On Classification of the Earth's Crust Areas by the Level of Geodynamic Threat

Andrian Batugin (as-bat@mail.ru)

• National University of Science and Technology «MISiS» https://orcid.org/0000-0002-9227-1160

Research Article

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Abstract

It is accepted as a well-known fact that a similar anthropogenic impact on the Earth's crust in different places causes dissimilar response. Seismic zoning maps are not designed to predict such geodynamic hazards as rock bursts, induced earthquakes, reactivation of tectonic faults, etc., and require careful adjustment in places of intense impact on the subsurface strata. In this regard, we consider the classification of the Earth's crust areas according to the degree of geodynamic hazard, i.e. its potential geodynamic response to anthropogenic intervention. This classification is based on the concept that there exists a critically stressed layer within the Earth’s crust. It is believed that such critically stressed layer within the Earth’s crust extends from the Earth's surface to a certain depth, which at each point depends on the nature of the interaction between crustal blocks of different hierarchical levels.

From this perspective, anthropogenic impact, such as mining operations, represents a direct impact upon the critically stressed zone. The hypothesis is accepted that the thicker is the critical stressed rock layer, the stronger might be the response to anthropogenic intervention, as it has more accumulated energy. Four categorized of the geodynamic threat were found and mapped. To verify this classification, the manifestations of the geodynamic hazards were studied. The intensity of geodynamic hazard increases from the 1st area to the 4th area. The phenomenon of large induced seismic events with hypocenters at great depths is explained by the base of this idea and could be associated with anthropogenic impacts from the surface directly on the regional zone of the critical stressed rock massif. The approach can be used to assess the geodynamic consequences of human exposure to the Earth's crust.

Introduction

The problem of seismic hazard assessment remains very relevant. New tools and research methods are used to refine maps of seismic zoning and identify hazardous areas [1-5]. Also in recent decades, issues involved in geodynamic phenomena associated with engineering activity are becoming ever more relevant despite the progress in solving these problems. In mining, the problem of rock bursts is transforming into the problem of induced earthquakes, which is especially threatening in case of mining areas with dozens of hazardous industrial facilities on the surface [6-16]. The activation of induced seismicity related to other types of engineering projects both underground and on the surface is also reported [17,18]. Obviously, it is the effect of engineering activity on the deeper parts of the Earth's crust that in many cases initiate tectonic earthquakes. Due to intensified induced seismicity in mining regions the seismic zoning maps have been significantly changed. For example, the map of seismic hazard of Germany was transformed after strong rock burst in the Werra mine [19], seismic zoning maps have been updated for mining regions of Kuzbass and for Sakhalin island (Russia) [20]. However, scientists point out that there is no adequate model to explain the occurrence of induced seismicity in some places, and the absence of such in other areas with seemingly the same impact [17, 21]. Also a lot of facts of the accidents concentration on pipelines and other engineering structures, occurring in certain places and not related to seismicity are difficult explained. Such places are called "geodynamically dangerous zones" because it is believed their nature is associated with the geodynamic processes in the Earth's crust and the relative movements of its blocks of different ranks [25].

It has been suggested that parts of the Earth's crust may be in a state "close to the stress- rupture strength" [22] "close to critically stressed state" [23], "in critically stressed condition" [24]. This idea is most explicitly expressed, in our opinion, in the works of I.M. Petukhov: "Generally, Earth's crust is in specific critical stress state". Petukhov I.M. believed that the Earth's crust is in critically stressed state from the Earth's surface to a certain depth, the latter determined by the interaction of crustal blocks. The key point in this hypothesis, came from rockmechanics researches, based on the similarity of geomechanical processes occurring in front of longwall (in coal seam) and in the Eearth's crust, is that the critically stressed part includes only a limited layer of the Earth's crust, namely from the surface to a certain depth [24]. In our opinion, these ideas can be used to develop a classification of the Earth's crust areas according to the degree of geodynamic hazard, which could to some extent add to the map of seismic zoning or replace it when planning engineering intrusion into the Earth's interior and engineering impact upon the Earth's surface. It is very important to know what kind of geodynamic response we will get for our intervention in the earth's interior. Considering that seismic zoning maps were made with no account of the technogenic impact on the Earth's interior and surface whereas our planet is quite densely populated and the effect on it is almost everywhere, we are in need to use all possibilities to estimate geodynamic hazards and risks. In this way the map of the Earth's crust areas ranked by the level of geodynamic threat might be considered as a new paradigm in assessing safe and harm-free human activities on the Earth.

Methods And Results

2.1 The seismically active layer of the Earth's crust and its connection with the critically stressed layer.

2.1.1 Earthquake source as an area of critically stressed condition of rock

One of the key factors indicating the threat of geodynamic events is the stressed state of the rock [26, 15, 27]. An integral reflection of the stressed condition of the Earth's crust is seismicity. The so-called shallow earthquakes occur in the inner parts of lithospheric plates, the source of such quakes is located within the Earth's crust.

The physics of the processes occurring in the seismic focus is the subject of numerous works, reviews of which are presented in [28, 22, 29]. In general terms, the earthquake focus zone is viewed upon as an area of destruction and the place where a new rupture develops or there is fault reactivation. It follows that the earthquake source at the final stage of the event preparation can be considered as a certain amount of rock in critical stressed condition.

2.1.2 Seismically active layer of the Earth's crust

It has been noticed that in seismic-active regions of the Earth most earthquakes occur at certain depths, which suggests the existence of a specific “seismically active layer” of the Earth's crust [30-33]. A typical distribution of seismic focuses by depth is provided in Figure 1, where it can be seen that their maximum number occur at a definite depth interval. These picture shows that there is a certain maximum depth of crustal earthquake hypocenters for areas inside lithospheric plates.

Generally, it is believed that a seismically active layer lies below the Earth's surface at a certain depth H, which corresponds to the brittle-plastic transition zone in the Earth's crust and approximately coincides with a temperature range of 300-400 ° [30, 33, 36, 37]. Based on statistical analysis of a large sample of data, in the review [33] is indicated that on average the H= 10 km and most earthquakes occurred within this seismically active layer. The source of earthquakes is the stress concentration in this area [30], associated with the interaction of the crust and mantle [31].

2.1.3 M. Petukhov’s hypotheses of the critically stressed condition of the Earth's crust.

Much earlier, the very first results of measuring rock stress showed that horizontal stresses exceed vertical values [38, 39]. This finding was explained by the presence of tectonic processes, and was subsequently confirmed by numerous tests and general conclusions [40]. I.M. Petukhov suggested that due to the strong compression of rock by horizontal forces, the source of which were global tectonic processes, certain areas inside lithospheric plates can accumulate critical stress [25]. By analogy with critically stressed zone in front of longwall (coal face), it was believed that critically stressed area in the Earth's crust extends through a certain layer under the earth's surface (Fig. 2). The depth of this layer depends on the magnitude of horizontal compression and the nature of the interaction between crustal blocks, and can vary from zero to the full thickness of the Earth’s crust.

Understanding of how the processes at the boundaries of plates affect the areas in remote parts of such plates is currently based on theoretical and experimental studies in this area. Geodynamic models have been developed for individual regions, demonstrating gradual transfer of deformations from the plate collision zone to internal parts of the blocks [41, 42].

2.2 Assessment of the thickness of the layer of crustal rock under critically stressed

We devised a calculation method based on a number of assumptions [43] to assess the thickness of the critically stressed layer of the Earth's crust. This calculations show that the thickness of this layer can vary from site to site, but these could not be used for practical purposes. Yet, if at a certain depth the rock accumulates critical stress, then this process should be accompanied by some or other seismic manifestation. It is the transition zone where rock acquires breaking stress that can be the main source of seismic events. Mining practice clearly demonstrates: microshocks and microseismic events occur in zones with maximum abutment pressure, in the transition zones where rock acquires critical stress. This concept of seismic event distribution throughout crustal depths underpins the author’s idea of classifying sections of the Earth’s crust according to the level of geodynamic hazard and risk.

3. Classifying sections of the Earth’s crust according to the level of geodynamic hazard.

3.1 Classification concept and classification attribute.

Rock can accumulate potential energy of elastic compression in critically stressed zones ahead of (coal) faces, where energy level is proportional to the squared value of acting stress and volume of the zone. Any impact on such stressed zone triggers instability, wherby part of the released energy transforms into the energy of geodynamic processes (bumps, spalling, rock bursts and tectonic rock bursts), and the remaining part is redistributed in the surrounding formation, causing rock displacements along the weakened surfaces and shifting stress to adjacent areas. As stress progressively builds up, the size of critically stressed zone increases, and the abutment pressure zone migrates into deeper areas. Hazardous condition is created if there is crushed or fractured material (tectonic fault zones) in those areas that is not able to absorb stress and that impedes movement of the abutment pressure zone depthward. Thus, an area of increased risk is created in front of such weakened zone, since in case of any impact on such stressed zone redistribution of energy into the surrounding formation gets constrained, and the proportion of energy that transforms into geodynamic energy increases.

Similarly, it can be assumed that anthropogenic impact on the deeper earth or the surface also creates instability due to the existence of critically stressed rock layer in the Earth’s crust. The significance of geomechanical effect imposed by engineering structures can be comprehended from the available research results. Observations of induced seismicity show that mining activity can cause earthquakes with epicenters located at 3-30 km distance from the mining area and with hypocenters that are several kilometers deeper [25, 44, 45]. A. McGarr believed that oil production activates the seismic process at great depths by relieving some of the load on fault planes [31]. In his book A. Sheydegger [46] cited F. Steinhauser and M. Caputo who had calculated that filling a dam pond with about 10^{10} m^3 of water brings about a change in the stress condition as far as the Moho discontinuity, i.e. for the entire thickness of the Earth’s crust.

It can be assumed that due to anthropogenic impact on the Earth’s interior or the surface part of the energy accumulated in the critically stressed rock layer transforms into the energy of geodynamic processes, and part is redistributed in the surrounding formation. The thicker is the critically stressed rock layer, the more energy is accumulated there and the larger energy can transforms into the energy of geodynamic processes. In other words, the thicker the critically stressed rock layer, the more hazardous it is to penetrate into underground area or impact to the Earth's surface, i.e. the greater is the geodynamic risk involved in antropogenic influence.

In addition, the thicker is the critically stressed rock layer, and the closer its thickness comes to that of the Earth's crust, the worse is the situation with redistribution of energy into the surrounding rock, since the rock of the upper mantle have a lower viscosity and cannot absorb the stress. In this situation, comparable with impacts on the critically stressed zone near a fault in a mine, the rate of energy redistribution into the surrounding rock may slow down, which will result in escalation of geodynamic threat (Fig. 3).

Consequently, geodynamic impact of engineering structures on critically stressed rock areas evokes immediate response. In some areas there are no extensive zones of critical stress, however, critical stress can be accumulated in sporadic small areas due to interaction of crustal blocks or engineering activities. Then, in response to engineering work geodynamic events might occur in these small critically stressed areas. The uniqueness of this critically stressed crustal layer is that it is not continuous, but includes sporadic sections (volumes) wherein stress has reached critical values; these volumes are distributed to a certain depth.

Next, conditions are created for excessive rock deformation in areas with critically stressed rocks. Under these conditions, the interaction and relative movement of crustal blocks can develop under stress well below the elastic limit. Moreover, deformation build-up (caused by displacement of blocks relative to each other along the boundaries separating them rather than by deformation of the entire rock mass) keeps occuring at ever lower stress values. Therefore, the thicker the layer of critically stressed rock, the easier and more intense the deformation of the Earth's surface can develop along the boundaries of the blocks under additional stress omposed by engineering structures, and the greater is threat to engineering facilities and technological operations.

Based on the foregoing, it is proposed to take - as a quantitative classification criterion - the ratio of the critically stressed rock layer thickness *Hs* to the thickness of the Earth's crust in this section *He.c.* : *n = Hs/He.c*. We can take the critically stressed rock layer thickness Hs in the Earth's crust equal to the depth of the bed of the seismically active layer, i.e. maximum depth of earthquakes in the area.

3.3 Estimation of the critically stressed rock layer thickness using data on the earthquake hypocenter

Since for estimating Hs we focus on the maximum depths of hypocenters, this greatly facilitates the selection of statistical data for analysis. Based on the data review on the maximum depths of hypocenters, the author obtained approximately 200 values of the relative depth of the seismically active layer, unevenly distributed throughout Northern Eurasia and having various errors, Figure 4. The number of points on the map (about 200) is statistically acceptable for testing the idea of classification. The part of data is in the Table 1.

Table 1

Data about earthquakes with maximum depth of hypocenter for areas

№	Date	Latitude	Longitude	Focal depth	Thickness of the Earth's crust, $H_{e.c.}$	H_s/ $H_{e.c.}$	Location
1	1467	57,2	39,4	7-30	40	25	Rostov-Yaroslavsky
2	1596	56,2	44,0	3	45	7	Nizhny Novgorod
5	1798	57,9	56,8	17-40	40	50	Perm Kungur
6	1803	53,1	23.1	5	35	14	Bialystok
7	1807	56,2	46,5	5	45	12	Kazan-N. Novgorod
8	1809	58,5	50,0	9	40	22	Vyatka
9	1813	58,7	59,9	15	40	37	Verkhoturye
10	1825	50,5	40,0	10	50	20	Pavlovsk Voronezh
11	1829	61,0	44,5	12	45	25	Middle reach of Sukhona river
12	1832	57,8	59,5	20	45	44	N. Tagil
13	1836	55,3	60,0	22	45	48	Between Zlatoust and Kyshtym
14	1847	58,4	59,5	15	45	33	Kushva
15	1858	50,0	36,3	5	50	10	Kharkov
16	1865	55,8	49,1	5	40	12	Kazan
17	1867	58,5	56,6	4	40	10	Dobryanka, Perm region
18	1881	59,4	28,1	4	45	10	Narva
19	1887	54,2	28,5	10	40	25	District of Borisov
20	1892	56,5	60,9	15	45	33	Sysert
21	1896	52,7	39,9	10	45	22	Lipetsk
22	1897	62,5	55,0	15	40	37	Soiva river
23	1902	56,1	59,3	12	45	27	Middle reach of Chusovaya river
24	1903	53,2	35,5	5	50	10	Oryol
25	1904	56,4	73,0	22-48	45	50	Ishim-Irtysh
26	1905	50,8	32,4	5	35	15	Chernigov region
27	1913	49,7	37,7	6	40	15	Kupyansk
28	1914	57,6	93,2	5	40	12	North of Krasnoyarsk
29	1914	65,5	53,5	15	40	37	Middle reach of Pechora river
30	1914	56,8	59,4	17-40	45	50	North of Sverdlovsk
31	1914	54,2	52,0	4	35	12	Soksky Yar, middle reach of Volga river
32	1926	57,3	67,0	20-80	40	50	Tyumen district
33	1934	58,9	57,5	5	40	12	Kizel district
34	1937	48,5	37,7	5	50	10	Donetsk region
35	1939	60,6	61,5	7	40	17	South of Syktyvkar
36	1944	51,7	36,2	5	45	12	Kursk
37	1954	53,0	40,0	7-30	40	25	Tambov district
38	1955	59,0	57,7	5-45	40	25	Bereznyaki district
39	1956	57,7	57,6	7-30	40	25	Perm region
40	1958	57,2	58,4	16	45	35	Between Sverdlovsk and Kungur

The author focused primarily on the most probable estimate of the earthquake depth, but for some earthquakes, a lower-bound estimate of the depth was used.

3.4 Classification of the Earth's crust areas by degree of geodynamic hazard

Based on the data obtained on the values of seismically active layer relative depth distribution and the block structure of the Earth's crust, it is possible to map the sections of the Earth's crust according to the geodynamic threat level. The possible number of map gradations (classification classes) can be selected taking into account the quality of the available factual information.

3.4.1 Defining possible number of gradations (levels).

Since there is only one quantitative attribute in the proposed classification (*n=Hs/He.c.*), the optimal number *r* of groups in the classification can be determined by the Sturges' formula (1):

$$r = 1 + 3{,}322 \cdot \lg N, \qquad (1)$$

where *N* is the number of statistical units. In this case, *N* = 200 and *r* = 9.

However, the number of groups defined with this formula is obviously overestimated due to the high uncertainty of the classification attribute. In our case, it can be shown that the squared relative error of the classification attribute *n = Hs/He.c.* is equal to the sum of the squared relative errors *Hs* and *He.c.* If we take the relative errors of values of *Hs* and *He.c.* as 0.1 (or 10%), then the relative error *n* will already be approximately 0.15. And since the values of *n* are in the range [0-1.0], the number of gradations (the number of groups) should be no more than 4 to 6. In addition, the *Hs* estimation relative errors can be much higher than 0.1, as follows from the materials in Table 1. As for the thickness of the Earth's crust *He.c.*, there are arguments that relative errors in its estimation can be significantly higher than 0.1.

Furthermore, the error in defining depth *Hs* increases with the depth value. And this leads to the fact that group intervals become uneven. So, for *n* > 0.5, the errors in the determination of *Hs* build-up so that it is no longer possible to divide the interval 0.5-1.0 into smaller groups. All this allows us to arrange the entire set of *n* values into three unequal intervals: 0-0.25; 0.25-0.5 and 0.5-1.0. In addition, aseismic territories can be represented as territories with a zero value of the critical stressed layer and spin them off into a separate (first) group.

3.4.2 Map of the Earth's crust sections with geodynamic threat rating

In 1990–2010 work was being done to draw a map of geodynamic zoning (I. Batugin's, I. Petukhov's terminology) for Russia and adjacent territories [25]. Maps were drawn for the territory of the former USSR and China. This work was based on the concept of hierarchically discrete structure of the rock and the Earth's crust as a whole. This concept is recognized at the current stage of the development of science as the most significant advance in geomechanical and geodynamic research made at the end of the last century [47] and is used in current research on geodynamics and rockmechanics [11, 48, 49]. To build a map montage of the Earth's crust sections with geodynamic threat rating, the author made use of a map of the crustal block structure from [25]. Following criteria were applied to the map montage:

- geometrical configuration of areas with different gradations on the map are selected with due account for the block structure of the Earth's crust. It is assumed that the shape of such areas, due to the fundamental nature of the crustal discrete structure, corresponds to the geometric shapes of individual blocks or groups of blocks

- if the coordinates of several earthquakes coincide, the earthquake with the maximum depth of the hypocenter is displayed on the map
- if earthquakes from different gradation groups fall into the same block of rank I, then the maximum value for the entire block is accepted. Blocks with equal gradations are combined into corresponding areas

Map montage where the above assumptions are taken into account is provided in Figure 5.

Discussion

4.1 Validation of classification

Take in account the distribution of a number of parameters attributed to geodynamic hazard to check the validity of the proposed hypothesis and classification. These parameters include presence of rock burst prone fields in the selected area, the initial depth of the rock burst occurence, the manifestation of induced earthquakes, the manifestation of strong rock bursts with walls displacements (tectonic rock bursts, according to Russian classification).

First consider, for example, the distribution of rock burst hazardous deposits through these areas. 40 rock burst hazardous ore deposits are listed in the Appendix to the Guidelines on the safe mining at deposits liable to and threatened by rock bursts [50]. Their distribution over areas of varying level of burst risk is presented in Table 2.

Table 2

Distribution of rock burst hazardous ore deposits over the regions of the former USSR by areas of varying level of geodynamic threat

The level of geodynamic threat	1	2	3	4
Number of deposits, %	0	10	40	50

It can be seen that both rows in table 2 are ranked in ascending order, and this shows a direct relationship between them: the higher the level of geodynamic hazard, the larger is the proportion of burst-hazardous deposits. Formally, the relationship between the data presented in the table can be estimated by calculating, for example, the values of the Spearman rank correlation coefficient [51]:

$$R_S = 1 - \frac{6\sum d^2}{n^3 - n} = 1 - \frac{6\sum d^2}{n(n^2-1)}, \qquad (2)$$

where n – number of gradations (ranks), d- rank difference.

To determine the Spearman rank correlation coefficient Rs between the geodynamic hazard level of the Earth's crust and the proportion of burst-hazardous deposits located in these areas, it is necessary to arrange the data in the rows of Table 3 in ascending order and replace their values with ranks. The rank of a value is its number in an ordered row.

Let us present the initial, ordered and ranked values of the two variables in question in a tabulated form (Table 3).

Table 3
Spearman rank correlation coefficient

Values of the first variable			Values of the second variable			Rank difference, d
Input value	Ordered value	Ranks	Input	Ordered	Ranks	
1st	1	1	0	0	1	0
2nd	2	2	10	10	2	0
3d	3	3	40	40	3	0
4th	4	4	50	50	4	0

Since d = 0 for all rows of Table 3, the required Spearman rank correlation coefficient Rs (according to formula 2) is 1.

The value of the rank correlation coefficient Rs = 1 indicates that there is already mentioned correlation between the level of geodynamic threat in the target area of the Earth's crust and the number of burst hazardous deposits located in these areas: the higher the level of geodynamic hazard, the more burst hazardous deposits are located there. For n = 4, according to Table 4 from [51], we conclude that the existence of this relationship (with Rs = 1) between the variables in this case can only be acknowledged at a significance level of q= 0.2, i.e. these data indicate with a probability of 0.8 that such relationship does exist.

Table 4
Spearman rank correlation coefficient critical values [51]

	Significance level q				
N	0.50	0.20	0.10	0.05	0.02
4	0.600	1.000	1.000		
5	0.500	0.800	0.900	1.000	1,000

Much the same, it can be shown that a similar relationship (only with Rs = -1) can be traced between the level of geodynamic hazard of the Earth's crust area and the minimum depth of rock burst manifestation (the greater the level of geodynamic threat, the lesser the depth of rock burst manifestation), Table 5. Also the greater the level of geodynamic threat, the bigger displacement amplitude along fault planes during strong rock bursts with walls displacements (tectonic rock bursts, according to Russian classification), Table 6.

Table 5

The minimum depth of rock burst manifestation at coal deposits

The deposit or region	The minimum depth of rock burst manifestation	The level of geodynamic threat
Mosbass (Tula region)	did not appear	1
Donbass (Ukraine)	800	2
North of Kuzbass, Siberia	350	2
South of Kusbass, Siberia	190	3
Shurab, Georgia	150	4

Table 6

The fault reactivation during strong rock bursts

Deposit	The displacement amplitude along fault plane during rock burst, cm	The level of geodynamic threat
The North Ural bauxite	7	3
The Tashtagol, Siberia	5	3
Beipiao, China	17	4

4.2 The analyses of induced earthquakes manifestation in the context of the critically stressed state of the Earth's crust concept

A number of strong earthquakes that occurred in areas of intensive exploitation of underground mineral resources or extensive works on the Earth's surface are being discussed regarding their possible nature, for example [52, 53, 31, 54, 55, 42, 56]. Oftentimes the argument against the anthropogenic nature of such earthquakes is the fact that its hypocenter is at a depth far exceeding the depth of anthropogenic impact. Another argument is that the magnitude of the main event is so great.

One of these events is the Bachat earthquake (M_L = 6.1), which occurred in the coal region of Siberia, Kuzbass [45]. The epicenter of this earthquake was located exactly at the Bachat coal pit site, which indicated its technogenic origin. The depth of the hypocenter is estimated at 4 km. The coal pit had a length of about 10 km, a width of 2 km, and a depth of about 320 m. The main shock of this earthquake came out as a reverse fault. It provided the ground to assume that the earthquake reactivated a major Salair reverse fault that undercuts the pit at a great depth and extends across the maximum compression axis of the current stress field [57, 58]. However, it is difficult to explain how mining work in a three hundred meter depth (only!) pit could activate a fault passing underneath at a depth of several kilometers. Yet, one can try to explain this using the concept considered in this paper.

4.2.1 Possible nature of the Bachat and other induced earthquakes

Relying on the empirical formulas where the size of the earthquake source L (cm) depends on its magnitude M, [59]:

$$\lg L = 0.57M + 2.64 \qquad (3)$$

We can obtain that size L of the Bachat earthquake source with a magnitude ML = 6.1 was about 10 km. Looking at the earthquake source as a zone of the critically stressed state of the Earth’s crust, we assume that the Earth’s crust in and around the pit was in a critically stressed state from the Earth’s surface per se to a depth of several kilometers (Fig. 6). In this case, mining operations in the pit where millions of tons of material (coal and rock) is rehandled annually and up to 350 tons of explosives are blasted on a weekly basis can be considered as the factor of the persistent direct geomechanical technogenic impact on the critically stressed crustal area. Under natural conditions, when geological processes proceed quite slowly, the energy of the critically stressed crustal zones has enough time to be redistributed in the rock mass and conditions for its release in dynamic form may not be created. However, in case of mining operations, blasting, injecting and pumping out fluids through wells, other intrusions into the rock mass, the rate of stress build up may exceed the rate of rock relaxation, which creates the conditions for the onset of geodynamic events.

We can recognize the nature of strong earthquakes, which supposed to be induced, is similar to the conditions of the Bachat earthquake described above: the depth of the hypocenter and size of the focal zone indicates that before the earthquake there were impacts to the critical stressed zone which propogating from the Earth's surface depthward.

The Neftegorsk earthquake on Sakhalin island (1995), for example, had a magnitude M = 7 and the depth of its hypocenter was 16-18 km [60]. The size of the focal zone, according to research materials, was up to 40 km. Earth's crust in vicinity of Sakhalin island is 32-35 km thick. Considering the earthquake source as a critically stressed area, we get that prior to the earthquake the Earth's crust in this area was in a critically stressed state throughout its entire thickness (4^{th} degree of the geodynamic threat). In this regard, oil exstraction activity can be looked upon as a geomechanical impact directed straight on the critically stressed crustal zone. The impact on this zone results in the prompt redistribution of stress in the Earth's crust, which, in case the entire rock thickness is in critically stressed condition, may turn into hazardous dynamic event.

Next some examples are shown in the Table 7. Size of focus zones L were calculated by formula (3). They can be represented by the above-described scheme: the hypocenter depth, magnitude and the size of the focus associated with it indicate that anthropogenic impact was brought about from the surface directly onto the regional zone of the critically stressed rock.

Table 7

Examples of earthquakes that apparently originated due to anthropogenic impact on the critically stressed crustal area

No	Event	Magnitude	H, depth of hypocenter, km	Source	L, size of focus zone, km	Ratio R/H	The answer for key question
1	Bachat, 2013	$M_L = 6.1$	4-10	[45]	10	2.5-1	Yes
2	Sachalin, 1995	M=7	18-20	[60]	42	2	Yes
3	Gazly, gas deposit, 1976 and 1984	$M_s = 7$	10 (1984); 16 (1976)	[52]	42	3-4	Yes
4	Caviaga Gastfield, Italy, 1951	5.4	5	[61]	6	>1	Yes
5	Gorkha, Nepal earthquake	Mw = 7.8	15	[42, 56]	100 (20)	Till 5?	Yes
6	Goalinda oil field, California, 1983	$M_w = 6.2$	10	[31]	14	>1	Yes
7	Kettleman North Dom oil field, California, 1985	Mw = 6.1	10	[31]	12	>1	Yes
8	Montebello Fields (oil), California, 1987	Mw = 5,9	10	[31]	8	1	Yes

*Key question: Is it possible to infer that there was critically stressed crustal zone in this place extended from the Earth's surface into the deeper Earth and anthropogenic impact influenced directly to this zone?

The data provided in this Table 7 can be considered as evidence that induced earthquakes are commonly manifested in the critically stressed layer of the Earth's crust under anthropogenic impact. The strongest of them occur in areas where the Earth's crust can be represented as being in an critically stressed state throughout its entire thickness (the 4th level of the geodynamic threat).

What happens here is obviously the overlapping impact of two factors (natural and anthropogenic) on realization of the geodynamic hazard. Actually, this has long been reflected in the terms denoting induced earthquakes: natural-technogenic, technogenic-natural, trigger-type earthquakes [12, 62, 31]. However, seismic zoning maps are still made taking into account just one single factor (natural). That is why the above examples can be used to substantiate the classification considered.

4.3 Hierarchy of areas prone to geodynamic hazard

As follows from the concept of hierarchical manifestation of the rock block properties and structure, areas of the Eearth's crust shown in Figure 5 same as the layers of critically stressed rock can include less hazardous sub-areas (blocks of lower rank). That is, the most risky sections of the 4th level of threat can include sub-sections of the 3rd, 2nd and 1st level; areas of the 3rd level of threat may include subsections of the 2nd and the 1st level; areas of the 2nd level of hazard may include sub-sections of the 1st level. It appears that such detailing could be done in the future.

The author considers this classification as a method for assessing the geodynamic threat to support the development of mineral resources and the Earth's surface. To use this classification, the location of the proposed project must be mapped. The level of geodynamic hazard determined on the map will also outline the range of possible geodynamic consequences of developing mineral resources and the Earth's surface for a given area.

Conclusion

1. Geodynamic hazard ranking of crustal areas can be made based upon the concept of the critically stressed layer in the Earth's crust. Four classes (types) of crustal areas can be distinguished in this ranking provided the key classification criterion is the ratio $n = Hs/H_c$ of the seismically active layer propagation depth Hs to the thickness of the Earth's crust $H_{e.c.}$. Areas included into the 1st class are the ones with least level of geodynamic threat, n = 0%; areas of the 2nd class have n = 0-25%; areas of the 3rd type have n = 25-50% and areas falling into the 4th category have n > 50%
2. If we assume that the geometric configuration of zones with different level of geodynamic threat depend on the shape of crustal megablocks, then distribution of empirical data on the manifestation of geodynamic hazards in the northern part of Eurasia shows that the diversity of forms and intensity increase from class 1 areas to class 4
3. Facts such as the minimum depth of the rock burst manifestations, the spatial localization of such deposits, the manifestation of tectonic rock bursts and induced earthquakes can be described in the frame of classification: the intensity of geodynamic hazard increases from the 1st area to the 4th
4. The phenomenon of mining operations giving rise to large seismic activations with hypocenters at great depths is based on the concept of critically stressed condition of the Earth's crust. The Bachat and other induced earthquakes where hypocenter depths, magnitudes and size of seismic focus are evidence that anthropogenic intrusion from the surface was directed onto the regional zone of the critically stressed rock mass. The strongest induced earthquakes occurred in area with 4th level of geodynamic

5. The ongoing increase in the influence of human activity on the Earth's crust and the Earth's surface and the relevance of issues involved in ensuring geodynamic safety makes it possible for the author to propose that the idea of creating an adequate classification should be discussed in professional

References

1. A.D. Zavyalov, S.A. Peretokin, T.I. Danilova, N.S. Medvedeva, K.N. Akatova, General seismic zoning from maps GSZ-97 to maps GSZ-2016 and maps of new generation in the parameters of physical characteristics, Voprosy Inzhenernoi Seismologii (Problems of Engineering Seismology), 45(4) (2018) 47–68. https://doi.org/10.21455/VIS2018.4-4.
2. S.D. Gregori, R. Christiansen, Seismic hazard analysis for central-western Argentina. Geodesy and Geodynamics, 9(1) (2018) 25-33. https://doi.org/10.1016/j.geog.2017.07.006.
3. H. Chao, Z. Wang, J. Li, Z. Cui, The latest activities of faults in the Tai'an region, Shandong province and the Taishan mountain earthquake, Dizhen Dizhi. 21(2) (1999) 105-114.
4. A.K. Nekrasova, V.G. Kossobokov, I.A. Parvez, X. Tao, Unified scaling law for earthquakes as applied to assessment of seismic hazard and associate risks, Izvestiya, Physics of the Solid Earth. 56(1) (2020) 83-94. https://doi.org/10.1134/S1069351320010097.
5. R. Stefánsson, Useful predictions ahead of large earthquakes and lessons learned for future progress, Geodesy and Geodynamics 11(1) (2020) 1-17. https://doi.org/10.1016/j.geog.2019.07.005
6. I.M. Petukhov, Rock bursts in coal mines, Moscow, 2004.
7. T. Li, M.F. Cai, M. Cai, A review of mining-induced seismicity in China, Int. J. Rock. Mech. Min. Sci. 44 (2007) 1149-71. https://doi.org/10.1016/j.ijmms.2007.06.02.
8. A. Lovchikov, Review of the strongest rockbursts and mining-induced earthquakes in Russia, Journal of Mining Science 49(4) (2013) 572-75. https://doi.org/10.1134/S1062739149040072.
9. R. Dyagilev, Induced seismicity and seismic hazard in mining regions, 2015. Proceedings of the 15th International Multidisciplinary Scientific GeoConference SGEM-2015. 3(1) (2015) 879-886. e153999.
10. A. A. Kozyrev, I.E. Semenova, O.G. Zhuravleva, A.V. Panteleev, Hypothesis of strong seismic event origin in rasvumchorr mine on January 9, 2018, Mining Informational and Analytical Bulletin. 12 (2018) 74-83. https://doi.org/10.25018/0236-1493-2018-12-0-74-83.
11. I. Yu. Rasskazov, B.G. Saksin, V.I. Usikov, M.I. Potapchuk, Rock mass geodynamics and mining-induced rockbursting at Nikolaev complex deposit, Gornyi Zhurnal 12 (2016) 13-19. https://doi.org/10.17580/gzh.2016.12.03.
12. V.V. Adushkin, Technogenic tectonic seismicity in Kuzbass, Russian Geology and Geophysics 59(5) (2018) 571-83. https://doi.org/10.1016/j.rgg.2018.04.01.
13. G. Feng, P. Wang , Y.P. Chugh, J. Zhao , Z.Wang, Z. Zhang, 2018. A coal burst mitigation strategy for tailgate during deep mining of inclined longwall top coal caving panels at huafeng coal mine, Shock and Vibration. e5929785, https://doi.org/doi:10.1155/2018/59297850.

14. A. Keneti, B. Sainsbury, Review of published rockburst events and their contributing factors, Engineering Geology 246 (2018) 361-73. https://doi.org/10.1016/j.enggeo.2018.10.005.
15. M. He, H. Xia, X. Jia, W. Gong, F. Zhao, K. Liang, Studies on classification, criteria and control of rockbursts, Journal of Rock Mechanics and Geotechnical Engineering 4(2) (2012) 97-114. https://doi.org/10.3724/SP.J.1235.2012.00097.
16. A. Batugin , K. Kolikov, A. Ivannikov, Yu. Ignatov, D. Krasnoshtanov, Transformation of the geodynamic hazard manifestation forms in mining areas, Proceedings of the 19th International Multidisciplinary Scientific GeoConference SGEM-2019, 19(1.3) (2019) 717- 24, https://doi.org/10.5593/sgem2019/1.3.
17. G.R. Foulger, V.P. Wilson, J.G. Gluyas, B.R. Julian, R.J. Davies, Global review of human- induced earthquakes, Earth-Science Reviews 178 (2018) 438-514. https://doi.org/10.1016/j.earscirev.2017.07.008
18. J-R Grasso, D. Amorese, A. Karimov, Anthropogenic seismicity as aftershocks for geo- resource production? Implications for Mmax estimates (reservoir impoundment cases), Geophysical Journal International. 219(2) (2019) 958-967. https://doi.org/doi:10.1093/gji/ggz337.
19. G. Grünthal, W. Minkley, Mining induced seismic activity as a source for seismic design load - the necessity of an amendment of the seismic zonation map of the DIN 4149:2005-04. [Bergbauinduzierte seismische aktivität als quelle seismischer belastungen zur notwendigkeit der ergänzung der karte der erdbebenzonen der DIN 4149:2005-04], Bautechnik. 82(8) (2005) 508-513. https://doi.org/10.1002/bate.200590167.
20. V.I. Ulomov, M.I. Bogdanov (Ed.), A set of maps of general seismic zoning of the Russian Federation territory OSR-2016, Moscow, 2016.
21. M.W. Hitzman, (Ed.) Induced Seismicity Potential in Energy Technologies, National Academies Press, Washington, D.C., 2013.
22. G.A. Sobolev, A.B. Ponomarev, Physic of Earthquake and precursor, Moscow, 2003.
23. W.L. Ellsworth, 2013. Injection-induced earthquakes. Science 341(6142), e1225942. https://doi.org/10.1126/science.1225942.
24. I.M. Petukhov, On the nature of horizontal forces in the Earth's crust, Study and forecast of displacements and deformations of rock mass, hydrogeomechanical processes during mining of deposits by underground and open-pit methods: Scientific works of Institute of Geomechanics (VNIMI), (1991) 237-243. Saint-Peterburg [In Russian].
25. I.M. Petukhov, I.M. Batugina, Geodynamic of Earth's Interrior, Moscow. 1999.
26. M. Batugina, I.M. Petukhov, Geodynamic zoning of mineral deposits for planning and exploitation of mines, Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi. 1990.
27. J. Han, H. Zhang, B. Liang B, et al., Influence of Large Syncline on In Situ Stress Field: A Case Study of the Kaiping Coalfield, China, Rock Mech Rock Eng. 49 (2016) 4423-4440. https://doi.org/10.1007/s00603-016-1039-4.

28. J. Rice, The mechanics of the earthquake rupture. Physics of the Earth's Interrior. (1980) 555-649, Amsterdam.
29. M. Ohnaka, The physics of rock failure and Earthquakes, Cambridge. 2013.
30. R.H. Sibson, Continental fault structure and the shallow earthquake source, J. Geol. Soc. 140 (1983) 741-767.
31. A. McGarr, On a possible connection between three major earthquakes in California and oil production, Bull.Seismol. Soc. Am. 81 (1991) 948-970.
32. K.G. Levy, Tectonic movements and seismically active (focal) layer of the continental lithosphere, Seismicity of the Baikal rift. (1990) 7-16. Novosibirsk. [In Russian].
33. S. Lin, J. Ji, & J. Su, Statistical analysis of global earthquake focal depth and distribution of seismic layer. [□□□□□□□□□□□□□□□□□□] Scientia Geologica Sinica. 54(4) (2019) 1167-1184. https://doi.org/10.12017/dzkx.2019.066.
34. Lithosperic dynamics atlas of China, Beijing,
35. F.N. Yudakhin, O.K. Chedia, T.V. Sabitova et al., 1991. Modern geodynamics of the Tien Shan lithosphere. Moscow. [In Russian].
36. K. Ito, Seismogenic layer, reflective lower crust, surface heat flow and large inland earthquakes, Tectonophysics, 306(3-4) (1999) 423-433. https://doi.org/10.1016/S0040- 1951(99)00069-4.
37. Z. Zhou, W. Deng, C. Xiang, Advances of research on the intracrustal seismogenic layer, Dizhen Dizhi, 20(4) (1998), 452-453.
38. N. Hast, The measurement of rock pressure in mines, Norstedt, Stockholm, 1958.
39. S.A. Batugin, A.T. Shamanskaya, Investigations of the stressed state of a rock mass by the stress-relieving method under conditions of the tashtagol iron-ore deposit, J. Soviet Mining Science 1(2) (1965) 100-104. https://doi.org/10.1007/BF02501935.
40. M.L. Zoback, M.D. Zoback, J. Adams et al., Global patterns of tectonic stress, Nature, 341(6240) (1989) 291-98.
41. N.L. Dobretsov, M.M. Buslov, D. Delvaux, Mezo- and Genozoic tectonics of the Central Asian mountain belt: effect of litospheric plate interaction and mantle plume, International Geology Revew 38 (1996) 430-66.
42. B. Kundu, N.K. Vissa, V.K. Gahalaut, Influence of anthropogenic groundwater unloading in Indo-Gangetic plains on the 25 April 2015 Mw 7.8 Gorkha, Nepal earthquake, Geophys. Res. Lett. 42 (2015) 10607-10613. https://doi.org/10.1002/2015GL066616.
43. A.S. Batugin, I.M. Petukhov, To the evaluation of the stressed state of the plots of the Earth's crust, J. Mining Inform. and Analytical Bull. 1 (1998) 146-151. [In Russian].
44. H. Marcak, G. Mutke, Seismic activation of tectonic stresses by mining, Journal of Seismology 17(4) (2013) 1139-48. https://doi.org/10.1007/s10950-013-9382-3.
45. A.F. Emanov, A.A. Emanov, A.F. Fateev, E.V. Leskova, Mining-induced seismicity at open pit mines in Kuzbass (Bachatsky earthquake on June 18, 2013, Journal of Mining Science 50(2) (2014) 224–

228.
46. A.E. Scheidegger, Principles of geodynamic, Moscow, 1984. [In Russian]
47. N.N. Melnikov (Chief Ed.) Geomechanical fields and processes: Experimental-analytical research into initiation and growth of accidental event in mining-engineering and natural systems, Vol 1-2. Novosibirsk, Russia. 2018 [In Russian].
48. J. Han, H-W. Zhang, S. Li, Research on rockburst based on the hierarchy of rock mechanics system, The International Symposium on Rockbursts and Seismicity in Mines, 8 (2009) 427– 434.
49. G.G. Kocharyan, Geomechanics of Faults, Moscow. 2016. [In Russian].
50. Instructions for the safe mining in ore and non-metallic deposits, Leningrad, Russia, 1999. [In Russian].
51. A.G. Stanton, Primer of Biostatistics. 7th Edition. San Francisco, 2012. (ISBN 978-0-07- 179440-4).
52. D.W. Simpson, W. Leith, The 1976 and 1984 Gazli, USSR, earthquakes—were they induced?, Bull. Seismol. Soc. Am. 75 (1985) 1465-1468.
53. I.M. Plotnikova, B.S. Nurtaev, J.R. Grasso, L.M. Matasova, , R. Bossu, The character and extent of seismic deformation in the focal zone of Gazli earthquakes of 1976 and 1984, M 7.0. Pure Appl. Geophys. 147 (1996) 377–387.
54. C.D. Klose, Evidence for anthropogenic surface loading as trigger mechanism of the 2008 Wenchuan earthquake. Environ., Earth Sci. 66 (2012) 1439-47. https://doi.org/10.1007/s12665-011-1355-7.
55. K. Deng, S. Zhou, R. Wang, R. Robinson, C. Zhao,Wanzheng Cheng. Evidence that the 2008 Mw 7.9 Wenchuan Earthquake Could Not Have Been Induced by the Zipingpu Reservoir, Bulletin of the Seismological Society of America, 2010. Vol. 100. (5B) (2010) 2805–2814.
56. L. Zhang, J. Li, W. Liao, & Q. Wang, Source rupture process of the 2015 Gorkha, Nepal Mw7.9 earthquake and its tectonic implications. Geodesy and Geodynamics, 7(2) (2016) 124- 131. https://doi.org/10.1016/j.geog.2016.03.001
57. A. Batugin, Critically Stressed Areas of Earth's Crust as Medium for Man-caused Hazards, 2018. Proceedings of the E3S Web of Conferences 56 e02007, https://doi: 10.1051/e3sconf/20185602007.
58. A. Batugin, Reactivation of major faults during strong rock bursts as realization of tectonic process, Rock Mechanics for Natural Resources and Infrastructure Development – Fontoura Rossa and Pavon Mendoza (Edd). IRSM-2019 (Brasil), (2020) 1261-1268.
59. M. A. Sadovski, Selected Works, Moscow, 2004.
60. A.Yu. Polets, T.K. Zlobin, The study of the features of the focal zone of the destructive Neftegorsk earthquake on May 27 (28), 1995, Proceedings of the International Conference Geodynamic Processes and Natural Hazards, Lessons of Neftegorsk (2015) 141-45.
61. M. Caciagli, R. Camassi, S. Danesi, S. Pondrelli, S. Salimbeni, (2015) Can we consider the 1951 Caviaga (Northern Italy) earthquakes as noninduced events?, Seismological Research Letters. 86(5) (2015) 1335-1344. https://doi.org/doi:10.1785/0220150001P.

62. D. V. Yakovlev, T. I. Lazarevich, S.V. Tsirel', S. V. Natural and induced seismic activity in Kuzbass. Journal of Mining Science, 49(6), (2013) 862-872. https://doi.org/10.1134/S1062739149060038

Declarations

Competing interests: I declare no competing interests.

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Figures

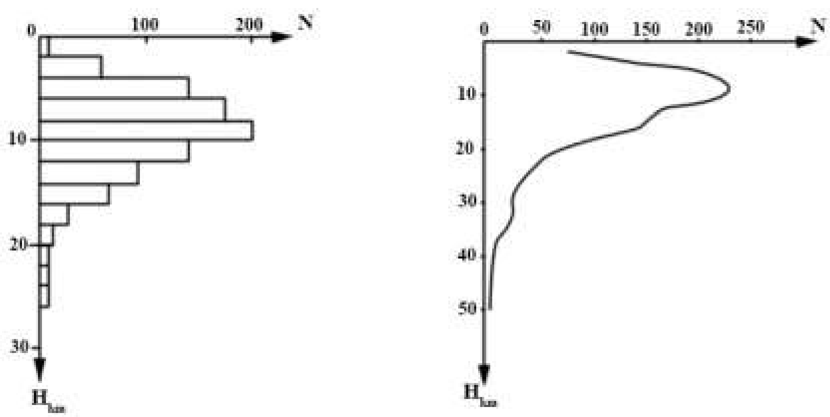

Figure 1

Seismic depth distribution in the northeast of China [34] and Tien Shan [35].

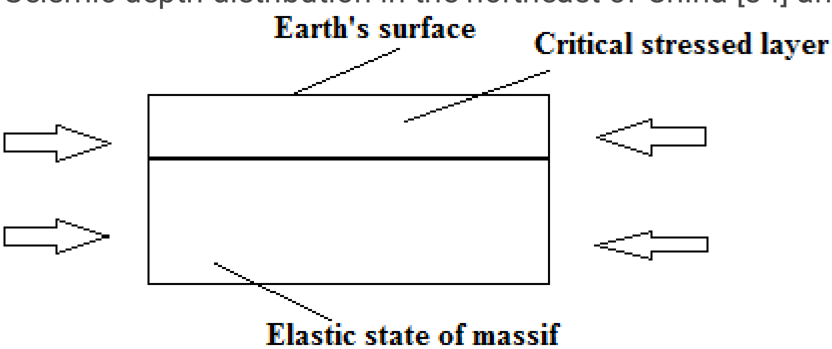

Figure 2

Scheme of lacation of critical stressed layer in the Earth’s crust (by Petukhov I.M.)

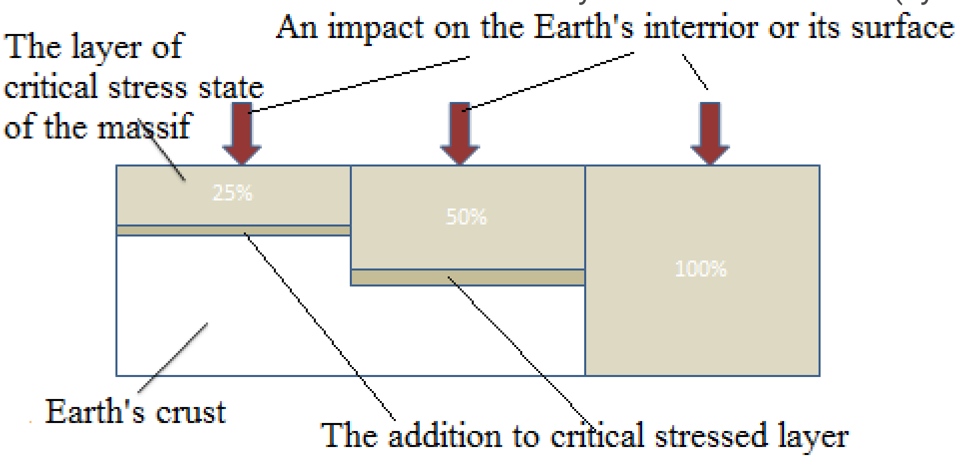

Figure 3

Scheme of Earth’s areas with various thickness of critical stressed layer

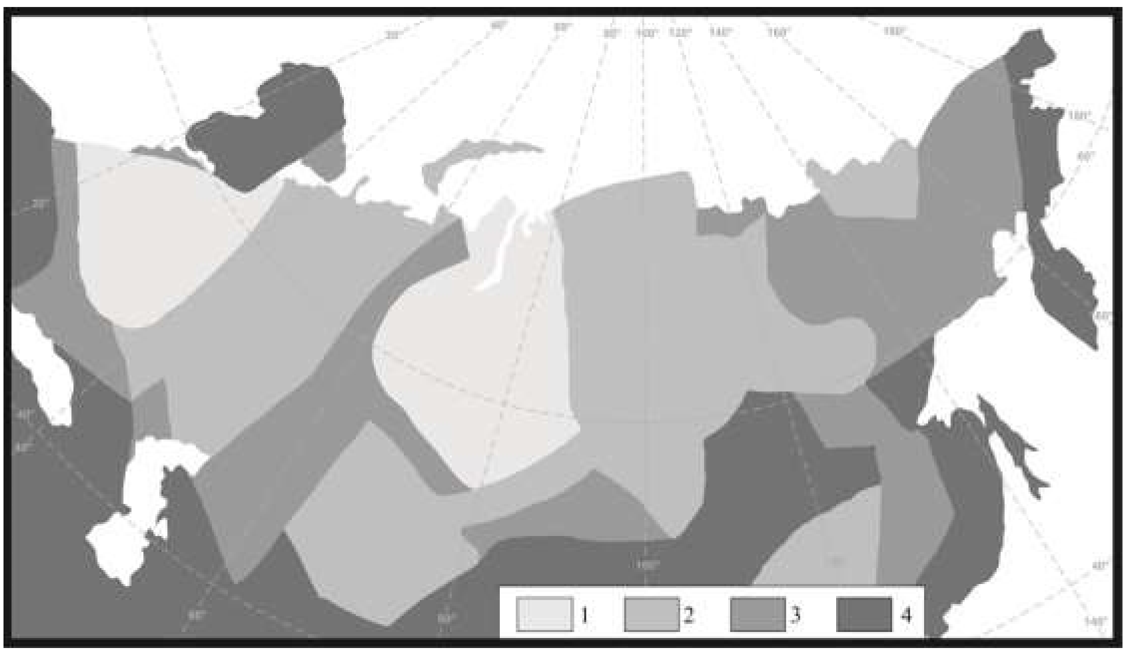

Figure 4

Scheme of crustal areas showing 1-4 levels of geodynamic threat. 1-4 – crustal areas according to 1-4 levels of geodynamic threat

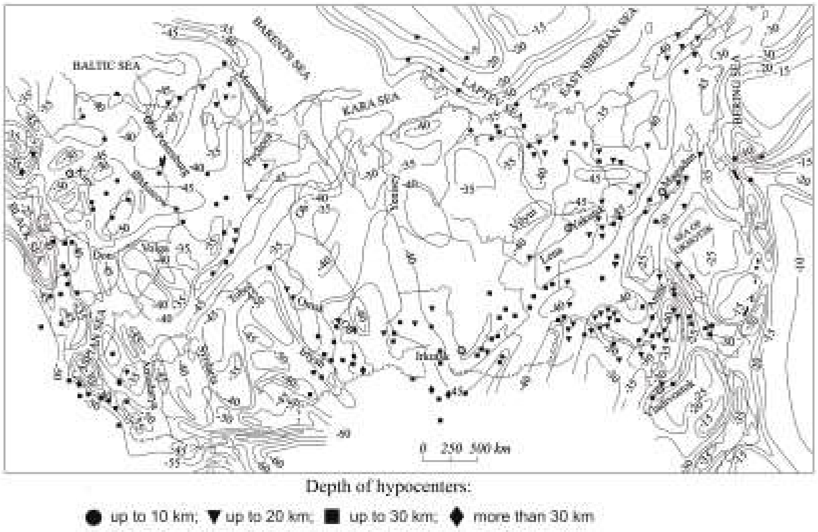

Figure 5

The earthquake epicenters layout with established focal depths on the map of thickness of the Earth's crust

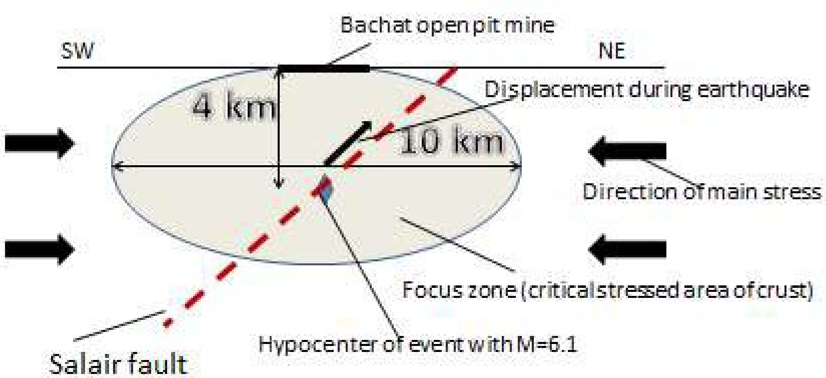

Figure 6

Scheme of the nature and the mechanism of the Bachat earthquake