Theses of PhD dissertation

RECONSTRUCTION OF MULTI-PHASE FLUID FLOW HISTORY AND TECTONIC EVOLUTION IN A VARISCAN GRANITE INTRUSION (VELENCE MTS., HUNGARY)

ZSOLT BENKÓ

Department of Mineralogy, Eötvös Loránd University, Budapest
PhD School in Earth Sciences
Geology-Geophysics PhD Programme
Head: Prof. Miklós Monostori

and

Université Henry Poincaré, Nancy 1, Faculte des Sciences & Techniques
U.F.R. Sciences & Techniques de la Matiere et des Procédés
Ecole Doctorale RP2E
Département de Formation Doctorale Géosciences

Supervisors

Ferenc Molnár	Professor, Department of Mineralogy, ELTE University
Marc Lespinasse	Professor, Henri Poincaré University, Nancy 1

2008

INTRODUCTION, MAIN GOALS

Principal flow channels of hydrothermal fluids and groundwaters in crystalline rocks are the microcracks (μm-mm scale) and fissures (cm-m scale). Subsurface fluids depending on their character can be interesting for the geologists from different aspects. Depletion of the classical sedimentary rock hosted hydrocarbon reservoirs has increasingly turned the attention to the exploitability of gas and oil reservoirs with primary fracture related porosity and permeability in crystalline rocks. In magmatic and metamorphic rocks, hydrothermal fluid flow is constrained by fissures and microfractures: importance of these features in formation of hydrothermal ore deposits is widely known. In the last decades, planning and designation of nuclear waste deposits in crystalline rocks has also attracted specific attention. Beyond the listed examples – from hydrogeological point of view – analysis of the fracture systems of water reservoirs is equally important since at many dry areas fractured rocks are the primary water reservoirs.

Earlier studies of fracture systems focused mostly on the large scale, well visible joints, faults and mineralised veins which can easily be surveyed on the field. In the past few decades, more and more attention has turned to the open and healed microcracks and to their relationships to fracture systems of other magnitudes. It has been proved that analysis of these microfractures has primary importance in evaluation of the permeability of the rock and it also contributes to the reconstruction of the tectonic history of the investigated area. Moreover, some specific microfractures entrap small portions of the fluids which migrated in the open space at the time of their formation, which enables us to determine the physical and chemical conditions during the microfracture-driven fluid flow. Such fractures are called the fluid inclusion planes (hereinafter FIP).

The subject of this work is the analysis of the relationship between fracture systems on different scales in a relatively homogeneous granite body and the temporal and spatial relationship of hydrothermal fluid percolation of different ages which interacted with the granite body. The selected area is the Velence Mountains in Western Hungary, which was affected by both the Variscan and Alpean orogeny. Owing to their special geotectonical position, the Velence Mts. and its region was involved in the whole Alpean cycle from the rift phase until the collision. Selection of this area for studies is also supported by the occurrence of sufficient amount of large outcrops. Also, earlier studies proved that the granite was affected by several high temperature fluid flow events and that these fluid migration events are easily distinguishable by means of fluid inclusion studies.

An important question of the work was – in addition to the how and when the fractures formed – how the hydrothermal and other old fractures influenced the formation of the current fracture network of the granite.

METHODS

Understanding of fracture evolution in the frame of the tectonic history of the granite required field observations on fractures and tectonic phenomenon's and characterization of their correlation with microfracture properties as well as more accurate knowledge of the age of alteration resulted from the fluid/rock interaction. Geochemistry, mineralogy and physical conditions of the fracture forming hydrothermal systems were also necessary to be determined.

To be able to compare the macroscopic data of fissures to each other and to the microscopic data of fluid inclusion planes and open microcracks, a new method of field analysis has been developed. Along selected base lines in rock exposures of the Velence Mts. I determined the geometrical and mineralogical parameters (dip direction and angle, mineralization, thickness, length as well as alteration of the host rock) of the veins, fractures, faults. The created database was useful for preparation of different statistical calculations. By fault slip analysis I also investigated the stress fields, related to the hydrothermal events.

Types and varieties of clay minerals are sensitive to the conditions of fluid/rock interaction therefore their systematic mineralogical characterization has been carried out to distinguish the different parts of a hydrothermal system. In addition hydrothermal clay minerals containing sufficient amount K (illite) are useful for K-Ar radiometric age determination of the hydrothermal system.

Sulphur isotope analysis has been performed on ore minerals. The $\delta^{34}S$ values themselves may represent the source region of the hydrothermal fluids and are applicable for the comparison of different mineralization. On the other hand, in coexisting mineral phases precipitating from the hydrothermal fluid $\delta^{34}S$ values can be used for calculation of the temperature of hydrothermal processes.

The aim of the lead isotope studies was two fold: to determine the model age of the galena and to compare the lead isotope data of mineralization in the Velence Mts. and the Szabadbattyán area with other deposits in Eastern and Southern Alps along the Periadriatic-Balaton lineament.

Regional fluid inclusion studies have been compiled on the secondary fluid inclusions of the rock forming quartz of the granite to determine the aerial extent of the hydrothermal fluid flow events of different ages. Fluid inclusion data yielded excellent additional information to the tectonic analysis of the granite and provided the basic information to the p-T determination of the hydrothermal fluid circulation events.

Formation of the fluid inclusion planes in the rock forming quartz of the granite is tectonically constrained. On the other hand their statistical parameters (length, density) is in correlation with the paleo-porosity and permeability of the rock during the hydrothermal fluid flow. Therefore by means of their geometrical analysis I was able to determine the minimum principal stress tensors of the stress filed. Analysis of the statistical and geometrical parameters of the fluid inclusion planes have been performed by the AnIma computer code and by universal stage.

This work was also supported by the fractal analysis of the mineralised veins, and the correlation of the fractal properties with other mineralogical characters and structural parameters.

In the knowledge of these general characteristics, it was possible to describe and compare the macroscopic and microscopic features related to the main hydrothermal processes.

THESES

1. In the Velence Mts., eight tectonic events can be distinguished. These events are related to the late Variscan and to the Alpean orogenic processes. The initial fracture system formed during the Variscan and Triassic magmatic and tectonic events. The formation and propagation of the younger fracture systems during the young Alpean tectonic phases were essentially determined by those older features.

2. Variscan fluid flow has solely been identified in the eastern part of the granite intrusion. It took place in a NW-SE oriented extensional stress field, which also determined the orientation of granite porphyry and aplite dikes.

3. The Triassic fluid flow took place in a permutating stress field which is usually characteristic for ascending rock bodies. Regionally, the extensional stress field was NW-SE oriented, parallel with the Variscan one.

4. In the Triassic fluid flow zones the characteristic clay mineral alteration assemblage is illite-kaolinite-smectite clay mineral assemblage, which surrounds the quartz-fluorite-base metal veins. The first mineral phase was the illite, which formed at 250°C, whereas the illite and smectite formed during the cooling of the hydrothermal system below 200°C.

5. It has been documented that the quartz-fluorite-base metal veins formed during the Triassic fluid flow events in relation to the advanced stage of rifting in the Neo-Tethyan system. Direct evidences are based on the K-Ar radiometric age dating. Indirect evidences are from the results of the regional fluid inclusion studies, mineralogical characteristics of argillic alteration zones and from the lead and sulphur isotope analysis.

6. Formation of the quartz-fluorite-base metal veins terminated at 250°C and at 700-1000 bar pressure. Vein formation was a multi-phase process, increasing salinity of the ore forming fluids was attended by decreasing temperature.

7. Bimodal distribution of the homogenization temperatures of the Triassic fluid inclusion assemblages confirms post-Triassic tectonic displacement between the two blocks of the granite.

8. The fluid inclusion properties, lead and sulphure isotope values, K-Ar radiometric age of the quartz-fluorite-base metal veins of the Velence Granite are similar to the Alpean-type epigenetic Mississippi-type stratiform-strtatabound Pb-Zn ore deposits located on the border of the Southern and Eastern Alps.

9. According to the similarities of the deposits and geology in the Velence Mts; the Szabadbattyán area and the Karawanken, the original position of the Velence Mts and the Szabadbattyán area before the Paleogene was in the close vicinity of Eisenkappel and Mesica.

10. The Palaeogene magmatic-hydrothermal process also affected the eastern part of the granite body. The Palaeogene fluid flow was confined to the zones of Palaeogene andesite dikes and stocks and some NE-SW trending structural zone, therefore it was a local fluid flow event.

11. According to the new K-Ar radiometric age data the magmatic activity and fluid flow happened between 32-28 Ma (early-Oligocene).

12. In the Palaeogene alteration zones, illite and illite-dickite are the characteristic clay mineral phases. The well crystallized illite with low smectite interstratifications indicates that for the Palaeogene fluids the minimum temperature was 250°C. The illite-dickite alteration indicates lower, 200-250°C temperature during the fluid mobilization.

13. Three different Palaeogene fluid inclusion assemblages were distinguished in the rock forming quartz crystals of the granite which are analogous with the fluid inclusion assemblages described earlier, from the hydrothermal veins and from the Palaeogene Volcanic Unit.

14. Palaeogene fluid inclusion assemblages appear only in the illite alteration zones in the fluid inclusion planes hosted by the rock forming quartz of the granite. Fluid inclusion assemblages record boiling parent fluids, thus salinities vary on a broad range. According to the homogenization temperatures, the minimum temperature of these fluids was between 240-250°C, accordantly with clay mineral thermometer. Locally, high temperature (up to 400-450°C) hydrothermal spots were also detected in the vicinity of the andesitic bodies. The fluid inclusion properties indicate shallow level volcanic and subvolcanic level.

15. The quartz-barite vein close to Sukoró, which was earlier believed to be Variscan, proved to be Palaeogene according to the new K-Ar radiometric age data and the fluid inclusion studies.

16. Appearance of volcanic and subvolvanic level related Palaeogene fluid inclusion assemblages at the same level in the granite indicates syn-magmatic and syn-hydrothermal tectonic activity east from the granite body. The Sukoró area of the granite lifted up during the Palaeogene while the Palaeogene Volcanic Unit – on the eastern side of the Nadap line – subsided.

17. Upheating of the Nadap area during the Palaeogene led to partial equilibration or total reopening and refilling of the Variscan and Triassic fluid inclusion assemblages.

18. It has been confirmed that FIP orientation analysis has essential importance during the investigation of the tectonic analysis of the granite: Variscan NE-SW trending FIP evidently confirm the NW-SE extensional stress field in which they formed. FIP orientation analysis was essential in the recognition of the uplift of the granite during the Triassic fluid flow. The orientation of the Palaeogene FIP confirmed that the initial fracture system of the granite basically influence the formation of the younger fractures.

Dating and understanding the evolution of the macroscopic fracture and fault systems was possible only by means of the FIP analysis.

19. FIP were parallel with the syngenetic mineralized veins, OC are parallel with the open macrofractures in the same outcrop. Its theoretical importance is that the fracture systems are self similar at different scales. Its practical importance during exploration is that if we lack large outcrops even a small piece of rock might be enough to analyze the tectonic evolution of the crystalline rock.

20. The number of fluid inclusion planes towards the main Triassic fluid flow channels increase in comparison to with the unaltered granite, whereas the average length decrease. As a result of these two phenomena the length density though increases in the Triassic alteration zones. Therefore the stress field influenced fracture evolution leads to increasing number of fractures.

21. Due to the magmatic and hydrothermal heat shock in the transitional zones, where the Triassic fluid inclusions reequilibrated, FIP connected to each other. This process led to the decrease in the number of FIP and the increase of the summa length of FIP. Eventually, a more intensely connected and better developed fracture system formed with high length density. In the illitic Palaeogene alteration zones the heat shock led to the reopening of the elder Triassic fractures and their refilling by Palaeogene FI. However refilling and reopening process was accompanished by formation of new fractures as well. The average length and the number densities increased, but due to the formation of the new and short fractures the rise in the average length was not characteristic. As a consequence thermal reopening leads to a well-connected fracture system, providing excellent fluid channels for the hydrothermal fluids.

22. The high fracture density areas indicate the main fluid flow channels during the period of the Palaeogene fluid mobilization. The most permeable zones and the main structural zones – mapped on the field – overlap with each other. From a practical point of view it can be very important when the mapping conditions on the field are insufficient and only some small rock chips are at hand.

CONCLUSIONS

This work has shown, that if the general characters of the hydrothermal system are known (e.g. fluid inclusion properties, clay mineral assemblage), the analysis of the healed microfracture systems yield an appropriate tool for delineation of fluid flow zones in crystalline rocks. The complex application of mineralogical, geochemical, fluid inclusion and structural data answered several open questions related to the evolution of the superimposing hydrothermal systems in the Velence Mts. Results also made it possible to correlate the tectonic evolution of the Velence Mts. in regional context.

Beyond the new local and regional geological knowledge, the work also conveyed new methodological approach for studies of fracture systems. This knowledge may be useful in the economic geology, reservoir geology, hydrogeology or even in environmental geology.

PUBLICATIONS RELATED TO THE SUBJECT OF THE PHD DISSERTATION

PAPERS

Benkó Zsolt, Molnár Ferenc (2003): „Application of studies on fluid inclusion planes for evaluation of structural control on Variscan and Alpean fluid mobilization processes in the monzogranite intrusion of the Velence Mts. (W-Hungary)"– *Acta Mineralogica-Petrographica*, Vol. 45/1 p. 123-131.

Benkó Zsolt, Molnár Ferenc, Marc Lespinasse (2008): Application of studies on fluid inclusion planes and fracture systems in reconstruction of fracturing history of granitoid rocksI.: introduction to methods and implication for fluid-mobilization events in the Velence Mts. – *Bulletin of the Hungarian Geological Society* (in press)

Szabó Bernadett, Benkó Zsolt, Molnár Ferenc, Marc Lespinasse (2008): Application of studies on fluid inclusion planes and fracture systems in reconstruction of fracturing history of granitoid rocks II.: Fracture systems of the Mórágy Granite – *Bulletin of the Hungarian Geological Society* (in press)

Poros Zsófia, Molnár Ferenc, Koroknai Balázs, Marc Lespinasse, Maros Gyula, Benkó Zsolt (2008): Application of studies on fluid inclusion planes and fracture systems in the reconstruction of fluid flow systems in granitoid rocks III: Results of studies in drillcores from the radioactive waste depository site at Bátaapáti (Üveghuta) – *Bulletin of the Hungarian Geological Society* (in press)

CONFERENCE ABSTRACTS

Benkó Zsolt, Molnár Ferenc (2003): Structural controls of fluid mobilization processes connected to the Variscan and Alpean igneous activity in the Velence Mts. (W-Hungary) on the basis of studies of fluid inclusion planes – „2nd Mineral Science in the Carpathians Conference", Acta Mineralogica-Petrographica Abstract Series, 2003 pp.11.

Benkó Zsolt Molnár Ferenc (2003): Tectonic control of fluid circulation related to Variscan and Alpean hydrothermal processes in the Velence Mts. (W-Hungary) on the basis of fluid inclusion planes – Geodynamics and Ore Deposit Evolution of the Alpine-Balkan-Carpathian-Dinarde Province, Final GEODE-ABCD Workshop, Seggauberg, Ausztria Abstracts, pp. 17.

Molnár Ferenc, Benkó Zsolt (2003): – Evaluation of Multi-phase crack evaluation in the granite intrusion of the Velence Mts. (W-Hungary) on the basis of studies on fluid inclusion planes – ECROFI XVII., Budapest, Abstract pp.127.

Benkó Zs., Molnár F. (2003): Granitoid kőzetek repedésrendszereinek fejlődéstörténete fluidzárványsíkok vizsgálata alapján. – Hungarian Geological Society, Proceeding of the Mineralogical Department

Benkó Zsolt. (2004): A Velencei-hegység hidrotermális rendszereinek szerkezeti kontrollja fluidzárványsík és repedésrendszerek vizsgálata alapján. - Young Scientists Conference, Sárospatak

Benkó Zsolt, Molnár Ferenc, Lespinasse Marc, Pécskay Zoltán (2005): The significance of analyses on fluid inclusion planes (FIP) in reconstruction of spatial and temporal evolution of fracture development in relation to multiple hydrothermal processes in granitoid rocks. - ECROFI, Siena 2005

Benkó Zsolt, Molnár Ferenc, Marc Lespinasse, Pécskay Zoltán (2006): Reconstruction of multi-phase fluid flow history and tectonic evolution in a Variscan granite intrusion (Velence Mts., Hungary). - EGU General Assembly, Wien.

Benkó Zsolt, Molnár Ferenc (2006): Több fázisú magmás-hidrotermális tevékenység rekonstrukciója a Velencei hegységben**.** – Young Scientists Conference, Balatonkenese

Benkó Zsolt, Molnár Ferenc (2006): Application of K-Ar age determination of Rock Forming and Hydrothermal Clay Minerals For reconstruction of Fluid Mobilization Processes on the Variscan granite intrusion (Velence Mts. W-Hungary). – „3rd Mineral Science in the Carpathians Conference" Miskolc Abstract pp. 11.

Benkó Zsolt (2007): Reconstruction of multi-phase fluid flow history and tectonic evolution in a Variscan granite intrusion (Velence Mts., Hungary). – Proceeding of the Royal Natural History Museum, Stockholm

PAPERS IN PREPARATION

Zsolt Benkó, Ferenc Molnár, Zoltán Pécskay, Marc Lespinasse: K/Ar age determination and mineralogy of Triassic and Palaeogene argillic alteration zones in a Variscan granite body along the Periadriatic Balaton Lineament system

Zsolt Benkó, Kjell Billström, Ferenc Molnár, Zoltán Pécskay, Bernadett Bajnóczi, Marc Lespinasse: Triassic fluid mobilization along the Periadriatic-Balaton Lineament system: genetics of the Pb-Zn mineralization of the Velence Mountains and Szabadbattyán (W-Hungary) and their geotectonic relationships

Zsolt Benkó, Marc Lespinasse, Ferenc Molnár: Combination of Fault slip analysis, Fluid Inclusion Plane measurements and Fluid Inclusion Microthermometry: Tectonic evolution of the Velence Mts. granite (W-Hungary)