Notable Events

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Excerpt from the
Summary of the Bulletin of the International Seismological Centre:

Dyagilev, R.A., N.S. Guseva and F.G. Verkholantsev, Macroseismic Field Anisotropy of the ML 4.7 Earthquake of 18 October 2015 in Central Urals, Russia, *Summ. Bull. Internatl. Seismol. Cent.*, July - December 2015, *52*(II), pp. 50–59, Thatcham, United Kingdom, 2018, https://doi.org/10.31905/KP7ZNV1Z.

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7.1 Macroseismic Field Anisotropy of the M_L 4.7 Earthquake of 18 October 2015 in Central Urals, Russia

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This publication is an English adaption of an article that was first published in Russian in the Russian Geophysics Journal (2016, Vol. 5, pp. 42–46).

7.1.1 Introduction

On 18 October 2015 at 21:44:55 (GMT) a unique event happened in the Central Urals – a tectonic earthquake with magnitude M_L 4.7 that was felt over a very large area in the Sverdlovsk region and Perm Krai. An event of this magnitude is quite rare for this region. It may be noted that this was the strongest earthquake in the last 100 years. Events with large magnitudes have only happened in the Central Urals twice before. According to the historical records, the first one took place in 1798 in the vicinity of Perm, the second in 1914 near Pervouralsk (Bilimbay). The Bilimbay earthquake was also recorded instrumentally.

The earthquake was registered by 10 stations of the Ural seismological network run by GS RAS and MI UB RAS and the instrumental data obtained allowed the determination of the source parameters for the event (Tab. 7.1, Fig. 7.1). Information on the macroseismic impact was collected as well. In this article we analyse the macroseismic field and obtain coefficients of the Intensity(I)-Magnitude(M)-Distance(R)-relation. In the 1970's the I-M-R relation was determined for a wider area including most of the European part of Russia, the Urals and Western Siberia. To obtain the coefficients only for the

Urals region was not possible because of low seismicity in the area and, thus, a lack of data. The M_L 4.7 event in October 2015 changed this situation substantially. Now, we can determine the I-M-R-relation for the Urals region which contributes to seismic hazard assessment in the area.

Table 7.1: *Source parameters of the earthquake on 18 October, 2015 in the Central Urals.*

Time UTC	Lat degrees	Long degrees	Depth km	M	Notes
21:44:55	57.12 ±0.04	59.05 ±0.11	12	M_L 4.7 ±0.2	MI UB RAS solution according to the records of the stations ARU, SVE, PR0R, PR1R, PR3R, PR4R, PR7R, KAUR, SVUR, BA1R.
21:44:53.84	57.08	59.03	14	mb 4.4	ISC solution (168 Stations, *International Seismological Centre*, 2018)

7.1.2 Macroseismic Data

To describe the effects of the earthquake on the Earth's surface, the experts at MI UB RAS and GS RAS collected macroseismic data in the epicentral area during the first few days after the earthquake. Answers to the main part of the questionnaires were obtained by a personal survey of local residents near the epicenter. Data on the macroseismic effects was also received via the website "Seismological monitoring at the territory of the Western Urals" (`http://pts.mi-perm.ru/region/index.html`, in Russian), where the residents of other settlements are able to answer the same questions in absentia. In addition, a survey questionnaire was sent to the local administration of the 50 settlements located on the periphery of the shaking zone.

The survey was aimed at identifying the nature of several macroseismic indicators: sensations felt by the people during the earthquake, shaking of household items, damage to buildings and structures, changes in the environment. To simplify the task of data collection, the questionnaire, with a total of 38 questions, was set up as a form with multiple descriptions of possible manifestations of the earthquake that may be marked or not by the respondent. The combination of marked manifestations is a base for calculating the earthquake's intensity at one point on the surface. A set of questionnaires collected from a group of randomly selected respondents in a local area is used to obtain a more reliable estimation of seismic intensity for this area or settlement. Statistically, the more respondents there are, the smaller the error in estimated intensity, which should be computed with an accuracy of 0.1 point. In some settlements the number of respondents was small due to low population density. In the end, more than 200 questionnaires from 85 localities were collected. The collected data became the basis for the assessment of seismic intensity in terms of the MSK-64 scale (*Medvedev*, 1968).

The results of the survey show that people were feeling the event quite clearly not only in the nearby localities but also at distances more than 100 km away from the epicenter. Within a radius of 10-20 km from the instrumental epicentre strong shocks were reported, as well as clattering of dishes, vibration of windows, swaying of light objects and shaking of major appliances. Many witnesses woke up and ran outside. The passage of seismic waves was accompanied by sound effects. People described their

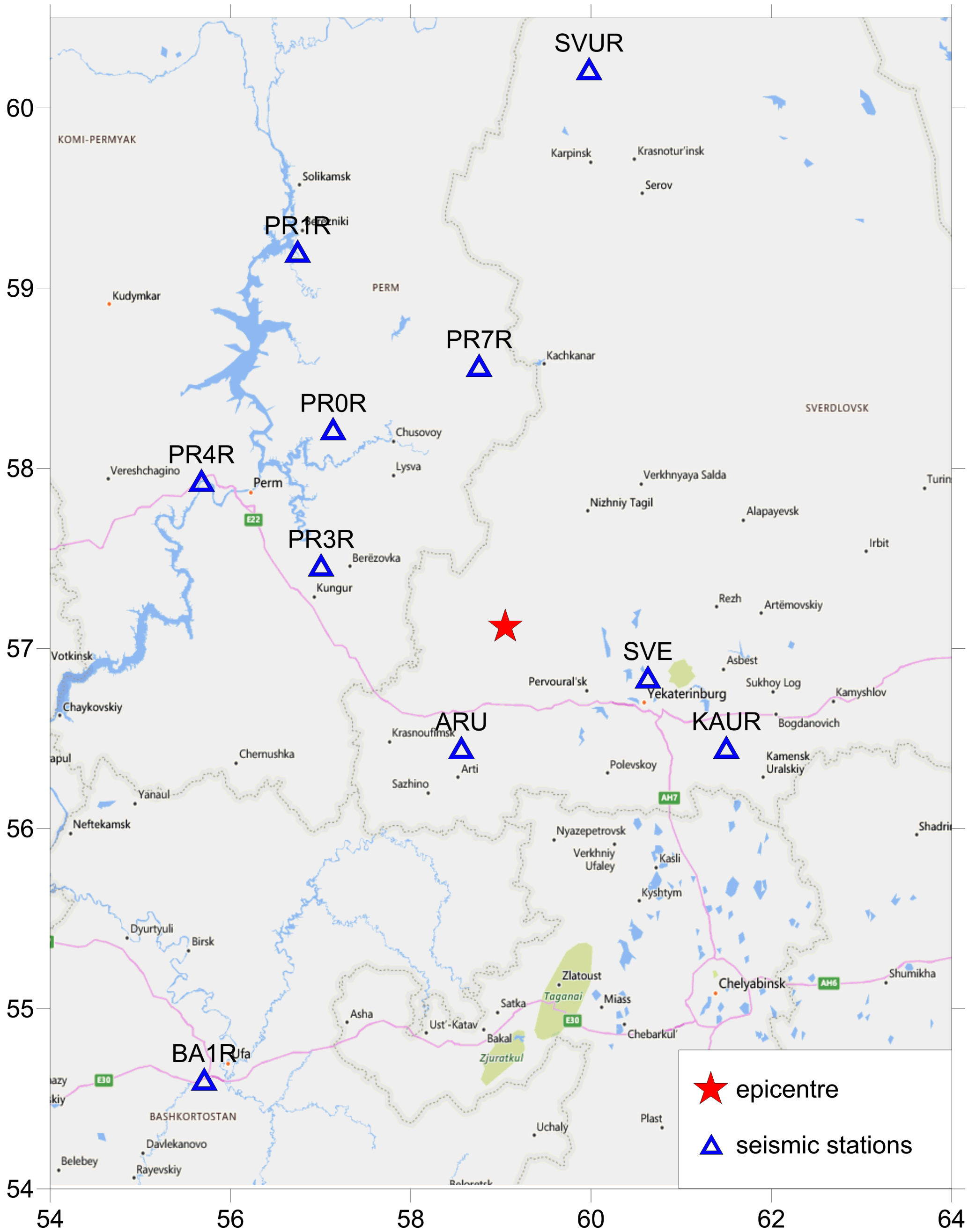

Figure 7.1: Map showing the epicenter of the earthquake and stations that provided data to calculate source parameters.

impressions as "shock, vibration, as if snow had fallen from the roof", "rumble, as if a truck had rammed into the corner of the house". At distances up to 100 km tremors, vibrations and shaking lasting up to 5 s were reported, as well as trembling of windows and glassware and a rumble "like a train passing by or a plane flying". The boundary of the shaking zone is located at a distance of about 130 km from the epicenter, where tremors were weak, barely perceptible or not sensed at all. It should be noted that ground motions were spreading considerably further to the NW of the epicentre than to other directions. For example, in Perm at a distance of 190 km on the upper floors of buildings distinctive shaking and tremors were felt. According to the collected surveys damage to buildings and constructions was not identified in any of the surveyed localities. However, on the internet there were some reports of cracked windows in the kindergarden no. 30 in the town of Novoutkinsk and concrete slabs being moved at the dam of Kamensky reservoir.

According to the questionnaires the intensity in every locality was defined based on the observations of the witnesses. Where several questionnaires were received, the average intensity I and its standard deviation σ were determined according to the following equations (*Federal Agency for Technical Regulation and Metrology*, 2017):

$$I = \frac{\sum n_i I_i}{\sum n_i},$$

$$\sigma = \pm\sqrt{\frac{\sum n_i I_i^2 - I_i^2 \sum n_i}{\sum n_i \sum (n_i - 1)}},$$

where I_i is the estimated intensity for the i^{th} macroseismic indicator and n_i the number of respondents presenting the i_{th} macroseismic indicator. A summary of intensities for the different localities is provided in Table 7.2.

Table 7.2: *Summary of intensities in terms of the MSK-64 scale.*

Localities	**Intesity points**
Sabik, Sarga, Chusovoye	5
Staroutkinsk, Pervomaiskiy, Starobukharovo, Kuzino, Sylva, Ilim, Novoutkinsk, Progress, Shalya, Pervouralsk	4-5
Bisert', Krylosovo, Pervomaiskoye, Taraskovo, Kalinovo, Bilimbay, Yekaterinburg	4
Novouralsk, Visim, Pochinok, Afanasievskoye, Russkiy Potam, Bol'shoy Ut, Arti, Verkhniaya Pyshma, Kungur	3-4
Shamary, Molebka, Nizhniy Tagil, Ust'-Kishert', Sysert', Bol'shoye Zaozerie	3
Achit, Kyn, Manchazh, Krasnoufimsk, Polevskoy, Sarana, Oktyabrskiy, Sars, Lys'va, Verkhniaya Salda, Kyshtym, Chernushka, Perm, Polazna, Chusovoy, Tyoplaya Gora, Gornozavodsk, Suksun, Kamensk-Uralskiy	2-3

7.1.3 Isoseismal Maps

An isoseismal map was built by interpolating the raw data using the software package Surfer 12 where the Kriging gridding method gave the best results (Fig. 7.2). The macroseismic field of the earthquake shows a prominent spatial anisotropy. Such behavior is common for many macroseismic fields of other

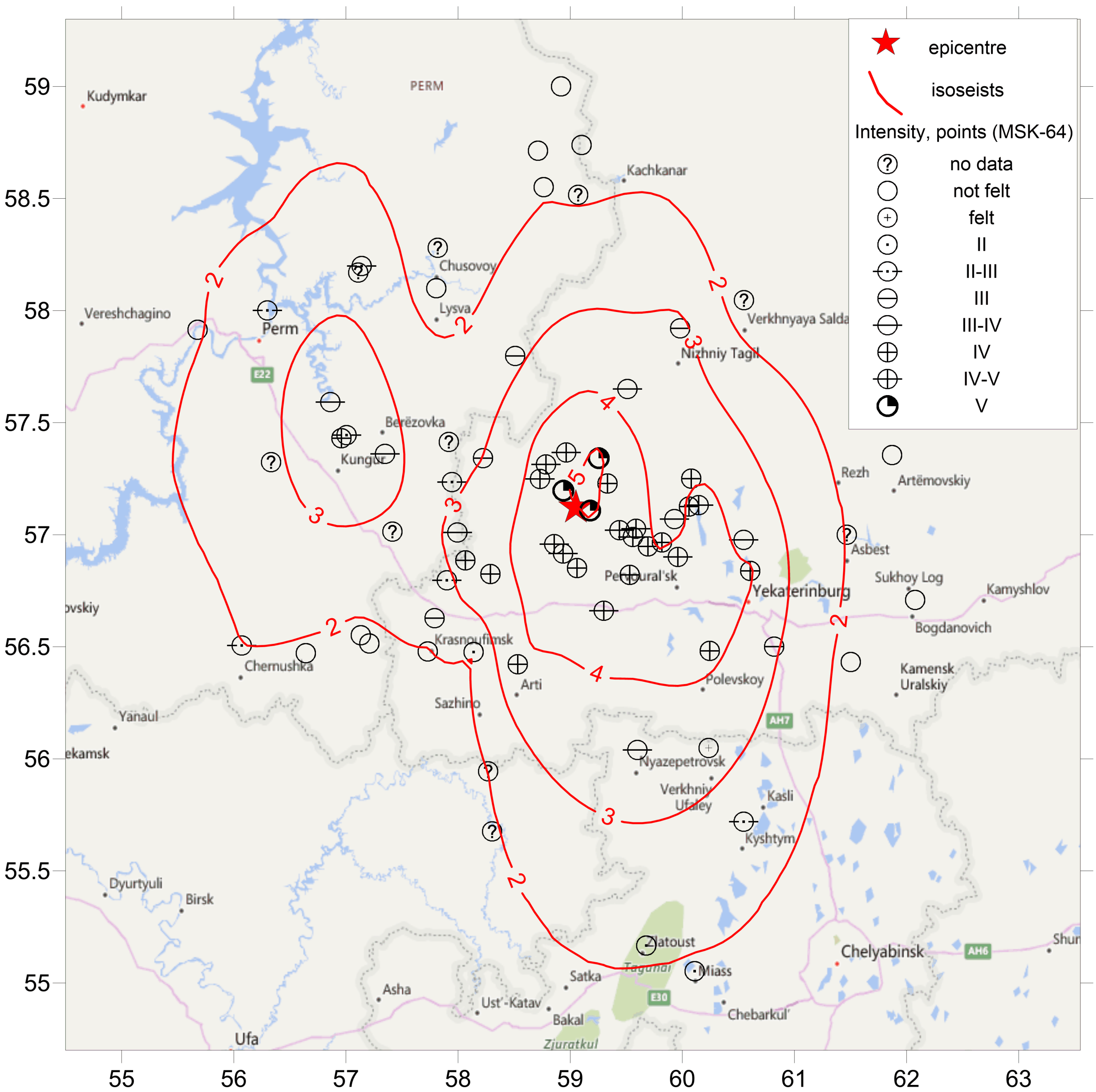

Figure 7.2: *Isoseismal map obtained by interpolation with Kriging gridding method.*

earthquakes (*Dzhanuzakov*, 2013). Further, the macroseismic fields shows two maxima of intensity: one maximum (5 points) at the epicenter and a second, slightly lower, maximum (3-4 points) to the West and North-West from the epicenter in the territory of Perm Krai. This distribution of macroseismic intensities in this area could also be observed for the Bilimbay event hundred years ago (*Veis-Ksenofontova*, 1940).

For modelling the macroseismic field there are a variety of methods in the literature. The earliest classic models, such as the model of Blake-Shebalin or Covesligeti-Shebalin (*Shebalin*, 2003; *Blake*, 1941), assume that the source is a point, and the seismic effect is distributed in a homogeneous environment, meaning that it is not direction-dependent. The simplicity of the classic models makes them appropriate to apply in more complicated cases. For example, in the work of *Dzhanuzakov* (2013) the effect along and across the structures of the Northern Tien Shan is described by two different equations. The similar approach can be found in other seismic areas (*Solomatin*, 2013) for earthquakes with different magnitudes. More modern approaches to describe the macroseismic effect distribution, such as the model of *Gusev and*

Shumilina (1999), consider a spreading source, due to which the intensity depends on the orientation of the fault plane and the location of the observation point relative to this plane. In the study of *Kulchitsky* (2014) the method of approximation is shown. It allows to correctly describe the macroseismic effect of earthquakes where only a limited amount of macroseismic data can be collected due to the location of the epicentre (e.g. in the sea or on the border to another country). Despite the point notion of the source, this approach still allows for indirectly taking into account spreading sources and regional patterns of seismic waves propagation, including the anisotropic component of the macroseismic field.

Since the Ural earthquakes are relatively small (maximum magnitude according to *Shebalin et al.* (2000) does not exceed 5.5) with an average depth of 15 km they can be considered as seismic point sources. Structures elongated from the North to the South in the basement and the sedimentary cover create conditions for anisotropic propagation of the seismic waves. The study area does not provide favourable geographical conditions for a representative collection of macroseismic data, despite the fact that it is located inside the continent and belongs to one state, because of an irregular arrangement of settlements and the existence of vast uninhabited areas. This makes the approach proposed by *Kulchitsky* (2014) appropriate, which will be discussed in more detail in the following paragraph.

According to *Kulchitsky* (2014), the basis for the description of the macroseismic field is the Intensity(I)-Magnitude(M)-Distance(R)-relation of Shebalin-Blake:

$$I(r) = 1.5\ M_{LH} - b\ \lg(r) + c, \tag{7.1}$$

where M_{LH} is another expression for M_S, r is the hypocentral distance in km, b and c are empirical coefficients. In this work the value of magnitude M_{LH} was calculated from M_L with the relationship: $0.8\ M_L - 0.6\ M_S = 1.04$ (*Ambraseys*, 1990). In Equation 7.1 the azimuthal-dependent heterogeneity for b can be defined, as follows:

$$b = b_0 + \sum_{k=1}^{n} (B_{sk} \sin(\alpha k) + B_{ck} \cos(\alpha k)), \tag{7.2}$$

where n is the order of the trigonometric polynomial responsible for the complexity of the spatial asymmetry in the calculated field and B_{sk}, B_{ck} are polynomial coefficients responsible for the shape and intensity of asymmetry. To find the unknown components c, b_0, B_{sk}, B_{ck} the method of least squares is used.

In the case of an isotropic field (coefficients B_{sk}, B_{ck} are neglected) the components are $b_0 = 3.18$ and $c = 2.48$, which slightly differs from the average values adopted previously for this region ($b_0 = 3.5$, $c = 3.0$) (*Medvedev*, 1968). However, the analysis of field residuals obtained with the new coefficients reveals that their distribution is dependent on intensity I. Red circles in Figure 7.3 show the residuals where the red dashed line is a linear approximation of the residuals. The residuals for $I < 3.1$ are slightly less than observed while for $I > 3.1$ they are slightly larger. After an iterative correction of coefficients b_0 and c we found the values $b_0 = 3.84$, $c = 3.76$ which make the residuals not dependent on intensity (blue circles and blue solid line in Figure 7.3). The standard deviation of residuals before correction is 0.2 points. After correction it increases to 0.3 points.

To calculate the anisotropic component of the macroseismic field, *Kulchitsky* (2014) recommends n to be $n = 5$ in Equation 7.1 for many and well distributed collected macroseismic data points. For a lower

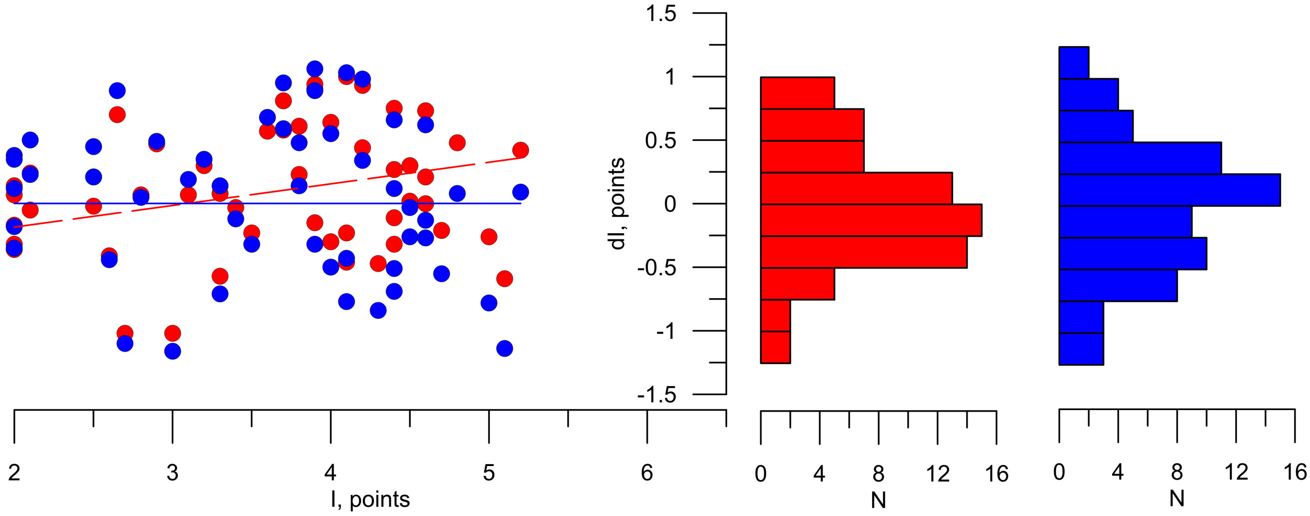

Figure 7.3: *Intensity residuals against intensity (left) and histogram of intensity residuals (right). Data without correction are shown with red circles and bars, adjusted data are shown with blue circles and bars.*

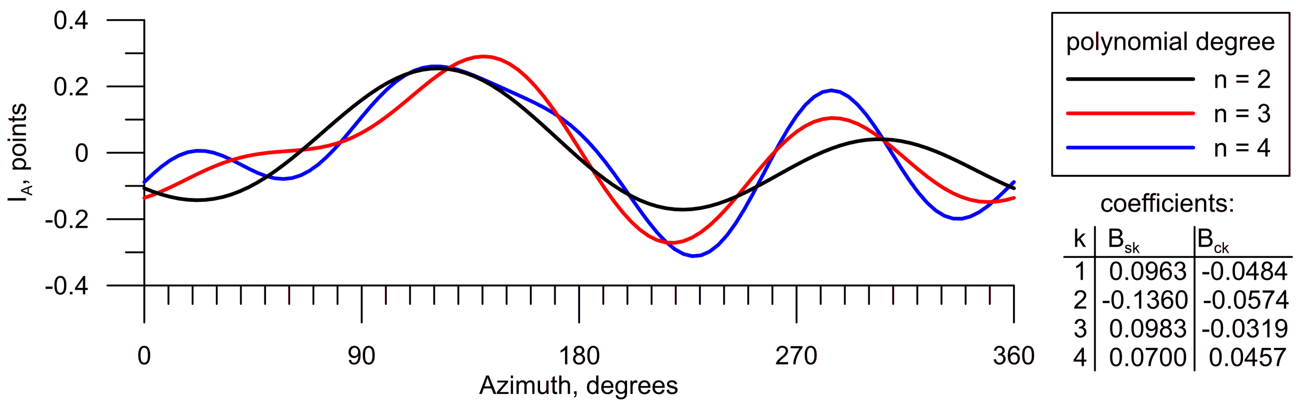

Figure 7.4: *The anisotropic component of the macroseismic field I_A for different polynomial degrees.*

amount of data with a poorer distribution n should be less than 5. The anisotropic component I_A of the macroseismic field for $n = 2, 3, 4$ dependent on azimuth is shown in Figure 7.4. A basic characteristic can be observed for all polynomial degrees described above with the largest deviations at azimuths about 120 degrees, 220 degrees and 280 degrees.

The results of constructing the macroseismic field for $n = 2, 3, 4$ are shown in Figure 7.5. The isoseismal map for $n = 2$ reflects a generalised understanding of the anisotropy and attenuation of seismic waves, for which the elliptical shape indicates a strong azimuthal deviation from a uniform propagation of the wave field. The axis of dominant propagation has an azimuth of 126 degrees (Fig. 7.4). For $n = 3$ the largest anisotropic component shows a similar azimuth (140 degrees) but the isoseismals do not follow a strict elliptical shape anymore and an additional component with an azimuth of about 40 degrees can be observed (Fig. 7.5). For $n = 4$ this second component is even stronger and the isoseismals are almost cross-shaped with azimuths of the axes of prevailing propagation of the seismic field at about 22 degrees and 284 degrees.

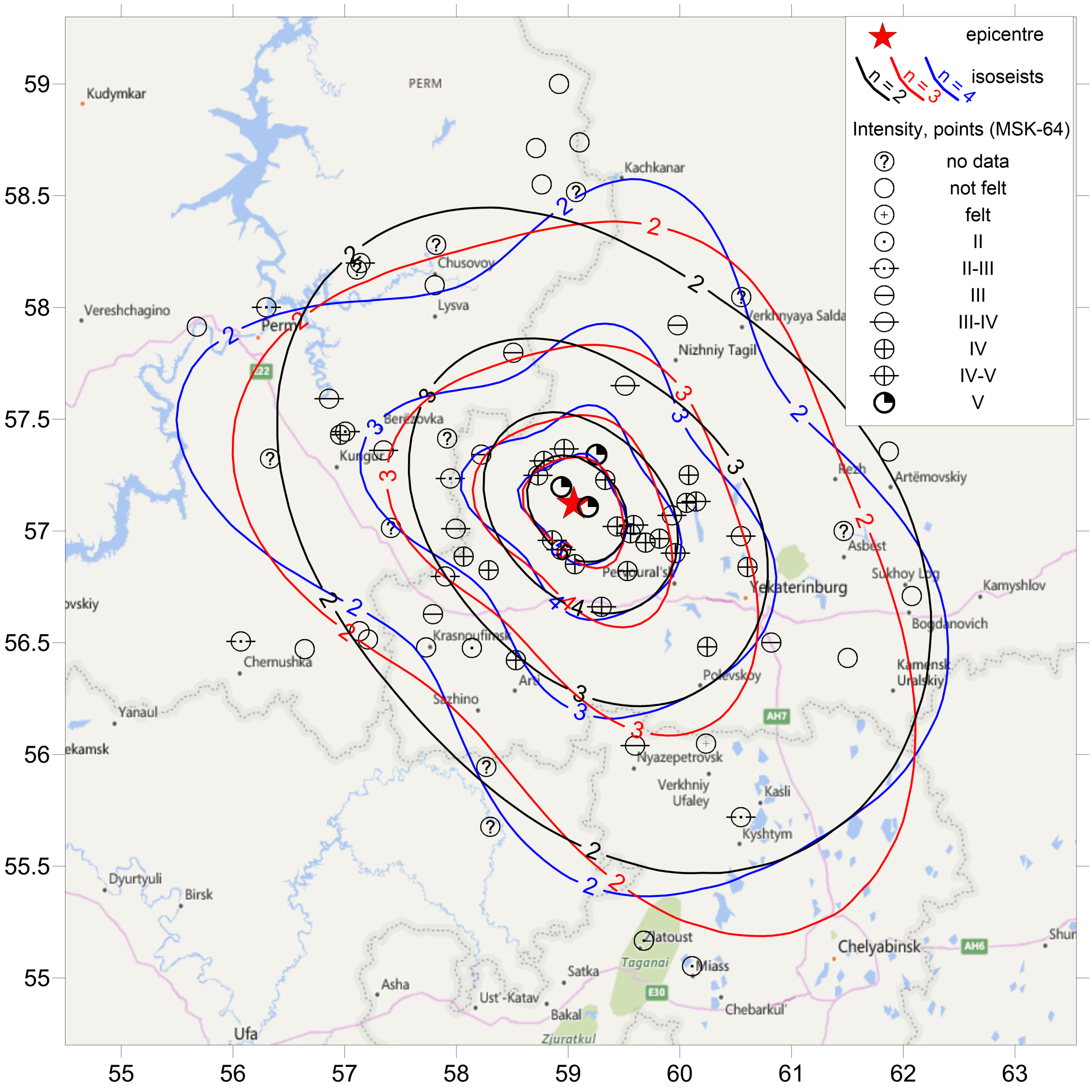

Figure 7.5: *Isoseismal map obtained by approximation method for* $n = 2, 3, 4$.

7.1.4 Discussion and Conclusions

By interpolating the results of the questionnaires and by modeling the macroseismic field by using the approximation method we constructed isoseismal maps of the M_L 4.7 event of 18 October 2015 in the Central Urals. An anisotropic distribution could be observed in each of the methods. The anisotropic component with an azimuth of about 22 degrees observed for $n = 3, 4$ can be explained by the orientation of the principal tectonic structures, folds and faults zones, of the Urals along which seismic attenuation is weaker. On the other hand, the component with a NW-SW direction which is observed in all isoseismal maps cannot be explained by geological features in the area. One of the possible reasons for such local enhancement of shaking in the Perm region could be soil features. However, as a rule ground amplifications are more patchy and the influence on the soil requires a separate research.

Modeling the macroseismic field by the approximation method with trigonometric polynomials allows a more accurate estimation of intensity of future strong earthquakes for a wide area of the Central Urals. We obtained two sets of coefficients with different sensitivity to intensity. Both sets provide acceptable levels of variance (0.2-0.3 points), therefore the intensity independent set of coefficients is preferable. The new macroseismic coefficients with an isotropic component ($b_0 = 3.84$, $c = 3.76$) are in line with values found in other regions. They also allow a direct estimation of the intensity at the epicenter (I_0) where there are no observation points. Substituting the coefficients in Equations 7.1 and 7.2 gives an intensity of $I_0 = 5.8$ points, with a possible error of ± 0.6 points. This is very close to the values reported by the settlements closest to the epicentre (Sabik, Sarga and Chusovoye).

The earthquake on 18 October 2015 gave for the first time in many years the opportunity to study the distribution of macroseismic effects on a wide area covering almost the entire Central Urals for a wide range of intensity values (from 2 to 5 points). None of the previously recorded instrumentally tectonic earthquakes in the Urals gave such a significant amount of primary data. All known major events with magnitude 5.0 or more, occurred in the period from the late 18th to the early 20th century when definitions of shaking intensities and instrumental observations were not as advanced as they are today.

The overall result of our study provides a basis for more accurate calculations of the seismic intensity for future earthquakes and allows a better assessment of the seismic hazard in the Central Urals.

7.1.5 References

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