GIS-based identification of active lineaments within the Krasnokamensk Area, Transbaikalia, Russia

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Abstract. Lineament analysis was carried out using detailed digital elevation models (DEM) of the Krasnokamensk Area, southeastern Transbaikalia (Russia). The results of this research confirm the presence of already known faults, but also identify unknown fault zones. The primary focus was identifying small discontinuities and their relationship with extended fault zones. The developed technique allowed construction and identification of the active lineaments with their orientation of the compression and expansion axes in the horizontal plane, their direction of shear movement (right or left), and their geodynamic setting of formation (compression or stretching). The results of active faults identification and definition of their kinematics on digital elevation models were confirmed by measuring the velocities and directions of modern horizontal surface motions using a geodesic GPS, as well as identifying the principal stress axes directions of the modern stress field using modern-day earthquake data. The obtained results are deemed necessary for proper rational environmental management decisions.

1. Introduction
Lineament analysis is one of the most effective remote sensing methods for studying faults framework and deep structures of a geological region. This analysis is based on the identification of lineaments with diagnostic features. These lineaments are recognized by their: 1) rectilinear negative forms of relief, 2) rectilinear exposed slopes, 3) escarpments and ledges, 4) sequences of small streams straight segments crossing (in one direction) watersheds and valleys, 5) watersheds with straight axial lines, 6) areas with isoline thickening and bending. One of the most difficult problem with of the lineament analysis for regional tectonic structure features determination is the identification of lineaments of tectonic origin, thus fault structures. In addition, it is necessary to determine which of the lineaments associated with active faulting, thus reflecting faults in a modern tectonic stage of regional development. This task is not always easy. The possibility of identifying active lineaments (faults) and their kinematics using newly built digital elevation models and horizontal surface displacement analysis according to GPS observations is clearly shown in this work. This approach was carried out using various GIS software – ArcView 3.2, Easy Trace 7.99 (Free version), QuantumGIS 2.14.3, and Surfer 9.0, as well as new modules developed by the authors.
2. Objectives of the research study
The main objective of this research study is to identify the active fault system of the Argun area, which located near the town Krasnokamensk in southeastern Transbaikalia (Russia). This territory includes the Argun complex composed mainly of Archean-Proterozoic and Paleozoic granitoids. As a result of the Late Mesozoic tectonic and magmatic activity of the region, within the Kuytunsky and Streltsovsky volcano-tectonic structures (calderas), a unique system of faults was formed (Petrov et al., 2013). The Streltsovsky Ore Field (SOF) is located within the Streltsovsky caldera and comprises 19 molybdenum-uranium hydrothermal deposits. Most of the uranium, lead, zinc, gold, and tin occurrences of the Kuitunsky caldera area were discovered during the early stages of the exploration programs. For environmental planning purposes and prospectivity analysis for new ore deposits, it is necessary to identify the tectonic structural features of the area. This facilitated, geodynamic reconstructions, including estimation of the stressed-strained state of the rocks and the kinematics of movement along major faults. In order to meet these objectives, the authors used a lineament analysis technique in combination with structural data and GPS data observations.

3. Construction and analysis of detailed digital elevation models
Lineament analysis of different regions was carried out by a special technique developed by the authors on the basis of newly-created, detailed digital elevation models (DEM) (Ustinov and Petrov, 2016). Previously conducted studies (Ganas et al., 2005; Oguchi et al., 2005; Biggs et al., 2006) have shown that this technique is most effective in areas with highly dismembered relief.

The digital model of any geometrical (geographical) object is considered to be a specific form of basic data representation. The method of their structural description makes it possible "to calculate" (to recover) an object by interpolation, approximation or extrapolation (Novakovsky et al., 2003). The DRMs are special types of three-dimensional mathematical models representing both real and abstract geofields (surfaces). At the same time within a digital model, other indicators and characteristics, like atmospheric pressure, air temperature, precipitation, oil reservoir pressure, geophysical and geochemical fields, and concentration of pollutants, can act as "a surface relief" (Khromikh and Khromikh, 2007). It is necessary to distinguish digital models of the relief cartographical image (digital maps) from the actual digital relief models which in practice are often understood to be the digital models of heights created by using a limited set of source map data on the topography (X, Y, Z). DEMs creation and their recalculation from one type to another are based on the use of a mathematical algorithm. Its correct application depends not only on the developed model adequacy but also on the optimality of computer memory resources costs and calculation times.

The method of DEMs creation, using an irregular network of starting points, requires recovery (interpolation) of the surface and recalculation to regular network. Currently, there are many methods used to solve this problem. Among them – the interpolation based on Delaunay triangulation, the average weighted interpolation, kriging, etc. However, in all cases for calculating the elevation or value of a point, it is necessary to use some interpolation algorithms (i.e. the values received in starting points are matching true values precisely) or approximations (the values received in starting points are matching true values with some degree of accuracy).

As the actual material for creation of detailed DEMs in the research were topographic maps at a scale of 1:100000 (isolines conducted through 20 m), as well as the geological map at a scale of 1:200000, the map of anomalous magnetic field, the gravitational anomalies maps, and the tectonic setting map. Also used were satellite images and maps of a topographic relief received from satellite images analysis. All the available material was enough to provide the necessary detail of the DEMs at the scale of research with the possibility of using the created models for lineament analysis.

The initial stage of operation was vectorization of cartographic material. This task was carried out by means of the EasyTrace 7.99 Pro software (free version). EasyTrace is a software package for semi-automatic interactive vectorization of color and black-and-white bitmap images working within the Microsoft Windows operating system. Vectorizing lines on a black-and-white raster (image) is much faster and more convenient. However, it is not always possible because the initial materials for
vectorization are color images in most cases. Therefore, the «binarization» tool in the EasyTrace program is provided. The binarization of a raster is intended for separation, from the color image, a subject black-and-white layer. For example, from a raster of the color topographic map, it is possible to select a two-color layer of isolines or rivers and save it in the form of a separate two-color (binary) raster. After this operation, the map objects of interest (isolines in this case) will be presented in one color and all other objects are painted in a different color. Also before vectorization, the raster of a topographical map can be modified in the graphical editor due to elimination of unnecessary elements, color correction, gain of definition, and visibility of the interesting elements. Such actions increase the accuracy of a binarization process.

Further vectorization (tracing) of initial topographic maps contour lines was also carried out. It is a rather long and monotonous process that takes place almost automatically therefore there is no sense to stop on it in detail. As the relief of the studied area is rather dismembered, this information is considered to be enough for objective digital relief model creation with adequate details for the lineament analysis. Besides, the considered vectorizing program allows connecting elevation values to each constructed vector contour and to appropriate attributes. As a result the constructed isolines were painted in various colors depending on values of heights.

DEMs of the studied area were constructed on the basis of two main mechanisms: 1) regular network of heights (GRID) and 2) irregular triangulation network (TIN). Both of these mechanisms of relief modeling are widely used in geographical and geological information systems and are supported by many types of GIS software. At the same time, each of these two mechanisms has both shortcomings and advantages, which need joint consideration. Model TIN is the model developed especially for relief description. During the creation of the TIN model, the irregular network of triangles corresponding to Delaunay triangulation is used. At the same time, flat areas are modeled by a small number of large triangles and areas of steep ledges where it is necessary to show in details all sides of a relief the surface is displayed by numerous small triangles. The GRID relief model provides splitting space into indivisible elements. At the same time the matrix of heights or regular network of elevation marks is formed. The regular network of heights is a lattice with equal rectangles or squares where tops are grid knots. The regular network of heights has received the name "GRID" because in calculating of similar model the Gridding method is used and files of such DRM have the GRD format (Khromikh and Khromikh, 2007).

It is more expedient to use the TIN model for the research of local objects – such as massifs of rocks. Since research in this study covered a large area, the GRID model was used (Figure 1). On the basis of the grid file of a GRID digital relief model, support maps were constructed in carrying out the lineament analysis.

Lineaments on DEMs were identified and analyzed by means of plugin module; created by the authors and integrated into GIS software. Initially, the module was developed as the tool for realization and partial automation of tasks of the microstructural analysis special technique (Ustinov, Petrov, 2015). After adding some user-friendly functions and tools, it became possible to use this module for spatial analysis of microstructures, and also most importantly of large linear zones corresponding to faults and extended linear segments of geological structures.

4. Results of the spatial lineament analysis
By using detailed digital relief models, lineaments within the investigated area have been identified and drawn. Identified lineaments are characterized by varying orientations with similar total lengths in most directions. So to understand the role of various structures within the tectonic regime of the area and to exclude lineaments of non-tectonic origin, it is necessary to carry out classification of the identified lineaments, based on length and orientation (Figure 2).

Small in accordance with the scale lineaments up to 2,000 m are characterized mainly by submeridional, sublatitudinal and less by NE orientations. Lineaments that are more than 2,000 m long form accurately defined systems, mainly with NW, sublatitudinal and less NEt and submeridional
orientations. After lineaments identification and their ranging by length the technique proposed Petrov et al. (2010) was used.

Large-scale objects presumably faults are allocated among the lineaments and near them the orientations of smaller lineaments, conditionally called megacracks, are considered. These small lineaments correspond to feathering microfractures in the fault zone. Orientation of the feathering microfractures and faults, as well as the direction of horizontal compression and expansion axes which has caused shear movement in relation to the plane of a fault changes, is dependent on the geodynamic setting. Four possible options of relative orientation of the shear plane and feathering triad cracks are shown in Figure 3.
Figure 3. Options for stress-strained conditions at the shear angles 45° (a), <45° (b), the situation of additional extension (c) and compression (d). 1 – break; 2 – mode I cracks; 3, 4 – shears with right (3) and left (4) kinematics; 5, 6 – extension (5) and compression (6) axes orientations in the horizontal plane (after Gzovsky, 1975).

If the orientation of megacracks relative to each other and to their orientation with respect to estimated fault (lineament) corresponds to one of the options, then it is assumed that the lineament and megacracks are of tectonic origin. Concurrently, the orientation of compression and expansion axes in the horizontal plane, the direction of shear movement along the fault (right or left), and the geodynamic setting of fault formation (compression or extension) are reconstructed.

On the basis of the obtained results, the latest fault tectonics scheme included information on new structures of I, II and smaller ranks with the indication of faults kinematics and orientation of tension and compression axes was created (Figure 4).
**Figure 4.** Scheme of the latest tectonics and neotectonic stress of the Streltsovsky and Kuytunsky calderas area. 1 – neotectonic faults of I rank; 2 – neotectonic faults of II and smaller ranks; 3 – shift movements; 4 – faults or uplifts (barbs directed to lowered wing); 5 – orientation of I rank faults compression axis in the horizontal plane; 6 – orientation of II and smaller ranks faults compression axis in the horizontal plane; 7 – geodynamic situation of three-axis tension; 8 – geodynamic situation of compression; 9 – settlements; 10 – contours of the calderas: a – Streltsovsky, b – Kuytunsky.

Within the considered territory the I rank faults are rather accurately expressed by relief. They are extensive (more than 5,000 m length) with predominant NE-SW and latitudinal orientations. The position of the I rank structures is also marked by a large number of feathering fractures formed in the zone of faults dynamic impact. These structures are presented by left lateral shifts with submeridional orientation of compression axes for NE-SW structures and NE orientation for latitudinal structures.

The II rank structures include all extended northwest-southeast faults, which are intensively breaking the Argun raising into numerous blocks. Within the considered study area there is a large amount of such faults. Within DEMs, there are signs that these faults displace and break into segments structures of other orientations that indicate a later time activation of the NW-SE structures. These faults are mostly right lateral strike-slip, which have been formed in the geodynamic setting of compression with (N)-NE orientation of the compression axis.

5. Results verification

The obtained results for the identification of active faults and the definition of their kinematics using digital relief models were confirmed by measured results of the velocities and directions measurements of modern horizontal movements monitored in the area of SOF by means of GPS geodesy. GPS measurements were carried out by specialists of the IZK SB RAS (Irkutsk) stations for permanent and temporary observations during 2010-2015. In addition, the controlling mechanism of earthquakes and orientations of the main tension compression and extension axes operating in the area were defined.

Conducted measurements of velocities and the directions of modern horizontal movements around the SOF by method of GPS geodesy have shown that the geodetic points located on surfaces of the Sukhoi Urulyunguy depression are displaced in a (E)-SE direction (Figure 5). It is determined that the velocities of horizontal movements vary from 20 to 25 mm/year.
Figure 5. The current intensely deformed state of SE Transbaikalia. At the left – velocities of modern horizontal movements and relative deformations of geodetic network near the SOF: a – vectors of GPS station (KRNK, KRNW, KRNN, KRNE, KRNS) movement and velocities (mm/year) according to measurements in 2010-2015 in the basis of ITRF2008, in 95% confidential interval; b – velocities of the main horizontal deformations in a year-1 (the meeting arrows – shortening axes, the diverging arrows – lengthening axes). The square area has designated the area of the observation ground and tectonophysics modeling (an explanation in the text). On the right – the average mechanism of earthquakes (atop) and orientation (bottom) axes of the main stress of compression (the meeting arrows) and extension (the diverging arrows) in the area.

It is assumed that the geodynamic setting of horizontal extension takes place here. Herewith one triangle of the counted deformations has given the maximum reduction in the NW direction at very small lengthening in the NE direction that contradicts data for three other triangles. For the fourth triangle, it was found that the maximum lengthening is focused vertically. This corresponds to the geodynamic regime of horizontal reduction. Such significant differences in the stress state modes of adjacent crustal blocks can be explained with results for modern stress state tectonic reconstructions of different orogens. For example, in (Rebetsky et al., 2012) it is shown that in areas of ridge raisings the
situation of horizontal compression or shear (transpression) prevails, and in deflections and lowlands the situation of horizontal extension or shear (transstension) prevails.

The studied area (according to the set ...., 1999) is characterized by low seismicity. Therefore, for modern stress-strained state assessment of rock massifs by data due to mechanistic of the earthquakes centers the extensive territory with coordinates 44°-54° of N latitude and 110°-124° of E longitude is considered. In total on this territory according to various references solutions of focal mechanisms for seventeen events are known. The analysis of stereograms of focal mechanisms and their classification charts has shown that the most earthquakes are characterized by shear type of shift in the center and also there are several events of uplifting type and two earthquakes of faulted type. By data about mechanisms of the earthquakes centers the average mechanism and orientation of main tension compression and extension axes of the studied area were determined by the Yunga’s (1990) method. The receiver results show that the average mechanism is close to the average shear type. Axes of compression and extension are nearly horizontal; however, the axis of compression is sub-latitudinal, and the axis of extension is sub-meridional (cf. Figure 5).

Using these observations for determination of the geodynamic setting in SE Transbaikalia the conclusion reached for the Baikal geodynamic polygon within which GPS network contained up to 20 stations (Sankov et al., 1999; 2005; Lukhnev et al., 2010) can be made. Probable influence on the horizontal movements is determined by rising and spreading of anomalous mantle substance in the Baikal rift. Although as shown by calculations (Lesne et al., 1998) modern strain can be explained by the influence of only one horizontal efforts from remote sources at plate boundaries. Important roles in formation of modern structures are played by erosion and sedimentation, the temperature field (for example, in connection with volcanic activity), fluid dynamics and other phenomena (Sherman, 2009).

On the basis of geostuctural, tectonic, and geomorphological analysis of the study area, the lack of significant vertical block movements due to large raisings at the neotectonic stage is interpreted. Along with this interpretation, the question of the neotectonic stress field structure remains open so far. Statistically, most part of interpretations for the late Cenozoic by the Sim’s (2011) method, points to extension in NW and compression in NE directions. Modern stress-strained state by data on mechanisms of the earthquakes centers is defined as NW-SE extension and NE-SW compression. These basic features are confirmed by the preliminary data analysis of GPS measurements.

6. Conclusions
By means of the lineament analysis carried out on the basis of digital relief model creation for the investigated area near the town Krasnokamensk in SE Transbaikali, linear elements such as lineaments were identified with a high degree of reliability. Among these, on the basis of a special technique, active lineaments were established and interpreted to reflect modern fault zones. Depending on the relative orientation of the large lineaments, which are presumably demarcating faults, and the small lineaments which are conditionally called megacracks, the tectonic setting and nature of these lineaments, orientation of compression and extension axes in the horizontal plane, the directions of shear displacements (right or left) and the geodynamic situation (compression or extension) of fault formation were reconstructed and established. The geodynamic setting of the recent fault tectonics, established by Petrov et al. (2010) was supplemented by new information on I, II and smaller rank structures with their kinematics and orientation of tension axes. The calculations of horizontal displacements according to GPS observations executed using triangulation and data on mechanisms of earthquakes have confirmed conclusions about the fault nature and kinematics of the revealed active lineaments.

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