An integrative approach to seismic hazard and its application to the UK region

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Estimation of hazard in regions of low seismic activity such as many parts of Western and Eastern Europe, the Urals, Western and Central Siberia is an important issue. The limited seismological coverage typical of low activity areas constrains detailed scientific studies and this reduces the quality of seismic zoning maps of many territories throughout Europe, Northern Eurasia and elsewhere. The lack of optimal techniques for estimating hazard in regions of low seismic activity such as the Western Ural region has led to re-examination of existing methods. This paper examines ways in which a wide range of geological, geophysical and seismological data, beyond those traditionally used, can be related to seismic hazard and to the estimation of the key parameter "maximum magnitude" in an integrated fashion. The focus of this technique is the identification of common characteristics of "geodynamically unstable zones". Characteristic features of geodynamically unstable zones previously identified for the West Ural region and tested by application to the Western Siberian plateau are here applied to the UK region and the model is developed through the identification of additional diagnostic characteristics. A regional model of these zones has been built within the "GEO" Geographic Information System and used to construct predictive maps of maximum magnitude for possible earthquakes in the United Kingdom. These initial results suggest that the method shows promise and is deserving of further, structured, development. *KEYWORDS: Seismic hazard; maximum magnitude; United Kingdom; Geographical Information Systems.*

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1. Introduction

The scientific and practical benefits of seismic classification and zoning have long been evident in terms of enabling construction to proceed with appropriate degrees of safety without incurring disproportionate cost. Even in regions of low seismic activity, earthquakes of magnitudes as low as $M = 5.5$ have caused loss of life, destruction of housing and other serious damage. Such regions are present worldwide, and in parts of Europe such as the UK are associated with high population densities. Thus, although the level of seismic hazard is low, substantial numbers of people and high-value infrastructures are nevertheless at some degree of risk. Standard methods of seismic mapping, classification and zoning can be applied to such regions, but alternative techniques based on the interpretation of regional geodynamics and calculation of associated seismic potential may offer additional insights.

Here, we present a model for the classification of seismic activity in the UK developed using a technique based on the identification of "geodynamically unstable zones" (GUZs). These are determined based on a range of geological and geophysical data leading to a model for the seismic potential of the region (Figure 1). GUZs are identified according to the condition, properties and dynamics of underlying geological processes, which suggest that the zone may be somewhat more susceptible than the region overall to deformation under the effects of regional and global forces. The deformation may be manifested in seismicity [*Blinova*, 2003]. Zones may be distinguished using geological and geophysical parameters that characterize the properties of the medium, or derived from data related to previous and current crustal movements in the region. This method therefore identifies areas of potential seismicity, although not all of them need necessarily be active at present. It leads to the possibility of

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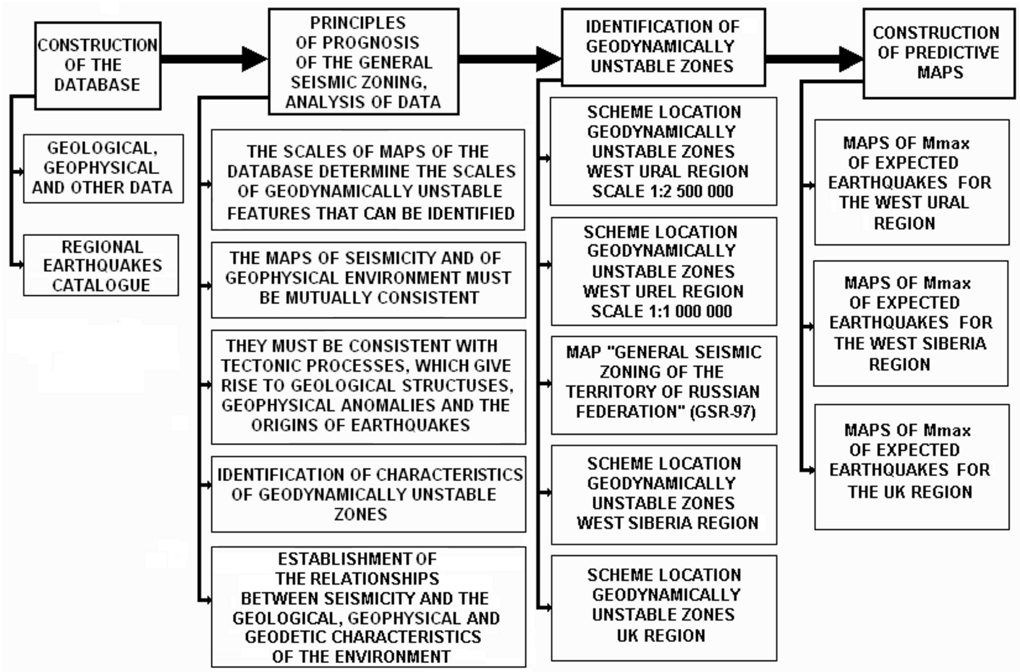

Figure 1. Program and schema for classification of regions of low seismic activity.

creating a regional model of GUZs incorporating a variety of levels of activity.

The technique was initially developed to address seismic classification for regions of low seismic activity, specifically for the Western Ural region. This is located at the junction of three geo-structures of the Earth's crust: the eastern outskirts of the Eastern-European platform, the Preduralsky foredeep, and the Western Urals folding zone [*Blinova*, 2003]. It has since been used to identify GUZs and to calculate seismic potential for the Western Siberian plateau [*Blinova*, 2009]. It is here extended and used to identify GUZs for the UK region. The technique is shown in schematic form in Figure 1.

The method is rooted in the construction of a database which includes a wide range of geological and geophysical parameters for the region as well as the catalogue of tectonic earthquakes over as long a period as is available. Its key concept exploits the notion that where a hierarchy of structures is present in the seismic, geological or geophysical environment, scale-lengths for heterogeneity in the underlying seismic, geological, geophysical or other relevant data can be identified. Whenever this analysis is consistent with what is known of the overall regional tectonic environment, any correspondence of scales and hierarchy orders within the zones identified establishes an empirical link between those geological and geophysical parameters and seismicity. A list of features characterizing the GUZs of the Western Ural region was initially determined, and this list has been expanded as the technique was applied to the Western Siberian plateau and, most recently, the United Kingdom.

The links between seismicity and geological, geophysical and geodetic characteristics of the environment for the Western Ural region and the Western Siberian plateau were described by [*Blinova*, 2003, 2009]. For each region, a model of GUZs was digitized and constructed within the "GEO" geographical information system [*Gitis and Yermakov*, 2004] (hereafter referred to as GEO-GIS). The resulting model was used as the basis for the next stage of research, and the construction of predictive maps of maximum magnitudes of possible earthquakes [*Gitis*, 1975; *Gitis and Yermakov*, 2004].

In its original form, these authors used an accumulation of earthquakes to identify and delineate seismic zones of different character, but this is not practicable in regions of low seismic activity. *Blinova* (2003) extended the method using geological and geophysical data to identify zones of differing geological properties and geodynamical characteristics and classify them according to the maximum earthquake magnitude observed in each zone. Whilst a rigorous mathematical formulation of this method is desirable, and a long-term objective of this research, the current state of knowledge and the wide variability in types and quality of data available mean that this is not yet practicable. The analysis and integration of numerous geological and geophysical data presently relies on the ability of an analyst to assess and integrate a large set of facts and considerations. Similarly, our current understanding of the relationship between the maximum magnitudes ($M_{\max}$) of tectonic earthquakes and the geological and geophysical features of a region are as yet too generalized to permit the construction of predictive maps of the maximum magnitudes of possible earthquakes that are both accurate and detailed. Nevertheless, we feel that this two-stage approach is deserving of further investigation and development.

Information modeling is the tool that makes it possible to combine all available approaches including descriptive knowledge, expert hypotheses, and processing methodologies. It facilitates analysis of diverse kinds of data and knowledge, enabling predictive relationships to be established and used, as here for example, in the construction of maps of maximum magnitude, $M_{\max}$ [*Blinova*, 2003; *Gitis and Yermakov*, 2004]. Information models become more reliable as additional data appears and as new expertise or knowledge becomes available.

In terms of constructing predictive maps of maximum magnitude, the key step is that of finding a function that reliably predicts $M_{\max}$ from geological and geophysical features and that can be used to forecast maximum magnitudes of possible earthquakes. For each region defined on the basis of geological and geophysical features – the GUZs [*Blinova*, 2003] – a relevant value of $M_{\max}$ is determined. The desired relationship is then calculated as the piecewise linear function which offers the best approximation for the known regions. $M_{\max}$ can then be estimated for all other points in the region as values of the prediction function calculated from the relevant geological and geophysical features at those points.

The technique described above permits geoscientific data to be used to produce results which are of immediate value in engineering, planning and social contexts. In the sections that follow, we illustrate its application by developing a model of GUZs for the United Kingdom region. Then, we move to the final stage of this technique and tentatively construct a predictive map of the maximum magnitudes of possible earthquakes for the UK.

2. Construction of an Electronic Database for Identification of Geodynamically Unstable Zones and Calculation of Seismic Potential for the UK Region

The first step in solving the seismic classification problem is to construct an electronic database of the available geological, geophysical and seismic data (see Figure 1).

For the UK region the database at our disposal includes results of the LISPB regional profile [*Bamford et al.*, 1976]. It also incorporates data on subsurface geology in interactive form and a graphical map of general and regional faults and a geological map of the UK and adjacent territories.

A second set of data maps is obtained using GEO-GIS with its subsystem generating knowledge and facts. Using GEO-GIS, the analyst is able to calculate numerical fields with schemes of linear objects, such as calculation of fields of fault density. She can work with fields of this sort undertaking isotropic or anisotropic filtering, calculation of gradients and azimuths, construction of maximal and minimal values in a circle, construction of differences and so on. We constructed maps of fault density without consideration of their ranges, of a field of maximal and minimal values and the variation in depth of the Moho surface, of relief of the Earth's crust, and of heat flow. Similarly, we calculated and constructed fields of moduli of their gradients, as well as fields of azimuths of gradients, for all of the geological and geophysical parameters for which this was practicable.

The earthquake catalogue is an essential part of the database. The available earthquake catalogue, covering the region bounded by latitude $N = 48\ldots63^\circ$ and longitude $E = -11\ldots7^\circ$, contains 1511 earthquakes between 1382 and 2009, with magnitudes ranging from 2.0 to 6.1 and depths between 0 and 33 km. Sub-catalogues for the magnitude ranges $M = 2.0$ to 2.9; $M = 3.0$ to 3.9; $M = 4.0$ to 4.9; $M = 5.0$ to 6.1 were constructed in order to develop the regional model using GEO-GIS.

3. Identification of Geodynamically Unstable Zones Using Geological and Geophysical Parameters and Construction of a Regional Model in the GEO-GIS System

The second stage of the technique is to use the available geological and geophysical data, here for the UK region (Figure 1), to identify GUZs. The initial set of parameters for identifying such zones was developed for the Western Urals region, and has since been used for identification of GUZs in Western Siberia [*Blinova*, 2003].

It was not possible to apply this schema to the UK in exactly the same fashion as was used in the Urals and Siberia. On the one hand, the relatively large number of earthquakes in the catalogue for this region meant that the relationship between the zones identified using geological and other data and regions of low-magnitude seismicity was not readily apparent as in the other regions. Consideration of the magnitude-restricted sub-catalogues provided some insight. On the other hand, certain types of data that had previously proved useful for the identification of GUZs were not available for the UK. These included limited details of crustal structure and neotectonic crustal movements, as well as information about features such as the temperature at key horizons within the sedimentary cover or their internal temperature gradients. All the available features were studied using the cross-section capabilities of GEO-GIS. Cross-sections were examined at one degree intervals from north to south along the region studied, and variation in parameters in these directions was analyzed. Consideration of all these parameters enabled us to identify new features that are diagnostic of GUZs for the UK region.

In previous studies of low activity regions, GUZs were found in locations where the depths of the Moho changed rapidly. This feature may well be connected with the activation of tectonic processes within the upper mantle [*Blinova*, 2003]. We traced the positions of such zones within the limits of the UK. Several areas were identified where the depth of the Moho surface changes from 27 to 34 km over a short distance, even though this parameter changes across the entire region only from 27 to 37 km (Figure 2).

Gradients of the depth to the Moho surface and gradients of the gravitational and magnetic fields were introduced as further indicators of GUZs. Maps of these parameters were calculated and constructed within GEO-GIS. We examined the map of modulus of gradient of depth to Moho. At the limits of the GUZs tentatively identified on the basis of the preceding analysis, the modulus of the gradient of the depth

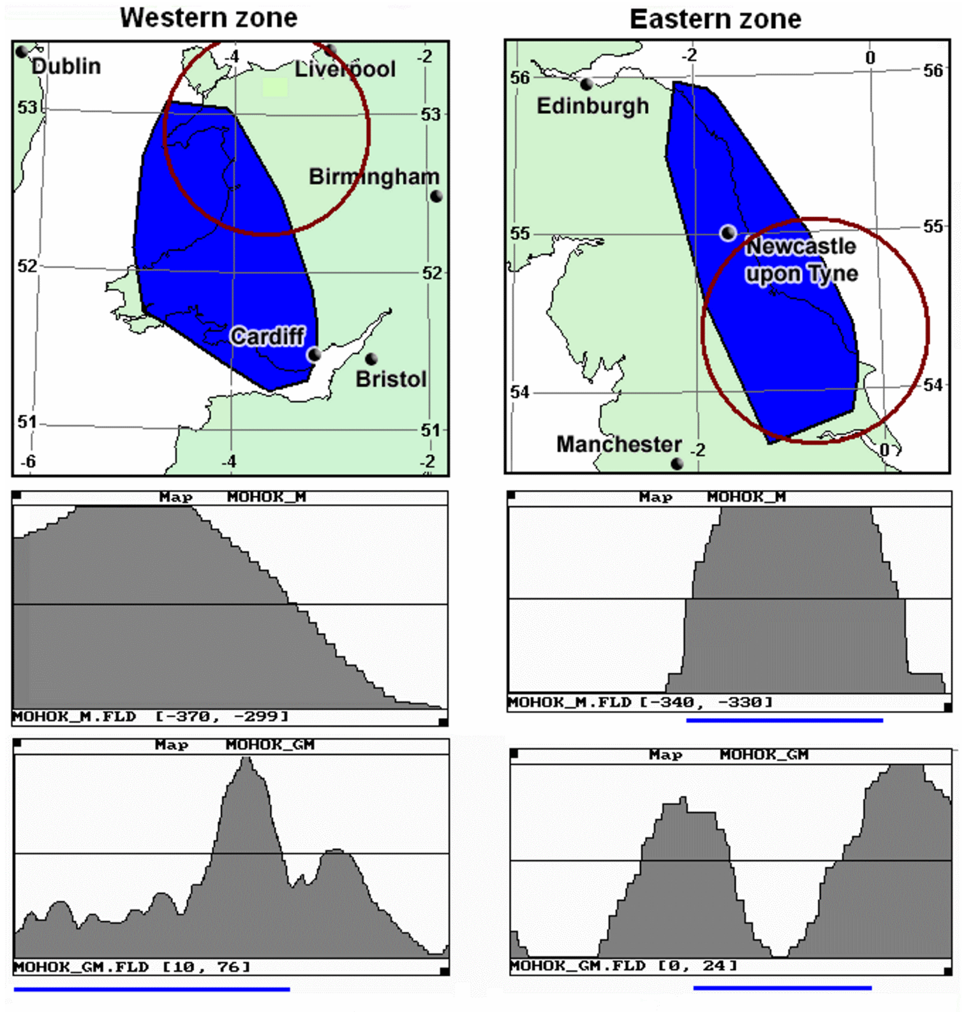

Figure 2. Features of identification of the Western and Eastern GUZs. Features: MOHOK_M – depth to Moho (scale, (:10) km), MOHOK_GM – gradient of the depth to Moho (scale, m/km). Circles – zones of intersection of fault systems.

to that boundary is small, whereas the value of this parameter increases at the edges of the zones. The margins of these areas were less clearly defined in the offshore regions. It is not clear whether this effect is real, or an artifact of data acquisition or analysis.

We also analyzed variations in the modulus of the (Bouguer) gravity field gradients. Within the GUZs in the onshore part of the region, the modulus of the gradients of the Bouguer gravity field takes small values – between 0.03 and 0.8 mGal/km – whereas the modulus of the gradient increases to between 1.0 and 2.1 mGal/km at the edges of the zones (Figure 3 and Figure 4).

The modulus of the gradient of the magnetic field behaves in an analogous manner, but any dependencies are less obvious (Figure 3 and Figure 4). At the limits of the GUZs the modulus of the gradients of magnetic field anomalies are small – between 1 and 6 nT/km – although the modulus of the gradient increases to the range 13 to 20 nT/km at the edges of the zones (Figure 3 and Figure 4).

This situation reveals new features that will be useful for future identification of GUZs, because these variations are co-located with other indicators of these zones. Such changes in the gradients of gravitational and magnetic fields were not previously anticipated. There are several possible explanations for the newly observed behaviour of these parameters. Consider first that sedimentary cover laid down over a mobile fault zone is subject to movements which are not present in cover laid down over stable blocks, and that the effects of that underlying movement are often visible in the gravitational and magnetic fields. Recalling that the junction between systems of faults is a primary identifying feature of GUZs, it is possible to draw an analogy between the behaviour of these fields over faults and over GUZs. An alternative explanation for the increased gradient of the gravitational and magnetic fields at the edges of zones is based on the relationship of those fields to the density of faults. The density of faults within previously identified GUZs characteristically takes average values. In other words, they are "living" parts of the Earth's crust characterized by neither the greatest nor the lowest density of faults. At those

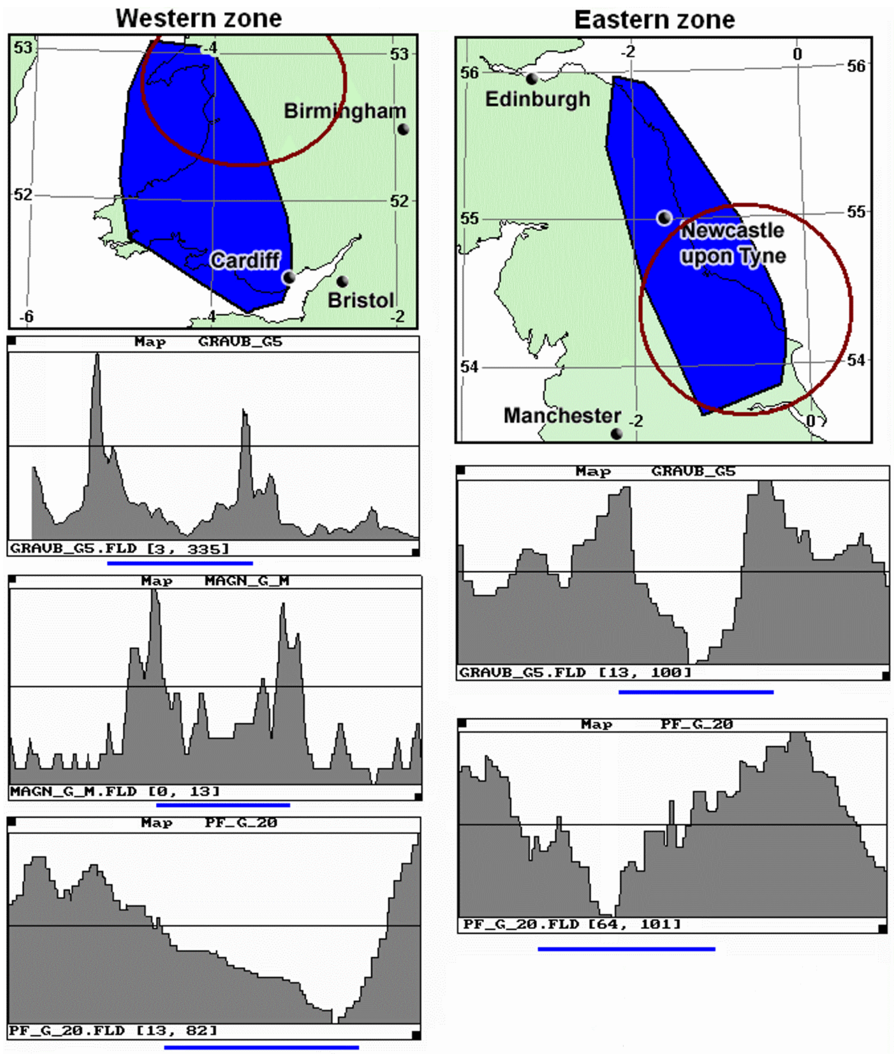

Figure 3. Features of identification of the Western and Eastern GUZs. Features: GRAVB_G5 – gradient of gravitational field (scale ($\times 10^{-2}$), mGal/km), MAGN_G_M – gradient of magnetic field (scale, nT/km), PF_G_20 – gradient of vertical crustal motion (scale ($\times 10^{-4}$), mm/yr/km). Circles – zones of intersection of fault systems.

sites, the conditions for the accumulation of elastic tectonic stresses and their relaxation are being created. The density of faults, as a rule, may therefore be expected to decrease at the edges of GUZs, resulting in an increase of values of the gradient of the gravitational and magnetic fields. In this way, it may be possible to draw some conclusions about the proximity of processes in geodynamically unstable areas and structures such as faults in the Earth's crust.

We also analyzed changes in the modulus of the gradient of contemporary vertical motions of the Earth's crust [*Teferle et al.*, 2009]. At the limits of the onshore zones, the moduli of the gradients of contemporary vertical motions of the Earth's crust take small values ($(13-90) \times 10^{-4}$ mm/yr/km). In this case the modulus of the gradient increases strongly and reaches $(72-130) \times 10^{-4}$ mm/yr/km at the edges of the zones (Figure 3 and Figure 4). This is characteristic of all regions previously considered.

Faults in the Earth's crust and lithosphere control a wide range of processes taking place both at depth in the Earth and near, even at, its surface. Seismic classification is traditionally undertaken based on data derived from seismic and geological studies, which take into account the distribution of epicenters of earthquakes and the known geological situation, within which fault movement plays a significant role. Fault zones, especially active fault zones, are regions of maximum seismicity within any area. This has been shown to be true for the regions of low seismic activity previously examined using our method, such as the West Ural region and the Western Siberian plateau.

However, it has proved very difficult to find such regularities within the UK and adjacent territories studied here.

It is generally accepted that fault maps can indicate the directivity, the genetic types and the age of the movements depicted. However, they do not always fully reflect the quantitative state of fragmentation of the crust, and from this perspective the information derived from such maps is

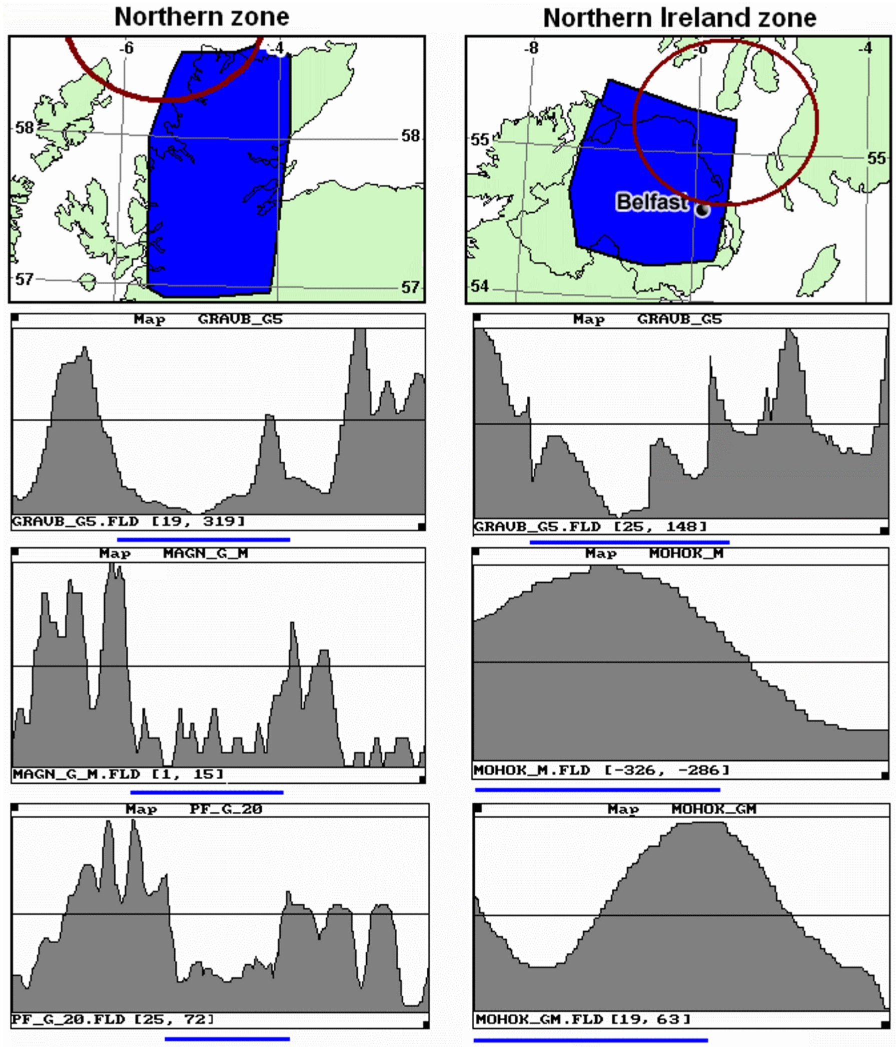

Figure 4. Features of identification of the Northern and Northern Ireland GUZs. Features: GRAVB_G5 – gradient of gravitational field (scale ($\times 10^{-2}$), mGal/km), MAGN_G_M – gradient of magnetic field (scale, nT/km), PF_G_20 – gradient of vertical crustal motions (scale ($\times 10^{-4}$), mm/yr/km), MOHOK_M – depth to Moho (scale (:10), km), MOHOK_GM – gradient of depth to Moho (scale, m/km). Circles – zones of intersection of fault systems.

not always complete. Maps of fault density [*Sherman*, 1977; *Sherman et al.*, 1983] were constructed as part of this study.

Maps of fault density for the UK region were constructed as follows. Fault density is defined as the number of faults per unit area. This parameter was calculated using GEO-GIS.

The fault density field is calculated as follows: for each point of the region under consideration, a value is assigned equal to the ratio of the number of fault lines in a circle of chosen averaging radius $R_{\max}$ to the area of this circle ($\pi R^2_{\max}$). The fault density map of the UK was initially constructed using circles of radius $R = 15$ km. This value was selected taking into account the maximum variation in the thickness of the Earth's crust, the typical length of faults and the depth of the epicenters of earthquakes. A larger averaging radius shows only larger scale processes, whereas a smaller radius causes the resulting map to be dominated by individual heterogeneities in the structure of the Earth's surface. Calculations were also undertaken for $R = 10$ km and $R = 20$ km and these confirmed our a priori view that $R = 15$ km constitutes a reasonable balance between these two extremes.

The identification of GUZs was undertaken by constructing east-west sections at one degree intervals from the north to the south of the region, complemented by three further sections through the whole region taken in different directions. The fault density map was compared with the GUZs as described above. It was apparent that, in all, three zones traced on the fault density map of the crust of the UK were associated with average values of fault density in the range 2.30 to 3.30×10^{-3} m^{-2}, compared to an overall range in this parameter of 0.41 to 4.97×10^{-3} m^{-2}. Thus the GUZs are characterized by average values of fault density. It appears that conditions for the accumulation of elastic tectonic

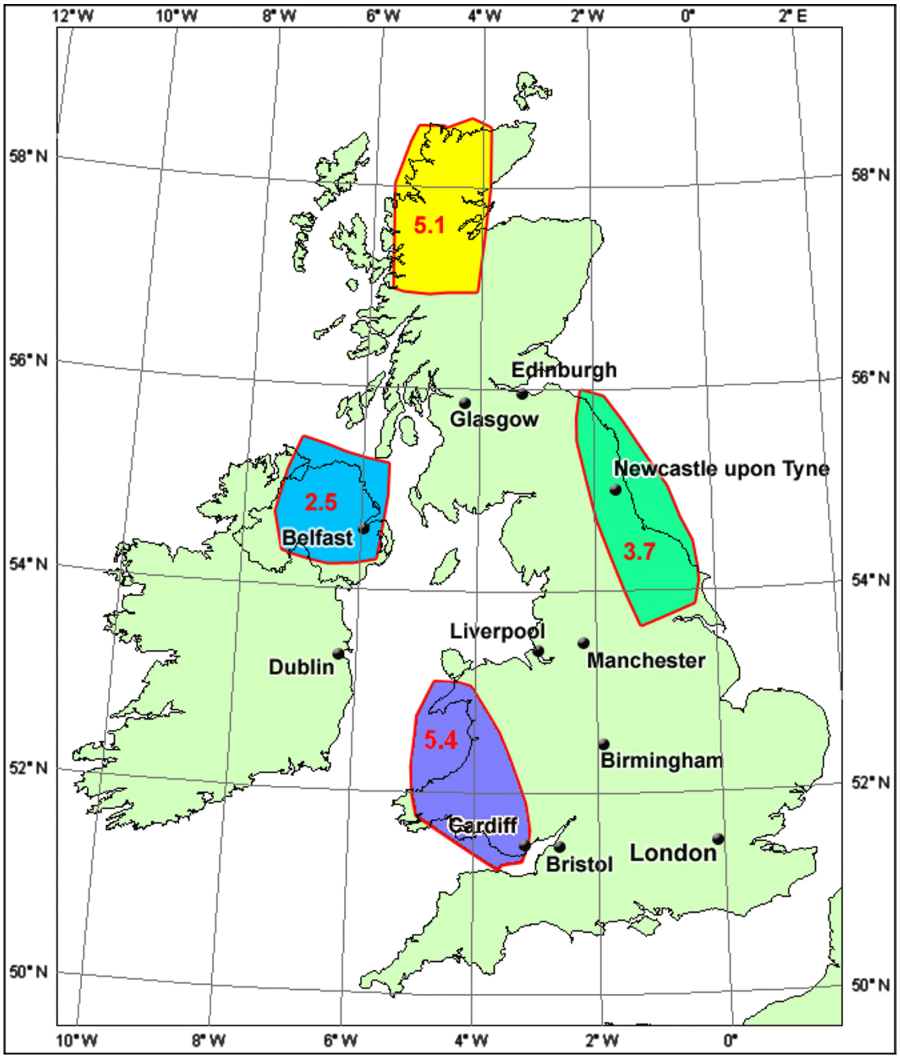

Figure 5. Regional model of the GUZs obtained using GEO-GIS. The numbers inside each zone indicate the predicted maximum earthquake magnitude within that zone.

stresses and their relaxation are created in these sections.

Zones of fault intersection are no less important for determining the positions of GUZs and understanding the reasons for their formation. These are primary tectonic structures influencing not only the intersection itself but the surrounding volume, and are sites of important geological and geophysical processes (structural, metamorphic, hydrogeological, geo-thermal and so on) including changes in the state of stress, all caused by the conjunction of differently oriented dislocation systems. The zone of intersection of faults is connected with many geological processes, from the motion of fluids and ore formation to strong earthquakes [*Sherman*, 1986].

However, in the case of the study of the UK reported here, it proved impossible to use the intersection of individual faults either for the identification of GUZs or for establishing the connection between fault tectonics and seismicity. However, it did prove possible to use the zones of intersection of systems of faults, an alternative previously proposed for the West Ural region [*Blinova*, 2003].

Five zones of intersection of systems of faults were identified, most of which coincided with the zones identified using the previous indicators of GUZs. In the northern part, one zone of intersection of systems of faults is identified but it does not fully explain the manifestation of seismicity in this part of the region. Seismicity in the north of the UK may be associated with the substantial past displacements on the Great Glen Fault and the Moine Thrust. Three western zones of intersection of three systems of faults trending in different directions partially or completely coincide with the GUZs. The eastern zone of intersection of faults coincides with the GUZ. It is both the intersection of three systems of faults and a zone in which the direction of propagation of faults changes by 90°. Zones of intersection of differently directed systems of the faults are typically seismically active.

Within the onshore and immediately offshore areas of the UK, four GUZs are identified. Their identification is based on known geological and geophysical features. Each zone is associated with specific characteristic motions. For example, the conjunction with the Great Glen Fault is characteristic of the northern zone, and the western and eastern GUZs are located in areas of ongoing motion of blocks, as is evident on the kinematic model for the UK region due to *Chadwick et al.* [1996] and *Musson* [2007]. Each of these is also characterized by an increase of gradients of current vertical motions at the edges of zones.

The regional model of zones was constructed in GEO-GIS and then digitized using specially constructed catalogues of earthquakes (Figure 5).

We created a map of geodynamic unstable zones. It should be noted that specific values of geophysical fields within the zones correspond to defined values of magnitudes of possible earthquakes. These values magnitudes are shown in zones (Figure 5). In constructing of the map of magnitudes our knowledge (connection the values of geophysical, geological and geophysical parameters and the values of magnitudes) will be disseminated on the throughout region. Each point of this map will have its value of magnitude of possible earthquakes.

Thus, $M_{\max}$ can then be estimated for all other points in the region as values of the prediction function calculated from the relevant geological and geophysical features at those points [*Gitis*, 1975; *Gitis and Yermakov*, 2004].

4. Discussion and Conclusions

The technique discussed here, originally developed for the Western Ural region of low seismic activity and since applied to the Western Siberia plateau, has been applied to the United Kingdom region. A database of geological, geophysical and seismic data was constructed and the "geodynamically unstable zones" of the region were identified. A regional model, based on the set of the indices and parameters, and characterizing the specific features of the tectonic structure was derived using specialized GIS technologies.

We used the results of this study to construct predictive maps of maximum magnitudes of possible earthquakes for the UK. The construction of these maps for the United Kingdom is of particular value because the number of earthquakes available in the historical record also permits the construction of predictive maps of seismic hazard using standard methods, so it will be possible in the future to compare the results of the standard approach with the results of this technique which has been especially developed for regions of low activity. This will in turn improve both the technique itself and our understanding of the processes associated with seismicity in the UK.

These investigations have demonstrated that different regions may require the introduction of new features for identification of GUZs, according to the geological and geophysical parameters that are available to make up the database. The technique, whilst originally designed for application to the Western-Ural region of low seismic activity, and tested for the Western Siberian plateau, and further developed through application to the UK region, can now be offered to address problems of seismic zoning of other suitable regions such as those parts of Europe with low seismic activity. To further improve the technique, to make it robust, and to test its outcomes, additional studies in different regions are required. Development of a body of further example use cases will permit generation of more accurate predictive maps of the maximum magnitudes of possible earthquakes.

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References

Bamford, D., S. Faber, B. Jacob, W. Kaminski, K. Nunn, C. Prodehl, K. Fuchs, R. King, P. Willmore (1976), A lithosphere seismic profile in Britain; I, Preliminary results, *Geophys. J. R. Astr. Soc., 44*, 1, 145–160.

Blinova, T. S. (2003), *Prediction of Geodynamically Unstable Zones*, Urals Branch Russian Academy of Science.

Blinova, T. S. (2009), Potential seismicity of the Western Siberian plateau, *Patriotic Geology*, 4, 73–81.

Chadwick, R. A., T. C. Pharaoh, J. P. Williamson, R. M. W. Musson (1996), *Seismotectonics of the UK. Final report*, British Geological Survey internal report WA/96/003.

Gitis, V. G. (1975), Algorithms of prediction and synthesis of features with the use of one-dimensional piecewise linear functions, in *Linear and Nonlinear Methods in Pattern Recognition, Gitis V. G. (ed.)*, Nauka, Moscow, 19–30.

Gitis, V. G., B. V. Yermakov (2004), *Fundamentals of Spatial-Temporal Prediction in Geoinformatics*, Physmathlit, Moscow.

Musson, R. M. W. (2007), British earthquakes, *Proc. Geol. Assoc., 118*, 305–337. (http://dx.doi.org/10.1016/S0016-7878(07)80001-0).

Sherman, S. I. (1977), *The Physical Laws Governing the Development of Faults*, Nauka, Novosibirsk.

Sherman, S. I., A. N. Adamovich, A. I. Miroshnichenko (1986), Terms of activization of joints zones of faults, *Geology and Geophysics, 3*, 10–17.

Sherman, S. I., S. A. Borniakov, V. Y. Buddo (1983), *Areas of Dynamic Influence of Faults (Modeling Results)*, Nauka, Novosibirsk.

Teferle, F. N., R. M. Bingley, E. J. Orliac, S. D. P. Williams, P. L. Woodworth, D. McLaughlin, T. F. Baker, I. Shennan, G. A. Milne, S. L. Bradley (2009), Crustal motion in Great Britain: Evidence from continuous GPS, absolute gravity and Holocene sea-level data, *Geophys. J. Int., 178*, 1, 23–46. (http://dx.doi.org/10.1111/j.1365-246X.2009.04185.x).

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