the elevations of mid-Quaternary sea-levels around the eastern Solent has given rise to speculations of neotectonics.

B19 Cornubia

Area zone Latitude and Longitude Vertices

49.6 -6.0; 50.3 -6.4; 51.0 -4.5; 50.2 -3.5; 49.6 -6.0

Magnitude Observation Thresholds: 5M: 1600 4.5M:1700 4M:1800

This zone occupies part of the Cornubian Platform, and has been subject historically to occasional moderate earthquakes. There is some tentative evidence of neotectonics near the Camel Estuary near Trebetherick.

B20 SW Approaches

Area zone Latitude and Longitude Vertices

50.3 -11.75; 50.3 -6.4; 49.6 -6.0; 47.75 -6.0; 47.75 -11.75; 50.3 -11.75

Magnitude Observation Thresholds: 5M: 1900 4.5M:1950 4.0M:1985

This area extends over the Western Approaches to the English Channel. This is a region of moderate historical seismicity, but evidence for neotectonics exists in the form of a WNW-ESE trending zone of flexure, some 2km wide, that extends for 75km from 8°17'W, 49° N to 9°15'W, 49° 12'N.

B21 Off Plymouth
Area zone Latitude and Longitude Vertices_
49.0 -6.0; 49.6 -6.0; 50.2 -1.0; 49.0 -6.0
Magnitude Observation Thresholds: 5M: 1600 4.5M:1800   4M:1900
This zone is occupied by the mid-Channel suture, which is a quiescent area,
which has only sparse seismicity.

B22 Brittany
Area zone Latitude and Longitude Vertices_
49.0 -6.0; 50.0 -1.0; 49.2 1.6; 47.75 -1.0; 47.75 -6.0; 49.0 -6.0
Magnitude Observation Thresholds: 5M: 1000 4.5M:1600   4M:1800
This is an active zone containing Late-Variscan NW-SE wrench faults, bordered to the north by the Ouessant-Alderney Fault.   Some notable Channel Islands earthquakes have occurred in this zone. On the Continental Shelf to the west of Brittany, seismic reflection profiles reveal evidence of fault zones with Pliocene/Quaternary movement.

B23 Paris Basin
Area zone Latitude and Longitude Vertices_
47.75 -1.0; 49.2 1.6; 50.3 3.7; 47.75 6.6; 47.75 -1.0
Magnitude Observation Thresholds: 5M: 1000 4.5M:1600   4M:1800
The part of the Paris Basin, which lies southwest of the Rhenish Massif, is a seismically quiescent part of France.

B24 Upper Rhine Graben
Area zone Latitude and Longitude Vertices_
47.75 6.6; 50.3 3.7; 49.5 8.25; 47.75 8.25; 47.75 6.6
Magnitude Observation Thresholds: 5M: 900   4.5M:1600   4M:1800
This zone includes the corner of NE France bordering on the Upper Rhine Graben, which is the northern part of the Rhenish earthquake zone.

B25 Central Belgium/ Germany
Area zone Latitude and Longitude Vertices_
51.0 3.7; 51.8 5.6; 51.2 8.25; 49.5 8.25; 50.3 3.7; 51.0 3.7
Magnitude Observation Thresholds: 5M: 900   4.5M:1600   4M:1800
This zone includes the Erft-Sprung Fault, which has a large Quaternary vertical displacement of up to 80m. The current activity of this block is attested by a number of sizeable earthquakes this century.

B26 Northwest Germany
Area zone Latitude and Longitude Vertices_
51.2 8.25; 53.4 8.25; 51.8 5.6; 51.2 8.25
Magnitude Observation Thresholds: 5M: 900   4.5M:1600   4M:1850
The Niedersachsen region of Northwest Germany, which borders Northeast Holland, is comparatively aseismic.

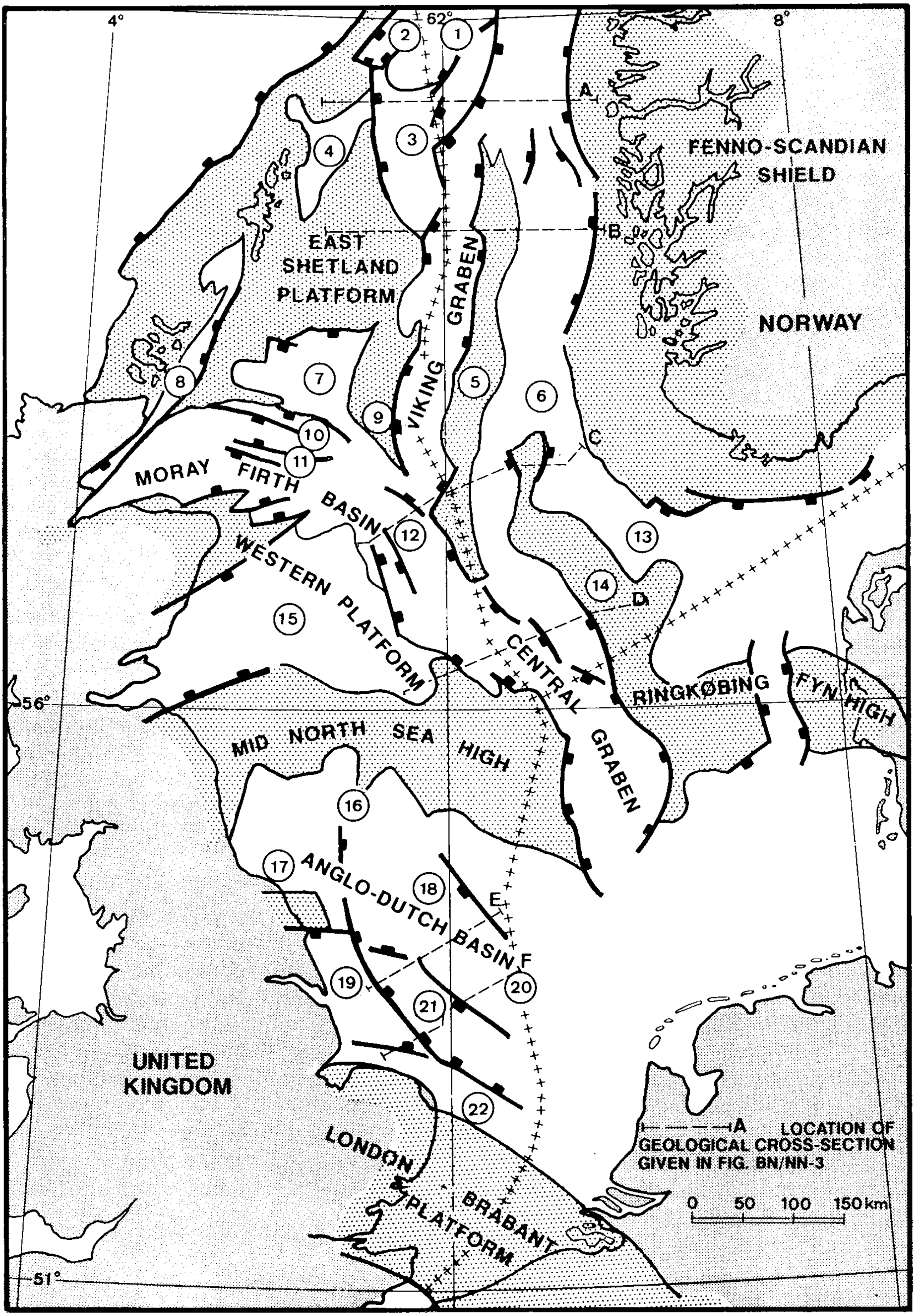

Figure 1.1
Map of the structural framework of
The UK and Norwegian North Sea

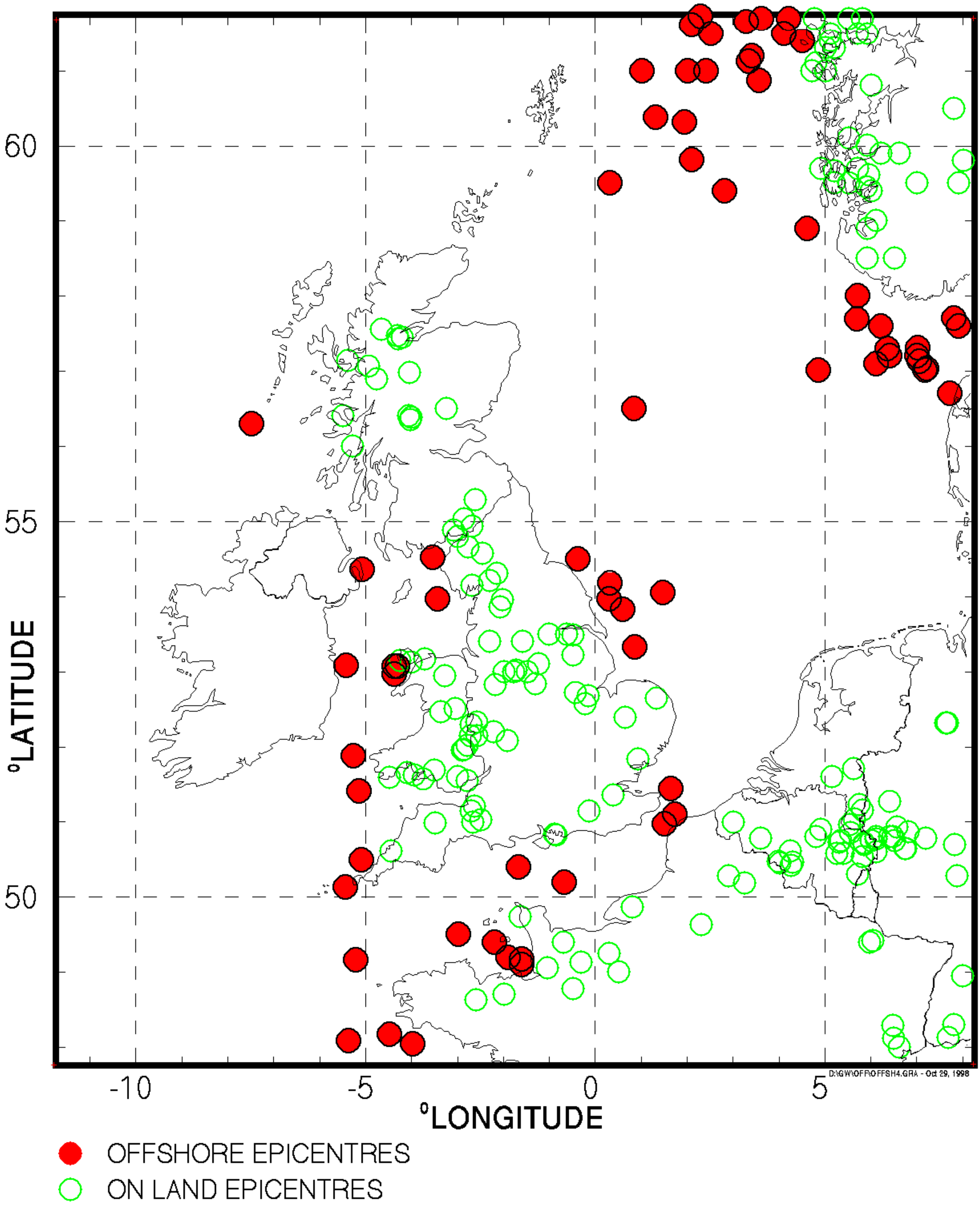

Figure 2.1

KNOWN N.W. EUROPEAN EPICENTRES: MAGN. ≥ 4M_S OR EQUIVALENT

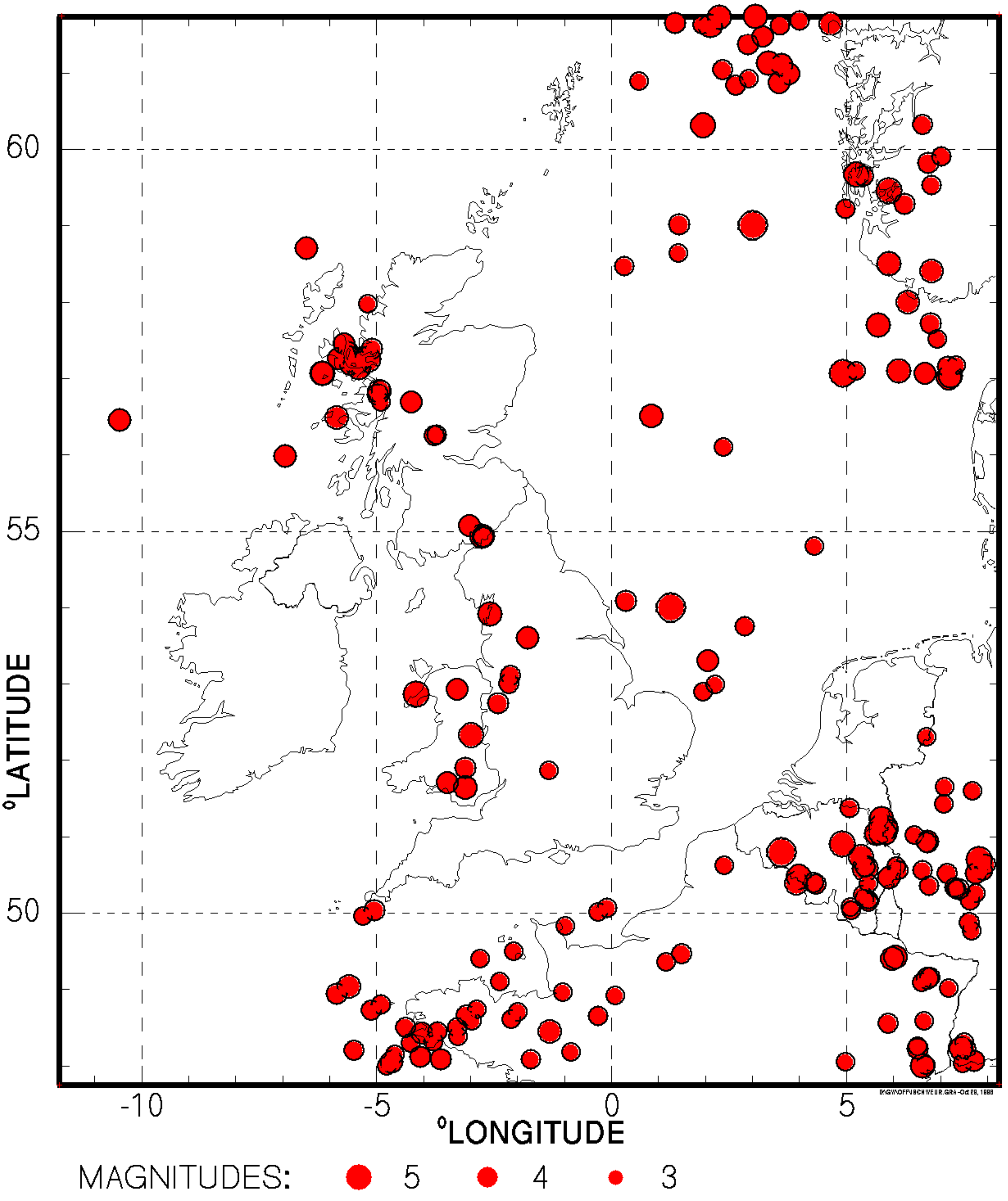

Figure 2.2
N.W. EUROPEAN EPICENTRES REPORTED BY ISC
1904 - 1990, MAGNITUDES ≥ 3

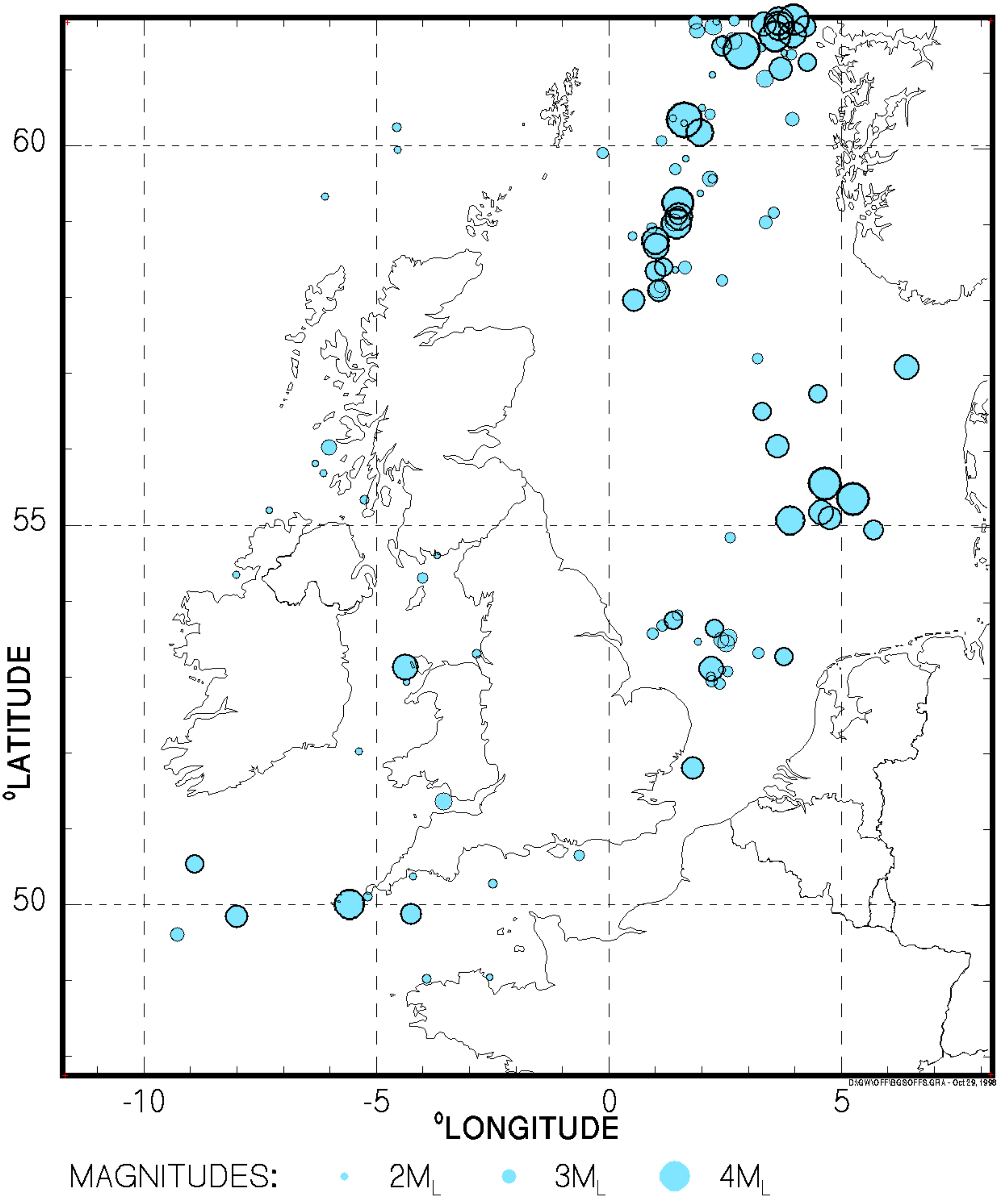

Figure 2.3

BGS OFFSHORE EPICENTRES: 1990 - 1996 incl., MAGNITUDES ≥ $2M_L$

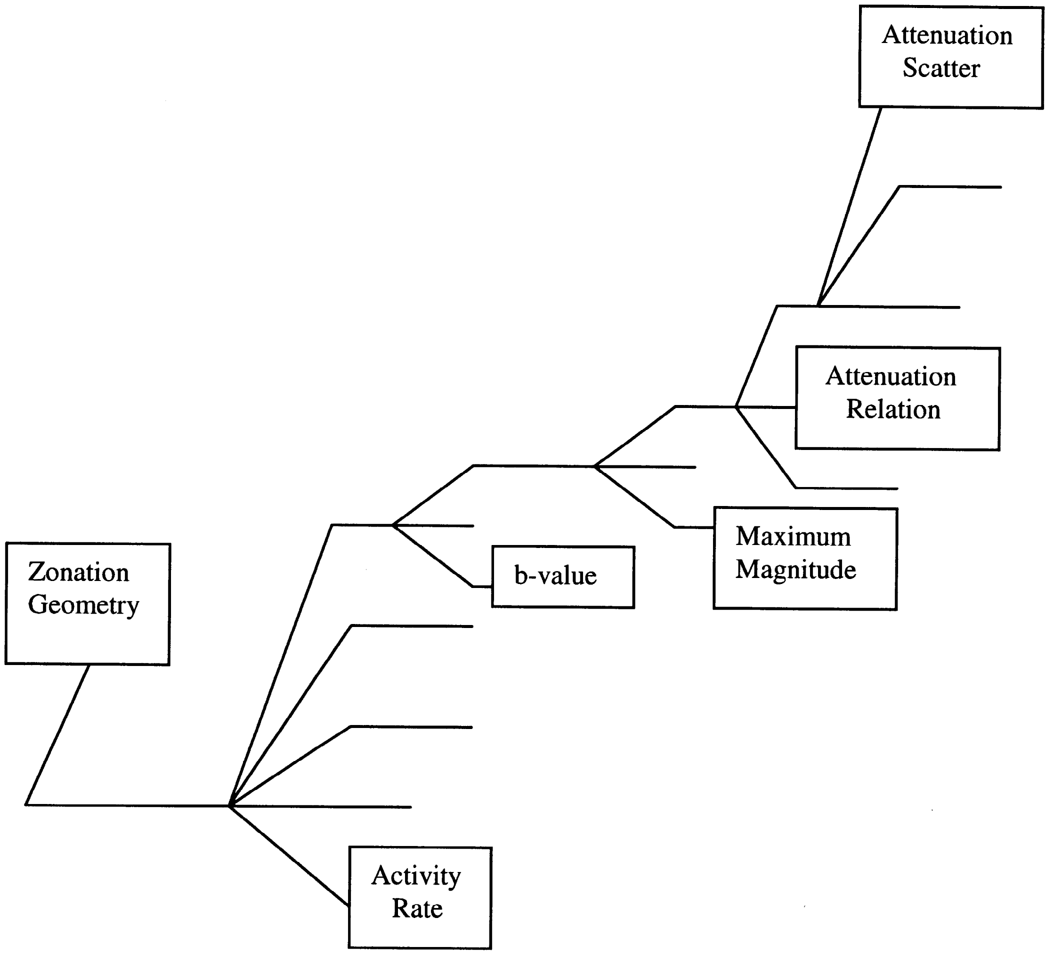

Figure 3.1
Logic-tree branches for representing Modelling parametric uncertainty

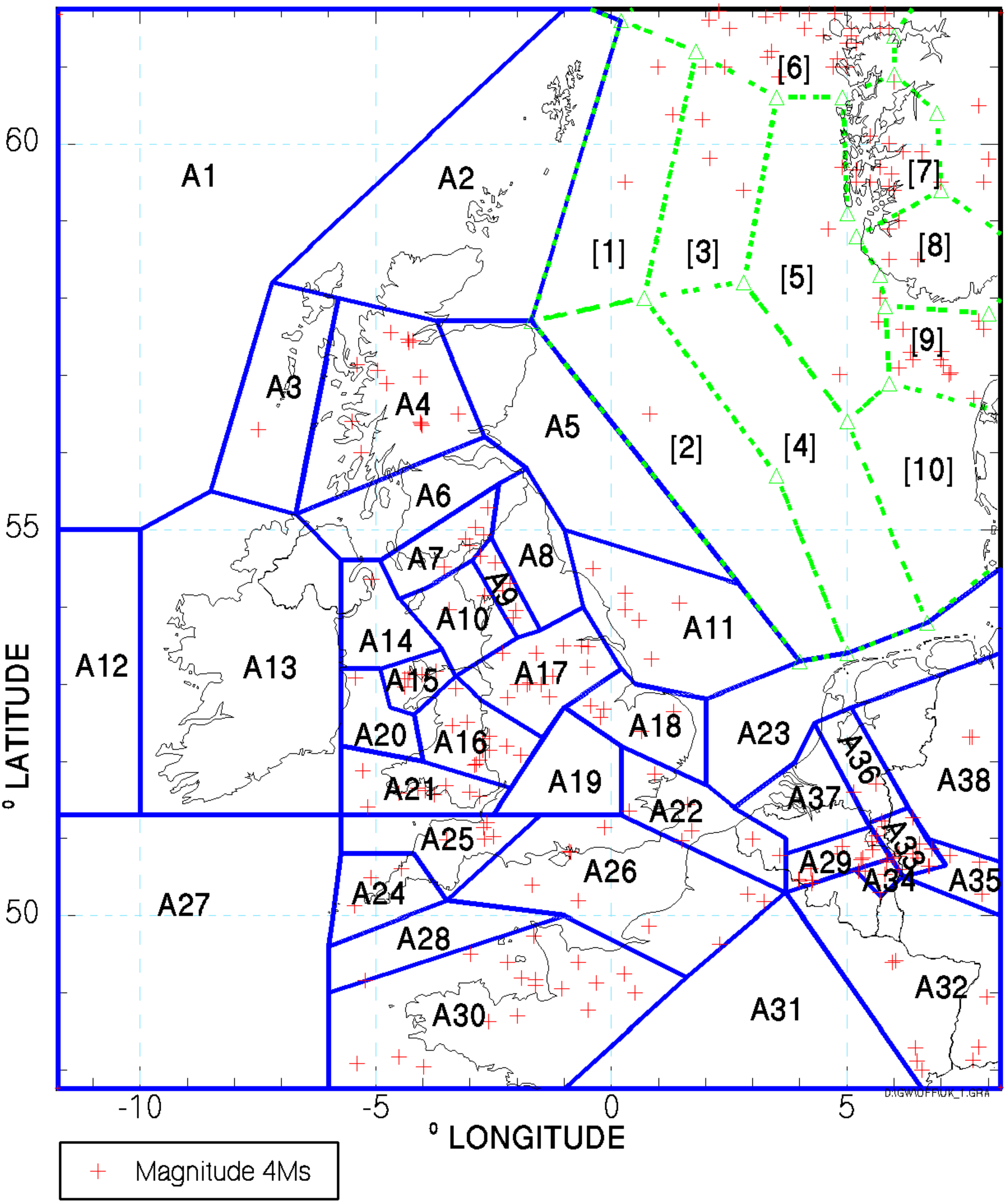

Figure 3.2

ZONATION MODEL "A"

[INTERFACED TO NORSAR MODEL 1]

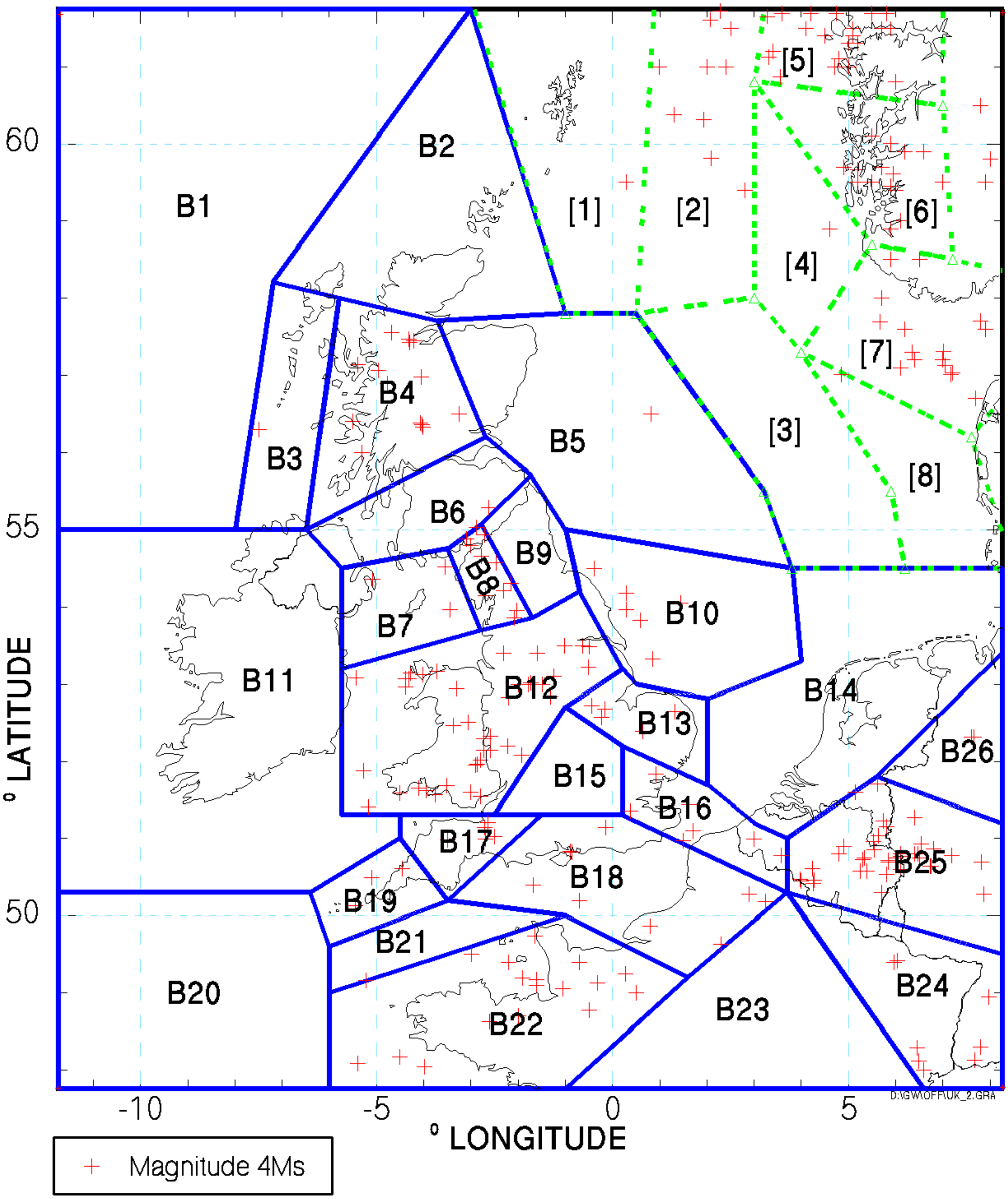

Figure 3.3
ZONATION MODEL "B"
[INTERFACED TO NORSAR MODEL 2]

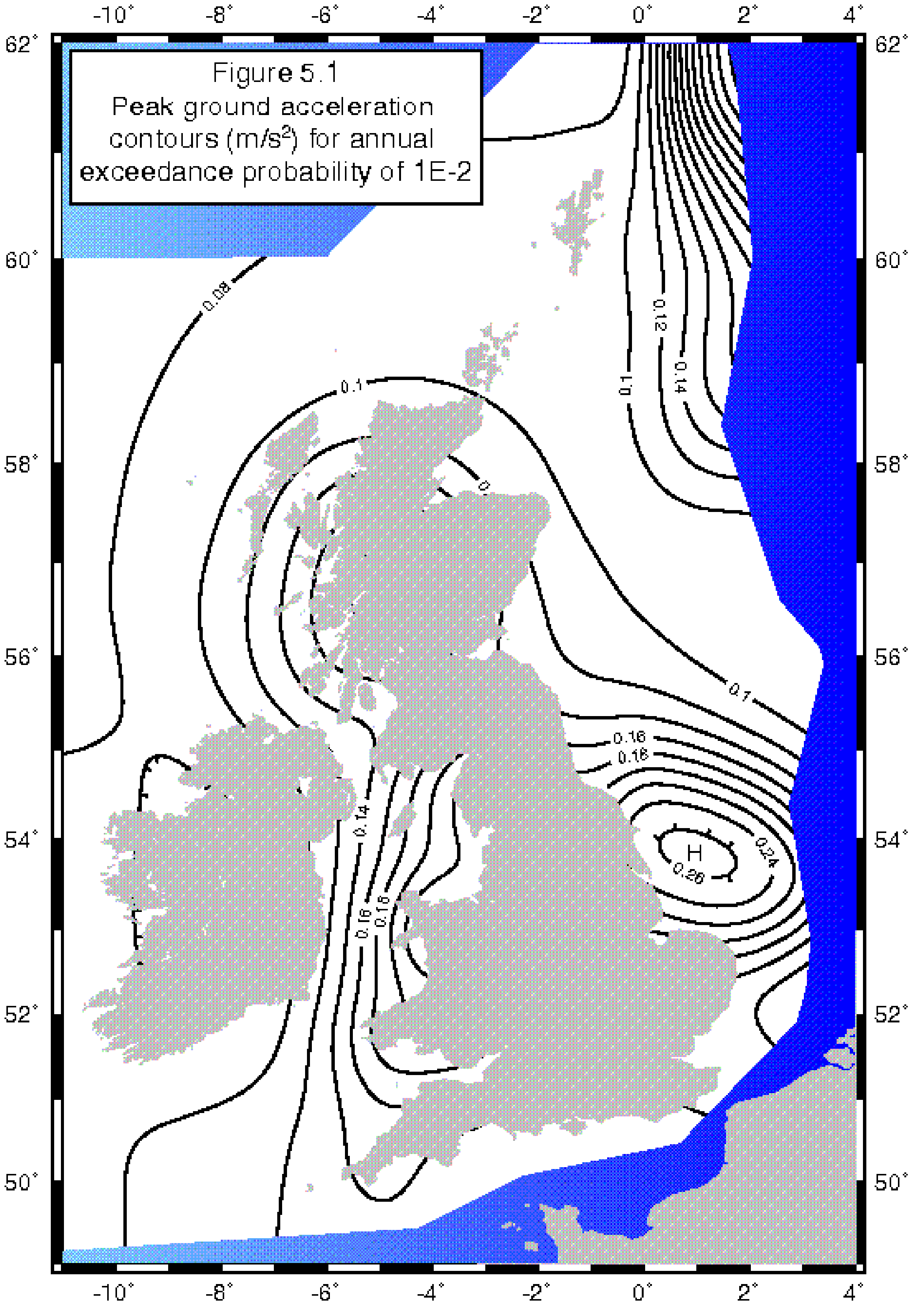

Figure 5.1
Peak ground acceleration contours (m/s²) for annual exceedance probability of 1E-2

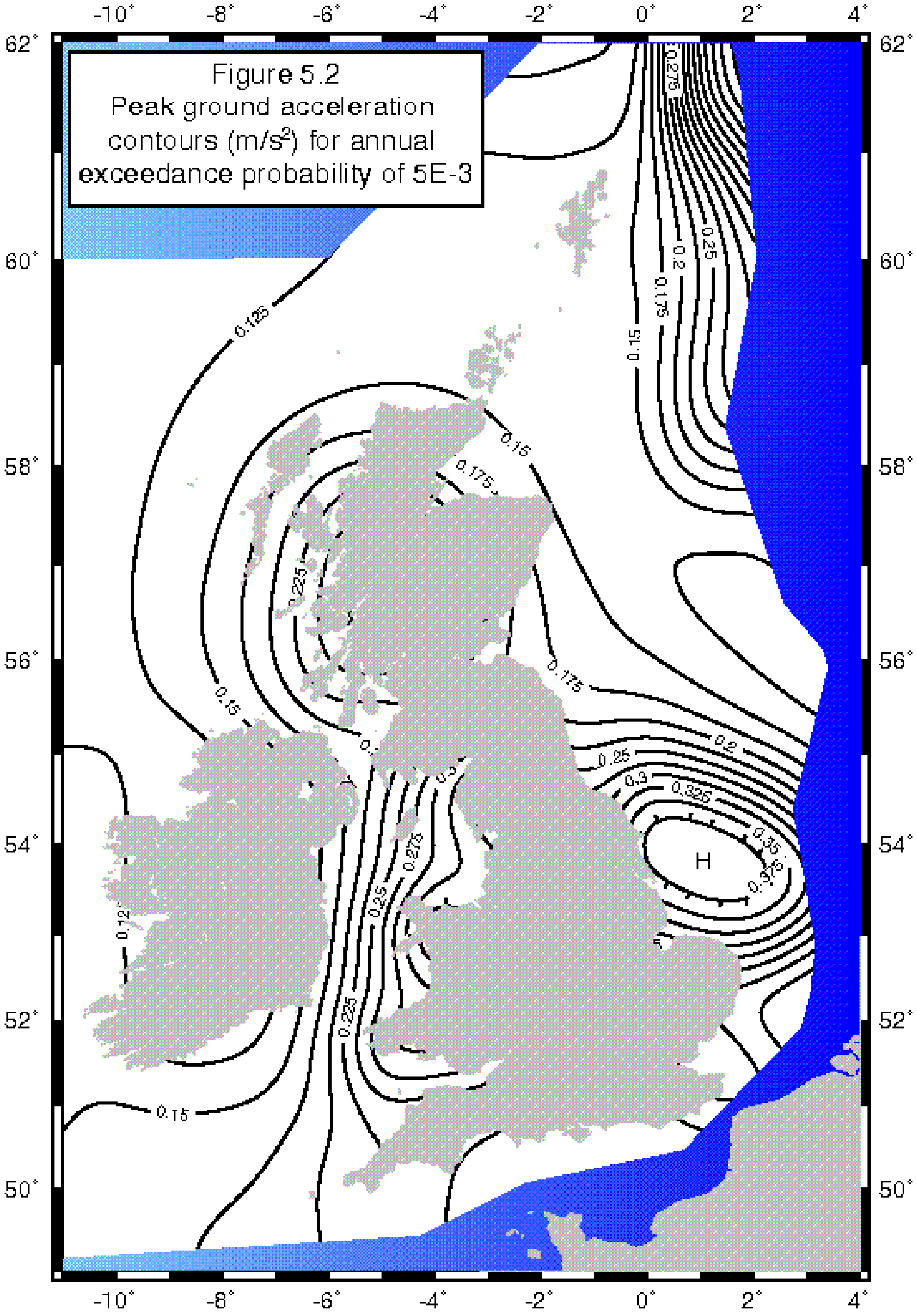

Figure 5.2
Peak ground acceleration contours (m/s^2) for annual exceedance probability of 5E-3

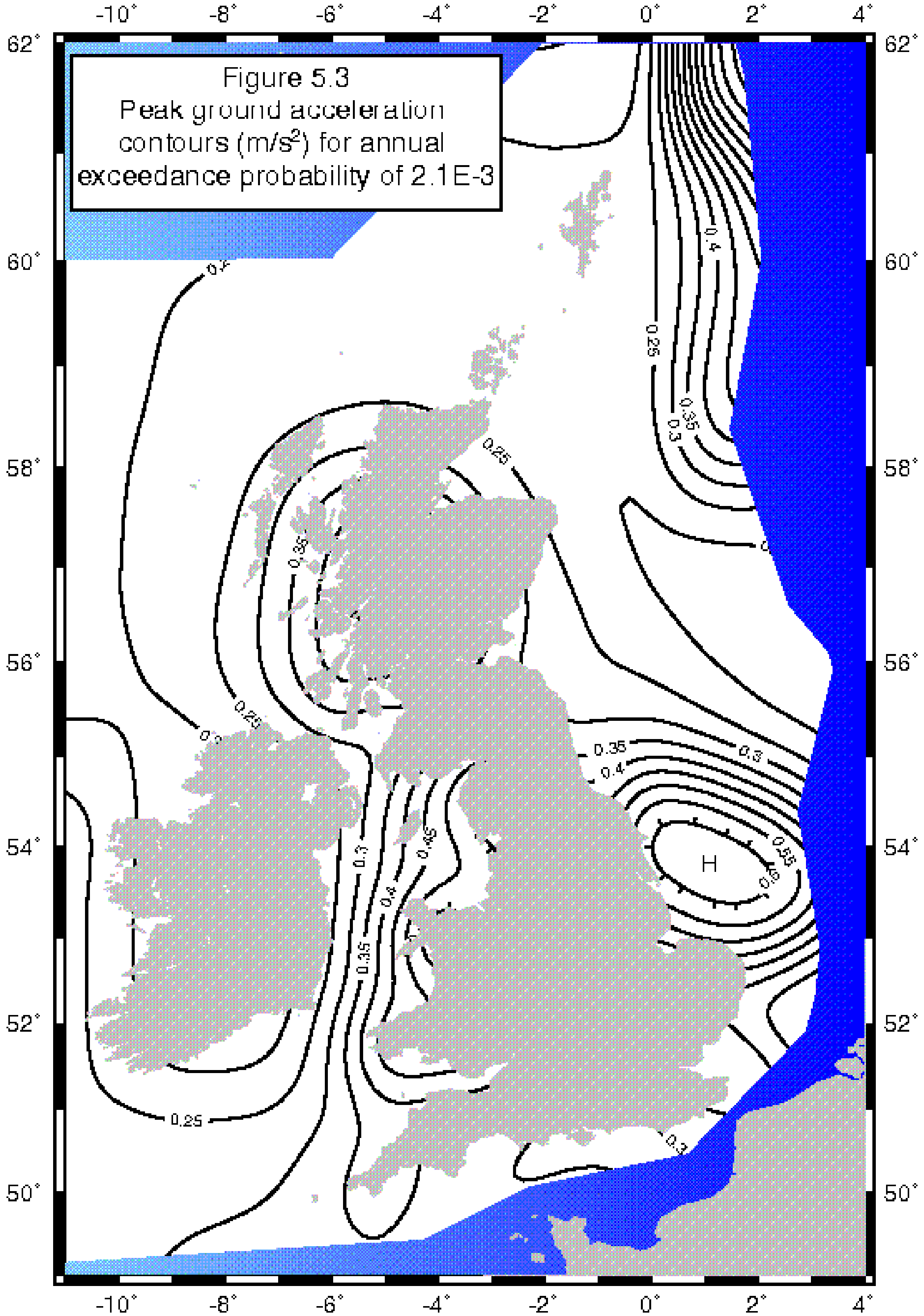

Figure 5.3
Peak ground acceleration contours (m/s^2) for annual exceedance probability of 2.1E-3

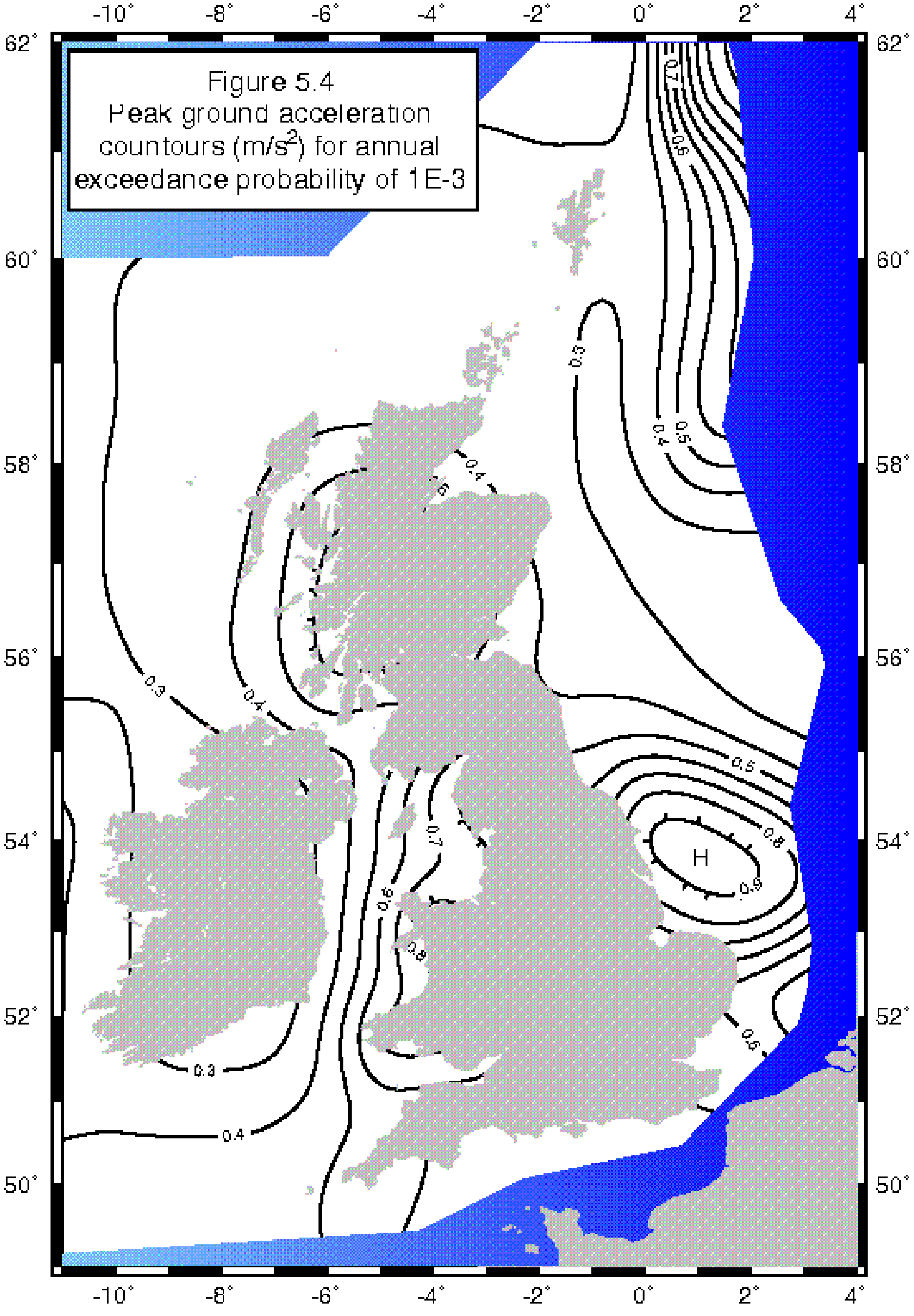

Figure 5.4
Peak ground acceleration countours (m/s^2) for annual exceedance probability of 1E-3

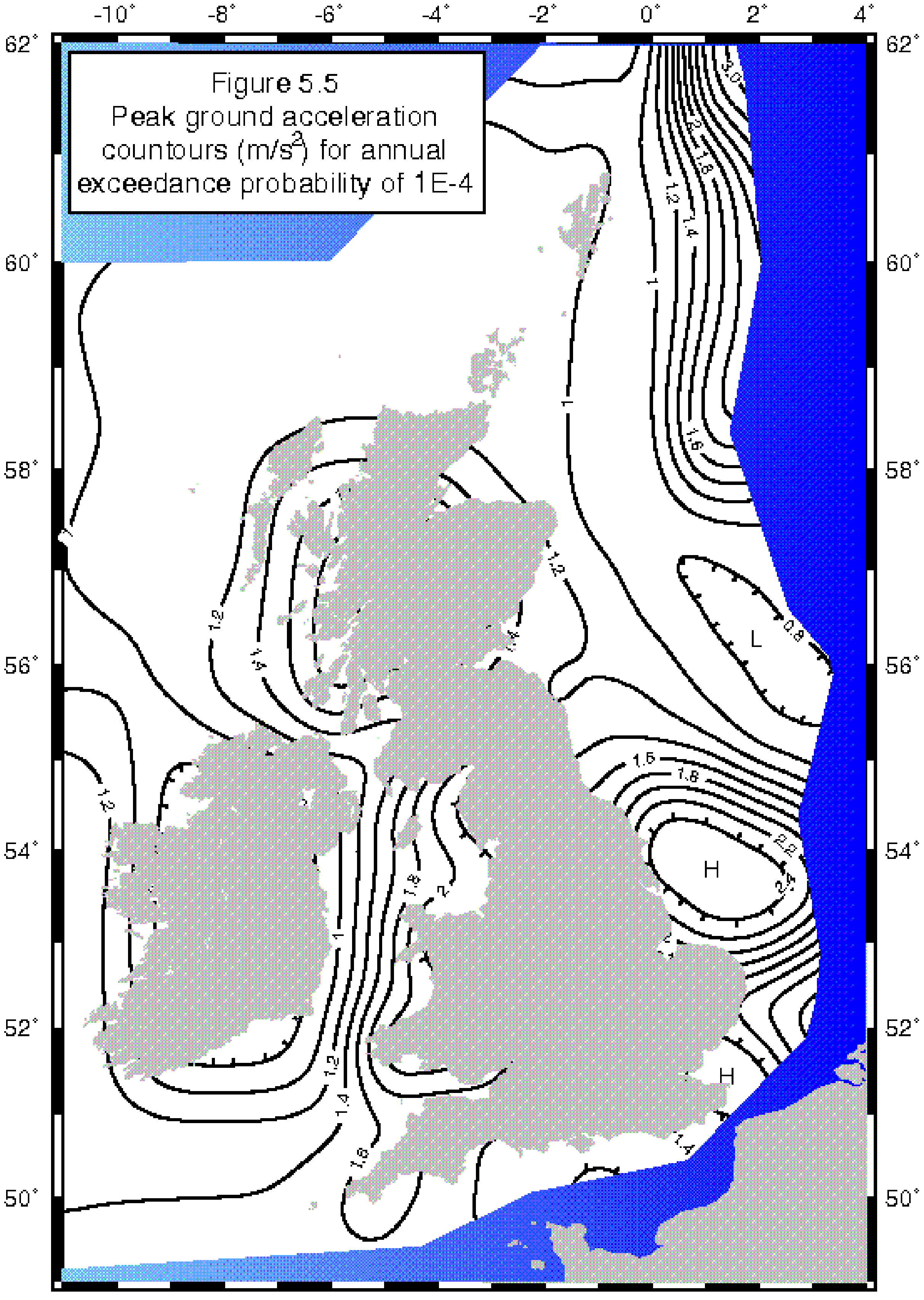
Figure 5.5
Peak ground acceleration countours (m/s^2) for annual exceedance probability of 1E-4

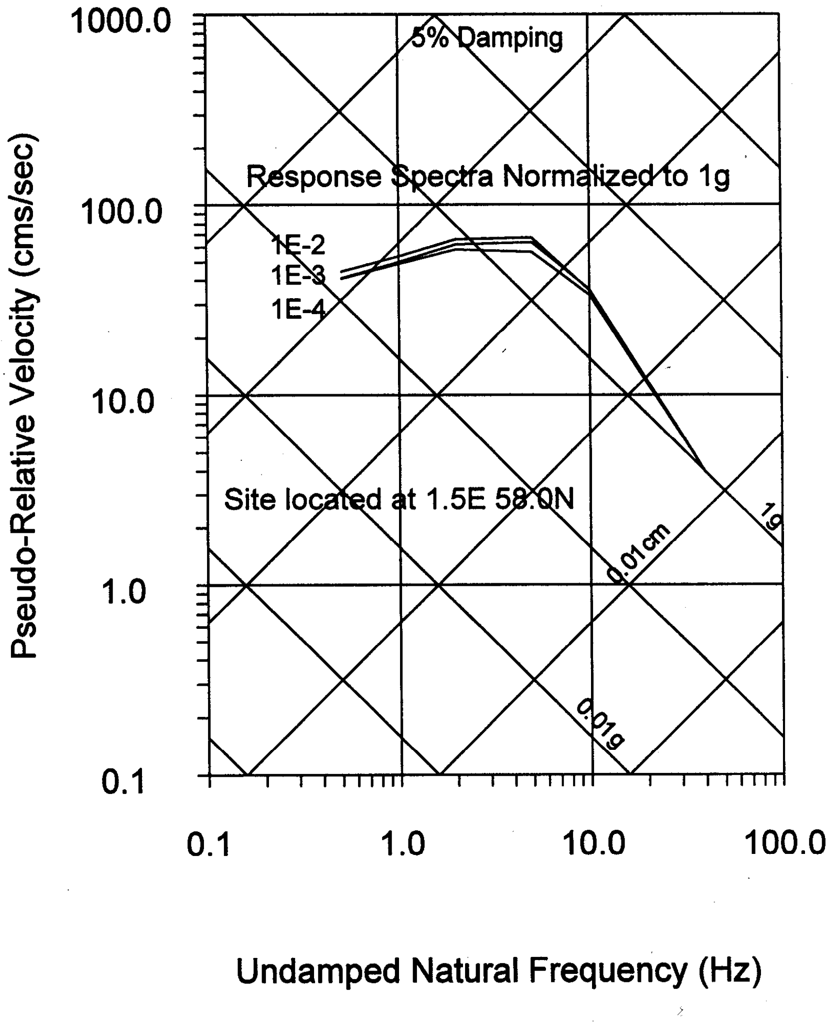

Figure 5.6
Comparison of spectral shapes at location [1.5E, 58 N] for annual exceedance probabilities of 1E-2, 1E-3 and 1E-4

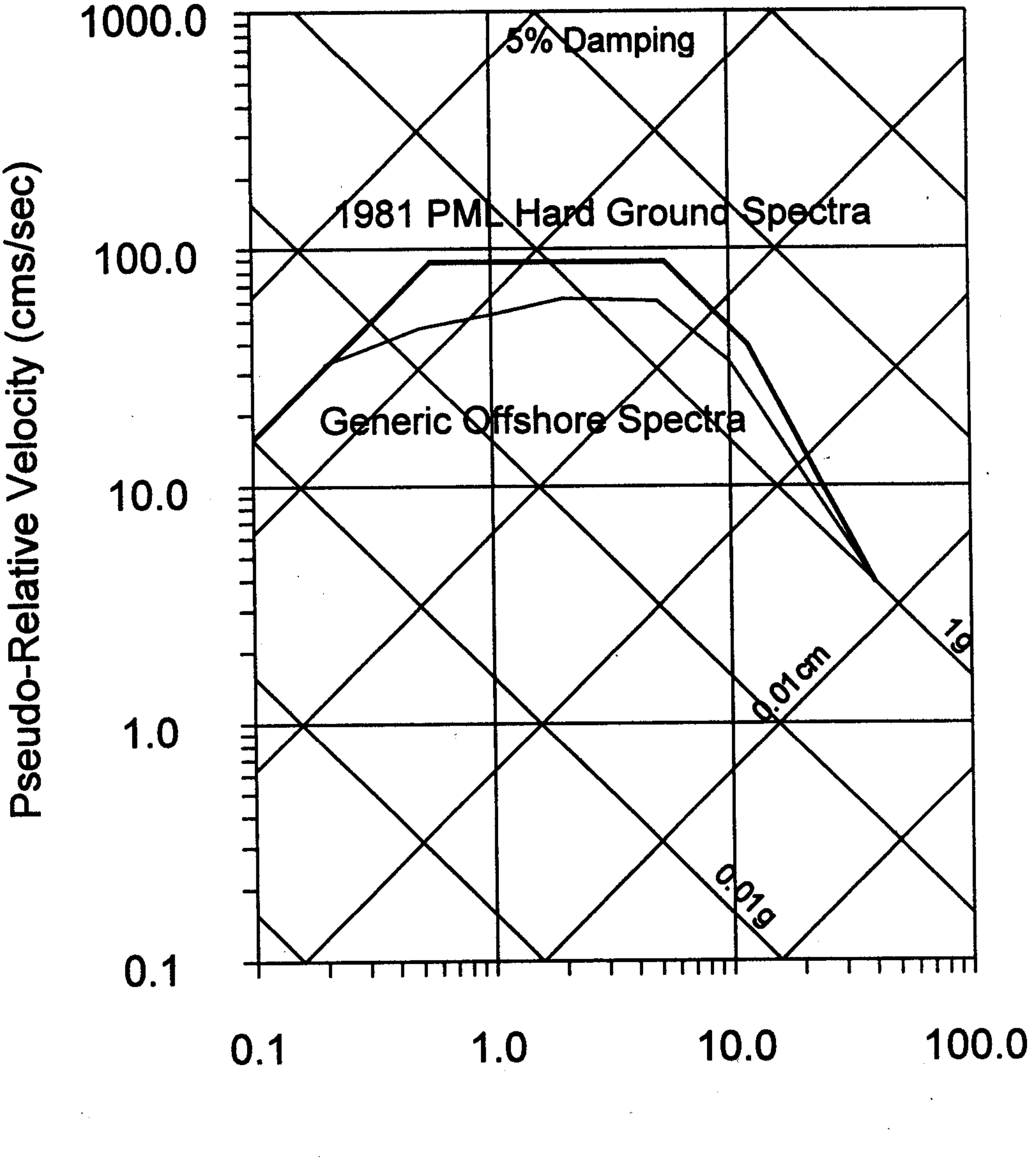

Figure 5.7
Comparison of generic offshore spectral shape with 1981 PML hard ground spectra normalized to 1g

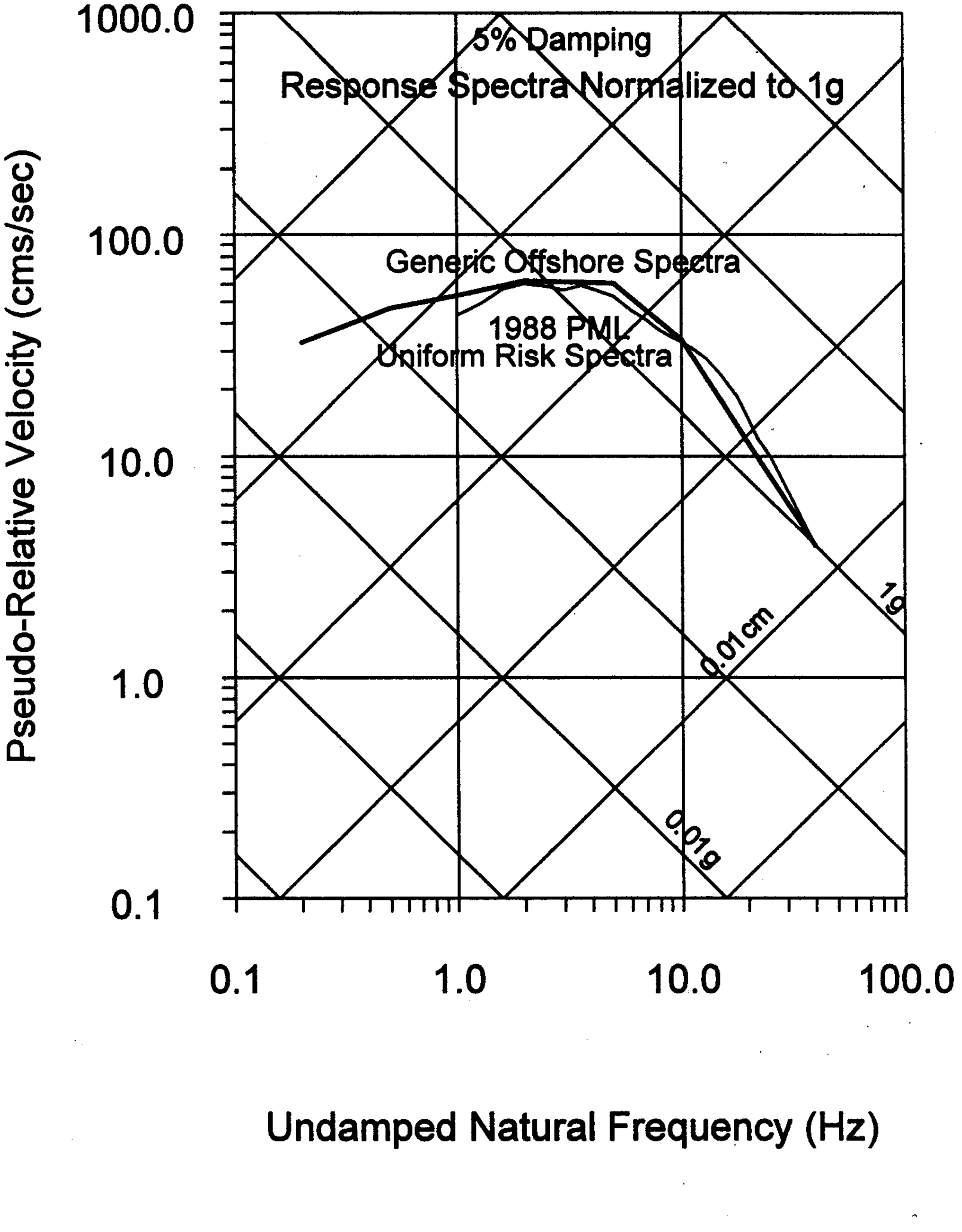

Figure 5.8
Comparison of generic offshore spectral shape with 1988 PML hard ground uniform risk spectral shape

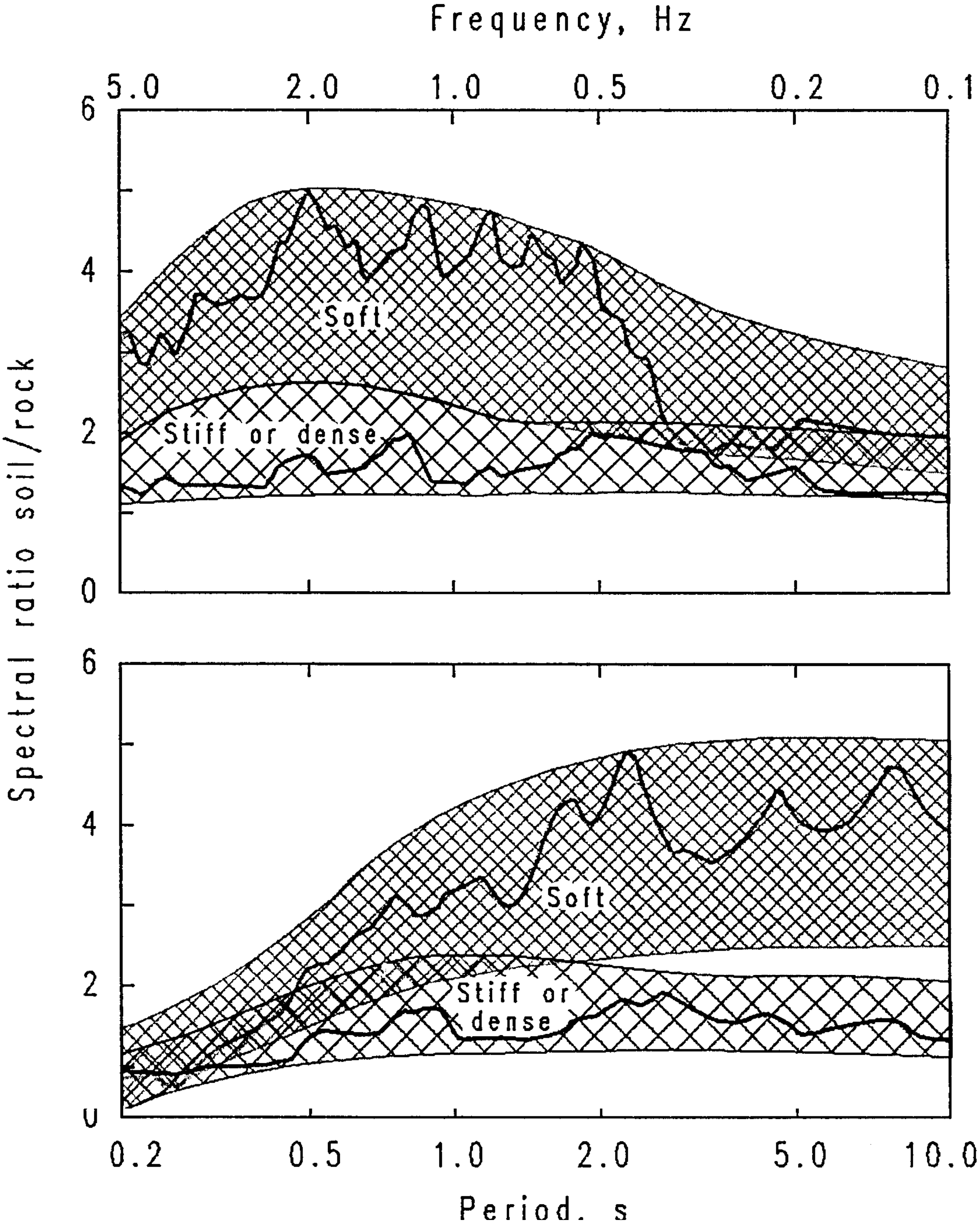

Figure 5.9

Ratio between the shaking in bedrock and on top of soil deposits for probabilities of exceedance of 10^{-4} [a] and 10^{-2} [b] . The shaded areas indicate the range in computed values, The thin continuous lines show the amplification for a specific site.

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