Doctoral School of Earth Sciences

Architecture and Hydraulic Relevance of Brittle Fault Zones in the Metamorphic Basement of the Pannonian Basin

Thesis of Ph.D. Dissertation

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I. Introduction, objectives

Brittle fault zones are lithologically strongly heterogeneous structural elements and significantly affect the hydrogeological systems in the upper part of the Earth's crust. The structural and hydraulic features of the fault zones may reflect extreme temporal and spatial variation. Though, for instance, fault zones that are early in development may be permeable, they may become a barrier to fluid flow when they are more mature. The main fault components, as detailed by Caine et al. (1996) and Evans et al. (1997), are the fault core and the associated damage zone.

The basement of the Pannonian Basin contains several fractured metamorphic hydrocarbon reservoirs where the brittle deformation and the fault zones have a key role in the local hydrogeologic system. Békés Basin, the deepest sub-basin of the Pannonian Basin, is bordered by several Paleozoic highs that contain significant amounts of accumulated petroleum (e.g., the Dévaványa, Endrőd, Sarkadkeresztúr fields). One of the largest reservoirs the Szeghalom Dome is located on the northern margin of the Békés Basin and is mainly composed of Variscan gneisses and amphibolites with different metamorphic evolutions. These petrologically incompatible blocks were juxtaposed by post-metamorphic tectonic activity with predominantly Alpine or Neogene ages. This process was accompanied by the formation of brittle fault zones with notable porosity enhancement and as a result these planes mainly act as migrational pathways in the hydraulic system of the metamorphic highs.

Lithological composition for the Szeghalom Dome was summarized by M. Tóth (2008), along with the most characteristic lithologies (diverse types of gneisses, amphibolite and micro-granite) and these results determined the conceptual lithological framework model of the basement high. Moreover, the post-metamorphic fluid and fracture network evolution was defined by Juhász et al. (2003) and Schubert et al. (2007) who described the possible timing of the petroleum migration and the details of hydraulic connectivity with the adjacent or overlying sedimentary rocks. Although these studies revealed the importance of the brittle fault zones in the juxtaposition of the diverse metamorphic blocks and subsequent fluid migration, no definition of their spatial arrangement has yet been achieved.

Aim of this study was to define the characteristics of the fault zones developed in metamorphic lithology with a special emphasis on their microstructural clast geometric and rock mechanical attributes. The throughout interpretation of the available borecores and well-log datasets aimed the determination of fault zones of the study area which provided the opportunity for the partial reconstruction of the post-metamorphic structural evolution of the Szeghalom Dome. Finally, discussing the relevance of the main shear zones in the petroleum system of the basement high was also a target of this work.

II. Methods applied

For the purpose of the classification of diverse fault rock samples from the fault zone of well A-180 in Szeghalom Dome detailed petrographic, macro- and microstructural investigations were carried out both on the available borecores and thin section.

The shape and size characteristics of the particles formed during brittle deformation were measured with Petrographic Image Analysis (PIA) method both in borecore and at the thin section scale. PIA of the borecore samples was performed on core-scanner pictures taken by the ImaGeo core scanner in the Hungarian Geological and Geophysical Institute. The micro-scale analysis was achieved on micro-photographs from selected, structurally representative parts of thin sections. The clast geometric measurements were completed using the selected parameters in ImageJ: Particle Size Distribution (*PSD*), Clast Complexity (D^R), Aspect Ratio (*AR*), Circularity (*Circ*), Convexity (*Conv*) and Clast Orientation (*Angle*).

The resulted database allowed for statistical processing with the goal of distinguishing the distinct fault rocks and revealing the prevalent brittle deformation mechanisms that operate during different stages of fragmentation. IBM SPSS 20.0 Statistics software was applied for the statistical evaluation of the results to answer the following questions:

1) how reliably can the lithologies be distinguished based on their geometric parameters?

2) which parameters are responsible for characterisation of each group?

3) how do the different stages of deformation manifest in the measured parameters?

Discriminant function analyses were performed to define which parameters participate in the distinction of differ tectonite types, and to what level, both for pairwise and for all three groups. The aim of multidimensional-scaling is to set the place of the samples in the theoretical six-dimensional space of the measured parameters and illustrate the evolution of the particles from the aspect of geometric parameters.

Rock mechanical attributes of the fault rocks were determined using a series of uniaxial compressive tests according to the suggestions of the International Society for Rock Mechanics (ISRM, 2006). Rock mechanical tests were carried out in the Rock Mechanics Laboratory at the Budapest University of Technology and the Economics.

The well-log data were calibrated on the depth intervals of well A-180 that overlapped with the core samples to define the lithologic composition of seven analyzed well from the central part of the Szeghalom Dome. The data set was statistically evaluated using the IBM SPSS 20.0 statistics software. The discriminant function analysis method was constructed to separate the lithologic groups based on available potential, caliper, resistivity, density, compensated neutron porosity, acoustic and natural gamma logs. First, a discriminant function was computed to define the difference between the undeformed wall rock and the tectonized depth intervals by calculating the proper linear combination of the measured well-log data. Discriminant functions were then calculated to define the different types of fault rocks (fault breccia, cataclasite, fault gouge) within the zones that were classified as tectonized in the previous step. The computed functions were then applied to construct the lithological column of the investigated wells. Spatial correlations between the reconstructed 1D lithologic columns revealed the main structural elements of the Szeghalom Dome.

III. New scientific results

1. In the fault zone of the well A-180 three dominant fault rock types can be classified: fault breccias, cataclasites and fault gouges. Most of the analyzed samples were composed of coarse fault breccia that contained weakly disaggregated structures and clast sizes that were typically greater than cm-scale. Several samples show characteristic micro-scale features of cataclastic deformation that resulted in a decrease in clast size an increase in the matrix ratio and the formation of preferred orientation. A third type of samples, the incohesive fault gouges, is present in thin deformational bands which probably define the localized slip zones of the faults.

2. The multivariate statistical processing of the clast geometric PIA results of the fault rocks demonstrated the importance of *PSD*, *Angle*, *AR*, and *Circ* parameters in the classification of diverse tectonite types. The calculated pair-wise and joint discriminant functions clearly separated the diverse fault rocks by the combination of the above parameters in descending order of importance. The discriminant functions also pointed out the relatively similar geometric features of fault breccias and cataclasites in contrast to the significantly different characteristics of fault gouges.

3. Multidimensional scaling resulted in a three-fold particle evolution scheme from the less deformed samples to the most fragmented ones. This statistical interpretation illuminated the strongly diverse attributes of the fault gouge compared with the other two groups of breccias and cataclasites. The multidimensional scaling demonstrated the evolution of the analysed brittle tectonites where the initial deformation is coupled with chaotic fabric giving a weakly disaggregated fault breccia texture. The transitional stage can be characterised by cataclastic flow while in the most deformed fault gouge samples the strong fragmentation, clast-rounding and oriented texture dominate.

4. The main fault zone units, the damage zone and the fault core were separated based on their rock mechanical features as a result of uniaxial compression tests series. Damage zone of the fault can be characterised by an extremely brittle nature and low uniaxial compressive strength coupled with a dominantly coarse fault breccia composition. In contrast, the gouge-rich fault core reflects a widespread plastic and inelastic nature with locally pseudo-ductile microstructure.

In the core of the fault zone, strain localization was the dominant deformation phenomenon, as implied by the pervasive formation of fault gouge ribbons.

5. Between the damage zone and fault core units of the shear zone a characteristic section was observed based on the uniaxial compressive tests with significant strain hardening relatively high uniaxial compressive strength and low brittleness. This transitional zone may suggest interplay between the brittle and ductile behaviors and presumably marks the strongest part of the fault zone based on rock mechanics.

6. The available borecores were calibrated with their well logs, and the dominant petrophysical attributes of the tectonised depth intervals were defined. The most essential difference between the undeformed wall rock and the tectonized zones in this metamorphic lithology are the high natural gamma values, the relatively lower resistivity and densities in the tectonized zones. These results suggest that the intensely deformed fault cores can be characterized by the low density and resistivity with elevated natural gamma activity and compensated neutron porosity values. In contrast, the interpreted damage zones with coarse fault breccias have higher density and resistivity values with lower gamma and neutron porosity values. The calculated results were extended to the 1D log intervals of the same well without borecores and their correlation was attempted on the seven available wells from the Szeghalom field.

7. The estimated tectonic boundaries between the juxtaposed lithologic blocks of Szeghalom reservoir were defined via the correlation of the constructed 1D lithologic columns. According to

their interpretation and to the structural evolution of the adjacent areas the spatial arrangement of the deformed depth intervals indicates the presence of low angle (<15°) thrust fault planes. These defined fault zones most likely developed due to north-northwest vergent Eoalpine (Late Cretaceous) compressional tectonics which was probably responsible for the juxtaposition of the different metamorphic blocks. The structure of the Szeghalom Dome was further complicated by high angle normal faults with approximately 100-150 meter of vertical displacement which are related to the middle Miocene extension. This phase of the geodynamical evolution of the basin is believed to be responsible for the horst-graben structure of the Szeghalom Dome.

8. The integration of the structural results with datasets of the paleo-fluid evolution recent production and fracture network geometry indicates the importance of these fault zones in both the migration of hydrocarbons from the adjacent sub-basins to the overlying sediments and to the strongly fractured amphibolite bodies within the basement. In this model, the damage zones of faults, with their limited width and spatial distribution served as migration pathways towards these sporadic bodies. The hydraulic compartmentalization of Szeghalom Dome can be explained most likely by the combined effects of the intense multistage Neogene tectonic activity (M. Tóth et al., 2009) and the strong permeability anisotropy of the fault zones (Evans et al., 1997) throughout the fractured reservoir.

IV. List of publications

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