Abstract of Andrzej Pasternacki PhD dissertation of entitled:

APPRAISAL OF HYDRAULIC FRACTURING EFFECTIVENESS IN THE SHALE GAS EXPLORATION BASED ON MICROSEISMIC MONITORING

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The aim of the PhD dissertation was to examine utilization o microseismic data for appraisal of hydraulic fracturing effectiveness and to establish a methodology of joint microseismic - reflection seismic interpretation. Chosen area of study was one of the first places in Poland where shale gas exploration with hydraulic stimulation was carried out. The thesis is a complementary study of microseismic data and reflection seismic supported by seismic modeling.

Exploration of conventional hydrocarbon resources is mainly connected with pinpointing location where all main parts of petroleum system occurred, inter alia: reservoir rock with adequate for exploration petrophysical parameters, presence of hydrocarbon trap and source rock with sufficient and matured organic matter, with their spatial and temporal conjunction. Exploration of shale gas resources has different character as those type of resources do not necessitate presence of geometrical hydrocarbon trap as shale gas resides in the source rock itself. Unconventional hydrocarbon resources are defined as those that require application of stimulation techniques to establish sufficient flow to concede them economically viable. Although there are studies that test different stimulation techniques currently hydraulic fracturing with water is one of the most common and widely used. The base of this operation is high pressure and flow rate water injection with chemical additives into the rock layers in order to form a disequilibrium of stresses thus producing fracture network which is preserved by propant, together they constitute flow conduits to wellbore for hydrocarbons and other fluids. Stored energy is partly released as small earthquakes.

The main subject of microseismic are man induced or triggered earthquakes. Although their energy is much smaller than most of the earthquakes studied in global seismology, physical descriptions can be adopted. Due to the ongoing mining operation natural stress equilibrium is perturbed and stored energy is released partly as seismic wave. Microseismic events induced during exploitation of unconventional oil, gas and hydrothermal reservoirs are expected, assuming that their magnitudes will not reach levels that can jeopardize local infrastructure and residents. Presence of microseismic events shows that fracture network have been developed.

Hydraulic fracturing utilized for exploration should be monitored to prevent grow of fractures in the less desirable areas like large scale tectonic discontinuities, which stimulated may not bring positive economic outcome for the performed project. Loss of fracture fluids injected through faults to vain in organic matter layers is leading generally to increase of the cost of stimulation project and can cause environmental concerns when shallower reservoirs are explored. Analysis of pressure and flow rate curves is the basic tool that is used to identify such situations but their interpretation is ambiguous thus prone to error. In case of real-time microseismic monitoring it is possible to identify occurrence of unfavorable happening and modify or stop stimulation program. Main area of utilization of hydraulic fracturing microseismic monitoring is appraisal of effectiveness of the stimulation project. Estimation of stimulated reservoir volume or microseisimicaly stimulated reservoir volume gives opportunity to quantify used stimulation parameters and to modify them if necessary. Moreover it has been showed that it can be linked to value of estimated ultimate recovery of hydrocarbons. Main goal of microsesimic monitoring is to detect and locate small amplitudes

quakes caused by hydraulic fracturing but in such a way that it will lead to determination of directions and sizes of formed fracture network. Properly executed microseismic monitoring project should include monitoring array that is suited for the geological background thus physical parameters of rock formations should be studied. During the interpretation phase uncertainty of the obtained locations should be analyzed as well as the identification of main disadvantages of used array. For example in case of surface array low detection threshold should be accounted, and in the deep borehole spatial variation of detection level and uncertainty should not be neglected.

In the course of the research a processing of weveforms acquired in Lubocino-1 well, during hydraulic stimulation of horizontal part in Lubocino-2H well was done. The main cause and justification of the reprocessing phase was to clarify the concerns that results of archival interpretation possessed. There was high spatial overlap of events from different stages and for the furthest stage from the monitoring well anomalous lineation of events was present. Above all carried out work give opportunity to test the worked out methodology and selected processing procedures on real data. During processing a velocity model was calibrated by perforation events for each stage separately. Such approach opened opportunity to use isotropic velocity model as the calibration takes into account partly also anisotropic behavior and includes it in the velocity model scaling parameters. As a supplementary study a seismic modeling was performed with processing of obtained results to check the performance of the array and also to propose, if any it's modification for future projects in similar geological set up, especially for the case of subsequent wells drilled and fractured from Lubocino well pad.

In the dissertation there are presented results of surface microseismic monitoring that was carried out during initial part of Lubocino-2H stimulation project. Lack of waves connected with induced seismicity on the surface array was examined on the basis of seismic modelling. Results of the numerical simulations and their interpretation have led to a conclusion that energy of the waves was not fully attenuated, and lack of detected induced or triggered events observed on the surface was caused by high level of noise during the time of the monitoring in the area of study. Proposed elastic and viscoelastic simulations of wave propagation where used also to compare different types of monitoring arrays. Based on the obtained results it have been noticed that when well bore is at the distance more than 1,5 [km] from the monitoring array, direct wave is weaken especially when receivers are placed in thin layers that have high impedance contrasts with neighboring layers, thus placing them in intervals more homogenous in acoustic impedance positively influences the obtained results.

One of the assumptions of this dissertation was to validate the opportunity of combined interpretation of microseismic and reflection seismic data. Vital part of this analysis was determination of pethrophysical parameters based on the standard tools used in exploration geophysics like seismic inversion and correlation of seismically derived parameters with those that cannot be estimated directly from it. To obtain the content of total organic carbon distribution number of correlations where performed. In the course of the work several accessory questions emerged, like the influence of the change of the organic content on the tuning effect and seismic modeling of small scale discontinuities.

Essential part of this work was the λ-μ-ρ analysis, which is relatively new tool for so called sweet spot identification that is places, which are characterized by high organic matter content and are prone for developing induced fracture networks, on the basis of seismic reflection data. This analysis

was complemented by analysis of well log data, for validation of its assumptions. λ-μ-ρ can be used for appraisal of layer hydraulic fracturing stimulation susceptibility, even when the seismic data lacks longer offsets, preventing well defined density estimation. Statistical analyses of total organic content have brought meaningful correlations for its interpretation with seismic inversion results. The interpretation of Lubocino3D seismic survey included structural, tectonic and reservoir study, leading to pinpointing locations that can be recognized to be more prospective. Obtained attributes were also used in the further study with microsesimic data.

One of the basic information that is obtained from microseismic data is the microseismic volume (MV) witch in the presented case was estimated for ~ 3 [mln m^3]. Analyzing the spatial distribution of the microseismic events this volume cannot be considered as producing volume in this case. In the result of the connected interpretation with seismic data it has turned out that part of the fracturing was done in a fault zone, being almost in the direction of regional maximum horizontal stress. This has negatively influenced the effectiveness of hydraulic stimulation as energy was dissipated in the zone of tectonic discontinuities and did not produced fracture network in the source rock layers. Above statement find confirmation in the event magnitude distribution, where the estimated b value was below 2. Taking into account the λ-μ-ρ analysis it has been stated that fracturing was conducted in area that did not had favorable geomechanical parameters for grow of induced fractures, as they can source rock layers be considered as ductile, which was also established by the brittleness factor.

In the course of the study was confirmed initially predicted dependency between locations of microseismic events and seismic attributes. Layers that where stimulated have sufficient total organic content to consider them as productive, although their susceptibility for development fractures was low. This interpretation is confirmed by the relatively low distances from stage initiation points and microsesimic volume achieved. Increase of MV in the latter stages from 4 to 6 was conducted with the transition to a more naturally fractured area, which influenced the estimated b value of Richer-Guttenberg relation.

In the course of combined analysis of seismic attributes with the induced seismicity processing results it was proven that hydraulic fracturing was carried out partly in a fault zone. This negatively influenced the effectiveness of the stimulation operation, as most of the energy was dissipated in the tectonic discontinuities and useful for exploration fracture network was not formed in the organic matter rich formations. Based on the seismically derived geomechanical parameters it can be stated that the area where fracturing was carried out was not optimal as the targeted layers where relatively ductile.