

## On the method of assessment of seismotectonic potential

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**Abstract** - In the scope of this work we have investigated the interrelation of seismicity with geological features and rock mechanical properties mainly on the example of the eastern part of the Baltic Shield. It has been found that earthquake occurrence depends on the rock lithology, its age and the geological evolution of the region. The empirical relationship between energy strength and maximum magnitude are offered. It was revealed that occurrence of the largest earthquakes of the region is connected with undeformed granitized blocks of the crust or granitoid batholithes that have been associated with compression processes. It is known that the typical Archean granite-greenstone highly fractured crust shows a layered formation with variable deformational properties and reduced efficient brittleness. The maps of energy strength, seismic potential and maximum magnitude of the north part of the Kola Peninsula were compiled.

### 1. Introduction

Seismic hazard assessment has some uncertainties in seismic regionalization or the maximum magnitude ( $M_{max}$ ) determination procedure, where  $M_{max}$  is defined as maximum magnitude (energy) of the earthquake that can occur in the local area. It seems likely that these problems cannot be investigated only by seismological methods. That is why a combination of geological, geophysical and seismological data is used in some research, (e.g. Assinovskaya and Solovyev, 1994).

This work is an attempt to solve seismic hazard assessment problems by means of the geomechanical representation of seismic processes.

It is known that earthquake occurrence and quantity of released energy ( $M_{max}$ ) depend on Earth crust geodynamical as well as geomechanical behaviour. Moreover, in the earthquake energy balance as a whole, the first component far exceeds the second one but generation

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of energy in impulse non-creep form is impossible without certain properties of the rock volume. It is particularly obvious in the regions with weak seismic activity and low velocity of seismotectonic deformations. Probably, it is also true for more active regions but at a higher magnitude level. We tried to relate geomechanical features to maximum possible earthquake magnitude using the Baltic Shield and especially its eastern part as an example (Assinovskaya, 2000). This region is a good natural laboratory because of a nearly uncovered basement where earthquakes originate, a well-studied deep structure and known geomechanical properties of the crust.

## **2. Relationship between seismicity and strength properties of crust**

Fennoscandian seismicity is a manifestation of destructive processes in the ancient crust. Tangential stresses and earthquake zones are concentrated in the most rigid parts of the basement. The comparison of seismicity (Ahjos and Uski, 1992) with geological data (Gaal, 1986) for the eastern part of the region shows that such structures as the Lapland granitoid intrusion, the Central Finland Granitoid Complex and parts of the Archean granitized crust are more seismically active than mafic greenstone areas. The earthquake zones often extend along borderline faults or they are situated in inner parts of granitoid structures. The source depths are not more than 15-17 km (Bungum and Lindholm, 1997). It can be shown that seismic event occurrences and maximum possible magnitude are determined by strength properties of the crust depending on: 1) rock lithology; 2) geological age; 3) present-day and past stress regimes, and 4) form and size of structures.

## **3. Rock characteristics. Brittleness**

The influence of rock lithology on strength properties is noticeable first of all if we compare coefficients of brittleness over a wide range of world rock morphologies (Dortman, 1992).

The coefficient of brittleness is a ratio of rock compressional strength to its tensile strength (Rzhevsky and Novik, 1984). Fig. 1 shows the distribution of these parameters for different kinds of rocks. One can see that rocks with high quartz contents (granitoid and quartzite) have the greatest values of coefficient of brittleness. The lowest value is the value for dunite, and the highest is the value for quartzite, and they differ by about a factor of five. It is worth emphasizing that the estimations obtained are highly approximated due to substantial scattering of rock property determinations that is caused by the influence of inhomogeneous crack structures of specimens and factors mentioned above such as lithology, age, etc.

There is also a specific geomechanics problem caused by the so-called "scale effect" (Mansurov, 1990), when rock strength parameters measured in a laboratory appear essentially greater than parameters measured in-situ in rock massif.

In this work we try to overcome the difficulties mentioned by the inclusion of corresponding corrections in the final results which may decrease the scale effect.

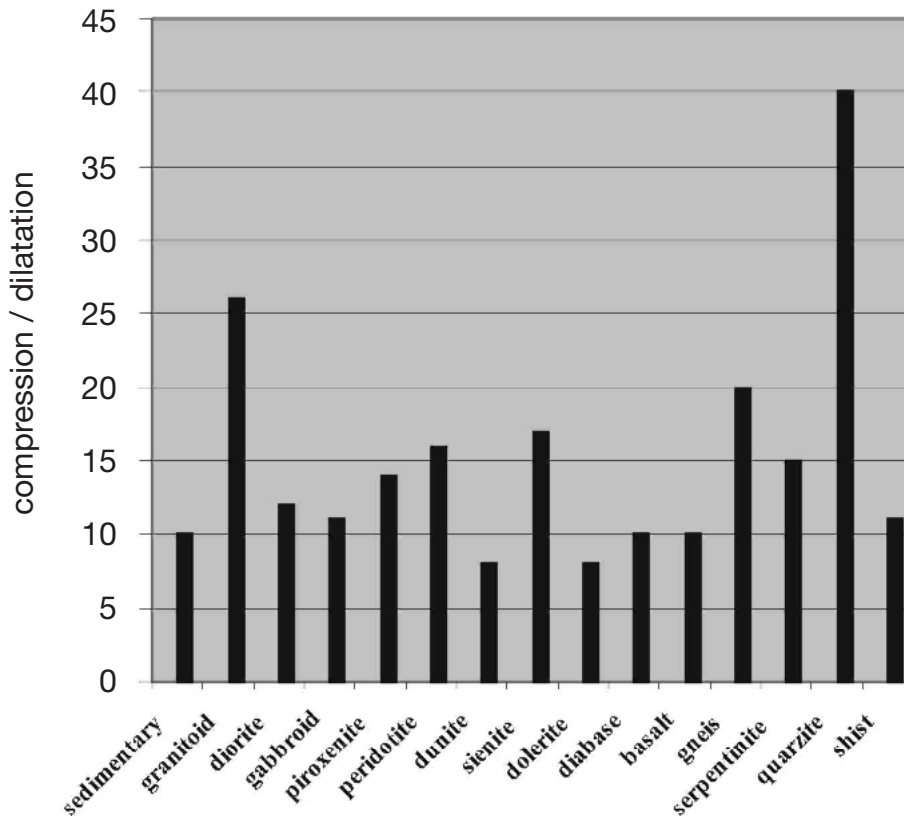


Fig. 1 - Coefficients of rock brittleness (dimensionless) for the whole world.

#### 4. Shear strength

It is known that deep-Earth ruptures are of shear type in the crustal earthquake sources (Aki and Richards, 1980), that is why the shear strength is the most important rock mechanical parameter in our research.

It is found that rocks with high quartz content have not only the maximum brittleness but the maximum shear strength also (Krilov and Ten, 1994).

The shear strength  $\sigma_{\tau}$  is determined according to the Mohr strength theory when there is a dependence between tangential and normal stresses in an isotropic body that is subjected to three-dimensional stress. This dependence can be described by linear, exponential, parabolic, hyperbolic etc. functions (Rzhevsky and Novik, 1984; Stavrogin and Protosenja, 1992).

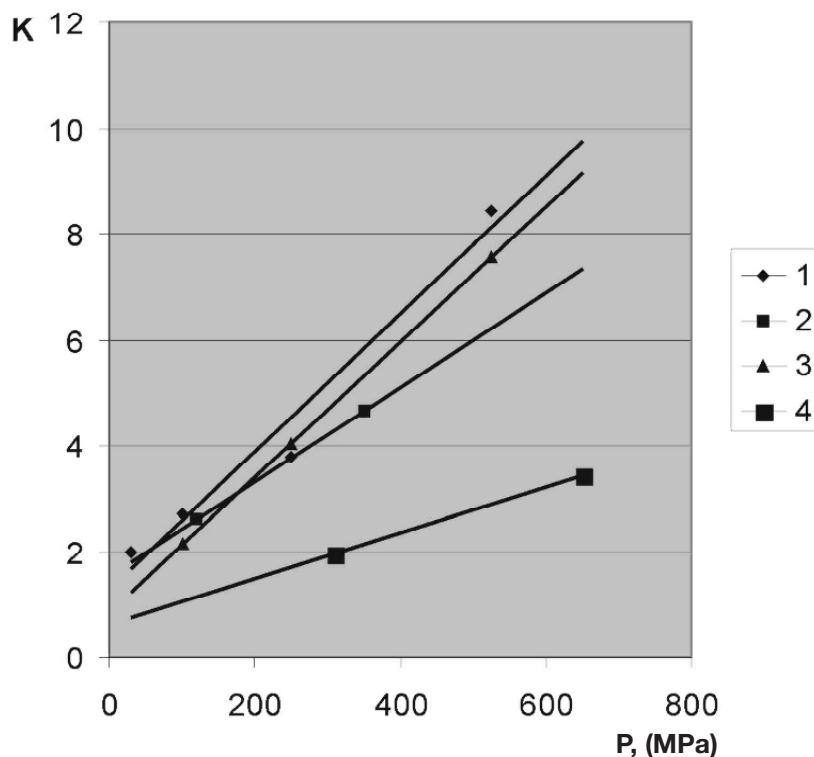
There are several ways to determine shear strength: it can be obtained from graphic interpretation of results of direct deformation-strength tests of rock specimens on high-pressure equipment for a wide range of temperatures and external pressures or derived from the known compression and dilatation data using the analytic Mohr relationship.

The first way is described in Krilov and Ten (1994), where instantaneous ultimate shear strength of all major types of magmatic and metamorphic rocks was determined. We used the

second way and applied the parabolic relationship to calculate ultimate shear strength (Fairhurst, 1964; Rzhovsky and Novik, 1984) but used some results of Krilov and Ten (1994) (see below).

$$\sigma\tau = [(\sigma_d' + P) * (2 * \sigma_d' - 2 * (\sigma_d' + \sigma_c')^{0.5} * \sigma_d') + \sigma_c']^{0.5} \tag{1}$$

where  $\sigma_d' = \sigma_d * K$  and  $\sigma_c' = \sigma_c * K$ ,  $\sigma_d'$  and  $\sigma_c'$  are the tensile and compressional strength in MPa at the pressure  $P$  (MPa) and temperature 20°C,  $\sigma_d$  and  $\sigma_c$  are the same parameters at the atmosphere pressure and temperature 20°C.  $\sigma\tau$  is the shear strength and  $P$  is the geostatic pressure (both in MPa) at the depth of interest. The special coefficients  $K$  (Fig. 2), that were obtained from Krilov and Ten (1994), allow for the increase of strength  $\sigma_c$  and  $\sigma_d$  with depth.



**Fig. 2** - Coefficients  $K$  of increase of strength  $\sigma_c$  and  $\sigma_d$  with depth for different morphologies. Explanations: 1 – felsic rock; 2 – mafic rock; 3 – intermediate rock; 4 – ultramafic rock.

The temperature as well as the pressure influences the strength and the elastic modulus of rocks. The values of these parameters decrease with the increase of temperature. The strength of basalt, peridotite and dunite decreases by a factor of 2 when heating to 400-600°C at a hydrostatic pressure of 500 MPa (Krilov and Ten, 1994).

But it is known that the heat flow is very low in the Baltic Shield (Muir Wood, 1993). According to the Kola superdeep well data the temperature at a depth of 15-20 km is not more than 200°C (Kozlovsky, 1984) and it does not have a significant influence on strength properties. So, the temperature effect was not taken into account in our case. But it is very important to take it into account for regions with high heat flow.

We used published information about geomechanical rock properties related mainly to the eastern part of the Baltic Shield (Melnikov et al., 1975, 1981; Kozlovsky, 1984; SSSRD 150-190, 1991) and certain world summaries (Dortman, 1992) as a basis for calculations. All this data were obtained from laboratory specimen measurements. The database of geomechanical properties of crustal rock was compiled and used to assess their impact on seismic potential.

## 5. Energy strength

It is known that the specific energy of shear deformation or specific potential energy  $W$  (energy strength), is connected with shear stress (in the limit with ultimate shear strength  $\sigma_t$ ) by the following relationship (Javorsky and Detlaf, 1964):

$$W = \sigma_t^2 / 2G \quad (2)$$

where  $G$  is shear modulus, and  $W$  means volume density of potential energy accumulated by the rock during its formation and geological history.

The rock potential energy release happens under the action of tectonic forces. If the averaged density of external energy (i.e tectonic forces) in a certain environment volume exceeds the rock energy strength then the elastic energy release happens (Sadovsky et al., 1987). For example, when rock specimen undergoes three-dimensional compression testing approximately half of the energy accumulated by rock over the strength limit releases as dynamic effects (seismic waves) (Stavrogin and Protosenja, 1992). The quantity of energy capable of being released depends on the level of external forces as well as the environment's ability to accumulate and to sustain energy (Sadovsky et al., 1987). It is clear that this ability will be defined by environment properties.

The theoretical model describing earthquake destruction criteria and seismic processes in terms of material strength limit does not exist only for the variable behaviour of strength parameters (Aki and Richards, 1980). The connection between the crust geomechanical properties and energetic earthquake characteristics is evident on qualitative and empiric levels (Burov and Diamant, 1995). For example, if examining not only the Fennoscandian seismicity but also the interplate seismicity in the global range, one can see that the seismically active is only the most brittle upper granite – methamorphic part of the crust. The sources (at least at the beginning of the rupture) of the largest crustal earthquakes in Central Asia, Sakhalin, India, and California are connected in one way or another with granitoids (Hain, 1971, 1977, 1984; MES, 1995). The maximum magnitudes of shallow intraplate earthquakes with source zones that are concentrated in basalts of the Middle Atlantic ridge did not exceed 7 – 7.2 for 40 years of observation (Boldyrev, 1998). The cases of seismic event occurrence with the sources in unstable sedimentary rocks are few in number (Grasso and Feigner, 1990).

So, the empiric relationship between energy strength  $W$  and source density  $SD$  was obtained on the basis of the following assumptions: crustal earthquakes of maximum energy ( $M = 8.9$ ) occur in the environment of the most solid but brittle quartz-type rocks, merely notional

earthquakes of minimum energy ( $M \cong 2$ ) can take place in sedimentary rocks, the occurrence of intermediate earthquakes ( $M = 7.2$ ) are connected with ocean basalts. The experimental data for limestone geomechanical parameters in induced earthquake sources (the Lacq gas field, France; Grasso and Feigner, 1990) were also used. The data for  $W$  calculation were taken from Dortman (1992) and Krilov and Ten (1994).

The relationship between rock energy strength  $W$  and source density of earthquake energy  $SD$  (seismic potential) was obtained from a spline fit to the above mentioned data for geostatic pressure of 400 MPa (15 km depth) and is expressed by the following formula:

$$\log SD = -2.0682 \log W^2 + 34.27 \log W - 136.1 \quad (3)$$

Knowing the rock properties in the probable source environments, it is possible to estimate seismic potential  $SD$  that can be corrected considering geological age and stress regime history.

Then it is easy to obtain magnitude value from seismic potential  $SD$  using the known Gutenberg – Richter relationship and the source radius (Gutenberg and Richter, 1956; Riznichenko, 1976):

$$SD = E / 1.33\pi R^3 \quad (4)$$

and

$$\log E = 1.8M + 4 \quad (5)$$

where  $E$  is earthquake energy,  $R$  is source radius.

The correction of the parameter  $SD$  for rock age was obtained due to correlation between rock age in the range  $(0.4 - 3.2) \cdot 10^3$  Ma and magnitudes between 4 and 6 of observed Fennoscandian earthquakes. We noticed that seismic activity in the region increases from east to west with the decreasing of the rock age. Considering that the greatest seismic events occur in the younger crust and low seismic activity is connected to the old destroyed crust, it is possible to make an empirical correlation between event size and rock age (Fig. 3). One proposed dot for  $M$  8.9 and age  $0.001 \cdot 10^3$  Ma was added to the analyzed data to cover larger magnitude range.

The correction coefficients  $K_a$  (Table 1) were calculated on the base of the obtained relationship and with the assumption that the maximum magnitude value is 8.9 at the minimum crust age.

The corresponding magnitude  $M_a$  values were obtained in accordance with known rock age (Fig. 3), then  $K_a$  were calculated by the formula:  $K_a = SD_{M_a} / SD_{8.9}$ . Accordingly, value  $SD$  from Eq. (3) with an age correction equals  $SD/K_a$ .

It has been observed that some rigid batholith massifs like Finland Rapakivi granite are characterized by a lower level of seismicity in spite of high rock strength (Ahjos and Uski, 1992). This fact was connected with the generation environment of the batholith. It is known that Rapakivi granites were formed in dilatation stress conditions (Korja, 1995). The comparison of observed earthquake magnitudes in this massif and corresponding data for the Ladoga-Bothnian old thrust (compression) zone shows that source density of earthquake energy  $SD$  can

**Table 1** - Age correction coefficients.

Age (10 <sup>3</sup> Ma)	<i>K<sub>a</sub></i>
3.1	658
2.5	298
1.9	99
1.3	36
0.8	17
0.3	8

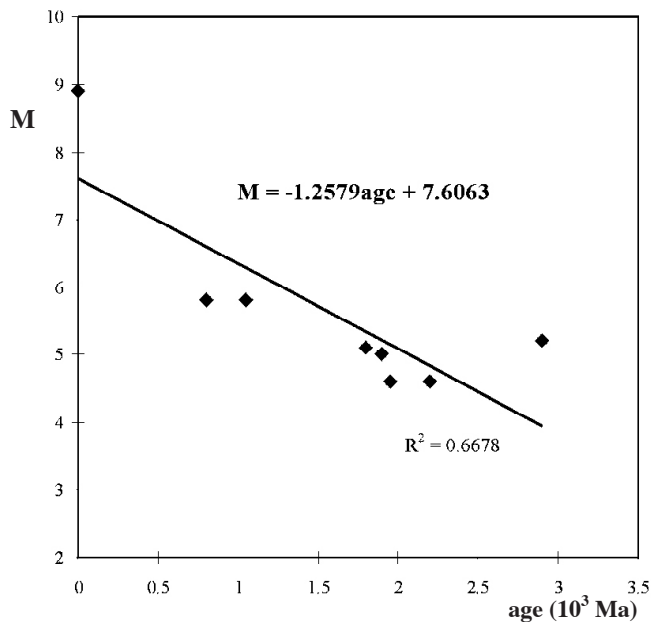
**Table 2** - *M<sub>max</sub>* determination.

<i>M</i>	<i>SD</i> (erg/cm <sup>3</sup> )
2.2	40
3.2	100
4.2	400
5.2	1500
6.2	5000
7.2	18000
8.2	66000

be lowered by a factor of 10 for structures that had mostly dilatation conditions during their geological history. By the way, present-day world stress data (Mueller et al., 2000) give a factor of 1.2.

It should be noticed that we determine here not the quantitative level of stresses but only the relationship between compression and dilatation features, considering that comparably young rocks exposed to the environment are characterized by maximum strength values. The combined stress fields of all geological development epochs have generated contemporary strength properties of the crust at great depth, while new tectonic stresses can mainly influence only surface structures (Wahlstrom and Assinovskaya, 1998).

So, we incorporate the common effect of present-day stresses into the whole stress regime correction. On the other hand, the present-day tectonic stress-strain level and its type point to the degree of external tectonic action on geological structures. As a result, a state of spatial stress occurs affecting the environment strength properties. The possible environment



**Fig. 3** - Relationship between the rock's geological age and observed 1375 -1999 Fennoscandian earthquake magnitudes of 4-6.

strengthening in earthquake sources under the action of additional high tectonic stresses is not taken into account by the Eq. (3) for the lack of necessary data. It leads to underestimation of the result. Though this underestimation is probably compensated by the neglect of seismic efficiency when only one half of the rock energy (Stavrogin and Protosenja, 1992) or still less is expended for seismic wave generation.

Finally, the maximum earthquake magnitude  $M_{max}$  is related to the size and form of structures (Table 2). The correlation between  $M_{max}$ , dimensions of quasihomogeneous area of earthquake preparation and fault length is shown, for example, in Kasahara (1985), Ulomov et al. (1990), Assinovskaya (1994). We take up only granitoid batholith bodies and their analogues in our research because intrusions of other forms have too little volume at a depth of earthquake occurrence.

The results obtained can be used for the first stage of seismic hazard assessment that is done by compiling a seismic zonation map. We offer the next sequence of steps:

- regionalization of area according to stress regime history, age, as well as depths and forms of structures;
- preparation of regional database of geomechanical properties. If it is impossible, using data for other parts of the world for similar rock types;
- calculation of shear strength  $\sigma_{\tau}$ , specific potential energy  $W$ , source density of earthquake energy (seismic potential)  $SD$  and maximum possible magnitude for each structure using given formulas;
- preparation of  $W$ ,  $SD$ ,  $M_{max}$  maps;
- correlation between potential and active faults data to get a seismic zonation map.

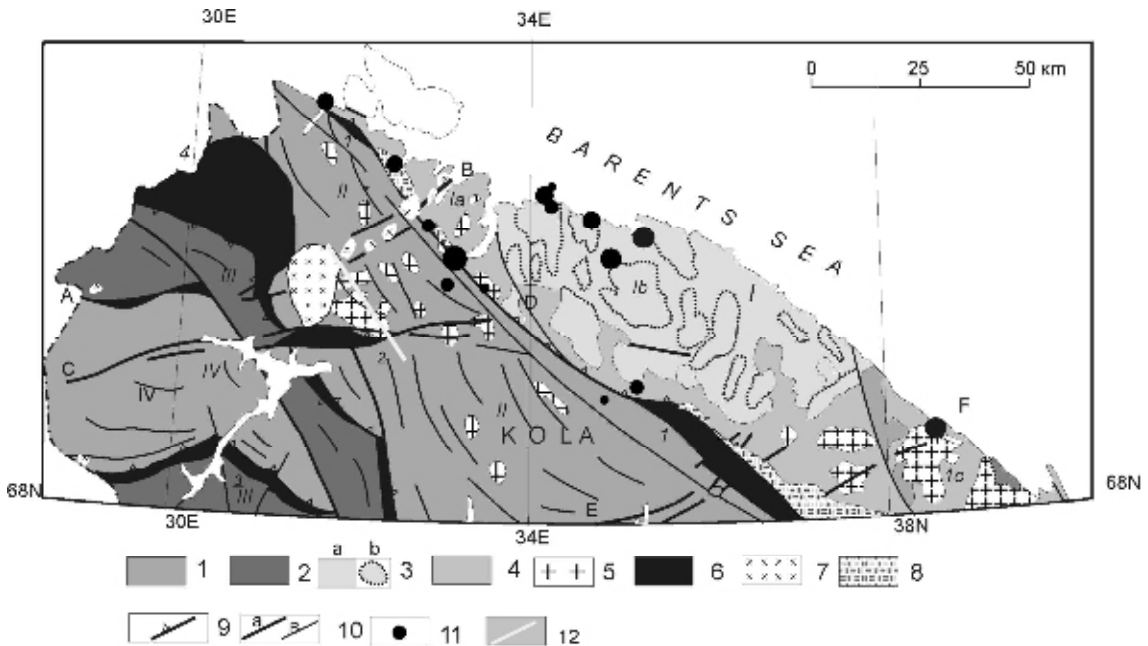
## 6. Application

The method was used in seismic hazard assessment of the northern part of the Kola Peninsula.

Tectonically, this region consists of two main terrains of Archean crust (Fig. 4): the Murmansk terrain, the Central–Kola terrain as well as parts of the Belomorian and Lapland terrains, which in turn are divided into small blocks (Radchenko, 1992). Each block is characterized by specific deep structure (Sharov, 1997), strength properties, seismotectonic potential and maximum possible magnitude. The Murmansk terrain is the most undeformed formation, solid structure not exposed to regional deformation but intensively granitized with charnockites formed at high temperature and high pressure (Vetrin, 1984). In our case, the most interesting feature of charnockites is the rather high quartz content, up to 60%. The presence of this charnockite formation in the deep section of the structure can point to higher strength and possible high seismic potential.

The greatest volume density of potential energy is in the Teriberka block, composed mostly of Archean granite that was originally deep-seated but lifted later. These granite-charnockite zones are up to 15 km thick, with earthquake sources within this depth range. Some earthquake zones are located here (Fig. 4). The felt events occurred during the last 20 years (1981-1998).





**Fig. 4** - Schematic tectonic map of the northern part of the Kola Peninsula with elements of geology (Vinogradova, 1998).

Explanations:

1-2 – intensively dislocated infracrustal Ar gneiss-granulite (1) and amphibolite-gneiss (2) blocks subjected to the Ar<sub>2</sub> and Pr<sub>1</sub> riftogenesis (dilatation zone).

3-5 – infracrustal blocks with intensively denudated upper part of section of monolithic type due to polymorphic granitization: granite-charnockite-enderbites (3a), intrusive facies (3b), granodiorite-tonalites (4), granite-migmatite-granites (5) (compression zone).

6 – Intra-block basite zones.

7 – Ar<sub>2</sub> plagiogranites; 8 – Pr<sub>1</sub> granodiorites.

9 – thrust faults deviding infracrustal blocks; 10 – strike-slip deep faults (a): A-B - Araguba, C-D - Lottinsko-Harlovskaya, E-F - Hibinsko – Kontozerskaya, uppercrust faults (b).

11 – earthquake epicenters (1778 – 1999), sign size is proportional to  $M/20$  where  $M$  is magnitude from 1.2 to 5.

12 – Part of seismic profile QUARTZ.

*Ar<sub>1</sub> infracrustal blocks with the continental type of the crust and their fragments:*

*I - Murmansk block: Ia - Uruguba fragment, Ib - Teriberka fragment, Ic - Iokanga fragment; II - Central-Kola block; III - Belomorian block; IV - Lapland block.*

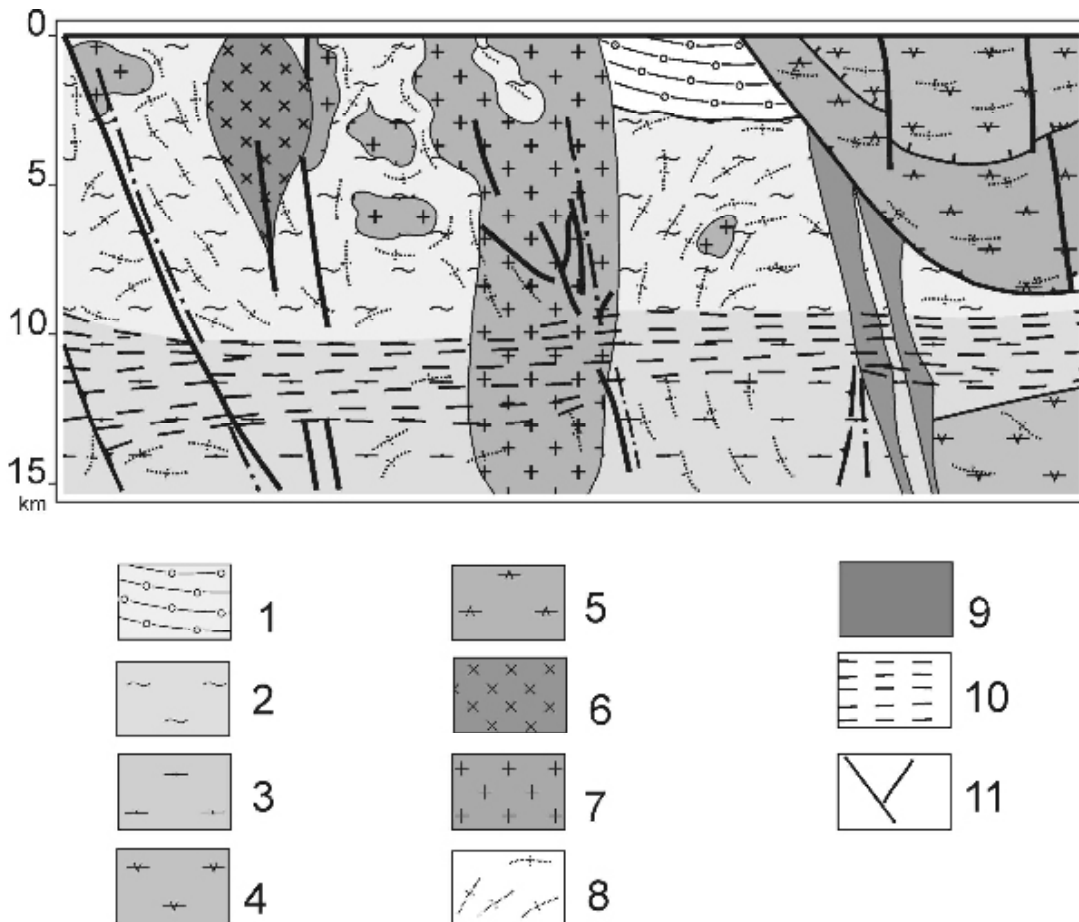
*(Ar<sub>2</sub> – Pr<sub>1</sub>) intrablock suture zones: AR<sub>2</sub> riftogenic greenstone belts and their fragments: 1 - Kolmozero-Voronja, (Severo-Keivsky thrust), 2 - Olenegorsk, 3 - Tanael; Pr<sub>1</sub> rift systems and their fragments: 4 - Pechenga -Imandra-Varzuga.*

The border between the Murmansk and Central-Kola terrains is the Severo-Keivsky thrust. Its north-west part is marked by late Archean granite intrusions with earthquake sources within them. The magnitude of the greatest event reached 5 (in 1772). It is very important to notice that the focal depth of earthquakes of this terrain is not more than 15-17 km.

The geological interpretation of the regional seismic profile QUARTZ provides information about the deep structure of the Archean granitoid massif generated as a result of mafic granulite-facies granitization (Egorov, 1993). It can be seen that the massif has a batholith form, large size and depth (Fig. 5). The earthquake of magnitude 5 is probably associated with it. Most of the

Central-Kola, Belomorian, Lapland terrains have layered Archean highly-fractured granulite crust. According to Kola drilling data, this crust is destroyed very much and is characterized by mafic content with low strength and reduced efficient (averaged) brittleness at possible earthquake source depths (Mitrofanov, 1991; Vinogradova, 1998). Several types of logging data such as acoustic velocity logs, cavern measurements, and others for the 10-11 km depth interval of the Kola superdeep well (Kozlovsky, 1984) testify that the Archean crust is faulted and destroyed and probably it is not able to sustain stresses required for earthquake occurrence. The mafic content of the crust still more increases within the Belomorian and Lapland terrains in comparison with the Central-Kola terrain.

All terrains except the Murmansk one were subjected to the late Archean and early Proterozoic intensive riftogenic processes.



**Fig. 5** - Geological interpretation of seismic profile QUARTZ (Egorov, 1993).

Explanations: **sedimentary-metamorphic formations**: 1 – Ar<sub>2</sub> gneiss-schist graywacke association, 2 – Ar<sub>1</sub> gneiss, amphibolite-gneiss association, upper part of section, 3 – Ar<sub>1</sub> granulite-gneiss association, middle part of section, 4 – Ar<sub>1</sub> gneiss-basite-granulite association, 5 – Ar<sub>1</sub> basite-granulite association; **magmatic formations**: 6 – Pr<sub>1</sub> granite, 7 – Ar<sub>1</sub> granite, 8 – Ar<sub>1</sub> migmatite-granite, granodiorite, tonalite, 9 – Ar<sub>1</sub> basite-ultrabasite-gabbro formation, 10 – low velocity layer, 11 – faults.

The above mentioned geological information can be related to rock strength and earthquake energy. The basic data for used rock strength values, standard deviations,  $W$ ,  $SD$  and  $M_{max}$  calculation results considering corrections are given in Tables 3 and 4. The results used for map compilations are shown in bold. It should be noticed that the error for the final  $SD$  value amounts to 20% on average and sometimes reaches 30%.

The estimation process was the following: 1) finding of  $\sigma_\tau$  by knowledge of  $\sigma_c$ ,  $\sigma_d$ ,  $K$  (Fig. 2) and Eq. (1); 2) calculation of  $W$  using obtained  $\sigma_\tau$ ,  $G$  and Eq. (2); 3) calculation of  $SD$  according to the Eq. (3); 4) correction of  $SD$  (Table 1) for an age and dividing of  $SD$  by 10 for dilatation stress regime; 5)  $M_{max}$  determination (Table 2).

**Table 3** - Geomechanical rock properties.

Type of rocks	$\sigma_c$ (MPa)	$\sigma_d$ (MPa)	$K$ (Fig. 2)	$\sigma_\tau$ (MPa)	$G$ (GPa)	$W$ (erg/cm <sup>3</sup> · 10 <sup>7</sup> )
granite-charnockite	222 ± 22	6 ± 2	6.5	676	34 ± 4	6.7
granite, migmatite-granite	182 ± 20	9 ± 3	6.5	589	28 ± 4	6.2
gneiss (felsic granulite)	159 ± 19	11 ± 2	6.5	538	34 ± 5	4.3
granodiorite, tonalite (intermediate granulite)	175 ± 32	16 ± 7	5.8	525	33 ± 3	4.2
gabbro- amphibolite (mafic granulite)	186 ± 58	19 ± 10	6.0	550	49 ± 6	3.1

The maps of  $W$ ,  $SD$  and  $M_{max}$  were compiled on that basis (Figs. 6, 7, 8).

Five gradations of strength energy  $W$  at the depth of existing seismic sources (15-17 km) are shown on the first map. The greatest value of  $W$  is given for granite-charnockite, migmatite-granite and Ar<sub>2</sub> granite formations, 2 intermediate values are assigned to granodiorite, gneiss-felsic granulite formations and the lowest  $W$  value is shown for basites.

The map of source density of earthquake energy  $SD$  is presented in Fig. 7. Eight gradations of parameters  $SD$  are shown on the map. The first four are for the Murmansk block (compressional regime), the last four are for regions situated to the south-west from the Sevro-Kejvsky fault (tensile regime). Accordingly, the Severo-Kejvsky fault is a border between areas with different stress regimes. As could be expected the greatest  $SD$  value has a granite-charnockite formation and Ar<sub>2</sub> granite intrusions associated with the fault due to their younger age. The lowest  $SD$  values are assigned to areas with a predominance of basites. The Ura-guba granitoides shown in Fig. 4 have a plutonic form and do not extend to a 15 km depth (Fig. 5).

The obtained  $M_{max}$  values are shown in Fig. 8. Four gradations of these parameters are marked out altogether. The greatest magnitude values (3.5-4.5) of future earthquakes should be expected in the Murmansk terrain. The Central-Kola terrain and others possess very weak seismic potential,  $M_{max}$  does not exceed a value of 2.5 here. It should be noted that obtained  $M_{max}$  values are a little below magnitudes of observed historical events but they lie within the assessment error ( $\pm 0.5$  units). Besides, the Kola earthquake of October 24, 1968 had a magnitude of 3.5, one unit greater than that predicted by calculations. This local area probably needs more detailed research.

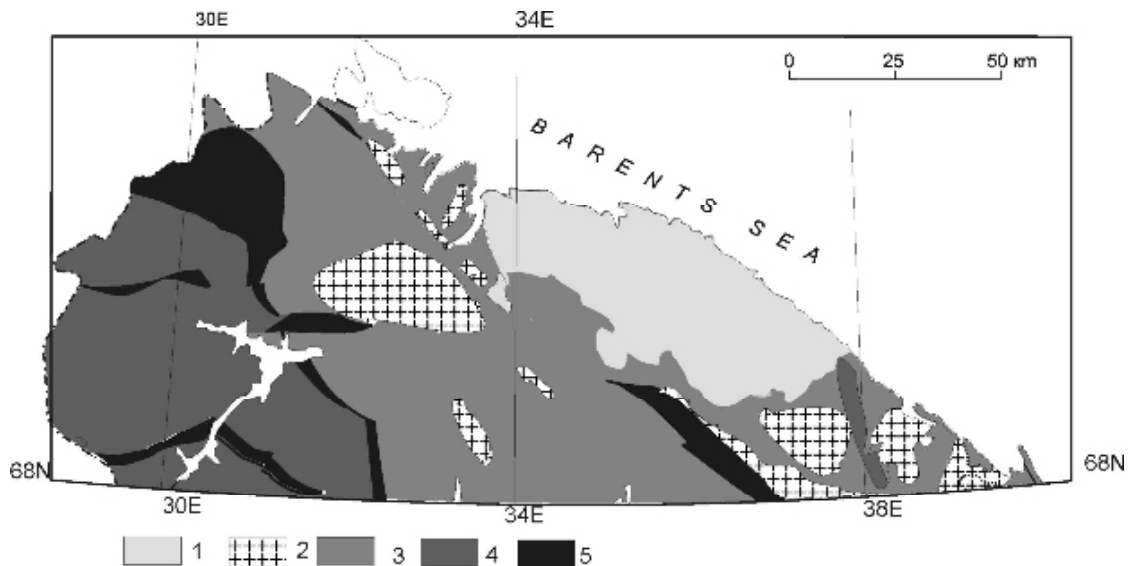
**Table 4** - Seismic potential  $SD$  and  $M_{max}$  calculation.

Types of rocks	$SD$ ( $\text{erg/cm}^3$ )	Age correction (Table1)							
		Archean ( $Ar_1$ ) 2900 Ma				Archean ( $Ar_2$ ) 2600 Ma			
		compression		dilatation		compression		dilatation	
		$SD$	$M_{max}$	$SD$	$M_{max}$	$SD$	$M_{max}$	$SD$	$M_{max}$
granite- charnockite	$2.09 \cdot 10^5$	<b>460</b>	<b>4.0 - 4.5</b>	50	2.0 - 2.5	600	4.5 - 5.0	60	2.4 - 2.6
granite, migmatite- granite	$1.78 \cdot 10^5$	<b>400</b>	<b>4.0 - 4.5</b>	<b>40</b>	<b>2.0 - 2.5</b>	<b>520</b>	<b>4.0 - 4.5</b>	50	2.4 - 2.6
gneiss (felsic granulite)	$7.41 \cdot 10^4$	160	3.6 - 4.0	<b>17</b>	< 2	220	3.6 - 4.0	20	< 2
Granodiorite, tonalite (intermediate granulite)	$7.16 \cdot 10^4$	<b>160</b>	<b>3.1 - 3.5</b>	<b>16</b>	< 2	210	3.6 - 4.0	20	< 2
gabbro- amphibolite (mafic granulite)	$2.84 \cdot 10^4$	60	2.6 - 3.0	<b>6</b>	< 2	80	2.6 - 3.0	8	< 2

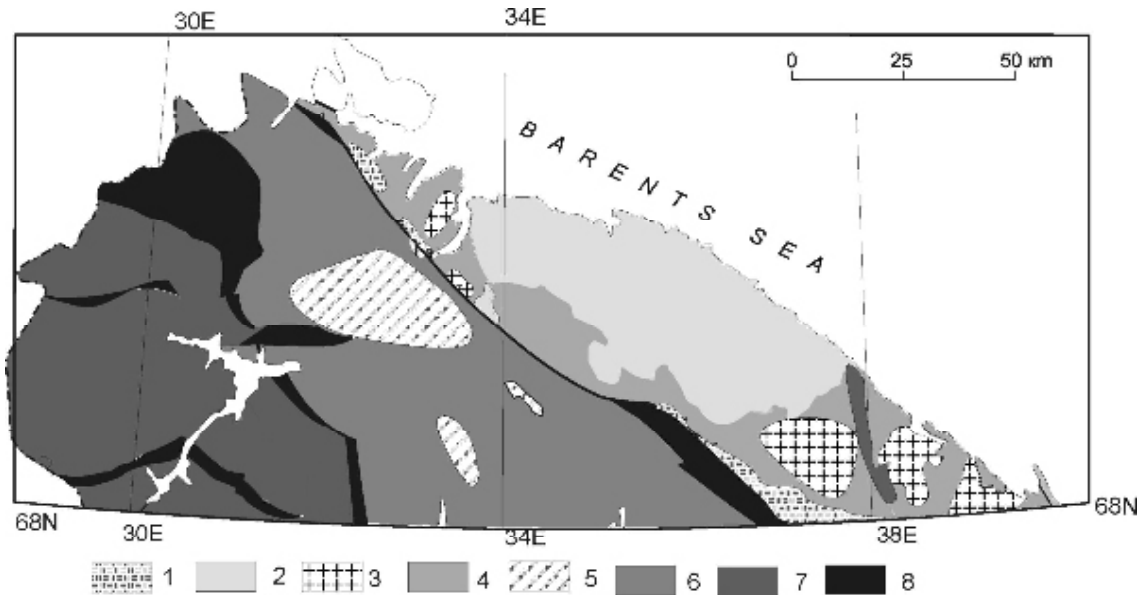
**7. Conclusion**

Some approaches to quantitative assessment of seismotectonic potential are offered in this work. It is clear that these suggestions should be treated as preliminary. They show the direction for future research.

First of all it is an account of the temperature effect. For the present the proposed method can be used only for regions with a so-called “cold” crust.



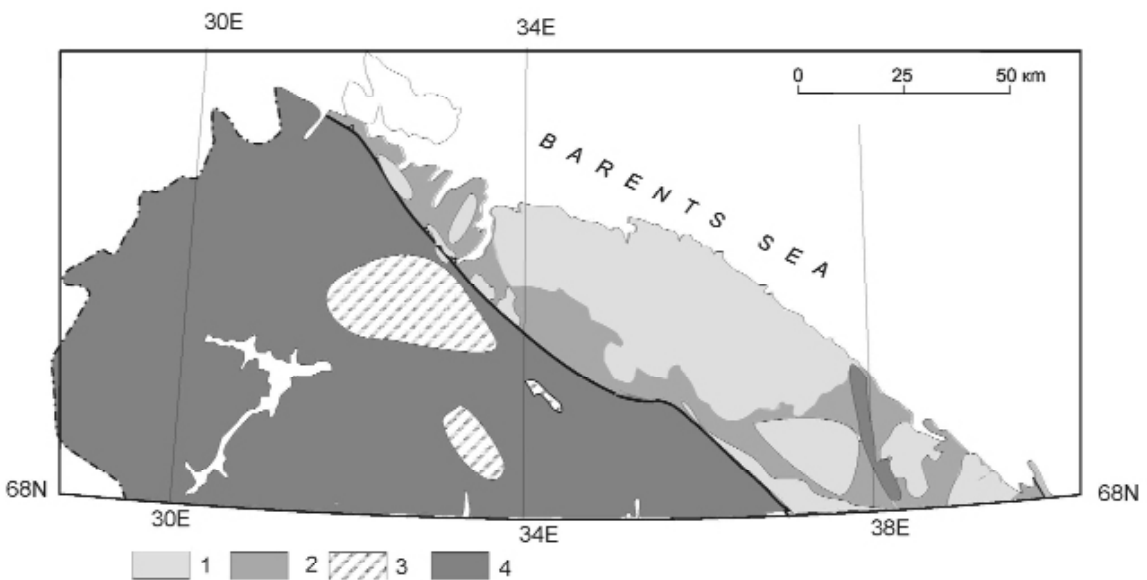
**Fig. 6** - Map of energy strength  $W$  ( $\cdot 10^7$  erg): 1 – 6.5-7.5; 2 – 5-6.5; 3 – 4-5; 4 – 3-4; 5 –  $\leq 3$ .



**Fig. 7** - Map of source density of earthquake energy  $SD$  ( $\text{erg}/\text{cm}^3$ ): compression zones: 1 –  $> 500$ ; 2 – 400-500; 3 – 200-400; 4 – 50-200; dilatation zones: 5 – 20-50; 6 – 10-20; 7 – 15-20; 8 –  $< 15$ .

Besides, the further upgrading of the final formula for  $SD$  will require expansion of the database of available rock geomechanical properties information for earthquake sources. It is also necessary to compose more formal methods of estimating stress condition effects. Other factors such as irregularities of recent stress fields can be included in the analysis as needed and, if required, basic data are available.

It would be interesting to apply the method to other parts of the Baltic shield and contemporary active tectonic regions.



**Fig. 8** - Map of maximal magnitude  $M_{max}$ : 1 – 4.0-4.5; 2 – 3.0-3.5; 3 – 2.0-2.5; 4 –  $< 2$ .

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