Methods of Semiautomatic GIS-based Mapping of Neotectonic Active Zones and Geomorphological Features

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INTRODUCTION

For several decades, the morphometric analysis of relief is being widely applied for the problem solving in various areas of geology and geomorphology (Strahler, 1957, Filosofov, 1960, Beasom et al., 1983, Riley et al., 1999). The Morphometric methods received huge development with the advent of geographic information systems, thanks to which it became possible to perform difficult calculations on the basis of geographically adhered data. The Modules for calculation of the numerous universal and widely used morphometric indicators became nowadays the standard options for various GIS-packages.

However, the experience in geomorphological map design and in the work on various structural-morphological schemes and neotectonic maps, allows affirming that a direct application of the standard morphometric parameters is not informative enough for the problem solving in structural geomorphology and in neotectonics, because a simple morphometric analysis describes only the geometry of a relief and does not describe the relation of various forms of relief. In particular for morphological structures which differ among themselves on genetic type and (or) on age. Accordingly, the analysis of the results of a simple morphometric processing (i.e. the interpretation of the morphometric heterogeneity of a relief) should necessarily be done with the consideration of the factor of heterogeneity of a relief on age and on genetic type.

This work is an attempt of the semi-automatic geomorphological GIS-analysis based on morphometric parameters as well as on structural-geomorphological models of development of a relief and on classical geomorphological principles. As an experimental area for our research we have chosen the region of the Alpine-Himalayan belt to the west of Pamir–Punjab syntaxis, within the Afghan-Tajik block. The purposes of our work have been the following. Firstly, working out the methodical approach to the semi-automatic GIS-analysis and to the structural-geomorphological and neotectonical mapping. Secondly, verification of the results received on the basis of independent geological-geomorphological data and analysis of correlation of the results received by different methods. Thirdly, to perform the qualitative analytical analysis of applicability of the given approach and the analysis of potential mistakes and artifacts of the similar semi-automatic GIS-mapping.

1. AREA OF RESEARCH, GEOLOGICAL SETTINGS

The research area is located in Afghanistan, Central Asia, in the tectonically active Alpine-Himalayan orogenic belt (fig. 1) that developed in response to the collision between the Indian and Arabian plates and Eurasian plate in Late Paleogene to Recent (Ruleman et al., 2007). The area of GIS-based mapping performed in our work is situated at the boundaries of different geological units: accreted tectonic blocks and North Afghan Platform, near the transpressional plate boundary between Eurasian and Indian plates (Ruleman et al., 2007, Geological…, 2006). Geologic and tectonic maps show for this region numerous active faults of different ages and kinematics. Some of them are: Bande Bayan, Bande Turkestan, Chaman, Darafshan, Hari Rod, Helmand, Onay, Qarghanaw (Wheeler et al., 2005). Majority of the faults have a surface expression and reveal Quaternary movements and deformation.

In addition, the seismic and Quaternary tectonic activity within and near the area of the GIS-mapping may be under the influence of the relative motion of the interior of Iran northward, with respect to the interior of southwestern Afghanistan (Sistan block) (Dewey et al., 2006). So, based on geologic, tectonic, and geomorphic analysis, we have concluded that the relief surface within the study area is modern and active. There are many neotectonic features developed under the regional stress and strain conditions. But each domain has its distinct geomorphic qualities that we interpret in order to reflect different styles of the Quaternary deformation.

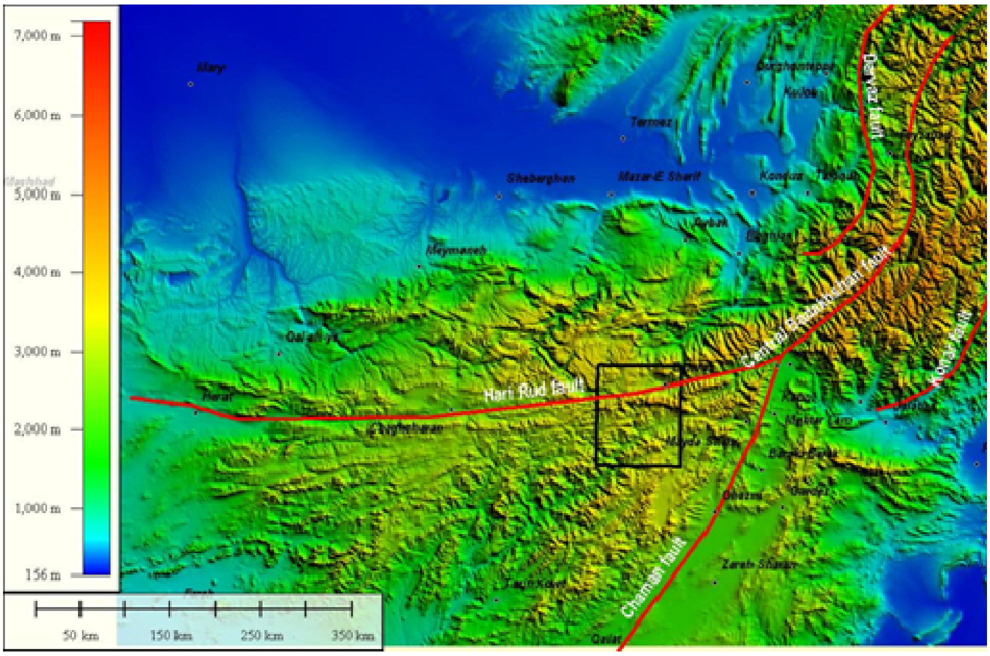

Figure 1: Layout of the region of research. The rectangle indicates the area of GIS-based mapping. The scheme is based on data SRTM 30", the red lines with signs show the main active faults (after Boyd et al., 2007).

2. METHODICAL APPROACHED TO THE SEMIAAUTOMATIC GIS-BASED MAPPING

In the basis of the semiautomatic GIS-mapping of a relief, neotectonic patterns and active geomorphological features are the methods of morphometric analysis and classic principles of geomorphology. In other words, GIS analysis is based on some expert prerequisites providing a correctness of the computer analysis of a relief surface.

On independent data, the following characteristics of a relief in parsed territory should be determined, i.e. at least: age of a relief, genetic types, stages of progressing of a relief, a degree of modern activity. In particular, should be determined the possible approaches to morphological development, the common trends, and principal nature of evolution of a relief. Intercouplings between regional morphotectonic development and evolution of discrete local forms and structural units should be observed.

In our case there is a set of the works about the problems mentioned above (for example, Chen et al., 2009, Singh et al., 2005). Therefore it is possible to consider the semi-automatic GIS-analysis of a relief fulfilled in our job is quite correct.

Thus, methodical approaches to semi-automatic GIS-mapping performed in this work include geological, geomorphological and tectonic features of the region. Taking into account these data, the main stages of the GIS-mapping are as follows. First, morphological (morphometrical) units of a surface of a relief which are rather homogeneous have been defined. That is any structural and morphological borders can be located only on the borders of these elementary geomorphological units, but not inside them. Secondly, for the characteristic and an estimation of evolution of a relief (and, in particular, for some quantitative characteristic of delineated geomorphological units) it is necessary to know about the relation of local morphological structures and regional base level. Further, for the reconstruction of geomorphological and tectonic evolution of the region (in that specific case the relief is young, that is neotectonic structures can be revealed in a modern relief) a set of planation surfaces which sequentially superimposed from older to younger. At the next stage more local morphological structures (the elementary geomorphological units delineated at the first stage) have been considered and quantitatively analyzed. Different regularities and distinctions of these units are reflected in a series of maps in this work. At last, at a following stage the analysis of smallest local structures for revealing separate neotectonic active zones has been made.

3. BASIC MORPHOLOGICAL BENCHMARKS AND THEIR CALCULATION

3.1. Identifying the morphological unities

In the basis of our GIS-analysis is the comparison of the morphometric indexes for uniform (homogeneous) structural (morphological) domains, or blocks. The most standard and generally accepted features for the morphological analysis are the terrains – morphologically homogeneous patterns which are rather confidently allocated by morphometric analysis.

It is necessary to specify, that in our work we use the term ‘terrain’ for a designation of a stretch of land with regard to its homogeneous morphometric and morphological features. As it is possible to be convinced at the analysis of geological data on the territory of researches (Geological …, 2006), all terrains delineated for GIS-mapping have also homogeneous geological (substantial) substratum. Terrain boundaries and the boundaries of geological structures (geological units) are rather similar each other. (In the geological literature the term ‘terrain’ also is used for a designation of discrete block of continental crust with unique evolution in relation to the blocks that surround it, however in this work the term ‘terrain’ has no such geological sense, like in a lot of work about terrain analysis in geomorphology).

One of the most effective indexes characterizing topographic heterogeneity is TRI (Topographic Ruggedness Index) index (Riley et al., 1999). We have fulfilled the TRI analysis of the relief surface (based on SRTM 3" data) for the study area, and have received a set of uniform geomorphological units – terrains. (This analysis can be fulfilled in different GIS-packages, such as ArcInfo, Esri Inc., SAGA, and many others.) We considered these terrains in the subsequent analysis as uniform (homogeneous) morphological blocks, i.e. geomorphological features. Thus one-type morphological and morphometrical structure of the blocks (with equal or close TRI-indexes) often points to the coincidence of genetic types for the different terrains.

3.2. Calculation of the base level

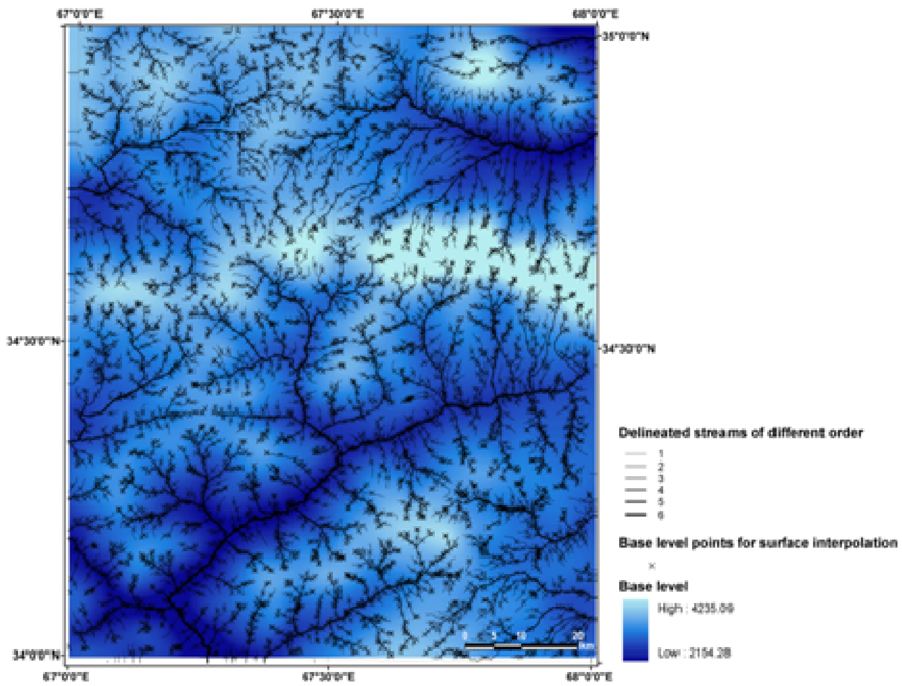

Figure 2: The surface of modern base level, calculated on the basis of a delineated erosion network by means of interpolation between the points located within a modern river network.

As it has been noted above, the morphology of a surface of basis of erosion and excess of various geomorphological elements over this surface in any geomorphological researches are of key importance. In this regard, calculation of this base surface is one of the fundamental stages of our GIS-analysis. Building the surface of base level (basis of erosion) has been conducted in several stages (fig. 2).

On the first stage, the modern erosive network on the basis of a grid-surface of the relief has been calculated (based of SRTM 3" data). This calculation can be performed in many GIS-packages, and we used ArcMap software (ESRI Inc.). Further, the received linear shape-file has been transformed into a point file. This step has been executed with consideration that each segment of the calculated river network (including each stream of each order) had a corresponding point in the point shape-file. Further, each point has been given a value of height on a relief grid-surface. At last, it has been executed the interpolation of point values for building a single surface on all area of research (in this case the correct methods of interpolation are Kriging and a radial basic function method).

4. ANALYSIS OF REGIONAL DEVELOPMENT OF THE TERRAIN ON THE BASIS OF GIS-ANALYSIS

Constructing of maps for planation surfaces on the basis of materials of radar data of a modern relief (SRTM 3" data) can be fulfilled in several ways. However at the heart of each way lays the fundamental geomorphological supposition that discrete positive topographic forms can label (that is to be residual patterns) the ancient surfaces of leveling. And the altitudes of these surfaces of leveling are not a constant; they are determined by excess over the surface of modern base level.

The issue of the planation surfaces and its meaning in long-term landscape evolution is one of the more controversial in geomorphology. However generally it is supposed, that each of planation surfaces reflects one of the development stages of the whole landscape (by analogy to formation of river terraces within river valleys). Each of surfaces (and as the name implies) characterised by practically zero amplitude of incising. And, ideally, planation surfaces should cut across bedrock structures. Certainly, such model representation not always proves to be true completely, especially in case of presence solid massifs which erode more slowly, than there is a formation of new, younger (accordingly, lower) regional planation surface.

Residual topography do not gives a clue to the mode of formation of surfaces, so they have not genetic connotations. Leading process of transformation of a surface is incision in low- and high-ordered values, and erosive processes on watersheds are rather slow (for example, creep and deluvial processes). Thus, for our model it is possible to accept that the sites of a modern relief located near to watersheds can be fragments of various planation surfaces. Generally, similar fragments of ancient planation surfaces can be appeared as flat terrace-like limbs, however automatic classification and delineation of these terrace forms is rather difficult.

One of the ways of constructing of the ancient surfaces of leveling consists in classification of a relief with the subsequent interpolation of the surfaces coupling positive topographic forms which have close values of altitude excess over the surface of modern base level (Georgievskiy, 2010). The distinction of the relative excess over basis of erosion testifies to different age of creation of a surface. Accordingly, more elevated surface is older (and on the contrary: the lower - the younger).

According to the succession stated above, for constructing a model from several surfaces of leveling, it is indispensable the expert appraisal of amount of ancient surfaces of leveling which can be developed in researched locale. And this appraisal should be based on the independent geomorphological data. After the performance of all indispensable steps, for the territory of the GIS-analysis we have received a set of such surfaces of the leveling having different age (and, accordingly, different altitude concerning basis of erosion).

The model representation for the set of surfaces of the leveling with different altitude (and, accordingly, different age) is shown on fig. 3. Matching of a configuration of surfaces of leveling allows drawing some qualitative takeouts on regional development of all territory. First, this model of surfaces of leveling (fig. 3) reveals some gradient zones for each of the leveling surfaces quite clearly. These gradients mark several zones of the most active development of a relief surface for the moment of the time at which the appropriate surface was the base level. Secondly, it is possible to draw a conclusion about configuration changes (including its space orientation) of such highly gradient zones. And, as it is represented on fig. 3, these changes have gradual nature and testifies to naturally determined changes of weak zones orientation (that have been characterized by maximum progressing of ancient erosive processes in the past).

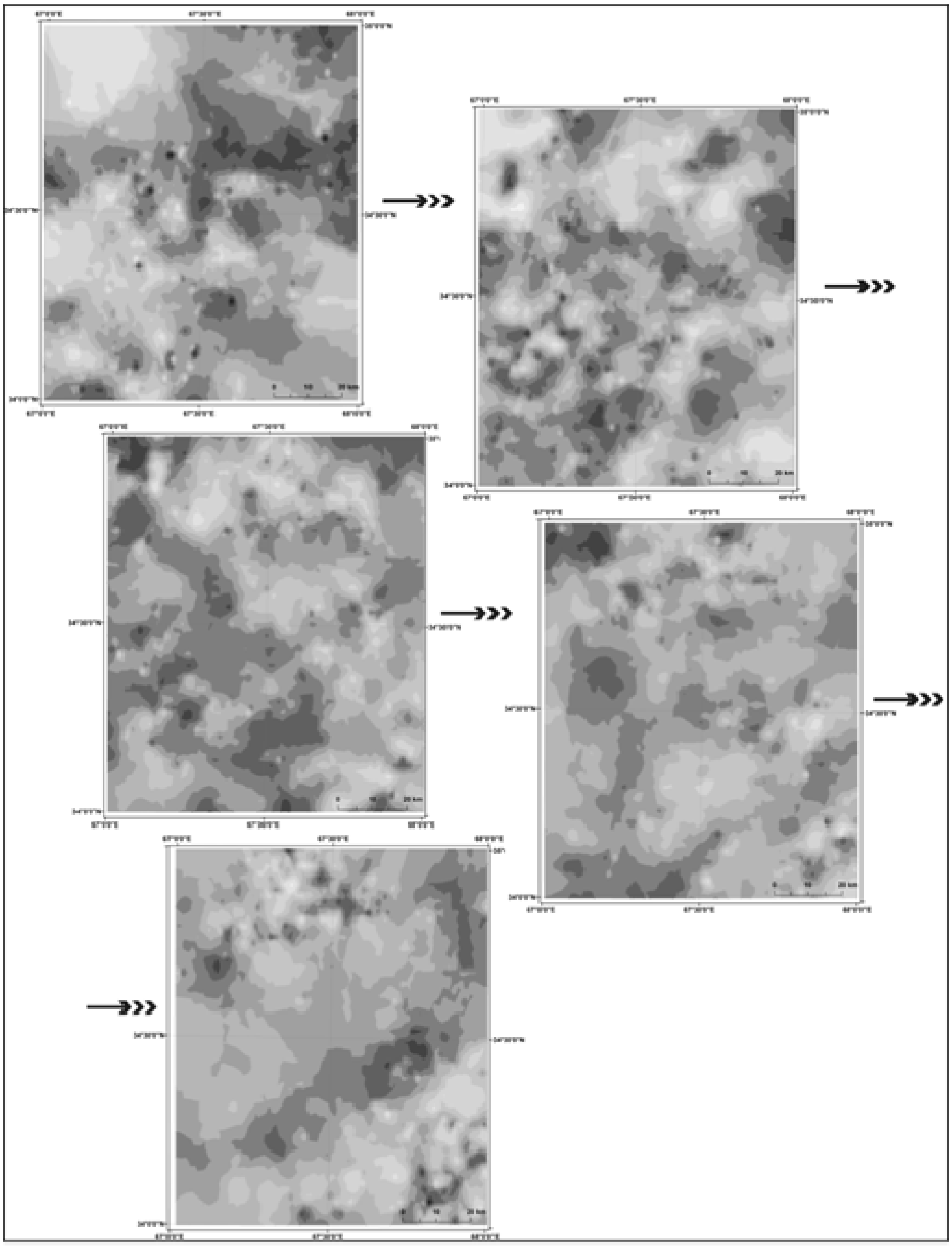

Figure 3: The model of transformation of Planation Surfaces from the highest and ancient (in the top of the figure) to the low and young (in the bottom of the figure). Each modeling picture in the figure presents an outline and a configuration of the most highly gradient zones. It is noteworthy the natural variation of configuration in transition from high surfaces to the young ones.

Besides, interpretation of a configuration of several consecutive planation surfaces can be useful for the typology of areas. First, the spatial arrangement of high gradient zones of various surfaces can differ, that is the configuration of weak zones in development of all landscape could change. Secondly, as the configuration of weak zones of ancient surfaces differs from a configuration of the modern weak zones (marked, particularly, by a modern drainage network). It means that the analysis of the set of planation surfaces can be useful to revealing potential weak zones which are not appeared in an explicit form in a modern landscape. These weak zones, in turn, can outline the active tectonic structures and neotectonic zones.

5. GIS-ANALYSIS OF THE LOCAL MORPHOLOGICAL STRUCTURES AND NEOTECTONIC EVOLUTION OF RELIEF

In this section are given the results of GIS-mapping that has been directed on the selection of the local morphological structures and neotectonically active zones. Herewith, as noted above, the geomorphological units are the homogeneous blocks (terrains) having similar values TRI. For each block (as geomorphological unit) there have been calculated different parameters intended for characterization of activity of modern geomorphological (and neotectonic) development. The list of such parameters, the way of their calculation, and their characteristic are shown in table 1.

Special features of the values shown in the table 1 consist in that the majority of indicators are calculated in relation to the geomorphological unit which they characterize. On the one hand separately taken tops are characterized under their relation to regional base level, and on the other hand – in relation to local, geomorphological homogeneous domains. For example, the value TopMinBas characterizes the relative excess of a separate top (peak) over base level (in the same point of space); the value TpMx_BasMx shows a difference between the maximum topographical marks within the block and the maximum mark of a base level surface within the same block. That is quantitatively characterizes the value which is related with the amount of erosion (which proceed within the block and is maintained by morphology of this block). The value TMB_min_A shows a difference between two values mentioned above. This value characterizes the difference between amount of potential erosion ("erosive potential") for discrete structures (i.e. separate morphological peaks) and for the delineated blocks with uniform geomorphological structure.

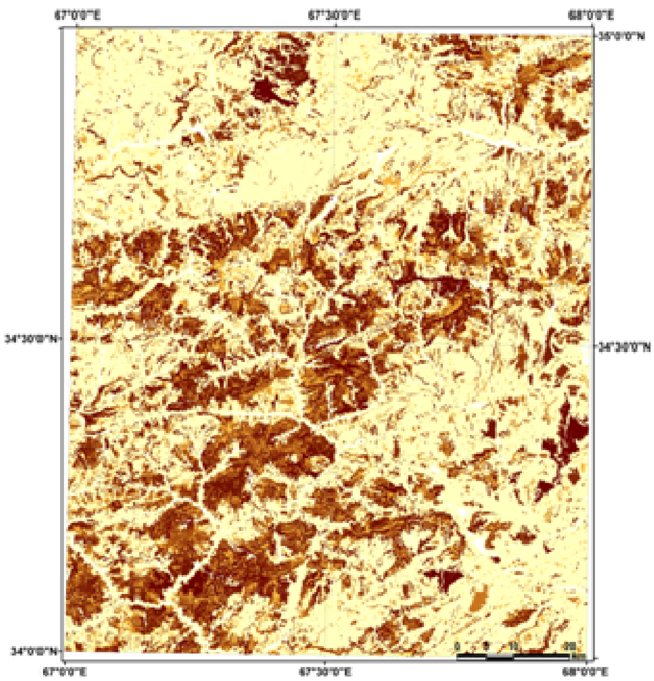

Figure 4: Map of the value TmxTn_TmxB, designed as a result of the semiautomatic GIS-based mapping of the neotectonic active structures. See text and table 1 for explanation. The structures which do not have accurately expressed topographic lineaments are designated on the map.

Table 1. The parameters calculated for morphologically homogeneous domains (blocks) in the studied area.

Value	Way of calculation	Characteristic of the parameter
TopMax	The maximum value of altitude of the block.	Characterizes the topographically highest area within the framework of morphologically homogeneous (including the unique genetic type) block.
TopMin	The minimum value of altitude of the block.	Characterizes the topographically lowest area within the homogeneous for genetic type block.
Rasch	Difference of values TopMax and TopMin.	Characterizes the maximum vertical amplitude of high-rise marks of the block.
TopMinBas	Difference between a topographical mark (altitude) for singly taken top (single morphologically expressed peak) and a high-rise mark of a surface of regional base level.	Excess of separate top over the basis of erosion. This value does not depend on absolute height of the top; it depends on relative height of the top over the basis of erosion.
TpMx_BseMi	Difference between the maximum topographical mark in the block and the minimum value (for the block) of the surface of regional basis of erosion.	Characteristics of potentially possible degree of erosion for the entire block. In this case the block represents a morphological unit which is developing under uniform erosive laws.
TpMx_BasMx	Difference between the maximum topographical mark and the maximum high-rise value of a surface of regional base level within the block.	Limit value of vertical amplitude of a relief which characterizes a degree of potential erosion processes supported by morphology of the block.
ToBaMin	The minimum value of difference between a high-rise mark of a surface and a high-rise mark (in the same point) of a base level surface, calculated for the block.	The minimum value representing a difference of an altitude of a surface and a high-rise mark of a base level surface within the block.
ToBaMax	The maximum value of difference between a high-rise mark of a surface and a high-rise mark (in the same point) of a base level surface, calculated for the block.	The maximum value representing a difference of an altitude of a surface and a high-rise mark of a base level surface within the block.
TMB_min_A	Difference between TopMinBas value and TpMx_BasMx value.	Characterizes degree of difference between local erosive potential (calculated for the separate positive form of a relief) and erosive potential of the block. This is the characteristic of degree of difference between local forms and structural domains where these forms are located.
TmxTn_ToBa	The relation of Rasch value to ToBaMax value.	Relation of the value of vertical ruggedness of relief to the value of the maximum excess of a relief over the base level (basis of erosion) within the block.
TmxTn_Tmax	The relation of Rasch value to TopMax value.	Relation of the value of vertical ruggedness of relief to the maximum absolute height (within the homogeneous block).
TmxTn_TmxB	The relation of Rasch value to TpMx_BseMi value.	Relation of the value of vertical ruggedness of relief to the value of the greatest possible erosive ruggedness within one block. Diapason of changes: from 0 to 1.

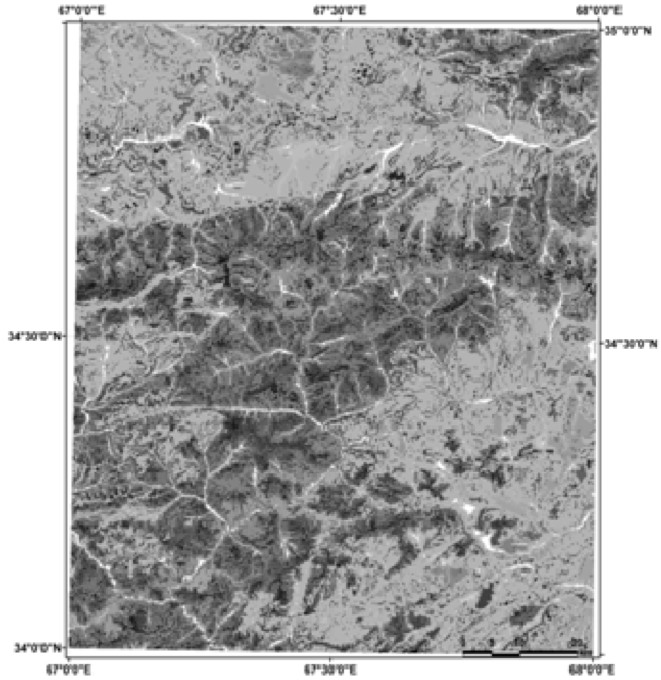

Figure 5: Map of value TmxTn_ToBa, designed as a result of the semiautomatic GIS-based mapping of the neotectonic active structures. See text.

Further, on the basis of these parameters, the maps of activity of the relief development have been designed. These maps characterize a degree of the newest (modern, quaternary) activity of relief for each of the homogeneous blocks. Examples of the maps of activity of relief on two of the parameters listed in the table 1 are shown in figures 4 and 5.

It is necessary to point out that in many cases the resultant maps have similar delineations while the parameters of the activity of relief (listed in table 1) have essentially different values. So, planned configuration and delineations of the majority of the structures marked on the map of fig. 5 have a similarity with the structures represented on fig. 4.

6. CHARACTERISTICS OF ACTIVE ZONES

Unlike the selection of the areas characterized by hyperactivity of evolution of a relief surface, one of methods of the performed GIS-analysis is directed on detection the local structures. In particular, linearly extended zones can be marked as quaternary faults or as zones of enhanced fracturing, etc.

The task of this method is a selection the local elements of relief that differ, on a ratio of several morphological parameters, from the adjoining territory surrounding the taken element. Such distinction can indicate a presence of a local (also linear) zone, within which the velocity of modern morphological development of surface differs (is bigger or lesser) from the velocity of morphological development of the adjoining (surrounding) surface. Most often such scenario can be observed near to active zone of faults (or, for example, near a zone of enhanced fracturing). In this case the planned configuration of these local zones corresponds to the planned configuration of tectonically active zones, and this similarity can be observed in different scales, up to regional similarity.

Due to the fact that with this approach the separate morphological unities have been analyzed (for example, the separate tops, indicated on the scheme described in section 4), it is necessary the further work on the results of the analysis: for example, the work with methods of space cluster analysis. On fig. 6 it is shown the scheme of configuration of the most active neotectonic structures, designed on the basis of Cluster Analysis using Anselin's Local Moran's I (performed using ArcMap, ESRI Inc.).

There is a likeness of a plan configuration of the active zones on this scheme and a plan configuration of the seismically active zones (fig.6, on right; after Boyd et al., 2007).

The important stage of this analysis is the interpretation of the received results (which are shown on fig. 6). As spatial cluster analysis has been performed for separate positive morphological structures (in particular, the value TMB_min_A has been statistically analyzed), the subsequent interpolation of point values and detection of the areas and zones with various degree of activity is necessary. On fig. 6 such interpolation is executed with one of the geostatistical methods, however similar results can be received with an expert estimation for one or several local areas.

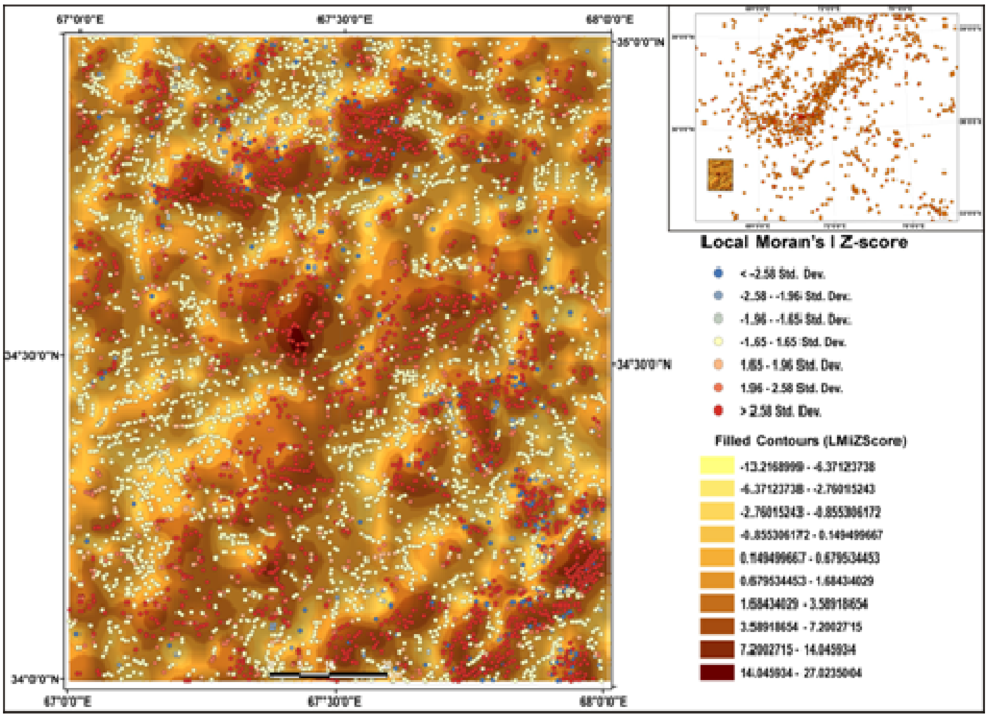

Figure 6: Scheme of configuration (on the left) of the most active neotectonic structures, designed on the basis of Cluster Analysis using Anselin's Local Moran's I (performed using ArcMap, ESRI Inc.). The scheme represents local sectors (darker sectors on the scheme) which have the most active mode of modern evolution against the background of general (regional) development of the terrain (lighter background on the scheme). Amazes the rather noticeable likeness of a plan configuration of active zones on the scheme at the left with a plan configuration of seismically active zones (after Boyd et al., 2007) in studied area in regional scale (see the scheme on inset) on the right. See text for explanation.

7. STRUCTURAL-MORPHOLOGICAL ANALYSIS OF THE TERRAIN ON THE MATERIALS OF REMOTE SENSING. VERIFICATION OF THE RESULTS OF THE GIS ANALYSIS.

A separate detailed work is indispensable for a correct substantiation of the results of the semiautomatic GIS-mapping and for the verification of the results received. Therefore we will bring out some very short illustrations (first of all, for observance of methodically completed nature of our research).

Fig. 7 and fig. 8 show the representations on remote sensing data for the regions that are defined by the modern tectonic activity. Area of the high activity on fig. 7 coincides with outlines and configuration of the regions identified by the cluster analysis and described as a zone of the greatest neotectonic activity (red points in the fig. 7). On the other hand, the radial configuration on fig. 8 is iterated completely on the map of value TmxTn_TmxB (see table 1 and fig. 4) and correlates with geometry of the zones on the map fig. 6.

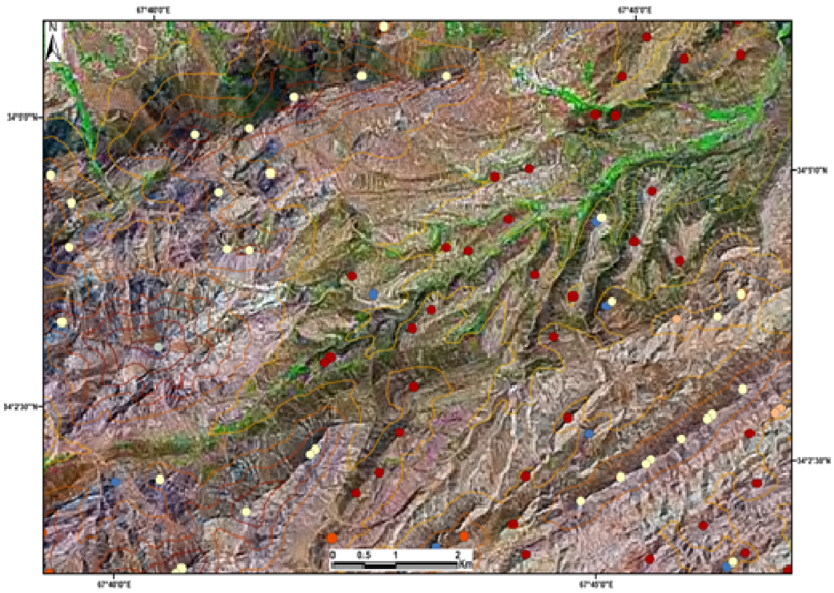

Figure 7: Representation on Remote Sensing Data of one of the regions that is defined by the modern tectonic activity (with diagonal rocker located structures in the middle area; on materials Landsat ETM +, https://zulu.ssc.nasa.gov/mrsid).

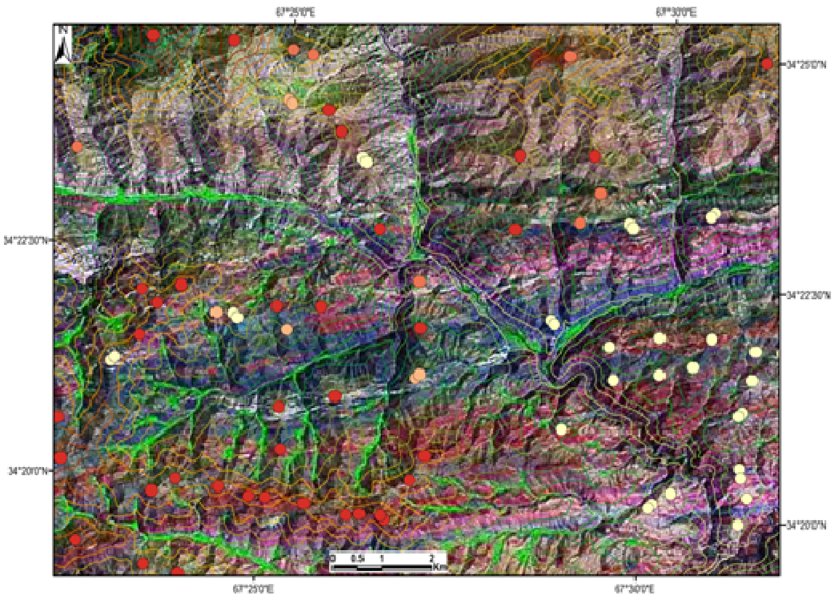

Figure 8: Representation on Remote Sensing Data (on materials Landsat ETM +, https://zulu.ssc.nasa.gov/mrsid) of one of the regions that is defined by the modern tectonic activity (with radial layout of the blocks with different neotectonic activity and, probably, with different age of relief).

CONCLUSION

The conducted research allows the following conclusions. The semiautomatic GIS-analysis of geomorphological mapping is a rather effective tool for selection the neotectonically active zones and the zones of local activity of relief. GIS-mapping should be associated with the expert analysis of structural, tectonic and geomorphological structure on the basis of independent geologic data and remote sensing data. The analysis and selection of morphometric and morphological unities should be on the basis of GIS-mapping. Besides, morphological unities should be described in terms of the age of their formation. For this purpose it is necessary to build the uneven-aged leveling surfaces which would include ancient planation surfaces and modern surface of base level. At last, the subsequent verification of the received results, based on independent geologic data, is indispensable.

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