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SEISMICITY OF RIFTING AND SUBDUCTION

Seismic waves accompanying the subduction process are predicted as catastrophic released energy from pre-stressed mega block in such structured medium. They will be investigated in future on a seismic time scale taking into account the peculiarities of lithospheric internal structure, dynamical processes occurring on the level of structural elements and the exchange of energy between different degrees of freedom. A new idea of earthquake source model is proposed.

Keywords: seismicity, subduction, earthquake source, model

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ПРОЯВИ СЕЙСМІЧНОСТІ В РИФТОВИХ ПРОЦЕСАХ ТА ПРИ СУБДУКЦІЇ

Чисельне моделювання показало, що при тектонічному стисненні і деформуванні в зонах субдукції виникають перенапружені мегаблоки. Передбачено катастрофічне вивільнення енергії з таких локалізованих областей структурованого середовища. Ці явища в майбутньому будуть більш детально промодельовані вже на сейсмічній шкалі часу з застосуванням динамічних рівнянь руху та рівнянь стану речовини літосфери, що враховують її структурованість. Таким чином запропонована нова модель джерела землетрусу.

Ключові слова: сейсмічність, субдукція, джерело землетрусу, моделювання.

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ПРОЯВЛЕНИЯ СЕЙСМИЧНОСТИ В РИФТОВЫХ ПРОЦЕССАХ И ПРИ СУБДУКЦИИ

Численное моделирование показало, что при тектоничесом сжатии и деформации в зоне субдукции возникают перенапряженные мегаблоки с катастрофическим высвобождением энергии из таких локализованных областей структурированной среды. Эти явления будут более детально промоделированы уже на сейсмической шкале времени с использованием динамических уравнений движения и уравнений состояния вещества литосферы с учётом её структурированности. Предложена новая модель источника землетрясения.

Ключевые слова: сейсмичность, субдукция, источник землетрясения, моделирование.

Introduction.

A lot of achievements of self-organization theory in geophysics are based on the existence of basic structured media models. The structure plays a key role in Earth's crust dynamic that is important for tectonic stress origin and localization as well as for next stress-relieved processes. We have developed and tested (Starostenko et al. 1999) a new fully dynamic theory of continental rifting based on a model of the lithosphere, incorporating both dynamic and thermal processes, by solving a coupled system of differential equations governing stress and temperature in a 2D block-structured geophysical medium. We will apply our theory for investigations of tension and compression processes in Earth's crust such as rifting, subduction and seismic related events.

The lithosphere as open system exchanges matter and energy with the environment mainly with matter from deep areas. Such a process can be considered as a self-organization process, for this reason the fully dynamic model of open medium that is characterised by the presence of internal block structure has been applied. In that case the blocked lithosphere can be separated or crushed by external load. Thus, the oceanic plate for example is a brittle-elastic medium that some authors frequently use on physical simulation of tectonics.

Method and Theory.

This report describes and applies such a method of numerical modelling of the dynamics of the lithosphere including faulting, based on the theory of generalised functions. Specifically, it allows explicit consideration of processes occurring in a non-homogeneously structured, thermally perturbed lithosphere during rifting and post-rift sedimentary basin formation as well as during the subduction of tectonic plates. Using the kinetic energy of block k in functional form (Danilenko, 1992):

$$T_k = \frac{m_k}{2}\left\{ \vec{\upsilon}_{k-1}^2 + 2\beta(\vec{r}_{ok-1} - \vec{r}_{k-1})\vec{\upsilon}_{k-1}\frac{\partial\vec{\upsilon}_{k-1}}{\partial\vec{r}_{ok-1}} + \beta^2(\vec{r}_{ok}-\vec{r}_{k-1})^2\left(\frac{\partial \vec{\upsilon}_{k-1}}{\partial\vec{r}_{ok-1}}\right)^2\right\} + \frac{1}{2}(1+b_k)^2(\vec{\omega}_{k-1}\times\vec{\omega}_{k-1})I_{k-1}^{l,j} +$$
$$I_{k-1}^{l,j}\left\{\frac{\beta^2}{2}(div\vec{\upsilon}_{k-1})^2 + \beta^2\frac{\partial\vec{\upsilon}_{k-1}}{\partial\vec{r}_{ok-1}}\, div\vec{\upsilon}_{k-1}\right\} + (1+b_k)\left[\vec{\omega}_{k-1}\vec{\upsilon}_{k-1}\right] m_k\, \vec{r}_{ok-1} + \frac{1}{2}\beta\vec{\upsilon}_{k-1}\cdot div\vec{\upsilon}_{k-1} m_k\, \vec{r}_{ok-1} \qquad (1)$$

the system of partial differential equations describing the movement of structural elements of a geophysical medium may be written as follows:

$$\frac{\partial}{\partial t}\left[\frac{\partial T_k}{\partial \dot{\vec{q}}}\right] + \frac{\partial T_k}{\partial \vec{q}} + \frac{\partial U_k}{\partial \vec{q}} = \vec{F}_k^{'} + \vec{F}_k^{''} + \vec{F}_{ok}^{''} + \vec{F}_{ky} + \vec{F}_{kn} + \vec{F}_o,\ k = 1,2,...n \qquad (2)$$

Blocks within the model interact with each other with a force (excluding non-mechanical forces) that can be divided into internal and external forces. The internal interaction forces inside the block $\vec{F}_k^{''} + \vec{F}_{ok}^{''}$ are assumed to be central. The external forces ($\vec{F}_k^{'} + \vec{F}_{ky} + \vec{F}_o$) are assumed to be partially central and potential. It is assumed that the surface (contact, external) forces are partially potential. The system of partial differential equations (2) describes the block movement of hierarchically structured geophysical medium with taking into account the wave processes and can be reduced in two-dimensional case to a system of ordinary differential equations and solved digitally.

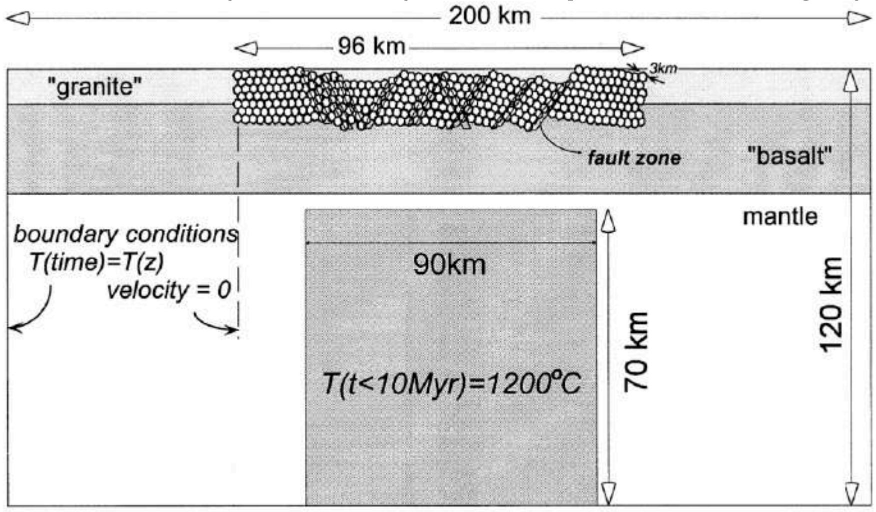

Figure 1. Schematic set-up of the numerical model with the upper crust as a block-structured medium and with an asthenosphere protrusion.

The method (see fig.1) has been applied to the formation and evolution of the Dnieper–Donets Basin (DDB) along set of regional profiles controlled by seismic and other geophysical and subsurface data. The results are compared with those published earlier for the same profiles using different methods of modelling the rift and early post-rift development of the region. The final basement geometry at the end of the rifting stage predicted by the new model satisfactorily corresponds with geological data and is qualitatively similar to that predicted by the previously published models. Fig.2 shows the numerical model with specific application to the typical profile crossing the north-western or central part of the Dnieper–Donets Basin (Ukraine). The model is 200 km in length and 120 km deep and comprises three layers - ‘granite’, ‘basalt’, and mantle with real thermo-physical parameters, the total amount of syn-rift extension along profile line is about 12%. The model has been applied (Vengrovich et al. 2010), integrating the available geophysical and stratigraphic data along seven geological profile crossing the Dnieper–Donets Basin and two profiles along Crimea region.

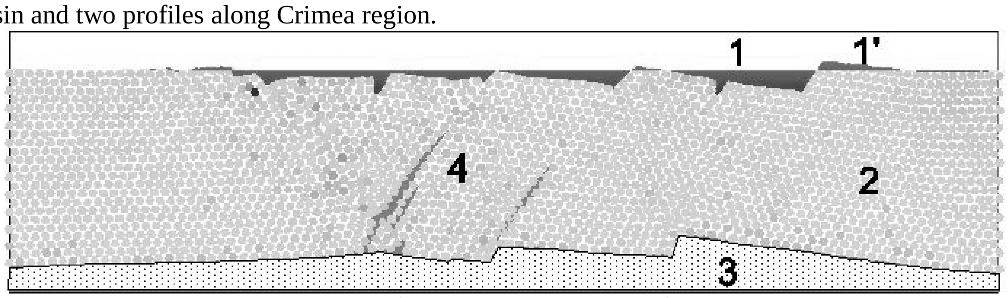

Figure 2. The resulting block-structured state of the lithosphere within the rift, according to modeling: 1’ – erosion, 1 – sediment, 2 - granite and basalt block-structured geophysical medium (color of blocks represents the stress), 3 – mantle, 4 – faults

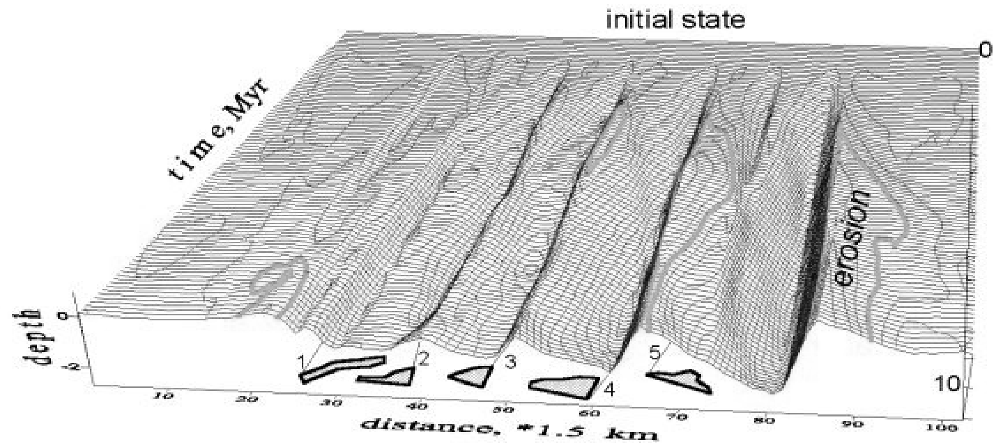

Figure 3. The resulting history of the block-structured lithosphere within the rift, according to modeling: 1-5 – real sedimentary deposits in DDB were formed in the shallow sea (at the left) and they are absent in the deep sea (at the right)

The key stages of the rifting and basin evolution, including the structural architecture of the rift as well as the overlying thermal sag basin, can be satisfactorily predicted with the described method as is shown in Fig. 2. The results are comparable to those of previously published methods. However, they not only characterise the cross-sectional character of basin subsidence through time but also the thermal evolution of the sedimentary succession, of crucial importance for the determination of hydrocarbon maturation. The results imply realistic that the asthenosphere was at a depth of as little as 40–50 km during the rifting period. All of this establishes the theory of structured geophysical media and method of its mathematical modelling.

Fig. 4a and b, referring to distinct events during the rift subsidence evolution, illustrates the pressure behaviour in the upper layer for moments t_1 and t_2, respectively. The radiation of the pressure impulse is interpreted as the result of a force equilibrium disturbance within the restricted volume of the model with unstable blocks being the sources of the radiated pressure impulse. The pressure distribution seen in Fig. 4 is similar to the pressure distribution of a non-linear, soliton-like wave propagating in a dispersive medium. They have been further investigated, and provisionally identified, with Eq. 1, but using a time step (Δt_i of ~0.1 s) reduced in comparison with the calculations made for the rifting process (Vengrovitch, 1995). The model consisted of an unstressed half-space, constructed from hexagonal elements with parameters as above, with the boundary layer of elements (y = 0) moved in the x direction with a constant velocity of 0.01. Pressure impulse type perturbations, with soliton-like character, were observed. Fig. 5 shows the amplitude V_y of the mass velocity of the longitudinal perturbation along a one-dimensional chain in direction x and the amplitude V_x of the mass velocity of the transverse perturbation. The ratio V_y^f/V_x^f is 1.6, close to that of seismic waves, which is 1.7 for the continental 'granitic' layer of the Earth's crust. Eq. 1, therefore, predicts wave propagation processes which accompany rift formation and lead to seismic events observed in actively extending depressions (Anan'in, 1980) with the waves generated during the rifting process shown in Fig. 4 being seismic non-linear soliton-like waves.

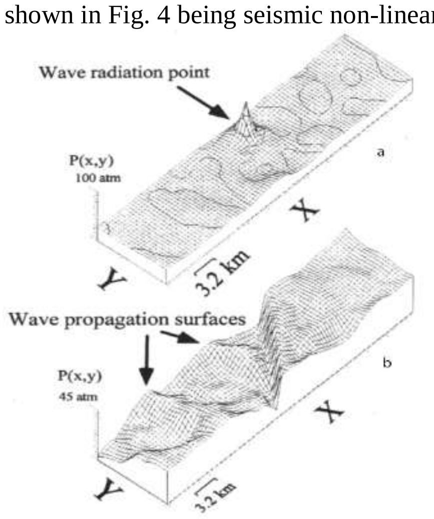

Figure 4. Pressure distribution within the upper brittle-elastic layer for half-graben model: (a) when one of the blocks in the vicinity of the fault has become unstable (Y = depth, X = horizontal distance) and (b) after the impulse caused by an unstable block in the vicinity of fault.

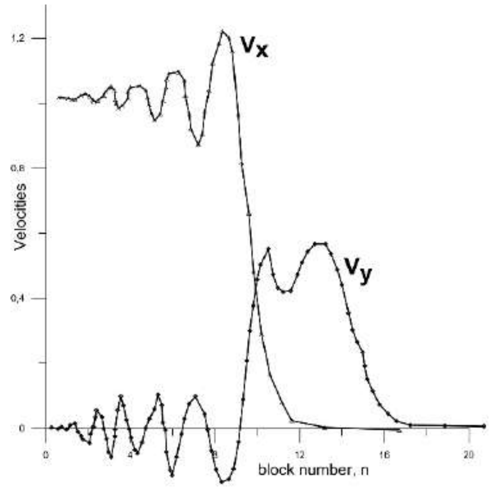

Figure 5. Absolute values of the velocities of P and S oscillations along the one-dimensional chain of blocks. Time t = 12.8 s from start, hence the wave velocity V f = 7 km/s.

Now we will apply our theory for investigations of compression processes in lithosphere using subduction model:

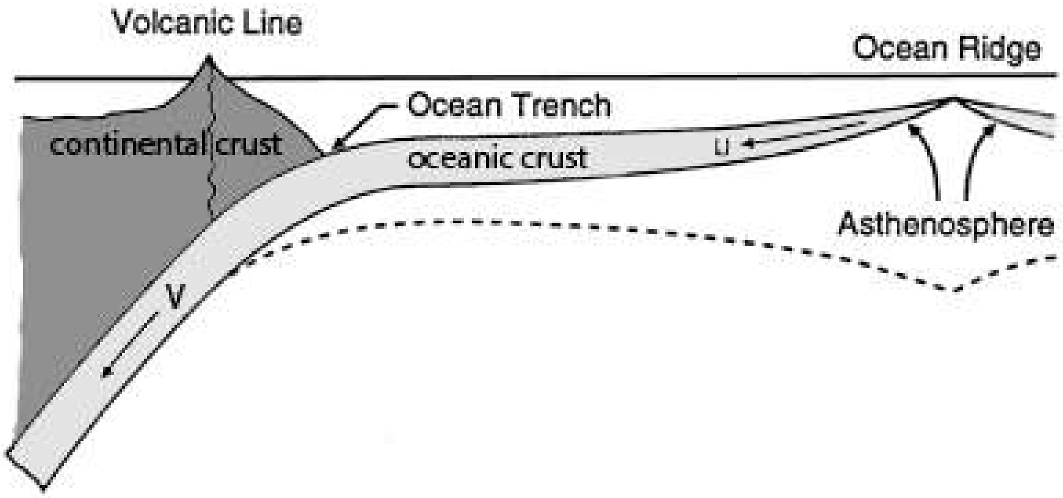

Figure 6 (Donald L. Turcotte, 2001) Accretion of a lithospheric plate at an ocean ridge (accretional plate margin) and its subduction at an ocean trench (subduction zone). The plate migrates away from the ridge crest at the seafloor spreading velocity V.

Now that we have a clear model of structured geophysical media behaviour and we will digitally simulate the tectonic process of subduction sketched in Figure 6 in the framework of our theory concentrating our attention on the dynamic of the region near the "oceanic trench". « oceanic crust» thus stated is presented in 2D model in Figure 7 as a set of hexagonal blocks (Vengrovitch D.B., 2010) and we equate the dynamics of block media by solving (3), the last is immediate from (1)-(2):

$$m_i \frac{d^2\vec{x}_i}{dt^2} = \sum_j \vec{\mathrm{F}}_{\mathrm{ij}}, \quad I_i \frac{d\vec{\varpi}_i}{dt} = \sum_j \vec{\mathrm{M}}_{\mathrm{ij}}, \tag{3}$$

where m_k is mass of block *k (*density ρ_k*)*; I_k is moment of inertia of block *k*; x,ω are co-ordinate and angular velocity; forces are presented as summarized frictional force, forces owning to energy dissipation, elastic interaction force (with neglecting of gravity force in simplified version of model) (Poliakov et al., 1996):

$$\vec{F}_{i,j} = F\,\vec{n}_{ij} = R(\varepsilon_{i,j})\,\vec{n}_{ij} \tag{4}$$

For example, in case of blocks interactions by law of Hertz, forces are defined as following:

$$\vec{F} = \frac{2\theta}{3}\sqrt{\frac{r}{2}}\varepsilon^{3/2}, \qquad \theta = \frac{E}{1-\nu}, \qquad \varepsilon_{ij}^{\substack{compresion \\ tension}} = \pm 2r - \Big(\sum_{k=1,2}(x_i - x_j)^2\Big)^{1/2}$$

(5)

where E is Young's module, ν is the Poisson ratio. In case of a set of hexagonal blocks interactions forces are defined as following:

$$\vec{F}_{i,j} = -[k_1 \vec{P}_{ij} + k_2 \vec{\varpi}_{i,j} + k_3 \vec{\varpi}^2_{i,j} / |\vec{\varpi}_{i,j}|], \quad \vec{P}_{i,j}\cdot(\vec{r}_{0i} - \vec{r}_{0j}) = \vec{U}_{ij}$$

$$\vec{U}^{[i,j]} = \vec{U}^{[i,j]}(\nu_i) = A\nu_i^{-2/3}\exp[B(1-\nu_i^{-1/3}] - C\nu_i^{-4/3}, \qquad \nu_i = \frac{1}{\rho_i} \tag{6}$$

The rheological properties of the model are determined by the material constants of the compression potential of granite A, B, C, by coefficients of friction k_1, k_2, k_3 and by density ρ_i. The results in the report are given for the case (6).

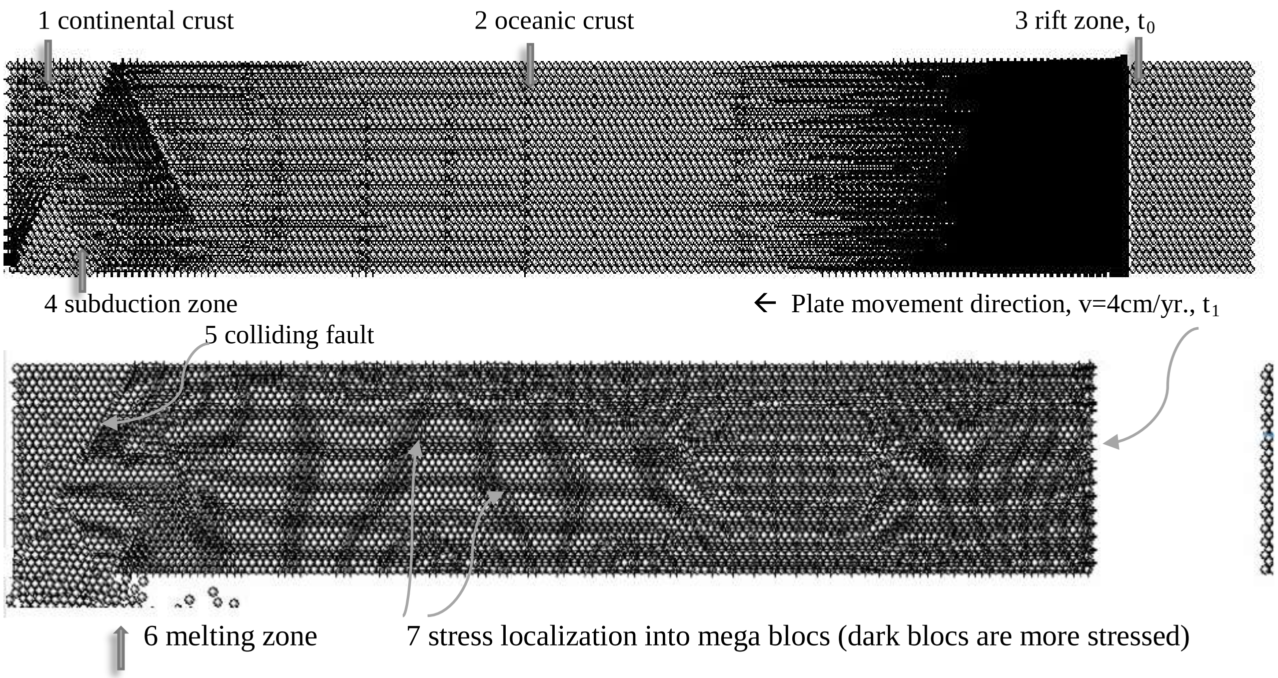

Figure 7. The model of subduction. (oceanic plate thickness averages 15 km; continental crust is fixed, t_0 ~ 0, t_1 ~ 3Myr)

Thus a model of subduction is illustrated schematically by Fig.7. It shows without taking into account gravity and isostatic forces the stress-strained state of the oceanic crust during the collision of block structured plates (Fig. 7 demonstrates a model with slip of the upper and lower blocks of the oceanic plate).

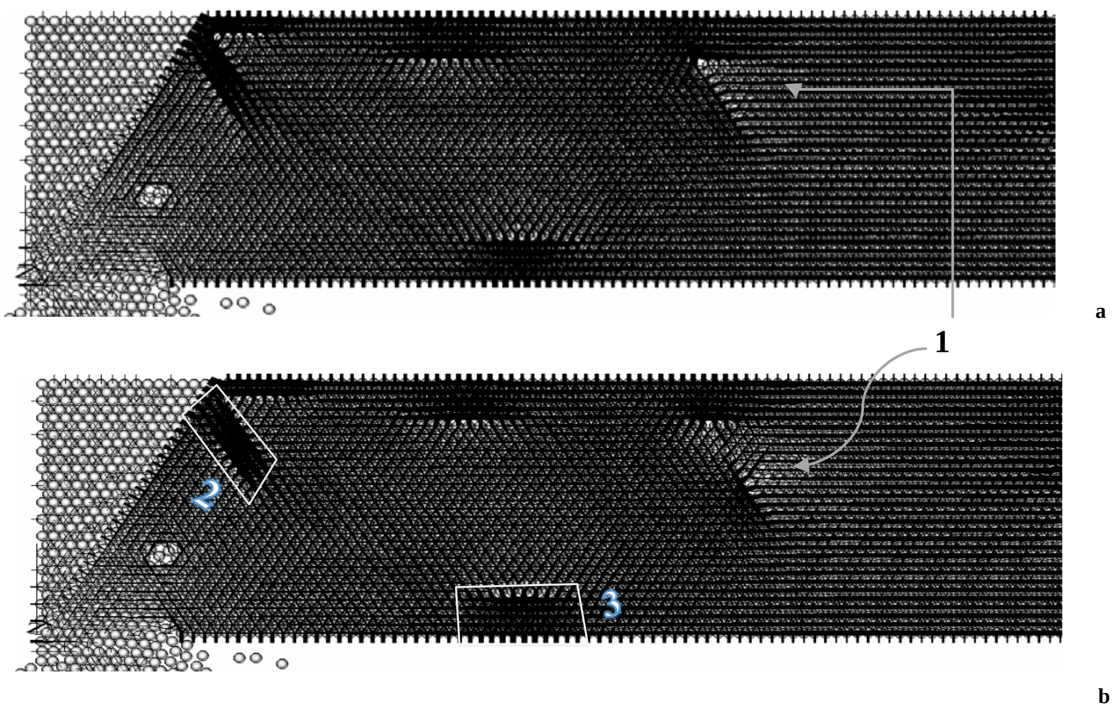

Figure 8. The idea of a new model of earthquake source in blocked oceanic crust near subduction zone. a, b - consecutively presented stress-strained states of the oceanic crust during the subduction, 1 - stress-relieved processes (at a depth of 7 km) observed over a 2,000 year, 2,3 – measured area of stressed zones – mega blocks.

During the block plates collision, there is regularly forming process of strained zones at different depths (see fig.8 - 1). During the simulation, we recorded 205 events of occurrence and relaxation of zones and determined their areas and times of existence (for example, see fig.8 – 2,3). An analysis of these observations is shown in Figures 9,10.

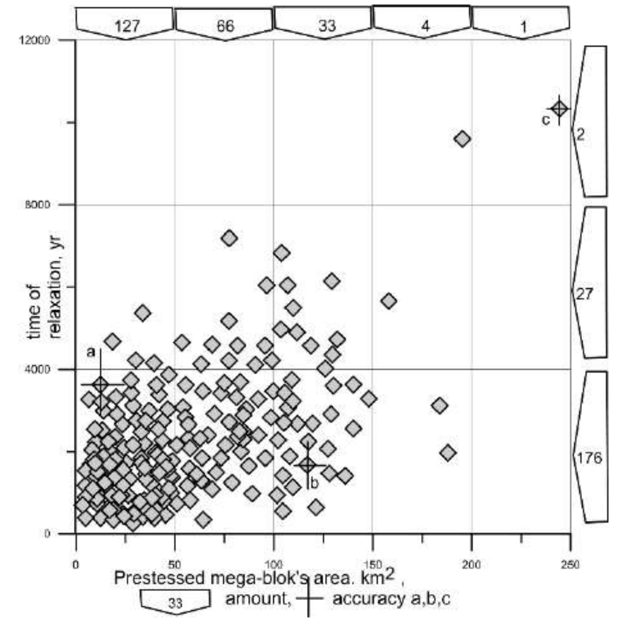

Figure 9. Time of relaxation and area of stressed mega blocks during the modelling of subduction,
for example, 33-amount: here number 33 represents the number of events in a strip - observed mega blocks with arias 100-150km^2
27-amount: these mega blocks existed for 4-8 thousand years

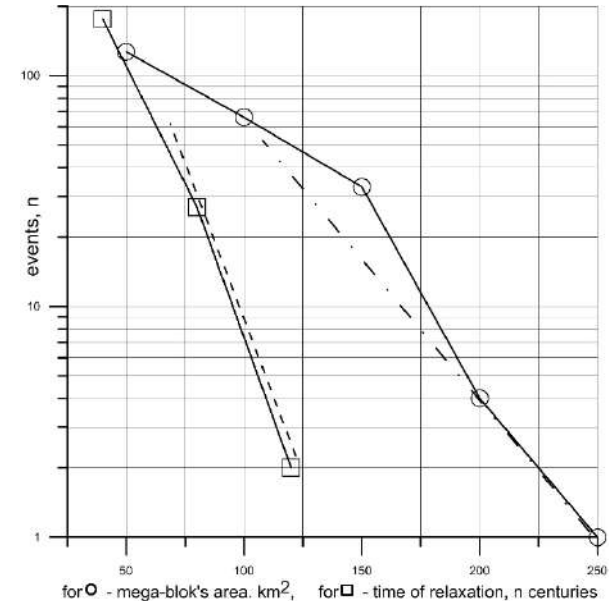

Figure 10. Functional connection of the number of events on the size of the mega block and on the time of its existence

We can assume that detailed modeling of such stress-relaxing zones will present the sources of seismic activity in subduction zones. This will be the subject of further study.

Conclusions

Seismic waves accompanying the subduction process are predicted as catastrophic released energy from pre-stressed mega block in such structured medium (see Fig.8 – zone 1). They will be investigated in future on a seismic time scale taking into account the peculiarities of lithospheric internal structure, dynamical processes occurring on the level of structural elements and the exchange of energy between different degrees of freedom.

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