



Long story encrypted in a small grain – zircon from meta-andesite in the Lower Köli Nappes reveals a complex history of the Virisen Arc Terrane, Scandinavian Caledonides, Sweden

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Abstract

This short report presents the investigation results on the zircon from meta-andesitic rock from the Ankarede Volcanite Formation of the Lower Köli Nappe Complex in Scandinavian Caledonides. Previous U-Pb dating revealed a wide span of dates ranging from ca. 520 to ca. 480 Ma, with a mean age of 491 ± 3 Ma for the zircon cores. Using cathodoluminescence and back-scattered electron imaging, along with chemical mapping, we identified distinct zones within the zircon grains; 1) cores of clear magmatic provenance, 2) mantles also of magmatic origin but with a slightly different chemical composition and 3) zircon rims that suffered metamictisation and fluid-induced alterations. These findings highlight a complex growth history and alteration of studied zircon that affect the interpretation of zircon dating results. This research underscores the importance of detailed zircon studies for understanding the intricate processes involved in the magmatic and metamorphic evolution of Virisen terrain in Scandinavian Caledonides.

Keywords: zircon chemistry, hydrothermal alterations, meta-igneous rock, Virisen Arc, Iapetus

1. Introduction

The Köli Nappe Complex (KNC) is a sequence of nappes derived from oceanic island arcs and their associated sedimentary basins, originating within the Iapetus Ocean. The lowest part of the Köli Nappe Complex, called the Virisen arc terrane in the tectonostratigraphic terrane scheme of Stephens and Gee (1985, 1989), is interpreted as the remnants of an ensimatic island arc (i.e., volcanic island arc system built on oceanic crust) outboard of the continent Baltica. It has also been suggested that the Virisen terrane was the island arc that collided with the Baltica margin (today the Svecofennian Complex; SNC) leading to its subduction beneath the arc

and subsequent UHP metamorphism (Andreasson and Albrecht, 1995). In previous years a lot of attention has been paid to understanding metamorphism in SNC (e.g. Root and Corfu, 2012; Klonowska et al., 2017; Barnes et al., 2019; Walczak et al., 2022), but yet the details of the origin of the Virisen arc rocks are still not well understood. Recently, more consideration has been given to previously understudied topics of the timing and nature of magmatism in lower KNC (e.g. Greiling and Grimmer, 2007; Grimmer and Greiling, 2012; Stephens, 2020; Carter et al., 2023). Igneous rocks within the lower Köli Ankarede Volcanite Formation (AVF) have been dated by U-Pb zircon at 512 ± 3.5 Ma and ca. 488-497 Ma (Claesson et al., 1983; Carter et al.,

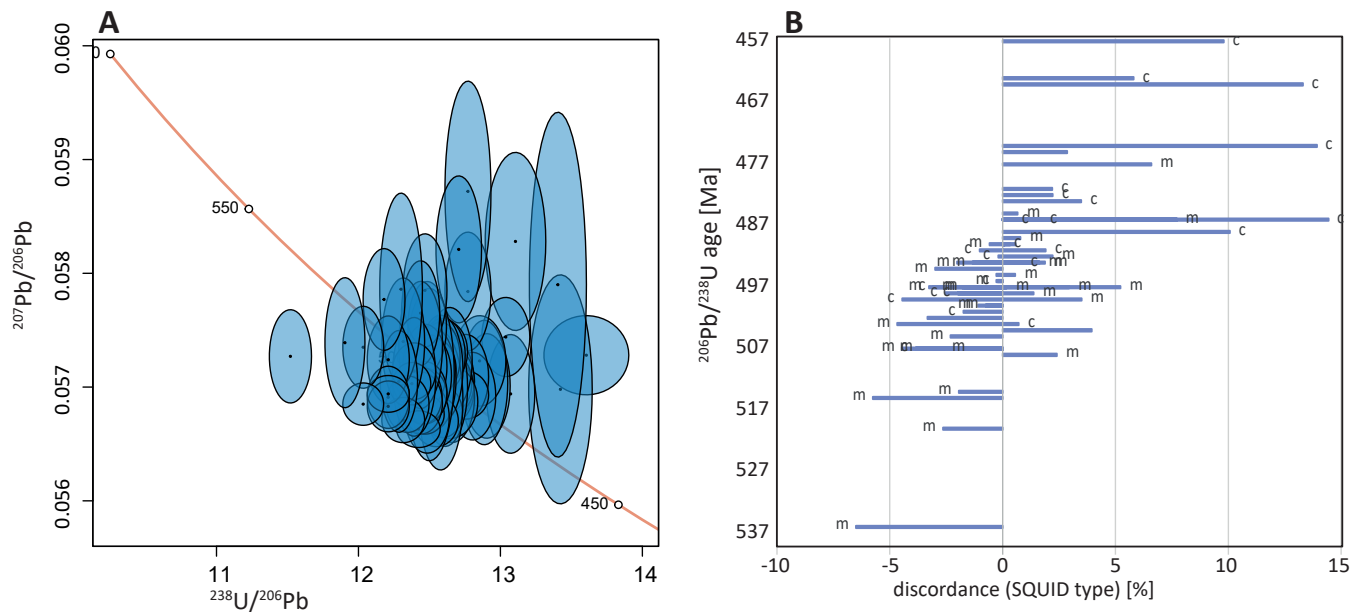


Figure 1. A) The whole U-Pb data set from Carter et al. 2023 (no selection) plotted on the Tera-Wasserburg concordia diagram. B) Zircon $^{206}\text{Pb}/^{238}\text{U}$ ages (Carter et al., 2023) versus their discordance ($\text{Disc} [\%] = (^{207}\text{Pb}/^{206}\text{Pb} \text{ age} - ^{206}\text{Pb}/^{238}\text{U} \text{ age}) \cdot (^{206}\text{Pb}/^{238}\text{U} \text{ age})^{-1} \cdot 100$), analyses placed in mantles (m) and cores (c).

2023;). However, zircon from one of the studied samples (Carter et al., 2023), the andesite from Gränssjö area, gave a wide range of U-Pb dates, from 520 ± 5 to 476 ± 5 Ma. Interestingly, zircon cores define a coherent cluster with a concordia age of 491 ± 3 Ma. At the same time, the oldest obtained dates are mostly related to zircon mantles (Fig. 1). The presence of older ages in zircon is not uncommon and such older ages are usually interpreted as elements inherited from earlier geological events. However, in this case, these oldest ages were found mainly in mantles, zones surrounding the innermost domains (cores) dated by Carter et al. (2023) to 491 ± 3 Ma. Moreover, the oldest ages are also reversely discordant (Fig. 1.A, B). The calculated values of the reverse discordance usually do not exceed -5 and are therefore not large, but their presence is puzzling. The situation in which younger cores are surrounded by older overgrowth seems illogical and geologically impossible. Hence, our work focused on explaining this phenomenon.

2. Samples and methods

2.1. Geological background and studied sample

The sample which is the focus of this study belongs to the Ankarede Volcanite Formation (AVF) of the Björkvattnet Nappe, the lowermost nappe unit of the KNC in the north Jämtland and Västerbotten region (e.g. Kulling, 1933; Sjöstrand, 1978; Stephens, 1982, 2001). The stratigraphically lowest strata of the Björkvattnet Nappe in the study area comprise a unit of mica schists and phyllites with local conglomerates and detrital serpentinites (Seima Fm.). The AVF overlies this and is composed of a predominantly acidic to intermediate metavolcanic rocks with subordinate metabasalts and interlayers of tuffitic phyllites. Coarser-grained varieties of metatonalite and metadiorite may have been subvolcanic intrusions (Claesson et al., 1983).

Trace element and geochemical compositions of the metavolcanites support an intra-oceanic island arc origin (Grimmer and Greiling, 2012). Magmatic rocks within the AVF have been dated by U-Pb zircon at 512 ± 3.5 Ma and ca. 488–497 Ma (Carter et al., 2023; Claesson et al., 1983). Stratigraphically above the AVF lies a metasedimentary flysch sequence of metagreywackes, phyllites and conglomerates capped by a probable Hirnantian-Llandovery quartzite-carbonate sequence with metabasalt. The Björkvattnet Nappe has experienced metamorphism at greenschist to lower amphibolite facies, as well as extensive pre-metamorphic sodium metasomatism; the reaction between felsic to intermediate volcanic rocks and seawater, under hydrothermal conditions, lead to the formation of quartz-keratophyres and spilites (Sjöstrand, 1978). Such metasomatic enrichments in Si and Na, probably related to ocean floor hydrothermal action, have been described in the similar Stekenjokk Quartz Keratophyre Formation in the structurally overlying Stikke Nappe (Middle Köli Nappes; Stephens, 1980, 1982). For a more detailed description of the tectonostratigraphy of the Köli Nappe Complex within the Västerbotten and North Jämtland region the reader is referred to Carter et al. (2023).

The studied meta-andesite sample (KW19-11B) belongs to the Ankarede Volcanite Formation. It was collected from the bank of a small stream near Gränssjö (65.422167° N 14.806194° E; for outcrop pictures see supplementary file in Carter et al. 2023: <https://doi.org/10.6084/m9.figshare.24168232.v1>) on the eastern limb of the Western Synform (Supplement S1). The rock is generally fine-grained and has a weak foliation defined by the alignment of white mica, chlorite and quartz laminae. Although chemical analysis indicates that the rock was originally an andesite (Carter et al., 2023), only relics of the original plagioclase can now be observed. Moreover, the rock comprises quartz

and secondary minerals such as zoisite, albite, epidote and chlorite resulting from the breakdown of primary plagioclase and amphibole. The titanium minerals are represented by ilmenite which is partly altered into titanite. Accessory minerals are zircon and apatite. The sample has been a subject of studies by Carter et al. (2023), therefore, we encourage interested readers to see the detailed petrographic and geochemical study of the sample in that publications. U-Pb dates (LA-ICP-MS) for zircon in this sample range from 520 ± 5 to 476 ± 5 Ma, with a coherent cluster for zircon cores, giving a mean age of 491 ± 3 Ma (Carter et al., 2023).

2.2. Analytical methods

For the study we used the same zircon mount used by Carter et al. 2023. Cathodoluminescence (CL) images of mounted grains were obtained using a Scanning Electron Microscope at AGH University of Krakow, Poland. Back-scattered electron (BSE) images, chemical mapping and chemical composition measurements of zircon were performed using a Jeol Superprobe 8230 electron microprobe at the Faculty of Geology, Geophysics and Environment Protection, AGH University of Krakow. Chemical mapping for Y, U, Hf, Si, Zr, and Al ($\pm$ P) has been performed. Si, Al and P maps have been used to locate the presence of inclusions in zircon. The operating conditions for zircon chemical maps were: acceleration voltage of 15 kV, probe current of 100 nA and dwell time of 0.1s. Final versions of chemical maps were prepared using XMapTools 4.1 (Lanari et al., 2014; 2019; 2023). The operating conditions for zircon chemical profiles were: acceleration voltage of 15 kV, probe current of 20 nA, counting times were 20 s on peaks and 10 s on background positions.

3. Results

3.1. Zircon morphology and internal structure

Zircon grains are mostly elongated and prismatic (up to 300 μ m long) with simple pyramids {101}, though some are fractured. Most grains are clear, lustrous and occasionally contain a small number of inclusions. Backscattered electron (BSE) images of studied zircon grains reveal an inner, apparently homogeneous interior surrounded by discontinuous, porous rims (Fig. 2). A faint oscillatory zonation is apparent in some of the grains. Zircon may contain inclusions of relatively large apatite (up to 10 μ m long) and tiny epidote, albite and quartz. Cathodoluminescence images reveal a more complex internal structure (Fig. 3). The apparently homogeneous inner part of the zircon can be divided into two zones separated by a very thin and high CL emission band. The most internal zones, the cores, display oscillatory zoning (e.g. Fig. 3A,I,J), however, some rare cores show chaotic zoning, usually with very low CL emission (Fig. 3H). Most of the cores have distinct, prismatic shapes with no obvious evidence of erosion or dissolution. Outside the cores, a second, more prominent zone (mantle) can be observed. These also display pronounced oscillatory zoning in CL, sometimes accompanied by sector zoning

(e.g. Fig. 3F,G). These internal zones can be observed in most of the zircons studied, but not all of them (Fig. 3C,D,L). This may be due to the intersection of the zircon not extending to its centre, or perhaps in some grains such zonation is not present. In some of crystals, zones of alteration can be observed developing within these parts of zircons, most likely along older cracks or other zones of discontinuity (Fig. 2E). The outermost, porous zones (rim) are present only in about 20% of documented crystals (Fig. 3A,C,D,E,G,L). The thickness of the rim reaches up to 20 μ m. These zones are characterised by patchy zoning and usually display low CL emission. The pores are typically filled with mineral inclusions such as chlorite, titanite, quartz and scarce thorite (Fig. 2).

3.2. Zircon chemical mapping

Complex zonation observed in CL images is also reflected in the distribution of trace elements in zircon (Fig. 4, Supplement S2), with the most pronounced zoning in Y. The cores, when present, can be clearly distinguished by their relatively higher Y concentration. The boundary between core and mantle, marked by a high CL emission band, corresponds to a rapid decrease in Y concentration. The mantle zones have relatively lower Y content, yet a high-Y band is present near the boundary with the porous rim. Y concentration drops again in the rims. On the other hand, Hf distribution does not display any zoning in the internal zones of zircon (i.e. in the cores and mantles) but shows elevated values in the porous rims. Uranium content, although very low in whole zircon, displays slightly higher levels in the rims. However, a detailed analysis of the U distribution shows that elevated U levels are present not only in the porous rims but often also along the edges of unaltered zircon (e.g. Fig. 4B).

4. Interpretation and discussion

4.1. Stages of zircon growth

Normalised REE diagrams presented by Carter et al. (2023; SupplementaryTableS6; <https://doi.org/10.6084/m9.figshare.24168223.v1>) show no obvious differences between cores and mantles. However, when considered in detail in connection with the CL and BSE images some of the cores display slightly higher heavy rare earth element (HREE) concentrations (Supplement S3). Likewise, chemical maps display higher Y content in the cores. Yttrium and HREE, due to their identical valency and similar cation radii, behave similarly in zircon, thus they mimic each other's behaviour (e.g. Zhang et al., 2019). Therefore, it can be concluded that the core zones of the zircons were enriched in Y and HREE simultaneously. Cathodoluminescence oscillatory zoning present in the cores clearly indicates their magmatic origin. The mantle zones also display prominent oscillatory zoning, thus mantles have also crystallized from a melt. However, mantles differ from the cores in their chemical composition as they have noticeably lower Y concentrations. Notably, the

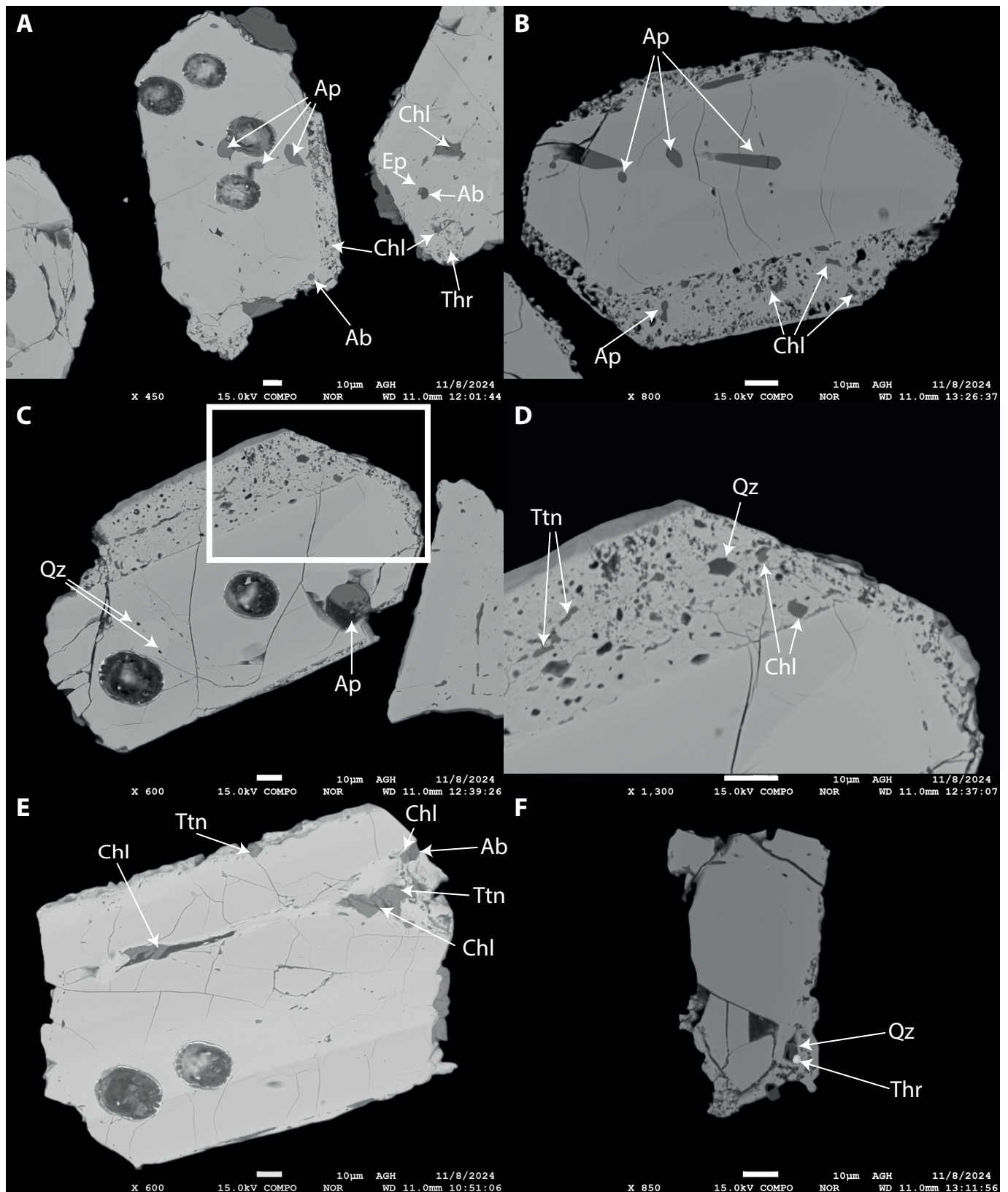


Figure 2. Backscattered electron (BSE) images of studied zircon grains with visible inclusions of apatite (Ap), epidote (Ep), chlorite (Chl), albite (Ab), quartz (Qz), titanite (Ttn) and thorite (Thr). Image D represents magnified fragment from the frame on picture C. The white scale bars are 10 µm.

boundaries between these zones are usually very sharp, with no signs of core dissolution or abrasion. This indicates continuous crystallization between cores and mantles. However, the difference in their chemistry must reflect a change in crystallisation conditions. Similar Ce and Eu anomalies in both zones indicate that the magma oxidation state did not change during

the transition, thus, two scenarios are possible. The change in zircon chemistry could reflect the beginning of mass crystallisation of other minerals competing for Y and HREE, most likely amphibole, but other Y-bearing minerals like apatite or titanite also may be considered (Schaltegger and Davies, 2017 and references therein). Alternatively, the change in zircon chemistry could

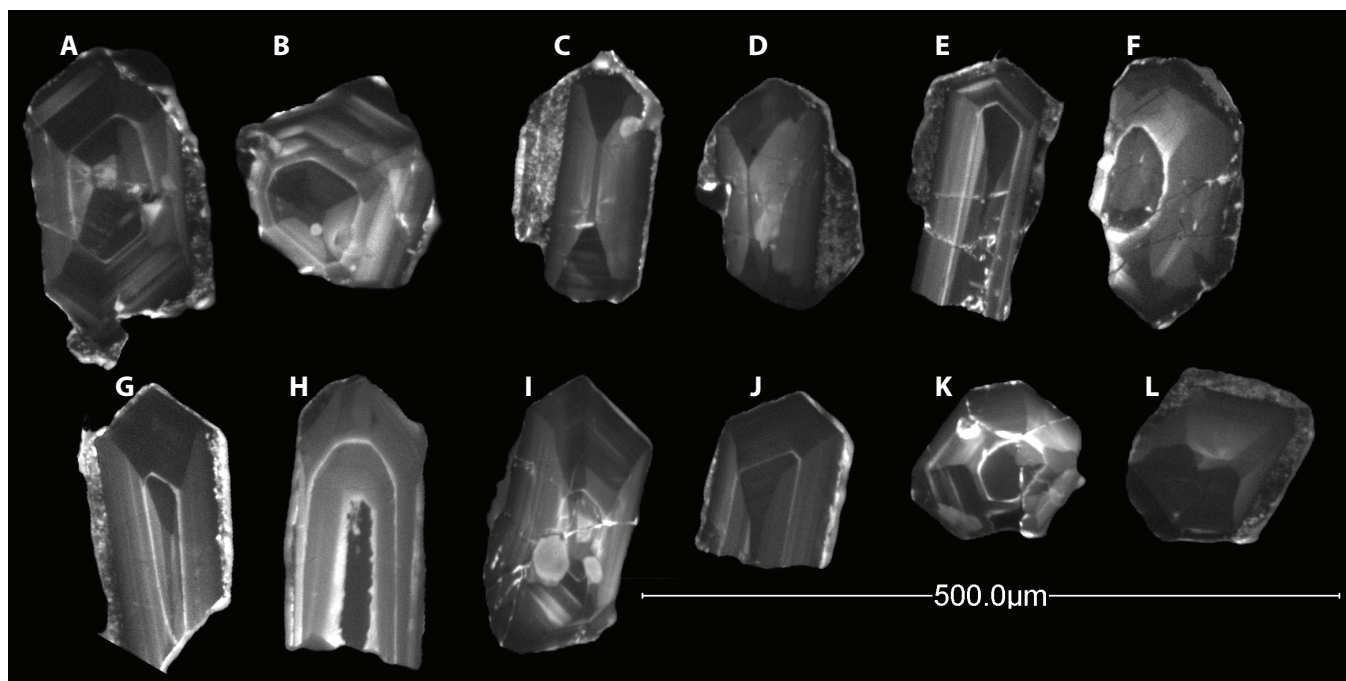


Figure 3. Representative cathodoluminescence (CL) images of analysed zircon grains showing variability of zircon internal structures.

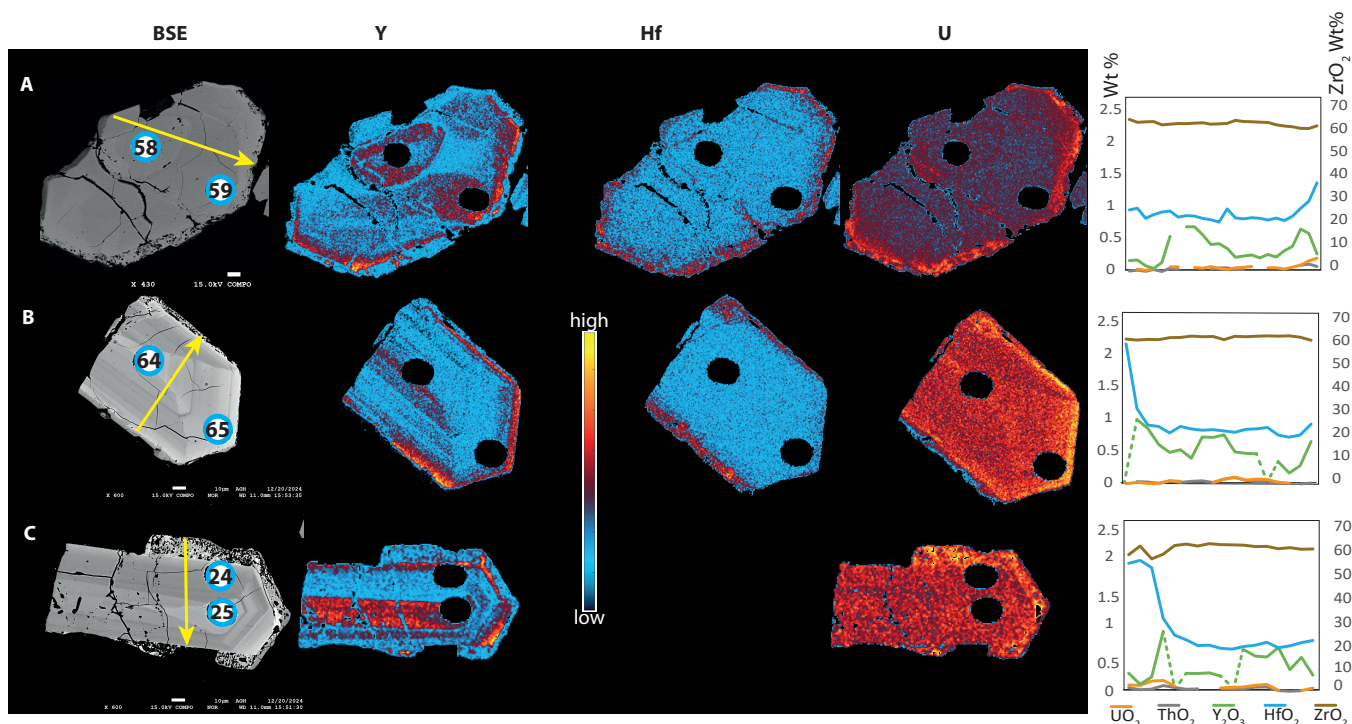


Figure 4. Backscattered electron (BSE) images, Y, Hf and U distribution maps and concentration profiles for representative zircon grains. Yellow arrows indicate the course of the profile. Blue circles represent U-Pb analytical points from Carter et al. (2023). The coloured scale bar: warmer colours indicate higher relative abundance of element (higher signal intensity). In Fig. 3 you can find CL images of the analysed crystals: A = Fig. 3.F, B = Fig. 3.J, C = Fig. 3.E.

follow a change in magma chemistry due to the mingling of different magma batches (Schaltegger and Davies, 2017 and references therein). Such changes may be very rapid; Wotzlaw et al. (2014; 2015) suggested that merging smaller, compositionally different, magma reservoirs into bigger ones may be as quick as $10^2 - 10^3$ years, so the age difference may not be recognised with most common dating methods. Our field observations of the AVF suggest evidence for at least localised mingling of acid and mafic magmas. For example at Ankarede, about 70 km south of Gränssjö, where metabasalts and

meta-andesites are more common in the AVF, metabasic greenstones have streaky appearance with numerous, distinct, leucocratic felsic domains (Fig. 5). The observed alteration of zircon rims and some internal zircon parts can be linked with high U and Hf concentration in those zones. Zircon is a very durable mineral and can survive even during high-grade metamorphic conditions, so it is not likely that fully crystalline zircon would become altered in low-grade metamorphic conditions (Rubatto, 2017 and references therein). However, high U zircon may suffer from radiation damage (metamictisation);

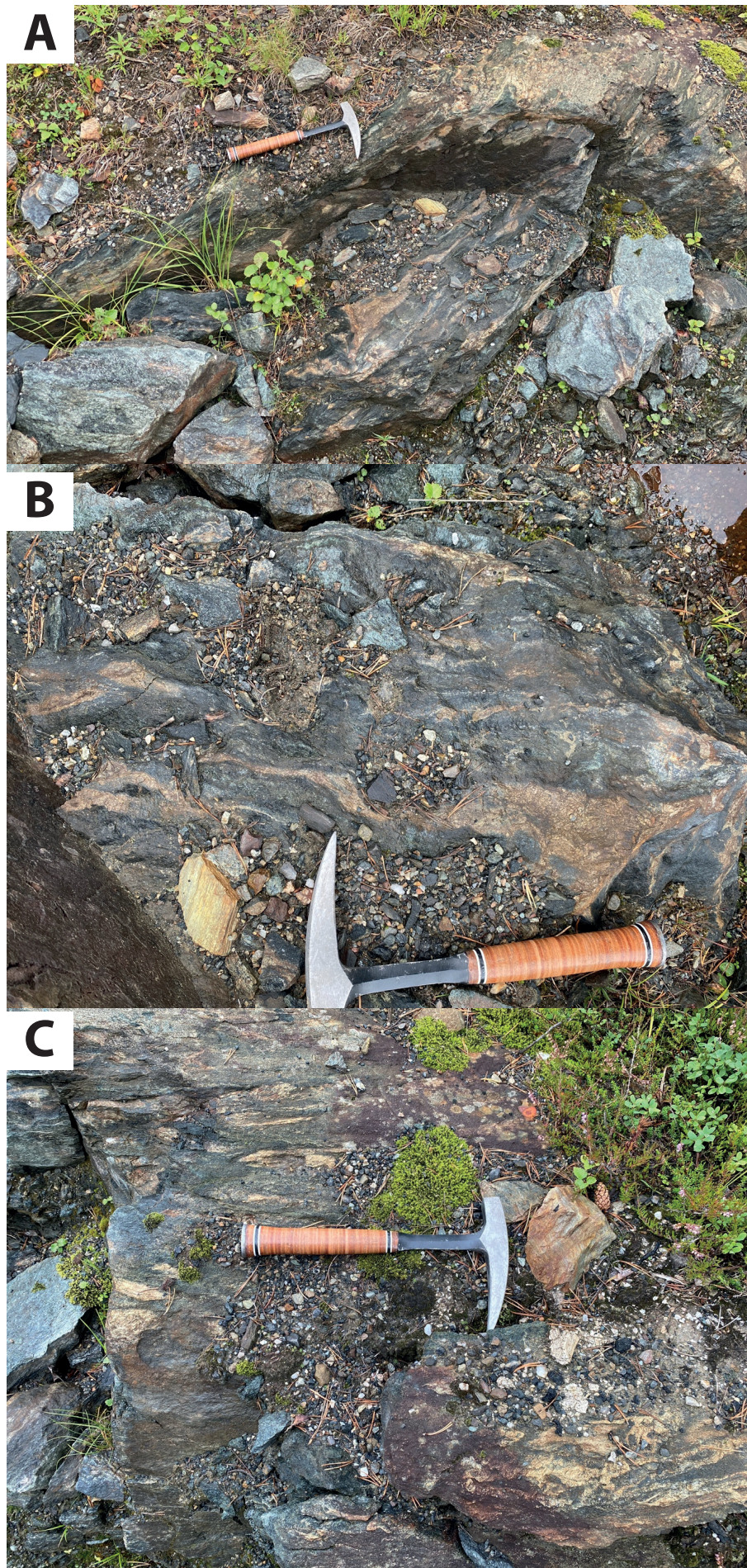


Figure 5. Examples of amphibolite-felsite mingling observed in the Ankarede Volcanite Formation of the Lower Köli Nappe Complex close to Ankarede (64.81717616° N, 14.21804096° E). The field photographs show mingled amphibolite-felsite (A), a close-up of mingled amphibolite-felsite (B) and mingled rock viewed perpendicular to a lineation - stretching direction (C).

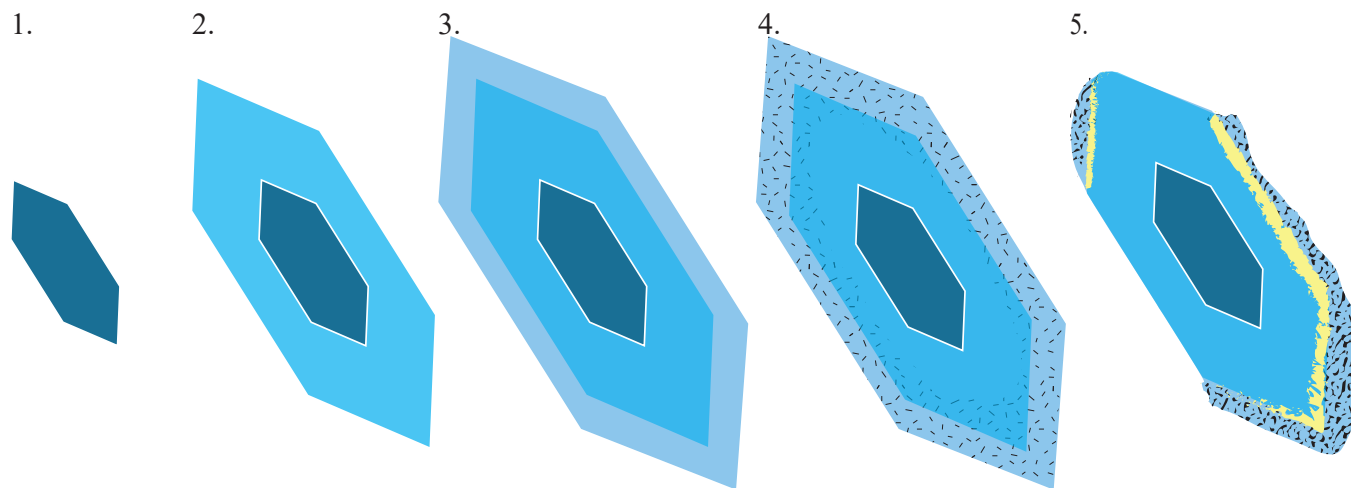


Figure 6. The summary of zircon growth history: 1. High Y and HREE magmatic zircon growth (the cores; dark navy blue). 2. The abrupt change in magma chemistry due to magma mingling or the crystallisation of other minerals competing for Y and HREE. Further growth of low-Y zircon (the mantles; blue). 3. Formation of high-U rims (grey-blue). 4. The high-U rims and adjacent zones accumulate radioactive damage, their internal structure is partially damaged and pathways for fluid infiltration are created. 5. Hydrothermal fluid infiltrate metamict zones causing alterations; dissolution of zircon rim and precipitation of new, porous zircon rims. High U concentration is inherited by the newborn zircon. Yttrium is resorbed into a non-altered zircon forming a high-Y band (yellow).

the internal structure of zircon is destroyed and thus creates pathways for hydrothermal fluids to infiltrate and alter damaged zircon. Low CL emission of these zones would also suggest lower degree of crystallinity of the rims (e.g. Nasdala et al., 2003 and references therein). It is considered that metamict zircon is a few times more susceptible to dissolution in the presence of hydrothermal fluids than zircon with no apparent radioactive damage (Ewing et al., 2003; Delattre et al., 2007). The studied rocks underwent sea floor metamorphism and subsequent low-grade (greenschist facies) metamorphism (Sjöstrand, 1978; Stephens et al., 1985), so pre-existing metamict zones were likely altered by related hydrothermal action. A new zircon would have grown during the dissolution-reprecipitation process (e.g. Geisler et al., 2007). Newly crystallised zircon would have had a high U concentration inherited from its predecessor. EMP results shows slightly lower values of Zr but higher values of Hf in the porous rims (Supplement S2), elevated Hf content at the rims can also be seen on Hf distribution maps. Such a feature is commonly observed in hydrothermal zircon (e.g. Ersay et al., 2022). However, the porous zones have a low Y content, which is consistent with the observations of Geisler et al. (2007), who noticed that domains altered by the dissolution–reprecipitation process tend to have a low trace element content. Furthermore, Huijsmans et al. (2022) confirmed that Y depletion results from the mechanisms of this zircon recrystallization process. We conclude that Y from dissolved zircon was resorbed into non-metamict zircon (back-diffusion), to form a thin, high-Y band at the boundary between the mantle and porous rim. Similar alterations, producing porous zircon at the expense of high U zircon were observed in zircon grains from different types of hydrothermally altered rocks by Corfu et al. (2003), Hay and Dempster (2009) and Hay et al. (2010). These authors also noticed that altered zircon grains were characterised by abundant cavities and nano-crystalline structure. Thus, like the cited authors, we believe that altered rims preserve a

complex low-temperature hydrothermal fluids induced growth history.

Figure 6 provides a summary of the growth history of the studied zircon.

4.2. Possible explanation of the older U-Pb dates in zircon mantles

Carter et al. (2023) provided U-Pb LA-ICPMS mean age of 491 ± 3 Ma for zircon cores, for the mantles most of the obtained dates are similar to the age of the cores but noticeably older dates, reaching up to ca 520 Ma, are also present. As described in the previous paragraph, the cores show no evidence of alterations, thus the age of the mantles should be the same as that of the cores. Williams et al. (1984) suggested that an anomalously old U-Pb age obtained by the SHRIMP method may be attributed to the presence of discrete zones within zircon crystals that may contain excess radiogenic Pb as a consequence of radiogenic Pb gain rather than U and Th loss. The idea of Pb mobilization and redistribution on a short scale distance within zircon crystal was supported by recent studies (Kusiak et al., 2013, 2015; Lyon et al., 2019; Ge et al., 2019) which described nano-scale Pb-enriched domains and their effects on zircon U-Pb spatial resolution geochronology i.e., laser ablation ICPMS or ion microprobe. However, all studies that present evidence for radiogenic Pb redistribution in zircon concern grains from high-temperature metamorphic rocks. Apart from these examples, Pb is generally considered to be an immobile element in zircon, except when the internal structure of zircon is partly damaged by radiation (metamictisation) or fractures. Metamict zircon becomes vulnerable to alterations even in relatively low-temperature hydrothermal conditions. The studied zircon had high-U metamict rims which were dissolved. It is possible that the adjacent zircon mantles also suffered from radiation damage, developing slight damage to the crystal lattice which would enable radiogenic Pb redistribution. Moreover, Pb mobility in low T fluids increases with fluids

salinity enabling the formation of Pb and Cl complexes (Barnes and Liu, 2012; Brugger et al., 2016). Thus, during sea floor hydrothermal activity radiogenic Pb from metamict rims might have been redistributed and formed localised accumulations in the mantles, affecting their U-Pb systematics. This thesis is also supported by the fact that most of the older ages in mantles are slightly, but yet reversely, discordant (Fig. 1). The zircon cores remained intact sheltered from both radiation and hydrothermal fluids by the mantles. We, therefore, suggest that both, zircon cores and mantles formed around 491 Ma and that this age corresponds to bimodal magmatism in the Virisen arc, while the much older (>500 Ma) dates appearing in the mantles have no distinct geological significance.

5. Significance for the evolution of Virisen terrain and direction for future research

The AVF represents the construction of an intra-oceanic arc within the Iapetus Ocean during the Cambrian and early Ordovician, indicating the early stages of closure of this ocean basin. Emerging geochronological evidence (e.g. Carter et al., 2023) indicates that this arc may have initiated only 80–90 Ma after this ocean opened, supporting previous suggestions (e.g. Waldron et al., 2014) that the expansion stage of Iapetus was remarkably short-lived. The arc edifice is now incorporated within the structurally lowest elements of the Köli Nappe Complex, which was equated to the “Virisen terrane” in the tectonostratigraphic terrane scheme of Stephens and Gee (1985, 1989). This terrane now rests with a thrust contact upon the Seve Nappe Complex, which represents the hyper-extended margin of Baltica. Collision of the Virisen arc terrane, and possibly other Iapetus terranes, with Baltica is likely to have caused the early Ordovician ultra-high pressure metamorphism in parts of the Seve Nappe Complex. This arc terrane, therefore, represents a substantial juvenile addition, by tectonic accretion, to the Fennoscandian craton of Baltica. Accretion of this terrane to Baltica and its incorporation into the Caledonide orogenic wedge led to intense deformation and regional metamorphism that has largely destroyed the primary magmatic and volcanogenic features of the arc edifice.

The outcomes of the present study suggest two important aspects of the magmatic and post-magmatic evolution of the Virisen intra-oceanic arc terrane and emphasise the significance of detailed zircon studies in elucidating them. First, the zircons record a substantial change in chemical, or physicochemical conditions in the magma system, either due to the appearance of new crystallising phases or injection of a new (mafic?) magma batch. Either of these processes may have influenced the magma volatile budget and could have acted as eruption triggers (see, e.g. Edmonds et al., 2010; Morgavi et al., 2017). Secondly, microstructures and associated chemical zoning in zircon suggest their modification by hydrothermal action, which is consistent with the chemical modification of the AVF volcanites (and the similar Stekenjokk metavolcanites of the overlying Stikke Nappe) by hydrothermal action

to generate spilite and keratophyre (Stephens, 1980). Na-metasomatism can be important for the generation of metalliferous ore deposits, for example copper as at Stekenjokk (Stephens, 1980). Direct evidence for both magmatic and hydrothermal processes has been largely obliterated by deformation and metamorphism, but in our opinion evidence has survived in the chemical and physical characteristics of the robust zircon grains, at least at the studied location. Hence, we propose that studies of zircon chemical zoning and microstructures yield information about the evolution of the Virisen Arc magmatic and hydrothermal systems, and are likely to give novel insights into critical metal prospectivity. Modelling of zircon compositional evolution in arc magmas and seeking analogues for zircon behaviour in modern intra-oceanic arc volcanoes will help to gain more detailed insights into these profoundly remodelled, ancient arc rocks.

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Data availability

The raw data related to this article is available online: <https://doi.org/10.58032/AGH/SH09G2>

Competing Interests

The authors declare no competing interests.

Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.2478/mipo-2025-0005>.

Supplementary materials

Supplement S1. Tectonostratigraphic map of the Scandinavian Caledonides (modified after Gee et al., 1985). Inset map shows simplified geological map of northern Jämtland and southern Västerbotten (modified after Carter et al., 2023).

Supplement S2. EMP chemical analyses of zircon (profiles).

Supplement S3. A) The juxtaposition of ages of zircon cores and mantles in the studied sample. B) REE concentration in zircon apparent cores and mantles (normalised to chondrites; King et al., 2020). All data from Carter et al., 2023.

References

- Barnes, S.J., Liu, W., 2012. Pt and Pd mobility in hydrothermal fluids: Evidence from komatiites and from thermodynamic modelling. *Ore Geology Reviews*, 44, 49–58. <https://doi.org/10.1016/j.oregeorev.2011.08.004>

- Barnes, C.J., Majka, J., Schneider, D., Walczak, K., Bułafa, M., Kościńska, K., Tokarski, T., Karlsson A., 2019. High-spatial resolution dating of monazite and zircon reveals the timing of subduction–exhumation of the Vaimok Lens in the Seve Nappe Complex (Scandinavian Caledonides). *Contributions to Mineralogy and Petrology*, 174, 0. <https://doi.org/10.1007/s00410-018-1539-1>
- Brugger, J., Liu, W., Etschmann, B., Mei, Y., Sherman, D.M., Testemale, D., 2016. A review of the coordination chemistry of hydrothermal systems, or do coordination changes make ore deposits? *Chemical Geology*, 447, 219–253. <https://doi.org/10.1016/j.chemgeo.2016.10.021>
- Carter, I.S.M., Cuthbert, S.J., Walczak, K., Ziemniak, G., Kooijman, E., Majka, J., 2023. Cambrian ages for metavolcanites in the Lower Köli Nappes, Swedish Caledonides: Implications for the status of the Virisen arc terrane. *Journal of the Geological Society*, 180 (6): jgs2022–130. <https://doi.org/10.1144/jgs2022-130>
- Claesson, S., Klingspor, I., Stephens, M.B. 1983. U-Pb and Rb-Sr isotopic data on an Ordovician volcanic-subvolcanic complex from the Tjopasi group, Köli Nappes, Swedish Caledonides. *Geologiska Föreningen i Stockholm Förhandlingar*, 105, 9–15. <https://doi.org/10.1080/11035898309455285>
- Corfu, F., Hanchar, J.M., Hoskin, P.W.O., Kinny, P., 2003. Atlas of Zircon Textures, in: Hanchar, J.M., Hoskin, P.W.O. (Eds.), *Zircon*. Mineralogical Society of America and Geochemical Society, Washington, DC, United States, pp. 469–500. <https://doi.org/10.2113/0530469>
- Delattre, S., Utsunomiya, S., Ewing, R.C., Boeglin, J.-L., Braun, J.-J., Balan, E., Calas, G., 2007. Dissolution of radiation-damaged zircon in lateritic soils. *American Mineralogist*, 92 (11), 1978–1989. <https://doi.org/10.2138/am.2007.2514>
- Edmonds, M., Aiuppa, A., Humphreys, M., Moretti, R., Giudice, G., Martin, R.S., Herd, R.A., Christopher, T., 2010. Excess volatiles supplied by mingling of mafic magma at an andesite arc volcano. *Geochemistry, Geophysics, Geosystems*, 11, Q04005. <https://doi.org/10.1029/2009GC002781>
- Ewing, R.C., Meldrum, A., Wang, L.M., Weber, W.J., Corrales, L.R., 2003. Radiation effects in zircon. In: Hanchar, H. M. & Hoskin, P. W. O. (eds) *Zircon*. Mineralogical Society of America, Reviews in Mineralogy and Geochemistry, 53, 387–420. <https://doi.org/10.2113/0530387>
- Ersay, L., Greenough, J.D., Larson, K.P., Dostal, J., 2022. Zircon reveals multistage, magmatic and hydrothermal Rare Earth Element mineralization at Debert Lake, Nova Scotia, Canada, *Ore Geology Reviews*, 144, 104780. <https://doi.org/10.1016/j.oregeorev.2022.104780>
- Ge, R., Wilde, S.A., Nemchin, A.A., Whitehouse, M.J., Bellucci, J.J., Erickson, T.M., 2019. Mechanisms and consequences of intra-crystalline enrichment of ancient radiogenic Pb in detrital Hadean zircons from the Jack Hills, Western Australia. *Earth and Planetary Science Letters* 517, 38–49. <https://doi.org/10.1016/j.epsl.2019.04.005>
- Gee, D.G., Kumpulainen, R., Roberts, D., Stephens, M.B., Zachrisson, E., Thon, A., 1985. Scandinavian Caledonides – Tectonostratigraphic Map, Scale 1:2 000 000, *Sveriges Geologiska Undersökning*, Ba 35.
- Geisler, T., Schaltegger, U., Tomaschek, F., 2007. Re-equilibration of Zircon in Aqueous Fluids and Melts. *Elements*, 3 (1), 43–50. <https://doi.org/10.2113/gselements.3.1.43>
- Greiling, R.O., Grimmer, J.C., 2007. Köli nappes in the north-central Swedish Caledonides – new views on stratigraphy and structural evolution. *GFF*, 129, 141–153. <https://doi.org/10.1080/11035890701292141>
- Grimmer, J.C., Greiling, R.O., 2012. Serpentinities and low-K island arc meta-volcanic rocks in the Lower Köli Nappe of the central Scandinavian Caledonides: Late Cambrian-early Ordovician serpentinite mud volcanoes in a forearc basin? *Tectonophysics*, 541–543, 19–30. <https://doi.org/10.1016/j.tecto.2012.03.014>
- Hay, D. C., Dempster, T. J., 2009. Zircon Behaviour during Low-temperature Metamorphism, *Journal of Petrology*, 50 (4), 571–589. <https://doi.org/10.1093/petrology/egp011>
- Hay, D.C., Dempster, T.J., Lee, M.R., Brown, D.J., 2010. Anatomy of a low temperature zircon outgrowth. *Contributions to Mineralogy and Petrology*, 159, 81–92. <https://doi.org/10.1007/s00410-009-0417-2>
- Huijsmans, J.R.; Hamers, M.; Drury, M.R.; Lee, J.K.W., 2022. Recrystallisation and Trace-Element Mobility in Zircons: Implications for U-Pb Dating. *Minerals*, 12, 1489. <https://doi.org/10.3390/min12121489>
- King, A.J., Phillips, K.J.H., Strekopytov, S., Vita-Finzi, C., Russell, S.S., 2020. Terrestrial modification of the Ivuna meteorite and a reassessment of the chemical composition of the CI type specimen. *Geochimica et Cosmochimica Acta*, 268, 73–89. <https://doi.org/10.1016/j.gca.2019.09.041>
- Klonowska, I., Janák, M., Majka, J., Petřík, I., Froitzheim, N., Gee, D.G. Sasinková, V., 2017. Microdiamond on Åreskutan confirms regional UHP metamorphism in the Seve Nappe Complex of the Scandinavian Caledonides. *Journal of Metamorphic Geology*, 35, 541–564. <https://doi.org/10.1111/jmg.12244>
- Kulling, O., 1933. Bergbyggnaden inom Björkvattnet—Virisen-området i Västerbottensfjällens centrala del. *Geologiska Föreningen i Stockholm Förhandlingar*, 55, 167–422.
- Kusiak, M.A., Whitehouse, M.J., Wilde, S.A., Nemchin, A.A., Clark, C., 2013. Mobilization of radiogenic Pb in zircon revealed by ion imaging: implications for early Earth geochronology. *Geology* 41, 291–294. <https://doi.org/10.1130/G33920.1>
- Kusiak, M.A., Dunkley, D.J., Wirth, R., Whitehouse, M.J., Wilde, S.A., Marquardt, K., 2015. Metallic lead nanospheres discovered in ancient zircons. *Proceedings of the National Academy of Sciences (PNAS)* 112, 4958–4963. <https://doi.org/10.1073/pnas.1415264112>
- Lanari, P., Vidal, O., De Andrade, V., Dubacq, B., Lewin, E., Grosch, E., Schwartz, S., 2014. XMapTools: a MATLAB®-based program for electron microprobe X-ray image processing and geothermobarometry. *Computers and Geosciences*, 62, 227–240. <https://doi.org/10.1016/j.cageo.2013.08.010>
- Lanari, P., Vho, A., Bovay, T., Airaghi, L., Centrella, S., 2019. Quantitative compositional mapping of mineral phases

- by electron probe micro-analyser. Geological Society of London, Special Publications, 478, 39–63. <https://doi.org/10.1144/sp478.4>
- Lanari, P., Laughton, J., Tedeschi, M., & Markmann, T.A., 2023. XMapTools 4.1 (v4.1). *Zenodo*. <https://doi.org/10.5281/zenodo.7656958>
- Lyon, I.C., Kusiak, M.A., Wirth, R., Whitehouse, M.J., Dunkley, D.J., Wilde, S.A., Schaumlöffel, D., Malherbe, J., Moore, K.L., 2019. Pb nanospheres in ancient zircon yield model ages for zircon formation and Pb mobilization. *Scientific Reports*, 9, 13702. <https://doi.org/10.1038/s41598-019-49882-8>
- Morgavi, D., Arienzo, I., Montagna, C., Perugini, D., Dingwell, D.B., 2017. Magma Mixing: History and Dynamics of an Eruption Trigger. In: Gottsmann, J., Neuberg, J., Scheu, B. (eds) *Volcanic Unrest. Advances in Volcanology* (2019). Springer, Cham. https://doi.org/10.1007/11157_2017_30
- Nasdala, L., Zhang, M., Kempe, U., Panczer, G., Gaft, M., Plöötze, M., 2003. Spectroscopic methods applied to zircon, in: Hanchar, J.M., Hoskin, P.W.O. (Eds.), *Zircon. Mineralogical Society of America and Geochemical Society*, Washington, DC, United States, pp. 427–467.
- Root, D. B., Corfu, F. 2012. U–Pb geochronology of two discrete Ordovician high-pressure metamorphic events in the Seve Nappe Complex, Scandinavian Caledonides. *Contributions to Mineralogy and Petrology*, 163, 769–788.
- Rubatto, D., 2017. Zircon: The Metamorphic Mineral. *Reviews in Mineralogy and Geochemistry*, 83 (1), 261–295. <https://doi.org/10.2138/rmg.2017.83.9>
- Schaltegger, U., Davies, J.H.F.L., 2017. Petrochronology of Zircon and Baddeleyite in Igneous Rocks: Reconstructing Magmatic Processes at High Temporal Resolution. *Reviews in Mineralogy and Geochemistry*, 83 (1): 297–328. <https://doi.org/10.2138/rmg.2017.83.10>
- Sjöstrand, T., 1978. Caledonian Geology of the Kvarnbergsvattnet Area, Northern Jämtland, Central Sweden: Stratigraphy, Metamorphism, Deformation. *Sveriges geologiska undersökning, Series C*, 735.
- Stephens, M.B., 1980. Occurrence, nature and tectonic significance of volcanic and high-level intrusive rocks within the Swedish Caledonides. In: Wones, D. R. (ed.) *The Caledonides in the U.S.A.* 289–298.
- Stephens, M.B., 1982. Field relationships, petrochemistry and petrogenesis of the Stekenjokk volcanites, central Swedish Caledonides. *Sveriges geologiska undersökning, Series C*, 786. 111 pp.
- Stephens, M.B., Furnes, H., Robins, B., Sturt, B.A., 1985. Igneous activity within the Scandinavian Caledonides. In: Gee, D. G. and Sturt, B. A. (eds) *The Caledonide Orogen – Scandinavia and Related Areas*. 623–656.
- Stephens, M.B., Gee, D.G., 1985. A tectonic model for the evolution of the terranes in the central Scandinavian Caledonides. In: Gee, D. G. and Sturt, B. A. (eds) *The Caledonide Orogen – Scandinavia and Related Areas*.
- Stephens, M.B., Gee, D.G., 1989. Terranes and polyphase accretionary history in the Scandinavian Caledonides. *Geological Society of America Special Paper*, 230, 17–30.
- Stephens, M.B., 2001. Berggrundskartan 24E Joesjö SO-24F Tärna SV, skala 1:50 000. Ai 161.
- Stephens, M.B., 2020. Chapter 22 Upper and uppermost thrust sheets in the Caledonide orogen, Sweden: outboard oceanic and exotic continental terranes. *Geological Society, London, Memoirs*, 50, 549–575. <https://doi.org/10.1144/m50-2019-12>.
- Walczak, K., Barnes, C.J., Majka, J., Gee, D.G., Klonowska, I., 2022. Zircon age depth-profiling sheds light on the early Caledonian evolution of the Seve Nappe Complex in west-central Jämtland. *Geoscience Frontiers*, 13, <https://doi.org/10.1016/j.gsf.2020.11.009>
- Waldron, J.W.F., Schofield, D.I., Murphy, J.B., Thomas, C.W., 2014. How was the Iapetus Ocean infected with subduction? *Geology*, 42, 1095–1098. <https://doi.org/10.1130/G36194.1>
- Williams, I.S., Compston, W., Black, L.P., Ireland, T.R., Foster, J.J., 1984. Unsupported radiogenic Pb in zircon: a cause of anomalously high Pb–Pb, U–Pb and Th–Pb ages. *Contrib. Mineral. Petrol.* 88, 322–327. <https://doi.org/10.1007/BF00376756>
- Wotzlaw, J.F., Bindeman, I.N., Watts, K.E., Schmitt, A.K., Caricchi, L., Schaltegger, U., 2014. Linking rapid magma reservoir assembly and eruption trigger mechanisms at evolved Yellowstone-type supervolcanoes. *Geology*, 42 (9): 807–810. <https://doi.org/10.1130/G35979.1>
- Wotzlaw, J.F., Bindeman, I.N., Stern, R.A., D’Abzac, F.X., Schaltegger, U., 2015. Rapid heterogeneous assembly of multiple magma reservoirs prior to Yellowstone supereruptions. *Scientific Reports*, 5, 14026. <https://doi.org/10.1038/srep14026>
- Zhang, B., Hu, X., Li, P. Tang, Q., Zhou, W., 2019. Trace element partitioning between amphibole and hydrous silicate glasses at 0.6–2.6 GPa. *Acta Geochimica*, 38, 414–429. <https://doi.org/10.1007/s11631-019-00322-4>

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