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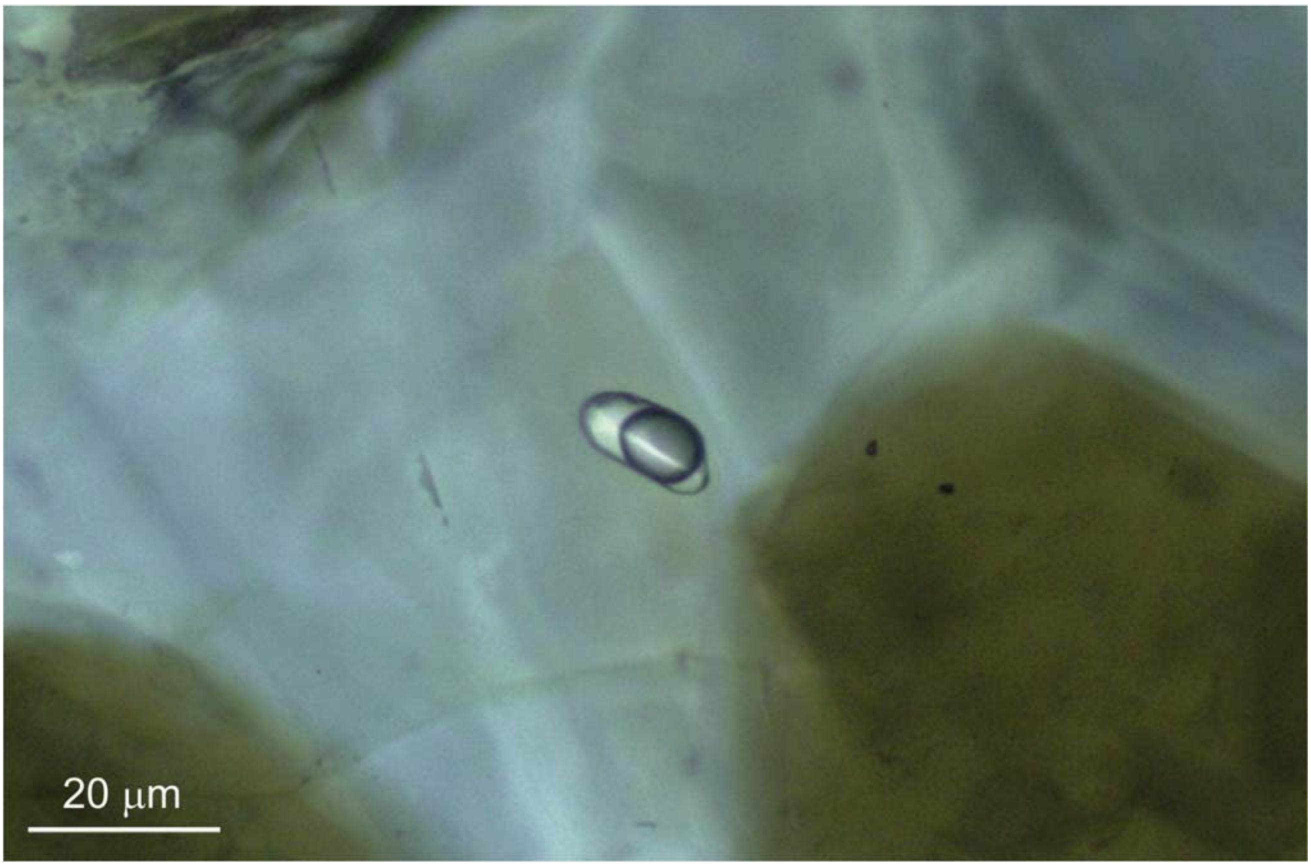
Jukka-Pekka Ranta

Geological evolution and gold mineralization in the northern part of the Peräpohja belt, Finland: Evidence from whole-rock and mineral chemistry, and radiogenic and stable isotopes



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Cover Figure:

Primary carbonic-aqueous fluid inclusion in tourmaline from the Palokas gold occurrence.

Geological evolution and gold mineralization in the northern part of the Peräpohja belt, Finland: Evidence from whole-rock and mineral chemistry, and radiogenic and stable isotopes

JUKKA-PEKKA RANTA

Academic dissertation to be presented with the assent of the Doctoral Training Committee of Technology and Natural Sciences of the University of Oulu for public defense in Auditorium L10, Linnanmaa, on the 23th November 2018, at 12 noon

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Geological evolution and gold mineralization in the northern part of the Peräpohja belt: Evidence from whole-rock and mineral chemistry, and radiogenic and stable isotopes

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ABSTRACT

Multiple occurrences of gold mineralization have been identified during the last decade in the municipality of Ylitornio, southwestern Finnish Lapland. The region enriched in gold is at least 10 x 10 km in size, and comprises two main parts, Rompas in the west and Rajapalot in the east. Geologically, the Rompas-Rajapalot prospect area is located in the northern part of the Peräpohja belt, a Paleoproterozoic supracrustal sequence deposited on the rifting Archean basement at ca. 2.4–1.9 Ga and metamorphosed during the Svecofennian composite orogeny at ca. 1.90–1.77 Ga. The northern part of the Peräpohja belt is highly deformed and locally migmatized and, therefore, the stratigraphic correlation of rock units with the more well preserved southern part of the belt has been difficult.

Due to the relatively recent discovery of the Rompas-Rajapalot gold occurrences, in 2008, only few studies have been published from the area and many basic questions regarding the gold occurrences and chronostratigraphy of the rock units are still open. The study area shows various styles of gold mineralization ranging from localized high-grade Au pockets in uraninite- and pyrobitumen-bearing calcsilicate-carbonate-quartz veins in mafic metavolcanic rocks (Rompas) to disseminated gold grains in Fe-Mg-rich metasediments and quartz-tourmaline-sulfide-native gold veins (Rajapalot). The observed mineralogical, petrological and geochemical features together with post- to late-orogenic timing of ore formation do not match well with the traditional classification of orogenic gold deposits or other gold deposit types.

The aim of this study is to obtain more geological, geochemical and geochronological information on the different lithological units of the northern part of the Peräpohja belt and to study the general features of the host rocks for gold, distribution of gold within the host rocks, composition and origin of mineralizing hydrothermal fluids, focusing mainly on the Palokas prospect, the best gold occurrence in the Rajapalot area. This study presents new U-Pb zircon data and whole-rock Sm-Nd isotope data from metasedimentary and intrusive rock units from the northern part of the Peräpohja belt, petrographic observations and mineral and whole-rock chemical data from the main lithological units associated with gold at Palokas. Furthermore, in order to evaluate the source of gold-bearing hydrothermal fluids, boron isotope compositions were determined for tourmaline from three rock associations: gold-mineralized cordierite-orthoamphibole rocks at Palokas, a 1.78 Ga granitic intrusion, and a metasedimentary rock unit with an evaporitic origin, with the latter two occurring close to the Palokas mineralization. Using microthermometry and Raman spectroscopy, analyses of fluid inclusions in tourmaline related to gold at Palokas were performed to obtain information on the composition of the hydrothermal fluids and temperature-pressure conditions during the formation of the gold-bearing quartz-tourmaline-sulfide veins. Whole-rock geochemistry from gold-bearing rocks and interlayered calcsilicate-albite rocks was employed to evaluate their potential protoliths.

The results of the U-Pb zircon dating of detrital zircon grains from the metasedimentary Martimo Formation, representing the Kalevian sedimentation cycle (1960–1900 Ma), revealed a 66 % Paleoproterozoic detrital zircon component, with the youngest zircon grains having an age of ca. 1.91 Ga. These results challenge the previous classification of these rocks as Lower Kalevian, assigning them instead to Upper Kalevian sediments.

U-Pb zircon dating by LA-MC-ICP-MS and Sm-Nd analyses by TIMS revealed two phases of granitic magmatism, at 1.99 Ga and 1.79–1.77 Ga. The former age is the first documented evidence for the presence of felsic plutonism of that age in the Fennoscandian shield. The strongly negative initial ε_{Nd} values from -3.4 to -11.4 measured for the granitoids are consistent with earlier studies, indicating the existence of Archean basement in northern Finland at the time of granite emplacement. The ca. 1.8 Ga rims around Archean zircon grains found in a migmatite sample from the northern edge of the Peräpohja belt constrain the timing of the migmatization and represent the main phase of magmatism in the Central Lapland granitoid complex.

The host rock typefor gold at Palokas is cordierite-orthoamphibole rock, which is distinctly poor in Ca and rich in Fe and Mg compared to the interlayered calcsilicate-albite rocks. Gold occurs in a native form in at least two different textural settings: 1) single, relatively coarse grains disseminated among the rock-forming silicates in cordierite-orthoamphibole rocks and 2) smaller grains occurring in fractures of tourmaline in quartz-sulfide-tourmaline breccias and in fractures of chloritized cordierite-orthoamphibole rocks adjacent to the tourmaline-rich breccias. The latter, fracture-related gold is associated with Bi-Se-S-bearing tellurides, native Bi, molybdenite, chalcopyrite, and pyrrhotite. Coarser, disseminated gold grains were not found to be clearly associated with sulfides nor any fractures. Statistical data show that Au correlates strongly with Te, Cu, Co, Se, Bi, Mo, and Ag (ρ=0.730–0.619), moderately with As, Fe, W (ρ=0.523–0.511) and slightly less with U, Pb, and Ni (ρ=0.492–0.407). Gold has the strongest negative correlations with Sr and Ca.

Tourmaline occurs as tourmaline-rich veins and individual tourmaline crystals within sulfide-rich gold-bearing rocks. Furthermore, it is abundant in late- to post-orogenic pegmatitic granites and in an evaporitic rock unit (the Petäjäskoski Formation), both located nearby the mineralized rocks. Tourmaline from all the mentioned units belongs to the alkali-group and can be classified as dravite and schorl. The $\delta^{11}B$ values of the three localities lie in the same range from 0 to −4 ‰. Based on the similar boron isotope composition, it is suggested that the gold-bearing tourmaline-rich veins are related to the extensive granite magmatism emplaced at around 1.79–1.77 Ga.

Tourmaline from the Palokas Au occurrence and the Petäjäskoski Formation has similar compositional trends. Magnesium is the major substituent for Al. The calculated low Fe^{3+}/Fe^{2+} ratios and Na values (<0.8 atoms per formula unit) of all tourmaline samples suggest that they precipitated from reduced low-salinity fluids, which is also supported by fluid inclusion data. Fluid inclusion compositions from tourmaline in gold-bearing quartz-tourmaline-sulfide veins indicate that the veins were formed from H_2O-NaCl-CO_2-CH_4-(H_2S) fluids in a boiling system under pressure conditions ranging from lithostatic to hydrostatic, at depths of ∼5 km and the temperature ∼300 ˚C.

Based on the whole-rock geochemistry, it is plausible that the cordierite-orthoamphibole rocks and interlayered calcsilicate-albite rocks are part of a basin-wide lacustrine and at least partly evaporitic sequence. The protolith of the cordierite-orthoamphibole rock was most probably a lake-margin sediment with abundant Mg-rich clays. The calc-silicate albite rocks were originally calcitic-dolomitic marls, common deposits in evaporitic basins. Analogies of similar cases can be found for example from north-west Queensland, Australia.

Based on the studies done in this work and performed by others, there seems to be a temporal, spatial and genetic link between the late orogenic granitoid magmatism and fracture-related gold at Palokas. Currently, there is no clear genetic classification that can be applied to the gold occurrences in the whole Rompas-Rajapalot area and hence further studies are required. Particularly, the textural setting of gold in the whole area needs further investigation in order to determine whether there are multiple generations of gold. Also, further studies of the structural geology of this multi-deformed area are crucial in order to understand and locate the mineralized rock intervals.

TIIVISTELMÄ

Vuonna 2008 paikannettiin Ylitornion kunnassa, noin 60 kilometriä Rovaniemeltä länteen sijaitseva esiintymä (Rompas), joka sisältää paikoin hyvin korkeita kultapitoisuuksia. Lisätutkimukset paljastivat vuonna 2012 toisen kullan suhteen rikastuneen alueen (Rajapalot) noin 8 kilometrin päässä ensimmäisistä löydöistä itään. Tällä hetkellä alueen tiedetään olevan laajuudeltaan ainakin 100 km^2 (Rompas-Rajapalot). Geologisesti alue kuuluu paleoproterotsooisen Peräpohjan liuskealueen pohjoisosaan. Liuskealue koostuu sedimenttisistä ja vulkaanisista kivilajeista, jotka kerrostuivat arkeeisen (<2.5 Ga) kuoren repeämisen tuloksena syntyneeseen altaaseen noin 2.4–1.9 miljardia vuotta sitten. Liuskealueen pohjoisosa on vahvasti deformoitunut ja kivilajien keskinäiset suhteet sekä niiden asema liuskealueen stratigrafiassa on ollut epäselvä.

Tässä väitöskirjassa esitetään zirkonin U-Pb-ikämäärityksiä ja Sm-Nd isotooppituloksia Peräpohjan liuskealueen pohjoisosan metasedimenttiyksiköistä ja graniittisista magmakivistä tarkoituksena tarkastella yksiköiden välisiä ikäsuhteita ja stratigrafiaa. Näiden lisäksi käsitellään petrografiaa, mineraali- ja kokokivigeokemiaa, fluidisulkeumatutkimuksia sekä isotooppigeokemiaa Rajapalojen alueen pääesiintymästä, Palokkaasta. Tarkoituksena on kuvata kultaesiintymän tyypillisiä piirteitä, kullan esiintymistä, isäntäkivien mineralogiaa sekä kultaan liittyvien hydrotermisten fluidien koostumusta ja alkuperää.

Tutkimusalueen graniitit edustavat ainakin kahta eri magmaattista vaihetta (n. 1.99 Ga ja 1.79–1.77 Ga). Näistä vanhempi, noin 1.99 miljardin vuoden ikäinen graniitti edustaa ensimmäistä syväkiveä, joka on ajoitettu tämän ikäiseksi Fennoskandian kilven alueella. Graniiteista mitatut negatiiviset initiaaliset ε_{Nd}-arvot (-3.4 – -11.4) tukevat aikaisempien tutkimusten johtopäätöksiä arkeeisen pohjan olemassaolosta liuskealueiden alla graniittien tunkeutumisen aikaan. Peräpohjan liuskealueen pohjoisosan kontaktin migmatiittinäytteestä saatiin arkeeisten zirkonirakeiden reunaosille noin 1.8 miljardin vuoden ikiä, jotka edustavat migmatisoitumisen ikää ja samalla Keski-Lapin granitoidikompleksin synnyn päävaihetta. Liuskealueen nuorimman sedimenttiyksikön, Martimon muodostuman nuorimmat ajoitetut detritaaliset zirkonit ovat noin 1.91 miljardin vuoden ikäisiä. Sen perusteella on mahdollista rajata Martimon muodostuman kiilleliuskeiden kerrostumisajankohta välille 1.88–1.91 Ga.

Palokkaan kultamineralisaation isäntäkivenä on kordieriitti-ortoamfibolikivi, joka erottuu selvästi kalsiumköyhänä sekä rauta- ja magnesiumrikkaana muista alueen kivistä. Kordieriitti-ortoamfibolikivi on paikoin vahvasti kloriittiutunut, sulfidoitunut ja turmaliinisoitunut. Kulta esiintyy metallisessa muodossa ja tekstuuriltaan sillä on ainakin kaksi erilaista esiintymistapaa: 1)

yksittäisinä rakeina isäntäkiven silikaattien välissä ja 2) myöhäisten rakosysteemien kvartsi-turmaliini-sulfidijuonissa sekä kloriittiutuneessa kordieriitti-ortoamfibolikivessä. Raoissa esiintyvän kullan seurassa on yleisesti Bi-Se-S-telluriideja, metallista vismuttia, molybdeniittia, kuparikiisua ja magneettikiisua. Karkeammat, yksittäin esiintyvät kultarakeet eivät tämän tutkimuksen näytteiden perusteella suoraan näytä liittyvän sulfideihin tai myöhäisiin rakosysteemeihin. Kokokivigeokemian antamien tilastollisten korrelaatiokertoimien (Spearmanin korrelaatiokerroin ρ) perusteella kullalla on vahva positiivinen korrelaatio telluurin, kuparin, koboltin, seleenin, vismutin, molybdeenin ja hopean kanssa (ρ=0.730–0.619). Kullalla on keskinkertainen positiivinen korrelaatio arseenin, raudan ja wolframin kanssa (ρ=0.523–0.511) sekä heikosti positiivinen korrelaatio uraanin, lyijyn ja nikkelin kanssa (ρ=0.492–0.407).

Turmaliini on tärkeä kullan kanssa esiintyvä mineraali Palokkaassa. Lisäksi turmaliinia on yleisesti mineralisaation lähellä sijaitsevissa, noin 1.78 miljardin vuoden ikäisissä pegmatiittisissa graniiteissa sekä metaevaporiittisessa Petäjäskosken muodostumassa. Mineraaligeokemian perusteella näissä kaikissa kolmessa yksikössä esiintyvät turmaliinit kuuluvat alkaliryhmään ja ne voidaan mineralogisesti luokitella draviiteiksi ja schorleiksi. Analysoitujen turmaliinien δ^{11}B-arvot eri yksiköiden välillä ovat samankaltaisia vaihdellen välillä 0 ja -4 ‰. Tällä perusteella voidaan päätellä, että Palokkaan kultaesiintymän turmaliinit ja kultapitoiset turmaliinirikkaat juonet liittyvät noin 1.79–1.77 miljardin vuoden ikäiseen graniittiseen magmatismiin. Turmaliinin koostumus indikoi, että se kiteytyi pelkistävissä olosuhteissa alhaisen suolapitoisuuden hydrotermisistä fluideista. Tätä tulosta tukee Palokkaan esiintymän turmaliinista tehdyt fluidisulkeumatutkimukset, joiden perusteella fluidit ovat koostumukseltaan H_2O-NaCl-CO_2-CH_4-(H_2S) -pitoisia. Kultapitoiset kvartsi-turmaliini-sulfidijuonet kiteytyivät noin 300 ^oC:n lämpötilassa äkillisen paineenlaskun seurauksena, josta seurasi hydrotermisen fluidin kiehuminen noin 5 kilometrin syvyydessä.

Palokkaan kultaesiintymän isäntäkiven ja välikerroksina esiintyvän kalkkisilikaatti-albiittikiven kokokivigeokemian perusteella on mahdollista, että nämä yksiköt ovat alun perin olleet osana lakustrista, evaporiittista sedimenttisarjaa. Kordieriitti-ortoamfibolikiven protoliitti on mahdollisesti ollut järvialtaan reunaosiin kerrostunut, magnesiumrikkaista savista koostuva sedimenttikerrostuma.

Yhteenvetona väitöskirjan tutkimuksista sekä muista alueelta tehdyistä tutkimuksista voidaan todeta, että ainakin myöhemmän raoissa ja turmaliinirikkaissa juonissa esiintyvän kullan osalta kultamineralisaatio koko Rompas-Rajapalojen alueella liittyy 1.79–1.99 miljardia vuotta vanhaan myöhäisorogeeniseen magmaattiseen vaiheeseen. Geneettistä luokittelua alueen kultaesiintymille ei voida vielä tässä vaiheessa tehdä. Etenkin kullan esiintyminen nähtävästi myöhäisissä raoissa sekä silikaattien väleissä (ei liittyen rakoihin) voi indikoida kullan malmiutumista useassa eri vaiheessa. Kullan rakenteellisen kontrollin kokonaisvaltainen tutkiminen on seuraava tärkeä askel alueen mineraaliesiintymien synnyn selvittämisessä. Lisäksi koko rakennegeologisen historian selvittäminen tällä vahvasti deformoituneella alueella on tärkeää kultakriittisten yksiköiden löytämiseksi.

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Oulu, May 2018
Jukka-Pekka Ranta

CONTENTS

Original publications and authors contribution

This thesis is based on the following three peer-reviewed articles:

Paper I Ranta, J.-P., Lauri, LS., Hanski, E., Huhma, H., Lahaye, Y., Vanhanen, E., 2015. U-Pb and Sm-Nd isotopic constraints on the evolution of the Paleoproterozoic Peräpohja Belt, northern Finland. *Precambrian Research* 266, 246–259. doi: 10.1016/j.precamres.2015.05.018

Paper II Ranta, J.-P., Hanski, E., Cook, N., Lahaye, Y., 2017. Source of boron in the Palokas gold deposit, northern Finland: evidence from boron isotopes and major element composition of tourmaline. *Mineralium Deposita* 52, 733–746. doi: 10.1007/s00126-016-0700-x

Paper III Ranta, J.-P., Molnár, F., Hanski, E., Cook, N., 2018. Epigenetic gold occurrence in a Paleoproterozoic meta-evaporitic sequence in the Rompas-Rajapalot Au system, Peräpohja belt, northern Finland. *Bulletin of the Geological Society of Finland*, 52, 733–746. doi: 10.17741/bgsf/90.1.00

The author's contribution to the multi-authored papers is as follows:

Jukka-Pekka Ranta is the corresponding author for all the published research articles and he wrote 80 % of article I, 95 % of article II and 80 % of the article III. For article I, samples were collected by the author and Laura Lauri with the help of Janne Kinnunen (Mawson Oy). U-Pb isotope analyses were conducted by the author under the guidance of Hannu Huhma and Yann Lahaye. Sm-Nd isotope analyses were completed by Hannu Huhma. Isotope data processing and analysis were carried out by the author with help of co-authors. In article II, samples were collected from drill core owned by Mawson Oy. The author studied and re-sampled the drill core. Mineral geochemistry and boron isotope analyses were conducted by the author. Yann Lahaye helped in the boron isotope analyses while the related data processing and interpretation were carried out by the author. In article III, re-logging and sampling of the Mawson Oy drill core as well as mineral geochemistry and petrography were carried out by the author. Tourmaline trace-element analyses were performed by Yann Lahaye. Fluid inclusion microthermometric studies were done by the author under the supervision of Ferenc Molnár. Raman spectroscopy measurements on fluid inclusions were made by the author with help of Laszlo Aradi, Csaba Szabo and Marta Berkesi at the Eötvös Lorand University in Budapest. All the co-authors and reviewers helped in finalizing the papers to their published format.

1. INTRODUCTION

Gold (Au) deposits have been formed over >3 billion years in Earth´s history. Gold occurs as a major commodity or as a by-product in various deposit types with different formation conditions. The classification of gold deposits has been constantly evolving, and major changes in the classification systems have taken place, especially in the 1980s, mostly due to the better understanding of crustal evolution and plate tectonics (Goldfarb et al., 2005) and increased activities in gold research and exploration as a result of the advent of more precise and less expensive analytical methods. Before the 1980s, the classification of gold deposits was based on the depth and temperature of their formation (e.g., mesothermal and hypothermal), host rock type (e.g., turbidite-hosted Au deposit), age (e.g., Archean gold deposit), structural style (e.g., stockwork style Au deposit), geographic area (e.g., Homestake Au deposit), or genetic model (e.g., metamorphic gold deposit; Goldfarb et al., 2005, and references therein). Later, researchers have been working towards classification systems that aim at simplifying the deposit types.

The currently used general gold deposit classes where gold is present as the main or a significant commodity are listed in Table 1. Porphyry-, epithermal- and skarn-type gold deposits form in igneous arcs above subduction zones (Sillitoe, 2010). Some of the deposits, for example Au-rich volcanogenic massive sulfide deposits, may form both in volcanic arc and in back-arc environments (Mercier-Langevin et al., 2011). Iron-oxide-copper-gold deposits (e.g., Hitzman et al., 1992) are magmatic-hydrothermal Au-Cu-Fe deposits formed most probably in anorogenic tectonic settings where hydrothermal activity was ultimately driven by mantle underplating and/or plumes (Groves et al., 2010). The most common type of gold deposits, the orogenic gold (e.g., McCuaig & Kerrich, 1998; Goldfarb et al., 2005; Goldfarb & Groves., 2015), forms at accretional or collisional tectonic settings. It was first introduced by Böhlke (1982) and later defined by Groves (1993) and Groves et al. (1998). Some of the deposits classes are globally uncommon and, so far, have really been reliably identified in unique locations such as the Carlin-type Au in the Carlin trend, USA (e.g., Cline et al., 2005), and the reduced intrusion-related gold systems (RIRGS) in the Tintina gold province, USA and Yukon, Canada (Hart et al., 2002). Groves et al. (2016) discussed the key factors that lead to formation of giant gold deposits and provinces excluding those forming in the arc settings (porphyry-, epithermal-, Au-rich VMS deposits). The giant deposits, despite the differences of many ore deposit types in district or in deposit scale, share similarities in crustal to lithospheric setting. Deposits are located in or close to deep-seated fault- and shear zones that follow craton margins or are located in primary suture zones between tectonic terranes (Groves et al., 2016). Furthermore, as pointed out by Richards (2013), some of the giant porphyry- and epithermal deposits, traditionally classified to form in active volcanic-arcs above subduction zones, show post-subduction formation age or even back-arc tectonic environment. Overall, despite all the efforts in classifying deposits throughout the world, the genetic type and mineralization history at many deposits remains unraveled.

Table 1. Selected key features of main gold deposit classes.

Deposit Type	Metal association	Tectonic Setting	Formation depth	Key features	Type examples	Example references
Orogenic Au	Au-As-Bi-Te-W-Sb	- Accretional or collisional - Syn- to late-orogenic	- 5-20 km	- Strong structural control by lower order structures - At or near crustal-scale faults and shear zones - Vertical continuity - Host rock usually the most competent rock unit within metamorphic sequence	Muruntau, Golden Mile	Groves et al. (1998) Goldfarb et al. (2005) Goldfarb & Groves (2015)
Reduced Intrusion Related Au systems	Au-Bi-Te-W-Mo-As-Sb-Ag-Pb-Zn	- Deformed shelf sequences inland from accreted terranes - Post-orogenic	- < 1 km - > 8 km	- Metaluminous I-type granitoids - Intrusion-hosted sheeted veins - Skarns, replacement, fracture-controlled, disseminated and vein style mineralization at the thermal aureole of the pluton	Tintina gold province	Hart et al. (2002) Goldfarb et al. (2005)
Porphyry Au	Au-(Cu)-(Mo)	- Calc-alkaline to alkaline magmatic arcs at convergent plate margins	- 1-6 km	- Proximal potassic (biotite-K-feldspar)-, chlorite-sericite alteration - Propylitic alteration in marginal parts, below lithocaps - Advanced argillic alteration in lithocaps - Au-Ag, Cu signature	Grasberg	Meinert et al. (2005) Sillitoe (2010) Pollard & Taylor (2002)
Epithermal Au	- Au-Ag±Cu (High sulfidation (HS)) - Ag-Au (Intermediate sulfidation (IS)) - Au-Ag (Low sulfidation (LS))	- Calc-alkaline to alkaline magmatic arcs at convergent plate margins	- <1.5 km	- Vuggy quartz to advanced argillic alteration in HS and IS deposits - Carbonate alteration and proximal sericite/K-feldspar alteration in LS deposits	Martha Hill	Simmons et al. (2005) Spörli & Cargill (2011)

Table 1 (continued). Selected key features of main gold deposit classes.

Deposit Type	Metal association	Tectonic Setting	Formation depth	Key features	Type examples	Example references
Carlin-type Au	Au-As-Hg-Sb-Tl	- Unmetamorphosed passive margin sedimentary basins - Extensional setting	- 0.3-5 km	- Strong structural and lithological control - Structurally bounded, submicron sized gold in As-rich pyrite and marcasite - Deposits occur in clusters within structural trends	Carlin trend	Cline et al. (2005)
Au-rich Volcanogenic massive sulfides	Au-Cu-Bi-Te-In	- Submarine volcanic, extensional seafloor environment	Submarine ~500 to ~2000 meter of water depth	- Banded and stratifrom massive sulfide lenses - Proximal advanced argillic alteration, silification	Kali Kuning, Boliden	Scotney et al. (2005) Mercier-Langevin et al. (2011)
Placers and Paleoplacer	Au-(U)-(PGE)-(Cr)	- Foreland or back-arc basins - Cratonic sedimentary basins		- Stratiform beds - Intraformational - In many places right above unconformity	Witwatersrand	Frimmel et al. (2005)
Iron oxide-copper-gold (IOCG)	Fe-Cu-Au	- Extensional settings - Anorogenic, hydrothermal activity driven by mantle underplating and/or plumes	- 4-10 km	- Regional scale Na-Ca alteration - Fe-K alteration - Coeval with voluminous crustal melts	Olympic Dam	Hitzman et al. (1992) Groves et al. (2010) Huston et al. (2012)
Au skarns	Au-As-Bi-Te-Cu	- Calc-alkaline to alkaline magmatic arcs at convergent plate margins		- Host is Ca-rich sedimentary or volcanic rock - Located within the contact-metamorphic aureole of the intrusion - Skarn mineral assemblage (garnet, clinopyroxene etc.)	Junction Reefs	Gray et al. (1995)

Finnish bedrock is dominantly Archean and Paleoproterozoic in age and has been subjected to multiphase deformation, with metamorphism ranging from greenschist to granulite facies. Hence, when discussing the gold deposit classification, this study focuses on the orogenic gold, as it is the most common deposit type in metamorphosed terranes (e.g., Goldfarb et al., 2005). In addition, reduced intrusion-related gold systems are described and discussed due to some similarities found in the study area. The preservation potential of gold deposits forming at relatively shallow levels in the crust (e.g., epithermal Au) is poor, being reflected in the paucity of Archean and Paleoproterozoic examples of this kind of deposits. In metamorphic terranes, gold deposits are dominantly epigenetic and make an episodic appearance in the geological record, with peaks at 2.8–2.55 Ga, 2.1–1.8 Ga, and 600–50 Ma (Goldfarb et al., 2005). These time intervals broadly correlate with thermal events associated with the growth of new continental crust (e.g., Goldfarb et al., 2001). However, examples of older epigenetic Au deposits are found in the northern Pilbara craton (ca. 3.4–3.0 Ga) in Australia and the Barberton greenstone belt (3.1 Ga) in South Africa (op. cit.).

Multiple gold occurrences with locally extremely high gold grades (>3 wt.% Au, grab sample) have recently been discovered in the northern part of the Paleoproterozoic Peräpohja belt, northern Finland (Fig. 1; e.g., Vanhanen et al., 2015; Molnár et al., 2016; Cook, 2017; Ranta et al., 2017). These gold enrichments display mineralogical, petrological and geochemical features that do not match with those of typical orogenic gold deposits found in Archean or Paleoproterozoic greenstone belts globally (cf. Groves et al., 1998; Goldfarb et al., 2001; Goldfarb & Groves, 2015; Eilu, 2015). The intense multiple deformation and episodes of pre-, syn- and post-metamorphic hydrothermal alteration (Molnár et al., 2017a) make the identification of the protoliths and genetic classification of these gold deposits problematic. Two main mineralized areas, *Rompas* in the west and *Rajapalot* in the east, are approximately 6–8 km apart and are currently assigned to the Rompas-Rajapalot prospect. The two areas differ in terms of their host rocks, mineralization style and gold grade. In the Rajapalot area, several mineralized locations with variable styles have been identified, with the main gold mineralization being the *Palokas Au occurrence* (Fig. 2).

The Rajapalot area contains multiple styles of gold mineralization, ranging from localized U-rich pockets of the Rompas style to more disseminated gold hosted by metasomatized metasedimentary rocks with variable alteration types (e.g., Vanhanen et al., 2015; Ranta et al., 2015a,b; Ranta et al., 2017; Cook, 2017; Ranta et al., 2018). Due to the recent timing of the discovery, no extensive and detailed studies have been made in the Rajapalot area and therefore basic questions regarding the rock types hosting the mineralization, mineralogy of the gold and gangue minerals and genetic classification of the Rajapalot deposits have not yet been fully answered. This work presents U-Pb dating and Sm-Nd isotopic results from the metasedimentary and granitic rocks of the northern part of the Peräpohja belt. The main focus is on the Palokas prospect, the most prominent gold occurrence in the Rajapalot area, though several features concerning the whole Rompas-Rajapalot area are also discussed. Petrographic, mineralogical, fluid inclusion, and geochemical data, including isotopic measurements, which help to resolve the key questions, are presented from the gold occurrences.

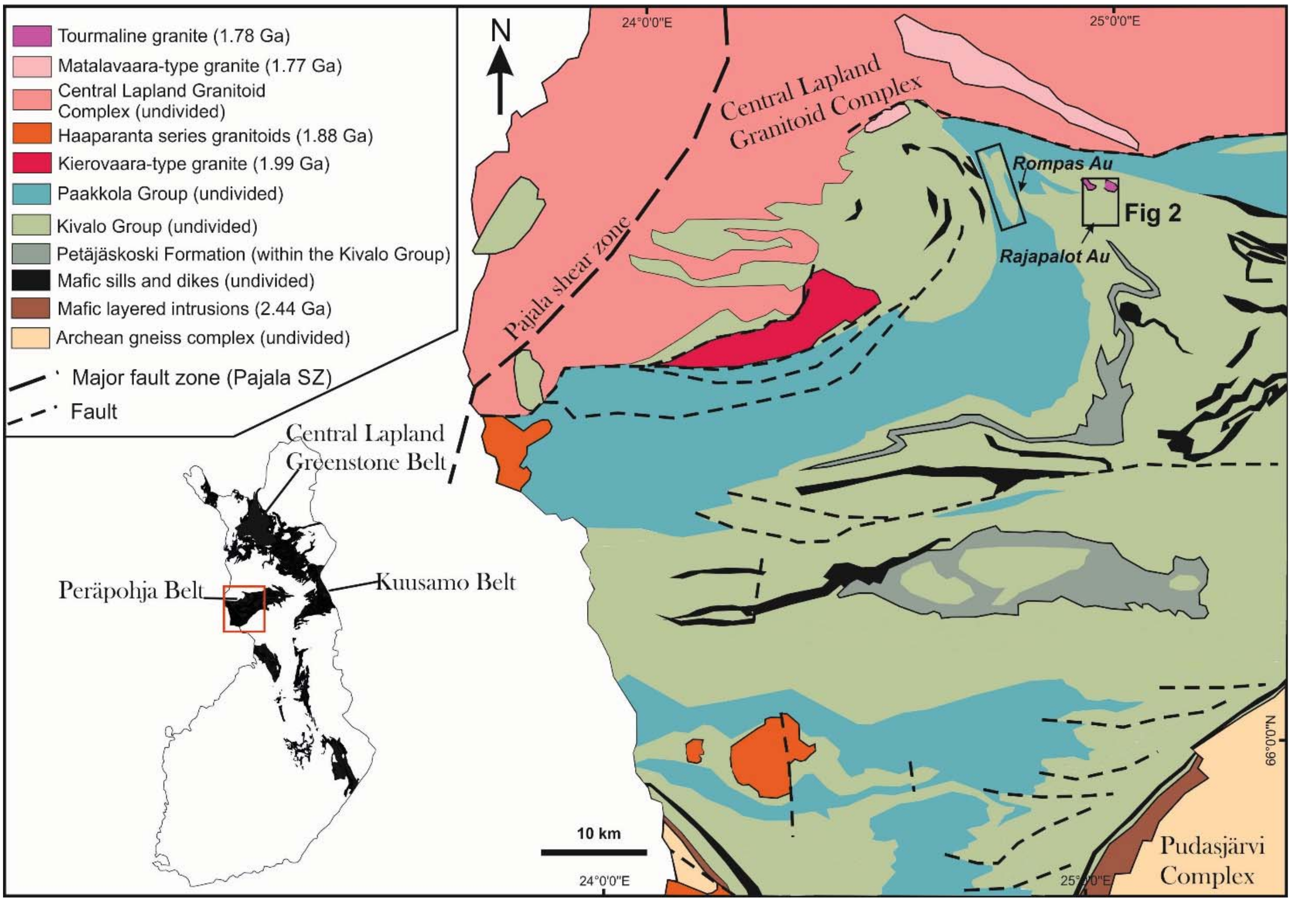

Figure 1. Geological map of the western part of the Peräpohja belt (modified after the DigiKP version 2.1., the "Digital map database for bedrock geology of Finland" [http://gtkdata.gtk.fi/Kalliopera/index.html], Geological Survey of Finland; referred on June 27th, 2017) and Ranta et al. (2017). The Petäjäskoski Formation is delineated after Kyläkoski et al. (2012). The Rompas and Rajapalot prospects are framed with rectangles. The small insert map of Finland shows the Paleoproterozoic Karelian supracrustal belts as black areas. Figure taken from Ranta et al. (2018).

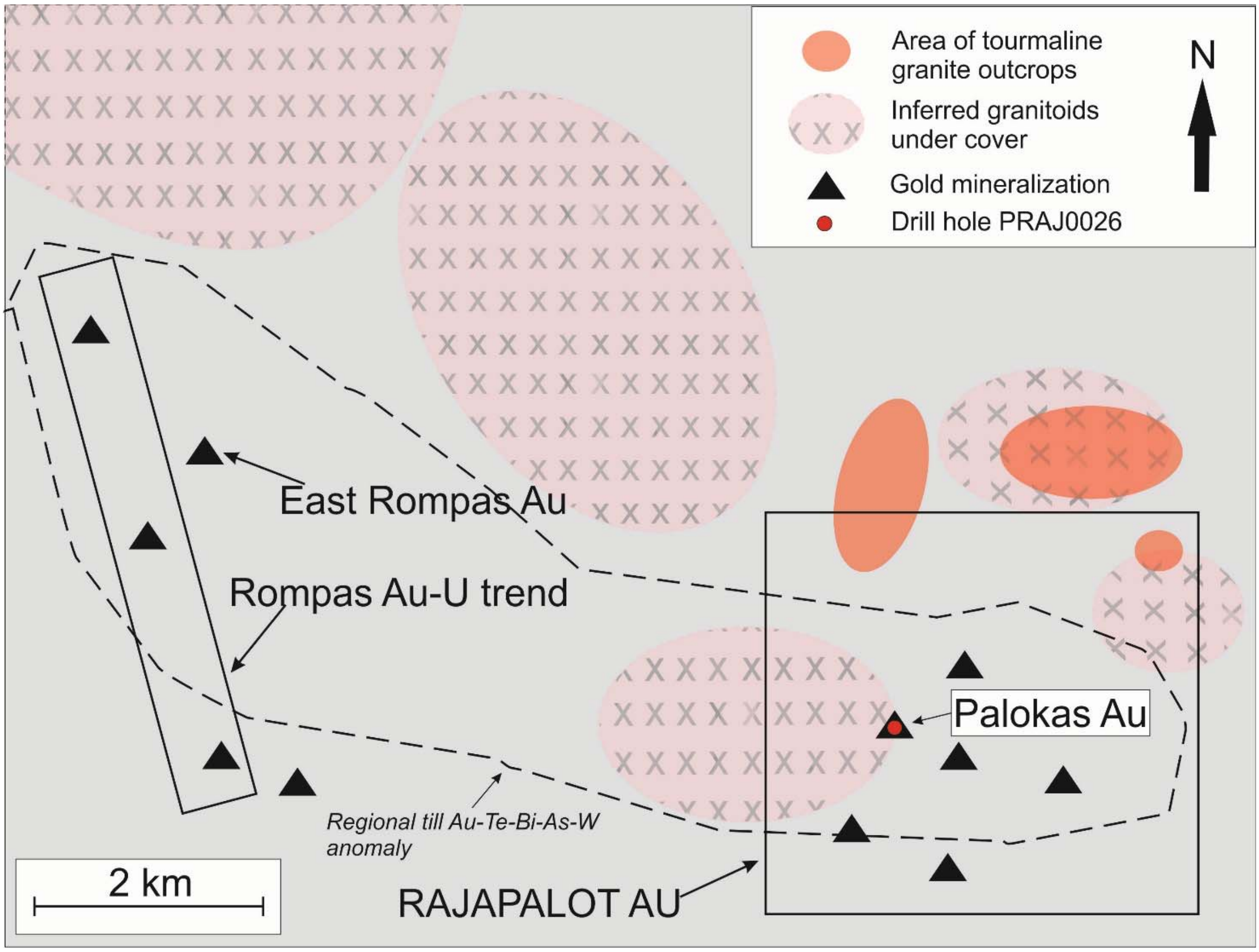

Figure 2. Schematic geological map of the Rompas-Rajapalot area. Figure taken from Ranta et al. (2018).

2. Gold deposits in metamorphic terranes

The following chapters describe some key features of the two most common gold deposit types found in metamorphosed terranes. A comprehensive review of the different types of gold deposits occurring in Finland published by Eilu (2015) is the best source of summary data on Finnish gold systems.

2.1 Orogenic gold deposits

By far, the most common gold deposit class is that of orogenic gold, with their age spanning from Mesoarchean to Paleogene and broadly correlating with the thermal events associated with the growth of new continental crust (e.g., Goldfarb et al. 2001). They show a wide range of formation depths from 5 to 20 km (Fig. 3) and are most commonly hosted by greenschist facies metamorphic rocks although significant ore bodies are also found in higher-grade rocks (e.g., Goldfarb & Groves, 2015). Orogenic gold deposits are typically formed from low-salinity H_2O-CO_2-CH_4-N_2-H_2S fluids with bisulfide complexes as the main gold carrier. They are generated under compressional to transpressional deformation in accretionary to collisional tectonic settings (op. cit.). The deposit model and the genesis of the orogenic gold deposits, especially the fluid and gold sources, are still debated as described by Goldfarb & Groves (2015). The most favored model for orogenic gold is based on metamorphic fluids produced during devolatilization reactions under prograde transition from greenschist to amphibolite facies conditions (e.g., Goldfarb & Groves, 2015). These reactions generate large volumes of metamorphic fluids (e.g., Phillips, 1986; Phillips & Powell, 2010), which can migrate upwards in the crust along major structures, depositing gold along retrograde P-T path, especially near the brittle-ductile transition via pressure fluctuations during seismic events (Sibson et al., 1988; Cox, 2005). Gold occurs in quartz veins and in sulfidized wall rocks in second- or third-order structures adjacent to first order regional fault zones. Ore bodies are vertically continuous and have a lateral alteration halo containing elevated As, Au, Bi, K, Rb, Sb, Te, and W. With a few exceptions, gold is the sole commodity. Depending on P-T conditions (see the crustal continuum model by Groves, 1993), mineralization styles vary from disseminated Au lodes in broad shear zones in a ductile environment (≥400 ^{o}C and 2.5 kbar), with bedding-parallel, deformed and recrystallized quartz veins, to brittle stockworks and breccias in more shallow settings.

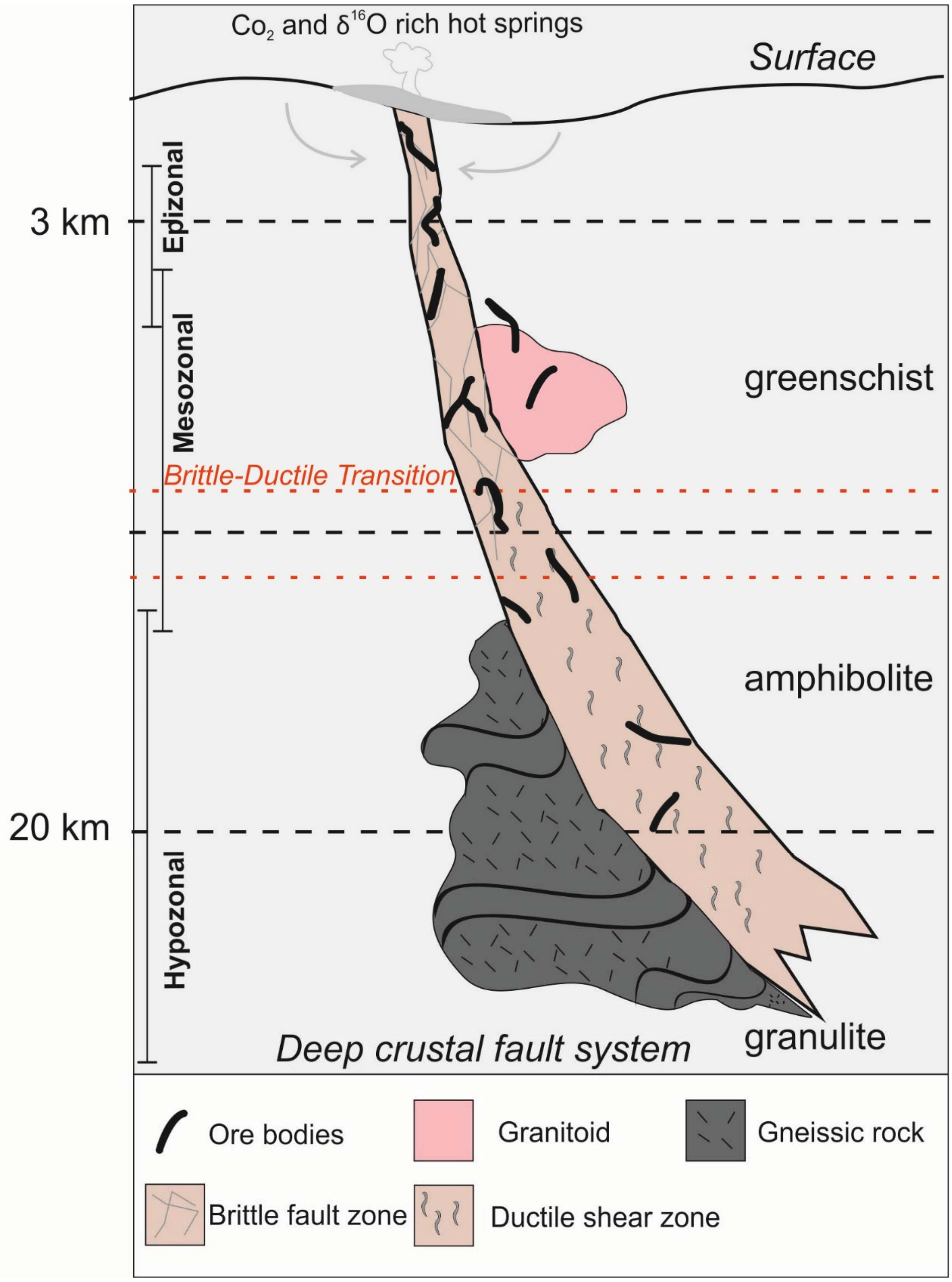

Figure 3. Schematic presentation of orogenic gold formation environments at various depths. Modified after Groves et al. (1998) and Goldfarb and Groves (2015).

In Finland, orogenic gold deposits have been detected in nearly all metamorphosed supracrustal belts. According to Eilu (2015), approximately a dozen Archean and 30 Paleoproterozoic gold deposits with available grade and tonnage reports exist in Finland (FODD, 2013, and references therein). The largest of them is the Suurikuusikko deposit (Kittilä) with proven and probable reserve of ~4.1 million ounces gold (Agnico Eagle, 2018). Most of the gold usually occurs in a native form and is located in fractures or within sulfides and gangue minerals, commonly closely associated with Bi-, Sb-, and Te-rich minerals. Locally, most notably at Suurikuusikko, the majority of the gold is refractory, located within the crystal lattice or as submicroscopic inclusions in arsenopyrite and pyrite (Wyche et al., 2015).

2.2 Orogenic gold deposits with atypical metal assemblages

In addition to the typical orogenic gold deposits, Finland hosts several gold deposits that can be classified as orogenic although they contain atypical metal assemblages, with some metals being potential commodities together with gold. Eilu (2015) classified these types of deposits as orogenic gold deposits with anomalous Ag, Cu, Co, Ni, or Sb. Similar deposit styles with an anomalous metal assemblage are reported around the world, with premetamorphic metal enrichment with circulation of saline fluids in intracratonic basements having been suggested as a potential mechanism for their genesis (e.g., Goldfarb et al., 2001; Eilu, 2015). For example, the Central Lapland greenstone belt hosts several base metal-rich orogenic gold occurrences (e.g., Eilu et al., 2007) with copper as a commodity along with gold (e.g., Saattopora deposit). Nickel and cobalt are present in high grades in some deposits hosted by or located near komatiitic rocks (Eilu, 2015). Ore fluids with salinities between 10–25 wt.% NaCl and pre-mineralization alteration, including carbonatization and albitization, are common features in base metal-rich orogenic gold deposits in the Central Lapland greenstone belt (op. cit.).

2.3 Reduced intrusion-related gold systems

Sillitoe (1991) defined epizonal to mesozonal (shallow- to mid-crustal levels) gold mineralization styles having a genetic association to intrusions, assigning them to the reduced intrusion-related gold systems model (IRGS). Thompson & Newberry (2000) introduced the reduced intrusion-related gold systems model (reduced IRGS or RIRGS) after Thompson et al. (1999) and Lang et al. (2000). The mineralization styles in the reduced IRGS range from granitoid-hosted sheeted auriferous veins to skarns, replacements, disseminations and hydrothermal breccias associated by the thermal aureole of a pluton (see Hart et al., 2002). Lang & Baker (2001) present a summary of the studies on the main IRGS deposits published until then, mainly referring to the work done in the Tintina Gold Province (Alaska, USA, and Yukon, Canada), which is used as a reference area for the reduced intrusion-related gold systems. In terms of tectonic setting, Goldfarb et al. (2000)

concluded that in general, the most favorable environment for intrusion-related gold systems (including porphyries and other oxidized intrusion-related deposits) is subduction-related accretionary to collisional orogenies (e.g., Flanigan et al., 2000). Hart & Goldfarb (2005) emphasized that reduced IRGS deposits are best developed in intrusions that were emplaced behind an accretionary orogeny, though postdating the active orogeny and peak metamorphism. The host rocks for the intrusions are usually unmetamorphosed or metamorphosed sedimentary rocks (op. cit.). The depth of the deposit formation can vary greatly from shallow (<1 km) to deeper environments (>8 km), with most of the deposits having been formed at depths between 4 and 6 km. The corresponding pressure varies significantly from 0.3 to 3.5 kbar (e.g., Baker & Lang, 2001). Baker (2002) proposed that depending on the depth of formation of the granitic pluton, the compositions of the associated magmatic-hydrothermal fluids vary, reflecting the exsolution of different volatiles (CO_2, H_2O and Cl) from felsic magmas at different crustal depths. In shallower crustal settings (<5 km), fluids form a heterogeneous system having a high temperature (>350 °C) and containing immiscible brines (>30 wt.%. NaCl equiv.) and low-salinity (<5 wt.%. NaCl equiv.), CO_2-bearing vapor. On the other hand, in deeper crustal environments (>5 km), low-salinity, CO_2-rich aqueous fluids (<10 wt.% NaCl equiv.) dominate. Locally in deeper systems, more saline brines are found, postdating low-salinity H_2O-CO_2 fluids (Baker, 2002).

The plutons and associated dikes and sills in the IRGS-critical areas generally form extensive igneous belts, as is the case of the Tintina Gold Province (e.g., Mortensen et al., 2000; Hart & Goldfarb, 2005). According to Hart & Goldfarb (2005), plutons are usually relatively small (<5 km^2), metaluminous, ilmenite series I-type granites with biotite and locally hornblende as common mafic minerals. Strongly negative initial ε_{Nd} values (between -8 and -20) indicate a significant crustal contribution to the magmas (e.g., Marsh et al., 2003). In addition to metaluminous granites, strongly fractionated peraluminous granitoids with muscovite, garnet and tourmaline are found in the plutonic belts. Mafic rocks, including lamprophyres, are common. The metal assemblages and mineralization styles within the IRGS vary depending on the formation depth of the mineralization and its spatial relationship with the pluton (see Fig. 4). Again, the Tintina Gold Province acts as a basis for the following classification scheme for the RIRGS:

1) intrusion-hosted sheeted veins with Au-Bi-Te association and local scheelite,
2) skarns with Au±W and Cu±Bi±Te association at the contact zone of the intrusion if calcareous rocks are available,

3) proximal zone of the thermal aureole with replacement- and fracture-controlled and disseminated deposits in the metasedimentary rocks with Au-As±Sb association, and
4) low-temperature ore assemblages occurring in veins (Au-As to Au-As-Sb to Pb-Zn-Ag) distally to the thermal aureole (e.g., Hart et al., 2002).

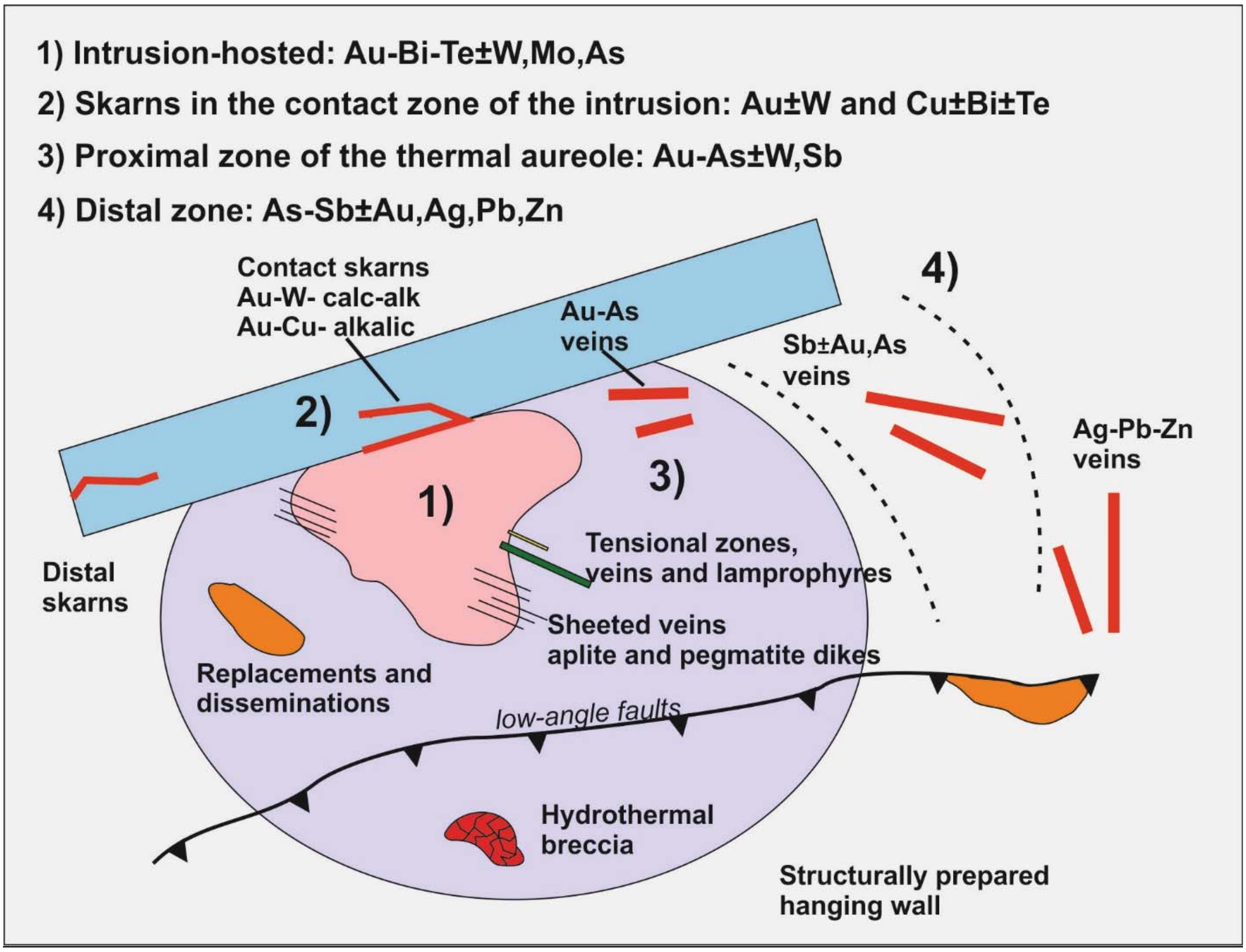

Figure 4. Schematic model for the reduced intrusion-related gold system (RIRGS), showing variation of mineralization styles within the thermal aureole of a pluton. The model is based on the deposit styles found in the Tintina Gold Province, which acts as a reference locality for the RIRGS. Modified after Hart et al. (2002).

2.4 Distinction between orogenic gold and reduced intrusion-related gold

The reduced intrusion-related gold system shares many common features with the orogenic gold systems (e.g., anomalous Bi, Te, W, low-salinity CO_2-bearing fluids etc.). Because of these similarities and the fact that both types are typically spatially/temporally associated with granitoids, controversies have emerged on whether a gold occurrence should be classified as an orogenic or reduced intrusion-related gold deposit (e.g., Wall et al., 2004; Goldfarb et al., 2005).

Nevertheless, there are distinctive features which can be used to discriminate between these two deposits types (Goldfarb et al., 2005; Hart & Goldfarb, 2005). According to Goldfarb et al. (2005), the following features of the reduced intrusion-related gold systems are distinguishable from the orogenic gold deposits and should be used as criteria when the evaluating genetic model of a deposit:

1) Low Au grade (<1 g/t in RIRGS vs. 5–10 g/t in orogenic gold deposit)
2) Location in a deformed shelf sequence inland from accreted terranes
3) Regional association with tungsten and/or less consistently, tin lodes
4) A post-deformational timing relative to more of a late synorogenic timing of orogenic gold deposits
5) An anomalous granitoid system indicating some input from mantle-derived mafic alkaline magmas into the base of the crust.

3. Regional geology of the Peräpohja belt

The Peräpohja belt represents a typical Paleoproterozoic volcano-sedimentary sequence deposited unconformably on rifted Archean basement between ca. 2.44 Ga and 1.88 Ga (e.g., Perttunen, 1985, 1989; Perttunen & Hanski, 2003; Iljina & Hanski, 2005). The basement complex (Pudasjärvi complex, Fig. 1) on the southern side of the Peräpohja belt consists of Archean granitoids and gneisses and greenstone belt relics. In the north and east, the Peräpohja belt is bound by the Central Lapland granitoid complex. In the west, the belt is separated from the Norrbotten craton in Sweden by the N-S-trending Pajala Shear Zone (e.g., Lahtinen et al., 2015). The basin evolution started with clastic, relatively mature sedimentary rocks and subaerial mafic volcanic rocks. Deepening of the basin accompanied deposition of shelf carbonate rocks, which show a heavy carbon isotope excursion diagnostic to Jatulian carbonate rocks (Karhu, 1993; Karhu & Holland, 1996), known as the Lomagundi-Jatuli carbon isotope anomaly (Melezhik et al., 2012). The rock sequence described above belonging to the Kivalo Group (2.44–2.06 Ga), the oldest of the two major lithostratigraphic units in the Peräpohja belt (Perttunen et al., 1995). The upper part of the sequence, the Paakkola Group (2.06–1.88 Ga), is dominantly composed of deep-water turbiditic mica schists and black shales. The Kivalo and Paakkola Groups are subdivided into 17 lithostratigraphic units (Perttunen et al., 1995; Hanski, 2001; Perttunen & Hanski, 2003; Hanski et al., 2005; Kyläkoski et al., 2012; Ranta et al., 2015b) as listed in Table 2.

Table 2. Lithostratigraphy of the Peräpohja belt after Hanski et al. (2005), Kyläkoski et al. (2012) and Ranta et al. (2015b).

LITHOSTRATIGRAPHY		LITHOLOGY	INTRUSIVES GRANITOIDS	AGE
GROUP	*FORMATION*		GRANITOIDS, INCLUDING TOURMALINE RICH PEGMATITES	ca. 1.70 - 1.77 Ga (U-Pb and Sm-Nd)[1]
			HAAPARANTA SERIES	ca. 1.88 Ga (U-Pb)[2]
	MARTIMO	Mica and black schist, qraywacke		<1920 Ma (U-Pb)[3]
PAAKKOLA	PÖYLIÖVAARA	Mica and black schist		
	KORKIAVAARA	Felsic and mafic tuff		<1973 ± 11 Ma (U-Pb)[4]
			KIEROVAARA	1989 ± 6 Ma (U-Pb)[5]
	VÄYSTÄJÄ	Pillowed basalt, dolomite and felsic porphyry		2050 ± 8 Ma (U-Pb)[6]
	LAMULEHTO	Mafic tuffite		
	RANTAMAA	Dolomite, quartzite		
	HIRSIMAA	Mafic tuffite		2106 ± Ma 7 (U-Pb)[7]
	POIKKIMAA	Dolomite, phyllite		
KIVALO	TIKANMAA	Mafic tuffite		
	KVARTSIMAA	Quartzite, dolomite		
	SANTALAMPI	Agglomerate, pillowed basalt		
	JOUTTIAAPA	Amygdaloidal basalt		2105 ± 50 Ma (Sm-Nd)[8]
	PETÄJÄSKOSKI	Mica-albite schist, dolomite, quartzite, breccias		>2140 ± 11 Ma (U-Pb)[9]
	KAISAVAARA	Quartzite, conglomerate		
	PALOKIVALO and MELLAJOKI SUITE	Quartzite, arkosic quartzite, orthoquartzite, mica gneisses, mica schists		>2220 Ma (U-Pb)[10]
	RUNKAUS	Amygdaloidal basalt, agglomerate		2250 ± 30 Ma (U-Pb)[11]
	SOMPUJÄRVI	Conglomerate, arkose, quartzite		<2440 Ma (U-Pb)[12]

Notes: 1) Ranta et al. (2015); 2) Perttunen & Vaasjoki (2001);3) Minimun age based on detrital zircons (Ranta et al. 2015 and Lahtinen et al. 2015); 4) Hanski et al. (2005) and Lahtinen et al. (2015); 5) Ranta et al. (2015); 6) Age of a quartz porphyry (Perttunen & Vaasjoki, 2001); 7) Karhu et al. (2007); 8) Huhma et al.(1990) and Hölttä et al. (2007);9) Age of a cutting mafic sill (Kyläkoski et al. 2012);10) Minimum age based on cutting mafic sills (Perttunen and Vaasjoki, 2001; Hanski et al. 2010); 11) Perttunen & Vaasjoki (2001); 12) Maximum age based on underlying mafic layered intrusions (Huhma et al. 1990)

The 2.44 Ga mafic–ultramafic layered intrusions exposed at the southern contact of the Peräpohja belt (Fig. 1) give the maximum depositional age for the basinal sequence, as these mafic–ultramafic bodies were partly eroded when the first sediments of the Peräpohja belt started to accumulate (Iljina & Hanski, 2005). The youngest sediments of the Peräpohja belt were deposited between 1.91 and 1.88 Ga, based on a detrital zircon population in mica schists of the Paakkola Group (Ranta et al., 2015b) and the age of the cross-cutting Haaparanta suite monzonite plutons (Perttunen & Vaasjoki, 2001). Lahtinen et al. (2015) regard the lithological units within the Paakkola Group as lithodemic.

Several stages of felsic to intermediate plutonism have been recognized within the Peräpohja belt. At least four age groups can be distinguished based on geochronological and petrological data:
1) pre-orogenic, ca. 1.99 Ga porphyritic Kierovaara granite (Ranta et al., 2015b),
2) ca. 1.88 Ga synorogenic Haaparanta suite granitoids (Perttunen & Vaasjoki, 2001),

3) ca. 1.80 Ga appinitic plutons (Tainio, 2014) and

4) late-orogenic, 1.79–1.77 Ga Ga pegmatitic granites (Ranta et al., 2015b).

The rocks of the Peräpohja belt have been subjected to polyphase deformation. The degree of metamorphism increases from greenschist facies in the southern part of the belt up to amphibolite facies in the north and east (Hölttä & Heilimo, 2017). At the northern margin of the belt, rocks are locally migmatized (Hanski et al., 2005; Ranta et al., 2015b). Lahtinen et al. (2015)

describe up to five deformation stages from the youngest metasedimentary formation of the Peräpohja belt (see also Lahtinen et al., 2018). According to them, the earliest deformation stage D1 (≤1.91 Ga) developed a N-S-trending fabric and recumbent folds due to the east-directed thin-skin thrusting. North-south-shortening in stage D2 (1.90–1.89 Ga) produced E-W-trending folds and a pervasive steeply dipping foliation. Stage D3 (1.88–1.87 Ga) is represented by NNW-SSE- and WNW-ESE-trending, heterogeneously developed structural trends. Stage D4 (1.83–1.81 Ga) is most clearly seen as NNE-SSW-trending lineaments in aeromagnetic maps. The latest deformation stage D5 (1.79–1.77 Ga) is characterized by WSW-ENE-directed shortening. Molnár et al. (2017a) present U-Pb uraninite and Re-Os molybdenite ages for hydrothermal processes, demonstrating that the radiometric ages obtained for the multiple hydrothermal events are in agreement with the ages of the major tectonic, metamorphic and some magmatic events in the Rompas-Rajapalot area.

The stratigraphy of the southern part of the Peräpohja belt is relatively well known (e.g., Perttunen et al., 1995; Kyläkoski et al., 2012) and is used as a basis for the current stratigraphic divisions. However, due to the intense deformation in the northern part of the belt, the stratigraphy of that area is more complicated and several important questions remain unanswered. Hence, the stratigraphic setting for the newly discovered gold and gold-uranium occurrences is remains unclear.

4. Geology of the Rompas-Rajapalot area

The Rompas-Rajapalot area is situated near the northern edge of the Peräpohja belt, bordering the Central Lapland granitoid complex (CLGC). Close to the contact with the CLGC, the rocks are migmatized during the main phase of the CLGC magmatism at ca. 1.8 Ga (Ranta et al., 2015b). As mentioned previously, in terms of stratigraphy, the northern part of the belt is still poorly characterized as the rocks are highly deformed and their original features are commonly completely destroyed. The so-called Rompas trend (Fig. 2) is approximately 6-km-long and few-hundred-m-wide, NW-trending ridge consisting of amphibolite-facies mafic rocks, representing most probably originally basaltic volcanic rocks, dolomite-bearing metasedimentary units, and strongly altered carbonate-albite rocks (Vanhanen et al., 2015). West of the Rompas trend, carbonaceous schists and arkosic and aluminous metasediments with local mafic metavolcanic rocks are present. Quartzites and dolomitic rocks characterize the eastern side of the Rompas trend.

The Rajapalot area is located a few kilometers to the east of the Rompas trend. The sparse outcrops in this area are dominated by reddish calcsilicate-albite rocks, variably altered quartzites and mafic metavolcanic, and mafic intrusive rocks (e.g., Ranta et al., 2017, 2018). Due to the Quaternary sediment cover and the scarcity of outcrops, no detailed geological map of the area has been published. In addition to the above-listed outcropping lithologies, cordierite-orthoamphibole rocks and black bituminous sedimentary rocks have been encountered by drilling (Ranta et al., 2015a, 2017, 2018). Tourmaline-rich pegmatites dated at ca. 1.78 Ga crop out in the northern part of the Rajapalot area (Ranta et al., 2015b).

Despite the complexities of the Rompas-Rajapalot prospect area, some attempts have been made to correlate lithological units of the mineralized area with the general stratigraphy of the Peräpohja belt. Based on major and trace element chemistry, Mustonen (2012) linked the mafic rocks in the Rompas Au-U-mineralized area with the lowermost mafic volcanic unit in the stratigraphy, the Runkaus Formation, running close to the SE margin of the Peräpohja belt (Perttunen & Hanski, 2003). If this correlation is valid, it would indicate that Runkaus Formation rocks exist at the northern margin of the Peräpohja belt in a close spatial association mica schists belonging to the uppermost stratigraphic units of the belt. Huttu (2014) studied ultramafic rocks found in drillcore and outcrop in the Rompas area and in drillcore in the Rajapalot area. He concluded that in terms of petrography and geochemistry, these rocks resemble 2.22 Ga mafic–ultramafic sills, the so-called Haaskalehto-type gabbros, which also are characteristic in the lower part of the stratigraphy of the Peräpohja belt, being emplaced into sedimentary rocks of the Palokivalo Formation of the Kivalo Group (Hanski et al., 2010).

5. Review of original publications

5.1 Overview

This academic dissertation is based on three papers published in internationally recognized peer-reviewed journals. These papers provide insights into recently discovered gold occurrences in the Paleoproterozoic supracrustal sequence in the northern part of the Peräpohja belt. In Paper I (Ranta et al., 2015b), U-Pb zircon dates from granitic rocks nearby the gold occurrences and Sm-Nd isotopic data from the metasedimentary rocks are presented. The purpose of that study was to examine the age relationships of different lithological units within the northern part of the Peräpohja belt and how they correlate to the evolution of the whole supracrustal belt.

In Paper II, boron isotope analyses conducted by LA-ICP-MS are used to constrain the source of boron in tourmaline (Ranta et al., 2017). Mineral chemistry and boron isotope data are presented from 1) tourmaline associated with the Palokas gold occurrence, 2) tourmaline occurring in post-orogenic granitoids, and 3) tourmaline found in the Petäjäskoski Formation, a stratigraphic unit inferred to be evaporitic in origin (Kyläkoski et al., 2012).

Paper III focuses on the petrography, mineral chemistry, whole-rock geochemistry and fluid inclusion compositions of the Palokas gold occurrence (Ranta et al., 2018). The purpose of this study was to examine the composition of the hydrothermal fluids responsible for formation of the tourmaline-sulfide-(gold) breccias. Whole-rock geochemistry of the gold-hosting lithologies is used to evaluate the potential protolith and correlation within the stratigraphy of the Peräpohja belt.

5.2 Paper I

U-Pb and Sm-Nd isotopic constraints on the evolution of the Paleoproterozoic Peräpohja belt, northern Finland.

Jukka-Pekka Ranta, Laura S. Lauri, Eero Hanski, Hannu Huhma, Yann Lahaye, Erkki Vanhanen, 2015

Precambrian Research 266, 246–259.

Paper I interprets U-Pb and Sm-Nd isotope data representing metasedimentary and granitic rocks from the northern part of the Paleoproterozoic Peräpohja belt. The data revealed two phases of granitic magmatism taking place at 1.99 Ga and 1.79–1.77 Ga. The former age corresponds to a pre-orogenic event of granitic magmatism as the Svecofennian orogenic magmatism in generally thought to have begun at ca. 1.95 Ga (Nironen, 2005). The obtained age for the Kierovaara granite represents the first example of pre-orogenic granitic plutonism of this age in the Fennoscandian Shield, though A-type felsic rocks of the same age, interpreted as volcanic rocks, have been previously recognized (Hanski et al., 2005). The younger magmatic event (1.79–1.77 Ga) represents the main stage of the generation of the Central Lapland granitoid complex. The presence of Archean basement in northern Finland at the time of the granitic magmatism is demonstrated by the strongly negative initial ε_{Nd} (-3.9 to -11.4) values obtained for the granitoids in this study (Table 3).

A minimum depositional age of the youngest sedimentary unit in the Peräpohja belt was defined to be between 1.91–1.88 Ga based on the youngest population of the detrital zircons and cutting 1.88 Ga Haaparanta suite granitoids published by Perttunen & Vaasjoki (2001). The new detrital zircon age data define the chronostratigraphy of the Peräpohja belt more accurately (Table 2). The quartzitic Mellajoki Suite, previously regarded as a lithodemic unit and part of the Central Lapland granitoid complex, is proposed to be correlative with the thick quartzitic Palokivalo Formation in the lower part of the stratigraphy of the Peräpohja belt, based on the presence of solely Archean detrital zircon populations in both of these formations.

Table 3. TIMS Sm-Nd data (modified after Ranta et al., 2015b).

Sample	Location	Rock type	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2se	T (Ma)	ε(T)	T-DM* (Ma)
A2160	Männikkömaa	Mica gneiss	5.52	31.83	0.1048	0.511005	0.000010	1900	-9.6	2864
A2160 grt	Männikkömaa	Garnet	0.37	0.32	0.6926	0.517778	0.000046	1700	-8.0	
A2161	Matalavaara	Granite	2.80	20.69	0.0819	0.510966	0.000010	1775	-6.6	2400
A2162	Matalavaara S	Granite	3.57	14.41	0.1496	0.511650	0.000018	1793	-8.5	3386
A2163	Mustivaara N	Granite	2.01	5.40	0.2254	0.512397	0.000011	1780	-11.4	
A2164	Mustivaara S	Granite	0.84	1.93	0.2638	0.512847	0.000031	1780	-11.4	
A2165	Karhurommas	Mica schist	10.49	63.94	0.0992	0.510996	0.000010	1900	-8.4	2730
A2166	Hosiovaara	Quartzite	0.54	3.03	0.1081	0.510982	0.000014	1900	-10.8	2990
A2167	Mäntylaki	Mica schist	5.57	28.81	0.1168	0.511499	0.000011	1900	-2.8	2429
A2168	Louevaara	Quartzite	1.07	5.59	0.1156	0.511052	0.000016	1900	-11.3	3116
A2169	Kierovaara	Granite	4.78	30.46	0.0948	0.511106	0.000010	1989	-4.0	2483

Error in $^{147}Sm/^{144}Nd$ is 0.4%.

*Depleted mantle model age after DePaolo (1981)

5.3 Paper II

Source of boron in the Palokas gold deposit, northern Finland: evidence from boron isotopes and major element composition of tourmaline.

Jukka-Pekka Ranta, Eero Hanski, Nick Cook, Yann Lahaye, 2017

Mineralium Deposita 52, 733–746

This paper focuses on the mineral geochemistry and boron isotopes in tourmaline associated with gold in the Palokas Au occurrence. Chemical and boron isotope compositions were also measured for tourmaline associated with a post-orogenic pegmatitic granite, located approximately one km from the Palokas occurrence and for tourmaline in a phlogopitic schist interpreted to be part of an evaporitic succession (Petäjäskoski Formation). In the gold mineralization, tourmaline occurs as crystals in sulfide-rich, metasomatized, gold-enriched rocks (Type 1 tourmaline) and as tourmalinite veins up to ~30 cm thick (Type 2 tourmaline).

Based on the X-site occupancies (Hawthorne & Henry, 1999), all the studied tourmaline samples belong to the alkali-group and can be classified as dravite and schorl in the Mg/(Mg+Fe) vs. Ca/(Ca+Na) diagram (Fig. 5 in Ranta et al., 2017). Crystal zoning was observed most notably in Type 1 tourmaline, which shows three distinct domains. Zoning is created by increasing Ca, Ti, Fe, Mg and X-site vacancies and decreasing Al towards the brighter rims. In Type 2 tourmaline zoning was weaker but where observed, responded similar elemental increase towards rims as in Type 1. Tourmaline in the tourmaline granite shows no clear compositional differences. In the tourmaline from the Petäjäskoski Formation, only local darker patches were observed. The AFM diagram of Henry & Guidotti (1985) and multiple scatter plots with reference substitution vectors were used to observe the variation in the analyzed tourmaline samples and to get indications of redox conditions during the formation of the crystals. Based on the cation substitution in all the tourmaline samples, no evidence of Al substitution by Fe^{3+} is observed and hence the environment seems to have been reducing. This interpretation is supported by the mineralogy of the samples, for example, the existence of pyrrhotite as the main sulfide phase.

Table 4 and Fig. 5 summarize the results of the isotope measurements. All the analyzed tourmaline samples share a similar boron isotope signature with very little variation. Such a homogeneous range of $\delta^{11}B$ values implies a common boron source for all the rocks which the samples represent. A comparison of the tourmaline boron isotope compositions obtained in this study (red stippled outline) with boron isotope data for tourmaline from different geological settings and for global reservoirs shown in Fig. 5. The $\delta^{11}B$ values of the tourmaline granite from this study fall in the heavier range of measured pegmatitic tourmalines (Jiang & Palmer, 1998) as usually they show more negative values, generally lower than -5 ‰ (e.g., Marschall & Jiang, 2011). Two textural types of tourmaline from the Palokas gold occurrence show similar $\delta^{11}B$ values, ranging from ~-4 to -1.1 ‰ with a minor core-to-rim variation. Tourmaline from the evaporitic Petäjäskoski Formation does not show a heavy marine evaporitic signature. On the other hand, all the measured tourmaline compositions show signatures similar those of non-marine evaporitic rocks.

The isotopic similarity of tourmaline cores and rims, and homogeneous isotope values between tourmaline grains within the tourmaline granite indicate that tourmaline in the tourmaline granite was crystallized during a single late magmatic-hydrothermal stage and not directly from magma. Boron isotope compositions do not easily vary during hydrothermal or metamorphic processes and hence retain their original signature of the source (e.g., Palmer & Swihart, 1996).

Table 4. Average $\delta^{11}B$ values (LA-ICP-MS) of analyzed tourmaline cores and rims (data from Ranta et al., 2017).

Sample	$Core_{avg}$	$Core_{s.d.}$ [2]	N_{core} [1]	Rim_{avg}	$Rim_{s.d.}$ [2]	N_{rim} [1]
Tourmaline Granite (A2164)	-3,15	0,59	9	-3,1	0,54	6
Petäjäskoski Formation (OY26383)	-3,32	0,38	6	-3,42	0,37	3
Type 1 (OY26382)	-2,27	0,79	11	-2,29	0,84	7
Type 1 (OY26380)	-2,31	1,48	16	-2,27	1,43	9
Type 2 (OY26381)	-4,05	0,28	6	-3,9	0,37	2

[1] Number of analyses

[2] Standard deviation

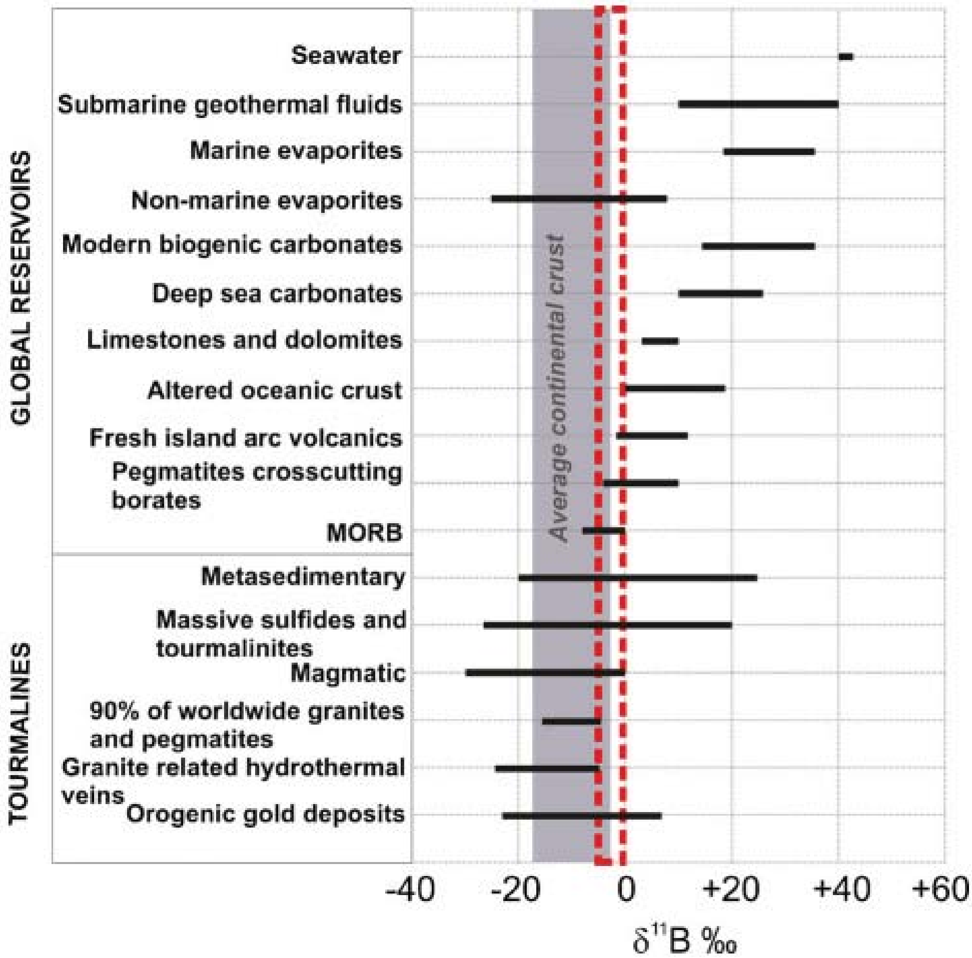

Figure 5. Boron isotope data of this study shown in red stippled outline compared with boron isotope data for tourmaline from different geological settings and global reservoirs (modified after Garda et al. (2009). The $\delta^{11}B$ values in natural reservoirs are after Palmer and Swihart (1996). Compilation of boron isotope data from granite and pegmatite is after Van Hinsberg et al. (2011), and from orogenic deposits after Jiang et al. (2002), Krienitz et al. (2008), Garda et al. (2009), and Beaudoin et al. (2013). Figure is from Ranta et al. (2017).

In summary, tourmaline from all three localities show uniform $\delta^{11}B$ values, implying a common boron source. Boron isotope data support the role of late- to post-orogenic igneous activity (1.79–1.77 Ga) in the formation of gold occurrences in the Rompas-Rajapalot area. The Re-Os age on a single molybdenite grain (1.78 ± 0.01 Ga; Molnár et al., 2017a) related to tourmaline-sulfide-quartz-gold veins provides further evidence for the link between the granitic magmatism and gold mineralization.

5.4 Paper III

Epigenetic gold occurrence in a Paleoproterozoic meta-evaporitic sequence in the Rompas-Rajapalot Au system, Peräpohja belt, northern Finland.

Jukka-Pekka Ranta, Ferenc Molnár, Eero Hanski, Nick Cook, 2018

Bulletin of the Geological Society of Finland 52, 733–746.

Paper III presents results of a petrographic and mineral chemical study of the gold occurrence at Palokas. Major and trace element characteristics, as well as fluid inclusion compositions of tourmaline, are also used to evaluate the origin and pressure-temperature-fluid composition parameters of the involved hydrothermal fluids. Whole-rock geochemical data are used to evaluate the nature of the protoliths of the host rocks.

At Palokas, the gold is hosted by cordierite-orthoamphibole rocks interlayered with calcsilicate-albite rocks. Cordierite-orthoamphibole rocks show a large range in the SiO_2 content, from 25 to 65 wt.%, which correlates negatively with the degree of chloritization and sulfidization. The CaO content is generally low, less than 2 wt.%. Most of the analyzed samples show an Al_2O_3 content between 10–14 wt.%, whereas in the most chloritized drill core intervals, Al_2O_3 is up to 18 wt.%.

The MgO content spans from about 4 to 13.5 wt.%, increasing with the degree of chloritization. Most of the non-chloritized samples have a MgO content between 6 and 10 wt.%. Na_2O varies from less than 1 wt.% in the chloritized samples to up to 6 wt.% in non-chloritized samples. The chondrite-normalized REE patterns are enriched in LREE compared to HREE, and negative Eu anomalies are evident (Eu/Eu* 0.20–0.81).

Gold occurs in a native form and is present, at least, as two textural types: 1) Single, relatively coarse grains, which are disseminated among the rock-forming silicates in cordierite-orthoamphibole rocks (Fig. 6a), and 2) Smaller grains occurring in fractures of tourmaline in quartz-sulfide-tourmaline breccias and in fractures of chloritized cordierite-orthoamphibole rocks adjacent to the tourmaline-rich breccias (Figs. 6b–d). Fracture-related gold is associated with Bi-Se-S-rich tellurides (Se-rich tetradymite mostly), native Bi, molybdenite, chalcopyrite, and pyrrhotite. Coarser-grained, disseminated gold was not found to be clearly associated with sulfides nor with any fractures. Statistical assessment of data shows that the gold concentration has a strong positive correlation with Te, Cu, Co, Se, Bi, Mo, and Ag (0.730–0.619), whereas moderate positive correlations are found with As, Fe, W (0.523–0.511), and to a lesser degree with U, Pb, and Ni (0.492–0.407). On the other hand, gold has the strongest negative correlation with Sr and Ca.

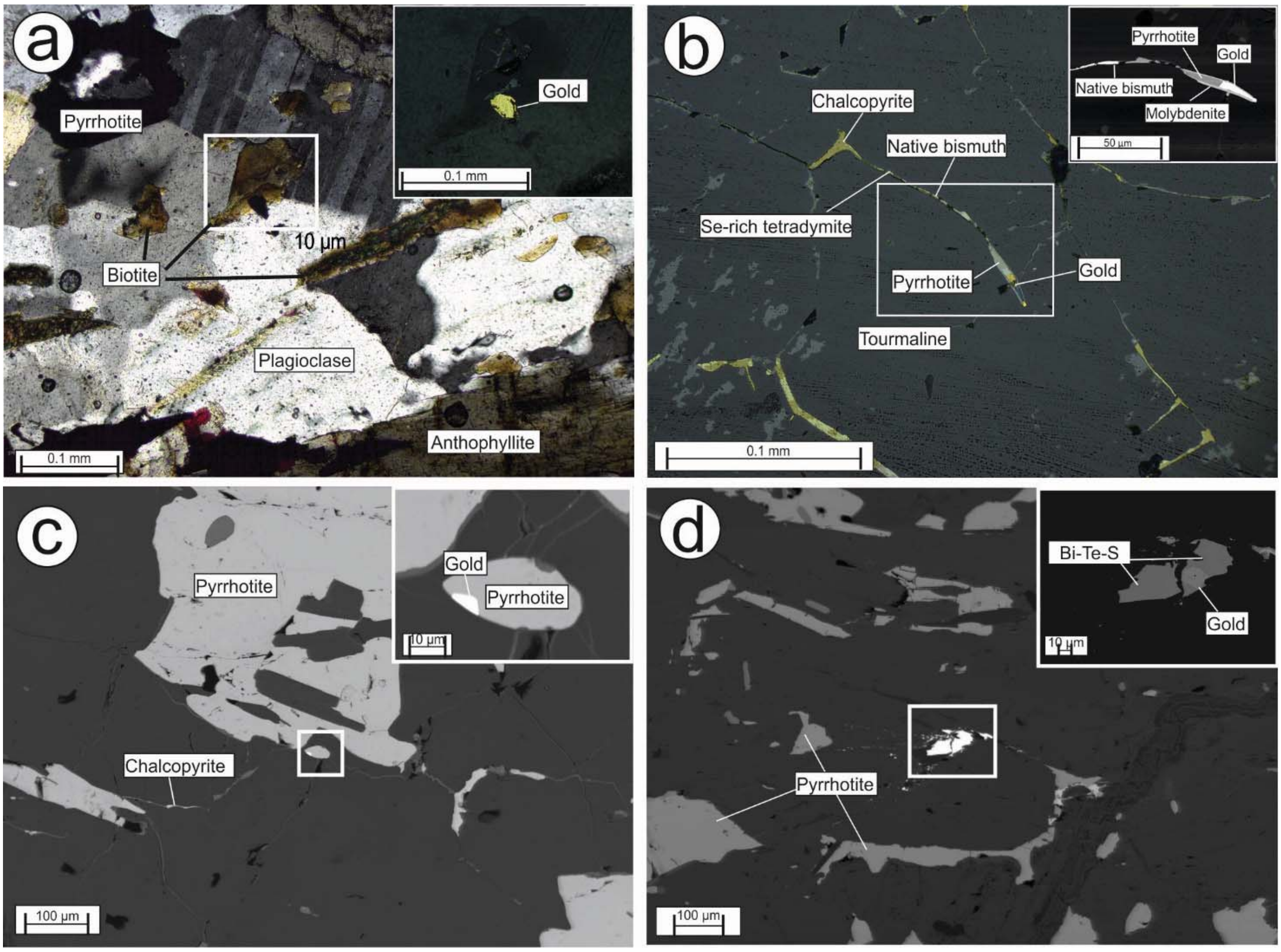

Figure 6. Native gold grains found at Palokas (modified from Ranta et al. (2018). Rectangle area indicates an inset area of each image. a) Photomicrograph of a native gold grain between silicates (plagioclase and biotite), cross-polarized light, sample JPR140501. b) Back-scattered electron (BSE) image of gold in fractures of tourmaline together with ore minerals, sample PRAJ0006-6m. c) BSE image of native gold in the edge of pyrrhotite in a highly chloritized interval, sample 131766. d) BSE image of native gold with an associated Bi-Te-S grain in fracture within a highly chloritized interval, sample JPR140527.

Tourmaline is more resistant against mechanical and chemical alteration compared to quartz and carbonates, hence it usually contains limited amounts of secondary fluid inclusions. Therefore, tourmaline from the gold-bearing veins was chosen for the fluid inclusion study. Two types of primary fluid inclusions were found in tourmaline. They can be divided into two types according to their phase composition observed at 40 ^{o}C and considering their microthermometric and Raman spectrum data. Type 1 inclusions have an aqueous liquid + carbonic vapor (Laq+Vcar) composition with a highly variable degree of filling (DF; vapor/total inclusion volume) ranging approximately from 0.3 to 0.7. Type 2 fluid inclusions have an aqueous liquid+carbonic liquid (Laq+Lcar) phase composition and their DF is also highly variable, falling between 0.3 and 0.8. Most of the Type 2 inclusions show a Laq+Lcar+Vcar phase composition at room temperature. The primary fluid inclusions are mostly found isolated with a variable DF, but when occurring in groups, they usually show a relatively constant DF ratio around 0.4. However, in some assemblages of Type 2 inclusions, highly variable DF ratios were also detected. Type 1 and Type 2 were not observed together in recognizable fluid inclusion assemblages (FIA). No clear relationship between the occurrence of the types of primary fluid inclusions and rims or cores of the tourmaline crystals were observed.

Fluid inclusion studies of tourmaline in gold-rich quartz-tourmaline-sulfide veins indicate that the veins were formed from H_2O-NaCl-CO_2-CH_4-(H_2S) fluids in a *boiling system* under pressure conditions ranging from lithostatic to hydrostatic at a depth of approximately 5 km and at a temperature of ∽300 ^oC. The brecciating nature of sulfides and gold in the late tourmaline-rich veins indicates a sudden pressure drop and boiling during metal precipitation, supporting the results of the fluid inclusion study. The salinities in the Type 1 fluid inclusions vary between 0.2 and 8.9 wt.% equiv. NaCl (avg. 6; n=9), whereas in the Type 2 fluid inclusions, they range from 1.6 to 6.9 wt.% equiv. NaCl (avg. 3.7; n=6). The properties of ore-forming fluids are compatible with the results of earlier studies, including the Re-Os molybdenite dating (Molnár et al., 2017a) and boron isotope data from tourmaline (Ranta et al., 2017), indicating the same timing and suggesting a genetic link between the late- to post-orogenic granitoid magmatism at ∽1.78 Ga and the formation of the fracture-hosted gold mineralization.

Whole-rock geochemistry of the cordierite-orthoamphibole and calcsilicate-albite rocks were compared to other rock units in the Peräpohja belt and to some of the cordierite-orthoamphibole rocks taken from the literature. Trace-element systematics of the cordierite-orthoamphibole rocks in the Palokas area indicate that the protolith is not a mafic rock, in contrast to the majority of the occurrences of similar types of rocks (e.g., Pan & Fleet, 1995). Geochemical data point to a sedimentary protolith with an unusually high Mg and low Ca content. Furthermore, many trace-element features are generally similar to those of the Petäjäskoski Formation, which is considered to be an evaporitic unit (Kyläkoski et al., 2012). Accumulation of magnesian clays (e.g., palygorskite and sepiolite) in a lake-margin environment could produce a composition which is required for the formation of a cordierite-orthoamphibole assemblage during metamorphism (Reinhardt, 1987). Usually these magnesian clay-rich sediments are interbedded with clastic sediments and carbonates (Warren, 2016). In the ternary Ca-Mg-Al diagram of Moine et al. (1981), cordierite-orthoamphibole rocks from Palokas plot in the middle part of the Al-Mg edge where the palygorskite composition also occurs (Fig. 7). Interlayered calcsilicate rocks plot in the central part of the diagram within the field that represents the non-evaporitic platform sediments from Moine et al. (1981 and references therein).

Albitization is a typical phenomenon during sedimentation and diagenetic processes in evaporitic sequences where dissolution of halite produces fluids rich in sodium (e.g., Warren, 2016). Widespread Na metasomatism has occurred in the Peräpohja belt and in other similar Paleoproterozoic supracrustal sequences shield-wide (e.g., Cook & Ashley, 1992; Eilu, 1994; Vanhanen, 2001; Melezhik et al., 2013; Melezhik et al., 2015). The origin of hydrothermal fluids producing such a regionally extensive Na (and also Cl) alteration has been proposed to be in the remnants of abundant accumulation of early Paleoproterozoic salts, which were remobilized and largely dissolved during diagenetic, orogenic, magmatic and metamorphic processes (e.g., Yardley & Graham, 2002; Melezhik et al., 2015). A preserved salt record of this time interval is represented by the halite and massive anhydrite intervals exceeding 200 m in thickness that have been found in the Onega Basin, Russia (e.g., Melezhik et al., 2013). Based on the widespread regional albitization and overall tectonic settings, the former presence of similar units have been proposed in the Kuusamo belt (Vanhanen, 2001; Vasilopoulos et al., 2016), Peräpohja belt (Kyläkoski et al., 2012) and Alta-Kvaenangen tectonic window in Norway (Melezhik et al., 2015).

The metamorphic mineral assemblages of the calcsilicate-albite rocks in the Rajapalot area indicate originally calcitic-dolomitic marls that were metamorphosed under amphibolite facies, producing calcsilicate minerals. Later, the prograde diopside was partly replaced by tremolite when the temperature decreased. A relatively thick (~60 m), black, bituminous rock unit has been penetrated by drilling in the northern part of the Rajapalot area. In addition, veins of black bituminous material (~0.5 m thick) have been found to cut mafic rocks in outcrops. This carbonaceuous material closely resembles shungite, black and dense amorphous carbon in the Karelian Zaonega Formation near Lake Onega in Russian Karelia (Melezhik et al., 1999). Melezhik et al. (1999) concluded that these rocks represent geologically the earliest stages of petroleum generation, being present both as autochthonous bitumen (now pyrobitumen) and migrated bitumen (originally petroleum). In lacustrine evaporitic settings, accumulation of oil shale is common during lake high-stand periods (Warren, 2016). The black pyrobituminous unit in the

Rajapalot area could represent such a high-stand period of a lacustrine basin where oil shale deposition and migration of hydrocarbons took place. This provides further evidence for the evaporitic model of the Rajapalot rocks.

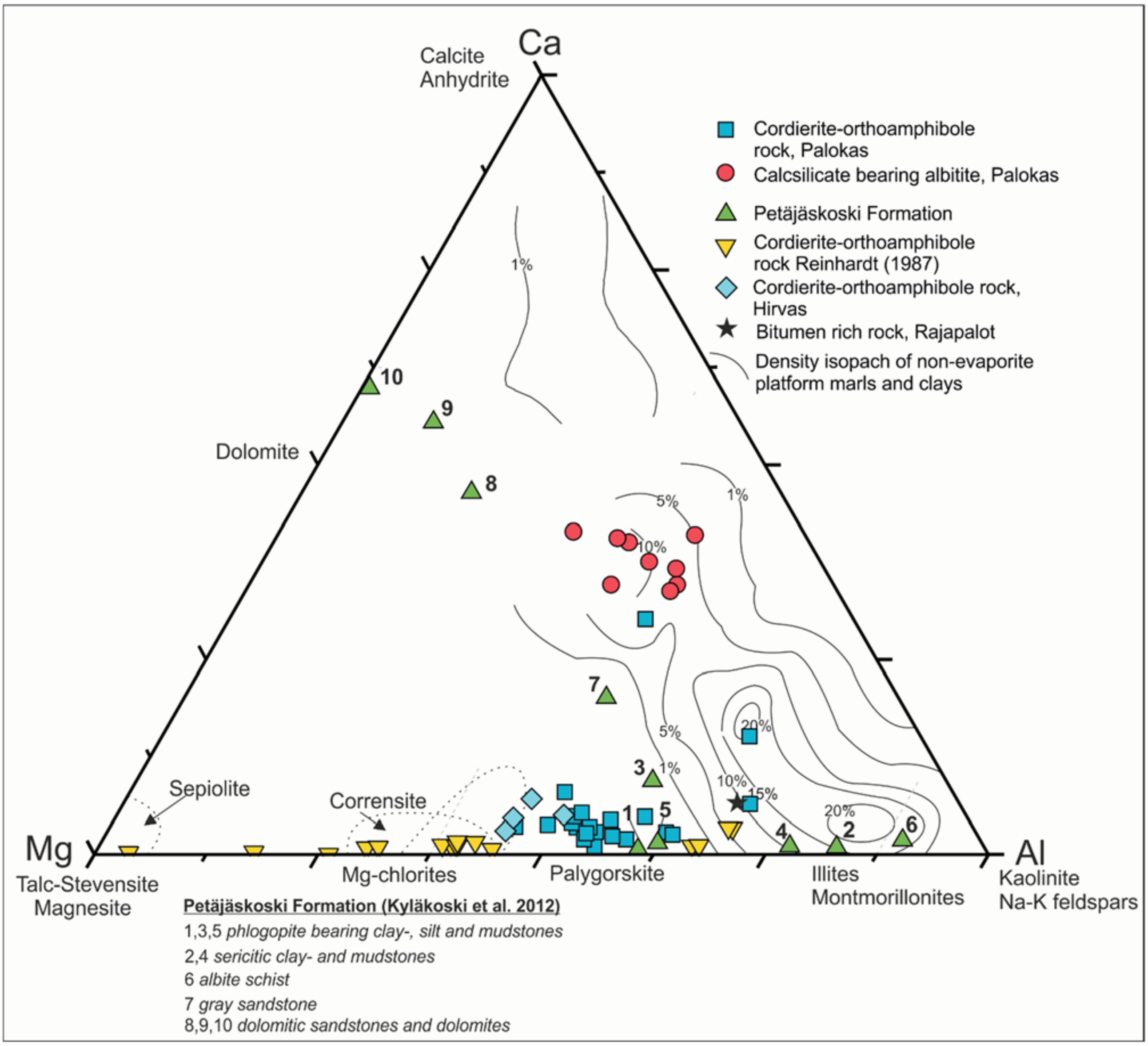

Figure 7. Al-Mg-Ca ternary diagram after Moine et al. (1981) and Warren (2016), developed for the identification of meta-evaporitic rocks. Figure taken from Ranta et al. (2018).

In summary, this study further supports the temporal, spatial and genetic link between the ca. 1.78 Ga magmatism and fracture-related gold, as proposed earlier by Molnár et al. (2016) and Ranta et al. (2017). However, the available exposures, drillcore and observations on geology and structures are not sufficient to classify the Palokas Au occurrence or the whole Rompas-Rajapalot system to any specific genetic class of gold deposits, as not enough is known from these occurrences. Nevertheless, at least two different textural settings for gold at Palokas, which were first described by Ranta et al. (2017), imply multiple stages of mineralization. The relationship between the different stages is not known at this point. The host rock is suggested to represent an originally evaporitic environment, producing the unusual whole-rock composition and mineral assemblage. Based on the available data, stratigraphically, these rocks could be correlated with the Petäjäskoski Formation described by Kyläkoski et al. (2012).

6. Discussion

6.1. Geology of the northern part of the Peräpohja belt

The Peräpohja belt records a typical intracratonic volcano-sedimentary rift basin evolution where deposition of sedimentary and volcanic rocks were active between ca. 2.44 and ca. 1.9 Ga. Similar belts are distributed throughout the Karelian craton and in Finland, they are referred to as the Karelian Supergroup or Karelian formations in the literature (e.g., Luukas et al., 2017) (Fig 1.). The Karelian formations were deformed and metamorphosed under greenschist- to amphibolite facies conditions during the Svecofennian composite of orogenies during 1.90–1.76 Ga. The complex deformation evolution of the Peräpohja belt comprising at least five different stages (Lahtinen et al., 2015; Lahtinen et al., 2018), and the upper greenschist to amphibolite facies metamorphism cause challenges to the interpretation of the stratigraphy of the belt, especially in its northern part. Furthermore, at the northern contact zone of the Peräpohja belt with the Central Lapland granitoid complex (CLGC), rocks are partly migmatized during the main phase of emplacement of the CLGC granitoids ca. 1.80 Ga (Ranta et al., 2015b: Lahtinen et al., 2018).

An overview of the tectonic evolution of northern Finland was recently published by Nironen (2017). From 1.93 Ga to 1.83 Ga, northern Finland experienced three major collisional events related to the Lapland-Kola, Norbotten-Karelia and Svecofennian orogenies, which were followed by thrusting, crustal thickening, metamorphism, and finally orogenic collapse of the formed mountain ranges. In addition, the formation of major shear zones (e.g., the Pajala shear zone) at this time played an important role in movements of metal-rich hydrothermal fluids along the shear zones during the late Svecofennian (1.84–1.77 Ga), resulting in the formation of orogenic gold deposits across the Paleoproterozoic terrain of Finland (e.g., Molnár et al., 2017b).

The Paleoproterozoic granites in Finland are divided into pre-orogenic (1.95–1.91 Ga), syn-orogenic (1.89–1.86 Ga), late-orogenic (1.84–1.80 Ga) and post-orogenic (1.80–1.77 Ga) types (Nironen, 2005). The age range of the pre-orogenic type is extended as more geochronological data have become available. In the Peräpohja belt, the pre-orogenic granitoids are represented by the 1.99 Ga Kierovaara granite (Ranta et al., 2015b). The oldest Paleoproterozoic granitoids in the Central Lapland granitoid complex, north of the Peräpohja Belt, are dated at ca. 2.43 Ga (Lahtinen et al., 2018). The ca. 1.88 Ga Haaparanta suite plutonic rocks cutting across supracrustal rocks of the Peräpohja belt belong to the synorogenic granitoid class. The post-orogenic granitoids are represented by the granitoids dated at 1.79–1.77 Ga in the northern part of the Peräpohja belt, including the tourmaline-rich pegmatitic granite in the vicinity of the Palokas gold mineralization. However, even though the age of these granitoids is similar to that of the post-orogenic granitoid phase in general, they cannot be classified as post-orogenic as many of them were emplaced during tectonic activity and commonly show a foliation (e.g., Ahtonen et al., 2007; Lauri et al., 2012; Ranta et al., 2015b). According to Ahtonen et al. (2007), during 1.79–1.76 Ga, the northern part of the Fennoscandian Shield was affected by intensive deformation, metamorphism and melting, which were coeval with the post-orogenic magmatism in the southern part of the shield. Evidence for the <1.8 Ga metamorphism is found from metamorphic zircon overgrowths in granitoids and metasediments at the northern edge of the Peräpohja Belt and in the Central Lapland granitoid complex (Lahtinen et al., 2018). Based on our work in the northern part of the Peräpohja belt, the 1.78 Ga granites are emplaced at the very end of tectonism. This interpretation is derived from field relationships, the lack of internal fabric development, and local porphyritic textures, all indicating post-tectonic emplacement across the boundary of the main Central Lapland granitoid complex.

The minimum age for the sedimentation in the Peräpohja belt has been defined from the Haaparanta suite granitoids, which cut the youngest sedimentary unit (Martimo Formation). In terms of evolution of the Karelian formations, the Martimo Formation can be assigned to the Kalevian system (1960–1900 Ma), containing turbiditic qreywackes and black shales (Hanski & Melezhik, 2012). The Kalevian system has been divided into autochthonous-parautochthonous Lower Kalevian and dominantly allochtonous Upper Kalevian, enclosing fragments of ophiolite complexes (Kontinen, 1987). The division was further defined by Lahtinen et al. (2010) showing that the Lower Kalevian rocks contains detrital zircon populations derived almost solely from

Neoarchean rocks of the Karelian craton whereas the Upper Kalevian rocks comprise a large component from Paleoproterozoic sources as evidenced by detrital zircon populations 1.95–1.91 Ga in age.

Lahtinen et al. (2013) challenged this relatively simple division by presenting relatively young zircon populations (ca. 1.91–1.92 Ga) from rocks previously assigned to the Lower Kaleva based on their difference from typical ophiolite-bearing allochtonous sedimentary strata at the western margin of the Karelian Province (Kohonen, 1995). Similarly, zircon populations with an age of ca. 1.92–1.90 Ga have been found from other “Lower Kalevian” rocks, including the Martimo Formation in the Peräpohja belt (Ranta et al., 2015b; Lahtinen et al., 2015). In addition, Kalevian-type deep-water metasediments in the Central Lapland greenstone belt contain phyllites and black shales that are older than or equal in age to the ca. 2.06 Ga Kevitsa mafic-ultramafic intrusion emplaced into the phyllites (Mutanen & Huhma, 2001). Based on the detrital zircon dating from the Martimo Formation, it is likely that at least two distinct Kalevian metasedimentary units exist in the Peräpohja belt, one containing solely Archean zircon populations (Hanski et al., 2005) and one containing mixed Archean and Paleoproterozoic population with the youngest grains between 1.95–1.91 Ga (Ranta et al., 2015b; Lahtinen et al., 2015).

6.2 Genetic classification of the Rompas-Rajapalot Au occurrences

The Peräpohja belt has drawn the interest of exploration industry and researchers as a potential host for world-class mineral deposits, especially after the discovery of the Rompas-Rajapalot area (initial discovery in 2008) showing multiple gold anomalies with local extremely high gold grades (>3% Au: Vanhanen et al., 2015) in an area extending over 10 x 10 km. The genetic classification of these gold occurrences has been challenging due to the atypical metal assemblages, timing and alteration features that do not fit into the classical genetic classification schemes of ore deposits (see Eilu, 2015).

The metal association of Te-Cu-Co-Se-Bi-Mo-W-Ag-Au at Palokas and the close spatial relationship of U and gold in the whole Rompas-Rajapalot area are not typical for the orogenic gold deposits nor for reduced intrusion-related gold deposit systems. However, as we are dealing with an old metamorphozed intracratonic basin, probably several hydrothermal events have occurred, each of them contributing to the metal enrichment. Goldfarb et al. (2001) suggested that in the areas where Paleoproterozoic tectonism has deformed older intracratonic basins, orogenic gold deposits could show anomalous metal associations, most notably Ag, Cu, Co, Ni or Sb, due to the saline fluids released from evaporitic strata during metamorphism (e.g., Yardley & Cleverley, 2013). It is clear that such a basinal fluid circulation was active in the Karelian supracrustal cover sequences, resulting in widespread albitization of the rocks (e.g., Eilu, 1994; Vanhanen, 2001; Melezhik et al., 2013). This alteration produced competent lithologies, preparing the ground for later ore-forming processes (e.g., Eilu, 2015). Molnár et al. (2016) proposed that uranium was enriched prior to gold at Rompas, initially during pre-orogenic processes and later during re-mobilization related to metamorphism. Moreover, a structural control, which is the most important feature in orogenic gold deposits, remains unidentified in the Rompas-Rajapalot gold system. Reactive lithologies and chemical traps seem to have played an important role in metal precipitation in the area (e.g., Molnár et al., 2016)

Goldfarb et al. (2005) stated that the following features of the reduced intrusion-related gold systems (RIRGS) distinguish them from the orogenic gold deposits and should be used when evaluating the RIRGS genetic model for a gold deposit:
1) *Low Au grade* (<1 g/t in the RIRGS vs. 5–10 g/t in orogenic gold deposits). Based on the current grades at the Rompas-Rajapalot area, this seems to be not the case. However, the occurrences are still at the exploration stage and no resource estimation have been done.
2) *Location in a deformed shelf sequence inland from accreted terranes.* The regional geological framework of the Peräpohja belt (intracratonic rift basin) in consistent with this argument.
3*) Regional association with tungsten and/or less consistently, tin lodes.* Elevated W contents in the gold-critical areas is a typical feature of the Palokas Au occurrence and can be seen as a moderate correlation between W and Au in the geochemical data (see Table 3). Scheelite is a common mineral in the area and a spatial correlation with scheelite and gold can be seen in drill core. However, so far, no tungsten nor tin lodes have been found.
4) *A post-deformational timing relative to more of a late synorogenic timing for orogenic gold deposits.* The Re-Os age of molybdenite associated with gold in the tourmaline-rich zones at Palokas shows an age of 1.78 ± 0.01 Ga (Molnár et al., 2017a). This is consistent with the age of the pegmatitic tourmaline-rich granite in the vicinity of the Palokas occurrence. The granite does not show obvious deformation and thus could be classified as post-deformational. However, as stated above, during 1.79–1.76 Ga, the northern Fennoscandian Shield was affected by intensive deformation, metamorphism and melting and therefore classifying the granitoids of that age as

post-deformational is misleading.

5) *Anomalous granitoid system reflecting some input from mantle-derived mafic alkaline magmas into the base of the crust.* In general, the granitoids of the 1.79–1.77 Ga age group in the Peräpohja belt show negative initial ε_{Nd} values indicating the presence of a strong crustal component from the underlying Archean basement (e.g., Ranta et al., 2015b). However, ca. 1.80 Ga appinitic intrusive rocks with suggested mantle-derivation have been reported from the Peräpohja belt and the Central Lapland granitoid complex (Väänänen, 2004; Mutanen, 2011; Tainio, 2014).

Based on the observed characteristics of the Palokas gold occurrence, the classification of the gold mineralization in the Rompas-Rajapalot Au prospect as a reduced intrusion-related gold system cannot be reliably made. The metal association, reduced sulfide assemblage, low- to moderate salinity of H_2O-NaCl-CO_2-CH_4-(H_2S) hydrothermal fluids, and the spatial, temporal and even genetic relationship to granitoids are not diagnostic solely to a single deposit type and can be found, for example, in orogenic gold deposits (Goldfarb et al., 2005). Furthermore, the most distinguishable feature for the RIRGS, the presence of sheeted auriferous veins within the granites, has not been observed. The geophysical (gravity and aeromagnetic) data of Mawson Resources from the outcropping granites suggest the subsurface presence of granitic rocks in the Rompas-Rajapalot area and thus, a possibility of the presence of such sheeted complexes still remains.

In the Rompas-Rajapalot (including Palokas) prospect area, the alteration and mineralization styles vary considerably from the Rompas-type vein-hosted, nuggety gold system (see Molnár et al., 2016) to more disseminated sulfidic style of gold mineralization in the Rajapalot area, east of Rompas (e.g., Cook, 2017). The real extent of the mineralized area and the diversity of the mineralization styles are not yet fully understood due to the lack of sufficient information (presently, the gold-anomalous area is 10 x 10 km in size) and, hence, not enough is known about the epigenetic gold occurrences in the Rompas-Rajapalot area to reliably classify them. Genetic types, including the orogenic gold and reduced intrusion-related gold classes, are not fully supported at this point due to the lack of several key features. The most important factor in the orogenic gold deposits, the strong structural control, is not obvious in the Rompas nor the Rajapalot area. At Rompas, the calcsilicate veins are earlier than the gold mineralization and the uraninite and the pyrobitumen in the calcsilicate veins acted merely as a trap for gold precipitation. In the Rajapalot area, especially in the Palokas occurrence, the mode of occurrence of gold appears to be more controlled by the reactive cordierite-orthoamphibole rocks than purely structural features. When considering the RIRGS, the apparent lack of mineralized sheeted veins within the granites and other critical features of the system listed by Goldfarb et al. (2005) are not enough to classify these deposits as RIRGS or to any other class at this point. Thus, for now, the use of the Rompas-type Au or Rompas-Rajapalot type Au is recommended. Future research with an emphasis on the structural setting of gold in different gold occurrences in the Rompas-Rajapalot prospect area will surely enhance our understanding of the gold occurrence in the northern part of the Peräpohja belt. The metal association at Palokas shows some similarities to the Kuusamo Au-Co-Cu-U-LREE deposits (see Vanhanen, 2001; Eilu, 2015), with both occurring in the Karelian supracrustal belts which underwent intense regional albitization, deformation and metamorphism. Both of these occurrence groups have a metal association and other features preventing their reliable assignment to any genetic type. The proposed genetic classification of the Kuusamo occurrences have ranged from IOCG- and Blackbird-type deposits (for Blackbird-type Fe-Co-Cu-Au-Bi-Y-REE, see Slack, 2012), syngenetic deposits to orogenic gold deposits with an atypical metal combination (Eilu, 2015 and references therein).

6.3 Formation of the Rompas-Rajapalot gold occurrences

Gold occurs at least in two structural sites at Palokas and, in addition to fracture-related gold, native gold grains are found within silicates with no clear relationship to any fractures. The exact timing of the latter gold type is still unknown. Molnár et al. (2016) concluded that the metal association identified in the Rompas Au-U occurrence was formed by multiple events, starting with the deposition of hydrothermal uraninite with some sulfides in quartz-dolomite veins at around 1.95–1.90 Ga. Early uraninite was recrystallized and concentrated in uraninite-bearing pockets during Svecofennian metamorphism and deformation at 1.90–1.80 Ga. A post-peak-metamorphic fluid flow event introduced hydrocarbons (now pyrobitumen) into the system and precipitated it on uraninite. Gold-bearing hydrothermal fluids reacted with uraninite and uraninite-pyrobitumen traps and precipitated gold together with gangue tellurides, arsenides and sulfides around 1.75–1.70 Ga. At Rajapalot area, the late appearance of gold in the fractures, the occurrence of granitoids within the mineralized area, the 1.78 Ga age for the molybdenite associated with gold (Molnár et al., 2017a), and the boron isotope composition of tourmaline imply that the fracture-related gold mineralization event is coeval with the 1.78 Ga granitoid magmatism (Ranta et al., 2017). Recently, similar late-orogenic xenotime U-Pb ages were reported by Molnar et al.

(2018) from late-stage native gold-bearing veins of the Iso-Kuotko gold deposit in the Central Lapland greenstone belt. The tourmaline-rich veins were formed during this late-orogenic thermal event and precipitated silicates, sulfides and probably gold during sudden pressure drops, causing phase separation (boiling) of the hydrothermal fluids. This is further supported by the gold-rich quartz-tourmaline-sulfide vein breccias.

7. Conclusions

Based on the research results of this dissertation, the following conclusions can be drawn:

1) Granites and migmatites in the study area represent at least two distinct magmatic phases that were emplaced at ca. 1.99 Ga and 1.79–1.77 Ga. The younger event was related to the main stage of the generation of the Central Lapland granitoid complex, whereas the older event is a previously unrecognized episode of felsic plutonism in northern Finland. During both magmatic events, an Archean granitoid basement existed under the Paleoproterozoic supracrustal cover.
2) The deposition of Kalevian rocks in the Peräpohja belt can be constrained in the time interval between 1.91 and 1.88 Ga based on the detrital zircon populations and cutting synorogenic granitoids of the Haaparanta suite.
3) In the Palokas Au occurrence, gold occurs in different textural settings: a) single relatively coarse-grained grains within rock-forming silicates in cordierite-orthoamphibole rocks and b) native gold grains in fractures of tourmaline in quartz-sulfide-tourmaline veins and in fractures of chloritized cordierite-orthoamphibole rocks adjacent to the tourmaline-rich veins. Fracture-related gold is associated with Bi-Se-S-bearing tellurides, native bismuth, molybdenite, chalcopyrite, and pyrrhotite.
4) The $\delta^{11}B$ values in tourmaline from gold-bearing veins at Palokas and tourmaline in the ca. 1.78 Ga pegmatitic tourmaline granite in the mineralized area are identical, ranging from 0 to −4‰ and implying a common boron source. This together with the Re-Os age of 1.78 ± 0.01 Ga from molybdenite (Molnár et al., 2017a) related to gold in the Palokas Au mineralization supports the genetic association of the post-orogenic magmatism and gold in the Rompas-Rajapalot prospect area.

5) Fluid inclusion data indicate that tourmaline in the gold-bearing veins formed from low- to moderate-salinity H_2O-NaCl-CO_2-CH_4-(H_2S) hydrothermal fluids in a boiling system under pressure conditions ranging from lithostatic (~1.5 kbar) to hydrostatic (250–500 bar) at a depth of ~5 km and temperature of around 300 ^{o}C. It should be noted that these characteristics do not allow us to make any firm conclusions about gold precipitation based on the fluid inclusions found in the tourmaline, as the gold is located in the fractures in tourmaline. However, boiling of hydrothermal fluids is a powerful mechanism to precipitate gold and the brecciating nature of sulfides and the mode of occurrence of gold in late tourmaline-rich veins is compatible with this model.
6) Based on the whole-rock geochemistry and lithological setting, it is highly plausible that the cordierite-orthoamphibole rocks and interlayered calcsilicate-albite rocks were originally part of a basin-wide lacustrine, and at least partly, evaporitic sequence. The cordierite-orthoamphibole rocks represent originally lake-margin sediments with abundant accumulation of Mg-rich clays. The calc-silicate albite rocks were originally calcitic-dolomitic marls, which are common deposits in evaporitic basins (Moine et al., 1981; Warren, 2016). These results are in line with the earlier studies conducted in the Karelian supracrustal belts, which have also proposed the presence of evaporitic rocks (e.g., Vanhanen, 2001; Kyläkoski et al., 2012).
7) The available data suggest a temporal, spatial and genetic link between the ca. 1.78 Ga magmatism and fracture-hosted gold, as proposed earlier by Molnár et al. (2016) and Ranta et al. (2017). However, the coverage of drillcores and field observations in the study area are not yet sufficient to assign the Palokas Au occurrence or the whole Rompas-Rajapalot gold system to any specific genetic class of gold deposits. Consequently, further studies are needed on the geological, geochemical and mineralogical characteristics of the area, leading to a better understanding of the genetic type of its gold mineralization.

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