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Modelling of Mantle-Crust Migrant Systems: A New Approach to Systems Analysis of Seismic Events

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Abstract: Fluids have a significant impact on seismic processes in the lithosphere and the earth's crust. They can form systems of mantle-crust migrants that rise in a solid plastic medium due to fluid-fracturing. When migrants are formed, the energy accumulated earlier in the parent chambers under the strength barriers is released. The accumulating energy includes the potential energy of lithostatic pressure W_P and the energy of deformation of the strength barrier W_E. The released energy includes the energy of cavity formation W_C in the strength layer and the energy of fluid ascent into the cavity W_F. According to the condition $W_P + W_E - W_C - W_F > 0$, the remaining mechanical energy is the cause of such seismic events as rock bursts, unstable zones of low longitudinal wave velocities and seismic "nails".

Keywords: mantle-crust migrants, seismic events, rheological barriers, fluid-fracturing.

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Research Article

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1. Introduction

The fluid factor in seismic events has received attention not so long ago [*Hickman et al.*, 1995]. And currently, research in this area is most often limited to studying the properties of fluid-saturated rocks and hydrocarbon reservoirs of the upper crust [*Xuan et al.*, 2023]. Meanwhile, the presence of H_2O, CO_2 and other fluid components in the mantle, lithosphere and plastic zone of the crust is beyond doubt. These components have a great influence on tectonic processes. Studies of this influence are being carried out [*Levin et al.*, 2010; *Park et al.*, 2021], but are still relatively rare. In this paper, the term "*fluid*" refers not only to H_2O and CO_2, but to the entire mobile group of phases "magma + aqueous solution + gas", and if at least one of these components is present, the *fluid* exists. The aim of the work is to apply a systems analysis of a number of seismic events in plastic medium and at the plastic-brittle transition (PBT) from the standpoint of the theory of systems of mantle-crustal migrants (MCM), which was developed and experimentally tested by N. S. Zhatnuev with the participation of the authors [*Vasiliev et al.*, 2019; *Zhatnuev et al.*, 2009; 2013; *Zhatnuev*, 2005]. They are *fluid*-filled cavities that rise through the solid plastic mantle and lithospheric environment by means of *fluid* fracture. The latter occurs as a result of excess pressure arising in the cavities due to the difference in density between the *fluid* and the enclosing medium [*Zhatnuev*, 2005].

2. Conceptual model

In the first approximation, the formation of the MCM can be described as follows. At a depth H from the PBT, under a layer with tensile strength S (strength barrier), a *fluid* with a significantly reduced density ρ_F relative to the density of the medium ρ_R ($\rho_F \ll \rho_R$) accumulates. It forms a chamber with a thickness Δ_H increasing due to the *fluid* supply (Figure 1). The difference in densities ($\rho_F - \rho_R$) and the increase in Δ_H create excess pressure in the roof of the chamber, which leads to the accumulation of normal stress σ_Z, causing deformation ε.

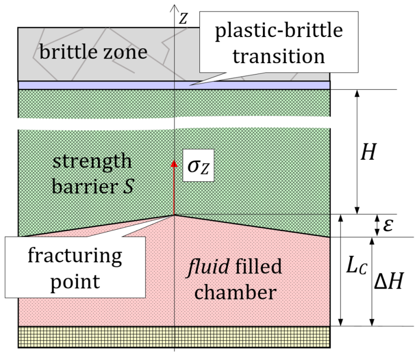


Figure 1. Schematic diagram of the initial chamber of the MCM under the strength barrier S. Explanations in the text.

When the chamber reaches the critical thickness L_C, the excess pressure in the chamber exceeds the strength of the overlying barrier S. In it, under the action of *fluid*-fracturing, an MCM is formed — a vertical cavity filled with the chamber material. Its formation is described by the condition [*Vasiliev et al.*, 2019]:

$$\int_0^{H+\Delta H} g\rho_R h \mathrm{d}h - \int_0^{H} g\rho_R h \mathrm{d}h - \int_0^{L_C} g\rho_F h \mathrm{d}h > S, \quad (1)$$

where g and h represent the acceleration of gravity and the variable of integration over depth, respectively. Note that the left-hand side of inequality (1) represents the excess pressure in the roof of the chamber (at the strength barrier).

3. Energy model

Let us consider, as a first approximation, the energy balance at the fracture point. It consists of accumulation (stress buildup) with increasing chamber height and discharging (relaxation) during the formation of the MCM. The accumulation consists of the potential energy of the lithostatic pressure of the overlying rocks W_P and the deformation energy of the strength barrier W_E. For the isotropic medium with a thickness H and a vertical density gradient $\nabla\rho_R$, located above a circular in plan *fluid* chamber with a diameter D and a thickness ΔH, the potential energy is described by the expression:

$$W_P = \frac{1}{4} H\pi D^2 g\Delta H \int_0^H \rho_R h \mathrm{d}h. \quad (2)$$

The deformation energy can be described in the simplest way [*Xuan et al.*, 2023]:

$$W_E = \frac{3\sigma_Z^2(1-2\mu)}{2E}, \quad (3)$$

where μ and E denote the Poisson's ratio and Young's modulus, respectively.

When estimating energy expenditure (without taking into account dissipation), it is necessary to take into account the expenditure for forming a cavity in the strength layer as a result of *fluid*-fracturing and of lifting the *fluid* into the cavity. The first process can be described as the energy of crack formation (including the energy of new surfaces formation). Previously, we conducted tectonophysics experiments to study the formation and evolution of *fluid*-filled cavities in a transparent plastic medium (gelatin matrices with different properties) [*Zhatnuev et al.*, 2009; 2013]. It was noted that most often the forming cavity has the shape of a subvertical close-to-rounded lens with a thickness of a few millimeters with a maximum thickness to diameter ratio of $\sim 1:k$, where the coefficient k is proportional to the ratio of kinematic viscosities of the *fluid* and the medium with a maximum lens diameter of up to ∼250 mm. The experimental conditions did not allow sizes larger than this due to the influence of edge effects. Within these limits, the average $k \approx 30$. This ratio, of course, cannot be directly applied to natural conditions, but the dependence on the viscosity ratio will be present. Taking this into account, the area of the resulting surface can be approximated by the doubled area of a circle with a radius of $l/2$. Then the energy of formation of the W_C cavity is:

$$W_C = \frac{\pi l^2 \sigma_Z^2}{4E}. \tag{4}$$

The energy of *fluid* ascent is calculated similarly to the potential energy of the rock massif. If we take the volume of a lens of the MCM as 2/3 of the volume of the its corresponding cylinder and assume that the volumes of the chamber and the MCM at the time of its formation are equal, then the height l is as follows:

$$l = \left(\frac{3kD^2\Delta H}{2}\right)^{\frac{1}{3}}. \tag{5}$$

Then the energy of *fluid* ascent W_F is described by the expression:

$$W_F = \frac{1}{8} H \pi l^2 g \Delta H \int_0^l \rho_F h \mathrm{d}h. \tag{6}$$

The accumulated deformation energy W_E can be almost completely spent on the formation of a crack with a small remainder of free energy, which can be neglected similarly to dissipation. But the potential energy W_P is physically much greater than the potential energy of *fluid* ascent W_F, therefore as a result of the formation of the MCM, a significant part of the energy will remain free and can be interpreted as mechanical (seismic) energy W_S:

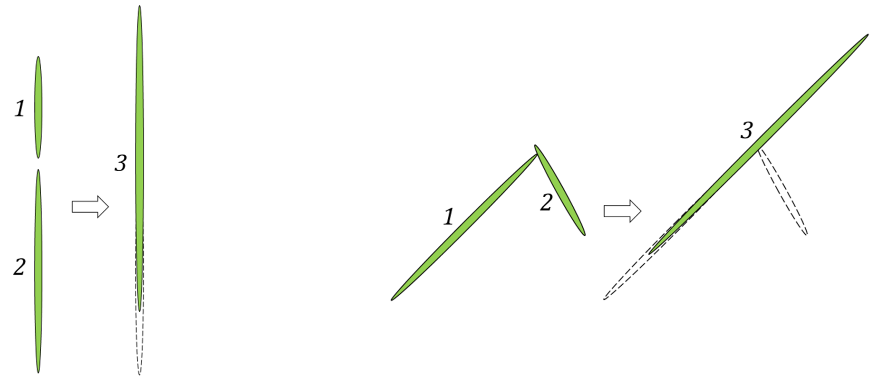
$$W_S = W_P + W_E - (W_C + W_F). \tag{7}$$

4. Application to seismic events

After the formation of the MCM at $l \ll H$, the accelerated ascent of the migrant in the plastic medium begins. It continues when condition (1) is true until it connects with another MCM, or until the migrant reaches the brittle zone or the next strength barrier. The location and strength of such barriers depend on the rheological profile in a specific geodynamic setting. The most significant barrier is undoubtedly the PBT, which S. N. Ivanov [*Ivanov et al.*, 2018] called a "detachment fault" and estimated its strength for continents at 150 MPa, which is 5–15 times greater than the strength of the underlying rocks: at depths of ∼8–15 km for granitoids, ∼25–30 km for gabbroids, ∼50–55 km for hyperbasites. Other barriers can appear due to viscosity and density abnormalities, as well as due to stress pressures, phase transitions of minerals, etc.

Relatively weak seismic events can occur not only on strength barriers, but also during the merging of the MCMs (Figure 2). The main factor of the rate of rise is the vertical length of the MCM, therefore the long cavity 1 will "catch up" with the short one 2 and "absorb" it. In this case, the length of the resulting cavity 3 will be the sum of the first and second ones, therefore its speed will increase sharply, which will cause additional energy release according to expressions (2)–(7). When calculating the energy, it is necessary to take into account two fundamentally possible variants of confluence of the MCMs: coaxial (Figure 2a) and angular (Figure 2b), and the latter requires simple mathematical transformations for σ_Z.

Thus, the formation and evolution of MCM is not a single phenomenon. The main mechanism of *fluid* transport from the core to the brittle crust are MCM systems. They are localized in column-form areas of significant vertical extension in rheologically weakened zones. At lower and upper mantle depths, such long-lived MCM systems can be interpreted



(**a**) (**b**)

Figure 2. Schemes of two basic types of MCM merging. Explanations in the text.

as mantle plumes. In lithospheric and crustal conditions, the formation and evolution of MCM systems can be the cause of difficult-to-explain and sometimes controversial seismic phenomena, among which we note the following.

1. Unstable thermodynamic zones of low velocities at depths of 9–16 km, "the nature of which has not been sufficiently studied" [*Korchin*, 2010]. They can be interpreted as areas of *fluid* accumulation under the PBT strength barrier, which is located precisely at these depths [*Ivanov et al.*, 2018; *Zhatnuev et al.*, 2009].
2. Rock-tectonic bursts that are practically not associated with anthropogenic processes, the problem of which "has been one of the most complex in world science and mining practice for many years" [*Marcak et al.*, 2013; *Rasskazov et al.*, 2023]. One of the factors causing such bursts is considered to be long-lived *deep faults*, which are possible with low probability in a plastic environment below the PBT. By the term "*deep faults*" we mean long-lived deeply propagated faults in a brittle environment, communicated with the surface, i.e. those in which the *fluid* is under its own hydrostatic pressure. In contrast, closed, non-communicating *fluid*-filled cavities in a plastic medium, which we consider in this paper as MCM, are under the lithostatic pressure of the surrounding rocks [*Zhatnuev*, 2005]. The mechanism described by equations (1)–(7) successfully explains such bursts, including in regions with weak seismicity.
3. Seismic "nails" [*Vadkovsky*, 2012; *Zakharov*, 2013], which are subvertical congestions of the earthquake hypocenters. They fit perfectly into the picture of systems with numerous MCMs localized in column-form areas. Seismic events in such systems occur not only and not so much on strength barriers as during numerous chaotic acts of MCM integration. This can explain the absence of a preferential direction of "nail" formation in time and the equally probable filling of the entire "nail" body with earthquake hypocenters during its formation. The best argument in favor of explaining seismic nails with the MCM theory is that the forming "nail" almost instantly (in less than a day) "grows" to a vertical length of 5–10 km or more [*Vadkovsky*, 2012]. This occurs due to jumps in the lengths of MCMs after their merging (Figure 2) and, as a consequence, a sharp increase in the velocity of their rise.

5. Conclusion

In connection with the systemic theme of the research, we connect the mantle, lithospheric and crustal processes of migrant evolution. They are, firstly, united by one mechanism for the formation of MCM (no matter in layer D'' or on some rheological barrier of the plastic crust), the same driving force (excess pressure), one method of migration (*fluid*-fracturing) and complete continuity: the initial MCM can originate at the core-lower mantle boundary as hydrogen-methane and rise, evolving and interacting with the host environment until unloading in the brittle crust [*Vasiliev et al.*, 2019; *Zhatnuev et al.*, 2013]. Another source of the initial substance for the migrant may be the dehydration of the plate in the subduction zone, but even there it remains precisely mantle-crustal, since it is formed in the mantle wedge and rises to the brittle crust as a component of the fluid-mantle system. Hypothetically, there may be other ways for a sufficient amount of *fluid* to enter a plastic medium to form a migrant, but we have not considered them yet.

The authors consider modeling of MCM systems as a promising direction in the system analysis of seismic events: both those described in the work and those left outside its scope. Significant assumptions and approximations (idealized isotropic medium, consideration of only the main types of stresses, deformations and energy, etc.) do not detract from the achievement of the main aim of the work: determining the direction of further research of MCM systems as one of the main seismo-generating factors. Undoubtedly, the considerations presented in the article are mostly preliminary and only outline the direction of system research, which are going to be interesting and useful.

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