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Fault kinematics of Sakhalin Island based on geological and seismological data

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Abstract. The paper presents a tectonic map of Sakhalin Island showing digitized faults derived from 1:1,000,000 scale tectonic maps and identified by geological surveys (detailed on 1:200,000 and 1:50,000 scale maps). The structural geological data on the kinematics of faults have been compared with seismological data on the earthquake focal mechanisms. A reasonable correspondence of these data has been obtained. The predominant kinematic type of faults is thrust/throw in the southern and northern parts of Sakhalin Island. In the central part of Sakhalin, a mixing of fault kinematic types is observed, mainly thrust faults with rare normal and strike-slip faults. Two uninformative zones have been identified with virtually no data on both structural geology and seismology. The earthquake focal mechanisms with a strike-slip component are dominant at their boundaries.

Keywords: fault, thrust, normal fault, strike-slip fault, GIS, digital map, Sakhalin, earthquake focal mechanisms

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Introduction

In regions of intense tectonic activity, faults are key geological structures that determine both the level of regional seismicity and the degree of danger from other geological processes. Therefore, the study and mapping of faults is one of the top priorities of numerous disciplines in geology and geophysics.

The rapid development of digital technologies in geology has led to the widespread application of Geographic Information Systems (GIS) in research practice. The main advantage of using such systems lies in the wide array of tools for working with large volumes of information structured as databases, allowing for the prompt replenishment, analysis, and updating of final information. Another equally important advantage is the ability to compare and analyze diverse geological-geophysical information, enabling the generation of new results and conclusions. In our case, this involves a comprehensive study of faults using methods from structural geology, tectonophysics, seismology, borehole logging (primarily caliper), deformation measurements of the Earth's surface based on GPS/GLONASS methods, and so forth.

The works [1–3] may be the examples of similar studies for the territory of Eastern Siberia

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with a high detailing and extensive geographical coverage, which were performed by native researchers. The authors of these publications used digital relief models, satellite images, topographic maps at a scale of 1:200,000, regional and global earthquakes catalogs, as well as extensive literary and cartographic sources. Diverse geological-geophysical information was mapped in GIS and, besides, supplemented by the results of their own comprehensive studies. Regional work [4] was carried out in the Central Tien Shan. Its authors used no GIS (in contrast to [1–3]), but applied their own method of tectonic stresses reconstruction.

The well-known «World Stress Map» project is to demonstrate an example of topical foreign research aimed to tectonic stresses reconstruction [5]. This project has integrated various data from seismology, drilling, and structural geology. Attempts to generalize and systematize diverse geological-geophysical information about Sakhalin were made also [6–10, and others]. The work [10] was performed without use of GIS, nevertheless it was detailed on high enough level. This study includes minimal analysis of geological information, the graphical realization was being in black-and-white mode. The research conducted on Sakhalin Island was rather localized due to limited instrumental, and especially geoinformation capabilities. So, they were not able to unite the entire complex of regional geological-geophysical studies.

The first steps to GIS-based unification have been undertaken in the present work to develop a systemic geodynamic model of Sakhalin Island on the ground of geological-geophysical data (at first, structural geological and seismological that).

Characteristics of the study area

Two systems of meridional uplifts are distinguished in the modern structure of Sakhalin Island (East Sakhalin and West Sakhalin). These uplifts extent along the western and eastern coasts and separated by a longitudinal system of lowlands or depressions (North Sakhalin Lowland, Tym-Poronaiskaya, and Susunaiskaya Depressions) (Fig. 1) [11]. The West Sakhalin uplift system is built by nearly continuous chain of mountain ridges. Unlike to this the East Sakhalin system consists of a chain of disjointed mountain structures. The southern segment includes the Tonino-Aniva and Susunai Ridges, the central part comprises a complex system of mountains of the East Sakhalin Mountains, and the northern segment includes the West and East Ridges of the Schmidt Peninsula [12].

Structurally, the West Sakhalin folding system is a complex monocline with westward-dipping layers, complicated by diagonal and longitudinal faults, as well as plicative dislocations [13]. The monocline consists of intermont depression deposits of an active continental margin [13–15]. The most ancient rocks of early Cretaceous are exposed in the eastern part of the monocline. Heading westwards, they are succeeded consecutively by late Cretaceous, Paleogene, and Neogene deposits.

The East Sakhalin folding system combines structurally different and age-diverse structural-material complexes (terrain collages) in its allochthonous and cover-fold structures, which have undergone various structural-material transformations [11, 15]. The North Sakhalin trough is a strike-slip-extensional structure overlain by a thick cover of terrigenous deposits of late Cenozoic age. The deposits formed by a large volume of solid paleo-Amur drainage, the delta of which evolved within the trough from the early Miocene [16, 17]. The structure of the trough is complicated by predominantly meridional and latitudinal tectonic disturbances and large gently dipping folds of the north-northwest and submeridional orientations [11]. The Susunai and Tym-Poronaiskaya depressions are overlaid asymmetrical basins, whose western margins exhibit fault nature [12]. The Susunai and Tym-Poronaiskaya depressions contacted to the West Sakhalin monocline on the west through the Central Sakhalin Fault, which is a major dextral thrust-strike-slip fault [18, 19].

Discontinuous disturbances have played a significant role in formation of the modern geological structure of the island. The main faults are actually the boundaries of tectonic zones or separate basic structural elements within them.

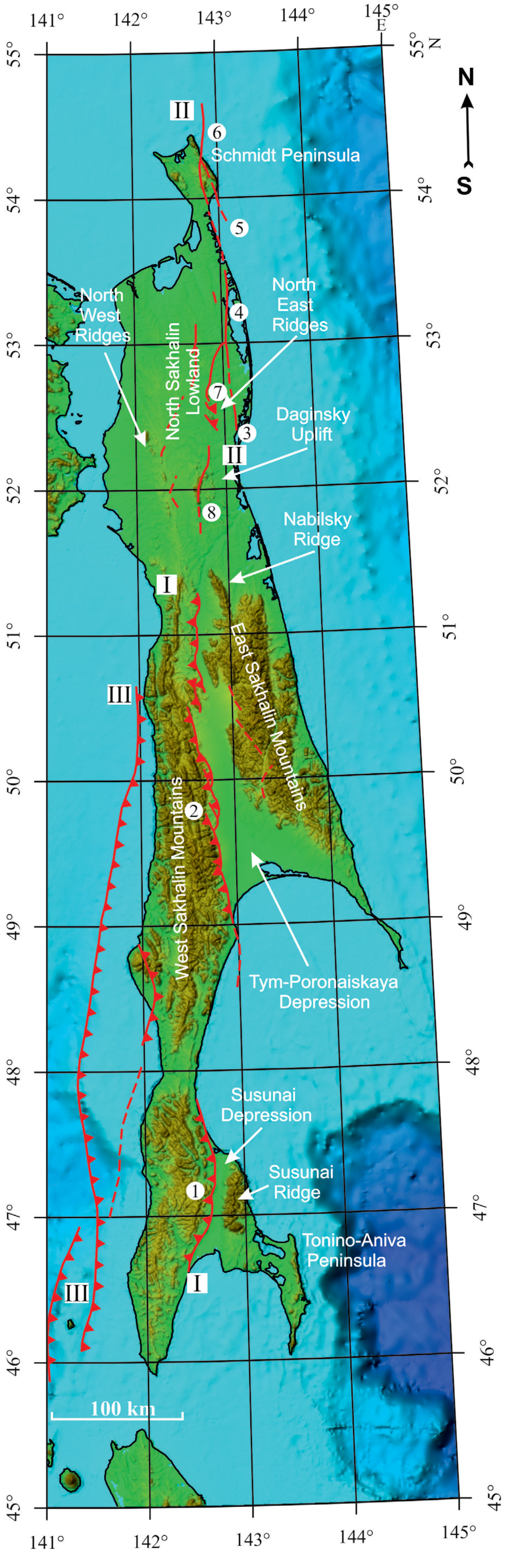

Fig. 1. The main fault systems of Sakhalin Island, according to [12]. The map base is Global Topography V19.1 [30]. Fault zones: I – Central Sakhalin (Tym-Poronai), II – North Sakhalin, III – West Sakhalin. Faults: 1 – Aprelovsky, 2 – Klyuchevskoy, 3 – Goromaysky, 4 – Piltunsky, 5 – Longriysky, 6 – Heytonsky, 7 – Verkhne-Piltunsky (Neftegorsky), 8 – Daginsky.

The major fault structures of submeridional strike —West Sakhalin Fault, Central Sakhalin (Tym-Poronaisk Fault), and Hokkaido-Sakhalin Fault (the latter described in some works as North Sakhalin one) — are expressed clearly in the relief as rectilinear tectonic scarps [18]. The kinematics of these faults exhibit clear indications of dextral strike-slips. Apart from submeridional faults, regional ones of northwest and northeast strike occur in the island structure. Discontinuous disturbances of various orientations are significantly different in structural type and morphology, and they are predominantly characterized by steeply dipping normal faults, thrusts and strike-slips, rarely by throws [11, 20, 21].

Materials and methods

At the initial stage, the data on regional faults structure from the sources as follows were used for faults mapping: the Third-Generation State Geological Maps of 1:1,000,000 scale [11, 20, 21], the data supplement from the First-Generation State Geological Maps of 1:200,000 scale [22–25], and several Geological Maps of 1:50,000 scale. These input data would be verified and updated later. Most of the maps exist only in paper format or scanned form, and their application are too difficult. Moreover, different sheets of maps of 1:1,000,000 and 1:200,000 scales are not always consistent mutually, and sometimes they contradict each other. Adjacent sheets of 1:50,000-scale maps from different authors often do not correlate well with each other and with maps at smaller scales. The use of GIS tools allows to build a maximally consistent digital map with the option of operative modification.

The Isoline GIS program has been used in the present work as that provided by the developers for educational and research purposes. Although this software is mainly assigned to the oil & gas and mining sectors of the economy [26], it can serve as a convenient interface when working with a digital database.

Mapping faults in GIS allows development the most reliable model for the existing state of the art in fault studies. The GIS additionally enables to superimpose layers of diverse comprehensive information. In the given work, this is implemented by comparing fault kinematics data obtained using structural-geological methods [11, 20, 21, 27] with data on earthquakes focal mechanisms taken from the catalog [28].

This significantly expands the potential of current research, involving the formation of giant massif of digital primary information to be used by other researchers for their specific problems. It is worth noting that an alternative regional digital project exists as part of the Active Faults Database of Eurasia and adjacent water areas [29], but its scale and detailing level do not meet our requests to generalize the regional geodynamic patterns.

Comparison of seismological and structural-geological data on the kinematics of faults

Based on maps [11, 20, 21] and works of prior researchers [18, 19, 27], the kinematic types of the main fault system of Sakhalin Island were determined, mainly for the West Sakhalin Fault, Central Sakhalin Fault, Hokkaido-Sakhalin, Nabilsky, Tymsky, and Katangliysky ones (Fig. 2). The results of determining the kinematics of faults for nearly half of the number of already digitized faults have been represented on the schematic map noted. The highest density of kinematic determinations is in the southern part of Sakhalin. There is less data available in the northern part, so the kinematics of a significant part of mapped faults remain undetermined up to now. This becomes the subject of further work on detailing and refining the geodynamics of Sakhalin.

The comparison of fault kinematic types identified by different methods (based on geological data, tectonophysical measurements, and earthquakes focal mechanisms analysis) is of unquestionable interest. The catalog of focal mechanisms of the Sakhalin earthquakes in 1962–2011 given in the work [28] was uploaded to our GIS for such analysis. The catalog incorporated 135 determinations of focal mechanisms, particularly 120 of which related to strong earthquakes with $M_{LH} \geq 4.5$. We also utilized weaker seismic events with $M_{LH} \geq 2$ (Fig. 2). Earthquake focal mecha-

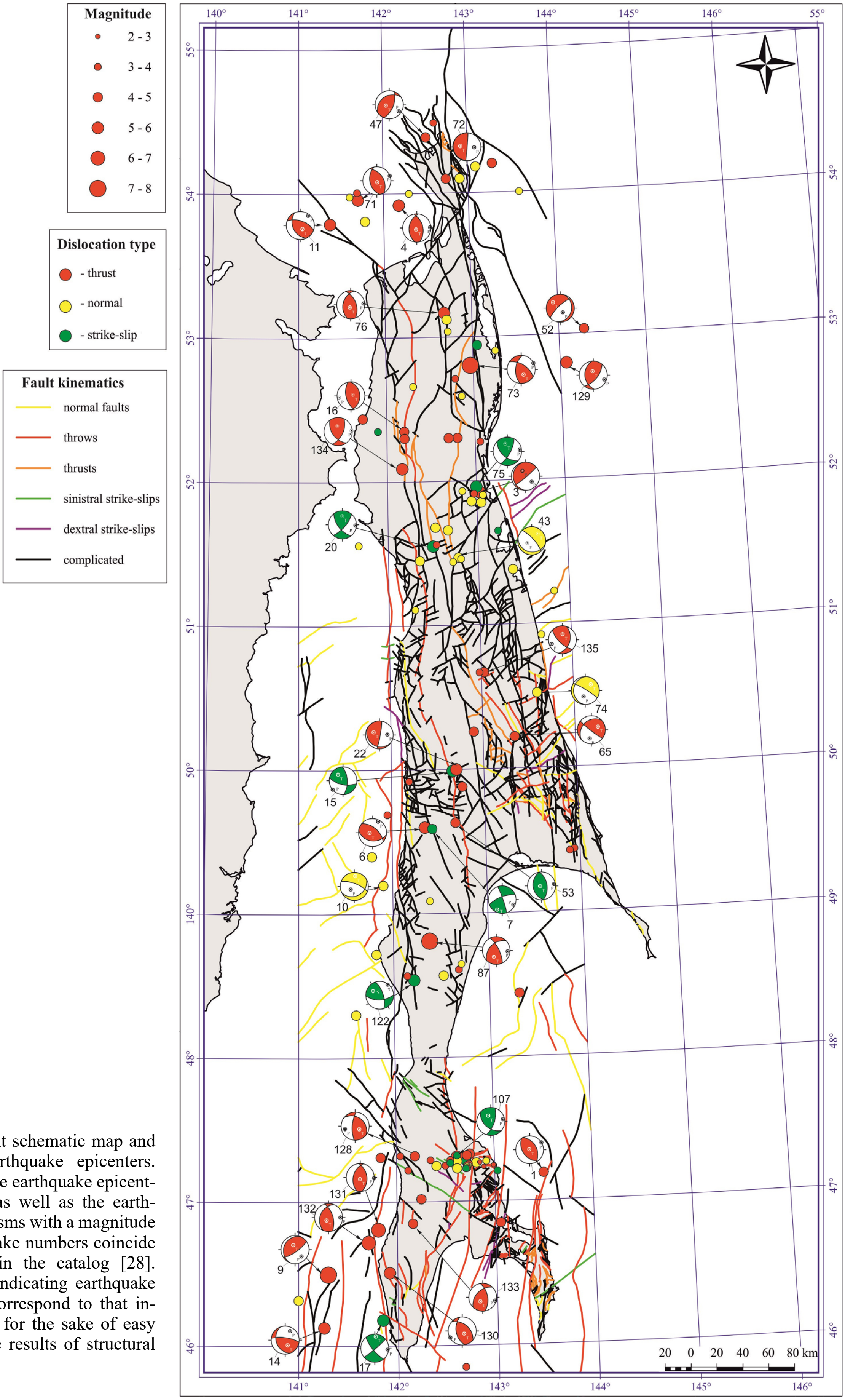

Fig. 2. Sakhalin fault schematic map and location of the earthquake epicenters. The map indicates the earthquake epicenters (filled circles), as well as the earthquake focal mechanisms with a magnitude of $M_{LH} \geq 4$. Earthquake numbers coincide with the numbers in the catalog [28]. Colors of symbols indicating earthquake focal mechanisms correspond to that indicating fault types, for the sake of easy comparison with the results of structural geology.

nisms are presented on Fig. 2 for 36 seismic events with $M_{LH} \geq 4$, that were described in [28]. The kinematic types are shown on the map in a simplified manner: thrust, normal, and strike-slip faults. Moreover, a number of the depicted faults remain without established type of kinematics, their kinematics to be specified additionally. This representation is definitely oversimplified; nevertheless, it allows to draw preliminary conclusions.

Analysis of the obtained results shows a reasonable correlation between data of structural geology and seismology. It is thrust/throw that is the most typical kinematic mode in the southern and northern parts of Sakhalin. In the central part of Sakhalin one can observe a mixing of fault kinematic types. The predominant number of faults are of thrust type, but normal and strike-slip faults occur occasionally.

One can distinguish clearly on the fault map of Sakhalin two uninformative zones: the Poiasok Isthmus (the narrowest part of Sakhalin) around 48° N and the section from Alexandrovsk-Sakhalinsky to Lunsky Depression around 51° N. A very low density of fault manifested itself in the Poiasok Isthmus, despite the thin cover of Quaternary deposits. This is due to the lack of large-scale geological surveys and exploration work in this zone. Besides, there is no data on earthquakes epicenters in this zone. The fault pattern in the zone at the 51° N is fairly dense, but their kinematics remain unclear, and the seismic data on epicenter are absent. Another pattern of these uninformative zones concerns the large number of earthquake focal mechanisms with strike-slip components at the boundaries of aseismic zones. These zones are of enhanced interest and are subject to further study, involving other research methods, particularly the approach of tectonophysics used in work [4].

Conclusion

Using GIS, fault disruptions of Sakhalin Island were mapped, as depicted on the 1:1,000,000 and 1:200,000 scale state geological maps, as well as on 1:50,000 scale maps. Additionally, results from other researchers, published both in articles and in the form of openly accessible digital information, were employed. The predominant kinematic types of the main faults system of Sakhalin Island were identified with the use of this structural-geological information.

The comparison of fault kinematic characteristics based on earthquake focal mechanisms with that obtained by structural-geological methods revealed the reasonable data correspondence. The predominant kinematic type of faulting in the northern and southern parts of Sakhalin Island is thrust. A mixture of fault kinematics type is typical for the central part of Sakhalin, with thrust prevailing, rarely normal faults and strike-slips.

Two uninformative zones have been distinguished inside which structural geological data as well as seismological that are practically absent. The earthquake focal mechanisms with a strike-slip component are dominant at their boundaries.

The authors consider the research performed as an initial stage of involvement of diverse geological-geophysical information into GIS. The development of new layers in the emerging database is in progress, in particular the addition of this database by tectonophysics data from our recent publications.

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