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List of the staff actively involved in the WP

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Objectives expected after 6 Month

The activity of WP4 on induced seismicity has four main objectives: the characterization of induced seismicity, tracking migration of induced fractures, and thus the motion of fluids, and assessment of the seismic hazard induced by shale gas exploitation operations. WP4 planned activites are: advanced seismic data processing, statistical description of the induced seismic process, multi-physical modelling of the fracturing process and timedependent seismic hazard assessment and mitigation.

The objectives for the 6 months period were achieved, as discussed in the following section for each task separately.

A summary of progress towards objectives and details for each task in the first six months;

WP4.1

- (4.1.1) Completed the tool to generate synthetic catalogue and waveform, and preparation of synthetic data for the Wysin site.
- (4.1.2) Application waveform-based event detector to realisitc synthetic data and to first real data (May-June 2016, before, during and after the first set of hydraulic fractruing operations); revision and characterization of detected seismic signals.
- (4.1.3) Full development of a method to estimate the detection performance and magnitude of completeness for hydraulic fracturing operations, using preoperational noise records.
- (4.1.6) Advanced processing of induced seismicity data.

The aim of this activity is to determine the source parameters of microearthquakes occurring in the area of The Geysers, the largest enhanced geothermal system (EGS) in the world. We focused on microseismicity close to EGS wells PRATI 9 and 29, with the purpose to investigate kinematic/dynamic fracture properties and their moment scaling, before/during/after the injection cycles and identify possible space-time variations in medium/source properties related to the fluid injection. We selected 130 events (ML 0.5÷2.5) occurred from 01/2010 to 02/2011 in a circular region (radius ~500 m) around the target injection wells. For the analysis of waveforms and spectral shapes, we applied the iterative multistep inversion procedure (Zollo et al., 2014), which solves the correlation among quality factor Q, corner frequency fc and high-frequency spectral fall-

off γ on the displacement spectra. Preliminary results show that the high-frequency, spectral decay parameter is highly variable with azimuth and greater than 2 (omega-square model, average □=3) and that most events distribute in the 0.1-1 MPa stress-drop range (average Δ□=0.4 □□□). The apparent stress increases with seismic moment, likely due to an fc-energy overestimate for larger events. In fact, events with Mw > 1.7 violate the near-constant stress-drop scaling of smaller events, whose corner frequency is well determined in the allowed frequency range. This is probably caused by the geophone low-frequency cut-off at 4.5Hz. From the overall behaviour of the source parameters (radius, stress drop, apparent stress, seismic efficiency), we found no clear evidence of variable fracture parameters at increasing distances from the injection points. Finally, we found an extremely low value for the radiation efficiency, computed as the ratio between the apparent stress and stress drop. This finding suggests that most of energy during the rupture process is spent by friction and fracture development at the source, with no fault lubrication. In other words, the low radiation efficiency could imply that dynamic overshoot is the dominant mechanism controlling the seismic radiation of investigated microearthquakes.

WP4.2
Within Task 4.2 the following research topics are realized by IGF-PAS:

- (4.2.1) The possibility to incorporate static stress drop into seismic hazard assessment was performed in data from the Geysers geothermal field. Preliminary results were demonstrated during the 35th General Assembly of the ESC in Trieste.
- (4.2.2) Multi-dimensional clustering was performed in data from the Geysers geothermal site, after transformation of focal and spectral parameters into equivalent dimensions. Preliminary results were demonstrated during the 35th General Assembly of the ESC in Trieste.
- (4.2.3) The correlation between spatio-temporal seismicity evolution and the variation of injection volumes/rates from The Geysers geothermal site has been analyzed and quantified for different time periods and distances from the injection wells. Preliminary results were demonstrated during the 35th General Assembly of the ESC in Trieste.
- (4.2.4) Seismic interferometry was performed in order to monitor changes in geological medium due to hydrofracturing of shale gas deposits, in Wysin-2-H well, at Wysin site, Pomerania, Poland. The influence of various effects on the produced cross-correlograms was also investigated.
- (4.2.5) The influence of intermediate principal stress (σ_2) on seismicity was investigated for combined coseismic and anthropogenic stresses. Spatial distribution of seismic events was studied in connection with the R parameter, which determines the relative magnitude of principal stresses.

WP4.3

- Sensitivity analysis (parameterised) modelling has now been completed to investigate the effects on flow distance, stress and fracture network area by changing various pumping parameters (flow rate, pressure and pump time) when hydraulically fracturing for shale. Results from Fracman software have been imported into Matlab for Coulomb stress analysis. This work is currently being written up and will be sent to a journal for publication by Christmas 2016. The next stage is to investigate the effect that pore pressure and fracking fluid properties have on the fluid migration and local stress.
- To recognize small amplitude low frequency (LP) events potentially indicators of the fluid participation in the seismicity generation, an Independent Component Analysis based approach for the Blind Source Separation of convolutive mixtures (CICA) has been developed and addressed to the specific SHEER constraints. The robustness of the method is checked by comparing it with other blind source separation techniques based on higher order statistics. The performance test using very noisy data shows that the CICA works even in the case of very poor quality data characterized by very low signal to noise ratio (SNR). Next step will be the analysis of the seismicity recorded by the SHEER seismic

network located in Wysin, with the objective to identify any LP presence and variation before, during and after the fracking experiment.

WP4.4

- The integration of the output of seismic hazard assessments has been fully implemented within the multi-risk framework. Regarding the procedures for hazard assessment, in particular, we are exploring different approaches based on probabilistic covariate models in order to be able to use technological information in the hazard assessment

Highlight clearly significant results;

WP4.1:

- Estimation and spatial mapping of the magnitude of completeness and detection performance at the Wysin site, based on a realistic synthetic dataset.
- Independent estimation of the magnitude of completeness, using our new detection algorithm.
- Generation of an unsupervised detection catalogue with real data (time period May-June 2016, before, during and after hydraulic fracturing); identification of strong temporal (night/day) changes in the detection performance or in the microseismic activity.
- Manual revision of the Wysin detection and seismic signal classification (May-June 2016)
- Adaptation of waveform based location algorithm for hydraulic fracturing, preliminary application to a microseismic event at the Wysin site.

WP 4.2

- Demostration that static stress drop significantly changes in time; Identification of the relation between static stress drop and injection rate at The Geysers geothermal site; Development of the methodology of calculating event occurrence probability maps on the basis of static stress drops spatiotemporal distribution.(4.2.1)
- Similar events locations don't necessarily imply a similarity of the source characteristics of these events and vice versa, although a sort of correlation is evident in some cases. (4.2.2)
- Clear correlation between seismic activity and operational parameters at The Geysers geothermal area is verified and quantified; This correlation is significant for distances > 200m from an injection well; No influence of injection on b-values was detected. (4.2.3)
- Direction of measurement profile – noise directivity strongly affects process of interpretation of seismic noise interferometry results; Presence of strong reflectors within the rock strata limits depth range. (4.2.4)
- Preliminary results indicate a moderate correlation between R-values and injection data. (4.2.5)

WP4.3

- Completion of sensitivity analyses investigating the effects on the fracture network and surround rock by changing pumping parameters.

WP4.4

- Exploration of different approaches based on covariate models for hazard assessment

If applicable, explain the reasons for major deviations from Annex I and their impact on other tasks.

Not applicable

If applicable, explain the reasons for failing to achieve critical objectives and/or not being on schedule and explain the impact on other tasks as well as on available resources and planning.

Not applicable.

If applicable, propose corrective actions.

Not applicable

Publications and papers in print

Leptokaropoulos, K.M., Staszek, M., Lasocki, S., and Kwiatek, G., 2016. Preliminary results for space-time clustering of seismicity and its connection to stimulation processes, in North-Western Geysers, Geothermal field, *35th General Assembly of the European Seismological Commission,* Trieste, Italy, ESC2016-165.

López Comino, J. Á., Kriegerowski, M., Cesca, S., Dahm, T., Mirek, J., and Lasocki, S., 2016. Assessing the monitoring performance using a synthetic microseismic catalogue for hydraulic fracturing. Geophysical Research Abstracts, Vol. 18, EGU2016-7031, EGU General Assembly 2016, Vienna, Austria.

López Comino, J. Á., Cesca, S., Kriegerowski, M., Heimann, S., Dahm, T., Mirek, J., and Lasocki, S., 2016. Seismic monitoring performance for hydraulic fracturing, 35th General Assembly of the European Seismological Commission, Trieste, Italy.

López Comino, J. Á., Heimann, S., Cesca, S., Milkereit, C., Dahm, T., and Zang, A., 2016. Automated detection of acoustic emissions at the hydraulic fracturing experiment at Äspö Hard Rock Laboratory, Sweden, 35th General Assembly of the European Seismological Commission, Trieste, Italy.

López Comino, J. Á., Heimann, S., Cesca, S., Milkereit, C., Dahm, T., and Zang, A., 2016. Acoustic emission analysis of a hydraulic fracturing experiment using continuous waveforms at 1 MHz. Extended abstract EUROCK submitted.

Orlecka-Sikora, B., and S. Lasocki, 2016. Interval estimation of seismic hazard parameters, *Pure Appl. Geophys.*, *accepted for publication on 17th October, 2016*.

Staszek M., Orlecka-Sikora B., Kwiatek G., 2016. Static stress drop of induced earthquakes in seismic hazard assessment: Preliminary results from The Geysers geothermal site*, 35th General Assembly of the European Seismological Commission*, Trieste, Italy, ESC2016-137.