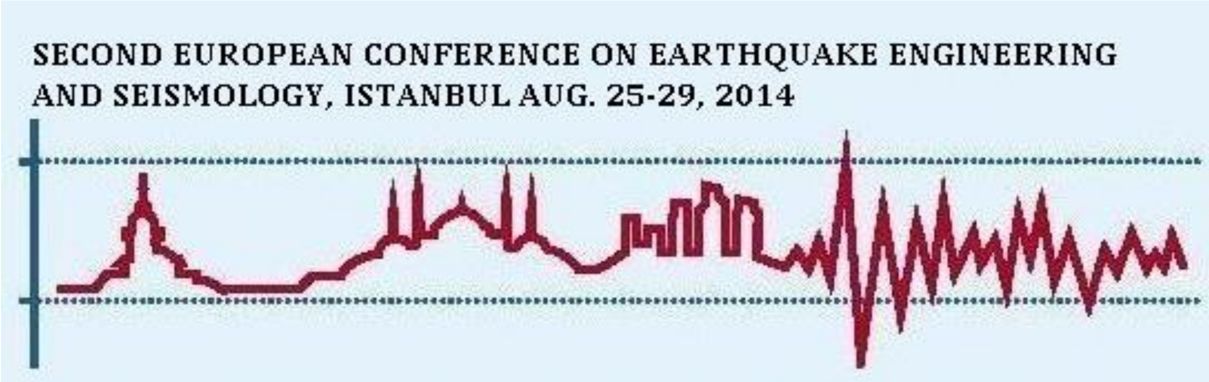

POSSIBLE FLUID AFFECT ON THE SEISMICITY OF STORFJORD STRAIT, SPITSBERGEN

Sergey BARANOV[1], Elena KREMENETSKAYA[2] and Anatoly VINOGRADOV[3]

The paper considers seismicity of Storfjord strait, Spitsbergen due to strong Mw = 6.1 (ML = 6) earthquake which occurred on 21.02.2008 at 02:46:17 UT. We used data for 2007-2013 recorded by seismic array SPI (NORSAR), situated near Longyearbyen at the distance of 150 km North of the epicenter. During the first days after the mainshock the intensity of the aftershock process exceeded 950 events with ML ≥ 0 per day. To process such a big data volume a special program UDL was developed by Asming and Fedorov (2010). Pirly et al. (2010) provided the most accurate estimation of the mainshock epicenter, using the data of regional network of 10 stations: the epicenter was at 77.007 N and 19.008 E, the depth was 15 ± 5 km; the best model for the mainshock moment tensor, simulated on the base of regional and teleseismic waveforms, was described as the oblique-normal faulting.

To study the aftershock process we used relaxation and trigger seismicity models. To model the stress relaxation we used LPL model, suggested by Narteau et al (2002):

$$n(t) = A \cdot t^{-q}[\gamma(q,\lambda_b t) - \gamma(q,\lambda_a t)], \tag{1}$$

where γ – is an incomplete gamma function; A, q, λ_a, and λ_b are the fitted parameters. The LPL depending on its parameters describes both hyperbolic decay like the modified Omori law, and exponential decay like the stretched exponent models. As the suitable model of trigger seismicity was selected the ETAS, suggested by Ogata (1989), defining that:

$$n(t) = \mu + \sum_{t_i<t} \frac{K_i}{(t-t_i+c)^p},\ K_i = K\exp[\alpha(M_i - M_0)], \tag{2}$$

where t_i – time and M_i – magnitude of the event with number i from the catalog; M_0 – cut-off magnitude. Parameters μ, c, p, K, α have to be fitted. The background rate μ describes an activity, which is not triggered by previous earthquakes, i.e., it is not a part of the aftershock sequence. As assumed, at tectonic plate boundaries, μ is linked with a stress accumulation due to tectonic plate motion, whereas in the intraplate areas with fluid intrusion μ refers to an activity, induced by the fluid (Hainzl, Ogata, 2005).

All the models were fitted with the maximum likelihood method. The best model was chosen with Akaike (1974) information criterion (AIC). The better model has the lower AIC value.

In the previous studies (Baranov, 2011; Baranov, 2013) was shown that the aftershock process in the Storfjord during time span of 21.02.2008 to 10.04.2009 might be presented as the superposition of two subprocesses, which are controlling by both trigger and relaxation geomechanics.

[1] Kola Branch of Geophysical Survey of Russian Academy of Sciences, Apatity, Russia, bars.vl@gmail.com
[2]Kola Branch of Geophysical Survey of Russian Academy of Sciences, Apatity, Russia, lenakrem@gmail.com
[3] Kola Branch of Geophysical Survey of Russian Academy of Sciences, Apatity, Russia, vino@admksc.apatity.ru

The trigger subprocess was controlling the events with ML ≥ -0.2 and < 2.0, and the relaxation was responsible for events set with ML ≥ 2. The ETAS is the best model for the trigger process, and the LPL-model describes the relaxation subprocess rather well. The conclusion was that ML ≥ 2 events would continue in Storfjord after 10.04.2009. The further data has proved this assumption (fig. 2a), which is also important for forecasting seismicity. Moreover, by the end of 2013 the seismicity rate in Storfjord did not decay to the level, observed before the mainshock (fig. 2). Such a long aftershock sequence is a very rare phenomenon in the intraplate condition.

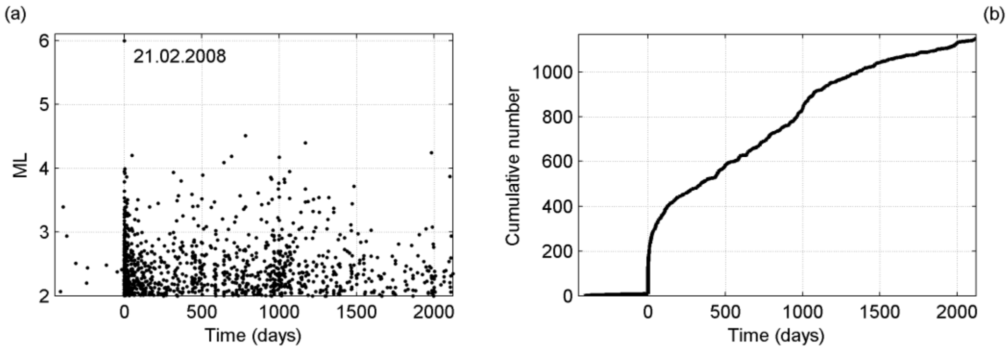

Figure. 2. Seismicity of the strait of Storfjord for 2007 - 2013 by UDL-program (Asming, Fedorov, 2010). Magnitudes (a) and cumulative number (b) of earthquakes as a functions of their occurrence. The time is measured from the moment of mainshock - 21.02.2008, 02:46:17 UT.

The cumulative curve (fig. 2b) shows that the ML ≥ 2 aftershock process in 450-500 after the mainshock stopped to be a relaxation one. Modeling the aftershock process using data for the period of 21.02.2008 – 31.12.2013 (table 1) also gives proof for that: the AIC value of ETAS model is lesser in compare with the LPL model one on 28%. Note, it means that trigger effect has appeared in the aftershock process, i.e., part of the events was not caused by the stress relaxation in the fault zone but was generated by the external reasons. Thus, the character of the aftershock process changed significantly.

Table. 1. Estimated LPL and ETAS models parameters and corresponding AIC values for the aftershock process from 21.02.2008 till 31.12.2013

Model	Parameters	AIC
LPL (1)	A = 20.91, q = 0.66, λ_a = 0, λ_b = 466.69	1911.7
ETAS (2)	μ = 0.02, K = 0.01, c = 0.004, α = 1.73, p = 0.93	1379.6

To make more detailed study of the phenomenon, we fitted ETAS model (2) in a moving time window with the length of 20 days. A systematic variation in the external forcing strength μ is revealed (fig. 3). The mainshock was initiated by a strong tectonic impulse. After the mainshock the stress was relaxing within 210 days. The second peak impulse was appeared about 450 days after the mainshock, and also manifested the decreasing trend of energy release with time. The third peak is visible at 1000 days after the mainshock, and the following events set shows the decreasing trend too. Further peaks of the forcing rate μ are smaller than the previous ones, so the rate decays with time.

We think that the observed peaks, excluding the first one, were not initiated by tectonic because their times did not correspond to the times of strong aftershocks occurrence (fig. 3). Near the times of these peaks the seismicity patterns are similar to swarm activity. The key question is the reason of the observed forcing rate variation? We suppose that this is an affect of fluid intrusion.

We suggest the following hypothesis. Strong tectonic impulse had initiated movements in faults (mainshock and strong aftershocks) which destructed the drainage system of raising flows of mantle fluids in the crystal basement. Thus, the transportation of mantle volatiles through the crust changed the local stress field and resulted to many earthquakes grouped as the swarms. The raising of the volatiles had to increase a heat flow in Storfjord. The aftershocks followed by the increased heat flow should destroy a gas hydrate layer (Collett, 2009) which is stable under conditions of low temperature and high pressure. The hydrate destruction increases the methane release up to 100 times. This forms seepages and pockmarks on the sea bottom.

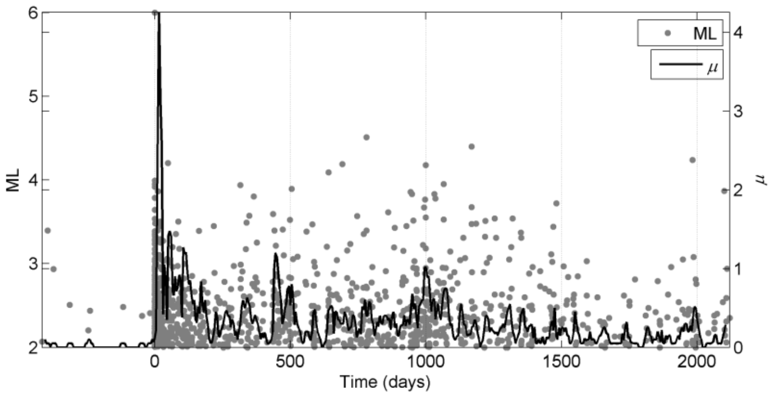

Figure. 3. Time dependences of the forcing rate μ (solid black line) resulting from fitting the ETAS parameters in a moving time window and magnitudes of events (gray points) for 2007 - 2013. The time is measured from the moment of mainshock - 21.02.2008, 02:46:17 UT.

To check this hypothesis we need data of heat flow in Storfjord before and after the earthquake of 21.02.2008. Also we need an isotope ratio of He^3/He^4 as an evidence of penetrated mantle volatilities and methane concentration in the sea water. As for nowadays, we only have three indirect confirmations. (1) The seepages and pockmarks were revealed in the Savlbard fjords (Forwik, et al., 2009) as an evidence of sea bottom degassing. (2) A heat flow exceeding 10 times the average meaning for the Barents Sea was measured toward the northeast of Spitsbergen (Hutorskoy et al., 2009) at the distance of 400 km from Storfjord. This means that there are hot mantle fluids near the bottom. (3) An area of cod catching moved to the south from Storfjord after the earthquake (Vinogradov, et al, 2011). It maybe because of methane released due to destroying the layer of gas hydrates.

This research was supported by Russian Foundation of Basic Research (Project N 14-05-93080).

REFERENCES

Akaike H. (1974) "A new look at the statistical model identification," *IEEE Transactions on Automatic Control1*, 19(6):716-723

Baranov S.V. (2011) "Modeling and simulating an aftershock process caused by a strong earthquake in the Barents Sea Shelf," *Russian Journal of Earth Sciences*, 12:1-9

Baranov S.V. (2013) "The Aftershock Process of the February 21, 2008 Storfjorden Strait, Spitsbergen, Earthquake," *Journal of Volcanology and Seismology*, 7(3):230–242

Collett T.S., Johnson A.H., Knapp C.C., Boswell R. (2009) Natural Gas Hydrates: A Review. Natural gas hydrates – Energy resource potential and associated geologic hazards, AAPG Memoir 89:. P. 146 - 219.

Forwick M., Baeten N.J., Vorren T.O. (2009) "Pockmarks in Spitsbergen fjords," *Norwegian Journal of Geology*, 89:65-77

Hainzl S., Ogata Y. (2005) "Detecting fluid signals in seismicity data through statistical earthquake modeling," *Journal of Geophysical Research*, 110. doi:10.1029/2004JB003247

Hutorskoy, M. D., et al. (2009), "Abnormal heat flow and nature of valleys in North part of Svalbard plate, " *Dokl. Akad. Nauk (in Russian)*, 424(2):227-233

Narteau C., Shebalin P., Holschneider M. (2002) "Temporal limits of the power law aftershock decay rate," *Journal of Geophysical Research*, 107(B12) doi:10.1029/2002JB001868

Ogata Y. (1989) "Statistical model for standard seismicity and detection of anomalies by residual analysis," *Tectonophysics*, 169:159–174

Pirly M., Schweitzer J., Ottemöller L. et al. (2010) "Preliminary Analysis of the 21 February 2008, Svalbard (Norway), Seismic Sequence," *Seismological Research Letters*, 81(1):63 –75

Vinogradov A., Baranov S., Zhichkin A., Moiseev D. (2011) "Seismic affect to distribution of fish clusters in western part of Barents Sea Basin," *Ribnye Resursy (in Russian)*, 2:18-21