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Integrated reconstruction of diagenesis and fluid evolution at Algyő High and surrounding deep subbasins (Dorozsma Basin and Makó Trough)

Az Algyői-aljzatmagaslat és a környező mélymedencék (Dorozsmai-medence, Makói-árok) integrált diagenezis-történeti és fluidumevolúciós rekonstrukciója

Final report

NKFI project K 108 375

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Project participants

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1. Major aims and key questions of the project according to the workplan

The crystalline basement at Algyő High (called also Szeged–Algyő High; Szederkényi 1998; Lelkes-Felvári et al. 2005), bounded by Miocene faults, and in its neighborhood is locally overlain by Carboniferous breccia, Mesozoic sandstones and carbonates, and middle Miocene clastic sediments (Bérczíné Makk 1998; Jámbor 1998). From the late Miocene to present, the related deep subbasins were filled up with a thick series of sediments termed Pannonian *sensu lato* (s.l. see Bérczi 1988; Juhász 1992, 1994, 1998).

- The Algyő High, representing a highly elevated basement block, is dominantly built up by metapelites of the Békés–Codru Unit (called also Szeged–Békés–Codru Unit; Szederkényi 1998; Lelkes-Felvári et al. 2003, 2005; and references therein). One of the most important characteristic features of this area is the occurrence of marble and dolomite marble, locally showing cataclastic and/or mylonitic deformation. According to the results of Lelkes-Felvári et al. (2003, 2005), these rocks form intercalations in a polymetamorphic complex with identical evolutionary stages. On the other hand, M. Tóth (2008) suggested that this marble interval suffered a different metamorphic history related to a low-angle shear zone, reflecting an intensive fluid migration. That is why understanding the lithological framework in this fractured zone is crucial and requires a detailed study of mineralogy, petrology, and microstructure of the given rock type.
- In the Algyő High, several boreholes near the town of Szeged and near the village of Üllés penetrated rock layers described as Carboniferous(?) breccia by Jámbor (1998, and references therein). These Paleozoic rocks were regarded as continental deposits which are tectonically covered either by Lower Triassic Jakabhegy Sandstone or by Middle Triassic dolomite (Jámbor 1998). On the other hand, according to the results of Lelkes-Felvári et al. (2005), this Carboniferous breccia was redefined as a tectonized, mostly cataclastic metamorphic rock. Thus, the presence of this Paleozoic lithostratigraphic unit was rejected. The complex analysis and integrated interpretation of the Paleozoic and Mesozoic basement units would make important contributions to determination of the tectonic evolution of the Békés–Codru Unit.

- The lithostratigraphic subdivision of the Pannonian s.l. sediments is based on well-log and/or petrophysical criteria; thus, the formations of the Pannonian sequence in the Great Hungarian Plain are *genetic, lithofacies units* (Bérczi 1988; Juhász 1992, 1994). One of the goals of this project is (i) to characterize the petrographic and geochemical features of the Pannonian sandstones and marls in the Dorozsma Basin and Makó Trough from different boreholes, and (ii) to provide further information about weathering and diagenetic processes of sandstones and mudrocks and to deduce their provenance.

The project was expected to provide novel results for basic research in the field of sandstone provenance, diagenesis and fluid evolution for the metamorphic, Paleozoic and Mesozoic basement as well as Neogene basin fill system in the Great Hungarian Plain (Algyő High and surrounding subbasins).

Additional studies and changes (not included in the original workplan)

- As a consequence of the personal changes, a slight reorganization of the project plan and scientific tasks had to be carried out.
- In the Paleozoic basement, the Permian Gyűrűfű Rhyolite was also studied (domestic and international collaborations: Réka Lukács, MTA-ELTE Volcanology Research Group; István Dunkl, Geoscience Center, Department of Sedimentology & Environmental Geology, University of Göttingen; Mihai Tatu and Ioan Seghedi Institute of Geodynamics, Romanian Academy).
- For regional correlation, volcanic and metamorphic rocks were collected in the Apuseni Mts (Romania).
- Dolomitization environments (Szeged Dolomite; Dorozsma marble) were assessed by analyzing strontium isotope ratios (international collaboration: Robert Frei, Department of Geosciences and Natural Resource Management, Geology Section, University of Copenhagen).

2. Main results of the project

Corresponding to the research plan, new mineralogical, petrographic, and geochemical investigations of the Neogene basin fill and the Mesozoic basement formations (Szeged Dolomite, Jakabhegy Sandstone) were carried out. The collected samples dominantly represent the basement of the Szeged Basin and Algyő High from wells near Üllés, Forráskút, Szeged, Dorozsma, and Mórahalom. Additionally, sampling and data collection about the crystalline basement rocks (near the villages of Ásotthalom, Üllés, Forráskút, and Dorozsma) and their Paleozoic cover (e.g., breccia, Szeged; Gyűrűfű Rhyolite, Kelebia) were also performed. For a regional correlation, volcanic and metamorphic rocks were collected in the Apuseni Mts (Romania). Stable isotope measurements for selected carbonates (Triassic basement rocks and carbonate veins; Dorozsma and Highiş marble samples) were run at the Institute for Geological and Geochemical Research, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Budapest (C, O, and H isotope studies; researcher: György Czuppon). Additionally, dolomitization fluid chemistry and precipitation environments were assessed by analyzing strontium ($^{87}Sr/^{86}Sr$) isotope ratios including ion chromatographic separation of dolomite and marble samples at the Department of Geosciences and Natural Resource Management, Geology Section, University of Copenhagen (researcher: Prof. Robert Frei).

The results of this project, including studies of regional (e.g., Apuseni Mountains, Romania) correlations, were presented at several domestic meetings (’Tisia Konferencia’ – Tisia Conference; ’Téli Ásványtudományi Iskola’ – Winter Mineralogical School, ’Ifjú Szakemberek Ankétja’ – Hungarian Young Earth Scientists Conference, and ’Kőzettani és Geokémiai Vándorgyűlés’ – Annual Meeting of Petrologists and Geochemists) and international conferences (MECC2016 – Mid-European Clay Conference, Košice; 15th Meeting of the Central European Tectonic Studies Group, CETeG, Zánka; Dolomieu Conference on Carbonate Platforms and Dolomite, Selva di Val Gardena; EGU, European Geoscience Union General Assembly, Vienna; XXI International Congress of the CBGA, Salzburg).

The main results (see below in detail) were published in domestic and international peer-reviewed journals as the followings:

- two papers in Q1/D1 journals (Marine and Petroleum Geology; Geofluids);
- a paper in Q3 journal (Geologia Croatica); and
- four papers in Q4 journal (Földtani Közlöny).

Preparation of further publications for Q1/Q2 journals is also in progress.

The research led to a better understanding of the water-rock interactions in the basement rocks and in the Neogene basin fills, Szeged Basin. The results could be applied in present and future research on geothermical applications and in ongoing hydrocarbon exploration.

2.1. Brief summary of the main results: basement rocks

2.1.1. Metamorphic basement rocks

2.1.1.1. Metamorphic basement in the Ásotthalom area

The metamorphic basement in the Ásotthalom area consists of altered (carbonatized, chloritized and sericitized) garnet-bearing biotite muscovite gneiss and/or garnet-bearing biotite muscovite schist and chlorite muscovite gneiss. Locally, graphitic layers also occur in the gneiss samples which has suffered strong cataclastic deformation and carbonatization. The cataclasites consist of fragmented quartz (often dynamically recrystallized) clasts in weakly foliated (pressure solution cleavage) muscovite+siderite matrix with large amount of graphite. Estimation of the metamorphic temperature for cataclastic rocks results in approximately T ~410 °C using carbonaceous material thermometer by Raman microspectroscopy.

2.1.1.2. Metapegmatoid rocks from the Dorozsma Complex

In the Békés–Codru Unit, the metamorphic basement near the village of Dorozsma consists mainly of micaschist, biotite gneiss, amphibole-biotite gneiss and amphibolite. Related to the biotite gneiss body, a special gneiss type (metapegmatite mylonite) occurs in thickness of few metres penetrated by several wells. Additionally, this unique lithology can also be found in the Üllés–Forráskút area to the northwest from the Dorozsma Complex. Therefore the occurrence of metapegmatite mylonite could be a powerful tool in order to correlate the metamorphic blocks as well as to reveal tectonic evolution of the study area. The studied rock type has a mineral composition of plagioclase + quartz + K-feldspar (microcline) + muscovite + chlorite. The asymmetric clast geometry and pressure shadows with the well-developed foliation as well as quartz and feldspar recrystallization reveal the presence of a ductile shear zone and formation of mylonites within the Dorozsma Complex. Based on the appearance of myrmekites the mechanism of the K-feldspar deformation and grain-size reduction was syndeformational recrystallization due to deformation induced myrmekite formation. This lower temperature type of K-feldspar recrystallization assumes upper greenschist to lower amphibolite facies metamorphic conditions during mylonitisation. The thermometry based on quartz–quartz grain-boundary complexity of quartz ribbons shows similar temperature ~400 °C with fractal dimension D~1.25. In the knowledge of the previous studies of metamorphic

history of the Dorozsma Complex this mylonitic deformation occurred during retrogression (*under preparation, manuscript for Central Euporean Geology*).

2.1.1.3. Dorozsma marble (Dorozsma Complex)

The metamorphic basement block near the village of Dorozsma contains a few-meter-thick marble zone within the Békés–Codru Unit. A petrographic study of archive thin sections representing this marble zone was carried out from the boreholes Dorozsma–4, Dorozsma–7 and Dorozsma–54. The fine-grained marble samples show heteroblastic texture with a composition of carbonate + quartz + muscovite + Mg-chlorite ± talc. The carbonate crystal boundaries are dominantly sutured, embayed and rarely curved. All the morphological types of deformation twins can be observed in the samples, but dominantly twin types II and IV are present. The characteristic features of the samples are small dissolution cavities filled with fine crystalline carbonate, blocky quartz and, in some cases, with saddle dolomite. In the samples from the borehole Dorozsma–4 small inclusion free carbonate grains substitute the deformation twins of the large carbonate crystals. In addition, small carbonate neoblasts and Mg-chlorite flakes can be found among the large carbonate crystals. Characteristic microstructures of the samples from the well Dorozsma–7 are large sigmoid carbonate clasts in a very fine-grained matrix. The deformation twins of the carbonate clasts can be easily identified and show the signs of recrystallization. These samples beside the carbonate clasts also contain irregularly shaped polycrystalline quartz grains with dissolved edges, undulose extinction and signs of incipient dynamic recrystallization. The microstructures presented above suggest a polyphase deformation. The D1 deformation event took place above 250 °C based on the relict microstructures. The subsequent D2 ductile deformation event was a low-temperature dynamic recrystallization with a simple shear component, which could be the result of a hydrolitic weakening effect of hydrothermal fluids during deformation of the Dorozsma marble (published in ***Földtani Közlöny, 147/4, 2017***; SJR: Q4).

Regional correlation of the Dorozsma marble (S Hungary, Tisza Mega-unit):

The Dorozsma basement belongs to the Algyő High, which forms a Hungarian part of the Biharia Nappe system according to some recent interpretations. The nearest outcrops of the Biharia Nappe system is located in the Highiș Mts (SW Apuseni Mts, Romania). The major aim of this study is to provide petrographic and isotope geochemical information about the marbles derived from Dorozsma basement and the Highiș Mts in order to reveal the relationship between them. Micropetrography, fabric-selective carbon and oxygen isotope measurements as well as $^{87}Sr/^{86}Sr$ isotope analyses were carried out for this purpose. The dominant part of the samples from borehole Dorozsma–54 is very fine–fine-grained marbles showing heteroblastic texture with a composition of dolomite+calcite+quartz+muscovite+Mg-chlorite±talc±phlogopite. The grain boundaries are mainly sutured and embayed. Dominantly, type II and IV deformation twins are present. The samples from borehole Dorozsma–4 show features of significant alteration. They contain many deformation structures and sheared domains with microcrystalline calcite+Mg-chlorite+talc, while the slightly altered parts of the marble consist of dolomite with core-mantle structure. Marble breccia is also present which contains clasts of marble and very fine-grained calcite. Microcrystalline calcite forms the matrix of the breccia, while fractures are cemented by dolomite+calcite. Dolomite cement usually shows saddle-like morphology. The marble samples from the Highiș Mts have a composition of calcite+quartz+plagioclase feldspar+muscovite+chlorite and show heteroblastic and homeoblastic texture. The grain boundaries are mainly curved, rarely embayed. Type II deformation twins are dominant. In some samples, lamination can be observed defined by the variation of very fine (20–30 μm) and fine-grained (200–400 μm) carbonate bands. The $\delta^{13}C_{V\text{-}PDB}$ values of Dorozsma marble range from –2.3‰ to 1.9‰, while the $\delta^{18}O_{V\text{-}SMOW}$ values fluctuate between 14.5‰ and 22.5‰. Significant part of the marbles was subjected to various degree of alteration, but the $\delta^{13}C_{V\text{-}PDB}$ and $\delta^{18}O_{V\text{-}SMOW}$ isotope data from some unaltered samples are very similar to those of the isolated marble lenses from the

eastern part of the Biharia Nappe system. The marble samples from the Highiş Mts have $\delta^{13}C_{V\text{-}PDB}$ values from –1.1‰ to –0.1‰, while the $\delta^{18}O_{V\text{-}SMOW}$ values vary between 15.2‰–19.7‰. The $^{87}Sr/^{86}Sr$ values of the marbles from the Highiș Mts range between 0.70861–0.70930 that is quite similar to the data of Reiser et al. (2017). In contrast, Dorozsma marbles provide higher values (0.70973–0.71372), suggesting a significantly different protolith and/or a distinct evolution. So, a direct correlation between the marble lenses of the Apuseni Mts and those of Dorozsma seems to be implausible (*unpublished data, EGU 2018 and 2019*).

More articles will be published in this topic (PhD student: Nikoletta Papp).

2.1.2. Paleozoic basement rocks

The Tisza Mega-unit forms the basement of the Pannonian Basin south of the Mid-Hungarian Zone. Within its pre-Alpine crystalline units, the low to medium-grade metamorphic rocks in the westernmost part of the Békés–Codru Unit belong to the Kelebia Complex. Non-metamorphosed Triassic carbonates and redbeds, corresponding to the Codru nappe system, Cisuralian rhyolite lava together with volcanosediments (Gyűrűfű Rhyolite Formation) and small erosive remnants of the underlying Korpád Sandstone Formation overlap the erosional surface of the metamorphic basement rocks in the area. A study combining petrographic data of drill cores and thin sections from the subsurface Permian rocks (Korpád Sandstone and Gyűrűfű Rhyolite, boreholes near the village of Kelebia, Hungary), microstructural observations, and mineralogical data (X-ray powder diffraction, XRD) has revealed a complex burial diagenetic to very low-grade metamorphic evolution. In thin section, the studied Gyűrűfű samples are thoroughly recrystallized which texture is defined by equigranular mosaic of subhedral to anhedral quartz and feldspar in the matrix. Locally dense networks of closed, spherical spherulites also occur. The strongly altered, sericitised pumices are oriented, strike paralell to each other, showing continuous, coherent sericite bands interpreted here as a spaced foliation due to ductile shortening. The phenocrysts have symmetric quartz and K-white mica pressure-shadows. Additionally, quartz crystals locally exhibit undulose extinction with deformation lamellae. The underlying metapelitic rocks have an S0-S1 primary foliation and an S2 zonal crenulation one, suggesting a late ductile deformation. Based on XRD data, the mineralogical composition of the Kelebia rhyolites is predominated by mica and quartz with subordinate amount of chlorite and feldspar. The studied slate of the Korpád Sandstone has almost the same mineralogical composition with some additional hematite. Clay fraction separated from both of the rhyolites and slate are composed of K-white mica (>90%; d00,10=1.99 Å) with some chlorite (5–10%) and quartz. Trace amounts of hematite contributes to the clay fraction of the slate as well. Non-calibrated FWHM values of the K-white mica scatter ~0.15Δ°2Θ suggesting (very?) low grade metamorphism. In the studied part of the Békés Unit (Codru nappe system), traditionally, the Permian volcanosedimentary sequence is regarded as non-metamorphic cover. The abovementioned features, however, demonstrate that these formations were affected by a much higher degree of ductile deformation and metamorphism than previously thought (*unpublished data, MECC 2016; under preparation, manuscript for Central Euporean Geology or Geologica Carpathica*).

The Tisza Mega-unit includes a Permian (~265 Ma) felsic volcanic assemblage known in the Mecsek and Villány region and in the basement of the Great Hungarian Plain. Additionally, it is well exposed in the central-western part of the Apuseni Mountains (Romania) where features of bimodal volcanic processes were documented. During the Alpine orogeny, facies zones were differentiated in the Jurassic and nappe-systems were formed in the Cretaceous. Consequently, three main zones are distinguished within the Hungarian part of the Tisza Mega-unit: the Mecsek Unit, the Villány–Bihor Unit and the Békés–Codru Unit. The Permian

volcanic and volcano-sedimentary rocks are represented by rhyodacitic/dacitic ignimbrites (Mecsek Unit), rhyodacitic/dacitic pyroclastic and lava rocks (Villány–Bihor Unit) and rhyolitic pyroclastic and lava rocks (Békés–Codru Unit). In the Apuseni Mts. several Alpine tectonic units were also recognized such as the Bihor Autochtone Unit, the Codru Nappe System (NS) and the Biharia NS. The Permian deposits are unevenly distributed in the Biharia NS, more abundant in the Codru NS and sporadic in the Bihor Autochtone Unit. Petrographically, the ignimbrites are similar in all the studied areas, they are rich in flattened, devitrified pumices and consist of 30–40% of quartz, feldspar, and hematitized biotite phenocrysts. In Transdanubia, strongly altered pyroxenes also occur. Interestingly, in the Villány–Bihor Unit and in the Finiş Unit garnet is also present. Lava rocks are porphyric with the same main mineral assemblage as ignimbrites and have various recrystallized textures. All samples are enriched in Rb, Th and U and depleted in Ba, Nb, Sr and Ti. The chondrite normalized REE patterns show higher enrichment in LREEs and a strong negative Eu anomaly. Most of the rocks, however, are affected by post-magmatic alterations (K-metasomatism, hydrothermal alteration, Alpine low-grade metamorphism) causing significant changes in their major and sometimes in immobile trace element compositions. Samples affected by low grade metamorphism are present in the area of Kelebia (Békés–Codru Unit) and in the Biharia NS. Based on the Alpine evolution the following traditional correlations are accepted within the Tisza Mega-unit: the Hungarian Villány and Békés Units correlate with the Bihor Autochtone Unit and the Codru NS, respectively. Regarding the Permian volcanic rocks, however, the Villány Unit shows greater similarity to the Codru NS than to the Bihor Unit, and at least one part of the Békés Unit (Kelebia area) can be in a close relationship with the Biharia NS. The abovementioned features demonstrate that the geological context of the Alpine facies zones could be more complex than previously thought (*unpublished data, CBGA 2018, EGU 2018 and 2019;* ***under review in International Journal of Earth Sciences****, SJR: Q1*).

More articles will be published in this topic (PhD student: Máté András Szemerédi).

2.1.3. Mesozoic basement rocks

The Pannonian Basin consists of several deep sub-basins separated by uplifted basement highs. One of these subbasins is the Szeged Basin. A significant part of its pre-Cenozoic basement comprises Triassic dolomite rocks. In numerous cases these carbonates are good hydrocarbon reservoirs and hydrocarbon production is significant in this region of Hungary. Nonetheless, the detailed petrology of the Triassic reservoir rocks has not been investigated for decades. This study attempts to reconstruct the formation and brittle deformation history of the studied reservoir rocks, belonging dominantly to the Szeged Dolomite Formation, using petrographic observations including fluorescence and cathodoluminescence microscopy. The investigations were performed on core samples collected from wells in the western part of the Szeged Basin. The aforementioned investigations reveal that the Triassic dolostones have been noticeably altered by several brittle deformation and cementation events. The original depositional environment can be reconstructed only for samples exhibiting a relict texture after dolomitization and which were affected by slight fragmentation. The formation of most of the examined sediments occurred in a shallow water marine environment with depositional conditions ranging from peritidal to subtidal. After the deposition and the early near-surface diagenesis, an extensional tectonic regime began and the subsidence continued during the Jurassic-to-Early Cretaceous interval, while the studied succession reached the deep-burial zone. During this period the rock bodies were completely dolomitized by fabric-preserving and fabric-destructive processes. Differences among the observed dolomite fabrics suggest multiple dolomitization episodes. The main dolomitization events were followed by the formation of porphyrotopic, sucrosic and saddle dolomite under intermediate or deep burial conditions. During the Middle Miocene, the Triassic rocks were uplifted and subaerially

exposed and this is indicated by abrasional sediments. De-dolomization could have been connected to this uplifting phase. The formation of a fluorescent sparry dolomite generation and bituminous veins seems to be related to the Neogene extensional regime and deformation. Remnants of organic matter (hydrocarbon inclusions and bituminous veins) suggest the occurrence of multiphase migration events. Recognition of the different hydrocarbon migration phases could provide the basis for the analysis of their relationship to the depositional, diagenetic and tectonic processes, and subsequent stages of the evolution of the basin (published in ***Földtani Közlöny, 147/1, 2017***; SJR: Q4).

The dark grey, brecciated dolomite, which is classified in the Szeged Dolomite Formation, is the most characteristic Mesozoic formation in the Szeged Basin. The representative feature of the formation is the pervasive dolomitization and recrystallization, which accounts for the poor preservation and low specimen number of fossils. This work is a report on the results of a study of an exceptionally rich and well-preserved fossil assemblage. In the thin sections of the Üllés–18 well (Core #6), besides a *Hoyenella–Glomospirella–Glomospira*-dominated foraminifer assemblage, algae colonies and ostracod double shells were also observed. The speciality of the sample was given by a juvenile specimen of a Megalodontidae (Bivalvia). The carbonate microfacies and fossil assemblage indicate Middle Triassic (Upper Anisian – Ladinian), shallow, backreef-lagoon environments and waters of elevated salinity during the deposition. This high salinity seawater could have played a role in the near-surface dolomitization of the formation (published in ***Földtani Közlöny, 148/2, 2018***; SJR: Q4).

The Middle Triassic shallow marine carbonates of the SE Pannonian Basin (Szeged Dolomite Formation) show evidence for multistage dolomitization and a complex diagenetic history. In first stage the whole sequence was completely dolomitized by reflux of slightly evaporated seawater. This process took place from the near surface till shallow burial realms and resulted in the formation of both fabric-preserving and fabric-destructive dolomite types. In the following stage nonplanar matrix dolomite and saddle dolomite cement were formed in the intermediate and/or deep burial realm. These later dolomite phases are likely generated by invasion of exotic fluids at relatively high temperature evidenced from the fluid inclusion homogenization temperatures, and stable isotope compositions. Vuggy, fracture, and solution enhanced porosity are also related to this local hydrothermal event. Microthermometry performed on saddle dolomite-hosted primary fluid inclusions confirm the presence of hot (138–235 °C) and moderately saline brines (4.1–8.7 mass% NaCl equivalent). The calculated $\delta^{18}O_{water}$ and the measured δD_{water} values of the fluid inclusions from the saddle dolomite cement together with the relatively low salinity values indicate a metamorphogenic (and/or magmatic) origin of the hydrothermal fluid that probably was channeled along the Upper Cretaceous subhorizontal overthrust zones. The pores formed by the leaching effect of these hydrothermal fluids were subsequently partly occluded by meteoric calcite during the Paleogene–Middle Miocene subaerial exposure but a remarkable part was preserved, and currently serves as reservoir space. Such an integrated study of the different dolomite and porosity types, the understanding of their genesis, and timing relative to hydrocarbon maturation and migration could aid in exploration and development (published in ***Marine and Petroleum Geology, 98, 2018***; IF: 3.281; SJR: Q1/D1)

More articles will be published in this topic (PhD student: István Garaguly).

2.2. Brief summary of the main results: Neogene formations

2.2.1. Endrőd Formation

For Pannonian calcareous marl and sandstone samples (Endrőd Formation, Tótkomlós Member), palynology (researcher: Viktória Baranyi), mineralogy, petrography and microtexture was investigated by X-ray powder diffraction, petrographic microscopy and

scanning electron microscopy on representative core samples from the Hódmezővásárhely–I well (cores 35 and 40, 5167.0–5183.0 m and 5468.0–5486.0 m, respectively). The studied sections comprise mixed carbonate-siliciclastic rocks with abundant silt- to sand-sized angular grains such as monocrystalline and polycrystalline quartz, muscovite, biotite, chlorite, carbonate, and metamorphic rock fragments. This polymictic and immature clast composition reflects the importance of local provenance, suggesting that intrabasinal structural highs represent additional source areas to the basin. Palynological analysis was carried out on selected core segments of the well in order to provide a biostratigraphic framework and palaeoenvironmental interpretation for the studied interval. In the investigated samples two biozones were distinguished: the *Spiniferites bentorii oblongus* Zone and the *Spiniferites paradoxus* Zone. The succesive changes of the dinocyst assemblages reflect changes in the distance form the shoreline or the terrestrial input from the margin of the Makó Trough. The older assemblage indicates a more proximal setting in relation to the shoreline and/or a higher terrestrial input, the younger dinocyst assemblage – with more open-water taxa point in relation to a greater distance from the shoreline – represents an increase in the water level, and/or decreased terrestrial input. The predominance of membranous dinocysts in this assemblage indicates a fluctuation in the lake surface salinity, or possibly a shift to a holoplanktonic lifestyle due to periodical oxygen depletion in the water column.
The assemblages of both zones demonstrate their regional distribution throughout the whole Pannonian Basin and therefore they can be used to document regional scale trends in phytoplankton communities, as well as implying the communication of water bodies. The color and preservation of the palynomorphs suggests significant burial heating and high maturity of the sedimentary organic matter. In the studied samples a series of paragenetic events have been identified using petrographic methods. Early diagenesis was generally represented by cementation (i.e. of framboidal pyrite and carbonates with variable iron content) and weak mechanical compaction. On the other hand, late diagenesis involved pressure solution (chemical compaction), cementation (late pyrite) and, occasionally, dolomite replacement and mineral transformation (smectite to illite) processes. It is noteworthy that in these two core sections neither significant macroporosity nor microporosity were observed, this being due to pervasive cementation (published in ***Földtani Közlöny, 147/1, 2017***; SJR: Q4).

2.2.2. Neogene formations (fracture-filling minerals): Kecel Basalt Formation (pyroclastic and lava rocks interbedded with up to several hundred meter thick layers of the Endrőd Formation)

Extensive Miocene volcanic activity produced basaltic and pyroclastic successions, which were penetrated by many wells in the area of Üllés–Ruzsa–Bordány, in the western and central part of the Great Hungarian Plain. The Kecel Basalt comprises primary porosity from a high proportion of vesicles and significant secondary fracture porosity, as well. Based on the textural and mineralogical features, four distinct vein types can be distinguished, named after their volumetrically most abundant cement phases, i.e. potassium-feldspar (Kfp-), calcite (Cal-), laumontite (Lmt-), and analcime (Anl-) types. Based on the study of veins and mineral sequences, the direction of temperature changes cannot be given unequivocally for every stage of cementation, but crystallization of the Anl-type veins might have occurred at lower temperatures than the formation of the Lmt-type veins. Fluid inclusion studies suggest that hydrocarbon migration and accumulation took place after cementation of the first three vein types (Kfp-, Cal-, and Lmt-types). In the newly opened fracture system, two types of hydrocarbon (HC1 and HC2)-bearing fluid inclusion assemblages were captured during precipitation of analcime and later zeolites. This refers to two stages of hydrocarbon migration in the fracture system. Observations of the fluorescence colors and low temperature behaviors of the hydrocarbon-bearing inclusions, the earlier HC1 petroleum-inclusions

captured heavier (presumably less mature oils), while the later ones (HC2) lighter (presumably more mature) oils. The HC2 petroleum seems to be very similar to the crude oil sampled in a well in the area based on their fluorescence parameters (published in ***Geologia Croatica, 69/3, 2016***; IF: 0.595; SJR: Q3).

2.2.3. Neogene basin fill – fluid evolution of the Pannonian Basin

The study area, Pannonian Basin (Central Europe), is characterized by high heat flow and presence of low-enthalpy geothermal waters. In the Szeged Geothermal Systems (Hungary), having Miocene to Pliocene sandstone aquifers with dominantly Na–HCO_3-type thermal water, unwanted carbonate scaling was observed. An integrated approach consisting of host-rock and scale mineralogical and petrographic analyses as well as water chemistry led to a better understanding of the characteristic natural (geogenic) environmental conditions of the geothermal aquifers and to highlight their technical importance. Analyses of the reservoir sandstones showed that they are mineralogically immature mixed carbonate-siliciclastic rocks with significant macroporosity. Detrital carbonate grains such as dolomite and limestone fragments appear as important framework components (up to ~20–25%). During water–rock interactions they could serve as a potential source of the calcium and bicarbonate ions, contributing to the elevated scaling potential. Therefore, this sandstone aquifer cannot be considered as a conventional siliciclastic reservoir. In mudrocks, significant amount of organic matter also occur, triggering CO_2 producing reactions. Correspondingly, framboidal pyrite and ferroan calcite is the main cement minerals in all of the studied sandstone samples which can suggest that calcite saturation state of the thermal fluid is close to equilibrium in oxygen-depleted pore water. Analysis of the dominant carbonate crystals in the scale can suggest that growth of the feather dendrites of low-Mg calcite was probably driven by rapid CO_2 degassing of CO_2-rich thermal water under far-from-equilibrium conditions. Based on hydrogeochemical data and related indices for scaling and corrosion ability, the produced bicarbonate-rich (up to 3180 mg/l) thermal water has a significant potential for carbonate scaling which supports the aforementioned statement. Taking into consideration our present knowledge of geological setting of the studied geothermal systems, temporal changes in chemical composition and temperature of the thermal water during the heating period can indicate upwelling fluids from a deep aquifer. Regarding the pre-Neogene basement, hydrologic contact with a Triassic carbonate aquifer might be reflected in the observed chemical features such as decreased total dissolved solids and increased bicarbonate content with high scale-forming ability. The proposed upflow of basin-derived water could be channeled by Neogene to Quaternary fault zones, including compaction effects creating fault systems above the elevated basement high. The results may help to understand the cause of the high carbonate scale precipitation rates in geothermal systems tapping sandstone aquifers (published in ***Geofluids, Special issue "Geothermal Systems: Interdisciplinary Approaches for an Effective Exploration", in press, 2019***; IF: 2.540; SJR: Q1).

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