Hydrothermal alteration and structural control on gold deposition in the Hanhimaa shear zone and western part of the Sirkka Line

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Abstract
This report presents preliminary results of the structural analysis from the Hanhimaa shear zone and Sirkka line and adjacent areas. Emphasis is put on the structural evolution and alteration along these two major gold-bearing structures in order to better understand the gold metallogeny of the Kittilä region.

Based on the field evidence five deformation stages were distinguished within the study area. The earliest D₁ stage is linked to early alteration (albitization, carbonation) and development of S₁ layering in altered rocks. The second deformation stage led to development of tight to isoclinal folding with SSE-NNW oriented fold axis. The peak of the regional metamorphism was reached during the D₂ stage. At Hanhimaa the D₃ (NE-SW shortening) deformation progressively localized into shear zones and is linked to first stage of precipitation of gold. Deformation during the D₄ stage led to development of crenulation folding in Sirkka line as well as in adjacent shear zones. The latest D₅ stage is linked to brecciation, fracturing and formation of gold-bearing quartz and quartz-carbonate veins along the Sirkka line. At Hanhimaa, D₅ stage gold-bearing quartz and quartz-carbonate veins indicate either remobilization of pre-existing gold or presence of second gold precipitation stage in the area.

Keywords
Structural analysis, gold deposits, Central Lapland, greenstone, hydrothermal alteration, shear zones

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1 INTRODUCTION

The Paleoproterozoic Central Lapland Greenstone belt is one of the most gold-potential areas in Finland. Many Au and Cu-Au occurrences show a strong spatial relationship with regional shear zones (e.g. Eilu 1999, Patison 2007). These Au and Cu-Au occurrences share many features with both IOCG and orogenic gold deposits (Eilu & Martinsson 2007). Gold occurs in zones of pronounced tectonization and hydrothermal alteration (e.g. Eilu et al. 2007, Patison 2007) and these relationships require a study of the gold-bearing structures, their relative age and link to regional-scale features as well as to the tectono-metamorphic evolution.

The Paleoproterozoic bedrock of the CLGB consist of 2.44 – 1.98 Ga supracrustal sequence of mafic to ultramafic metavolcanic rocks, quartzites, phyllites, and graphitic schists that are intruded by 2.2 – 2.05 Ga mafic dykes and sills, 1.89-1.86 Ga mafic to felsic intrusions, and 1.80-1.77 Ga felsic intrusions (e.g. Hanski et al., 2001; Hanski and Huhma 2005). The supracrustal sequence is divided into six groups which are (from oldest to youngest) Salla, Kuusamo, Sodankylä, Savukoski, Kittilä, and Kumpu Groups (Table 1., Lehtonen et al., 1998; Hanski and Huhma, 2005). The Salla, Kuusamo, Sodankylä and Savukoski Group rocks were deposited in cratonic to cratonic margin rift settings and the youngest Kumpu Group in molasse environment (Lehtonen et al., 1998, Hanski and Huhma, 2005). The Kittilä group rocks have been suggested to represent an oceanic crust being allochtonous or para-autochtonous block (Hanski and Huhma, 2005).

<table>
<thead>
<tr>
<th>Group</th>
<th>Lithology</th>
<th>Age</th>
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<tbody>
<tr>
<td>Kumpu</td>
<td>Quartzite, conglomerate, siltstone, minor felsic to intermediate metavolcanic rocks</td>
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</tr>
<tr>
<td>Kittilä</td>
<td>Tholeiitic metavolcanic rocks, BIF, minor mica schists and arkosic graywackes</td>
<td>~2.0 Ga</td>
</tr>
<tr>
<td>Savukoski</td>
<td>Graphitic schists, phyllites, mica schists, tuffite, tholeiitic volcanic rocks, komatiitic volcanic rocks</td>
<td>&lt; 2.05 Ga</td>
</tr>
<tr>
<td>Sodankylä</td>
<td>Quartzite, mica schist, mica gneiss</td>
<td>&lt; 2.2 Ga</td>
</tr>
<tr>
<td>Kuusamo*</td>
<td>Tholeiitic and komatiitic metavolcanic rocks</td>
<td>&lt; 2.44 Ga</td>
</tr>
<tr>
<td>Salla</td>
<td>Intermediate to felsic metavolcanic rocks</td>
<td>2.5-2.44 Ga</td>
</tr>
</tbody>
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The Paleoproterozoic rocks have undergone several phases of deformation and metamorphism. However, the tectono-metamorphic evolution of the Central Lapland Greenstone belt is relatively poorly understood. One reason for this is the poor exposure; moreover, many exposures are restricted to trenches opened for ore exploration, which, as a consequence, are located in strongly altered rocks where several hydrothermal stages have overprinted older structures and may have obliterated important structural information. Väisänen (2002) presented a structural overview of the greenstone belt with an attempt to establish a succession of events and regional
correlation. This scheme has been adopted by Hölttä et al. (2007) who distinguish a number of metamorphic zones.

Deformation is complex and varies regionally; in particular the D3 event of Väisänen and Hölttä et al. (op. cit.) groups a number of different and variably oriented structures lacking unambiguous and systematic overprinting relationships so that they are difficult to correlate from one region to another, but are believed to have formed more or less contemporaneously during progressive deformation. This complex deformation event requires further study, in particular considering its importance for mineralization as noted by Patison (2007) stating that the gold-bearing structures are related to the D3 event.

As part of the Fennoscandian Gold Transect (FENGOT) and Central Lapland 3D modelling project the authors of this report made a five day field trip to the key target areas of the CLGB. This report describes the observations made during the field trip (24.-28.08.2009) and presents some preliminary results and ideas of the topic. The limited time did not allow detailed studies, and only few structural measurements could be made, just for rough orientation. The observations are restricted to macroscopically visible structures and fabrics; comprehensive and further studies would require microstructural analysis of oriented samples. The following observations and conclusions therefore have a preliminary character and are partly rather speculative since many points require further and detailed studies. As a consequence, many questions remain open.

The aim of the excursion was rather to get an overview and impression of gold mineralization in this area, to discuss existing models, and to express ideas and questions that may serve as an impetus for further and more detailed studies. The structural and hydrothermal evolution within single prospect areas allows the distinction of a number of alteration and deformation stages. The succession within the exposures is numbered as “stages” with a roman number (stage I to VI). These are used just as a descriptive label for successive groups of structures, styles and hydrothermal phases and should not be confused with orogenic events. The discussion following the description of the prospect areas is an attempt to regional comparison and correlation of these stages in order to link them to specific kinematic environments considered as deformation events D1-Dn. Different stages may belong to a prolonged deformation phase/event. The label D1-Dn is used for grouping structural styles and generations and illustrating their temporal succession.

The D1-D3 in this study should not be confused with D1-D3 of Väisänen (2002) and Hölttä et al. (2007) although they certainly partly overlap and correlate. It was decided not to use the scheme presented by Väisänen (2002) and Hölttä et al. (2007) and not to try to correlate our observations. One reason is that our study concerns a much smaller regional extent. Furthermore, the metamorphic degree in the gold prospects reached greenschist facies only whereas many observations presented by Väisänen and Hölttä et al (op. cit.) have been made in higher grade rocks. Finally, any interpretation in the present stage of knowledge should consider the possible existence of tectonic domains, some of them may represent nappes of far-traveled allochthonous origin, containing rocks that were affected not only by a varying metamorphic degree but also followed different deformation paths in different crustal depths with different deformation styles and kinematics and maybe even different tectonic settings. This inhibits a “quick” correlation. It is suggested here that structural studies at first should determine and establish the tectonic histories of various metamorphic and/or structural domains and then try to link them to regional and belt-scale processes. This will in turn enable regional comparisons.
Figure 1. Lithological map of the study area with excursion localities. KoSZ = Kolari shear zone, SiTh = Sirkka line (Sirkka Thrust), MuSZ = Muusa shear zone, HaSZ = Hanhimaa shear zone, KiSZ = Kiistala shear zone, PiSZ = Pierkukoski shear zone. Modified after GTK digital bedrock map database.
2 THE VISITED LOCALITIES
The field trip focused into Western part of the Sirkka shear zone and to the Hanhimaa shear zone. The visited excursion localities are shown in Figure 1.

3 GOLD OCCURRENCES RELATED TO THE HANHIMAA SHEAR ZONE (KELLOLAKI, KIIMALAKI, KIIMAKUUSIKKO)

The visited outcrops of this target area were mostly exploration trenches opened by Dragon Mining NL. The trenches are located in the approximately N-S trending Hanhimaa Shear Zone that cuts the Kittilä group. The trenches cover an area of several hundreds of meters in width and the extent of strongly sheared rocks exposed give an impression of the width and regional importance of this major shear zone.

The bedrock of the area consists dominantly of Kittilä Group tholeiitic volcanic rocks and cross-cutting quartz-feldspar porphyry dykes. The mafic volcanics are tuffs and lavas, locally well preserved as pillow lavas (Fig. 2). Locally phyllite intercalations can be seen within the metavolcanic rocks. The rocks record a multiple-phase history of deformation and alteration (Table 2).

3.1 Stage I: first stage of alteration
Many phyllite layers and porphyry dykes have been strongly and pervasively albitized (Fig. 3). Mafic volcanic rocks are in places carbonated (Fig. 2), and carbonation locally affected also the porphyry dykes. This alteration is pervasive and regionally widespread, though it does not affect the whole rock column but probably was also originally regionally localized. It occurs also in rocks outside the Hahnimaa Shear Zone or in domains less affected by shearing. The latter can be demonstrated, for example, in well-preserved pillow lavas that do not show strong shearing but are pervasively carbonated (Fig. 2). The close-by sheared rocks in contrast show a strong rusty alteration that is less pervasive and that formed during a later stage (Figs. 4 & 5, see below).

This first stage of alteration took place either prior to deformation and is syngenetic, possibly formed during diagenesis or volcanism, or it occurred during the earliest stages of deformation and metamorphism (“early orogenic”).

The layering of the rocks probably records the bedding and volcanic layering; however, it cannot be excluded that alteration was accompanied by development of a first cleavage (sub-parallel to bedding S0; Fig. 4) since the rock layering is defined by albitized and/or carbonated layers. The layering is therefore labeled as S1 here. An associated folding F1 could not be detected in the strongly altered rocks.

3.2 Stage II: Metamorphism and folding
The layering S1 of the rocks, including the albitized and carbonated layers, has been deformed to tight to isoclinal folds, F2 (Fig. 6) Many folds have relatively angular and narrow hinge zones with thickened layers and thinned limbs; they can be classified as shear folds. Other folds have rounder hinges and show less pronounced layer thickness variations between limbs and hinge zones. The varying fold shapes may suggest heterogeneous distribution and intensity of flattening during folding.

F2 folds are best preserved in domains that have not been strongly affected by later shearing, i.e. in low strain domains within the Hanhimaa Shear Zone. These relationships suggest that F2 folding occurred after stage-I alteration and prior to shearing.
3.3 Stage III: Development of major shear zones accompanied by fluid flow

The third stage is related to the formation of major regional roughly N-S (NNW-SSE to NNE-SSW) = trending shear zones, like the Kiistala, and Hanhimaa Shear zones. In a river bank at Pierkukoski outside the Hanhimaa Shear Zone, a SW-NE trending shear zone of several 10 of meters thickness is exposed. In geophysical maps these zones apparently represent another set of shear zones. Structures are very similar to the Hanhimaa Shear Zone, likewise the relative timing in the structural evolution (post-dating S₁, F₂). Therefore, N-S and SW-NE trending shear zones may have formed at the same time. The relationship to the N-S shear zones is, however, unclear and requires further study.
Figure 2. Carbonated tholeiitic metalava with pillow texture. Kiimakuusikko A area, Hanhimaa. Length of the compass plate is 12.5 cm.

Figure 3. Intense pervasive albitization (pale) in phyllite. Subsequent carbonate infilled fracturing (rusty brown) overprint the earlier albitization. Kellolaki area, Hanhimaa.
Since the trenches are located within the Hanhimaa Shear Zone the dominant structural element in these outcrops is an intense and locally very closely spaced shear zone foliation, S3. This foliation overprints and locally obliterates the older fabric (S1, F2). Low strain domains are less intense foliated but are cut by spaced and anastomosing narrow shear bands and shear zones, locally with sigmoidal planes and S-C fabric that indicates a component of dextral shear (Fig. 5). An additional oblique dip slip component is indicated, the sense of shear, however, is not resolved because the strong foliation and later fracturing of the rocks does not provide macroscopically detectable shear sense indicators. In some places a sub-horizontal rodding-like lineation, oriented NNW-SSE (e.g. 340/10), can be recognized that is probably related to shearing. In addition an intersection lineation between the layering S1 and the shear zone foliation S3 is developed.

The heterogeneous intensity of S3 and the observable partitioning into strongly sheared and less deformed zones suggest that the major shear zones themselves consist of sets of ± anastomosing high strain zones surrounding low strain domains where the original rock and pre-existing structures (D1, D2) are still recognizable. F2 folds are cut and overprinted by S3 shear zones and are consequently better preserved in trenches that expose less affected areas between the strongly sheared rocks. This explains the apparent absence of these structures in large parts of some trenches.

Figure 4. Carbonated mafic metavolcanic rock with clearly visible S1 layering (or primary bedding S0; see text). Note the folding of the carbonated layers and later cross cutting second stage carbonate-quartz veins that cross cut the S1. Kellolaki area, Hanhimaa.
Stage-III shearing was accompanied by fluid flow leading to sericite formation in the quartz feldspar porphyry dykes (Fig. 7). These rocks show high sericite contents that increase with increasing intensity of the S3 shear zone foliation. Breakdown of feldspar to sericite probably further lowered the shear strength of the rock, which in turn resulted in enhanced concentration of shear deformation into these zones.

Some phyllites are cut by anastomosing narrow sericite veins sub-parallel to S3 that are interpreted as having formed during shearing.

Fluid flow caused local alteration of the rocks. Spaced narrow shear zones, that formed during dextral shearing, cut mafic volcanic rocks and illustrate the intimate relationship of shearing and fluid flow: Within few meters the intensity of alteration (chloritization) and likewise of shearing increases, and decreases again towards the other margin of the high strain zone.

Shearing caused mainly ductile to semi-ductile deformation; local higher fluid pressures may have caused brittle fracturing in some domains during this event as well. Shear deformation in competent rocks in the shear zone margins is characterized by semi-brittle to brittle deformation rather than ductile behaviour. Narrow breccia zones along S3-(sub-)parallel faults (Fig. 8), NNE-SSW trending quartz-carbonate veins and a gold-bearing brecciated quartz vein (Fig 9.) both sub-parallel to the shear zone foliation S3 either formed during late stages of shearing or during later brittle reactivation (see stages V and VI below). This brittle deformation preferentially occurs in albitized rocks due to their higher competence.
Figure 6. $S_2$ folding in pervasively carbonated mafic metavolcanic rock in Kellolaki area, Hanhimaa. Length of the compass plate is 12.5 cm.

Figure 7. D$_3$ stage shearing related sericite (green, arrows) alteration overprints earlier albitization in quartz-feldspar porphyry in Kiimalaki, Hanhimaa. 1. = Breccia clast of early carbonate (brown) albite
(white) altered quartz-feldspar porphyry, 2. = quartz-carbonate vein parallel to foliation. Kellolaki area, Hanhimaa. Length of the birch leave below the breccia clast (1.) is about 3 cm.

Figure 8. Breccia zone in carbonated mafic metavolcanic rock. Paler coloured breccia clasts can be outlined in the cut surfaces. Kellolaki area, Hanhimaa. Width of the photo equals about 35 cm.

3.4 Stage IV: crenulation folding

The SW-NE striking shear zone foliation at Pierkukoski (see below) is locally crenulated by low-amplitude crenulation folds. Such a crenulation has not been observed in the Hanhimaa shear zone. On the other hand this shear zone is strongly affected by later fracturing and faulting, and in large parts of the exposures the rocks broke into small rock flakes so that folding of S3 cannot be recognized any more.

In gold occurrences along the Sirkka Line, post-peak metamorphic crenulation folding is more common and pre-dates brittle fracturing (see below). Because of similar relative timing within the structural evolution it is possible that it could be correlated with the open crenulation of S3 in the Kittilä group.

3.5 Stages V and VI – brittle faulting and fracturing and third stage of alteration

Brittle fracturing affected in particular porphyric volcanic rocks and phyllites that have been strongly albitizied during stage I. The rocks are cut by subvertical and flat-lying veins of various orientations that build a network of mm- to cm-thick quartz-carbonate and carbonate veins. These veins cut the shear zone foliation S3 and therefore post-date shearing. The breccias (Fig. 10) often contain sulfides locally concentrated in spots and domains (in contrast to more disseminated sulfides precipitated during older alteration stages). The stage V breccia zones are enriched in gold. The albitized rocks have a high competence allowing the accumulation of high
fluid pressures before the $p_{\text{fluid}}$ finally exceeded the lithostatic pressure resulting in fracturing and brecciation and a sudden pressure release which led to precipitation of minerals – as well as gold. Deformation became more localized with time. Two sets of faults developed, which are common features in the trenches: 

NW-SE (130°-150°) trending and c. 70°NE-dipping faults 
S(SW)-N(NE) (0-20°) trending subvertical (mostly 80°E-dipping) faults

Both faults locally led to formation of breccia zones, some of which contain hematite veins. NW-SE and ~N-S striking quartz veins (Fig.11) are also related to this stage; c. 20° trending carbonate veins have also been observed but are less frequent. The veins suggest that fluid flow still continued during these late stages of the Paleoproterozoic evolution in the Hanhimaa Shear zone.

Figure 9. Gold-bearing, brecciated, quartz-carbonate vein sub-parallel to the shear zone foliation $S_3$ in Kiimalaki, Hanhimaa. These veins were probably formed during late stage of the shearing, prior to late faulting and fracturing. Kiimalaki area, Hanhimaa. The size of the rubber boot in upper left corner of the photo is 43 (EUR).
Figure 10. Quartz-carbonate±pyrite veins brecciate carbonated mafic metavolcanic rock (1.) in Kellolaki area, Hanhimaa.

Figure 11. D₅ stage quartz±carbonate vein (white) in intensely sheared and altered mafic metavolcanic rock. These late veins follow the latest VI-stage fault planes in Hanhimaa area. From Kellolaki area, Hanhimaa. Width of the photo equals about 50 cm.
3.6 Geochemistry

A total of 31 mafic metavolcanic rock samples were assayed from the Hanhimaa area. The sample set consists of a series ranging from very weakly altered/unaltered metavolcanic rocks to intensely altered metavolcanic rocks. The chemical composition of the samples used in mass balance calculations is shown in a table in the Appendix. Despite the intense alteration and evident mobility of some elements, the generally immobile elements and some of the trace elements are relatively well preserved even in the most intensely altered samples (see below).

The geochemistry of the variably altered mafic metavolcanic rocks indicate that they are Fe-tholeiites with relatively flat primitive mantle normalized REE patterns (Figs. 12 and 13). Despite the variable and locally intense alteration the REE patterns are considerably homogenous indicating a similar source for all volcanic rocks. The Th-Zr-Nb discrimination diagram of Wood et al. (1980) indicates that the closest modern analogue for the Hanhimaa mafic volcanic rocks are E-MORB type rocks (Fig. 14). The general geochemical characteristics of the samples are similar to the Vesmajärvi formation mafic volcanic rocks of the Kittilä Group (e.g. Lehtonen et al., 1998; Hanski and Huhma, 2005).

As described above, several different alteration styles were recognized in the Hanhimaa area rocks; at least two stages of carbonation, albitionization, sericite alteration, chlorite ± biotite alteration, and silicification. Alteration varies depending on the protolith and stage in which the alteration took place. Earliest alteration phases in the Hanhimaa area were pervasive carbonation (mafic metavolcanic rocks, Fig. 2) and albitionization (porphyry dykes, phyllites, Figs 3 & 7). Pervasive carbonation was also noted in porphyry dykes depending on location. Chlorite- and chlorite-biotite alteration is shearing related overprinting earlier carbonation stage. It is unclear whether this stage was accompanied with carbonation, however in general the most intensely sheared and chloritized rocks were typically also intensely carbonated. In felsic rocks (porphyres, phyllites) the early albitionization is overprinted with sericite alteration where shearing is prominent.

In order to better understand the alteration in Hanhimaa rocks mass balance calculation were carried out comparing sample pairs of unaltered or weakly altered protoliths and intensely altered varieties of the same rock. Mass balance calculations were carried out using method presented by Grant (1982).

The mass balance calculations indicate that the early, regional to local scale carbonation caused moderate net mass increase in mafic metavolcanic rock (Fig 15). As a result of the alteration, significant amount of Ca and C was introduced into the rock. K₂O appears to be also slightly enriched in altered rock. Mg is the only major element that shows signs of depletion during the alteration. Of the trace elements, Cr, Ni, and Zn are depleted. However, it cannot be excluded that the apparent depletion in MgO, Cr, and Ni between the sample pair is related to primary fractionation rather than result of hydrothermal alteration. Although Ag and Te appear to be enriched in the rock during the alteration, their general concentration in the samples is too low for any conclusions to be drawn.

Figure 16 shows the isocon for carbonate-chlorite-biotite altered mafic metavolcanic rock compared and weakly altered mafic metavolcanic rock. Based on the field evidence the chlorite-biotite alteration overprints the early pervasive carbonation thus this diagram reflects the effects of first stage carbonation and overprinting, shearing related chlorite-biotite alteration stages. The two alteration stages resulted from net mass increase of 20% which is considerable. The CaO, and CO₂ appear to be enriched in similar levels as in the previous case, however, increase in K₂O and Ba is significant. Of the trace elements the enrichment of Cu and Te shows about two fold
and three fold increase, respectively. However, their general concentration is low in both rocks. The only element that appears to be depleted in this case is Na$_2$O.

The isocon shown in Figure 17 shows another sample pair with intense chlorite-biotite alteration overprinting carbonated mafic metavolcanic rock from Kellolaki area. In general the mass balance change is the same as it is with the similarly altered sample pair from Kiimakuusikko area shown in Figure 16. The K$_2$O, CaO, Ba, and C show higher gains reflecting the increase in the intensity of the alteration in the Kellolaki samples compared to the Kiimakuusikko samples.

The only sample of our sample set that showed elevated Au concentration was from sericite altered quartz-feldspar porphyry from Kiimakuusikko. Unfortunately, no unaltered example of quartz-feldspar porphyry was available, thus comparison was made between carbonate-albite altered quartz-feldspar porphyry and mineralized sericite altered porphyry (Fig. 17). The isocon indicates that gain in Au was accompanied with gains in Ag, Zn, Sb, Cu, Rb, and W. Also, the sericite alteration is reflected in gains in K$_2$O and Ba. The strongest depletion during the sericite alteration and mineralization can be noted on Na$_2$O and Sr. Depletion of these elements probably relates to break down of albite into sericite.

The mass balance calculations presented suggest that during the first stage carbonation the only significant change in chemical composition of the mafic metavolcanic rocks was an increase in the Ca and CO$_2$ content of the rocks coupled with net mass increase. The shearing related alteration (chlorite-biotite and sericite alteration) was accompanied with influx of K$_2$O, Ba ± Au, Ag, Zn, Sb, Cu, Rb, and W. It also appears that during the shearing related alteration Na$_2$O, and Sr became depleted in the rocks.

![Jensen Cation Plot](image)

Figure 12. Jensen (1976) classification of the Hanhimaa mafic metavolcanic rocks.
Figure 13. Primitive mantle normalized REE patterns of the Hanhimaa mafic metavolcanic rocks.

Figure 14. Th-Zr-Nb discrimination diagram of Wood (1980) of the Hanhimaa mafic volcanic rocks.
Figure 15. Isocon diagram for least altered mafic volcanic rock (1.1.-TTN-09) vs. early pervasive carbonated mafic metavolcanic rock (1.2.-TTN-09). Major elements in wt-%, trace element in ppms. $C^0 =$ correlation co-efficient. CO$_2$ is calculated assuming all C is tied to carbonates. Kii-makuusikko area, Hanhimaa.

Figure 16. Isocon diagram for least altered mafic metavolcanic rock (1.1.-TTN-09) vs. carbonated and chlorite-biotite altered mafic metavolcanic rock (1.4.-TTN-09). Major elements in wt-
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%, trace element in ppms. $C^0 =$ correlation co-efficient. $CO_2$ is calculated assuming all C is tied to carbonates. Kiimakuusikko area, Hanhimaa.

Figure 17. Isocon diagram for least altered mafic metavolcanic rock (6.1.-TTN-09) vs. carbonated and intensely chlorite-biotite altered mafic metavolcanic rock (6.2.-TTN-09). Major elements in wt-%, trace element in ppms. $C^0 =$ correlation co-efficient. Kellolaki area, Hanhimaa.

Figure 18. Isocon diagram of moderately albitized and carbonated quartz-feldspar porphyry (11.2.-TTN-09) vs. moderately sericite-altered variety (11.3.-TTN-09) of the same rock. The lat-
ter sample was also weakly Au-mineralized. Major elements in wt-%, trace element in ppms except Au which is in ppbs. $C^o=$ correlation co-efficient. Kiimakuusikko area, Hanhimaa.

4 OBSERVATIONS ON GOLD OCCURRENCES ALONG THE SIRKKA LINE

The visited gold occurrences are located in the western part of the Sirkka Line where it strikes approximately E-W to WSW-ENE. The Sirkka Line separates the Kittilä group in the north from greenschist facies rocks of the Savukoski group and overlying quartzites and conglomerates of the Kumpu group. It is interesting to note that the gold occurrences are located south of the Sirkka Line and thus, in the Savukoski-Kumpu succession. These rocks have been affected by a number of alteration events in addition to polyphase folding and shearing (Table. 2).

The phyllitic and tuffaceous rocks of the Savukoski group are pervasively albitized (Fig 19), which causes the whitish color of these rocks. Mafic tholeiitic and komatiitic metavolcanic rocks are carbonated. This alteration (stage I) is regionally widespread along the Sirkka Line. It either overprinted a layering (bedding) or formed coeval to formation of a foliation that formed (sub-) parallel to the original layering. In any case, this alteration stage (stage I) occurred prior to the peak of regional deformation and metamorphism, i.e. either syngenetic shortly after deposition, e.g. during diagenesis, or during the onset of deformation and metamorphism (“early orogenic”). Since the layering is associated with alteration (either overprinted by or formed during this process) it is labeled as S$_1$ here.

Tight folding (F$_2$) of the layering S$_1$ with sub-horizontal fold axial surfaces probably correspond to F$_2$ folds in the Kittilä unit. The dm-scale folds are subordinate (parasitic folds) to larger fold structures. The shapes of the parasitic folds vary from limb to the hinge zone.

Figure 19. Pervasively albitized phyllite overprinted by the D$_3$ stage carbonate veins. Harrilompolo, Saattopora area. Easting = 3392 000, Northing = 7524 810 (YKJ). Length of the compass plate is 12.5 cm.
A second stage of alteration is represented by carbonation and emplacement of carbonate veins parallel or sub-parallel to the foliation/layering (Figure 20, stage III). These veins probably post-date the metamorphic peak. Komatiites at Loukinen have been carbonated and transformed to Cr-rich talc-chlorite-carbonate schist ("Cr-marble"). It could be speculated whether this alteration stage was accompanied by shear zone activity accompanied by fluid flow and thus, could be correlated with development of the Hanhimaa and other shear zones in the Kittilä unit. Comparable skarn veins that are sub-parallel to the foliation and apparently associated with shearing exposed in Laaviova would support this interpretation. This would infer also an intimate relationship between alteration, fluid flow and (renewed) activity along of the Sirkka shear zone.

The stage III carbonate veins and the layering $S_1$ are folded and crenulated (stage IV). The crenulation fold axes, $F_4$, can be observed in many outcrops along the western Sirkka Line, they strike consistently SW-NE and mostly plunge gently to NE (Figs 21 and 22). The constant orientation of $F_4$ implies a ~NW-SE shortening direction, which would cause dextral oblique reverse shear along the E-W to WSW-ENE striking segments of the Sirkka Line. The crenulation is stronger and better developed in fine-grained and finely laminated rocks, like phyllites, talc-chlorite schist (former komatiites and tholeiites) and fine-grained tuffaceous layers.

Figure 20. Multi-stage alteration in phyllite at Saattopora Au deposit. Early albitization (pale, $D_1$) overprinted with stage III carbonate veins (brown, horizontal) that occur parallel to sub parallel to foliation. Note also the folding of the III-stage carbonate veins. Latest, completely brittle carbonation event ($D_5$) relates to the brittle, coarse grained carbonate veins (vertical brown veins) that cross cut the foliation. These veins also carry the gold at Saattopora. Saattopora waste rocks piles.
Figure 21. Crenulation folding (F₄) on foliated mafic metavolcanic rock. Outcrop at Harrilompolo. Easting = 3392 200, Northing = 7525 240 (YKJ). Length of the magnet is 11 cm.

Figure 22. Crenulation folding (F₄) in foliated mafic volcanoclastic rock in Pittarova. Easting = 3388 300, Northing = 7526 265 (YKJ). Length of the compass plate is 12.5 cm.
Brittle NW-dipping thrust planes and associated NNW-dipping imbricates observed in the southern part of Saattopora could have formed during this stage IV NW-SE shortening stage but are more likely younger structures that developed when deformation became more brittle and localized in discrete faults and narrow fault zones (stage V).

Brittle fracturing leading to brecciation, carbonation and development of and ~N-S (NNW-SSE to NNE-SSW) trending veins (Figs. 19, 20, 23) was intimately related to gold-bearing fluids (stage V). Gold was precipitated in approximately N-S trending carbonate-filled extension fractures and carbonate veins (e.g. Saattopora, Fig. 23). These veins clearly cut the foliation and also post-date the F₄ crenulation folds. They occur preferentially in the previously albitized rock units suggesting that the higher competence of these rocks, gained during stage I albitization, played an important role for the later mineralization process. The hydrothermal breccia of ore body B in Saattopora also formed during this stage (Figs 24 and 25). Mineralised quartz-carbonate-albite veins and breccias that cross-cut the foliation and post-date the folding also occur in other prospects along the Sirkka Line.

Kink bands in finely laminated rocks are associated with NNE-SSW to NE-SW trending faults that formed during ongoing deformation but decreasing fluid flow. The SSE-directed thrusts at Saattopora are sub-parallel to the Sirkka Line suggesting ongoing activity and multiple stage re-activation of this major lineament until the late stages of the Paleoproterozoic tectonic evolution. Hydrothermal breccias and carbonate, quartz-carbonate and sulfide-bearing veins are characteristic mineralized structures in the Harrilompolo Cu-Au prospect close to Saattopora. The veins do not show signs for considerable deformation indicating that they formed in the late and waning stages of the Svecofennian tectonic history.
Figure 24. Hydrothermal breccia at Saattopora. Variably rounded clasts of dominantly albitized phyllite in carbonate-quartz-sulfides matrix. In places clasts of mafic tuff and altered komatiite can be seen too. Saattpora open pit B.
5 DEFORMATION, ALTERATION AND HYDROTHERMAL EVENTS AT LAAVIROVA, PAHTAVUOMA AREAS

The Pahtavuoma and Laavirova are also located at the western Sirkka Line, but close to a ~N-S to SSW-NNE trending shear zone that is parallel and probably has a genetic link with the Kolari-Pajala shear zone. Phyllites and tuffites, volcanic agglomerates as well as local mafic lavas of the Savukoski group are exposed. At Laavirova the Kumpu group quartzites are exposed as well. The Savukoski group rocks show a well-developed foliation that is in turn tight to isoclinally folded. The agglomerates contain stretched clasts aligned parallel to the foliation. Two stages of alteration can be distinguished. The older alteration at Laavirova is a greenish skarn alteration (Figs. 26-29) with formation of actonilite-hornblende veins parallel to the foliation. This alteration stage however, probably did not take place prior to deformation but is apparently rather linked with shear deformation and foliation development and thus, may have formed during shearing along the Kolari-Pajala shear zone, which would correspond to stage III in the other prospect areas. It is possible that the skarn-alteration overprints an earlier, pre-foliation (stage I) alteration.

Subsequent crenulation folding of the foliation and skarn vein formation correlates with stage IV and F₄ folds in other prospects along the Sirkka Line. The F₄ fold axes strike SW-NE and mostly plunge gently (c. 15°) to NE. At some localities fine-grained rocks show a spaced crenulation cleavage. The heterogeneous distribution of crenulation folds and crenulation cleavage is on the
one hand depending on the grain size, i.e. fine-grained and laminated rocks can be easier crenu-
lated (and a crenulation is easier visible) than massive and coarse-grained rocks like conglomer-
ates and coarse-grained quartzites of the Kumpu group. However, in some localities, the Kumpu 
rocks show a strong stage IV deformation. This suggests that in addition to lithology the inten-
sity of this deformation is controlled by heterogeneous strain and either only occur along shear 
zones or the strain is partitioned into high strain zones and only weakly deformed to nearly unde-
formed low-strain domains.

Figure 27. Skarn breccia at Laavirova. Green parts consist of actinolite-hornblende skarn, pale parts of 
albite with small amount of quartz. Easting = 3380 450, Northing = 7526 990 (YKJ). Length of the 
magnet is 11 cm.

Local kink folds at SW-NE trending fault zones and a SW-NE trending fracture cleavage charac-
terize subsequent deformation (stage V). Deformation became dominantly brittle and increas-
ingly localized into discrete faults. A local rusty alteration is associated with faulting. It affects 
also volcanic rocks that have not been altered before during earlier alteration stages. SW-NE 
trending mineralized quartz-carbonate-albite veins and greenish skarn veins are also associated 
with faulting. This younger alteration stage also affected the Kumpu group since the veins cut 
Kumpu quartzites exposed in Laavirova area (Fig. 29). The SW-NE to SSW-NNE trending faults 
are sub-parallel to the Kiistala shear zone and probably belong to this fault set. Fracturing and 
alteration is similar to the structures observed elsewhere along the Kiistala Line, like in Pittarova 
and adjacent exposures. Strongly altered U and Zn-Cu deposits at Pahtavuoma are cut by faults 
and narrow shear bands associated with a rusty and greenish alteration. Such a fault-related al-
teration also occurs in volcanic rocks that have not been previously altered. The U and Zn-Cu 
deposit as thus been overprinted by the faults, and the accompanying hydrothermal fluids may 
have remobilized some metals.
Figure 28. Crenulated skarn breccia at Laavirova. Dark green material is actinolite-hornblende skarn, bright green epidote, pale parts are albite-rich. Protolith for the albite-rich clasts is probably the Savukoski Gp tuffite or phyllite. Easting = 3380 450, Northing = 7526 990 (YKJ). Length of the magnet is 11 cm.
Figure 29 (Previous page). Albite-actinolite-epidote skarn veins cross cut the bedding in the Kumpu Gp quartzite at Laavirova. Easting = 3380 640, Northing = 7526 770 (YKJ). Length of the magnet is 11 cm.

6 PRELIMINARY SYNTHESIS AND CORRELATION

A number of deformation structures and associated alteration stages have been observed, which reflect distinct deformation phases and even events during the tectonic evolution. This chapter attempts to correlate these features observed at different localities and to assign them to regional-scale orogenic episodes (labelled Dₙ) (Table 2). For the reasons mentioned in the introduction this synthesis can only have a preliminary character.

The different prospect areas located along the western Sirkka Line and within the Kittilä unit show a number of similarities concerning the structural geometry, relative timing of hydrothermal events and structural evolution.

6.1 D₁ – stage I alteration

All visited areas have in common an early alteration stage (stage I) that pre-dates the main deformation, but is probably related to diagenesis, volcanism, possibly associated with activity along normal faults within the cratonic rift basins. Alternatively the onset of stage I alteration took place during the early stages of orogenic evolution. Alteration is associated with the development of the layering S₁ and thus, marked as D₁ event. This alteration is regionally widespread although it may have originally been intimately related with and spatially restricted to faults and shear zones since most outcrops today are also recognized in the vicinity of such major – and very likely multiply reactivated – structures. Limited geochemical work on the early carbonation at Hanhimaa area suggests that Ca and CO₂ were introduced to the rocks without significant depletion or increase in concentration of other elements. No direct data could be obtained for the early albitization.

6.2 D₂ – folding, thrusting and peak metamorphism

Tight to isoclinal folding of S₁, associated with shearing (thrusting?) and peak metamorphism can be recognized in the Kittilä unit. It is apparently best preserved in higher grade metamorphic rocks; however, it is very likely also present in the lower-grade rocks south of the Sirkka Line, though less visible there because of a strong later overprint. Stage II folding, shearing and metamorphism represents a major stage of the tectonic evolution. This D₂ event was probably associated with collision, thickening and nappe stacking. It is likely that major shear zones like the Sirkka Line formed already at this time. Steep SSW-NNE to SSE-NNW trending shear zones like the Hanhimaa and Kiistala zones could likewise have formed already during D₂ acting as transfer faults during nappe emplacement. The original transport directions could not be reconstructed in the visited outcrops.

6.3 D₃ – ductile shearing

The main fabrics in the major shear zones observed today post-dates the metamorphic peak and the shear zone foliation overprints the F₂ folds. This important event formed distinct structures and was associated with fluid flow and hydrothermal activity leading to local alteration (stage III). It is thus regarded as a distinct deformation event, D₃. Shear deformation became progressively localized into shear zones that were up to several 100 m in width, but it is likely that in
lower strain regions folding of the rocks took place instead of ductile resulting in an overall ductile fold and thrust belt geometry. This hypothesis has to be proved, however.

Few kinematic indicators can be seen macroscopically in the outcrops, but they generally indicate a dextral sense of shear (in addition to an unresolved dip-slip component). Dextral movement along ~N-S trending shear zones would imply a c. NE-SW oriented shortening direction. D3 regional scale major shear zones are characterized by ductile deformation. However, they generally show a semi-brittle and even brittle overprint with development of narrow breccia zones, NNE-SSW trending quartz carbonate veins, and a gold-bearing brecciated quartz vein (in Kiimalahti) that is oriented parallel to the shear zone foliation S3. This semi-brittle shearing may have occurred either during the waning stages of D3; alternatively shear zone reactivation resulting in shear zone-parallel fracturing and brecciation took place during later stages (V and VI, see D5). The first explanation is favoured here.

6.4 D4 – reactivation of shear zones and crenulation folding

Crenulation folding around SW-NE trending axes (stage IV) can be observed in all visited prospect areas. This deformation also affects the siliciclastic sedimentary rocks of the Kumpu group. It therefore marks the beginning of a new orogenic episode, D4, that is separated from the earlier and higher metamorphic ones (D1-D3) by a period of erosion and deposition of the molasse-type Kumpu deposits. The stress system changed to ~NW-SE oriented shortening, which would imply dextral shear along ~E-W trending segments of the Sirkka Line. The deformation intensity varies and strain is heterogeneous. In some areas, the Kumpu rocks show a well developed cleavage that crenulates the bedding planes, and conglomerates in high strain zones have strongly aligned and strained pebbles. Other outcrops in contrast look nearly undeformed. D4 deformation was therefore probably concentrated to the major reactivated shear and fault zones, which would explain the widespread occurrence of F4 folds particularly in outcrops along the Sirkka Line.

6.5 D5 – faulting and fracturing associated with fluid flow

During subsequent deformation, D5, the shortening axis was oriented ~NNW-SSE to N-S. This can be inferred from NW-SE (c. 140°) and N-S to SSW-NNE (0-20°) trending faults provided they form a conjugate set. This is supported by roughly N-S oriented carbonate veins in tension fractures. D4 folding and D5 fracturing and faulting may be transitional; however, the clearly brittle D5 deformation forms a distinct group of structures that differ from the semi-brittle D4 deformation. Moreover, the stage V carbonate veins and the hydrothermal breccias both containing elevated gold contents are evidence for fluid flow accompanying D5. Such gold mineralization has not been observed in association with D4 structures. These observations point to the existence of a distinct tectonic and hydrothermal event D5.

Gold was transported with the hydrothermal fluids and precipitated in hydrothermal breccias, quartz-carbonate and carbonate veins, and fracture fills. These features formed during the initial and main stages of D5 (stage V, Tab. 2). Deformation became increasingly localized into faults during progressive D5 resulting in development of distinct fault sets and local kink bands (stage VI).

Faulting and fracturing affected also granites of the Naattanen type, the age of which is about 1.77 Ga (Lehtonen et al. 1998) providing a maximum age for D5.
7 CONCLUDING REMARKS ABOUT GOLD MINERALIZATION AND OPEN QUESTIONS

Gold mineralization has been found in D₃ shear zones (Hanhimaa, Kiistala, Sirkka Line) as well as in D₅ breccias and extension veins.

D₃ shearing along the Hanhimaa, Kiistala and parallel shear zones was accompanied by fluid flow leading to local alteration of the rocks within the shear zone. Skarn veins in Läaviröva may have formed during this event as well. The Hanhimaa and Kiistala shear zones have high potential for gold. Breccias and quartz veins within these zones formed during D₃ show elevated gold contents. They possibly represent a second stage of gold mineralization while the first stage occurred during D₃ taking into account Pb-Pb sulfide ages that indicate pre-1.85 Ga mineralization stages in the Central Lapland greenstone belt (Mänttäri 1995) - although Pb-Pb sulfide ages should be interpreted with care. The importance of D₃ for gold mineralization nevertheless requires a critical evaluation because these D₃ zones as well show a strong overprint during D₅, and the D₅ hydrothermal fluids certainly were gold-bearing. In order to evaluate the gold deposition during D₃ it is necessary to trace the gold contents along the shear zones with respect to D₅ brittle fracturing; in other words, to check whether considerably elevated gold concentrations occur also outside D₅ breccia zones. This task is challenging however, considering possible brittle shearing already at the end of D₃ in Hanhimaa. Hence, gold-bearing fluids may have entered the shear zones in the later, more brittle stages of D₃. In any case, the shear zones play an important role for mineralization in being favourable pathways for the fluids during both D₃ and D₅ reactivation.

Gold occurrences along the western Sirkka Line strikingly almost always occur close to intersection points between major NNE-SSW tending faults that truncate the Kittilä unit and the Sirkka Line as well as the stratigraphic units south of the Sirkka Line. They are (sub-)parallel to the Kiistala, Hanhimaa and related shear zones. The gold prospects are located at the intersection points of subordinate faults paralleling the major SSW-NNE striking regional shear zones and faults suggesting an intimate relationship to brittle fault activity and hydrothermal fluid flow along these faults. Similar observations were already done at Levijärvi and Loukinen area by Holma and Keinänen (2007). We suggest that the gold bearing roughly N-S trending D₅ extension fractures and carbonate veins that clearly cut the foliation and are nearly undeformed are linked to activity along the SSW-NNE striking faults. Hence, at least in the Sirkka Line prospect the D₅ gold mineralization seems to be the most important gold precipitating phase. The brittle nature and similarity of some gold-related structures in Hanhimaa (stage V), furthermore suggests that the stage V/D₅ alteration and gold precipitation took place in these areas as well. Moreover, the SSW-NNE Kiistala shear zone probably has also been reactivated - probably likewise accompanied by gold precipitation in fractures and faults.

Approximately NNW-SSE oriented shortening during D₅ implies a dextral component of shear along ~E-W trending segments of the Sirkka Line, sinistral slip along SSW-NNE striking faults, and dilatation along NW-SE ~NNW-SSE oriented segments. Such dilational shear zone segments would have acted as channels for the mineralizing fluids, in particular at intersection points with NNE-SSW oriented faults (Kiistala fault and parallel structures) whereas dextral contractional W-E segments would be sites where high fluid pressures could be built-up that led to fracturing due to local overpressuring leading to brecciation and formation of extension veins or extensional shear fractures. Similar build-up of high fluid pressure resulting in fracturing and mineral precipitation could occur along the SSW-NNE faults and reactivated shear zones providing an explanation for gold-bearing breccias and veins in these structures.
Stage I/D1 early alteration indirectly partly controlled gold mineralization as well – in particular during D3 – since albitized rocks gained a higher competence than the unaltered phyllites. In a contractional tectonic environment these zones had the potential for high amplitude fluid pressure cycling from fault-valve action.

To summarize, two main gold mineralization stages can be distinguished so far: one stage related to ductile D3 shearing (Hanhimaa, Kiistala), and a second stage during D5 associated with brittle faulting and reactivation of older (in particular D3) structures in a different stress field.

It remains a question for future work how many gold stages could be distinguished and which of them has greater potential for economic deposits or whether the importance of a distinct mineralization phase varies from region to region. This would also have important implications for future exploration.

8 ACKNOWLEDGEMENTS

We would like to thank Dragon Mining NL representatives for opportunity to study and carry out lithological sampling in their exploration trenches at the area.

9 REFERENCES


# APPENDIX 1.
Chemical composition of the samples used in mass balance calculations

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**Appendix 1. continued.**

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Major elements assayed with XRF, trace elements with ICP-MS. Au, Bi, Sb, Se, and Te assayed with GFAAS, C and S was assayed using LECO. Coordinate system Finnish National (YKJ).