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SPATIAL ANALYSIS OF SEISMIC STRESS DROP AT THE HDR - SOULTZ GEOTHERMAL SITE

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SUMMARY - Variogram analysis for stress drop from induced seismicity generated during injection experiment at HDR- Soultz geothermal site in France was performed. The objective of the study was to examine the relationship between spatial variability of stress drop and distribution of joint and fracture zones within a granite reservoir. For a selected slice of 60 meters thickness and horizontal extension over the whole reservoir a set of directional variograms was computed both along horizontal and vertical planes. Several variograms exhibited spatial correlation of stress drop along certain directions which could be then associated with the direction of the maximum horizontal stress or strike and dip of the main joint sets at Soultz derived from other measurements. The suggested methodology offers a potential to gather some quantitative information about structural features within a reservoir by analysis of seismic source parameters.

1. INTRODUCTION

Induced microseismicity offers the possibility of closer insight of subsurface structures. Many techniques are currently applied to identify structural details in the seismic event cloud and to link them with physical features characterising a reservoir e.g. joints, fracture or weak zones and fault planes. Fehler *et al.* (1987), Jones and Stewart (1993), Phillips *et al.* (1997), suggested methods relying on the location of the event hypocenters to define features in the event cloud. Additionally, Phillips *et al.* (1997) proposed a clustering technique based on similar waveforms of events to delineate planes which could be considered to be hctures within the reservoir. Fehler (1990) used a fault-plane solution to obtain information about structure and mechanism of shearing. Another approach by Roff *et al.* (1996) is the use of the ratio of the first arrival P- to S-wave amplitudes at a given station as an expression of focal mechanism to cluster events. Recently, Starzec *et al.* (in prep.) are formulating a procedure for relating spatial variation of shear displacement to permeability enhancement during stimulation of HDR-reservoir.

While event location techniques are mainly focused on an accurate identification of existing subsurface structures, source parameters derive infoxmation related to focal mechanism, its size and character. To find a quantitative relationship between source parameters and physical properties of subsurface structure is by no means a trivial task, there are however, some successful approaches reported in the literature. An interesting study on a relationship between seismic source parameters and mechanical properties of rocks was performed by Feigner and Grasso (1991) who associated seismic stress drop with the mechanical strength of the geological strata.

This" paper -presents a methodology for geostatistical analysis of seismic stress drop distribution within the HDR reservoir at Soultz-sous-Forêts, France as a possible indicator of joint and fracture zones network.

2. METHODOLOGY

2.1 Concept of Spatial Analysis

Analysis of spatial variability is a common geostatistical approach to examine whether or not there is any significant pattern in data distribution in space. Joumel and Huijbregts (1978) presented the fundamentals of spatial analysis and its application in the field of mineral exploration for locating mineralised ore bodies, their shape and size. Hohn (1988) described the applicability of the method in fields related to petroleum and structural geology for delineating structural discontinuities like fold axes or fault planes.

The core of spatial analysis is termed variography or variogram analysis. The detailed description of variogram analysis is beyond the scope of this manuscript, interested readers are referred to Journel and Huijbregts

(1978) or Isaaks and Srivastava (1989). Formula for calculating variogram function, $\gamma(h)$ for 1-D data is presented by equation (1) adapted from **Isaaks and** Srivastava (1989):

$$\gamma(h) = \frac{1}{2N}\sum[z(x) - z(x+h)]^2 \qquad (1)$$

where h is a distance between sampling locations, $z(x)$ is a value of a variable at location **x**, and N is a number of all possible data pairs separated by distance h.

In general, $\gamma(h)$ is plotted versus increasing h and its shape is then interpreted. In the case where the variogram keeps constant value, the studied variable exhibits **no** spatial correlation, in other words, the variable in question is randomly distributed. Usually, for parameters exhibiting some spatial correlation the variogram **starts** at the origin and rises with increasing pair distance, h. At a certain distance, called range **(Isaaks** and Srivastava, 1989) the variogram reaches a **sill** i.e. a value at which it levels off. The range, **sill** and shape of the variogram are crucial parameters providing information **on** spatial behaviour of **an** investigated variable. Variograms can be calculated in different directions to study if a phenomenon reveals any directional dependence i.e. anisotropy.

2.2 Source Parameters versus Reservoir Properties.

Seismic source parameters: source radii, seismic moment, S- and P- wave amplitudes, stress drop or shear displacement can provide some quantitative information **on** size of the seismicity and focal mechanism. The methodology for calculation source parameters and their physical interpretation were treated among others by Brune (1970), Hanks and Thatcher (1972), Aki and Richards (1980). Some authors (Båth, 1982, Feigner and Grasso 1991) found evidence for a relationship between structural features observed in the field or in the laboratory experiments and seismic source parameters.

Shear displacement seems to be directly related to fracture enlargement and in turn to permeability increase during reservoir stimulation. Seismic stress drop reflects the status of shear stress prior and after earthquake and source radii correspond to the size of a fault plane (assuming circular source and shearing mechanism).

2.3 Soultz Data Set

The status of the HDR-Soultz project has been comprehensively covered by many authors, for extended descriptions see Bresee (1991) or Baria ***et al.*** (1996). In this study we concentrate on a microseismic **data** set from an injection experiment performed in September 1993. A segment of deep borehole, GPK1 between 2850m and 3400m was exposed to injection of in total 25300m^3 water during 22 days. The experimental set up and microseismic monitoring are described by Dyer ***et al.*** (1994). For 6600 events out of 13000 which were located, source parameters were calculated. For details pertaining to the calculation procedure see Jones (1997). For the purposes of **this** study a reservoir section showing relatively **high** fluid acceptance **obtained** fiom flow log interpretation (Evans ***et al.***, 1996) was selected. The vertical extension of the selected slice was fiom 2880m to 2940m, which in fact **was** slightly thicker than the one identified by Evans ***et al.*** (1996) to increase the analysis accuracy due to event location errors. The horizontal extension was practically unlimited; i.e. it included all the events for which source parameters were calculated. Figure 1 presents the distribution of seismicity within the selected slice in a horizontal projection. Horizontal location of the openhole section of GPK1 is also shown. Only events for which source parameters were calculated are presented.

3. RESULTS

The 2-D variogram analysis **was** performed **on** 1140 sampling points (event locations) **with** stress drop **as** the variable. Variography was covered separately for horizontal (west-east- and south-north-direction as co-ordinates), and vertical planes (west-east and depth **as** co-ordinates). Calculations **and** visualisation were performed using Vario2DP-software (Pannatier, 1994). For each plane, variograms were calculated in 18 different directions to cover the entire area of investigation with the smallest possible directional tolerance. For each direction, the distance between pairs (called lag in geostatistical terminology) **was** varied to examine if the spatial variation of stress **drop** is scale dependent.

For analysis in horizontal plane, two directions exhibited a clear pattern of spatial correlation of stress drop. They were: N70E and N20W, oriented in respect to the co-ordinate system on Figure **1.**

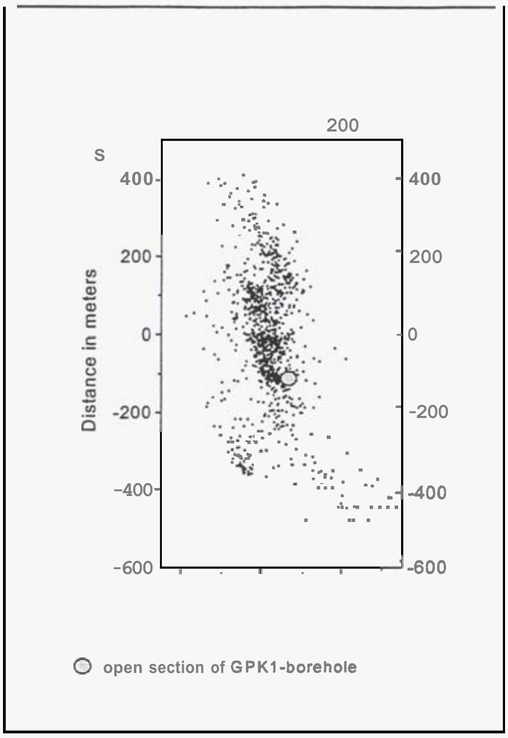

Figure 1- Distribution of microseismicity at Soultz HDR-site during GPK1-injection experiment in September 1993. Horizontal slice, depth interval: 2880-2940m. Number of events: 1140.

Figures 2 and 3 present experimental variograms for these two directions. |h| on the x-axis denotes lags in meters. Labels, directly on the curve correspond to the number of pairs within a particular lag. Variogram function, $\gamma(h)$ is expressed in MPa^2.

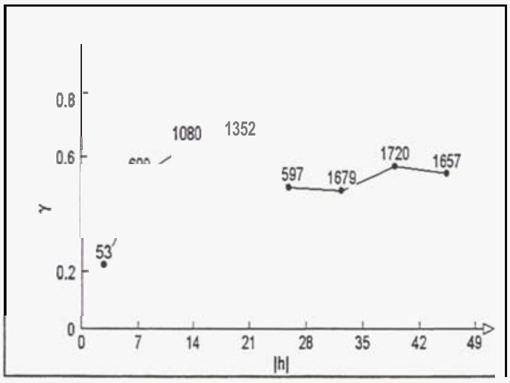

Figure 2- Variogram for stress drop in horizontal plane. Direction: N70E, directional tolerance: 16 degree, lag spacing: 6.5m.

The units for stress drop, in fact, does not have any practical importance in this study as it is the shape of the variograms and the relationship between their parameters which is of interest.

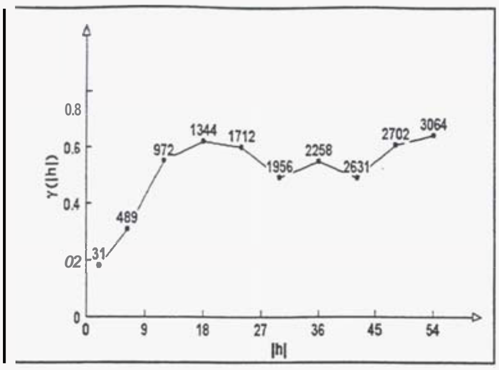

Figure 3- Variogram for stress drop in horizontal plane. Direction: N20W, tolerance: 16 degree, lag spacing: 6m.

Both variograms (see Figures 2 and 3) manifest a clear pattern of spatial correlation. Nugget values (i.e. a variogram value at |h| = 0 meters) are both very low; 0 MPa^2 for N70E-direction and 0.1 MPa^2 for N20W-direction (after approximation). The net sills and ranges are about the same; respectively 0.5 MPa^2 to 0.6 MPa^2 and 18-20 meters. The overall shape of the variograms indicates that stress drop distribution is spatially dependent within an interval from 0 meters to 20 meters and beyond this exhibits random distribution. Variograms in other directions demonstrated no spatial dependence of stress drop. To illustrate this, one direction (N30E) was selected as an example and is presented in Figure 4. The shape of the variogram in Figure 4 differs considerably fiom variograms in Figures 2 and 3. High nugget at low |h|-values reveals distinct micro variation; it seems that in this case there are two structures represented, but even after reducing both lag spacing and directional tolerance it was not possible to separate them.

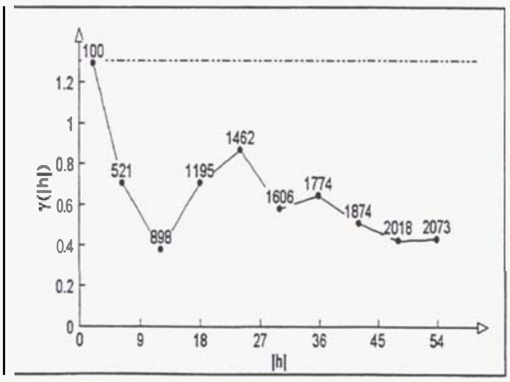

Figure 4- Variogram for stress drop in horizontal plane. Direction: N30E, tolerance: 15 degree, lag spacing: 10m.

Among variograms calculated in the vertical plane there were two directions manifesting spatial correlation, see Figures **5** and ***6***. The shapes of the variograms are different **from** those in the horizontal plane, but spatial dependence of stress drop is clearly demonstrated. The directions for vertical variograms represent dip angle in respect to the horizontal plane.

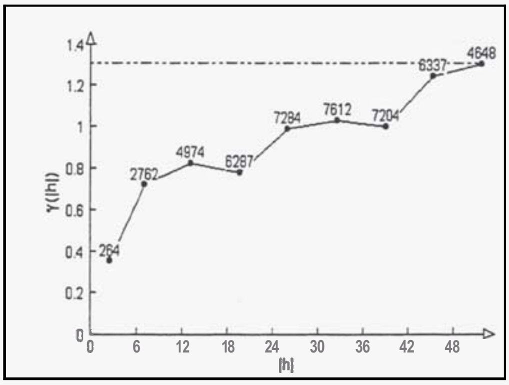

Figure 5- Variogram for stress drop along vertical plane. Direction: 80 degree, tolerance: 15 degree, lag spacing: ***6.5* m.**

Nugget values are about 0.2 MPa^2 and in both cases variogram function demonstrate "staircase" appearance, i.e. it consists of several structures of different size. In other words, the variogram is a combination of, in **this** case, three variograms of different **sills** and ranges. In addition to that, these variograms do not level off in contrast to the variograms in the horizontal plane. Vertical variograms calculated for directions different from the two presented in Figures **5** and ***6***, exhibited random patterns of stress drop spatial distriiution. Figure **7** displays an example for the N30E degree direction. The nugget is very large, about 1 MPa^2, range does not exist, and the variogram hction is semi-constant within the same |h|-interval **as** in Figures **5** and ***6***.

4. DISCUSSION

The computed variogram analysis within selected horizontal and vertical planes clearly indicates spatial correlation of stress drop along some specific directions and not others. In the horizontal plane, the continuity of stress drop along N20W corresponded to the direction of the maximum horizontal stress at Soultz estimated to be round N25W (Bresse 1991) and to the one of the two main joint sets **striking** NNW-SSE mapped by means of BHTV (BRGM, 1998).

The continuity of stress drop along N70E could be associated with another joint set orthogonal to the first one (N25W).

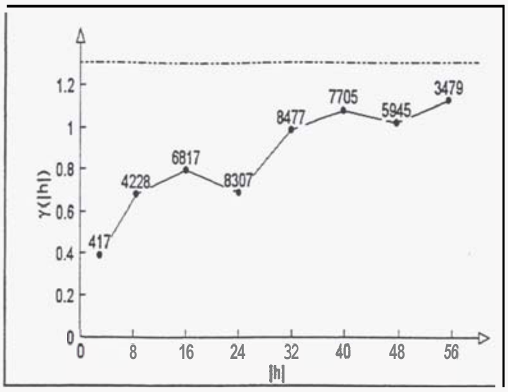

Figure 6- Variogram for stress drop along vertical plane. Direction: 70 degree, tolerance: 12 degree, lag spacing: 8 **m.**

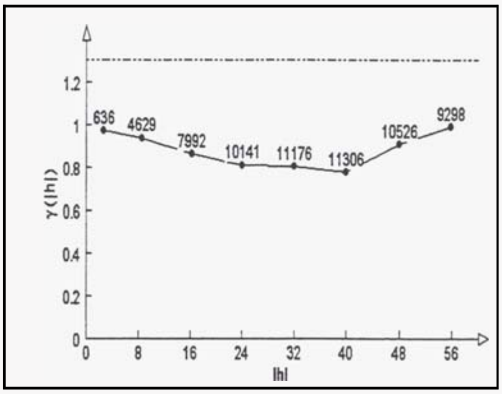

Figure 7- Variogram for stress drop along vertical plane. Direction: **30** degree, tolerance: 15 degree, lag spacing: 8 m.

The directions **of** spatial continuity within vertical planes agreed with dipping angles of joint sets determined **from** several borehole measurement performed at Soultz. After converting the variogram's co-ordinate system to the field co-ordinates, the directions of greatest continuity of stress drop were 70° and 80°, dipping respectively east and west. **This** was in excellent agreement with the results provided from the analysis of **BHTV**, FMI, FMS and **ARI** (BRGM, 1998).

The spatial distribution **of** stress drop demonstrates scale-dependency i.e. variograms exhibit different shapes and ranges while being computed with varying lag spacing.

To recap, it was found that the directions of stress drop continuity correspond to the directions of the joint or fracture sets. **On** the other **hand**, the directions manifesting **no** spatial correlation of stress drop, as for example, the N30°E direction within the vertical plane (see Fig. **7**) do not correspond to directions in which there are **no** structures. It is to be expected that repeated movement on the same joint will typically be more similar than movements on different joints. Therefore the continuity of stress drop in a specific direction during shearing is interpreted as showing that this direction has significant structure (i.e. is perpendicualr to the joint set) and the range is related to the spacing of the joints.

By analogy to mining geology, the range of the variogram could provide information about the extent of the identified fracture zones, i.e. an average fracture spacing in our case. In the horizontal plane, the range for N70E-direction reached about 20 m (see Fig. **2)** and for N20W-direction it was about 18 m (see Fig. **3).** Figure 8 presents a very simple conceptual hcture pattern in horizontal plane derived from variogram analysis with the two **orthogonal** fracture sets and the average fracture spacing. The estimated average fiacture spacing was in relatively good agreement with the analysis presented by BRGM (1998) who derived a cumulative graph of fracture spacing from GPKl borehole with the median value around **30** m. **A** simplified, conceptual fracture pattern for the vertical plane derived fiom the variogram analysis is presented in Fig. ***9,*** where two dominating fracture sets, dipping 80°W and 70°E as well as the average fracture spacing are shown.

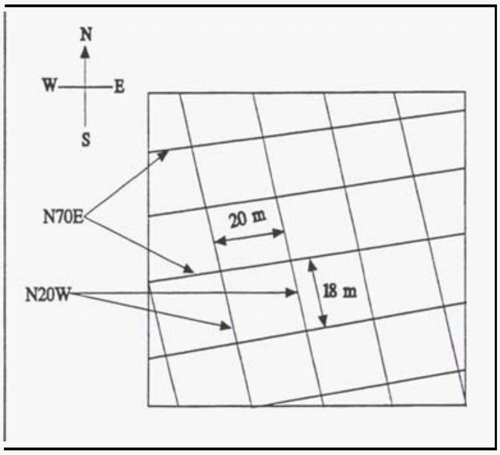

Figure 8 - Simplified, conceptual fracture pattern derived from variogram analysis within horizontal plane. Two main fracture sets, N20W and N70E, and average fracture spacing are displayed.

The outcomes of the presented approach demonstrated a potential to delineate structural discontinuities (weak zones, fractures, joints) and estimate their sizes from source parameter(s) calculated from induced seismicity. The main limitation would appear to lie in the fact that event location uncertainties are comparable to the estimated size of the structural features (fracture spacing).

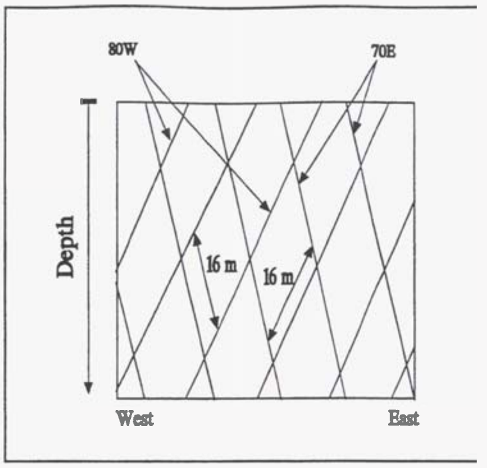

Figure 9 - Simplified, conceptual fracture pattern derived from variogram analysis in the vertical plane. Two main fracture sets dipping 80°W and 70°E, and average fracture spacing are displayed.

5. CONCLUSIONS

The analysis of spatial variability of stress **drop** fiom induced seismicity during an injection experiment at HDR-geothermal site at Soultz in France was performed. The analysis was conducted within a high permeability reservoir segment along both horizontal and vertical planes. In several distinct directions, the distribution of stress drop exhibits a spatial correlation. These directions are associated either with the principal horizontal stress direction or with joint sets and zones **of** weakness determined by other methods. Two main joint sets in horizontal and vertical plane were estimated. The horizontal joints were **striking** N20W and N70E and vertical joints were dipping 80°W and 70°E. In other directions, the variogram functions manifested random distributions. From the ranges of the variograms the average fracture spacing could be inferred to be between 18m and 20m in horizontal plane and 16m in vertical plane.

6. ACKNOWLEDGEMENTS

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