On slow wave process in rocks

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Abstract. A study was made of the general regularities of localized plasticity development in deforming rocks. The potential usefulness of speckle photography techniques in applications to problems of deformation and fracture in rocks was explored and circumscribed. The evolution of localized plasticity in rocks was addressed using wave ideas. The tests were performed for the compression samples of marble, silvinite and sandstone; the deformation occurred in these materials via different micromechanisms of plasticity. By the deformation, autowaves would form in the compression samples of rocks. The autowave propagation rates are in the range \(\sim10^{-5}\)…\(10^{-4}\) m/s (0.3…3 km/yr), which is close to slow motion rates observed in the earth crust after an earthquake or a rockslide. A correlation has been established between the calculated and experimental data on the time and coordinates of fracture in rocks.

1. Introduction
The search for law-like regularities of plastic flow development enabled one to predict novel phenomena in deforming solids. Thus on the macro-scale level the deformation was found to develop by stages, with each stage clearly distinguishable from the rest. The success in using wave ideas has reached its peak in a new concept of plastic deformation; an autowave model has been put forward to account for the inhomogeneous behavior of plastic flow in metals and alloys [1-3]. This has prompted a search for equivalent effects in other fields, in particular, geophysics, which might provide an insight into the problem of so-called slow motions, i.e. waves propagating at low rates of a few kilometers per year in rocks after an earthquake or a rockslide [4-7]. The very existence of slow motions, to say nothing of their nature, remains an open question thus far [7].

On the base of available evidence for mechanisms involved in viscously deforming rocks [9], we examined the different ways in which rock materials respond to stress. W→e have also attempted to give numerical evaluation of the same response. The recognition and interpretation of deformation mechanisms was performed for rocks deforming via different mechanisms, i.e. dislocation glide or twinning in silvinite (NaCl+KCl) and marble (CaCO₃) or grain boundary sliding in sandstone (SiO₂).

2. Materials and experimental techniques
The ultimate goal of this study was to define deformation mechanisms which can operate in rocks and give numerical evaluation of the same. Therefore, the choice of marble, sandstone and silvinite was guided by a knowledge that these materials differ from one another in deformation mechanisms (Table 1). The rock samples were tested in compression along the axis x in a testing machine 'Instron-1185'.

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at cross head motion rates $V_{\text{mach}} = 1.67 \cdot 10^{-3}$ and $1.67 \cdot 10^{-2}$ m/s. The compression-test diagrams were plotted for the test samples of rocks. These differ from the smooth flow curves $\sigma(\varepsilon)$ of most metals and alloys [9] in that they have ‘saw-tooth’ segments, which evidently correspond to a jump-wise decrease in the stress due to rock cracking locally [13]. The rock samples would undergo brittle fracture at the total deformation $\varepsilon_{\text{tot}} = 1.7\ldots3.5 \%$.

Using digital speckle image technique and an automated complex ALMEC-TV [1,10], the compression-test diagram was recorded for the test sample of rock; simultaneously, local strain patterns were being registered for the rock sample face [15,16]. The technique employed enables one to define all the components of the plastic distortion tensor $\beta_{ik} = \nabla r$ (here $r$ is the displacement vector, which can be determined from the speckle patterns). In what follows, we shall restrict our consideration to the axial strain $\varepsilon_{xx} = \partial u / \partial x$ (here $u$ is displacement along the axis $x$). The spatial patterns $\varepsilon_{xx}(x)$ were analyzed and the distribution of local strain zones was thus obtained. Using the local nuclei’s positions, $X$, as a function of deformation or time, the kinetics of macrolocalization patterns was examined.

3. Experimental results
Numerical evaluation of local strains was performed for the test samples of rocks. The results obtained suggest that on the macro-scale level the deformation would exhibit a localization behavior. Non-deformed material volumes are found to alternate with local strain zones; the deformation fronts travel at varying rates along the compression sample.

A localized deformation pattern obtained for the test sample of marble is illustrated in Figure 1; the deformation fronts are designated by the dashed lines and are numbered in the order of appearance. We take it as convincing evidence that on the macro-scale level the deforming material volume would undergo fragmentation with the fragment boundaries changing with time.

![Figure 1](image1.png)

Figure 1. The localized deformation zones moving at different compressive strain levels (%) in the test sample of marble; the arrows point to the front numbers.
With growing total deformation, the emergent localized plasticity zones will start traveling over the sample surface, forming thereby a kind of autowave. The behavior of local strain zones will plot on the flow curve $\sigma(\varepsilon)$ as a linear segment. The motion rates of localized plasticity nuclei (autowaves) are listed in Table 1 for the studied rocks. It is found experimentally that the autowave motion rate $V_{aw}$, depends on the sample loading rate, $V_{mach}$, as $V_{aw} \approx 20V_{mach}$, which agrees with the experimental data obtained previously for metallic materials [1]. The motion rates of localized plasticity fronts were determined for the test samples of rocks using the complex ALMEC-TV; the values obtained are in the range $(2.8...4.4) \times 10^5$ m/s, i.e. 0.9...1.3 km/yr, which is close in order of magnitude to slow motion rates. One cannot but infer that slow motions are localized plasticity autowaves, which form deep in the earth crust where earthquakes or rockslides are generated. Thus, in the laboratory studies we examined the different ways in which rock materials respond to stress, in particular, the deformation processes occurring at rates close to slow motion rates.

Another regular feature of the autowave evolution is worthy of notice. It has been found previously that the evolution of localized plastic flow in metals ends in collapse of the autowave [1]. In the case of rocks, sandstone and marble the same regularity is observed. Of particular note is the point on the plot $X(t)$ at which collapse of the autowave occurs, since the point’s coordinates coincide with the place and location of imminent sample fracture [10].

### Table 1. The kinetics of localized deformation fronts in rock samples.

| Rock          | Silvinite | Marble | Sandstone |
|---------------|-----------|--------|-----------|
| Fronts’ motion rate at the linear stage, m/s | $\sim 2.8 \times 10^5$ | $\sim 4.2 \times 10^5$ | $\sim 3.0 \times 10^5$ |
| Wavelength, m | $\sim 10 \times 10^3$ | $(4 \pm 1) \times 10^3$ | $(4 \pm 1) \times 10^3$ |
| Interplanar distance, m | - | $0.386 \times 10^{-9}$ | $0.41 \times 10^{-9}$ |
| Transverse elastic wave rate, m/s | - | 1905 | 1860 |
| Coefficients in Equations (2) and (3) | | | |
| $\alpha \cdot 10^3$, c | 3.08 | 1.7 |
| $\alpha_0 \cdot 10^3$, m/c | Failed to | -2.15 | -1.9 |
| $\xi^* = \alpha_0 / \alpha$, mm | establish | -0.7 | -1.1 |
| $t^* = t_0 + 1/\alpha$, c | 415 | 730 |
| Matching of experimental and calculated times (4) and coordinates (5) of fracture | | | |
| $t^*_\text{exp}/t^*_\text{calc}$ | Failed to | 380/415 | 600/730 |
| $X^*_\text{exp}/X^*_\text{calc}$ | establish | 6/3 | 5/6 |

The motion of local plasticity nuclei plots as a bundle of straight lines, since their rate depends linearly on the coordinate of the point of nucleation $\xi$. Hence, the relationship established in [1] will hold good, i.e.

$$V_{aw}(\xi) = \alpha \xi + \alpha_0, \quad (1)$$

where $\xi$ – a coordinate counted from the stationary localization nucleus; $\alpha$ and $\alpha_0$ – empirical constants. The values $t^*$ and $X^*$ are, respectively, the time of nucleus arrival and the place of sample fracture (see Table 1). These are calculated as

$$t^* = t_0 + 1/\alpha, \quad (2)$$

$$X^* = X_0 + \alpha_0 / \alpha, \quad (3)$$

where $t_0$ – the instant of time at which the prefracture stage begins; $X_0$ – the position of the stationary nucleus calculated in the laboratory system of coordinates for the beginning of prefracture stage. The coordinates $X^*$ and times $t^*$ were calculated for marble and sandstone; the values obtained are $X^* \approx 3$ mm and $X^* \approx 6$ mm, respectively; $t^* \approx 415$ s and $730$ s, respectively. In point of fact, fracture
occurred in the test samples of marble and sandstone within 380 s and 600 s, respectively, due to sample cracking at 6-mm and 5-mm distance, respectively, from the immovable clamp.

The values $t^*$ and $X^*$ were calculated and obtained experimentally. The correlation of two sets of data obtained for metals and rocks is given as

$$t_{\text{calc}} = t_0 + b \cdot t_{\text{exp}},$$  \hspace{1cm} (4)

$$X_{\text{calc}} = X_0 + a \cdot X_{\text{exp}},$$  \hspace{1cm} (5)

where $t_0 = -18$ s; $b = 0.96; X_0 = -0.5$ mm; $a = 1.02$.

There is a satisfactory agreement between the calculated and experimental sets of data. This suggests that the point where plots intersect (so-called ‘pole’) has coordinates which are close to the time and place of real fracture; hence, formulas (2) and (3) enable one to predict with sufficient accuracy the time and location of imminent fracture in the test sample.

On the base of the above, it is hypothesized that the place and time of fracture in rocks can be predicted using experimental linear dependencies $\chi(t)$, which admit of extrapolation to larger times. Similar problems were previously formulated in [11]. The response to stress of rock samples is in many ways similar to that of metals and alloys, which were used for plastic flow localization investigations; hence, one can look forward to a successful solution of this problem.

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4. Conclusions

1. The development of localized plastic deformation in metals and rocks is found to have similar general features.

2. Quantitative assessment has been made of the autowave features of localized plasticity evolution in studied rocks.

3. It is shown that slow motions in rocks occur at rates close to the propagation rate of localized plasticity autowaves observed for the rock samples studied.

References

[1] Зуев Л Б, Данилов В И и Баранникова С А 2008 Физика макролокализации пластического течения (Новосибирск: Наука)

[2] Zuev L B, Danilov V I, Barannikova S A and Gorbatenko V V 2009 Phys. of Wave Phen. 17 66-75

[3] Barannikova S A, Nadezhkin M V and Zuev L B 2009 On the localization of plastic flow under compression of NaCl and KCl crystals PSS 51 No 6 (Pleiades Publishing, Ltd.) pp 1142-1148

[4] Митлин В С и Николаевский В Н 1990 Нелинейная диффузия тектонических напряжений ДАН СССР 315 1093-1096

[5] Быков В Г 2005 Деформационные волны Земли: концепция, наблюдения и модели. Геология и геофизика 46 1176-1190

[6] Гольдин С В 2008 Сейсмические волны в анизотропных средах (Новосибирск: Изд-во СО РАН)

[7] Опарин В Н, Таписев А П, Розенбаум М А 2008 Зональная дезинтеграция горных пород и устойчивость подземных выработок (Новосибирск: Изд-во СО РАН)

[8] Ботвиных Л Р 2008 Разрушение. Кинетика, механизмы, общие закономерности (Москва: Наука)

[9] Pelleg J 2013 Mechanical properties of materials (Dordrecht: Springer)

[10] Zuev L B, Barannikova S A, Gorbatenko V V and Nadezhkin M V 2013 On the observation of slow wave processes in deforming rock samples Journal of Mining World Express 2 31-39

[11] Введенская А В 1969 Исследование напряжений и разрывов в очагах землетрясений при помощи теории дислокаций (Москва: Наука)