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Historical earthquakes studies in Eastern Siberia: State-of-the-art and plans for future

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ABSTRACT

Many problems in investigating historical seismicity of East Siberia remain unsolved. A list of these problems may refer particularly to the quality and reliability of data sources, completeness of parametric earthquake catalogues, and precision and transparency of estimates for the main parameters of historical earthquakes. The main purpose of this paper is to highlight the current status of the studies of historical seismicity in Eastern Siberia, as well as analysis of existing macroseismic and parametric earthquake catalogues. We also made an attempt to identify the main shortcomings of existing catalogues and to clarify the reasons for their appearance in the light of the history of seismic observations in Eastern Siberia. Contentious issues in the catalogues of earthquakes are considered by the example of three strong historical earthquakes, important for assessing seismic hazard in the region. In particular, it was found that due to technical error the parameters of large $M = 7.7$ earthquakes of 1742 were transferred from the regional catalogue to the worldwide database with incorrect epicenter coordinates. The way some stereotypes concerning active tectonics influences on the localization of the epicenter is shown by the example of a strong $M = 6.4$ earthquake of 1814. Effect of insufficient use of the primary data source on completeness of earthquake catalogues is illustrated by the example of a strong $M = 7.0$ event of 1859. Analysis of the state-of-the-art of historical earthquakes studies in Eastern Siberia allows us to propose the following activities in the near future: (1) database compilation including initial descriptions of macroseismic effects with reference to their place and time of occurrence; (2) parameterization of the maximum possible (magnitude-unlimited) number of historical earthquakes on the basis of all the data available; (3) compilation of an improved version of the parametric historical earthquake catalogue for East Siberia with detailed consideration of each event and distinct logic schemes for data interpretation. Thus, we can make the conclusion regarding the necessity of a large-scale revision in historical earthquakes catalogues for the area of study.

1. Introduction

In the last few decades, considerable efforts have been made to reconstruct seismic history in many regions of the Earth using methodical approaches on disciplines ranging from instrumental observations to paleoseismological studies (Guidoboni, 2002; Caputo and Helly, 2008). Particular emphasis has been placed on the analysis of documentary historical evidence for the past earthquakes. The use of historical data significantly (sometimes by one order of magnitude) extends the timeframe for our concept of seismicity as compared to the instrumental records whose duration is at best only a little over a century. The historical materials often provide a detailed description of macroseismic manifestations, which is why large historical earthquakes may be taken into account in seismic hazard assessment. These problems are also important for East Siberia whose seismicity is mainly due to the intracontinental Baikal rift zone (BRZ) (Fig. 1). A high-level activity of the BRZ is evidenced by both historical events (e.g. the 1862 Tsagan earthquake, $M = 7.5$) and instrumentally recorded earthquakes, e.g. the 1957 Muya earthquake, $M_{LH} = 7.6$ (Kurushin and Mel'nikova, 2008).

It is agreed that the period of instrumental seismological observations in East Siberia began in 1960 with deployment of the regional seismic network (Golenetsky, 1990) though the first instrumental observations in the region formally started in December 1901 after the "Irkutsk" station had been put into operation. The observations made in the first half of the XXth century should not be considered reliable because no more than three seismic stations could be working simultaneously at that time that provided neither preliminary earthquake records nor precise earthquake parameter estimations. Nevertheless, the date when the "Irkutsk" station started operation (1901) may be considered as the upper limit of the historical period. The lower limit is determined by

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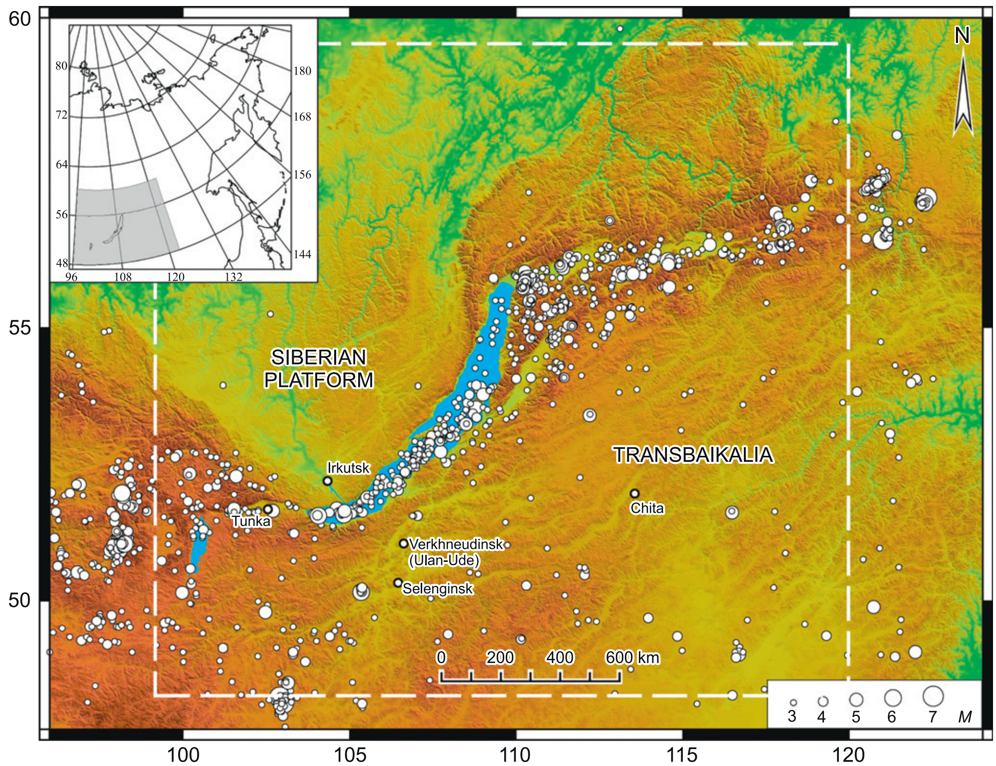

Fig. 1. Digital elevation model and seismicity of East Siberia. A white dashed contour line indicates the investigation area – "Baikal region" (48–60°N, 99–120°E) in accordance with zoning accepted in the «New catalogue...» (Kondorskaya and Shebalin, 1982). The epicenters of earthquakes presented here were recorded instrumentally between 1960 and 2008 by the Baikal Division of Geophysical Survey of Siberian Branch of Russian Academy of Sciences. Some settlements shown in Fig. 1 are important in terms of research on historical seismology in East Siberia as some of the oldest administrative centers of Siberia from which regular macroseismic information arrived.

the history of multidisciplinary explorations and investigations in Siberia, the most important of which are primarily written accounts. The duration of historical period in the seismic studies of East Siberia lasted from the late XVIIth century to the early XXth century. During this period, the number of reports of felt earthquakes gradually increased. The increase in number of reports is associated with the development of postal service in Siberia, as well as with the appearance of regional periodicals in the middle of the XIXth century. Since the beginning of the XXth century the surveys of strong earthquakes in Eastern Siberia were carried out with the mailing of questionnaires.

One of the most acute problems in the analysis of historical seismicity of East Siberia is the lack of reliability and quality of information sources. The historical part of the parametric catalogues available is generally based on information from various dissimilar sources. However, borrowing materials from one source and publishing them in another one, particularly in a foreign one, often leads to the distortion of the primary data and accumulation of errors that may have a profound impact on the analysis of results – estimation for the major source parameters of a historical earthquake. This necessitates making thorough search and revision for the original *primary sources* of the historical–seismological data.

For East Siberia, the studies of historical seismicity were made by Nikonov (1997), Golenetskii (1996a, 1996b), Chipizubov (1988, 1997, 2010) and Radziminovich and Shchetnikov (2005). Nevertheless, these studies are not sufficient to characterize historical seismicity of the region and many problems remain unsolved.

This paper provides a historical review of macroseismic information in East Siberia and presents the major data sources. The paper deals with the analysis and use of the available earthquake catalogues, related problems and probable solutions.

2. Brief history of earthquake studies in East Siberia

2.1. A period of "random" information

Seismic activity of the Lake Baikal area is known since at least the end of the XVIIth century. In the XVIIIth – the first quarter of the XIXth centuries, Siberia was rather poorly developed and sparsely populated. The settlements were generally located on the banks of large rivers. The houses that were for the most part made of wood adequately resisted earthquake motions. Stony buildings remained the exception rather than the norm for a long time.

Most of the information on earthquakes arrived occasionally from the settlements of administrative or trading importance, among them the town of Irkutsk. Founded as fortification in 1661, Irkutsk acquired the status of a town in 1686 and became an administrative center of a vast area and, therefore, a center for collection of diverse information.

Some random evidence was provided by I. Ides, a head of the diplomatic mission sent to China by Russian tsar Peter I. Ides who stayed in transit at the town of Udinsk (now Ulan-Ude) in Late March–Early April of 1693 witnessed a rather large earthquake and cited brief data about this earthquake in his travel description. This earthquake is the first rather precisely dated seismic event in East Siberia, though it is still not included in macroseismic catalogues.

In the XVIIIth – first half of the XIXth centuries, the earthquakes of Lake Baikal region were of particular interest to scientists specializing in natural environment of Siberia. Valuable materials are found in the works of Messerschmidt (1966), Georgi (1775), Gmelin (1767), Pallas (1778) and Erman (1850), and others. Their direct observations as well as purposely collected data on earlier events were used in the European and Russian macroseismic earthquake catalogues (Orlov, 1872; Mushketov and Orlov, 1893) later on. However, an intensive research pursued by these scientists into the earthquakes of Baikal region was limited to the period of their stay in Siberia, and the proper nature of research was predominantly random.

Therefore, seismicity of Eastern Siberia was not studied purposefully up to the first third of the XIXth century, and the macroseismic data were only accumulated through felt earthquake reports in national periodicals, Irkutsk chronicles, and memoirs of naturalists who worked in Siberia.

2.2. "A time for enthusiasts" – first systematic observations

The situation changed somewhat when the participants of the Decembrist revolt (December 1825) in St.-Petersburg were exiled to Siberia. The arrival of highly educated people to the eastern part of the country that was far removed from administrative centers favored the advancement of culture in Siberia. Some of the exiled noblemen – the so-called Decembrists (N.A. Bestuzhev, P.I. Borisov, A.N. Muravyov and others) – settled in different points of Siberia had an opportunity to perform natural studies and kept their own registers for regular meteorological observations wherein the felt earthquake data were also recorded.

From the middle of the XIXth century, the study of earthquakes in Baikal region received a new impulse thanks to Kehlberg, a resident of the town of Selenginsk (Transbaikalia region). He was a man of wide scientific interests who did much for the study of the region's natural environment. Kehlberg's activity was thoroughly investigated by Demin (2002). We will only mention some of the most important dates. Kehlberg started making systematic observations of earthquakes in Selenginsk in 1847 and from that time published his data in the Russian scientific periodicals for more than 40 years. He tried to record earthquakes using a simple instrument (Fig. 2) he constructed and described in Kehlberg (1863). Kehlbersg's material were widely used, not only in Russia but also in Europe particularly by Perrey (1862, 1866). Kehlberg's activity makes it possible to suggest that Russian seismology goes back to Siberia.

An important role in collecting data on earthquakes in Eastern Siberia belongs to Shchukin, a director of the Irkutsk gymnasia. The data he had collected were published as correspondences in metropolitan and regional periodical press. Besides, Shchukin regularly wrote a weather column for the "Irkutsk Governorate News" newspaper, where he published the information on felt earthquakes in weekly meteorological bulletins. A list of earthquakes felt in Irkutsk during 120 years was published by Shchukin (1862) as a supplement to the "Amur" newspaper (Irkutsk). The reason for making such a list had to do with the Tsagan earthquake that inspired interest in seismicity of Lake Baikal region. Shchukin's list of earthquake is actually the first earthquake catalogue of Siberia. The materials from this list were further used for compiling the Russian macroseismic and parametric catalogues.

2.3. Tsagan earthquake of 1862 as a milestone in the study of seismicity in Eastern Siberia

The Tsagan earthquake that occurred on January 12, 1862 may be considered as the first seismic event studied expertly by the Siberian scientific community. This earthquake resulted in subsidence of a crustal block, which gave rise to the formation of a new Baikal's bay with a surface area of more than 200 km^2 near the Selenga River delta. During 1862, the geological effects of the earthquake were studied by the members of the East-Siberian Branch of the Imperial Russian Geographical Society, with the result that the flooded area was sketched with reference to the depths of the newly formed bay (Fig. 3). This area sketch is the first experience of mapping the geological effects of an earthquake in Siberia.

The Tsagan earthquake had an important impact on the seismicity concept in Siberia. It is in fact the largest seismic event among those localized more or less precisely over the history of observations in South of Baikal region. The earthquake is considered as a reference event in publications on seismic zoning in East Siberia (Solonenko, 1968, 1977; Golenetskii, 1996a). Its magnitude ($M = 7.5$) was estimated from the available macroseismic data using regional macroseismic equation (the details are given below) (Kondorskaya and Shebalin, 1977). The $M = 7.5$ is precisely the value which determines seismic potential for seismically active structures of the Middle Baikal.

2.4. The first seismology studies

In the second half of the XIXth century, the study of earthquakes in East Siberia is associated with the name Orlov, Inspector of Gymnasia in Irkutsk, who took active interest in seismic phenomena. Orlov is the author of the first complete Russian catalogue of earthquakes published in 1872. This catalogue contains information from various sources – from Orlov's personal observations to extracts from macroseismic reports. Orlov fully exploited the data from the catalogue of Perrey (1849) and from his annual reports. The first catalogue of Orlov was geographically constrained to Siberia, Far East and in part to Middle Asia. It was characterized by rather careful reproduction of borrowed materials, most of which were textual quotations. Thereafter Orlov compiled the earthquake catalogue for the whole Russian Empire and adjacent areas. After Orlov's death in 1889, the «Earthquake Catalogue of the Russian

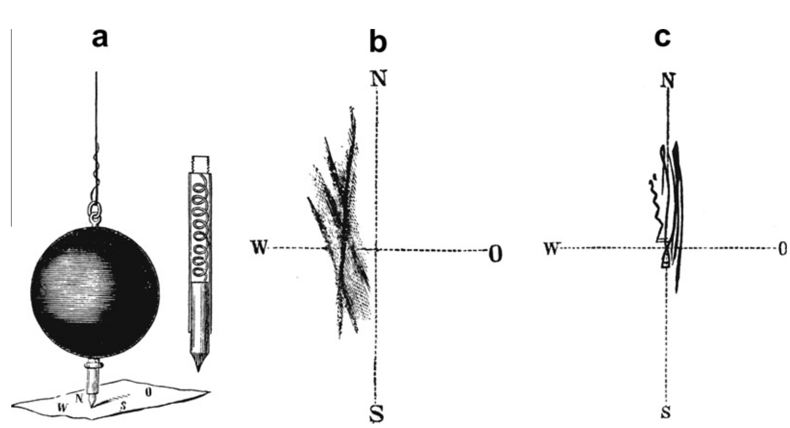

Fig. 2. Earthquake recording instrument designed by P.A. Kehlberg (a), which was installed in the Selenginsk cathedral (after Kehlberg, 1863) and some examples of "seismograms" recorded (b and c) (after Kehlberg, 1856).

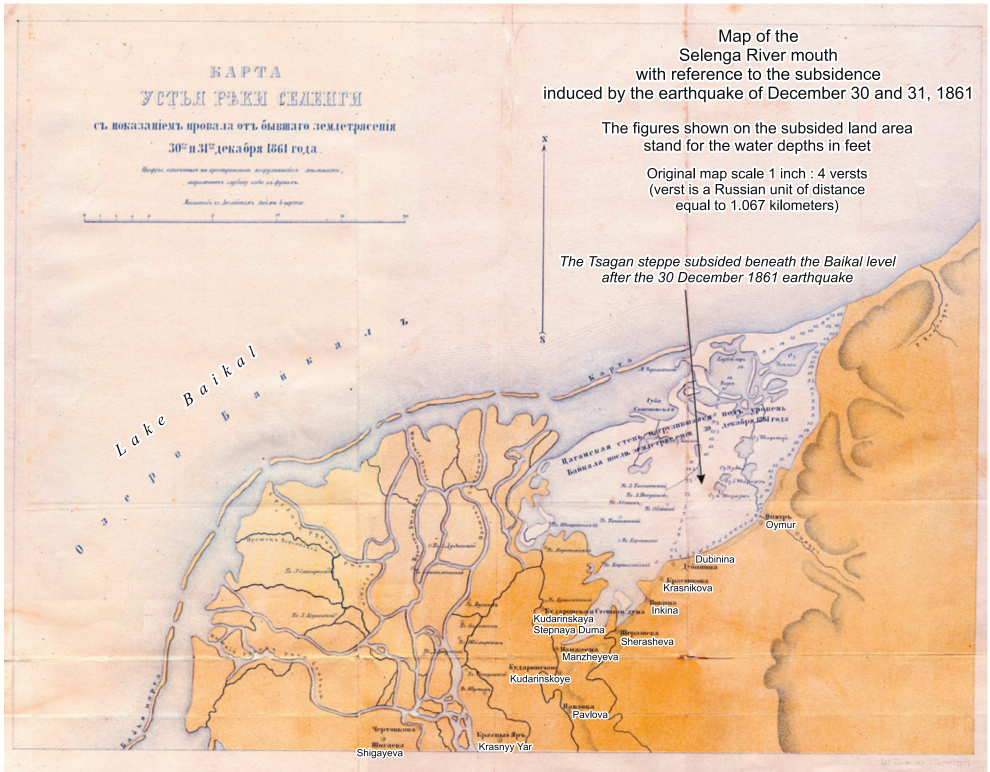

Fig. 3. The first experience in mapping the geological consequences of an earthquake in East Siberia – "Map of the Selenga River mouth with reference to the subsidence induced by the earthquake of December 30 and 31, 1861". The map was compiled by Colonel A. Ryabov during the expedition of the Russian Geographical Society in summer 1862 and published as a supplement to Orlov's catalogue (1872). The mapping materials were used later on by Golenetsky (1996) to specify the epicenter location for the catastrophic Tsagan earthquake.

Empire» was edited by Professor I.V. Mushketov, a Russian geologist, who published it in 1893.

The Irkutsk seismic station commenced operation in December 1901, in the very beginning of the XXth century. From that time on, the macroseismic data began to be collected purposefully and professionally. Voznesenskii, the station's director, distributed questionnaires widely after large earthquakes and established a network of permanent correspondents in different settlements. The macroseismic materials of that time played an important role in localizing epicentral zones of earthquakes and kept their importance up to the late fifties (Chipizubov, 2010), when a network of seismic stations was deployed in Lake Baikal Region. The first half of the XXth century defined as an early instrumental period is thoroughly considered in Golenetsky (1977).

3. Major sources of historical data

Reliability and quality of information sources are known as one of the most acute problems in historical seismicity analysis. This problem was approached differently at different times (Tatevossian and Mokrushina, 2003; Ambraseys, 1971, 2004; Ambraseys et al., 1983; and others). These authors concluded to the necessity of a thorough revision of the historical seismicity by using the primary sources. The interpretation of initial data should eliminate the occurrence and accumulation of errors that may have a pronounced effect on the result of analysis related to determining basic source parameters of a historical earthquake.

Below is a brief description of historical data sources with regard to the degree of reliability and completeness of the information presented.

3.1. Irkutsk chronicles

In spite of their considerable historical value, the early chronicles of Irkutsk (XVIIIth–early XIXth centuries) (Serebrennikov, 1911; Kulikauskene, 1996) should be considered the least reliable historical seismological sources. Note that these chronicles were published much later than they had been compiled. They were stored in the archives for a long time and became available after the publication in 1911 and 1996. The low reliability of these chronicles is related to the impossibility of verifying the chronicle information; it is not particularly clear which data were used as a basis for earthquake reports in each individual case. These might be personal impressions of chroniclers, extracts from the town archive records, verbal information obtained from other eyewitnesses, memoirs included, and so on. Even large earthquakes are often reported very briefly, without detailed description of an earthquake's effects observed. The lack of detailed macroseismic information leads to high variability in shaking intensity estimates for the town. Earthquake effects in any other settlements are reported by the chronicles very occasionally. This makes difficult to circumscribe the perceptibility of area of earthquake reported as felt at Irkutsk.

The Irkutsk chronicle compiled by Romanov (1914) and intended as a continuation of the Irkutsk chronicle of Pezhemsky and Krotov (Serebrennikov, 1911) seems to be more seismologically informative. Most of the information on earthquakes was taken by Romanov from the Irkutsk periodicals and newspapers and can thereby be verified; many earthquake reports in the chronicle follow the newspaper accounts almost textually. Owing to Romanov's chronicles, some materials, unknown until recently, became available to specialists.

3.2. Macroseismic catalogues

Two macroseismic catalogues (Orlov, 1872; Mushketov and Orlov, 1893) containing the data from a wide range of sources are traditionally used for East Siberia. The dissimilar nature of the data is well exemplified by Musketov and Orlov's "Earthquake Catalogue of the Russian Empire" (1893). The sources used to compile the catalogue differ widely in their origin and range from the authors' direct personal observations to borrowings from earlier reports including foreign ones. In some cases, it is not clear which sources used are primary and which are secondary. A similar statement is true for the logical continuation of the "Catalogue..." – "Materials for the earthquake study in Russia" (Mushketov, 1891, 1899) wherein the data for Siberia are presented very briefly and often without reference to the source. Note that the "Earthquake Catalogue of the Russian Empire" is now considered as an authoritative fundamental edition (Tatevossian, 2004; Ambraseys, 2008) and one of the major sources of data on historical earthquakes of North Eurasia.

Most problems arise when using foreign catalogues. One of the most high demand information sources is the earthquake catalogue compiled by Perrey (1849). In his introduction to the catalogue, Perrey refers to some foreign periodical and scientific special editions whose content served as the basis for his work. The information on earthquakes of the Russian Empire was surely borrowed from foreign sources wherein it might be obtained through different channels. This does not preclude misspelled geographical names, dates and time errors, omitting some of the details, or adding details that are not in accordance with the facts (in particular, exaggeration of earthquake effects). Borrowing data from the European catalogues that contain information on earthquakes of Asian Russia and using them in the Russian seismic reports of the XIXth century makes sometimes much confusion: the distortion or loss of information may be maximal.

3.3. Metropolitan and regional periodicals

The international practice shows that periodical press may be considered as one of the sources on historical earthquakes (Musson, 1986; Mäntyniemi, 2004). At least in East Siberia the periodicals were one of the major sources of information.

Before the 1850th, the information on seismicity was only published in newspapers issued in the capital and in large cities of the European part of Russia. The metropolitan press did not provide completeness of the information on earthquakes occurred because most of the correspondences published came from relatively large settlements and concern relatively large earthquakes.

In East Siberia, the first newspaper – "Irkutsk Governorate News" – only appeared in 1857. This is a lower temporal threshold when using newspaper reports as the source of data on earthquakes for East Siberia. The advent of local newspapers in the second half of the XIXth century considerably increased the amount of earthquake reports including those from remote areas of Siberia. In the periods of increased seismic activity in Eastern Siberia the earthquakes were of particular interest to newspaper editorial boards that made it possible to generate more detailed reports and extend their geographical context.

The reports from both metropolitan and regional periodical press are used in the catalogues (Orlov, 1872; Mushketov and Orlov, 1893) and contribute much to the content of the catalogues. However, the mentioned catalogues do not include all the information about seismic events recorded in Siberia. This was particularly due to Orlov's departure from Irkutsk in 1871, which did not allow him to make full use of the Irkutsk periodicals later on. Therefore, we may consider Siberian newspapers as a primary source that is far from being completely used in studies. A careful examination of documentary files (newspapers) allowed us to find new information on earthquakes located within the Siberian platform and East Transbaikalia (Radziminovich and Shchetnikov, 2008, 2009).

4. "Historical part" of parametric catalogues

4.1. Atlas of earthquakes in the USSR

In the second half of the XXth century, the parameterization of historic events was performed for the whole Soviet Union. The first parametric catalogue of earthquakes in Russia (and the former Soviet Union as a whole) is "Atlas of earthquakes in the USSR" (1962). The Atlas contains the results from instrumental observations performed by the network of seismic stations of the USSR over the period 1911–1957, summarized in its regional sections. Besides instrumentally recorded events, the regional section "Baikal region" included the parameters of the largest historical earthquakes estimated from the available macroseismic data: date, time, and approximate coordinates of epicenters. No estimates are available for the source depths and magnitudes of historical events. The Atlas has the advantage that the parametric line includes a reference list for each event catalogued: this makes the estimates transparent and provides a possibility of validating estimates. The regional section (Atlas of earthquakes in the USSR, 1962 only includes four earthquakes occurred in Baikal region prior to 1902. The spatial distribution of their epicenters assessed from the macroseismic descriptions, is shown in Fig. 4a. For one of them – the earthquake of 1814 – the figure only shows a probable location area of the epicenter instead of numerical values of the coordinates. Such a small number of historical earthquakes parameterized could be attributed to the fact that the emphasis was at that moment on instrumental observations and development of regional networks at the expense of historical data analysis.

4.2. New catalogue of strong earthquakes in the USSR (NC)

The "Atlas of earthquakes in the USSR" was chronologically followed by the "New catalog of strong earthquakes in the USSR" (Kondorskaya and Shebalin, 1977), whose English version appeared in 1982 (Kondorskaya and Shebalin, 1982). The catalogue had been compiled since 1969 and primarily pursued the applicative objectives, among them seismic hazard and risk assessment. The compilers of the catalogue emphasize its two principal features. First, the catalogue contains all historical earthquakes known from the earliest times. Second, it provides a unified format for all the earthquake data (historical and recent) with the same set of parameters (date, time, epicenter coordinates, source depth, magnitude, epicentral intensity). Intensity values are given in points of the MSK-64 scale. All basic parameters of historical earthquakes were determined from available macroseismic data using regional macroseismic equation (Kondorskaya and Shebalin, 1982):

$$I = bM - v \lg \sqrt{\Delta^2 + h^2} + c$$

where I is the earthquake intensity; M, magnitude; Δ, epicentral distance; h, focal depth; b, v, and c, coefficients, which equal 1.5, 4, and 4, respectively, for Baikal region.

The parameter estimation procedures are described in detail by the authors-compilers in the catalogue section dealing with the research technique. The most probable value is provided for each parameter with reference value error. By analogy with (Atlas of earthquakes in the USSR, 1962) all parametric lines in the catalogue are provided with a list of references used in estimating earthquake parameters.

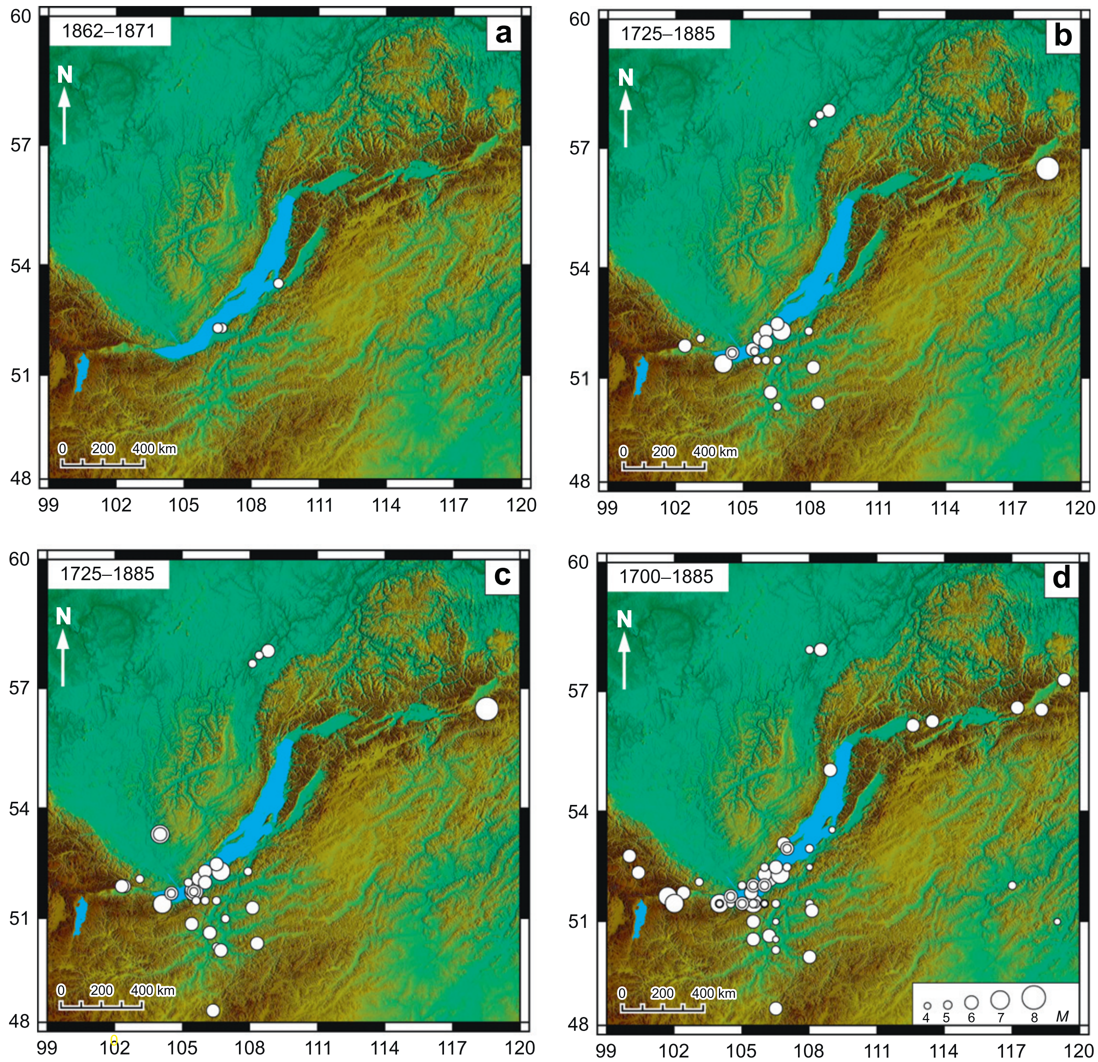

Fig. 4. Spatial distribution of the earthquakes reported in different catalogues. The events shown are only those having a complete parametric line in the catalogue. (a) "Atlas of earthquakes in the USSR" (1962). The historical earthquakes are not magnitude-ranked; the epicenters are shown using the same symbol. (b) "New catalog of strong earthquakes in the USSR from ancient times through 1977" (NC) (Kondorskaya and Shebalin, 1982). (c) "Earthquake catalogue for the former Soviet Union and borders up to 1988" (FSUCAT) (Shebalin and Leydecker, 1997). (d) Special Earthquake Catalogue of Northern Eurasia (SECNE) exists in electronic format only and is now unavailable. A series of schemes (a–d) shows distinctly the number of parameterized earthquakes increasing from early to late parametric catalogues.

The information on earthquakes in East Siberia has been summarized in the section devoted to the Baikal region. For the period prior to 1901, the catalogue reports 42 seismic events (Fig. 4b). Of this amount, 16 events cannot be characterized by a complete set of parameters because of the lack of the data for unambiguous localization and absence of precise coordinates. Instead of coordinates of the epicenter, the catalogue provides the coordinates for areas of equiprobable epicenter location for these 16 events. On the one hand, there is evidence of an abrupt increase in the number of events catalogued that positively affected the representativity of the catalogue as compared to Atlas of earthquakes in the USSR (1962). On the other hand, the NC might have contained much more parameterized earthquakes if an analysis were performed on the data for all earthquakes earlier reported in macroseismic catalogues and some additional sources (e.g. newspapers). Parameterization of some earthquakes was not carried out because of the impossibility to propose reasonable error limits for their epicenter localization. This is particularly true for the earthquakes occurred in the XVIIIth century. Besides, a magnitude threshold assigned in the NC to each region enabled the compilers to neglect small events; the threshold assigned to Baikal region is $M \geqslant 5$.

Noteworthy also are some other shortcomings of the regional section. First, the use of primary macroseismic data sources was actually limited to the analysis of only two compiled catalogues (Orlov, 1872; Mushketov and Orlov, 1893) and some later publications without independent significance. Consequently, the errors, inaccuracies and distortions in the data contained therein resulted in misinterpreting the data on some of the earthquakes. Almost no validation of the macroseismic catalogue data compiled from primary sources (newspaper reports, original publications, etc.) (Orlov, 1872; Mushketov and Orlov, 1893) has been performed for Baikal Region.

Second, there is no complete and correct information about aftershocks of large earthquakes unsystematically referred to in the "Notes" column. The magnitudes presented are approximate values without estimation error, and date and time are often unspecified. Note that as a first approximation the macroseismic data available can sometimes provide a possibility of reconstructing the aftershock process of large earthquakes. For example, having analyzed the catalogues (Orlov, 1872; Mushketov and Orlov, 1893), Golenetsky and Penzina (1995) made a parametric list of aftershocks of the Tsagan earthquake of January 12, 1862 that includes about 200 events.

Nevertheless, the NC regional section is now to be considered the most qualitative data report on historical earthquakes of East Siberia. At any rate, it was published in accordance with the transparency requirements for all data processing and primary source quotation procedures that provides a possibility of validating the results.

4.3. Earthquake catalogue for the former Soviet Union and borders up to 1988 (FSUCAT)

A new parametric catalogue named "Earthquake catalogue for the former Soviet Union and borders up to 1988" (FSUCAT) (Shebalin and Leydecker, 1997) is a direct machine-readable continuation of the NC extended to 1988 and compiled in a machine-readable format. FUSCAT includes 43 parametric earthquakes of Baikal region for the period up to 1901 (Fig. 4c). There are three fundamental distinctions between NC and FSUCAT. First, FSUCAT does not have any regional sections. The earthquake parameters are presented chronologically for the former Soviet Union with reference to the region where the earthquake occurred. Second, FSUCAT was from the outset intended to be machine-readable that required changing the parametric representation of a line as compared to NC: one line for one event instead of two. On the one hand, such format makes it possible to take all advantages of electronic data processing and on the other hand, it is sometimes incorrect in relation to the representation of final earthquake parameters (e.g., the 1742 earthquake information, see below). NC only presents probable epicenter locations for the events localized unambiguously. FSUCAT provides certain numerical values for the coordinates with reference to accuracy code. On map-based visualization of epicentral fields the epicenters of some earthquakes are found in localities other than those initially expected by the NC authors (see Section 5). Third, in FSUCAT parametric lines there are no references to the primary sources of data used to parameterize historical events. This is a direct violation of the transparency rules for inferences and evaluations though in FSUCAT introduction there is an obvious reference to the necessity of revising data and making the required corrections.

4.4. Special Earthquake Catalogue of Northern Eurasia (SECNE)

Special Earthquake Catalogue of Northern Eurasia (SECNE) under the editorship of N.V. Kondorskaya and V.I. Ulomov was compiled as part of a new map of general seismic zoning of Russia and Global Seismic Hazard Assessment Program (GSHAP) (Giardini and Basham, 1993). The catalogue only exists as Internet database. SECNE is not to be considered a direct continuation of previous parametric catalogues such as NC and FSUCAT. It was compiled using additional information that allowed revising the parameters of some earthquakes and cataloguing new events. Over the period 1700–1901, the number of parameterized events in the catalogue amounts to 69 (Fig. 4d), which is considerably larger than that in NC and FSUCAT.

The main drawback of SECNE is the lack of references to the primary sources of data used to parameterize historical events. It explains neither selection criteria nor parameterization procedures for historical earthquakes. Hence, the strings of logic that led the authors of the catalogue to any conclusions about each of the events remain unclear. In this context, it is almost impossible to validate the data.

Having analyzed the known catalogues containing the parametric data on historical earthquakes of East Siberia, we may conclude the following.

First, the increase in the number of parameterized events for East Siberia in the last catalogue versions demonstrates a research possibilities in this scope: previously unknown events can be identified and parameterized, and the parameters of earthquakes already known can be revised and corrected.

Second, the recent priority focus on machine-readable surely provides their availability and possibility for automatic processing. However, it decreases transparency of estimates for historical earthquake parameters.

Third, there is the trend toward a low-magnitude range extension for catalogued earthquakes.

5. Discussion of some examples

Historical earthquakes may sometimes give a better indication of seismic potential of an active fault than the instrumental data. This refers even more largely to estimating recurrence intervals for large earthquakes. The instrumental period is too short to let the fault go through its complete seismic cycle and realize its potential. Besides, the basic challenge is confining a historical event correctly to this or that structure, in other words, localizing it correctly.

During the last decades, a study of historical seismicity in the Baikal region supported the stereotypical belief that all large earthquakes in Baikal region have been investigated and there is nothing to add to the data already available. Among the probable reasons for the occurrence of such concepts are authoritativeness of traditionally used macroseismic catalogues and lack of attention to the entire spectrum of potential primary data sources. Hence, the parametric catalogue compilation based on the already available macroseismic data is actually regarded as unrevisable.

In view of the limitations imposed by completeness of historical data, the evolution of parametric catalogues of historical earthquakes in Baikal region has caused a number of problems hampering the use of catalogues as an application-oriented final product. The most acute problems are: (1) uncertainty in estimating parameters and (2) completeness of catalogues at least for large earthquakes. Below we consider some examples to illustrate direct consequences of existing problems.

5.1. Earthquake of 1742

The regional section of NC includes 16 events only with reference to the areas of equally possible epicenter locations without numerical values of the coordinates. Of these earthquakes, the event of June 27, 1742 is the most significant one.

Estimating parameters of this earthquake is based on macroseismic effects in the only site – in Irkutsk, where there were reports of damage to chimneys and stoves in wooden houses and severe damage to a stony church. Shaking intensity is estimated at VII–VIII on the MSK-64 scale. In Irkutsk the shakings were obviously related to remote earthquake. If it is granted that the epicenter was located within the nearest seismoactive zones, the epicentral distance to Irkutsk would be about 100 km. These assumptions, together with the regional macroseismic equation, enabled the NC authors to estimate the magnitude at $M = 7.7$ (±0.7). No coordinates were estimated for the epicenter location; instead, the location was supposed to be equiprobable within a vast area whose geometry was specified: *"Epicenter within ± 30 km of section of a circle of 185-km radius with center at 53.3°N, 104.0°E, from 102° to 106°E"*. The location of the inferred area of the epicenter is visualized in Fig. 5 in accordance with (Kondorskaya and Shebalin, 1982).

FSUCAT (Shebalin and Leydecker, 1997) presents the data on the earthquake of 1742 just in the form of the parametric line of the catalogue with reference to each parametric error. The point that is nothing more than the center of a circle describing a probable (but not only possible) location of the epicenter and thus has quite different significance in accordance with (Kondorskaya and Shebalin, 1982) was taken for the epicenter coordinates. The

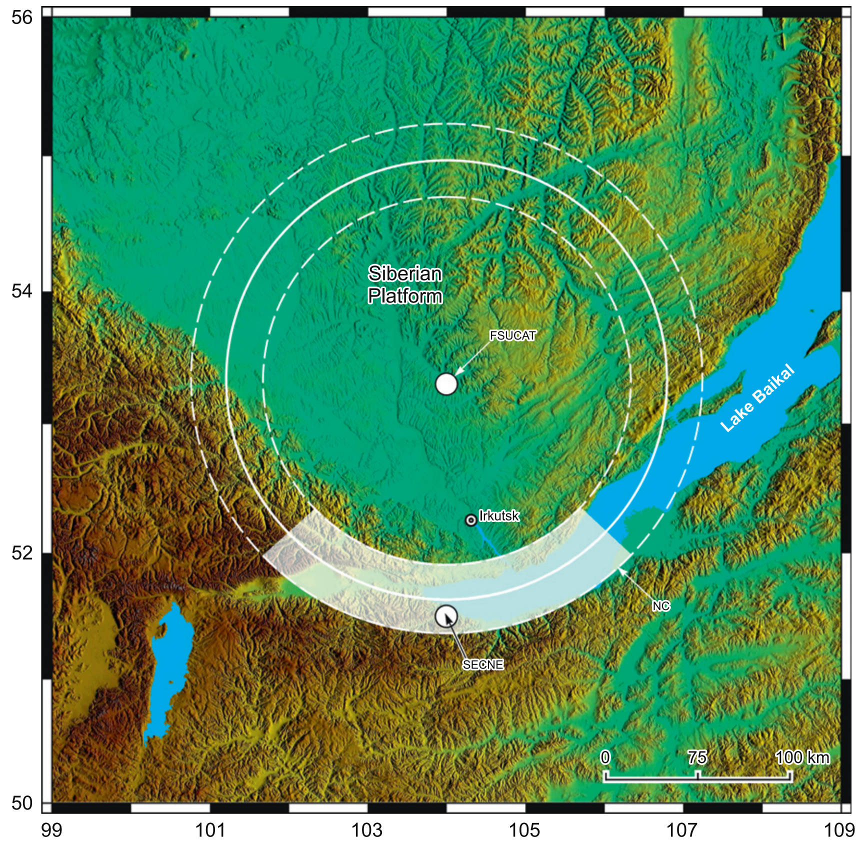

Fig. 5. Epicenter location for the June 27, 1742 earthquake ($M = 7.7$) according to the data from various parametric catalogues. NC – "New catalog of strong earthquakes in the USSR from ancient times through 1977" (Kondorskaya and Shebalin, 1982); FSUCAT – Earthquake catalogue for the former Soviet Union and borders up to 1988 (Shebalin and Leydecker, 1997); SECNE – Special Earthquake Catalogue of Northern Eurasia. Circles and half-transparent area show the epicenter localization according to NC. It is not possible to localize the epicenter precisely at the moment.

coordinates are placed with reference to accuracy code "E" corresponding to estimation error ±2°. The machine-readable format of the catalogue, as applied to electronic databases, will interpret this point precisely as an epicenter that appears to be within the stable Siberian platform, which could hardly be viewed as the location of similar-magnitude seismic event. The Siberian platform and Baikal rift have dramatically different levels of seismic activity (Seminskii and Radziminovich, 2007). An $M > 7$ earthquake is an expectable occurrence for the Baikal rift, whereas it would be a very-low probability event in the Siberian platform. Therefore, in this case there is an error made in converting the NC data into FSUCAT.

The error made in converting NC into a digital form subsequently propagated into some world databases such as Significant Worldwide Earthquakes (2150) BC – 1994 AD) compiled by USGS. Therefore, a large event with an erroneous epicenter may be included into global seismicity analysis. An example may be found in Vergnolle et al. (2007) whose authors used the USGS catalogue for visualizing the epicentral field of Central Asia. Fig. 1 of this publication shows clearly the $7 < M < 8$ earthquake epicenter located precisely at the point reported in FSUCAT. The same error is present in Fig. 2 in Mackey et al. (2010).

SECNE also provides point coordinates of the epicenter (51.5; 104.0, northern slope of the Khamar-Daban Range), though the logic of such interpretation is not clear. The SECNE authors may have related the epicenter to the Babkha paleoseismic dislocation after the suggestion earlier made in Kondorskaya and Shebalin (1982). Note that due to the insufficient knowledge on the Babkha paleoseismostructure, it was not included into the last revised lists of seismodislocations in Baikal region (Khromovskikh et al., 1993; Smekalin et al., 2010). This does not allow certain historical events to be confined to this structure prior to its dating and detailed paleoseismological studies.

The uncertainty in the location of the 1742 earthquake epicenter resulted in the fact that different researchers have unreasonably associated this event with different active faults. For example, Ivanov et al. (2010) assume the location of the epicenter at the Main Sayan fault zone. Such interpretation is generally in agreement with the probable epicenter location as reported in Kondorskaya and Shebalin (1982) but as only one of various variants. On the basis of their assumption, the authors made conclusions on regular trends in seismic regime of Southern Baikal region and predict the most probable earthquake return period for this fault (440 years). Implicitly referring to the historical data, Lunina et al. (2009) assign the 1742 earthquake epicentral area to the Gusinoozersk basin. This, however, requires much more convincing arguments because the 1742 earthquake epicenter location near Lake Gusinoe contradicts the historical data available. Besides, such statement would require revising seismotectonics and seismic hazard of West Transbaikalia.

Therefore, it should be clearly realized that the approach to this earthquake localization is *multivariate*. Having regard to the current state-of-the-art, we see little reason for confining the 1742 earthquake to a certain seismically active structure.

5.2. Earthquake of 1814

Distortions of the epicenter localization may be due to not only the lack of the macroseismic data but also to some long-standing concepts of seismic activity on these or those faults. We consider a similar situation by the example of the Baikal–Mondy fault and historical earthquake of 1814 with discussion of localization.

The earthquake that occurred on August 22 according to the Julian calendar (September 2 according to the Gregorian calendar) is one of the largest events confined to the Tunka system of basins (southwestern flank of the Baikasl rift zone). According to the parameters reported in NC (Kondorskaya and Shebalin, 1982), the earthquake epicenter is confined to the northern side of the Tunka basin exhibiting the trace of the large Tunka fault (Fig. 6). The magnitude is estimated at $M = 6.4(\pm 0.7)$. The epicenter coordinates were derived using available macroseismic data expressed in shaking intensity units on the MSK-64 scale. However, the publication (Orlov, 1872) contains a description of earthquake effects in terms of geological hazards, or environmental effects in accordance with the Environmental Seismic Intensity (ESI 2007) scale (Michetti et al., 2007). This is a relatively new scale that allows the use of earthquake effects in the environment to assess the shaking intensity, particularly for the epicentral area of historical earthquakes (Papanikolaou, 2011). To date the scale was tested on some earthquakes worldwide (Papanikolaou et al., 2009; Mosquera-Machado et al., 2009; Tatevossian et al., 2009; Lekkas, 2010), including one earthquake in Baikal region (Berzhinskii et al., 2010). The phenomena of soil liquefaction and "pumping" that occurred near the village of Shimki suggest that the epicenter was located in its immediate vicinity. Besides, the catalogue (Orlov, 1872) reports an unambiguously large-scale damage to chimneys and stoves in Shimki that also implies a small epicentral distance to this village.

Nevertheless, the epicenter was confined to the northern side of the basin, not to its central part where the village of Shimki is located. We suppose that such epicenter localization was due to the long-standing traditional concept considering the Tunka fault as a major seismoactive structure responsible for large earthquakes within the Tunka system of basins, which is why the epicenter was confined to the nearest fault considered active. However, the studies conducted over the last 20–25 years allowed the recognition of another active structure within the Tunka basins. The latitudinal fault extending about 500 km is traced through the system of basins along the Khamar-Daban Range piedmont to Lake Baikal (Loukina, 1989). This fault named either Baikal–Mondy (Loukina, 1989; Arjannikova et al., 2004) or South Tunka (Lunina and Gladkov, 2004) is located just near the village of Shimki and other settlements of the Tunka system of basins. The September 2, 1814 earthquake epicenter is most likely to be confined to this fault. It is precisely this interpretation that is presented in Loukina (1989) though it was made intuitively rather than through detailed analysis of the initial data.

Two other large earthquakes with nearby epicenters at the westernmost segment of the Tunka system of basins may also be confined to the Baikal–Mondy fault. These are Mondy earthquake of April 4, 1950 ($M = 7.0$, $Mw = 6.9$) (Treskov and Florensov, 1952; Delouis et al., 2002) and the earthquake of March 7, 1829 ($M_{LH} \sim 7.0$) (Golenetskii, 1996b; Radziminovich and Shchetnikov, 2005). The occurrence of three large earthquakes during 150 years implies that the Baikal–Mondy and Tunka faults are equally important seismogenerating structures. This in turn led us to give more attention to seismic hazard assessment for the settlements therein using all historical data available.

5.3. Earthquake of 1859

Some recent efforts in the investigation of historical seismicity in Eastern Siberia refute stereotypical belief that strong earthquakes are studied in detail. We consider the situation by the example of March 3 (February 19 O.S.), 1859 earthquake.

This seismic event was first emphasized by Chipizubov who analyzed the primary data and determined its basic parameters (Chipizubov, 1988, 2010). This earthquake provides reason enough to be parameterized as well as other large earthquakes of Baikal region in the XIXth century, though it has not been included in any of the official parametric catalogues thus far (Chipizubov, 2010). This question requires independent investigation.

The information on the March 3, 1859 earthquake is included only in the catalogue data (Orlov, 1872; Mushketov and Orlov, 1893) describing briefly the effects in Irkutsk that correspond to IV–V on the MSK-64 scale. The data source was referred to as Shchukin's report published in the supplement to the "Amur" newspaper in 1862. Shchukin's report may be considered as the primary data source.

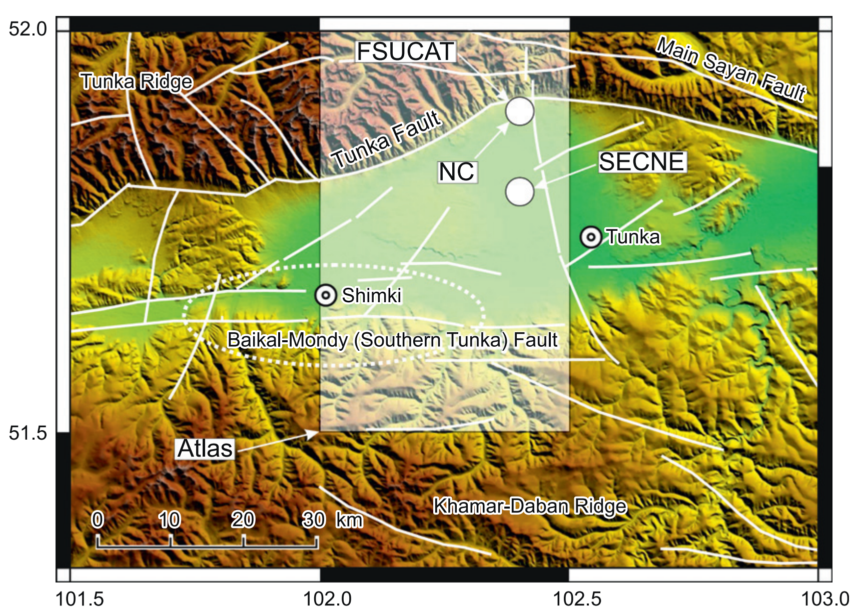

Fig. 6. Epicenter location for the September 2, 1814 earthquake ($M = 6.4$) according to the data from various parametric catalogues. Atlas – Atlas of earthquakes in the USSR (1962); NC – "New catalog of strong earthquakes in the USSR from ancient times through 1977" (Kondorskaya and Shebalin, 1982); FSUCAT – Earthquake catalogue for the former Soviet Union and borders up to 1988 (Shebalin and Leydecker, 1997); SECNE – Special Earthquake Catalogue of Northern Eurasia. A half-transparent rectangle shows a probable epicenter location area according to Atlas of earthquakes in the USSR (1962). White lines indicate the faults after (Lunina and Gladkov, 2004), with simplifications. A dashed ellipse shows the most probable epicenter location area with regard to environmental impact of earthquake. Ground-surface fracturing and liquefaction observed therein may be considered as distinctive features of the epicentral area.

The secondary data source is a review paper of Solonenko (1950) who cited the data on a large earthquake in the Batagol graphite mine that belonged to merchant Jean-Pierre Alibert. Considering the data on damage caused to the chimneys and stoves, shaking intensity occurred therein may be estimated at VII on the MSK-64 scale. The publication (Solonenko, 1950) does not contain reference to any data source except for the earthquake description in Alibert's diary. Therefore, Solonenko's paper can only be considered as a secondary data source.

The data from Mushketov and Orlov (1893) and Solonenko (1950) were never compared over the next 40 years until Chipizubov paid his attention to this situation in 1988, having characterized the earthquake as "forgotten". According to his estimate, the earthquake magnitude was as high as $M \sim 6.5$–7.0, and the epicenter was located in southwest Cis-Baikal region (Chipizubov, 1988, 2010).

The data source in Solonenko (1950) remains unclear. The most likely version would be as follows: the supplement to Carl Ritter's "Asian Earth Sciences" Russian Edition (1894) contains a review of the latest studies on Baikal region among which there is a brief description of the trip made by Gustav Radde, a naturalist, who visited the graphite mine of Alibert in 1859. The merit of Gustav Radde lies in his publications of materials from the meteorological observations diary with particular reference to three earthquakes including the event of March 3, 1859. The description is as follows: *"On February 19, 1859, at 3.25 a.m. there was a SE–NW trending earthquake lasted 30 s and reached an intensity that caused damage to chimneys and stoves"* (Ritter, 1894). It is obvious that Solonenko borrowed the data from (Ritter, 1894) but did not refer to the source for some unknown reason.

Therefore, the historical earthquake of March 3, 1859 might have been studied much earlier, but the reason wherefore it has not been studied is now apparent. NC was mainly compiled from the catalogue (Mushketov and Orlov, 1893) whereas alternative, additional sources were almost unused. The data on the effects in Aliber's mine from the original publication of G. Radde were not catalogued in Mushketov and Orlov (1893), and NC compiling might give the impression that the earthquake data are only available for Irkutsk. However, it is strange that the materials from (Solonenko, 1950) were unclaimed in spite of the fact that this article is cited in the NC reference list.

6. Plans for future

Analysis of the problems existing in historical seismicity of East Siberia allows us to make conclusion about a long-felt need for improving the historical earthquake catalogue, which may comprise three main areas of activity.

(1) Extending the geographical context of the investigations. Most of the previous research efforts were concentrated on the high-activity rift zone whereas seismicity in the adjacent areas of Siberian platform and Transbaikalia was almost entirely unconsidered in its historical context. As a result, only a small part of the earthquakes recorded was catalogued in existing regional catalogues. This was also due to traditional assumptions about low-level seismic activity in the areas lying beyond the rift. For example, although on NC compilation the regional section included three parametric lines for earthquakes epicentered in the marginal part of the platform, the concept of large platform earthquake reality alone was rather sharply criticized later on Solonenko and Mandelbaum (1985). Nonetheless, the earthquake with $M = 4.1$, which occurred in February 26, 1996 in the southern Siberian platform (Golenetskii, 1998), has encouraged a subsequent interest in the historical data. Finally, a number of previously unknown or "forgotten" earthquakes were recognized, with the epicenters to be localized within the platform (Chipizubov, 1997, 2010; Golenetskii, 1999; Radziminovich and Shchetnikov, 2008). A similar statement is true for Transbaikalia (Chipizubov, 2010; Radziminovich and Shchetnikov, 2009). Therefore, new historical events may be found even in low-activity areas of East Siberia that allows extending territorial coverage of the catalogue.

(2) Low-magnitude range extension for the earthquakes catalogued. In NC compilation, many events were omitted because they did not satisfy the magnitude threshold ($M \geqslant 5$) for the Baikal region. Large amounts of materials from macroseismic catalogues of the XIXth century remained almost entirely unused and, therefore, there is a potential for parameterization and cataloguing of earthquakes with magnitudes from 4 and higher, though the magnitude threshold may sometimes be lower than 4. It is certainly not a final solution for the representativity problem of the catalogue (a historical earthquake catalogue is inherently incomplete), and yet it may provide the possibility of introducing additional information. The low-magnitude earthquake data are of particular importance for tectonically low active, stable areas that are often characterized by rather high population density and a large number of industrial facilities.

(3) Extending the range of potential data sources. As discussed above, most of the estimates for the main parameters of historical earthquakes are based on the data represented in two macroseismic catalogues of the XIXth century (Orlov, 1872; Mushketov and Orlov, 1893), whose limitations inevitably influenced the precision of parameter estimate and completeness of parametric catalogues as a whole. Nevertheless, there are a number of sources that were incompletely used or completely ignored. For example, the use of periodicals, containing a significant part of the total amount of macroseismic data for the historical period, is far from being complete. Important information is contained in published memoirs, diaries and correspondences of the persons lived in the XVIII–XIXth centuries in East Siberia. Such materials can sometimes be a determinative argument in favor of a certain historical earthquake. A similar situation is shown in the article by Kozyreva and Sidorin (2009) who supplemented the data on the large earthquake of March 8, 1829 with the information content of the letters belonging to private correspondence of Decembrist Muravyov and provided support for our earlier conclusions about this event (Radziminovich and Shchetnikov, 2005). Another important potential resource is represented by documents available in regional and metropolitan archives. So far, no search was actually made for historical information about past earthquakes in East Siberia, though there is a good opportunity to find some additional important data on this problem.

It is apparent that the way of representing information in historical earthquake catalogue should be revised. In other words, we must understand clearly what kind of information will be catalogued. The parametric catalogues traditionally contain only numerical values, more or less completely characterizing a seismic event. The precision of estimating parameters for historical events depends directly on completeness and quality of the primary macroseismic data that are often disseminated among multiple sources of different origin, completeness and availability. The earthquake catalogue is certainly perceived as an unquestionable result for the seismological data processing, though its end-user may sometimes entertain doubts about the adequacy of interpretation of the initial macroseismic data and hence about the catalogue quality. It follows that there is a necessity to study the primary data that is by no means always possible. A direct reference to primary sources solves the problem only partially, because many materials that were used for cataloguing several decades ago become less available with time. Some sources may forever be lost for various reasons.

It is possible to obtain an optimal solution to the problem by supplementing the parametric catalogues with a descriptive part containing a literal reproduction of the original text and distinct logical schemes of data interpretation. Such case study approach may provide a complete transparency of estimates and, finally, a possibility of obtaining more reliable and verifiable results. As an example, we refer to a brief reproduction of the primary data on some large earthquakes in the parametric "New catalog..." (Kondorskaya and Shebalin, 1982). Another example can be found in Chipizubov (2010) that is a generalization of all parametric data now available for historical earthquakes, including those revised and supplemented. This publication also presents the initial data and logic of their interpretation, but unfortunately not for all the catalogued events. Therefore, the first steps have been already made toward solving the problem. Note that such problem solution by no means should be considered coming back to an old practice of compiling descriptive macroseismic catalogues. The main objective is to make and develop combined catalogues of historical earthquakes. This seems extremely important for East Siberia whose initial historical database is rather poor.

7. Conclusions

The state-of-the-art in the study of historical seismicity in East Siberia may be judged by quality of the "historical part" of a parametric earthquake catalogue. As discussed above, the regional section of "New catalogue..." (Kondorskaya and Shebalin, 1982) should be considered most appropriate regarding observation of transparency practices in making estimates. Nevertheless, we emphasize that this section was compiled using primarily two macroseismic catalogues of the XIXth century (Orlov, 1872; Mushketov and Orlov, 1893). Consequently, the quality of parameter estimation for historical events in NC depends largely on the quality of the macroseismic data representation in the compilation reports mentioned.

The efforts made by Orlov and Mushketov in generalizing and cataloguing the historical earthquake data are surely an important basis for further investigations of the past earthquakes in East Siberia, though the use of compilation catalogues, traditionally considered authoritative, gave an erroneous impression of knowing the problem. In case of East Siberia, the "authoritativeness" of compilation catalogues actually overweighed the reliability of real primary sources. The data of the catalogues (Orlov, 1872; Mushketov and Orlov, 1893) were considered final and unrevisable during interpretation that resulted in occurrence of errors or uncertainties in parametric catalogues.

The accumulation of errors in regional parametric catalogues may have impact on the data of global parametric catalogues. A transfer of erroneously determined parameters from regional to global catalogue may be exemplified by the 1742 earthquake in East Siberia. The epicenter of this large earthquake incorrectly reported in the Significant Worldwide Earthquakes was reproduced in two publications on seismicity of Central Asia. Such errors are to be found and corrected.

Eventually, we see the necessity of a large-scale revising the historical part (to 1901) of the parametric earthquake catalogues for East Siberia. The starting point may be addressing the maximum possible range of the primary data source to supplement or specify the data on macroseismic effects of historical earthquakes. The next steps should include (1) database compilation including initial descriptions of macroseismic effects with reference to their place and time of occurrence; (2) parameterization of the maximum possible (magnitude-unlimited) number of historical earthquakes on the basis of all the available data; (3) compilation of an improved version of the parametric historical earthquake catalogue for East Siberia with detailed consideration of each event. These tasks may be considered first priorities in the nearest future.

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