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PREFACE AND KEY NOTE LECTURES



MELT INCLUSIONS IN MIGMATITES AND GRANULITES

by

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The study of melt inclusions is a recent, small-scale approach to a better understanding of melting in the continental crust. It builds on the discovery of glassy inclusions (CESARE et al., 1997) and their crystallized counterparts (“*nanogranites*”, CESARE et al., 2009) in garnet and other host minerals from anatectic crustal enclaves in lavas and from regional migmatites.

By producing a melt of broadly granitic composition and a silica-poor solid residue, crustal anatexis is of paramount importance in shaping the continental lithosphere: on one hand it determines the geochemical differentiation of the crust; on the other it allows easier and faster deformation of the crust, with important tectonic and geodynamic implications. Among the several aspects of crustal melting that are still poorly known to scientists, one is the composition of the *natural* melts produced during anatexis, as both leucosomes in migmatites and allochthonous crustal granites aren't representative of primary melts.

Such gap of knowledge has led to a new approach to characterize the composition of natural crustal melts: the study of melt inclusions. Building on the extensive work and literature on fluid and melt inclusions in mafic rocks, we realised that tiny droplets of the melt phase produced during crustal anatexis can be trapped by, and preserved within, those minerals that grow simultaneously with the melt, i.e. the *peritectic* phases produced during incongruent melting. For example, a garnet crystal that forms during the incongruent melting of biotite has the potential of trapping *primary* inclusions of the melt that is in contact with. Albeit straightforward, this perspective has found little application to migmatites and granulites in the past, until our first works in the crustal enclaves and xenoliths from El Hoyazo, SE Spain (CESARE et al., 1997). In these fragments of crustal rocks entrained in lavas that rapidly ascended, extruded and cooled on the Earth surface, the inclusions of anatectic melt could solidify to, and be preserved as, rhyolitic glass. The mineralogical and chemical composition of these rocks is comparable to that of residual melanosomes in migmatites, but here abundant glass is present, particularly as melt inclusions in all the minerals.

Glass inclusions were studied in particular in garnet and plagioclase (ACOSTA-VIGIL et al., 2007, 2010, 2012). They range in size between 5 and 50 μm , have a primary texture, contain fresh and undevitrified glass, and show very little evidence of melt crystallization upon cooling.

The peraluminous leucogranitic and close-to-eutectic compositions of glasses support the conclusion that they represent natural anatectic melts. Zircon and monazite saturation temperatures of 665-750°C suggest that melts were produced by muscovite breakdown melting early in a process of rapid anatexis, and mostly under H₂O-undersaturated conditions. The analysis of trace elements in the glass inclusions also allowed the first precise evaluation of the extent of chemical equilibrium between felsic melt and crystalline residuum during the anatexis of metasediments in a natural context.

Crustal enclaves such as at El Hoyazo are extremely unusual and rare. Nonetheless, they boosted an important development of melt inclusion studies by raising the question: “*Why shouldn't inclusions formed by the same process occur also in “normal” migmatites and granulites?*”

We (re)examined migmatite and granulite localities worldwide looking for garnet-producing incongruent reactions, until the first occurrence of melt inclusions was found in the slowly cooled granulites of the Kerala Khondalite Belt (KKB), India (CESARE et al., 2009). There, the inclusions are hosted within garnet: those in the range of 15-25 µm are fully crystallized to a cryptocrystalline aggregate of quartz, alkali feldspar, biotite and plagioclase (Fig. 1), locally showing micrographic intergrowths of quartz and feldspars. Inclusions generally have a negative crystal shape, and grain-size of crystals ranges from hundreds of nm to a few µm. Given the microstructural and chemical features, the cryptocrystalline aggregate found within these inclusions was named “nanogranite”

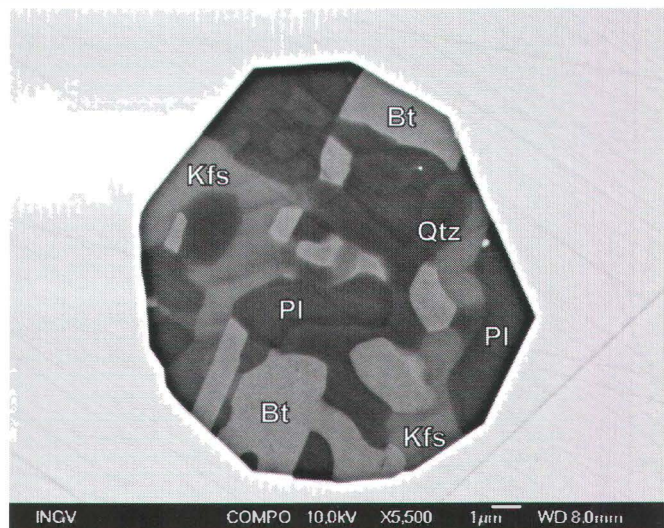


Figure 1:
Backscattered SEM image of a nanogranite inclusion hosted in garnet from a granulitic migmatite of the Kerala Khondalite Belt, India. (From HOLNESS et al., 2011).

Bt: biotite; Kfs: K-feldspar
Pl: plagioclase; Qtz: quartz

Another exceptional and intriguing discovery was that, despite the very slow cooling rate of the host rock, some inclusions <15 µm are still completely glassy. This has been explained by inhibition of nucleation in the inclusions with the smallest volumes, by analogy with the behavior of aqueous solutions in sediments or of glass in films and pores of contact meta-morphic rocks. Since the first finding, nanogranite and glassy inclusions have been identified also in regional metamorphic migmatites from other geological settings of various P-T conditions, such as the Ivrea Zone and the Ulten Zone (Italy), Ronda (Spain), the Barun Gneiss (Nepal), the Kaligandaki valley (Tibet), and south-central Massachusetts (U.S.A.).

Inclusions are hosted in garnet at all these localities, and also in ilmenite at Ronda. Their peculiar microstructural features (FERRERO et al., 2012) make nanogranites one of the most reliable indicators for the former presence of melt in a rock. Moreover, their appropriate characterization and analysis can provide the missing information on the composition of natural anatectic melts before these undergo modification processes. But while glassy inclusions can be directly analysed with minimal sample preparation, nanogranites need to be remelted to a homogeneous liquid and then quenched: to prevent the decrepitation of inclusions and loss of volatiles, remelting is achieved in a piston cylinder apparatus (BARTOLI et al., 2013a). EMP, Raman and nanoSIMS analysis of major elements and H₂O contents of remelted nanogranites shows that despite being all leucogranitic, compositions of natural anatectic melts generally plot away from those of minimum melts, and display systematic differences among samples, particularly concerning Qtz-Ab-Or relationships (Fig. 2).

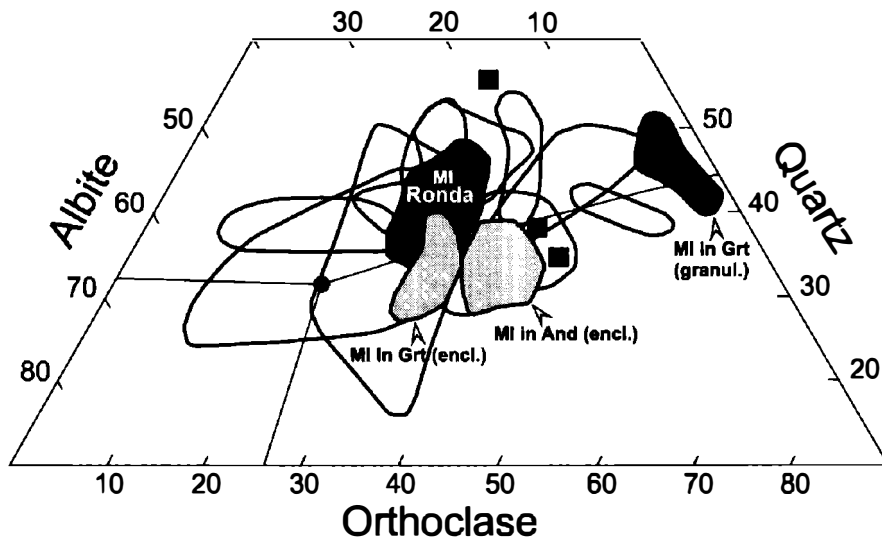


Figure 2:

Composition of remelted nanogranites (dark grey fields), of melt inclusions (MI) in garnet (Grt) and andalusite (And) from Spanish enclaves (encl.; light grey fields), and of experimental melts produced from metasedimentary starting materials (white fields), plotted in the CIPW Q-Ab-Or diagram. Gray squares are leucosomes in the migmatite from Ronda. Black dot and lines show the eutectic point and cotectic lines for the subaluminous haplogranite system at 5 kbar and $a_{H_2O} = 1$.

Redrawn after BARTOLI et al. (2013b), where details of the sources of data of experimental melts can be found.

The analysis of H₂O in the rehomogenized inclusions demonstrates that nanogranites preserve the primary fluid contents and that melts produced at Ronda were mainly H₂O-undersaturated even at low degree of melting (BARTOLI et al., 2013b). Since H₂O is one of the main parameters determining melt viscosities and, in turn, the strength of partially melted rocks, our characterization of the fluid contents of nanogranites is key for obtaining more realistic constraints to the rheological behaviour of the deep crust, and to the timescales of melt extraction from it.

Melt inclusions should be targeted in the most chemically inert and mechanically strong mineral hosts (e.g., spinel, ilmenite, zircon) from the least deformed rock domains. A major problem associated with this research is analytical and relates to the small size of the objects of study, enhancing the possibility of contamination by the host phase and loss of alkalis (in particular Na) due to the use of focused beams during analysis. Another problem is methodological and resides in the necessity of determining, case by case, the extent to which inclusions preserve their primary features, including the degree of chemical interaction with the host and the degree of crystallization upon cooling.

Because the composition of anatectic melts can now be analysed rather than assumed, we foresee that our investigation will stimulate further research on melt inclusions in migmatites and granulites. With extension to melting of mafic protoliths and to HP to UHP conditions of anatexis, our approach promises important impacts on a wide spectrum of disciplines including petrology, geochemistry, mineralogy, volcanology and geodynamics. As many occurrences of melt inclusions have been overlooked because they simply were not searched for, they will be uncovered by careful re-investigation of migmatite and granulite samples worldwide. In addition, the small size of inclusions (often <10 μm) and crystals within nanogranite (often <1 μm) offers new challenges and applications for cutting-edge micro-analytical techniques such as field emission gun-based SEM and EMP, LA-ICP-MS, nanoSIMS, synchrotron-based micro-XRF and micro-XRD. The fast technological development is likely to eliminate all analytical obstacles in a few years.

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LAYERED STRUCTURES: EXAMPLE OF DISORDER

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Three examples of layered structures from the authors recent work will be presented. All structures show disorder due to stacking fault mechanisms.

The first example, is the *layered brownmillerite* $\text{Ca}_4\text{Fe}_2\text{Mn}_{0.5}\text{Ti}_{0.5}\text{O}_9$. This material shows strong one-dimensional diffuse scattering (Fig. 1). A simulation study revealed the stacking fault mechanism and using high-resolution transmission electron microscopy the faults could be imaged (KRÜGER et al., 2011).

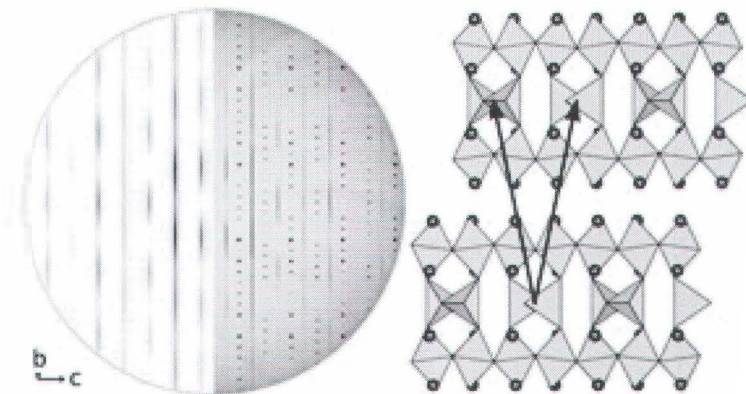
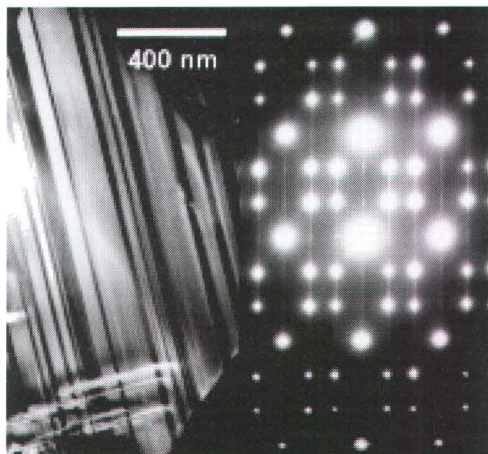


Figure 1:

Left side: a combination of calculated (left, Bragg scattering neglected) and observed (right) diffraction patterns (3kl) is shown. The right side shows two brownmillerite layers with alternative stacking vectors.

Potassium aluminate $\text{KAl}_9\text{O}_{14}$ exhibits a mullite-type structure. In single crystals grown from a vapour phase, we found a monoclinic superstructure which causes a complex nano- and micro-structure due to multiple twinning and stacking faults (Fig. 2, LAZIĆ et al., 2013).

Figure 2:
 TEM of monoclinic KAl_9O_{14} : electron micrograph (left) showing the nano-sized twin domains, and electron diffraction pattern [010] (right) with super-structure reflections and diffuse scattering.



The third example highlights an interesting case of stacking faults in an ordered aluminosilicate framework structure: the monoclinic kalsilite phase $KAlSiO_4$ -O1 (KREMENOVIĆ et al., 2013). Our recent results revealed that the stacking faults are related to non-stoichiometry with silicon excess and potassium vacancies according to $K_{1-x}\square_x Al_{1-x} Si_{1+x}$. The proposed stacking faults do not break the framework, however, its topology is modified at the fault planes. Pseudo-hexagonal twinning causes a complex diffuse scattering pattern (Fig. 3).



Figure 3:
 Reciprocal space section $hk0$ of non-stoichiometric $KAlSiO_4$ -O1. Strong one-dimensional diffuse scattering with twin-related additional directions.

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IN VERY TIGHT PLACES! – STRUCTURAL TRANSFORMATIONS OF MINERALS UNDER EXTREME CONDITIONS

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Extremes of pressure and temperature shape our planets and extraterrestrial bodies, turn everyday gases and liquids within the interior of gas giants into condensed solids, form unexpected compounds, and densify any matter (including our Earth's geomaterials) exposed to that kind of non-ambient conditions. Densification of crystalline solids follows the given freedom as determined by simple geometry aspects in stereochemistry, changes in electronic structures and chemical bonding, but also as controlled by symmetry and energetics related to the long-range order of the crystal structure. In many cases structural transformations in the sense of rapid transitions between long-lived structural states are the consequence of dynamically changed conditions.

Mineral transformations are in the focus of interest for mineral physics, as they control e.g. geochemical element distribution, considering the formation of new host phases, or account for anomalies in seismic wave propagation, seismic discontinuities, and related geophysical heterogeneities at our planets deep interior. Our current knowledge about mineral transformations is the result of experimental and computational advances of the past decades. In particular in-situ techniques, such as the diamond-anvil cell, nowadays allow to directly probe materials exposed to pressure, temperature, to electric and magnetic fields, radiation, and combinations of them.

Access to advanced in-situ characterization tools, including diffraction, scattering, spectroscopy, microscopy, and imaging is provided through dedicated large-scale facilities. In this context the newest technical developments including the advances made for in-situ high-pressure high-temperature experiments will be demonstrated, and an outlook for upcoming technical developments will be provided. A particular focus is dedicated to single-crystal techniques, which most currently started to experience a renaissance owing to the demand for very small sample sizes on approaching multi-megabar pressures at temperatures relevant to the Earth interior. Examples of selected mineral transformation are supposed to illustrate the recent activities in experimental crystallography and extreme-condition research, the application of developed techniques, and the efforts to use synchrotron radiation for in-situ investigations. Case studies encompass investigations of geologically relevant transitions in carbonate phases (transformation of calcite polymorphs, the pressure-induced transformation in dolomite-type norsethite).

OROGENIC GOLD DEPOSITS IN FINLAND

by

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Introduction: general characteristics of orogenic gold deposits

Orogenic gold deposits are typical metallogenic features in moderate to high temperature - low to moderate pressure metamorphic belts of convergent plate margins (GROVES et al., 2003). They formed in large scale metamorphic fluid dominated fluid flow systems at 3-20 km depths, along compressional-transpressional shear zones in accreted terrains during the late stages of orogenies. Their host rocks most typically consist of mafic metavolcanic and metasedimentary sequences which also often host felsic (porphyry) and lamprophyre dikes and granitoid intrusions and thus magmatic input into the fluid flow system cannot be ruled out in some deposits. Location of ore is controlled by brittle-ductile shear zones and it is also influenced by competency contrasts among host rock lithologies as well as by superimposition of shear zones on each other or on fold structures. The mineralization forms disseminations, stockworks and veins. Gold enrichments are usually associated with elevated concentrations of Ag, Bi, Sb, As, Te, W. The base metal content of the ore is usually low; exceptions are the orogenic gold deposits with atypical metal associations. Epizonal (3-6 km depth) deposits may be enriched in Sb and Hg whereas concentration of As and Te is more typical to meso- and hypozonal (6-10 and >10 km depths, respectively) deposits. Native gold most commonly associates with pyrite and/or pyrrhotite, arsenopyrite and telluride minerals in carbonate-quartz veins. Hydrothermally altered host rocks are characterised by enrichments of K, Na, Ca, Fe, Mg, CO₂, B and S. Thus albite, K-feldspar, K-micas, biotite, phlogopite, amphibole, tourmaline, carbonates and Fe-sulphides are the typical alteration minerals. Parent fluids of mineralisation are dilute (<6-8 NaCl equiv wt%) H₂O-NaCl-CO₂ (± CH₄ ± N₂) type fluids. These reduced, near-neutral fluids transport gold in sulphur complexes and precipitation of gold is triggered by phase separation as a consequence of pressure fluctuation, removal of sulphur by sulphurisation of Fe-rich silicate/oxide minerals in the wall rocks and changes in the oxidation state by mixing with more reductive/oxidative fluids or carbonatisation of wall rocks. Most of the giant (>250t Au) and world class (>100t Au) deposits were formed in relation to Archean and Paleoproterozoic supercontinent cycles at around 2.6-2.7 and 1.8-1.9 Ga, as well as during the Phanerozoic, modern-style orogenic cycles between 600 and 50 Ma (GOLDFARB et al., 2001). Therefore it is especially interesting to study this kind of deposits on the Fennoscandian shield where the Archean cratonic nuclei are surrounded by Proterozoic and Phanerozoic orogenic belts (Fig.1).

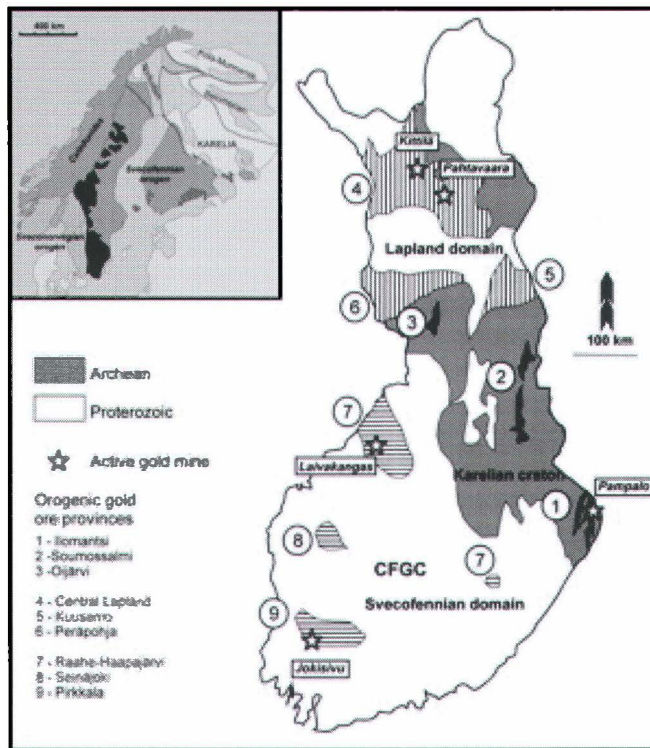


Figure 1: orogenic gold provinces in Finland.

Archean greenstone belts of the Karelian craton

The northerly trending, up to 200 km long, narrow greenstone belts with green amphibolite facies metasedimentary and metavolcanic units are surrounded by granite-gneiss complexes on the Karelian craton (Fig.1). The most important deposits are located in the Hattu schist belt (HSB) in the eastern part of the Ilomantsi greenstone belt. Similar deposits are also known in the Soumussalmi belt and in the Oijärvi belt. The latter belts have comparable geology to the Ilomantsi greenstone belt. However, mafic rocks and related cumulates are more widespread in relation to sedimentary units. The currently known cumulative ore resource of gold deposits in the HSB is 4.8208 Mt. The Pampalo mine has 1.6488 Mt resources with 4.3 g/t Au grade. In the HSB, the deposits are located along the major N-S trending shear zones which cut folded, sedimentary and volcanic units. Pre- and syn-deformation emplacement of tonalitic granite plutons and felsic porphyry dikes took place between 2.75 and 2.72 Ga. Amphibolite facies peak metamorphic conditions were established at around 2.7 Ga (VAASJOKI et al, 1993). According to SORJONEN-WARD (1993), formation of gold deposits took place before the peak of metamorphism, but STEIN et al. (1998) reported a 2.7 Ga Re-Os isochron age for pyrite associated to gold and suggested syn- to post-peak metamorphic timing of gold ore deposition.

Results of Pb-isotope studies on galena, altaite and hydrothermal K-feldspar, sulphur isotope data for sulphides from the Pampalo mine and regional boron-isotope studies on tourmaline in the HSB suggest that an early stage ore formation was synchronous with emplacement of granitoids and the hydrothermal circulation included magmatic fluids. Occurrences of high salinity (30-40 NaCl equiv wt.%) high temperature (min. 300-350°C) carbonic-aqueous fluid inclusions in addition to the dilute CO₂-CH₄-NaCl-H₂O type ones in some deposits of the HSB (and in the Suomussalmi belt; POUTIAINEN & PARTAMIES (2003) probably also indicate this input of magmatic fluids. The gold mineralisation consists of disseminated-stockwork, locally vein type ore which is enveloped by sericite-chlorite alteration zones with tourmaline in the host metasedimentary units and felsic dikes. Gold is associated with pyrrhotite, pyrite, arsenopyrite and various telluride minerals. The ore of the Pampalo mine is slightly different due to the presence of more widespread K-feldspar alteration zones and almost total absence of pyrrhotite and arsenopyrite. At ca. 1.85-1.7 Ga, tectonothermal processes affected the western parts of the Karelian craton due to overthrust of the up to 5-6 km thick east-verging Svecofennian nappe complex. (KONTINEN et al., 1992; O'BRIEN et al., 1993). Pb-isotope and fluid inclusion data from the Pampalo mine indicate local re-mobilisation of ore and overprinting wall rock alteration during interaction of carbonic-aqueous dilute (5-12 NaCl equiv. wt.%, 350-400°C temperature) fluids with the Archean mineralisation. Pb-isotope and fluid inclusions data also record an even more younger and lower temperature (200-250°C) saline (up to around 20 NaCl equiv. wt.%) fluid flow and ore remobilisation event.

Orogenic gold provinces of the Lapland domain

The Lapland domain (Fig.1) contains three orogenic gold provinces: the Central Lapland greenstone belt (CLGB), the Kuusamo belt (KS) and the Peräpohja belt (PB). One of the largest gold producer of Europe, the Kittilä mine (Suurikusikko deposit, 59 Mt total resources + reserves with 4.18 g/t average gold grade) is located in the CLGB. Pahtavaara (5.5 Mt total resources and reserves with 2.65 g/t average grade) is another active mine in this belt. In addition to these active mines, several other orogenic gold deposits and occurrences are known in the CLGB and KS. The PB is underexplored but the current discovery of extremely high grade (over 1000 g/t Au) showings in the northern part of this province highlights further exploration potential. The host rocks of gold deposits in these belts deposited during the elongated (2.45-2.0 Ga) intracontinental rifting of the Karelian craton. The early stage rifting produced bimodal komatiitic and felsic volcanic accumulations which are covered by quartzite, carbonate, BIF, turbidite, and graphitic schist bearing metasedimentary sequences with inter-calations of tholeiitic basalts and repeated emplacement of mafic dikes and sills (LAHTINEN et al., 2005). The KS and PB represent failed rift zones but a narrow oceanic basin was developed in the zone of CLGB at around 1.97-1.95 Ga. SW oriented subduction and final collision took place between 1.93-1.91 Ga. Metamorphism and synorogenic plutonism between 1.96-1.88 Ga and repeated deformation events with development of ore controlling shear zones between 1.92 and 1.77 Ga established the final geological architecture of the Lapland domain. The common feature of the CLGB and KS is that the zones of ore deposits along the major shear zones and connected second to fourth order structures show low grade (greenschist facies) metamorphism whereas the metamorphic grade is increasing apart from these zones (HÖLTTÄ et al., 2007).

The peculiar feature of the mineralised zones is the presence of pre-ore albite-carbonate (\pm scapolite) alteration which resulted in formation of competent massive albitites. This alteration most likely indicates mobilisation of formational brines during the early stages of the development of crustal scale fault structures (VANHANNEN, 2001). The same structures were reactivated during the development of major ore controlling shears and competency differences between albitites and the metasedimentary-metavolcanic units supported development of favourable conditions for ore deposition. The Fe-rich composition of mafic metavolcanic host rocks also supported precipitation of gold by extraction of sulphur from hydrothermal fluids. The most common Fe-minerals in association to gold are pyrite, pyrrhotite, arsenopyrite and löllingite. In the Suurikusikko deposit, most of the gold is refractory and is hosted by arsenopyrite and pyrite. Typical wall rock alteration assemblages around ore veins and stockwork zones contain quartz, carbonate, sericite/fuchsite, biotite, chlorite and feldspars. Another interesting feature of the CLGB and KS is that about half of the orogenic gold deposits have atypical metal associations with possible economic concentrations of cobalt (gersdorffite) and enrichments of Cu, Ni, Mo, U, Se, Ba and LREE (EILU et al., 2003). This specific geochemistry of ore may be connected to remobilisation of these metals by saline fluids from the Paleoproterozoic basin sequences. Age of formation of orogenic gold deposits in the Lapland domain is not well established; Pb-isotopic data from galena suggest 1.84-1.80 Ga ages (MÄNTTÄRI, 1995). Lead isotopes data also indicate Caledonian reactivation of ore controlling structures and local redistribution of metals.

Orogenic gold provinces in the Svecofennian domain

Orogenic gold provinces in the Svecofennian domain are located in collision zones surrounding the Central Finland granitoid complex (CFGC; Fig. 1). Gold is currently mined at Laivakangas (22Mt@ 2.03 g/t Au) in the southern Ostrobothnia part of the Raahe-Haapajärvi province and at Jokisivu (1.9 Mt@ 5.8 g/t Au) in the Pirkkala province. The basement of the CFGC, the Keitele microcontinent with a ca. 2.0 Ga old continental crust (LAHTINEN et al., 2005) formed the upper plate in those subduction zones which were developed along its eastern, western and southern boundaries between 1.92-1.89 Ga. Subduction related volcanism and plutonism, then metamorphism and deformation of accreted domains took place between 1.9 and 1.87 Ga. Formation of orogenic gold deposits post dated the mid to upper amphibolite facies metamorphism: results of studies by SAALMAN et al. (2010) support 1.83-1.80 Ga age for ore deposition in the Jokisivu deposit. The mineralized shear zones have NW-SE most typical orientation in the Svecofennian domain. They are mostly located in intrusive-volcanic complexes in Ostrobothnia: these host rocks also contain earlier formed porphyry-Cu type ore at some places. In the Seinäjoki and Pikkala province, turbiditic rocks are also common hosts of orogenic gold deposits. In the Seinäjoki province, and subordinately in the Pirkkala province (Jokisivu deposit) composition of ore is characterised by enrichments of antimony (aurostibnite, native antimony). The deposits usually contain free gold in association to pyrite, pyrrhotite, löllingite, arsenopyrite and Bi-Te minerals.

Conclusions

Orogenic gold deposits in Finland were formed at around 2.7 Ga and 1.8 Ga in correlation with the Archean and Paleoproterozoic global crustal growth cycles. This feature and their comparable mineralogical, petrological, geochemical and structural peculiarities with orogenic gold deposits on other shield areas highlight the exploration and mining potential in the metallogenic provinces introduced in this brief summary.

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ÜBER GESTEINE UND MINERALVORKOMMEN DER KORALPE

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Der am Ostrand der Alpen gelegene Gebirgszug der Koralpe gehört innerhalb der Austroalpinen Einheit (Ostalpin) zum Koralpe-Wölz-Deckensystem und wird aus einer Tausende Meter mächtigen Abfolge von Gneisen und Glimmerschiefern aufgebaut. Der durch Scherbewegungen in der Erdkruste „ausgewalzte“ Plattengneis spielt unter den verschiedenen Gneistypen eine Hauptrolle und bildet einen für die Koralpe typischen und markanten Bewegungshorizont. Ebenso charakteristisch sind die weithin verbreiteten Disthen-Paramorphosenschiefer. In diese Gneis-Glimmerschiefer-Abfolge sind Amphibolite, Eklogite, Gabbros, Pegmatite, Marmore und Kalksilikatgesteine eingeschaltet. An den Gesteinen sind zumindest zwei Metamorphosen erkennbar. Die letzte eoalpine Metamorphose, mit ihrem Maximum vor rund 90 Millionen Jahren, war sehr druckbetont und hat zur Eklogitbildung geführt (siehe MILLER et al., 2005, cum lit.). Eine Besonderheit der Koralpe ist es, dass der im Perm gebildete Gabbro an einigen wenigen Vorkommen nur gering verändert erhalten geblieben ist. Übergänge von Gabbro zu Eklogit im Dezimeterbereich sind petrologische Leckerbissen (HERITSCH, 1973; PROYER & POSTL, 2010). Schließlich können verschiedene, permisch gebildete Pegmatit-Typen unterschieden werden. Dazu gehört das Vorkommen von Spodumenpegmatit nahe der Weinebene, das als größte Lithium-Lagerstätte Europas gilt (GÖD, 1989), aber auch jene, oft nur einige cm-dicke Pegmatitmylonit-Lagen im Plattengneis, die sich durch die Führung von beachtlich großen Schörl-Kristallen auszeichnen. Tonnenschwere, anpolierte Blöcke aller in der Koralpe auftretenden Gesteine, u.a. herausragende Exemplare mit Gabbro-Eklogit-Übergängen, werden seit 2001 im Geopark Glashütten einer breiten Öffentlichkeit präsentiert (POSTL, 2009). Eine ähnliche Open-Air-Einrichtung ist kürzlich am neuen Dorfplatz von Wiefresen entstanden.

Nur beispielhaft werden der typische Mineralbestand einiger Koralpen-Gesteine, aber auch in diesen auftretende Kluftmineralbildungen vorgestellt. Noch vor wenigen Jahrzehnten war man der Auffassung, dass im Kristallin der Koralpe keine alpinen Kluftmineralisationen größeren Ausmaßes auftreten. Seit dem Fund der bedeutendsten Kluftmineralisation der Steiermark in einem nahe Deutschlandsberg temporär betriebenen Amphibolit-Steinbruch Anfang der 1970er-Jahre, mit bis 90 kg schweren Bergkristallen und den größten Titanitkristallen der Alpen (ALKER, 1975), sind weitere beachtenswerte Funde gefolgt.

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MECHANICAL FUNCTIONALIZATION OF MINERALS BY ORGANISMS

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Despite the brittleness of Ca-carbonate and –phosphate minerals, these substances are found almost ubiquitously in skeletons or teeth of organisms (LOWENSTAM, 1981). However, unlike inorganic minerals, biominerals are always hybrid composites which include intra- and intercrystalline organic matrix. This matrix controls the structure from the nanofabric to the macroscopic morphology, and the resulting hierarchical composite has dramatically improved mechanical strength, hardness, and, most importantly, fracture toughness (DUNLOP & FRATZL, 2010). With our increasing inventory of detailed investigations by electron backscatter diffraction (EBSD), TEM, AFM, and X-ray microdiffraction, we can now establish systematics of biomineral hierarchical architectures. Bioapatite, the main biomineral in vertebrates, always occurs in the form of nanocrystals embedded in organic matrix. With the possible exception of protozoa, the biocarbonate crystals also consist of primary particles in the 20-80 nm range. However, these particles are crystallographically co-oriented and constitute sub-micro- to-micrometer sized *mesocrystals* (SCHMAHL et al., 2012a, b), which are separated by organic membranes. The bioaragonite of corals (PRZENIOSŁO et al., 2008) and the nacre layers of mollusc shells (GRIESSHABER et al., 2013) consist of such poly-*mesocrystals* with a strong axial crystallographic texture. Biocalcite occurs in this form e.g. in the hard layer of brachiopod shells (GOETZ et al., 2011). More frequently in molluscs and brachiopods the calcite forms long *mesocrystal* fibres, columns, or prisms; and morphologically similar *mesocrystals* are sometimes combined to submillimeter-to-millimeter-sized *hybrid composite crystals*, in which the mesocrystal subunits are separated by organic membranes but are crystallographically co-oriented (KELM et al., 2012, SCHMAHL et al., 2012a, b). If *mesocrystal* subunits of different sizes and shapes are combined and display a “single-crystal”-like 3D crystallographic co-orientation, a *multiplex composite crystal* architecture (SCHMAHL et al., 2012b) is present, e.g. in sea urchin teeth where this architecture is essential for precise and reproducible self-sharpening of the tooth.

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