Doctoral School of Geosciences

METAMORPHIC EVOLUTION AND STRUCTURAL ARCHITECTURE OF THE ALGYŐ–FERENCSZÁLLÁS–KISZOMBOR CRYSTALLINE BASEMENT HIGH

Az Algyő–Ferencszállás–Kiszombor térség kristályos aljzatának metamorf fejlődése és szerkezeti felépítése

Theses of the PhD Dissertation

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I. Introduction and the aims of the study

The crystalline basement of the Algyő–Ferencszállás–Kiszombor (AFK) area, situated in the southeastern part of the Pannonian Basin, forms a key component of one of the most essential hydrocarbon systems in the region; however, its characteristics are poorly understood. This basement high, part of the Tisza Mega-unit, is buried beneath 2.5–3.0 km of Neogene sediments, which serve as the main reservoirs of the local petroleum system. Although the primary hydrocarbon reservoirs are located within these Neogene formations, fractured crystalline basement rocks may also act as significant fluid migration pathways and potential reservoirs. Due to its burial beneath a thick sedimentary sequence, the AFK basement can only be characterised using indirect information obtained from hydrocarbon exploration boreholes and geophysical datasets.

The crystalline basement of the Pannonian Basin forms a complex mosaic of blocks with diverse metamorphic histories, arranged along structural boundaries due to its polyphase tectonic evolution. This structural arrangement has essential effects on hydrocarbon migration and storage. However, within this regional context, the internal structure and metamorphic development of the AFK basement have largely remained unclear. Previous interpretations have proposed conflicting geological models; some viewing the basement as lithologically uniform, while others recognising local variations without integrating these into a cohesive model (Szalay 1977; Szederkényi 1984; T. Kovács & Kurucz 1984; Lelkes-Felvári et al. 2003, 2005; Horváth & Árkai 2002). The distribution and relationships of rock units remain uncertain, and the published metamorphic evolutions of the basement rocks are inconsistent (Szederkényi 1984; Lelkes-Felvári et al. 2003, 2005; Horváth & Árkai 2002). Previous studies have been fragmented, mainly focusing on scattered samples from various localities and lacking a comprehensive spatial or metamorphic context. As a result, the available data have not been systematically analysed.

The main goal of this PhD research was to produce a comprehensive and integrated study of the AFK basement, combining petrographic, geochemical, thermobarometric, and geophysical methods, to reconstruct its internal structure and unravel its metamorphic history. This approach enabled the development of a new geological model for the AFK basement, highlighting its structural complexity and offering insights into its potential for hydrocarbon migration and storage. Such an investigation was crucial to improve understanding of the geological evolution of the AFK basement and to refine its assessment within the context of hydrocarbon exploration in the Pannonian Basin.

II. Applied methods

In this research, all available datasets, including drilling documentation, core and thin-section samples, geochemical analyses, and geophysical well-log data, were systematically collected and examined using modern analytical techniques.

A total of 144 hydrocarbon exploration boreholes intersecting the crystalline basement of the AFK area were evaluated. Core samples from 119 boreholes yielded approximately 580 thin sections for petrographic analysis, with about 520 from the Algyő High (AH) and approximately 60 from the Ferencszállás and Kiszombor regions. The available core material was mainly fragmented, and continuous recovery from the drilled rock column was absent, making the thin-section studies the most reliable basis for petrographic examination.

Petrographic analysis was carried out at the Petrographic Laboratory of the Department of Mineralogy, Geochemistry, and Petrology (Department of Geology) at the University of Szeged. An Olympus BX41 polarisation microscope was used for examining thin sections, while an Olympus SZX7 stereomicroscope was employed for macroscopic core samples. A THERMO Scientific DXR Raman microscope, equipped with a 532 nm Nd-YAG laser, was also utilised to identify specific mineral phases. For the qualitative assessment of the chemical composition of mineral phases, cathodoluminescence (CL) microscopy was performed using a Reliotron VII CL instrument mounted on an Olympus BX43 microscope. Petrographic investigations provided data on mineral composition, microtextural and microstructural features, as well as pre-, syn-, and post-kinematic mineral assemblages. The analysed samples were classified based on similar petrographic characteristics, enabling the identification of major rock types with distinct qualitative metamorphic histories.

From the AH area, whole-rock major element compositions of 87 samples are available from previous research (Szederkényi 1991). These data were utilised to estimate the protoliths of the lithologies by applying discriminant diagrams. Three types of discriminant diagrams were employed to determine the protolith character of the rocks.

In metamorphic rocks, identified in the AH area, P–T conditions of mineral paragenesis were estimated using the TWQ 2.3 software (Berman 1991). This software was employed to determine the positions of potential metamorphic reactions in P–T space, based on chemical systems representing the parageneses of the studied microtextural domains. Since the compositions of most phases were unknown, end-member reactions were modelled.

To determine the composition of the main mineral phases of the rock types, mineral chemical analyses were performed on samples from the AFK area. Representative samples of each lithology were analysed using a Hitachi TM4000Plus scanning electron microscope (SEM) equipped with an Oxford Instruments Xplore Compact 30 energy-dispersive spectrometer (EDS) at the Research and Industrial Relations Center at the Faculty of Science, Eötvös Loránd University.

Based on the chemical composition of minerals, calibrated thermometers and barometers were used to estimate the metamorphic P–T conditions of the mineral paragenesis in the rock types. For T calculation, Ti-in-biotite (Henry et al. 2005; Wu & Chen 2015), garnet–biotite (GB) (Ferry & Spear 1978; Holdaway 2000) and chlorite-based thermometers (Hillier & Velde 1991; Kranidiotis & MacLean 1987; Zang & Fyfe 1995) were utilised. P was determined using biotite–muscovite (Bt–Ms) (Wu 2020), single garnet (Wu 2019) and Si-in-phengite (Caddick & Thompson 2008) geobarometers. The same thermobarometric methods were applied to each lithology to enable comparisons of their evolution.

The geophysical interpretation incorporated natural gamma-ray (NGR) logs from 66 boreholes reaching the basement of the AH area. These logs were processed and interpreted to identify lithological changes and metamorphic domains. The geophysical well-logs were integrated with lithological and petrographic datasets, extending core-based interpretations into a 3D spatial context. The geophysical–lithological correlations, through the development of 3D block models based on well-log data, have enabled a more precise reconstruction of the lithological and structural organisation of the area, and facilitated the identification of previously unrecognised rock units. Such modelling allows for the continuous spatial correlation of lithological units throughout the basement.

The rock types identified in each borehole, representing distinct petrological features, were mapped onto a point map projected onto the basement surface. The distribution of various rock types indicated the approximate spatial extent of each lithology, enabling the delineation of blocks composed of rocks with different metamorphic histories. The boundaries between these blocks were interpreted as post-metamorphic structural zones.

III. New scientific results

T1. The crystalline basement of the Algyő–Ferencszállás–Kiszombor (AFK) area comprises separate lithological blocks that have experienced different metamorphic evolution.

This conclusion is drawn from an integrated interpretation of petrographic, geochemical, and thermobarometric datasets obtained from core and thin-section samples, supported by geophysical well-log data, all obtained from

144 boreholes penetrating the crystalline basement. The findings refine the model of the internal structure of the area and illustrate its metamorphic and post-metamorphic evolution.

T2. The principal lithologies of the AFK basement are garnet–kyanite gneiss, garnet–biotite gneiss, pseudomorph-bearing gneiss, epidote orthogneiss, chlorite schist, and metagranite, each representing distinct lithological units.

Petrographic and mineral chemistry analyses, alongside thermobarometric calculations, demonstrated that these lithologies vary in their petrographic features and metamorphic evolution. Lithological classification was based on detailed petrographic analysis, including mineral composition, microtextural and microstructural characteristics, and pre-, syn-, and post-kinematic parageneses. The observed petrographic features and P–T conditions indicate formation under different metamorphic environments. Spatial distribution shows that garnet–kyanite gneiss predominates in the northwest and southeast parts of the AH, as well as the northern part of the Ferencszállás dome. Garnet–biotite gneiss is confined to the Ferencszállás area, while pseudomorph-bearing gneiss occurs in Kiszombor. The highest section of the AH consists of epidote orthogneiss, whereas chlorite schist dominates along a northwest–southeast-oriented zone. Metagranite is identified in boreholes near the northern area of Ferencszállás.

T3. The metamorphic evolution of the three main gneiss types (garnet–kyanite gneiss, garnet–biotite gneiss, and pseudomorph-bearing gneiss) is genetically related. It can be interpreted within a unified metamorphic model.

All three genetically related medium-grade gneisses experienced an initial amphibolite-facies regional metamorphism (M1), overprinted by a contact metamorphic (metasomatic) effect (M2), both occurring under varying P–T conditions. Thermobarometric calculations reveal a clockwise metamorphic path for each gneiss variety. The peak conditions of the M1 event in the garnet–biotite gneiss reached ~9.5–10.5 kbar and ~670–720 °C, followed by an M2 overprint at T_{max}~570–630 °C. In the garnet–kyanite gneiss, M1 reached ~7.5–8.5 kbar and ~600–650 °C, with M2 at T_{max}~730 °C. In the pseudomorph-bearing gneiss, M1 peak conditions were ~6.5–7.0 kbar and ~550–580 °C, overprinted by a contact effect within the andalusite stability field. These P–T variations suggest metamorphism at different crustal depths. Earlier geochronological data imply that the M1 metamorphism is of Variscan age, while the M2 event is likely related to an Alpine magmatic event.

T4. The M2 contact metamorphic (metasomatic) effect in gneiss rocks is interpreted as resulting from Alpine granitoid intrusions.

The M2 metamorphic overprint caused different mineral assemblages in various gneiss types. In garnet–kyanite gneiss and pseudomorph-bearing gneiss, this overprint led to the formation of fine-grained kyanite aggregates and tourmaline crystals. The main difference lies in the precursor phase of kyanite: in garnet–kyanite gneiss, kyanite aggregates replace garnet, whereas in pseudomorph-bearing gneiss, they are considered pseudomorphs after andalusite. In garnet–biotite gneiss, contact metasomatic effects are evidenced solely by undeformed, post-kinematic tourmaline grains. Assuming the M2 parageneses originate from the same granitoid intrusion, the gneiss bodies must have experienced contact metamorphism at varying crustal depths, which permitted tourmaline crystallisation under different conditions.

T5. The metagranite body in the Ferencszállás area constitutes an intrusion into the surrounding gneiss terrains, which may have been the source of the M2 contact overprint, and has resulted in intrusive dykes within the host gneiss.

Microtextural and microstructural features clearly show that the metagranite body in the Ferencszállás area is younger than the surrounding gneiss. No mineral assemblages indicative of progressive or retrograde metamorphic overprint were observed, and the presence of oriented tourmaline crystals aligned parallel to the foliation indicates pre-kinematic growth. Additionally, NGR geophysical well-log data confirm the existence of intrusive granite/granodiorite dykes in the southeastern part of the AH area, which locally define metasomatic alteration zones within the gneiss. Previous research has shown that during the Late Cretaceous, granite/granodiorite (banatite) intruded into the metamorphic terrane, leading to metasomatic alteration and tourmaline crystallisation within the host gneisses (Szalay 1977; Szederkényi 1984; Berza et al. 1998). The metagranite bodies identified in the region are believed to be related to these Late Cretaceous intrusions.

T6. The chlorite schist and epidote orthogneiss-dominated blocks in the central part of the AH area represent unique low-grade structural domains.

The metamorphic histories of epidote gneiss and chlorite schist differ significantly from what is typical in the gneiss terrains. The protolith of the epidote orthogneiss is an intrusive granitoid rock that underwent metamorphism along a retrograde greenschist facies pathway. In contrast, chlorite schist shows a progressive greenschist facies metamorphic texture. The independent evolution of these two blocks is also supported by the metasomatic overprint in the chlorite schists, characterised by post-kinematic pyrite, chalcopyrite, as well as magnetite crystals. If these minerals resulted from granite or granodiorite magmatism, it suggests that the medium- and low-grade blocks must have been located at considerably different crustal depths during the metasomatic overprint.

T7. The lithological units with different metamorphic evolutions most probably became juxtaposed along normal faults during intense brittle deformation associated with extensional processes coeval with the opening of the Pannonian Basin during the Miocene.

If the post-kinematic mineralisation – tourmaline crystallisation in the gneiss rocks and sulphide mineralisation in the chlorite schist – is interpreted to be of Late Cretaceous age, the juxtaposition of blocks must have resulted from an even younger tectonic event. As the large-scale structural event of the Middle Miocene, the low-grade blocks in the central part of the AH were probably moved to their current position along normal faults due to the subsidence of the Pannonian Basin during the Miocene extension. This extensional phase may also be responsible for the segmentation of the medium-grade gneiss domain. The supposed brittle structural boundaries between the blocks could provide hydrocarbon migration pathways from the adjacent over-pressured sub-basins or could even serve as suitable reservoirs.

IV. Összefoglalás

A Pannon-medence délkeleti részén elhelyezkedő Algyő–Ferencszállás–Kiszombor (AFK) kristályos aljzata a régió egyik legjelentősebb szénhidrogén rendszerének központi részét képezi, azonban szerkezete és metamorf fejlődése mindmáig kevéssé ismert. Az értékezés célja az aljzat átfogó és integrált vizsgálata volt petrográfiai, geokémiai, termobarometriai és mélyfúrási geofizikai adatok együttes elemzésével. A vizsgálat során összesen 144 db, az AFK térség metamorf aljzatát elért fúrás elérhető adata került feldolgozásra, amely során feltárásra került az aljzat belső szerkezete és metamorf fejlődéstörténete.

Az eredmények alapján bizonyítható, hogy a terület kristályos aljzata több, eltérő metamorf fejlődésű litológiai blokkból épül fel. A terület fő kőzettípusaként a gránát–kianit gneisz, gránát–biotit gneisz, pszeudomorf-tartalmú gneisz, epidot ortogneisz, kloritpala és metagránit volt azonosítható, melyek mindegyike önálló, eltérő metamorf fejlődésű, térben is lehatárolható litológiai egységet képvisel. A termobarometriai becslések kimutatták, hogy a három fő gneisz típus metamorf fejlődése genetikai kapcsolatban áll, ugyanakkor a metamorfózis idején eltérő kéregmélységben helyezkedtek el. A gneiszek mindegyikét egy feltételezett variszkuszi korú regionális metamorfózis érintette (M1), melyet egy feltehetőleg alpi granitoid intrúzióhoz köthető kontakt metamorf (metaszomatikus) felülbélyegzés (M2) írt felül. Az M2 felülbélyegzés feltételezett forrása a Ferencszállás térségében feltárt metagránit test. Az Algyő-hát központi részén elhelyezkedő epidot ortogneisz és kloritpala eltérő fejlődéstörténettel és posztkinematikus metaszomatikus átalakulással jellemezhető unikális, kisfokú metamorf blokkokat képviselnek. Az AFK kristályos aljzatában azonosított eltérő metamorf fejlődéssel jellemezhető kőzetblokkok feltehetőleg normál vetős szerkezeti határok mentén kerültek jelenlegi pozíciójukba a Pannon-medence miocén kori extenciós tektonikai folyamatához köthető rideg deformáció során. E rideg szerkezeti zónák nemcsak az eltérő metamorf fejlődésű litológiai egységek közötti szerkezeti határokat jelölik ki, hanem potenciális szénhidrogén-migrációs útvonalakat és tározókat is jelenthetnek az aljzaton belül.

A kutatás egy olyan új földtani modellt eredményezett a területre, amely részletesen feltárja a terület metamorf fejlődését és szerkezeti összetettségét. Az eredmények hozzájárultak a Pannon-medence délkeleti részének regionális fejlődéstörténetének pontosabb megértéséhez, és új szempontokat kínál a térséget érintő szénhidrogén-kutatás számára.

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VI. List of publications

Henrietta Kondor (MTMT author ID: 10065299)

Articles used in the PhD Dissertation

Kondor, H., M. Tóth, T. (2021). Contrasting metamorphic and post-metamorphic evolutions within the Algyő basement high (Tisza Mega-unit, SE Hungary). Consequences on structural history. *Central European Geology*, 64(2), 91–112. (Scopus-indexed; Scopus Impact Score: 0.67 (2024); SJR: 0.225 (2024, Q3); no JCR Impact Factor)

Kondor, H., M. Tóth, T. (2025). Metamorphic and post-metamorphic evolution of the SE part of the Pannonian Basin in the Algyő–Ferencszállás crystalline high: Thermobarometric constraints on Variscan to Alpine events. *Geologica Carpathica*, 76, 1–21. (Indexed in Scopus and Web of Science; JCR Impact Factor: 1,5 (2024, Q2); CiteScore: 2,5 (2024); SJR: 0,526 (2024, Q2))

Kondor, H., Braun, B.Á, M. Tóth, T. (2025). Architecture of the metamorphic Algyő High (SE Pannonian Basin) based on lithological interpretation of natural gamma-ray logs. *Földtani Közlöny, (In press)*. (Scopus-indexed; Scopus Impact Score: 0,35 (2024); SJR: 0,21 (2024, Q3); no JCR Impact Factor)

Other publications

M. Tóth, T., Fiser-Nagy, Á., **Kondor, H.**, Molnár, L., Schubert, F., Vargáné Tóth, I., Zachar, J. (2021). Az Alföld metamorf aljzata: a köztes tömegtől a tarka mozaikig. *Földtani Közlöny*, 151(1), 3–26. (in Hungarian)

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VII. Co-authors statements

I, *Tivadar M. Tóth*, hereby declare that the role of **Henrietta Kondor**, the doctoral candidate, in the publication of

Kondor, H., M. Tóth, T. (2021). Contrasting metamorphic and post-metamorphic evolutions within the Algyő basement high (Tisza Mega-unit, SE Hungary). Consequences on structural history. *Central European Geology*, 64(2), 91–112.

Kondor, H., M. Tóth, T. (2025). Metamorphic and post-metamorphic evolution of the SE part of the Pannonian Basin in the Algyő–Ferencszállás crystalline high: Thermobarometric constraints on Variscan to Alpine events. *Geologica Carpathica*, 76, 1–21.

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was decisive and that I have not used it to obtain a scientific degree and will not do so in the future.

Szeged, 25 August 2025

……………………………..
Tivadar M. Tóth

I, *Bence Ádám Braun*, hereby declare that the role of **Henrietta Kondor**, the doctoral candidate, in the publication of

Kondor, H., Braun, B.Á, M. Tóth, T. (2025). Architecture of the metamorphic Algyő High (SE Pannonian Basin) based on lithological interpretation of natural gamma-ray logs. *Földtani Közlöny, (In press)*.

was decisive and that I have not used it to obtain a scientific degree and will not do so in the future.

Szeged, 21 August 2025

…………………………..
Bence Ádám Braun

VIII. Declaration of the supervisor

I, *Tivadar M. Tóth*, hereby confirm that the content of the dissertation is based on the independent work of the **Henrietta Kondor**, the doctoral candidate, and that she has contributed decisively to the results through her independent creative activity. I consider the entire dissertation to be eligible for support from a professional and academic point of view and recommend its acceptance.

Szeged, 25 August 2025

……………………………..

Tivadar M. Tóth

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Tisztelt Henrietta Kondor, Bence Ádám Braun, Tivadar M. Tóth!

Értesítjük, hogy a(z) Földtani Közlöny folyóirathoz beküldött "A metamorf Algyő-hát (DK Pannon-medence) kőzettani felépítése természetes gamma szelvények értelmezése alapján" című kézirata elfogadásra került.

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