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Focus paper

Southern East Siberia Pliocene–Quaternary faults: Database, analysis and inference

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ABSTRACT

This paper presents the first release of an Informational System (IS) devoted to the systematic collection of all available data relating to Pliocene–Quaternary faults in southern East Siberia, their critical analysis and their seismotectonic parameterization. The final goal of this project is to form a new base for improving the assessment of seismic hazard and other natural processes associated with crustal deformation. The presented IS has been exploited to create a relational database of active and conditionally active faults in southern East Siberia (between 100°–114° E and 50°–57° N) whose central sector is characterized by the highly seismic Baikal rift zone. The information within the database for each fault segment is organized as distinct but intercorrelated sections (tables, texts and pictures, etc.) and can be easily visualized as HTML pages in offline browsing. The preliminary version of the database distributed free on disk already highlights the general fault pattern showing that the Holocene and historical activity is quite uniform and dominated by NE–SW and nearly E–W trending faults; the former with a prevailing dip-slip normal kinematics, while the latter structures are left-lateral strike-slip and oblique-slip (with different proportion of left-lateral and normal fault slip components). These faults are mainly concentrated along the borders of the rift basins and are the main sources of moderate-to-strong ($M \geq 5.5$) earthquakes on the southern sectors of East Siberia in recent times. As a whole, based on analyzing the diverse fault kinematics and their variable spatial distribution with respect to the overall pattern of the tectonic structures formed and/or activated during the late Pliocene–Quaternary, we conclude they were generated under a regional stress field mainly characterized by a relatively uniform NW–SE tension, but strongly influenced by the irregular hard boundary of the old Siberian craton. The obtained inferences are in an agreement with the existing models of the development of the Baikal region.

1. Introduction

The study of Pliocene–Quaternary faults is crucial for a better assessment of the seismic hazard and other natural processes associated with crustal deformation. Moreover, a better knowledge about faults promotes the development of geodynamic conceptions on the general formation mechanisms and the evolution of specific structural elements in mobile belts. In order to effectively use this knowledge, specific databases containing active or conditionally active faults have been created in several countries (Valensise and Pantosti, 2001; GNS Science Ltd, 2004; U.S.G.S, 2006; A.I.S.T, 2007; Basili et al., 2008, 2009, 2013; Caputo et al., 2012, 2013; Yu et al., 2012). In Russia, the first experience devoted to the elaboration of a digital map and a database of active faults was carried out by Ioffe et al. (1993), Trifonov and Machette (1993), Ioffe and Kozhurin (1996), Trifonov (1997, 2004), Trifonov et al. (2002).

It is worth to note that an active fault is defined as one which has moved in recent geological time and is considered likely to move again in the future (GNS Science Ltd, 2004). Although there are different opinion on the definition of "recent geological time" (Allen, 1975; Vita-Finzi, 1986; Nikonov, 1995; Trifonov, 2004), we believe it is corresponding to the Quaternary period followed by the

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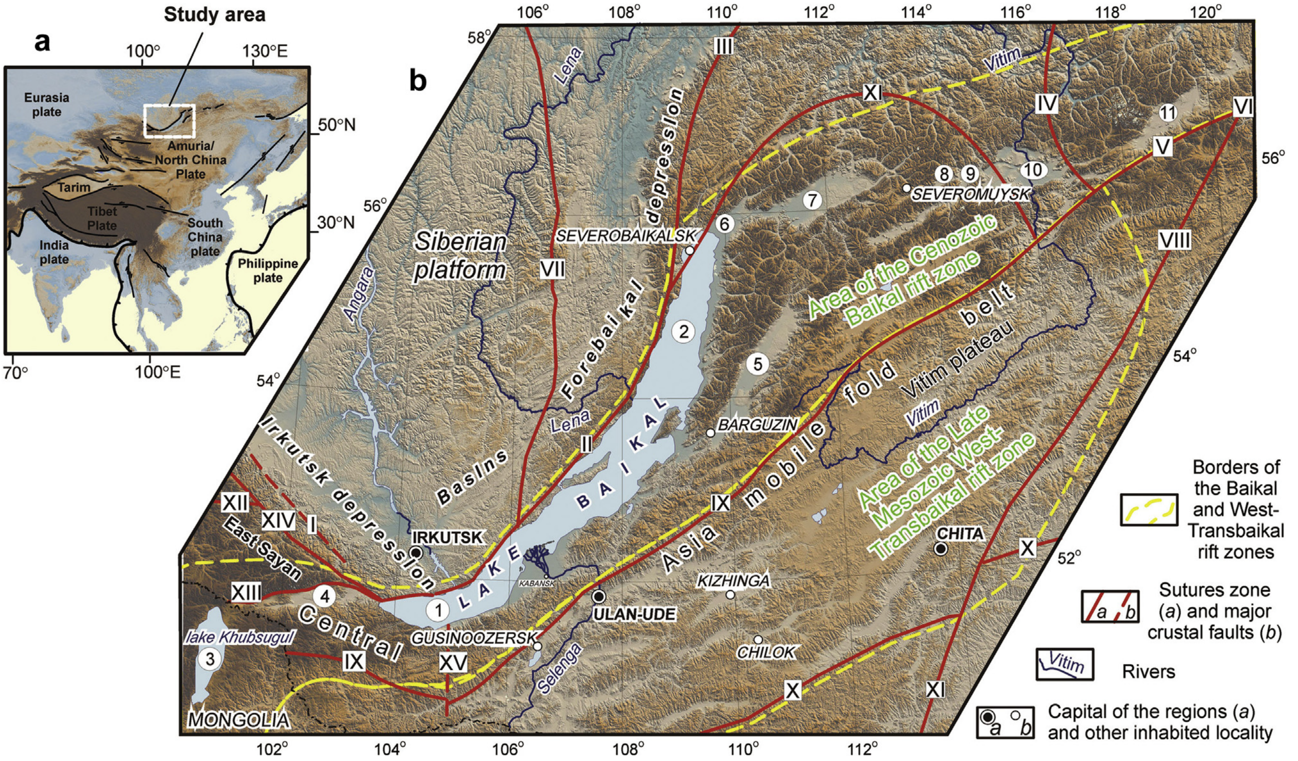


Figure 1. Topography and principal tectonic elements of the Asia (**a** – faults after Petit and Deverchere, 2006) and southern sector of East Siberia (**b** – faults after Khrenov, 1982). Roman numbers refer to the segments of marginal suture zones of the Siberian platform (I: Main Sayan, II: Pribaikalsky, III: Akitkan-Dzherbin, IV: Zhuin, V: Kalar, VI: Stanovoy), other structural sutures (VII: Baikal-Taymyr, VIII: Kalarsk-Karengsky, IX: Dzhida-Vitim, X: Mongol-Okhotsk, XI: Baikal-Muya, XII: Sayan-Tuva, XIII: Tunkinsko-Khamar-Daban) and major crustal faults (XIV: Prisayan-Enisey, XV: Torey). Numbers in circle refer to the major basins within the Baikal rift zone (1: South Baikal, 2: North Baikal, 3: Khubsugul, 4: Tunka, 5: Barguzin, 6: Kichera, 7: Upper Angara, 8: Muyakan, 9: Ulan-Makit, 10: Muya, 11: Chara).

Research Group for Active Faults of Japan (1992). Some Quaternary faults with an obscure displacement history and pre-Quaternary faults which can reasonably have attributes consistent with the current tectonic regime refer to conditionally active faults (Fraser, 2001).

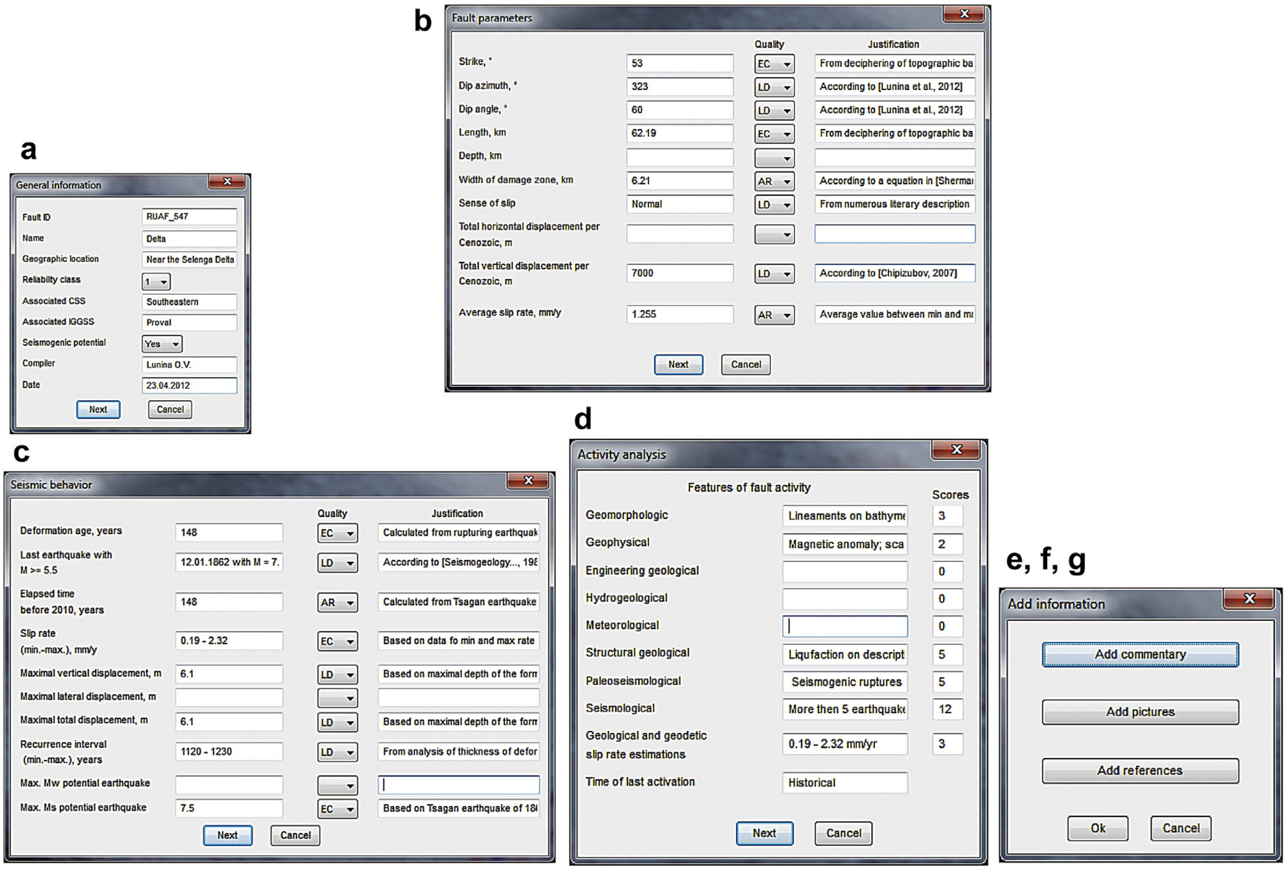
According to a nowadays well established approach to seismic hazard assessment (SHA), mainly based on the construction of specific databases, the collection of geological information, its critical analysis and the intercorrelation of all data by means of a dedicated software have become a standard (Haller and Basili, 2011). Indeed, SHA analyses are impelling especially in densely inhabited zones like the southern sector of East Siberia, whose central part is characterized by the highly seismic Baikal rift zone. A huge amount of geological and geophysical data on Pliocene–Quaternary faults and recent earthquakes, which represent the core information for seismotectonic and geodynamic analyses, has been collected in the past years by many researchers (Sherman et al., 1973, 2004; Solonenko, 1981; Khrenov, 1982; Solonenko et al., 1985; McCalpin and Khromovskikh, 1995; Levi et al., 1996, 1997; Delouis et al., 2002; Lunina and Gladkov, 2002, 2004, 2007, 2008; Lunina et al., 2009; Smekalin et al., 2010; references therein). However, the problem for their representation as well as for a systematic analysis was not solved. A relational database allowing to keep the information in several sections intercorrelated with field data, keywords or identifiers could certainly represent a step forward. Eventually a relational database gives the possibility of a simple and quick access using structured query language (SQL) reports and provides an increased reliability and integrity of data whose analysis could allow to get new results.

The aim of this paper is to present the first version of an Informational System devoted to the systematic collection of all available data relative to Pliocene–Quaternary faults, their critical analysis and their seismotectonic parameterization of the included structures. The IS has been exploited to create a first regional database of neotectonic faults in southern East Siberia and therefore includes both active (late Quaternary, 10 ka, 130 ka, 0.5–2 Ma by different authors) and conditionally active (up to late Pliocene) faults. This IS represents the first such attempt for the whole Russia and it could represent an important scientific tool for many researchers as well as for improving seismic hazard maps of the region.

2. Geological background

The southern sector of East Siberia includes two large structural elements: the Siberian platform and the central Asia mobile foldbelt containing both Caledonian and Baikalian folding and thrusting phases (Solonenko, 1981; Belichenko et al., 2003). In this region, the West-Transbaikal and Baikal rift zones (Fig. 1) formed during the late Mesozoic and Cenozoic, respectively. This polyphased crustal deformation is the principal cause of the complex and quite heterogenous geological setting of southern East Siberia, which includes pre-Cambrian, Paleozoic, Mesozoic and Cenozoic rocks from different geodynamic environments and undergoing different deformational events (Malich, 1999).

The late Mesozoic West-Transbaikal rift zone (Yarmoluk et al., 1995) consists of NE–SW trending basins bounded by normal faults and controlling the volcanic fields during the late Mesozoic and Cenozoic. The general extent of the zone from the head of the Selenga River to the Vitim plateau is ca. 1000 km while its width is 200 km. The first grabens started forming at the end of the early Jurassic, but the main rifting stage occurred 130–140 Ma. At



Fault ID	RUAF_547
Name	Delta
Geographic location	Near the Selenga Delta
Reliability class	1
Associated CSS	Southeastern
Associated IGGSS	Proval
Seismogenic potential	Yes
Compiler	Lunina O.V.
Date	23.04.2012

		Quality	Justification
Strike, °	53	EC	From deciphering of topographic ba
Dip azimuth, °	323	LD	According to [Lunina et al., 2012]
Dip angle, °	60	LD	According to [Lunina et al., 2012]
Length, km	62.19	EC	From deciphering of topographic ba
Depth, km			
Width of damage zone, km	6.21	AR	According to a equation in [Shermaı
Sense of slip	Normal	LD	From numerous literary description
Total horizontal displacement per Cenozoic, m			
Total vertical displacement per Cenozoic, m	7000	LD	According to [Chipizubov, 2007]
Average slip rate, mm/y	1.255	AR	Average value between min and mı

		Quality	Justification
Deformation age, years	148	EC	Calculated from rupturing earthquak
Last earthquake with M >= 5.5	12.01.1862 with M = 7.	LD	According to [Seismogeology..., 198
Elapsed time before 2010, years	148	AR	Calculated from Tsagan earthquake
Slip rate (min.-max.), mm/y	0.19 - 2.32	EC	Based on data fo min and max rate
Maximal vertical displacement, m	6.1	LD	Based on maximal depth of the forn
Maximal lateral displacement, m			
Maximal total displacement, m	6.1	LD	Based on maximal depth of the forn
Recurrence interval (min.-max.), years	1120 - 1230	LD	From analysis of thickness of defor
Max. Mw potential earthquake			
Max. Ms potential earthquake	7.5	EC	Based on Tsagan earthquake of 18

	Features of fault activity	Scores
Geomorphologic	Lineaments on bathyme	3
Geophysical	Magnetic anomaly; sca	2
Engineering geological		0
Hydrogeological		0
Meteorological		0
Structural geological	Liqufaction on descript	5
Paleoseismological	Seismogenic ruptures	5
Seismological	More then 5 earthquake	12
Geological and geodetic slip rate estimations	0.19 - 2.32 mm/yr	3
Time of last activation	Historical	

Figure 2. Input information in the active fault database (for Delta Fault, see location in Fig. 9). Letters indicate its seven sections.

present, the area is characterized by a weak seismic activity; however, in historical times some moderate earthquakes are documented (Radziminovich, 2007; Radziminovich and Shchetnikov, 2010).

The Baikal rift zone is geographically adjoined to the West-Transbaikal zone (Fig. 1) and located along a 2200 km-long curved belt. A rough morphology, Neogene–Quaternary volcanism along the flanks of the rift zone, several geophysical anomalies and almost ubiquitous thinning of the Earth's crust are general features characterizing the Baikal rift (Solonenko, 1981), similar to other rift basins worldwide (Logatchev and Florensov, 1978). Minimum Moho depth, encountered over the central Baikal, is 32 ± 5 km (Petit and Deverchere, 2006) in striking contrast with the thicker Siberian Platform (ca. 40–43 km; Pavlenkova et al., 2002) and central Asia mobile fold-belt (ca. 45–50 km; Petit and Deverchere, 2006), northwest and southeast respectively.

The basin subsidence within the Baikal rift started in the southern sector near the delta of the Selenga River at the end of the K–T boundary (Logatchev, 2003; Lunina et al., 2009; Jolivet et al., 2009; Mats and Perepelova, 2011) and it still continues. Recent and historical earthquakes with magnitude $M > 7$ and evidence of strong palaeoevents are known in the broader zone (Solonenko, 1981; Solonenko et al., 1985; Ruzhich, 1997; Smekalin et al., 2010).

The southern sector of the Siberian platform (Fig. 1) bordering on the Baikal rift zone from the west consists of a crystalline basement and a sedimentary cover, where the volumetric distribution of both detachments and sub-vertical faults affecting lithological units played a basic role in the evolution of the area (Gladkov et al., 2000). To the southwest, the platform is bordered by the Main Sayan left-lateral strike-slip (with some reverse component) crustal shear zone (Chipizubov and Smekalin, 1999; Malich, 1999; Lunina and Gladkov, 2002). Evidence of morphotectonic lineaments and earthquake distribution within this area suggest that the southern part of the craton is still undergoing some convergence along the Sayan-Baikal segment of the central Asia mobile fold belt (Seminsky et al., 2008).

3. Rationale of the database

Whereas the major rifting activity within the Baikal region accelerated in the last ca. 3–5 Ma according to various estimates (Logatchev, 2003; Lunina et al., 2009; Mats and Perepelova, 2011), we decided to include in the database all tectonic structures whose movements are documented or suspect for the Pliocene–Quaternary period after the last noticeable compressional stage (ibid). In fact, it is important for estimating natural hazards because an earthquake on an active fault creates seismogravitational phenomena, liquefaction cases and etc. while the location and geometry of surrounding neotectonic faults affect their distribution in the pleistoseist area.

The conception and general scheme of the proposed IS were approached similar to countries which already faced the problem of seismic and geodynamic hazard estimations, a geologically-based seismic zonation and the creation of specific databases (Solonenko, 1981; Wesnousky et al., 1984; Matsuda, 1990; Reiter, 1990; Levi et al., 1996; Ulomov and Shumilina, 1999; Valensise and Pantosti, 2001; Trifonov et al., 2002; Koravos et al., 2006; Basili et al., 2008, 2009; Petersen et al., 2008; Caputo et al., 2012, 2013; Stirling et al., 2012; Basili et al., 2013; GEM, 2013) and recently published (Lunina et al., 2012).

The relational database of the Pliocene–Quaternary faults of southern East Siberia presented in this paper focuses on an area included between 100°–114° E and 50°–57° N (Fig. 1). It was built based on morphotectonic analysis of SRTM-90 digital elevation models and topographic maps at 1:200,000 scale, field structural and geological data as well as the collection and critical analysis of all available geological and geophysical information relative to neotectonic structures. A significant part of our data on structural mapping was published previously (Lunina and Gladkov, 2002, 2004, 2007, 2008; Lunina et al., 2009; references therein). Based on this systematic approach, the included structures have been primarily distinguished between 'seismogenic' and 'non-seismogenic' faults. In principle all faults within the uppermost brittle crust produce earthquakes and hence should be considered seismogenic; however, for the sake of simplicity and for the aims of seismic hazard assessment, we distinguish a class of 'non-seismogenic' faults including structures not capable of generating events with $M_{\max} \geq 5.5$. The recognition and characterization of the latter structures, and hence their inclusion into the database, are also important steps for better evaluating the geohazard of the region, because even small and/or slow movements on such structures may lead to emergency situations at industrial facilities located in aseismic and low-seismic areas (Kuz'min and Zhukov, 2004; Schenk et al., 2007).

4. Database structure and software

The software for operating the IS of database has been elaborated by authors of the present paper in the Institute of the Earth's Crust, Siberian Branch of Russian Academy of Sciences that is confirmed by a certificate (Lunina and Gladkov, 2013). It works in the MapInfo environment and it exploits its GIS software package. For each identified tectonic structure, the information is distributed in seven principal sections whose user interfaces are represented by different windows (Fig. 2). The first and second sections (Fig. 2a,b) contain the general fault information and the principal geometric, kinematic and seismotectonic parameters. The third section (Fig. 2c) includes data relative to the seismic behavior.

The fourth section (Fig. 2d) includes nine groups of direct and indirect fault activity features, like geomorphic (linear and areal morphological expression), geophysical (local release of radon or other geophysical anomalies), geo-engineering (occurrence of large land-slides), hydrogeological (aligned hot-springs, anomalies of piezometric and chemical changes), meteorological (periodic linear clouds along faults), structural (fractures in Pliocene–Quaternary sediments and seismites), paleoseismic (fresh and prominent fault scarps), seismological (number and magnitude of instrumental events) and geological and geodetic slip rate estimation. Different scores have been assigned to each feature, following the procedure proposed by Lunina (2010). The sum of all scores associated with a specific fault enables to quantify the activity index and the software calculates it automatically (Fig. 3). According to the total score, the index of fault activity is classified as low (1–5), medium (6–10), relatively high (11–20), high (21–30) or very high (more than 30). Faults in the database are also classified based on the timing of their last activity and they are consequently grouped in Pliocene, Pleistocene, Holocene and historical ones (Table 1).

Table 1
Features of fault activity to distinguish the time periods.

Timing of last activity	Fault activity features
Pliocene	Scarps; linear valleys; deformations of valleys; deformation of Pliocene sediments (including fractured, crushed and schistosity zones, fractures with displacements, seismites, striations and impacts on pebbles, clastic dykes).
Pleistocene	Open gashes in surface topography; deformation of benches; palaeoseismic deformation of Pleistocene sediments.
Holocene	Palaeoseismic deformation of Holocene sediments.
Historical (since 1700 to present-day, according to first known seismic event occurred in the East Siberia)	Fault associated with a historical or instrumental earthquake with $M \geq 5.5$; movements established by geodetic methods; seismogenic or creep deformations of old and recent buildings as well as sediments within the fault damage zone.

Detail description of the above input information is given in Appendix A.

The fifth section (Fig. 2e) could contain all possible comments added by the compiler(s) relative to specific choices on the parameters, annotations of used publications, summaries of the results from the selected papers, speculative matters and open problems.

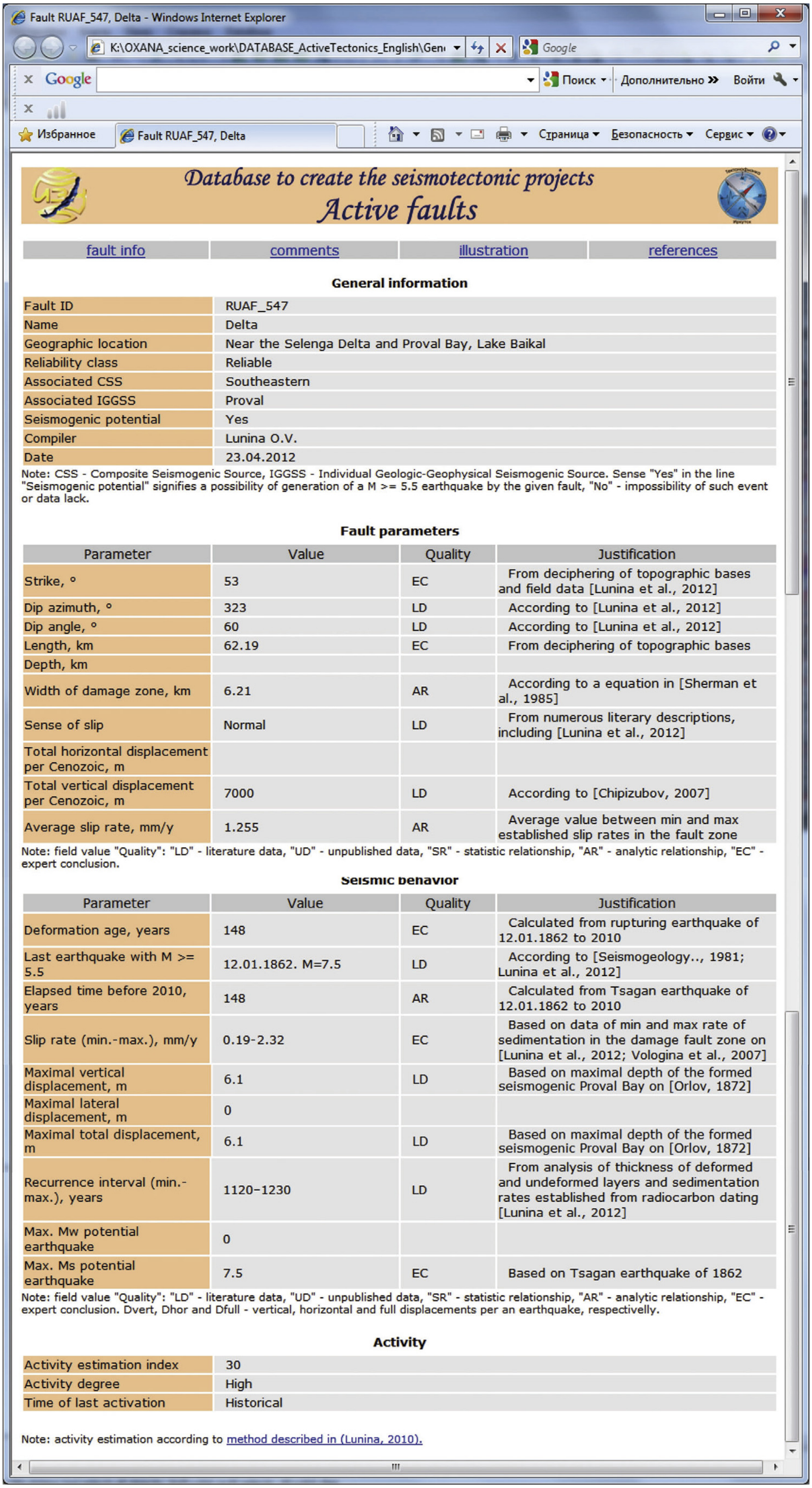
The sixth section (Fig. 2f) includes illustrative materials about faults, like photos, schemes and diagrams, while the seventh section (Fig. 2g) contains cartographic and literature sources of information, both used when filling in the database as well as the relative references and reports.

The compilation procedure in the frame of the database is assisted by the software tool "ActiveTectonics", which allows to associate all data (Fig. 2) once a fault has been drawn on a georeferenced map (or DEM) using the MapInfo GIS software. The same tool allows to calculate automatically some parameters and generating several client outputs as HTML pages (Figs. 3–5).

5. Analysis of the Pliocene–Quaternary faults

Based on (i) the previously described tools and software, (ii) abundant geological and geophysical literature information as well as (iii) original geological and structural data, it was possible to construct the map of Pliocene–Quaternary faults of southern East Siberia shown in Fig. 6. The faults within Mongolia are missing as we mapped them only on the Russian area. For the included structures we also compiled the 7-sections database containing parametric tables, text and pictures fully interconnected via a fault identifier (ID). Anyone may request full version of database that is distributed on DVD-disc together with the software tool till there is no URL-address. At present, the whole database consists of 797 'reliable' and 1004 'possible' fault segments (Appendix A), which are mainly defined by one strike or spatial separation of a fault. All of them with a few exceptions are expressed in relief and/or hydrographic network. Reliable class is assigned to structures which are confirmed by at least one of the following direct evidence: fractured zones or well-defined fracture systems of relevant direction in rocks of any type and age; seismogenic deformations; linear alignment of $M \geq 5.5$ earthquake epicenters along the fault; fault planes observed from underwater vehicles; seismoacoustic data about displacements of sediments. Other faults evident only morphologically and/or from geophysical and hydrological anomalies are referred to possible ones.

Many Pliocene–Quaternary faults in southern East Siberia have no parameters and sufficient description; nevertheless, it is practicable to analysis the information from the first version of the database. It is possible to extract selected details by area or by parameter and therefore to construct different thematic maps and investigate specific datasets. As an example, in this chapter, we describe and analyze some important parameters, like fault kinematics, orientation, pattern, age and seismogenic potential, as well as their areal distribution.



Database to create the seismotectonic projects
Active faults

fault info | comments | illustration | references

General information

Fault ID	RUAF_547
Name	Delta
Geographic location	Near the Selenga Delta and Proval Bay, Lake Baikal
Reliability class	Reliable
Associated CSS	Southeastern
Associated IGGSS	Proval
Seismogenic potential	Yes
Compiler	Lunina O.V.
Date	23.04.2012

Note: CSS - Composite Seismogenic Source, IGGSS - Individual Geologic-Geophysical Seismogenic Source. Sense "Yes" in the line "Seismogenic potential" signifies a possibility of generation of a M >= 5.5 earthquake by the given fault, "No" - impossibility of such event or data lack.

Fault parameters

Parameter	Value	Quality	Justification
Strike, °	53	EC	From deciphering of topographic bases and field data [Lunina et al., 2012]
Dip azimuth, °	323	LD	According to [Lunina et al., 2012]
Dip angle, °	60	LD	According to [Lunina et al., 2012]
Length, km	62.19	EC	From deciphering of topographic bases
Depth, km			
Width of damage zone, km	6.21	AR	According to a equation in [Sherman et al., 1985]
Sense of slip	Normal	LD	From numerous literary descriptions, including [Lunina et al., 2012]
Total horizontal displacement per Cenozoic, m			
Total vertical displacement per Cenozoic, m	7000	LD	According to [Chipizubov, 2007]
Average slip rate, mm/y	1.255	AR	Average value between min and max established slip rates in the fault zone

Note: field value "Quality": "LD" - literature data, "UD" - unpublished data, "SR" - statistic relationship, "AR" - analytic relationship, "EC" - expert conclusion.

Seismic behavior

Parameter	Value	Quality	Justification
Deformation age, years	148	EC	Calculated from rupturing earthquake of 12.01.1862 to 2010
Last earthquake with M >= 5.5	12.01.1862. M=7.5	LD	According to [Seismogeology.., 1981; Lunina et al., 2012]
Elapsed time before 2010, years	148	AR	Calculated from Tsagan earthquake of 12.01.1862 to 2010
Slip rate (min.-max.), mm/y	0.19-2.32	EC	Based on data of min and max rate of sedimentation in the damage fault zone on [Lunina et al., 2012; Vologina et al., 2007]
Maximal vertical displacement, m	6.1	LD	Based on maximal depth of the formed seismogenic Proval Bay on [Orlov, 1872]
Maximal lateral displacement, m	0		
Maximal total displacement, m	6.1	LD	Based on maximal depth of the formed seismogenic Proval Bay on [Orlov, 1872]
Recurrence interval (min.-max.), years	1120-1230	LD	From analysis of thickness of deformed and undeformed layers and sedimentation rates established from radiocarbon dating [Lunina et al., 2012]
Max. Mw potential earthquake	0		
Max. Ms potential earthquake	7.5	EC	Based on Tsagan earthquake of 1862

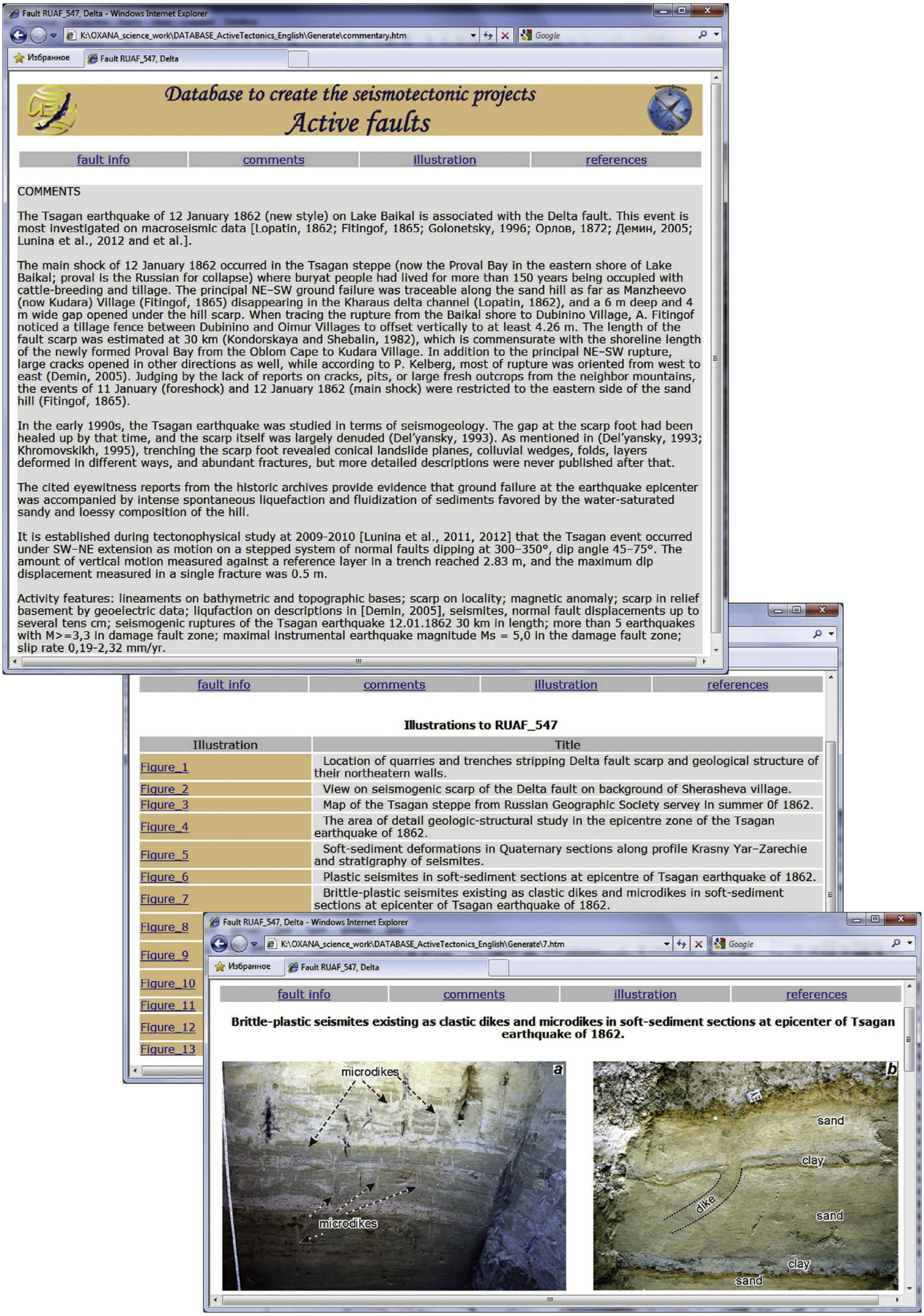
Note: field value "Quality": "LD" - literature data, "UD" - unpublished data, "SR" - statistic relationship, "AR" - analytic relationship, "EC" - expert conclusion. Dvert, Dhor and Dfull - vertical, horizontal and full displacements per an earthquake, respectively.

Activity

Activity estimation index	30
Activity degree	High
Time of last activation	Historical

Note: activity estimation according to method described in (Lunina, 2010).

Figure 3. Output from the active fault database in HTML pages: "fault info" section (for Delta Fault, see location in Fig. 9).



COMMENTS

The Tsagan earthquake of 12 January 1862 (new style) on Lake Baikal is associated with the Delta fault. This event is most investigated on macroseismic data [Lopatin, 1862; Fitingof, 1865; Golonetsky, 1996; Орлов, 1872; Демин, 2005; Lunina et al., 2012 and et al.].

The main shock of 12 January 1862 occurred in the Tsagan steppe (now the Proval Bay in the eastern shore of Lake Baikal; proval is the Russian for collapse) where buryat people had lived for more than 150 years being occupied with cattle-breeding and tillage. The principal NE–SW ground failure was traceable along the sand hill as far as Manzheevo (now Kudara) Village (Fitingof, 1865) disappearing in the Kharaus delta channel (Lopatin, 1862), and a 6 m deep and 4 m wide gap opened under the hill scarp. When tracing the rupture from the Baikal shore to Dubinino Village, A. Fitingof noticed a tillage fence between Dubinino and Oimur Villages to offset vertically to at least 4.26 m. The length of the fault scarp was estimated at 30 km (Kondorskaya and Shebalin, 1982), which is commensurate with the shoreline length of the newly formed Proval Bay from the Oblom Cape to Kudara Village. In addition to the principal NE–SW rupture, large cracks opened in other directions as well, while according to P. Kelberg, most of rupture was oriented from west to east (Demin, 2005). Judging by the lack of reports on cracks, pits, or large fresh outcrops from the neighbor mountains, the events of 11 January (foreshock) and 12 January 1862 (main shock) were restricted to the eastern side of the sand hill (Fitingof, 1865).

In the early 1990s, the Tsagan earthquake was studied in terms of seismogeology. The gap at the scarp foot had been healed up by that time, and the scarp itself was largely denuded (Del'yansky, 1993). As mentioned in (Del'yansky, 1993; Khromovskikh, 1995), trenching the scarp foot revealed conical landslide planes, colluvial wedges, folds, layers deformed in different ways, and abundant fractures, but more detailed descriptions were never published after that.

The cited eyewitness reports from the historic archives provide evidence that ground failure at the earthquake epicenter was accompanied by intense spontaneous liquefaction and fluidization of sediments favored by the water-saturated sandy and loessy composition of the hill.

It is established during tectonophysical study at 2009-2010 [Lunina et al., 2011, 2012] that the Tsagan event occurred under SW–NE extension as motion on a stepped system of normal faults dipping at 300–350°, dip angle 45–75°. The amount of vertical motion measured against a reference layer in a trench reached 2.83 m, and the maximum dip displacement measured in a single fracture was 0.5 m.

Activity features: lineaments on bathymetric and topographic bases; scarp on locality; magnetic anomaly; scarp in relief basement by geoelectric data; liqufaction on descriptions in [Demin, 2005], seismites, normal fault displacements up to several tens cm; seismogenic ruptures of the Tsagan earthquake 12.01.1862 30 km in length; more than 5 earthquakes with M>=3,3 in damage fault zone; maximal instrumental earthquake magnitude Ms = 5,0 in the damage fault zone; slip rate 0,19-2,32 mm/yr.

Illustrations to RUAF_547

Illustration	Title
Figure_1	Location of quarries and trenches stripping Delta fault scarp and geological structure of their northeatern walls.
Figure_2	View on seismogenic scarp of the Delta fault on background of Sherasheva village.
Figure_3	Map of the Tsagan steppe from Russian Geographic Society servey in summer 0f 1862.
Figure_4	The area of detail geologic-structural study in the epicentre zone of the Tsagan earthquake of 1862.
Figure_5	Soft-sediment deformations in Quaternary sections along profile Krasny Yar–Zarechie and stratigraphy of seismites.
Figure_6	Plastic seismites in soft-sediment sections at epicentre of Tsagan earthquake of 1862.
Figure_7	Brittle-plastic seismites existing as clastic dikes and microdikes in soft-sediment sections at epicenter of Tsagan earthquake of 1862.
Figure_8	
Figure_9	
Figure_10	
Figure_11	
Figure_12	
Figure_13	

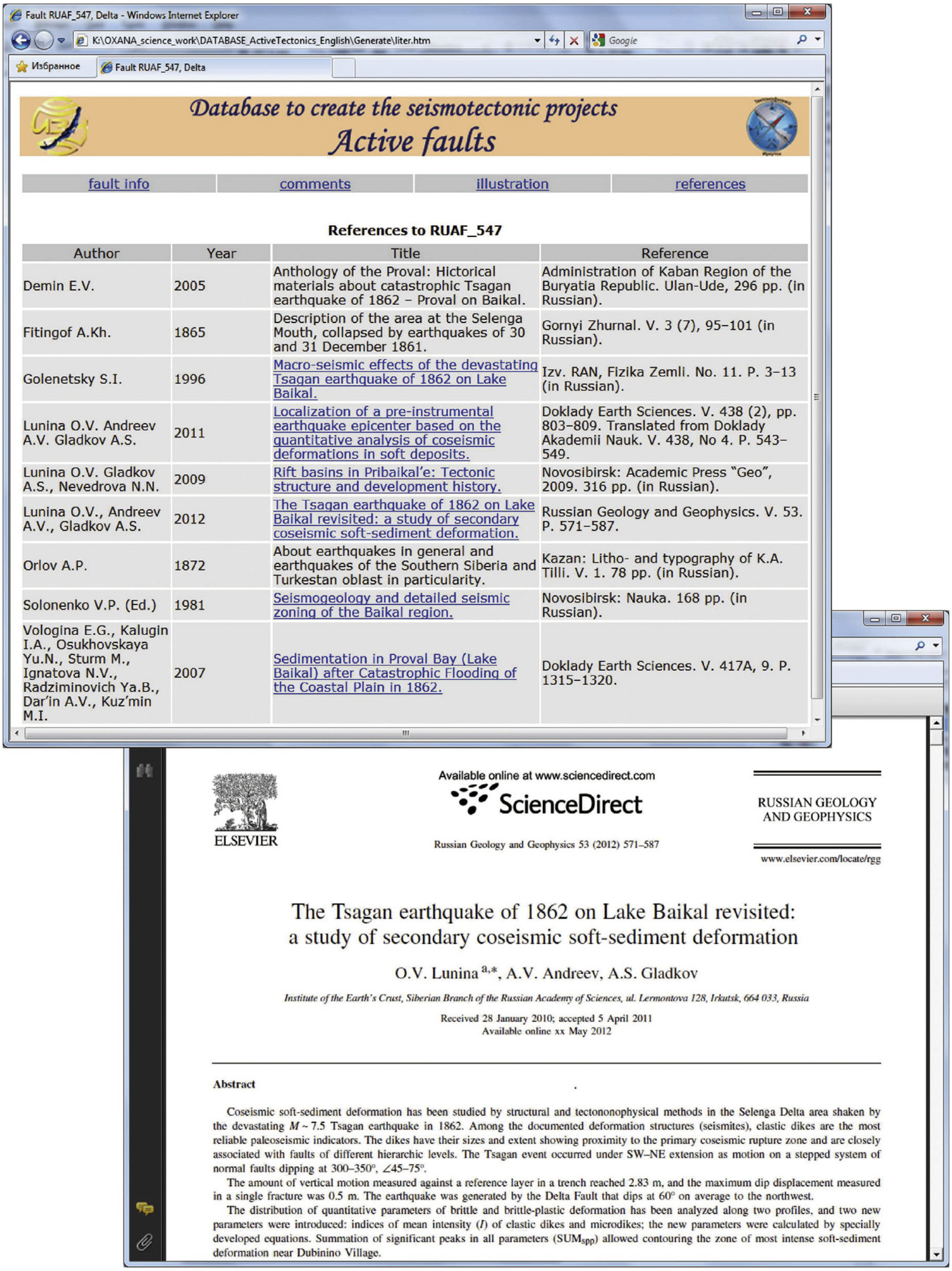
Brittle-plastic seismites existing as clastic dikes and microdikes in soft-sediment sections at epicenter of Tsagan earthquake of 1862.

Figure 4. Output from the active fault database in HTML pages: "comments" and "illustration" sections (for Delta Fault, see location in Fig. 9).

5.1. *Fault kinematics and orientation*

Differentiation of the data based on kinematics shows that dip-slip normal faults dominate the southern sector of East Siberia (Fig. 7). Oblique-slip faults with different combinations of normal and left-lateral component of motion are also well represented, while reverse faults, right-lateral strike-slip faults, normal right-lateral strike-slip faults and reverse left-lateral strike-slip faults are much less developed.

Also, as concerns the azimuthal orientation of the faults a specific query of the database shows a clustering of strikes when combined with their kinematics (Fig. 7). Indeed, the large majority



Database to create the seismotectonic projects
Active faults

fault info | comments | illustration | references

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The Tsagan earthquake of 1862 on Lake Baikal revisited: a study of secondary coseismic soft-sediment deformation

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Abstract

Coseismic soft-sediment deformation has been studied by structural and tectononophysical methods in the Selenga Delta area shaken by the devastating $M \sim 7.5$ Tsagan earthquake in 1862. Among the documented deformation structures (seismites), clastic dikes are the most reliable paleoseismic indicators. The dikes have their sizes and extent showing proximity to the primary coseismic rupture zone and are closely associated with faults of different hierarchic levels. The Tsagan event occurred under SW–NE extension as motion on a stepped system of normal faults dipping at 300–350°, ∠45–75°.

The amount of vertical motion measured against a reference layer in a trench reached 2.83 m, and the maximum dip displacement measured in a single fracture was 0.5 m. The earthquake was generated by the Delta Fault that dips at 60° on average to the northwest.

The distribution of quantitative parameters of brittle and brittle-plastic deformation has been analyzed along two profiles, and two new parameters were introduced: indices of mean intensity (I) of clastic dikes and microdikes; the new parameters were calculated by specially developed equations. Summation of significant peaks in all parameters (SUM_{spp}) allowed contouring the zone of most intense soft-sediment deformation near Dubinino Village.

Figure 5. Output from the active fault database in HTML pages: "references" section (for Delta Fault, see location in Fig. 9).

of the dip-slip normal faults has a prevailing NE–SW strike. The left-lateral strike-slip faults and normal left-lateral strike-slip faults are nearly E–W. Reverse faults are mainly NW–SE and partly nearly N–S; right-lateral strike-slip faults range between NNW–SSE and NNE–SSW. The normal right-lateral (311°–330° and 0°–20°) and the reverse left-lateral strike-slip faults (301°–320° and 50°–80°) are of minor statistical importance, both showing two directions.

If we consider geometry and kinematics together, the tectonic framework within the investigated region shows a general agreement in terms of mechanical compatibility (Fig. 7). Therefore, this suggests a common origin of most structures, associated with a unique regional stress-field, which was statistically uniform in space and time and characterized by prevail NW–SE tension.

Also as concerns the spatial distribution of faults, it is possible to observe some regional patterns (Fig. 7). Indeed, the normal faults and strike-slip-normal faults (with either some right-lateral and left-lateral components) are developed everywhere across southern East Siberia. They are particularly concentrated in the central sector of the Baikal rift, where they form an almost continuous fault belt, and in the West-Transbaikal rift zones.

Although less numerous, also the left-lateral strike-slip faults and the normal left-lateral strike-slip faults are present in all the

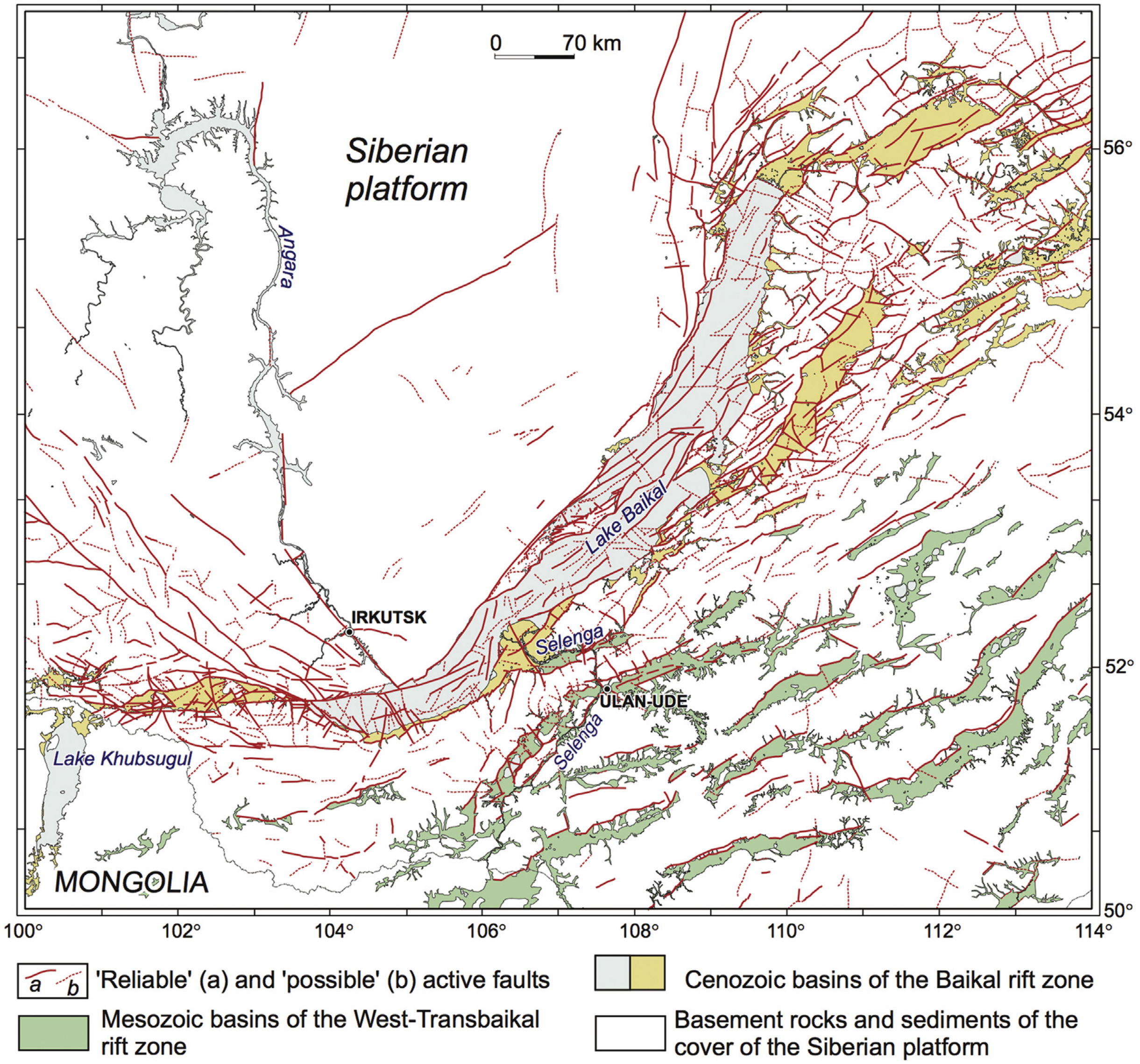

Figure 6. Map of the active faults of the southern sectors of East Siberia.

investigated area (Fig. 7). They are in general shorter than the faults of the former group, with the notable exception of the Zhigalovsky fault affecting the Siberian platform. These sinistral structures show a relative concentration along the southwestern flank of the Baikal rift zone and this pattern likely reflects the development of a transtensional tectonic regime.

The right-lateral strike-slip faults and the normal right-lateral strike-slip faults certainly represent local and minor structures, of limited dimensions and likely associated with second-order stress fields. The few reverse faults have been recognized along the margins of the Siberian platform at the transition with the Baikal rift zone. Finally, the few reverse right-lateral strike-slip, left-lateral reverse and reverse left-lateral strike-slip faults occur at the northeastern limits of the investigated area and along the East Sayan mountains.

5.2. Fault age

By querying the fault database using the criterion of timing of the last activity (Pliocene, Pleistocene, Holocene, Historical; Fig. 8), it is clear that many faults have been active during the Quaternary. If we do not take into account Zhigalovsky and Khandinsky faults within the Siberian platform, the zone is narrowest, 60–140 km-wide, between the Angara River head and the Barguzin Gulf (Fig. 8). It runs along the NE–SW trending segment of the crustal suture bordering the Siberian platform. Towards the WSW and NE, the width of the recently activated zone widens up to 360 km and this mechanical behavior is likely due to a lateral inherited variation in geological and tectonic setting along the boundary of the old craton. The influence of the latter on the development of the Baikal rift zone, repeatedly discussed earlier (Logatchev and Florensov, 1978; Zorin et al., 2003; Petit and Deverchere, 2006).

The map shows that the area affected by faulting has progressively narrowed since Pliocene and this tendency seems to continue in Holocene and historical times. In particular, co-seismic displacement in the southern part of the Lake Baikal and along the eastern lake side from the Selenga River delta to Saint Nose peninsula an almost continuous fault belt has been activated in historical times that is in the last centuries (Fig. 8). These most recent faults seem to continue northeastwards into the Barguzin basin (no. 5 in Fig. 1) and correspond with a zone of the recent fracturing of the lithosphere identified using seismological data

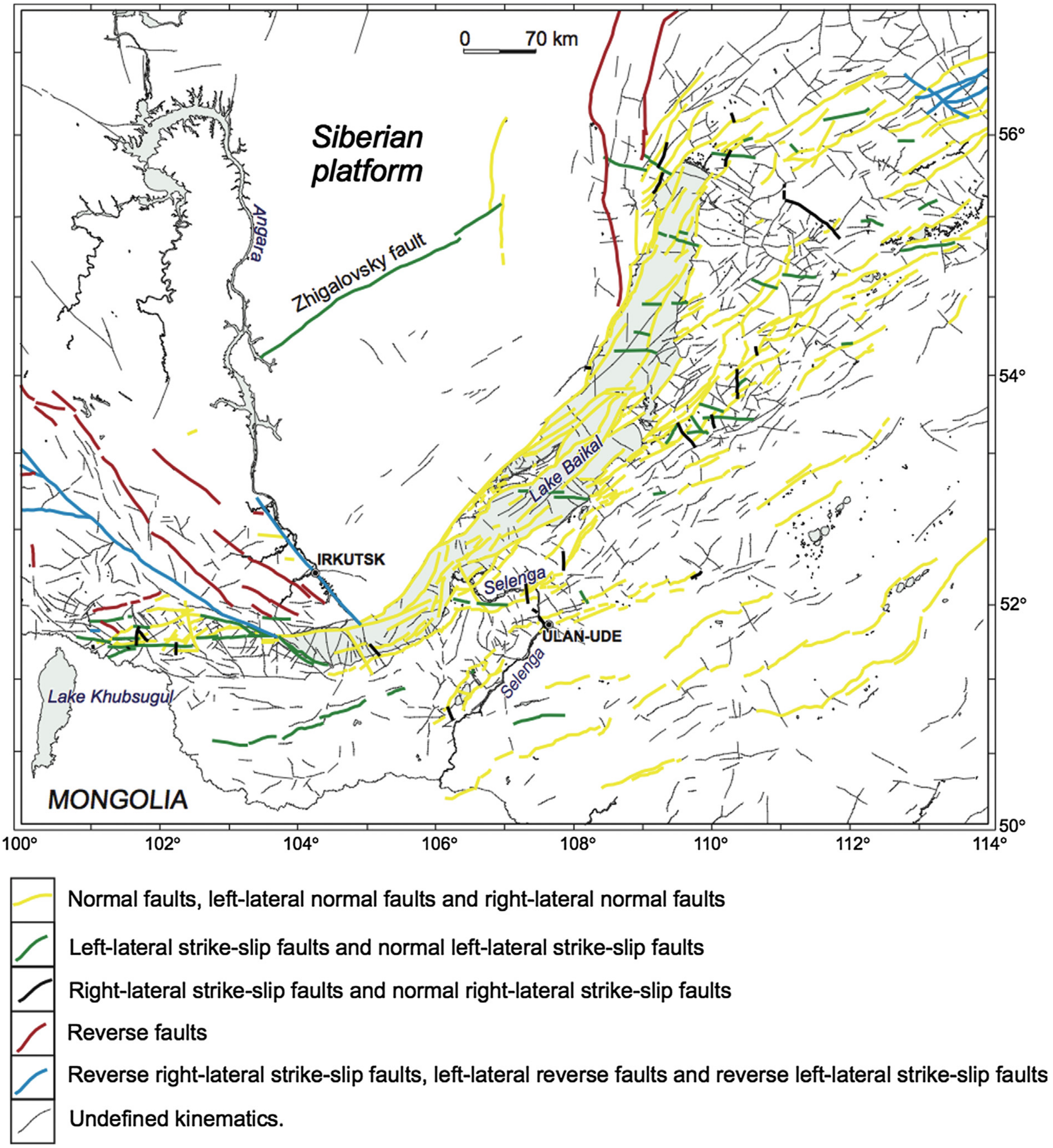

Figure 7. Spatial distribution of the faults according to their sense of slip.

(Sherman et al., 2004). In the same historical time some faults selectively re-activated on the northeastern and southwestern flanks of the Baikal rift zone.

It is worth to note that both in Holocene and recent times the NE–SW and nearly E–W trending faults have been reactivated being characterized by normal, left-lateral normal, left-lateral strike-slip and normal left-lateral strike-slip kinematics as previously discussed (Fig. 7).

5.3. *Seismogenic potential*

Among all Pliocene–Quaternary faults affecting the southern sector of East Siberia, the seismogenic structures capable of generating $M \geq 5.5$ earthquakes are of utmost interest. Indeed, such seismic events are the most hazardous ones, which generally produce surface ruptures in extensional environments (Pavlides and Caputo, 2004), diffuse slope processes (landslides, rockfall and etc.), liquefaction phenomena (Papathanassiou and Pavlides, 2011) and sometimes sinkholes (Clifton and Einarsson, 2005) and anomalous waves.

Faults within the database are referred to as ‘seismogenic’ only when the likelihood of generating $M \geq 5.5$ earthquakes is not negligible. This is obvious for the causative faults of historical and instrumental events and in all cases paleoseismological features are correlated to the specific fault, therefore documenting the occurrence of superficial co-seismic displacements associated with ‘linear morphogenic events’ (Caputo, 2005).

Faults are also marked as ‘seismogenic’ when belonging to a Composite Seismogenic Source (Basili et al., 2008) containing another seismogenic segment. When a fault is marked as

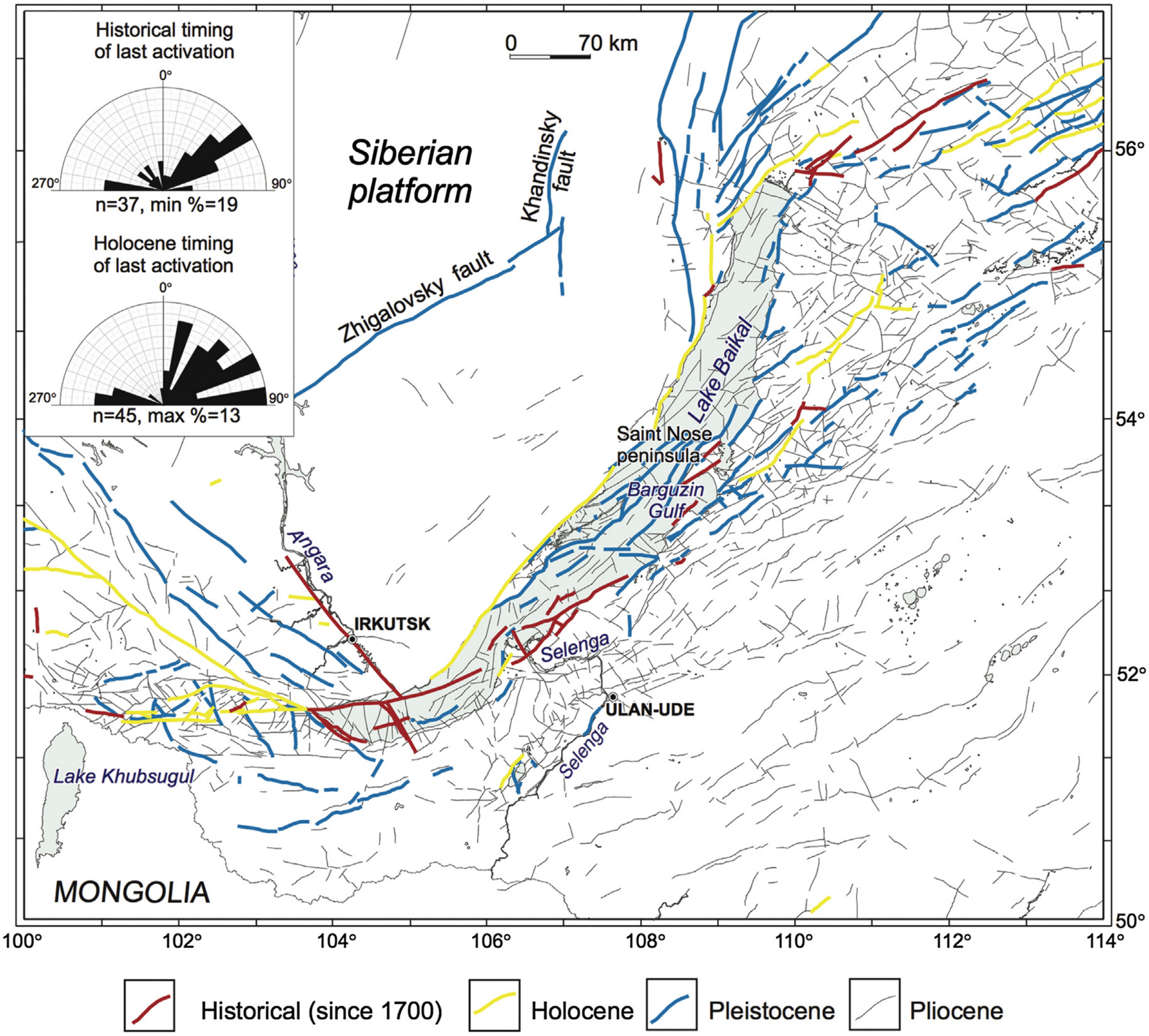

Figure 8. Spatial distribution of the faults according to the timing of their last activation in the southern sectors of East Siberia. Rose-diagrams of strikes for faults re-activated in historical and Holocene times are in the upper left corner.

seismogenic this appears in the window containing the general information of the structure (Fig. 3).

From the database and following the approach proposed by Lunina (2010), two classes of seismogenic faults could be extracted and plotted on a map (Fig. 9): faults characterised by activity estimation index >10, which are the most hazardous ones, and faults with lower activity estimation index (≤10). The latter class of faults has a low likelihood of generating earthquakes with $M > 6$. In some cases a low value could be due to insufficient data for correctly estimating the real seismogenic potential.

The most hazardous seismogenic faults are concentrated along the Baikal rift zone and East Sayan mountain system (Fig. 9). Faults with a lower seismic hazard generally affect the northwestern borders of the several depressions characterizing the West-Transbaikal rift zone. Secondarily, they also occur inside the basins of the Baikal rift zone and in the transition zone from Sayan-Baikal mobile belt to the Siberian platform. Two seismogenic faults (Khandinsky and Zhigalovsky) affect the old craton (Fig. 9).

A detailed analysis of the seismological parameters (such as focal mechanisms, hypocenter depths, earthquake epicenters) for $M \geq 5.5$ earthquakes occurred during the instrumental period (1950–2011) (Solonenko et al., 1993; Melnikova and Radziminovich, 1998, 2003, 2004, Global CMT Catalog) allowed to associate most seismic events with their causative fault. These structures are marked as ‘recent seismogenic faults’ (Fig. 9). Some earthquakes have not been assigned to the faults that can be due to the existence of blind seismogenic structures. The dominating NE–SW and nearly E–W strikes of the recent seismogenic faults fit well with the trends observed in the rose-diagrams for all sets of the seismogenic structures (Fig. 9) as well as with our observations showing that the tectonic deformation in Pliocene–Quaternary soft and poorly consolidated sediments in the Baikal and West-Transbaikal rift zones are concentrated along the NE–SW and nearly E–W trending fault zones documenting their more recent activity in comparison with other faults (Lunina et al., 2009).

6. Discussion

The overall tectonic pattern affecting the southern sectors of East Siberia and particularly the fault geometry, kinematics and the timing of the deformation, could be interpreted and explained as a consequence of the NW–SE (310°–330° average) trending lithospheric stretching affecting the Baikal rift zone and the curved

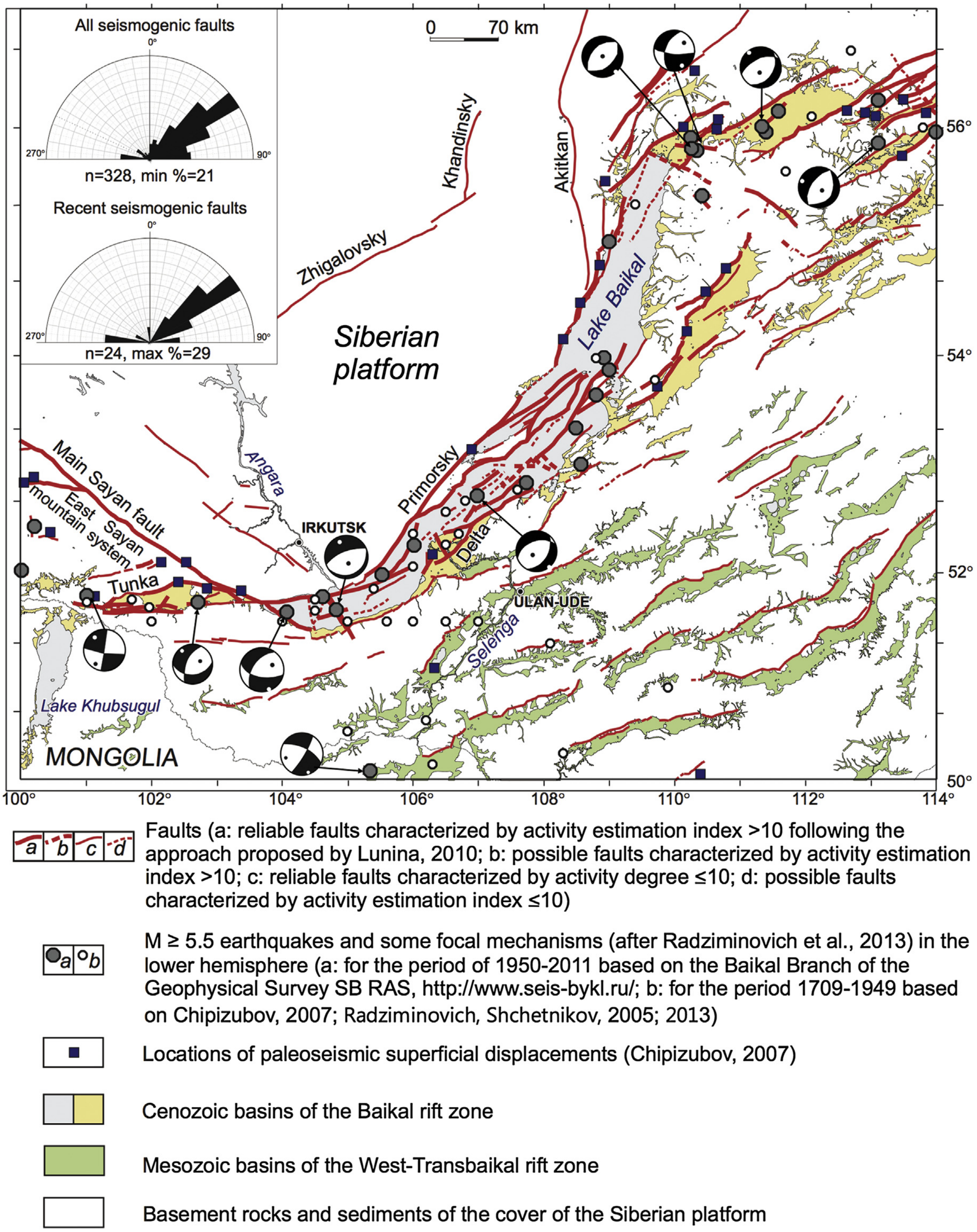

Figure 9. Map of the seismogenic faults capable of generating moderate-to-strong ($M \geq 5.5$) earthquakes. Rose-diagrams of strikes of all seismogenic faults shown in the map and recent seismogenic faults, with which $M \geq 5.5$ instrumental earthquakes for the period of 1950–2011 are associated, are in the upper left corner.

geometry of the border of the Siberian platform suture. Primarily the marginal Siberian platform suture hampered the westwards advancing of the rifting process and its curved geometry governed the kinematic behavior of pre-existing faults with non-ideal orientation in the frame of the neotectonic stress regime, which was characterized by a horizontal NW–SE trending tension caused by upwelling of anomalous mantle (Petit et al., 1998; Tiberi et al., 2003; Zorin et al., 2003; Lebedev et al., 2006; Kulakov, 2008; Mats and Perepelova, 2011) or effect from the India-Eurasia collision (Molnar and Tapponnier, 1975; Petit and Deverchere, 2006; San'kov et al., 2011). In such structural and geodynamic conditions, major crustal discontinuities and weakness zones parallel to the northeastern sector of the old lithospheric boundary were mainly re-activated as normal faults (Levi et al., 1996, 1997; Lunina et al., 2009). This general behavior favored the development of several extensional basins trending in this direction.

The southwestern sector of the marginal Siberian platform suture, which was bounded by the Main Sayan reverse left-lateral strike-slip fault, behaved similar to a transform fault (Zonenshain et al., 1995). Indeed, the average strike is 305° which is at low angle with the mean direction of regional tension. Deformation within a fault zone under such combination of (i) geometrical setting and (ii) distribution of tectonic forces (NW–SE tension and NE–SW compression) commonly generate a transpressional regime, which is typical indeed of the Main Sayan fault (Chipizubov and Smekalin, 1999; Lunina and Gladkov, 2002).

The occurrence and relatively spread diffusion of nearly E–W left-lateral strike-slip faults, often with normal component of motion, in southern East Siberia can be explained by left-lateral displacement of blocks that is considered as a main factor of evolution of basins and faults in the Baikal rift zone from analog experiments (Seminsky, 2009) and supported in some regional models (Sherman and Levi, 1978; Jolivet et al., 2013). The E–W trending faulting is particularly developed in the Tunka rift basin (southwestern sector of the Baikal rift zone; no. 4 in Fig. 1) as the initiating processes are overlapped on the old Tunkinsko-Khamar-Daban suture (no. XIII in Fig. 1) due to the collision of two terrains in early Paleozoic (Belichenko et al., 2003).

The above discussion shows that the inferences from the database analysis correspond to the prevailing representations about tectonics and geodynamics of southern East Siberia and therefore it is important to develop the IS continuously. Now it is in progress in order to include additional layers, like coseismic effects, composite and individual seismogenic sources, as well as new structural, geological and geophysical information and a software application for the overall management and its exploitation by an end-user online. The active fault map and database will be an essential support to create this.

It should be recalled that maps of active faults were compiled before (Levi et al., 1996, 1997) for the study area, including in a digital form (Trifonov et al., 2002; Sherman, 2009). Thus, one of them (Levi et al., 1997) illustrates active tectonic elements of the Baikal basin and adjacent areas established by geomorphologic, seismoacoustic and structural data collected on the shores of the lake Baikal. Another map (Levi et al., 1996) reflects only the main fault zones in eastern Siberia and Mongolia activated in the Cenozoic. Active fault map of Sherman (2009) contains a summary of all known faults separated by a quantitative index of seismicity based on seismic data for 1960–2000. Major faults of southern East Siberia have been shown on the map of active faults for the whole Eurasia (Trifonov et al., 2002).

The principal difference between the electronic map of the active faults of southern East Siberia submitted in this article and previous works is its comprehensive framework, in which important place belongs to the direct geological and structural evidence of the faults and associated deformations in rocks of different ages (Lunina and Gladkov, 2002, 2004, 2007, 2008; Lunina et al., 2009; among). In addition, it has been performed based on the 1:200,000 scale with using the latest achievements of GIS-technologies. Thanks to the detailed design of a variety of materials, it has been reasonably succeeded to show the faults within the rift basins and at the same time to critically examine the structural network that was previously allocated for the entire territory of the Baikal region.

Thus, the electronic map of the Pliocene–Quaternary faults accompanied by the relational database containing both previous and new information is principally innovative development for southern East Siberia and can be used for seismotectonic and geodynamic construction, including a prediction of the seismic and other geologic hazards.

7. Concluding remarks

In order to improve the capacity of the authorities in performing realistic seismic hazard assessment analyzes, in several countries it has been proved of utmost importance the systematic study of active faults, the application of GIS-technologies and the implementation of dedicated software, but especially the integration of all available information. Such approach has been applied for the first time to the southern sectors of East Siberia and consequently the following results have been produced:

- The first modulus of the IS referred to as “ActiveTectonics” has been fully realized. The software application works in a GIS environment (MapInfo package) and allows input of georeferenced object, to add and associate numerous data using dedicated windows and automatically calculate some parameters. The software enables the exploitation of the information contained in the database and generates several output clients as HTML pages in offline browsing. For example, it is possible to create digital maps of Pliocene–Quaternary faults or make a query of all data associated with a specific seismogenic fault, including the several seismotectonic parameters as well as their degree of uncertainty and the reasons for their choices.
- For the southern sector of East Siberia included between 100°–114° E and 50°–57° N, the relational database of Pliocene–Quaternary faults has been completed. All available information, both literature and original data, for each fault segment is contained and organized in the database as tables, texts and pictures intercorrelated through a fault identifier.
- Based on the created database, we have analyzed the diverse fault kinematics and their variable spatial distribution with respect to the overall pattern of the tectonic structures formed and/or activated during the late Pliocene–Quaternary in the broader Baikal zone. We conclude they were generated under a regional stress field mainly characterized by a relatively uniform NW–SE tension, but strongly influenced by the irregular hard boundary of the old Siberian craton.
- The general fault pattern with the most recent activity (Holocene and historical time) is quite uniform and dominated by NE–SW and nearly E–W trending faults. A dip-slip normal sense of slip prevails in the former, while the latter are mainly characterized by left-lateral strike-slip and oblique-slip (with different proportion of left-lateral and normal fault slip components) motion. Faults are concentrated along the borders of the rift or within it. The only exception to this regional pattern is represented by the WNW–ESE trending Main Sayan fault, whose recent activity is confirmed by Holocene co-seismic deformation (Chipizubov and Smekalin, 1999), and the Angara fault, showing small but recent co-seismic displacements.
- In historical times, the co-seismic re-activation of the tectonic structures in the southern sector of East Siberia mainly occurred in a narrow bend extending from the southern end of the Lake Baikal through the Selenga River delta and further northeastwards along the eastern side of the lake to Saint Nose peninsula as well as along the broader flanks of the Baikal rift zone.
- The NE–SW trending normal faults and the nearly E–W trending faults with an important left-lateral component of motion are the main sources of moderate-to-strong ($M \geq 5.5$) earthquakes on the southern sectors of East Siberia in recent times.

The inferences from the database analysis of the Pliocene–Quaternary faults are in an agreement with the existing models of the development of the Baikal region. Nevertheless, the database should be constantly replenished with new data that will come from future studies of faults.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.gsf.2013.12.006

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