EÖTVÖS LORÁND UNIVERSITY
FACULTY OF SCIENCES

From mantle evolution to intensive surface CO_2 degassing in the Southeastern Carpathians, Central Europe

Thomas Pieter Lange

Thesis of Doctoral Dissertation

DOI: https://doi.org/10.15476/ELTE.2024.199

Ph.D. program for Environmental Geosciences at Doctoral School of Environmental Sciences, Faculty of Science, Eötvös Loránd University

Head of the Doctoral School of Environmental Sciences: Tamás Turányi, D.Sc.
Head of the Environmental Geosciences Program: Zoltán Szalai, Ph.D.

<u>Supervisor</u>

István János Kovács, Ph.D.
Acting director

Institute of Earth Physics and Space Science
Hungarian Research Network

<u>Consultants</u>

Csaba Szabó, Ph.D.

Lithosphere Fluid Research Lab,
Eötvös Loránd University

Márta Berkesi, Ph.D.
senior research fellow
Institute of Earth Physics and Space Science
Hungarian Research Network

Budapest
2024

I. Introduction and aims

Along with the growth of the population, more human living areas are, in one way or another, affected by deep geodynamic processes (e.g., earthquake, degassing, volcanism; e.g., Vacareanu and Ionescu, 2016). These processes are strongly linked to global element cycling, that support volatile-rich (e.g., CO_2, H_2O) fluid flow from the mantle towards the surface in various tectonic environments (e.g., Kerrick and Caldeira, 1998; Bräuer et al., 2016). Sometimes, when an intense tectonic evolution is observed, geological CO_2 emanation can far exceed the flux of anthropogenic CO_2 production (e.g., Holloway et al., 2007). These geologic CO_2 emanations are linked to flux of the upwelling fluid that strongly supports preservation of deep fluid signatures linked to the physical and chemical properties of the infiltrating fluid and the infiltrated lithospheric segment (Hilton, 2007). Consequently, to better understand the evolution of fluid upwelling, a multidisciplinary approach has been established by combining geochemical mineralogical, geophysical and geodynamic approaches (e.g., Cloetingh et al., 2023). This strategy can provide novel results to gain a deeper insight into the Earth's mantle, a reservoir that can host significant amount of volatiles (e.g., CO_2, H_2O) (Gibson and McKenzie, 2023) and fluid pathways. Upper mantle xenoliths (e.g., Bodinier et al., 1990; Berkesi et al., 2012) are all good examples to directly study the lithospheric upper mantle source. Based on the major and trace element content of mantle minerals (e.g., olivine, pyroxenes, amphibole), entrapped fluid inclusions and the nano- and micronscale textural relationship, a complex geodynamic history can be revealed. In addition, surface processes like intensive degassing in a geodynamically active region can carry deep geochemical fingerprints on shallow fluids indicating their connection with deeper lithospheric regions. If such geochemical signatures are present, then the tectonic settings (e.g., lithology and fault distribution, nappe stacking) can provide pathways along which fluid can migrate towards the surface.

In the Southeastern Carpathians a significant number of mid-depth (70-170 km, Tondi et al., 2009) mantle earthquakes can be observed, produced by the sinking Vrancea slab (Martin et al., 2006) forming the Vrancea Seismogenic zone. At the northwestern end of the seismogenic zone, in the Târgu Secuiesc intramountain basin, an intensive, non-volcanic surface degassing sites can be observed (Gyila and Csige, 2014) assuming a connection between surface emanations and the active geodynamic evolution of the Southeastern Carpathians. Furthermore, the Perșani Mountains Volcanic Field is situated ~ 50 km west from the Vrancea Seismogenic zone. During the volcanic activity, it carried abundant, fertile, highly deformed mantle xenoliths to the surface from a mantle wedge setting (e.g., Vaselli et al., 1995; Falus et al., 2008; Faccini et al., 2020). The joint occurrence of the ongoing intensive surface emanation in the Târgu Secuiesc intramountain basin and the young age of the Perșani Mountains Volcanic Field (1.2-0.6 Ma; Panaiotu et al., 2013) provide a good opportunity to better understand the upper mantle to surface connections within the Southeastern Carpathians.

II. Study area and samples

The study focuses on two key areas within the Southeastern Carpathians. The first area is the Perșani Mountains Volcanic Field located in the northern part of the Perșani Mountains (southeastern Transylvanian Basin, Romania) that is one of the youngest mantle xenoliths-bearing alkali basaltic monogenetic volcanic field within the Carpathian-Pannonian region (Central Europe). From this volcanic field, the focus will be put on upper mantle xenoliths. The second area is the southeastern Târgu Secuiesc intramountain basin (Covasna town and vicinity together with Tamașfalău) that is known for the ongoing intensive surface CO_2 emanations. In this thesis, spring and well waters and their dissolved gases will be put in focus.

Perșani Mountains Volcanic Field and nanoscale amphibole precipitation and growth

In the last 30 years, over 1000 mantle xenoliths were collected from the Perșani Mountains Volcanic Field that provide a robust sample series from which representative xenoliths from all xenolith-bearing localities could be chosen mostly collected in 2000, 2003, 2005, 2014 and 2018. Representative xenoliths (excluding composite xenoliths) were chosen based on their freshness, textural variety and lack of basalt infiltration. Several xenoliths host secondary fluid inclusions that are associated with amphibole lamella. Based on detailed petrographic observations one sample was selected for the detailed study of amphibole formation and growth at the nanoscale.

Târgu Secuiesc intramountain basin – Eastern Carpathians

In total 12 mineral waters and 5 dissolved gases were collected on-site from natural springs and wells. From these samples 11 mineral waters were collected throughout Covasna and its vicinity supplemented by the mineral water from Tamasfalău. The spatial distribution of the sampling sites makes it possible to put the results in spatial and geological context. Water samples were stored in plastic containers at low temperature to slow down microbiological activity, whereas the dissolved gases were stored in metal cylinders.

III. Methods

Various analytical methods were applied to determine the major and trace element composition of the upper mantle xenolith rock-forming minerals and their textual relationship, the nanoscale structural relationship of clinopyroxene and amphibole and the stable isotopic ratio for both mineral waters and dissolved gas samples.

Petrographic features of the Perșani Mountains Volcanic Field mantle xenoliths were observed with three methods: by optical microscopy in the Lithosphere Fluid Research Lab, at the Faculty of Science, Eötvös Loránd University (ELTE, Budapest, Hungary); with HitachiTM 4000Plus electron microscope Research and Instrument Core Facility, Faculty of Science, Eötvös Loránd University (ELTE-FS-RICF; Budapest, Hungary); and by Zeiss EVO MA 15 SEM equipped with Oxford Instruments Nordlys Nano electron backscatter diffraction (EBSD) system at the Instituto Andaluz de Ciencias de la Tierra (CSIC, Armilla, Spain).

The major element composition of the rock-forming minerals were determined with a HitachiTM 4000Plus electron microscope equipped with an electron dispersive X-ray detector at the (ELTE-FS-RICF; Budapest, Hungary). All studied polished surfaces were carbon coated before measurements. Trace element compositions of pyroxenes and amphibole were determined using a New WaveUP 213 laser ablation system coupled to a quadrupole inductive coupled plasma mass spectrometer (Perkin Elmer Elan DRCII) at the Supervisory Authority for Regulatory Affairs (Budapest, Hungary). The structural hydroxyl content of nominally anhydrous minerals was studied with a Perkin Elmer Spectrum 400 infrared spectrometer and a coupled Spotlight 400 FTIR imaging system out at the Department of Applied Biotechnology and Food Science at the Budapest University of Technology and Economics (Budapest, Hungary). Fluid inclusions were studied with a confocal HORIBA Labram HR800 spectrometer at the ELTE-FS-RICF (Budapest, Hungary). Fluid inclusion milling and preparation of transmission electron microscopy (TEM) lamellae were conducted on a FEI Quanta 3D dual beam scanning electron microscope at the ELTE-FS-RICF (Budapest, Hungary). The TEM lamellae were studied at the Nanolab at the University of Pannonia, Veszprém (Hungary) by using a Talos F200X G2 scanning transmission electron microscope (STEM). Electron back-scatter diffraction (EBSD) analysis was done on a Zeiss EVO MA 15 SEM equipped with Oxford Instruments Nordlys Nano electron backscatter diffraction (EBSD) system, and a 170 mm2 Ultim Max Energy Dispersive Spectroscopy (EDS) silicon drift detector (SDD) at the Instituto Andaluz de Ciencias de la Tierra (CSIC, Armilla, Spain).

All collected water and gas bulk and isotopic measurements were conducted at the Laboratory of Climatology and Environmental Physics (ICER), Institute of Nuclear Research (Debrecen, Hungary). Stable isotope analyses were carried out on the collected spring and well water and dissolved gas samples (CO_2, He and Ne) from the southeastern Târgu Secuiesc intramountain basin. H_2O was distilled and stored in small plastic tubes prior to stable hydrogen and oxygen isotopic measurements. The stable hydrogen and oxygen isotopic ratios were measured with a LGR Liquid Water Isotope Analyser (model: 912–0050). Bulk dissolved gas measurements were conducted prior to isotopic measurements with a quadrupole mass spectrometer. Stable carbon and oxygen isotope ratios of CO_2 were determined with a Thermo Finnigan DELTA^{PLUS} XP mass spectrometer. All H_2O and CO_2 results were normalized for SMOW (Standard Mean Ocean Water; Coplen et al., 1996) and V-PDB (Vienna Pee Dee Belemnite; Coplen et al., 1996), respectively. Helium was measured using a Thermo Scientific HELIX-SFT mass spectrometer, whereas Ne gas were measured using a VG-5400 mass spectrometer. The noble gas isotopic ratios were normalized to atmospheric air. Air correction was applied by using the equation of Giggenbach et al. (1993).

IV. Scientific theses of doctoral study

1. I classified the xenoliths as lherzolites and harzburgite that dominantly have protogranular and porphyroclastic, rarely equigranular textures, often containing olivine and pyroxene equilibrium textures. Both rock types contain amphibole, which is absent in the equigranular textured xenoliths. The protogranular and porphyroclastic mantle xenoliths derived from fertile mantle domain based on the major element composition of rock-forming minerals (e.g., moderately high Mg# (~90) of olivines, the high Al_2O_3 content of orthopyroxene and clinopyroxene (up to 5.0 and 8.0 wt. %, respectively) and the low Cr# (<15) of spinel). This is also supported by trace element composition of orthopyroxene, clinopyroxene and amphibole, from which the former two have high structural hydroxyl content (up to 250 and 700 ppm wt., respectively) and latter two often show tenfold enrichment in their rare earth element (including Y) content compared to chondrite values. In contrast, variation of MgO vs. Al_2O_3 for both orthopyroxene and clinopyroxene assumes 5-10 % degree of partial melting for the protogranular and porphyroclastic xenoliths and up to 33 % degree of partial melting for the equigranular harzburgite xenoliths. The difference in bulk chemical composition of the most depleted and the most fertile xenoliths to trace the extent of metasomatism. The calculation showed that asthenospheric upwelling and subsequent

heating led to mantle fertilization occurred simultaneously with sublateral extension of the lithospheric mantle. During this process, amphiboles and clinopyroxene were partially melted in the lower part of the lithospheric mantle, which was followed asthenospheric fluid infiltration enriching the overlying lithospheric mantle in such elements as Na, Ca, Al, Si, H. Thus, during the metasomatic event the equigranular depleted samples transformed into a fertile, protogranular lithology (Lange et al., 2019; Liptai et al., 2021, 2024).

2. I demonstrated that secondary fluid inclusions of the studied mantle xenoliths contain solid phases. Fluid inclusions are seldom associated with amphibole intergrowth in clinopyroxene indicating the interaction between the host clinopyroxenes and trapped fluid that is rich in CO_2, associated with minor amount of H_2O, N_2, H_2S and small amount of silicate melt components (Na_2O, Al_2O_3, TiO_2 and SiO_2). After entrapment, within the fluid inclusions a hydrous, nanometer thick monolayer formed at the fluid-clinopyroxene boundary increasing the H_2O activity in the near solid region. The joint composition of the hydrous monolayer and outermost clinopyroxene unit cells should be approximately equal to the amphibole composition. The distortion of the fluid-solid interface (and hydrous nanolayer) due to surface and monolayer distortion led to clinopyroxene dissolution that was followed by amphibole precipitation (Lange et al., 2023a).

3. I demonstrated the nanoscale phase transformation of clinopyroxene to amphibole. The newly formed fluid-clinopyroxene-amphibole triple phase boundaries support fluid escape into the clinopyroxene-amphibole interface along misfit structures (i.e., nanochannels). This leads to significant fluid fractionation from the micron to the nanoscale. Nanochannels have high surface charges that support diffusion of elements, such as H, Na, Al, Si. Along the nanochannels, the clinopyroxene transforms to pyribole at the even-odd clinopyroxene-amphibole interface followed by pyribole and clinopyroxene merge that results in amphibole formation. During this process, the composition of the escaped fluids, that is most likely hydrous, Na_2O and Al_2O_3-rich, yet SiO_2 undersaturated, is consumed. This is supported by the composition of hydrous nanosilicate melt inclusions present along the clinopyroxene-amphibole interface that support amphibole growth. These results, together with the major element composition of clinopyroxene and amphibole, show that excess fluids are needed for amphibole formation. Nevertheless, this model presents that hydrous mineral (e.g., amphibole) formation can occur in regions where H_2O activity is low (Lange et al., 2023a; Liptai et al., 2024).

4. I determined the hydrogen and oxygen stable isotopic ratios of spring and well waters from the southern Târgu Secuiesc intramountain basin. The Covasna and vicinity water samples (δ^2H ~ -70.0 ‰, $\delta^{18}O$ ~ -9.0 ‰, respectively) indicate metamorphic origin best preserved at elevated topography, where abundant deformation zones occur. The dissolved CO_2 ($\delta^{13}C$ = -2.00 – -0.47 ‰) and air corrected helium stable isotopic ratios (R_c/R_a = 1.88 – 2.45) are uniform and suggest metamorphic and subordinate mantle origin. The low surface heat flow of the Târgu Secuiesc intramountain basin favors crustal fluid release due to deeper mantle fluid infiltration and not to thermal break-down of carbonate minerals. Based on the tectonic settings, mantle fluids can originate from three different sources (asthenosphere, sinking Vrancea slab and ambient fertilized lithospheric mantle) that in the shallower lithosphere becomes relatively more CO_2 enriched supported by fluid inclusion composition. The CO_2-rich mantle fluids migrate into the lower crust along deep-seated weakening zones and initiate dehydration metamorphic reactions (due to the change in fluid CO_2 and H_2O activity). This provides metamorphic origin H_2O deliberation and thus contribution to the upwelling fluids. In the upper crust, during its subvertical migration, fluid infiltrates into the Mesozoic carbonate that shifts the carbon stable isotopic ratio of CO_2 towards more positive $\delta^{13}C$ stable isotopic ratio (Lange et al., 2023a).

V. References

Berkesi, M., Guzmics, T., Szabó, C., Dubessy, J., Bodnar, R. J., Hidas, K., & Ratter, K. (2012). The role of CO_2-rich fluids in trace element transport and metasomatism in the lithospheric mantle beneath the Central Pannonian Basin, Hungary, based on fluid inclusions in mantle xenoliths. *Earth and Planetary Science Letters*, 331, 8-20. https://doi.org/10.1016/j.epsl.2012.03.012

Bodinier, J. L., Vasseur, G., Vernieres, J., Dupuy, C., & Fabries, J. (1990). Mechanisms of mantle metasomatism: geochemical evidence from the Lherz orogenic peridotite. *Journal of Petrology*, *31*(3), 597-628. https://doi.org/10.1093/petrology/31.3.597

Bräuer, K., Geissler, W. H., Kämpf, H., Niedermann, S., & Rman, N. (2016). Helium and carbon isotope signatures of gas exhalations in the westernmost part of the Pannonian Basin (SE Austria/NE Slovenia): Evidence for active lithospheric mantle degassing. *Chemical Geology*, *422*, 60-70. https://doi.org/10.1016/j.chemgeo.2015.12.016

Cloetingh, S., Sternai, P., Koptev, A., Ehlers, T. A., Gerya, T., Kovács, I., Oerlemans, J., Beekman, F., Lavallé, Y., Dingwell, D., Békési, E., Porkoláb, K., Tesauro, M., Lavecchia, A., Botsyun, S., Muller, V,. Roure, F., Serpelloni, E., Matenco, L., Castelltort, S., Giovannelli, D., Vitale Brovarone A., Malaspina N., Coletti, G., Valla, P., Limberger J. (2023). Coupled surface to deep Earth processes: Perspectives from TOPO-EUROPE with an emphasis on climate-and energy-related societal challenges. *Global and Planetary Change*, 104140. https://doi.org/10.1016/j.gloplacha.2023.104140

Coplen, T. B. (1996). New guidelines for reporting stable hydrogen, carbon, and oxygen isotope-ratio data. *Geochimica et Cosmochimica Acta*, 60(17), 3359-3360. https://doi.org/10.1016/0016-7037(96)00263-3

Faccini, B., Rizzo, A. L., Bonadiman, C., Ntaflos, T., Seghedi, I., Grégoire, M., Ferretti, G., & Coltorti, M. (2020). Subduction-related melt refertilisation and alkaline metasomatism in the Eastern Transylvanian Basin lithospheric mantle: Evidence from mineral chemistry and noble gases in fluid inclusions. *Lithos*, *364*, 105516. https://doi.org/10.1016/j.lithos.2020.105516

Falus, G., Tommasi, A., Ingrin, J., & Szabó, C. (2008). Deformation and seismic anisotropy of the lithospheric mantle in the southeastern Carpathians inferred from the study of mantle xenoliths. *Earth and Planetary Science Letters*, *272*(1-2), 50-64. https://doi.org/10.1016/j.epsl.2008.04.035

Gibson, S. A., & McKenzie, D. (2023). On the role of Earth's lithospheric mantle in global volatile cycles. *Earth and Planetary Science Letters*, *602*, 117946. https://doi.org/10.1016/j.epsl.2022.117946
Giggenbach, W. F., Sano, Y., & Wakita, H. (1993). Isotopic composition of helium, and CO2 and CH4 contents in gases produced along the New Zealand part of a convergent plate boundary. *Geochimica et Cosmochimica acta*, *57*(14), 3427-3455. https://doi.org/10.1016/0016-7037(93)90549-C
Gyila, S., & Csige, I. (2014). A mofetta-jelenségkör a gázüledékek meteorológiai és geodinamikai függőségének szemszögéből vizsgálva.[The mofetta-phenomena from the perpective of meteorological and geodynamical dependency]. *Magyar Földtudományi Szakemberek XII. Találkozója, Debrecen*, 85-88.
Hilton, D. R. (2007). The leaking mantle. *Science*, *318*(5855), 1389-1390. https://doi.org/10.1126/science.1151983
Holloway, S., Pearce, J. M., Hards, V. L., Ohsumi, T., & Gale, J. (2007). Natural emissions of CO2 from the geosphere and their bearing on the geological storage of carbon dioxide. Energy, 32(7), 1194-1201. https://doi.org/10.1016/j.energy.2006.09.001
Kerrick, D. M., & Caldeira, K. (1998). Metamorphic CO_2 degassing from orogenic belts. *Chemical Geology*, *145*(3-4), 213-232. https://doi.org/10.1016/S0009-2541(97)00144-7
Martin, M., Wenzel, F., & CALIXTO Working Group. (2006). High-resolution teleseismic body wave tomography beneath SE-Romania-II. Imaging of a slab detachment scenario. *Geophysical Journal International*, *164*(3), 579-595. https://doi.org/10.1111/j.1365-246X.2006.02884.x
Panaiotu, C. G., Jicha, B. R., Singer, B. S., Ţugui, A., Seghedi, I., Panaiotu, A. G., & Necula, C. (2013). 40Ar/39Ar chronology and paleomagnetism of Quaternary basaltic lavas from the Perşani Mountains (East Carpathians). *Physics of the Earth and Planetary Interiors*, *221*, 1-14. https://doi.org/10.1016/j.pepi.2013.06.007
Tondi, R., Achauer, U., Landes, M., Davi, R., & Besutiu, L. (2009). Unveiling seismic and density structure beneath the Vrancea seismogenic zone, Romania. *Journal of Geophysical Research: Solid Earth*, *114*(B11). https://doi.org/10.1029/2008JB005992
Vacareanu, R., & Ionescu, C. (Eds.). (2016). The 1940 Vrancea Earthquake. Issues, Insights and Lessons Learnt*:* Proceedings of the Symposium Commemorating 75 Years from November 10, 1940 Vrancea Earthquake. *Springer*. https://doi.org/10.1007/978-3-319-29844-3
Vaselli, O., Downes, H., Thirlwall, M., Dobosi, G., Coradossi, N., Seghedi, I., Szakács, A., & Vannucci, R. (1995). Ultramafic xenoliths in Plio-Pleistocene alkali basalts from the Eastern Transylvanian Basin: depleted mantle enriched by vein metasomatism. *Journal of Petrology*, *36*(1), 23-53. https://doi.org/10.1093/petrology/36.1.23

VI. Publications related to doctoral study

6.1 Papers published in peer-reviewed scientific journals

Lange, T. P., Szabó, C., Liptai, N., Patkó, L., Gelencsér, O., Aradi, L. E., & Kovács, I. J. (2019). A földköpeny reológiai kutatása: mennyiségi Fourier transzformációs infravörös spektrometria alkalmazása egy Persány hegységi xenolit példáján. *Földtani Közlöny*, *149*(3, 4), 233-233. https://doi.org/10.23928/foldt.kozl.2019.149.3.233 (In Hungarian with English abstract)

Lange, T. P., Pálos, Z., Pósfai, M., Berkesi, M., Pekker, P., Szabó, Á., Szabó, Cs., Kovács, I. J. (2023a). Nanoscale hydrous silicate melt inclusions at the clinopyroxene-amphibole interface in a mantle xenolith from the Perşani Mountains Volcanic Field. *Lithos*, 454, 107210. https://doi.org/10.1016/j.lithos.2023.107210

Lange, T. P., Palcsu, L., Szakács, A., Kővágó, Á., Gelencsér, O., Gál, Á., Gyila, S., M. Tóth, T., Matenco, L., Krézsek, Cs., Lenkey, L., Szabó, Cs., Kovács, I. J. (2023b). The link between lithospheric scale deformations and deep fluid emanations: Inferences from the Southeastern Carpathians, Romania. *Evolving Earth*, 1, 100013. https://doi.org/10.1016/j.eve.2023.100013

Kovács, I. J., Liptai, N., Koptev, A., Cloetingh, S. A., **Lange, T. P.**, Maţenco, L., Szakács, A., Radulian, M., Berkesi, M., Patkó, L., Molnár, G., Novák, A., Wesztergom, V., Szabó, Cs., & Fancsik, T. (2021). The 'pargasosphere' hypothesis: Looking at global plate tectonics from a new perspective. Global and Planetary Change, 204, 103547. https://doi.org/10.1016/j.gloplacha.2021.103547

Liptai, N., **Lange, T. P.**, Patkó, L., Pintér, Z., Berkesi, M., Aradi, L. E., Szabó, Cs., & Kovács, I. J. (2021). Effect of water on the rheology of the lithospheric mantle in young extensional basin systems as shown by xenoliths from the Carpathian-Pannonian region. *Global and planetary change*, *196*, 103364. https://doi.org/10.1016/j.gloplacha.2020.103364

Liptai, N., **Lange, T. P.**, Patkó, L., Aradi, L. E., Berkesi, M., Tollan, P. M., Padrón-Navarta, J. A., Hermann, J., Gergely, Sz., Szabó, Cs., & Kovács, I. J. (2024). Formation of amphibole lamellae in mantle pyroxene by fluid-mediated metasomatism: A focal plane array FTIR study from the Carpathian-Pannonian region. *American Mineralogist*, *109*(1), 87-102. https://doi.org/10.2138/am-2022-8662

6.2 Further publications

Kovács, I., Patkó, L., Liptai, N., **Lange, T. P.**, Taracsák, Z., Cloetingh, S. A. P. L., Török, K., Király, E., Karátson, D., Biró, T., Kiss, J., Pálos, Zs., Aradi, L. E., Falus, Gy., Hidas, K., Berkesi, M., Koptev, A., Novák, A., Wesztergom, V., Fancsik, T., & Szabó, C. (2020). The role of water and compression in the genesis of alkaline basalts: Inferences from the Carpathian-Pannonian region. Lithos, 354, 105323. https://doi.org/10.1016/j.lithos.2019.105323

Patkó, L., Novák, A., Klébesz, R., Liptai, N., **Lange, T. P.**, Molnár, G., Csontos, L., Wesztergom, V., Kovács, I. J., & Szabó, C. (2021). Effect of metasomatism on the electrical resistivity of the lithospheric mantle–An integrated research using magnetotelluric sounding and xenoliths beneath the Nógrád-Gömör Volcanic Field. Global and Planetary Change, 197, 103389. https://doi.org/10.1016/j.gloplacha.2020.103389

Spránitz, T., Váczi, B., **Lange, T. P.**, & Józsa, S. (2017). Dumortierites gneisz, klinohumitos márvány és szkapolitos amfibolit Dunavarsányban. *Földtani Közlöny*, 147(3), 311-326. https://doi.org/10.23928/foldt.kozl.2017.147.3.311 (In Hungarian with English abstract)

6.3 Selected conference abstracts

- **Lange T. P.** (2019). The role of pargasite in the Earth's rheology beneath the Perşani Mountains Volcanic Field. *The New National Excellence Programme Conference*. (In Hungarian)
- **Lange, T. P**., Liptai, N., Patkó, L, Aradi, L.E., Berkesi, M., Szabó, Cs., Kovács, I. J. (2019). A study on the physical properties of the lithospheric mantle based on upper mantle xenolith from the Perşani Mountains: the role of quantitative Fourier transform infrared spectroscopy, *14th Workshop of the International Lithosphere Program Task Force Sedimentary Basins conference abstract book*, 74-75.
- **Lange, T. P.**, Liptai, N., Patkó, L., Berkesi, M., Kesjár, D., Szabó, Cs., Kovács, I. J. (2019). Structural hydroxyl contents of nominally anhydrous minerals in peridotite xenoliths and their geophysical importance, Perşani Moutains Volcanic Field, Transylvania (Romania), *Golschmidt2019*.
- **Lange, T.P.**, Liptai, N., Patkó, L., Berkesi, M., Kesjár, D., Szabó, Cs., Kovács, I. J. (2019). Structural hydroxyl content of nominally anhydrous minerals and their relation to fluid inclusions in peridotite xenoliths (Perşani Mountains Volcanic Field, Transylvanian Basin, Romania), *European Current Research On Fluid and melt Inclusions*, Abstract book, 68.
- **Lange, T. P.**, Pálos, Zs., Szabó, Á., Aradi, L. E., Pekker, P., Szabó, Cs., Kovács, I. J. (2020). Nanoscale amphibole formation in the lithospheric mantle beneath the Perşani Mountains Volcanic Field, *15th Winter School in Mineral Sciences, Veszprém.* (In Hungarian)
- **Lange, T.P.**, Pálos, Zs., Berkesi, M., Molnár, G., Pósfai, M., Pekker, P., Szabó, C., Kovács, I. J. (2021). Dislocation controlled amphibole growth in the earth's lithospheric mantle, Perşani Mountains Volcanic Field (Transylvania, Romania). *11th Assembly of Petrology and Geochemistry*, Abstract book, Sopron, p. 31. (In Hungarian)
- **Lange, T. P.**, Pálos, Zs., Berkesi, M., Molnár, G., Pósfai, M., Pekker, P., Szabó, C., Kovács, I. J. (2021). *Dislocation channels at the clinopyroxene-amphibole boundary, Perşani Mountains Volcanic Field (Transylvania, Romania), 3rd European Mineralogical Conference*, Abstract book, p. 223.
- **Lange, T. P.**, Berkesi, M., Pálos, Zs., Pósfai, M., Pekker, P., Szabó, C., Kovács, I. J. (2022). Nanoscale fluid-solid interaction in the Earth's lithosphere, *17th Winter School in Mineral Sciences*.
- **Lange T. P.** (2022). The role of the gas emanation in Covasna and geological implication. *The New National Excellence Programme Conference*. (In Hungarian)
- **Lange, T. P.,** Pálos, Zs., Berkesi, M., Pósfai, M., Molnár, G., Pekker, P., Szabó, Cs., Kovács, I. J. (2022). Dislocation channels at the clinopyroxene-amphibole boundary: a TEM study. *23rd International Mineralogical Association General Meeting*, Abstract book, p. 330.
- **Lange, T. P.**, Palcsu, L., Szakács, A., Kővágó, Á., Gelencsér, O., Gál, Á., Gyila, S., M. Tóth, T., Maţenco L., Krézsek, Cs., Lenkey, L., Szabó, Cs., Kovács, I. J. (2022). Deep CO_2 gas emanation linked to lithospheric scale deformations in the Southeastern Carpathians. *6th Workshop of the International Lithosphere Program Task Force Sedimentary Basins & 7th Geoscience Symposium*.

- **Lange, T. P.**, Palcsu, L., Szakács, A., Kővágó, Á., Gelencsér, O., Gál, Á., Gyila, S., Szabó, Cs., Kovács, I. J. (2022). Determining the origin of the CO_2 gases in the Covasna area. *23rd Mining, Metallurgy and Geology Conference*. (In Hungarian).
- **Lange, T. P.**, Pálos, Zs., Berkesi, M., Pósfai, M., Molnár, G., Pekker, P., Szabó, Cs., Kovács, I. J. (2022). Nanoscale amphibole formation and growth in the lithospheric mantle, *4th Earth Mantle Workshop*, abstract book.
- **Lange, T. P.**, Palcsu, L., Szakács, A., Kővágó, Á., Gelencsér, O., Gál, Á., Gyila, S., M. Tóth, T., Mațenco, L., Krézsek, Cs., Lenkey, L., Szabó, Cs, Kovács, I. J. (2022). Deep CO_2 degassing in a tectonically active region at the boundary of the Transylvanian Basin and the South-Eastern Carpathians. *in Cristian Arion, Alexandra Scupin, Alexandru Țigănescu (Editors) Proceedings of the 3rd European Conference on Earthquake Engineering and Seismology, September 4-9, Bucharest*.
- **Lange, T. P.**, Palcsu, L., Szakács, A., Kővágó, Á., Gelencsér, O., Gál, Á., Gyila, S., M. Tóth, T., Mațenco, L., Krézsek, Cs., Lenkey, L., Szabó, Cs, Kovács, I. J. (2023). The link between deep fluids and surface gas emanation in the Southeastern Carpathians, *19th meeting of the Central European Tectonic Studeis Group (CETeG)*, 53.
- **Lange, T. P.**, Pálos, Zs., Berkesi, M., Pekker, P., Szabó, Á., Szabó, Cs., Kovács, I. J. (2023). Hydrous nano-silicate melt inclusions revealed by transmission electron microscopy, Persani Mountains Volcanic Field. *European Current Research on Fluid and Melt Inclusions*, 27.
- **Lange, T. P.**, Pálos, Zs., Berkesi, M., Pekker, P., Szabó, Á., Szabó, Cs., Kovács, I. J. (2023). Hydrous nano-silicate melt inclusions in the lithospheric mantle, Persani Mountains Volcanic Field (Transylvania). *Goldschmidt2023*.
- **Lange, T. P.**, Pálos, Z., Berkesi, M., Pekker, P., Szabó, Á., Szabó, C., & Kovács, I. J. (2024). Hydrous nano-silicate melt inclusions supports amphibole growth, Persani Mountains Volcanic Field (Transylvania), *EGU24-19855*.