STRUCTURAL CONTROLS ON GOLD MINERALISATION IN THE CENTRAL LAPLAND GREENSTONE BELT

by


Early Proterozoic gold mineralisation in the Central Lapland Greenstone Belt (CLGB) has a distinct spatial correlation with structural features generated by convergence events, and by subsequent wrench deformation during the orogenic development of the CLGB. This research aims to provide basic guidelines for assessing the prospectivity of CLGB structures, and involves examining the deformation history and timing of gold mineralisation at 10 locations. Mineralisation at these occurrences is in or near discrete strike-slip shear zones, or other deformation products of a similar relative age developed within zones of complex earlier deformation. Gold-bearing structures are typically part of the final regional deformation phase to affect the CLGB (D3), and are overprinted by only minor (low-displacement) brittle faults.

While identifying D3 shear zones is a useful exploration guideline, the localised effects of earlier deformation and alteration events also need to be considered. In many cases, the combined effect of early and late events constrains mineralisation to a particular location. The late orogenic timing of mineralisation is one of many features making CLGB gold mineralisation comparable to well-documented global examples of orogenic greenstone-hosted gold mineralisation.

Key words (GeoRef Thesaurus AGI): gold ores. structural controls, deformation, shear zones, Central Lapland Greenstone Belt, Paleoproterozoic, Kittilä, Sodankylä, Lapland Province, Finland.

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INTRODUCTION

Gold mineralisation occurs at numerous sites within the Central Lapland Greenstone Belt (CLGB) of northern Finland. The area has clear potential for further discoveries, exemplified by the discovery of the now 2+ million ounce Suurikuusikko gold deposit. The Geological Survey of Finland found the deposit in 1996 after ten years of exploration in the region. The Ministry of Trade and Industry sold it to Riddarhytitan Resources in 1998 and it is currently owned by Agnico-Eagle Mines Limited. Mining of the deposit will begin in 2008, targeting 14.2 million tonnes of estimated probable reserves with an average gold grade of 5.16 grams per tonne (Agnico-Eagle Mines Ltd. media release 06.05.2006).

Known CLGB gold occurrences are orogenic greenstone-hosted gold mineralisations, analogous in many ways to those in more established mineral districts such as the Yilgarn region of Western Australia (e.g., Witt
Table 1. Comparison of selected features defining the 'orogenic gold' deposit class (after Groves et al. 1998) and CLGB gold occurrences

<table>
<thead>
<tr>
<th>Orogenic gold mineralisation</th>
<th>CLGB mineralisation</th>
</tr>
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<tbody>
<tr>
<td><strong>Host terrane:</strong></td>
<td><strong>Host structures:</strong></td>
</tr>
<tr>
<td>• Volcano-plutonic rocks (greenstone belts hosting Archaean deposits interpreted as most commonly having an oceanic back-arc setting, dominated by back-arc basalt and felsic to mafic arc rocks)</td>
<td>• Hosted by second- or third-order brittle ductile structures near large-scale compressive structures</td>
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<tr>
<td>• Convergence-dominated deformation</td>
<td>• Mineralised structures have vertical and down-plunge extents of several 100 m to 2 km</td>
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<tr>
<td>• Typically greenschist-facies metamorphic grade</td>
<td><strong>Deposit mineralogy and alteration:</strong></td>
</tr>
<tr>
<td></td>
<td>• Au in carbonate-dominated vein systems (with quartz ± albrite) or sulphide disseminations</td>
</tr>
<tr>
<td></td>
<td>• Au mostly within pyrite and arsenopyrite, and also in gersdorffite (Ni-Co-As sulphide) at some sites. Au occurs as inclusions and/or within the lattice of sulphide phases. Free Au is less common</td>
</tr>
<tr>
<td></td>
<td>• Insufficient data, but Suurikuusikko values are within this range (ratio increases with increasing Au grade)</td>
</tr>
<tr>
<td></td>
<td><strong>Timing:</strong></td>
</tr>
<tr>
<td></td>
<td>• Au in carbonate-dominated vein systems (with quartz ± albrite) or sulphide disseminations</td>
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</tr>
<tr>
<td></td>
<td>• Au grades 5 – 30 g/t</td>
</tr>
<tr>
<td></td>
<td>• Limited available data, but Au, Cu, Ni, Fe, and Ag typically enriched, ± Sb, Te, Ni, and W. Cu and/or Ni enrichment common at several occurrences (see Eini 1999)</td>
</tr>
<tr>
<td></td>
<td><strong>Deposit mineralogy and alteration:</strong></td>
</tr>
<tr>
<td></td>
<td>• Au mostly within pyrite and arsenopyrite, and also in gersdorffite (Ni-Co-As sulphide) at some sites. Au occurs as inclusions and/or within the lattice of sulphide phases. Free Au is less common</td>
</tr>
<tr>
<td></td>
<td>• Au in carbonate-dominated vein systems (with quartz ± albrite) or sulphide disseminations</td>
</tr>
<tr>
<td><strong>Alteration involving CO₂, S, K, H₂O, SiO₂, Na and LILE addition Typical phases pyrite, pyrrhotite, arsenopyrite, sericite, fuchsite, biotite, k-spar, albite, and amphibole</strong></td>
<td>• CO₂ (distal calcite, and proximal ankerite/dolerite±amorphous ‘graphitic’ carbon), S (sulphide), Na (albite) and Si (quartz) addition dominates.</td>
</tr>
<tr>
<td><strong>Low salinity, near-neutral pH, H₂O+CO₂±CH₄ ore fluids</strong></td>
<td>Potassic alteration limited except for areas with fuchsite alteration (Cr+K). Biotite, sericite, potassic feldspar, amphibole, leucoxene and tourmaline at some sites only</td>
</tr>
<tr>
<td><strong>Timing:</strong></td>
<td>• Insufficient data. Ore fluids likely to be similar given the abundance of carbonate associated with mineralisation. High base-metal content (Cu) at some sites may suggest more saline fluids for these areas1. Reducing fluids likely at occurrences with ‘graphitic’ alteration</td>
</tr>
<tr>
<td>• Late orogenic Au mineralisation</td>
<td>• Late orogenic Au mineralisation</td>
</tr>
<tr>
<td>• Precordambrian Au typically 20-70 million years after the youngest volcanism</td>
<td>• Gold is late (related to D₃ structural features present at each location)</td>
</tr>
<tr>
<td></td>
<td>• Insufficient dating, but probably 230-460 million years after the majority of mafic volcanism (see Table 4)</td>
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</table>

1 Low salinity fluids have been attributed as responsible for the common lack of base-metal enrichments within orogenic lode-gold deposits (Kerrich & Fryer 1981). However, CLGB Cu-rich gold occurrences are also proximal to Savukoski Group sediments that could be a source of base metal enrichment in these deposits. Documented orogenic deposits in other regions with high-salinity fluids have a spatial association with sedimentary basin sequences (see Groves et al. 2000 and references within).
1998 the Geological Survey of Finland initiated a multidisciplinary research project aiming to generate new information on regional structure and deformation events, metamorphic events, and deposit-scale structure and fluid-flow. Combined with the revised stratigraphic reinterpretation of the CLGB (Lehtonen et al. 1998), the results of this project will provide solid background information of benefit to both future research and exploration in the region. This article presents the initial results for a component of this research entitled ‘Structural and fluid-chemical characteristics of gold mineralisation in the CLGB, northern Finland’.

The gold occurrences included in this research are the three gold mines – Sirkka (Sirkka Kaivos) which underwent test mining 1955–1956 (Räisänen 2001), Saattopora (mined 1988–1995), and Pahtavaara (mined 1996–2000, reopened 2003–); the Suurikuusikko
deposit; and six mineralised prospects – Isomaa, Iso-Kuotko, Karessellä, Loukinen, Soretialehto and Soretiavuoma North (Figs. 1 & 2). Gold mineralisation at these sites is usually associated with intense albite- and carbonate-rich alteration assemblages. At some occurrences mineralised rocks also contain fine ‘graphitic’ carbon indicating extremely reduced conditions. This carbon is extremely fine-grained amorphous carbon with a graphitic appearance and it is referred to as graphitic alteration within this article, but the material is not crystalline graphite. In most occurrences gold is within sulfide minerals (mainly pyrite, arsenopyrite and gersdorffite (Ni-Co-As sulfide)) and less commonly as free gold grains.

The data presented here was derived from detailed mapping of man-made bedrock exposures of limited extent, from sporadic natural outcrops, from drill core, and from aeromagnetic images. The aim of this paper is to briefly summarise the field-based results of this research, and other information relating to the structural setting of a selection of CLGB occurrences. Basic conclusions regarding host structures and regional-scale guidelines to the likely prospectivity of CLGB deformation features will be presented.

REGIONAL DEFORMATION EVENTS – KEY FEATURES

The following sequence of deformation events, modified and simplified from interpretations by Ward et al. (1989) and Väisänen (2002), is used as the regional structural framework for the occurrence-scale work reviewed here, and is consistent with current results of this project. Extensional deformation relating to volcanism and some intrusions can be expected to have occurred during the deposition of CLGB rocks, and there is some evidence for later extensional events. The summary presented here does not include extensional events as these are yet to be clearly documented. The compressional deformation phases are simplistically correlated with the regional event likely to be generating deformation. See Hölttä et al. (this volume) for details of individual deformation products assigned to each phase.
The oldest mappable deformation features relate to thrusting at CLGB margins. N- to NE-directed thrusting occurred at the southern margin, driven by Svecofennian orogenic events occurring to the south. The Lapland Granulite Belt was placed over the N and NE margins of the CLGB by S- to SW-directed thrusting during another collision event at a similar time. Belt-wide thrusts and related deformation were produced by each event. A lack of clear overprinting relationships and precise geochronology discriminating these two events currently prevents denoting either as D1 or D2, respectively, but these are the first two major regional deformation events after volcanism ceased for which clear evidence exists. Away from CLGB margin areas correlating to convergent zones, it is difficult to assign deformation products formed at this time specifically to D1 or D2. This is mostly because the tectonic transport directions of each event were opposite, the bulk strain orientations during each event were approximately parallel, resulting in the generation of structural features with similar strike orientations. The D1 phase reported by Hölttä et al. (this volume) is here grouped with the major thrust events of D1/D2.

The Sirkka ‘Line’ or Sirkka Shear Zone (Figs. 1 & 2) includes a series of closely spaced S-dipping, sub-parallel thrusts and fold structures relating to convergence at the southern margin of the CLGB. Thrusts within this zone have average dips of approximately 40°, interpreted from seismic refraction profiles (Berthelsen and Marker 1986; Gaál et al. 1989). The Sirkka Line is the main rheological boundary within CLGB stratigraphy, separating a sequence of sediment-dominated rocks to the south (Savukoski Group) from a volcanic-dominated package to the north (Kittilä Group). In detail it is a complex structural zone involving several parallel shear zones and shear zone segments. Some segments along this zone were at least partially reoriented and/or reactivated during subsequent deformation, although interpreting exact movement histories on these shear zones is difficult. Thrust zones shown on regional maps for the western and eastern margins of the CLGB (Fig. 1) have unresolved origins and are poorly understood.

D2 involved the development of strike-slip shear zones (e.g., Kiistala Shear Zone, Fig. 1) that displace or intersect D1/D2 thrust zones. D2 shear zones generally strike NW-SE, N-S and NE-SW, at high angles to the strike of most D1/D2 thrusts. Neither the external events driving the development of these shear zones nor the exact timing of their initiation is clearly understood. It has been suggested that these shear zones may utilise segments of early thrusts (Väisänen 2002), or transfer shear zones formed during pre-D1 extension relating to volcanism (Ward et al. 1989). It is also possible that these shear zones were initiated as a response to the opposing compressions operating during D1/D2 as a compensating response to thrusting. Strike-slip shear zones relating to CLGB deformation and potentially correlatable events further south were also recognised by early researchers, although interpreted using a variety of theoretical frameworks (e.g., Tuominen et al. 1973; Talvitie 1976; Mikkola & Vuorela 1977). Other deformation products were also generated during D3 (e.g., Väisänen et al. 2002), but strike-slip shear zones are the most obvious features. D3 is a complex and incompletely understood deformation phase, with shear zones here classified as D3 likely to have formed late within this phase.

Ward et al. (1989) proposed that movement on large D3 shears produced a dextral rotation of the entire CLGB, generating its SE-bulging geometry and controlling the distribution of high and low strain zones associated with D3 shears. A dextral rotation of maximum principle stress (σ1) throughout the development and/or activity of D3 shears is supported by observations made during this research for the Kiistala Shear Zone, where σ1 rotates through NW- and NNW-directed to a final NE-directed σ1 for deformation events observed in the immediate area of the Suurikuusikko occurrence. favourably oriented sections of D1/D2 thrusts were potentially reactivated during this rotation, in particular a NW-striking section of the Sirkka Line coinciding with several gold occurrences (section containing the Soretiavehma North occurrences labeled in Fig. 1). The orientation of D3 features is strongly influenced at a local scale by pre-existing structures, especially in areas south of the Sirkka Line.

Importantly, an association between gold mineralisation and D3 shearing has been recognised by this and other studies (e.g., Sorjonen-Ward et al. 1992; Väisänen 2002). A summary of selected key features associated with D1 to D3 deformation is given in Table 2. D3 involved numerous discontinuous, low displacement brittle shear zones (usually conjugate sets).

CLGB stratigraphy ranges in age from 2.5 Ga to 1.88 Ga (Lehtonen et. al. 1998). The absolute ages of deformation events require further constraint, but a maximum age for deformation (D1/D2) of 1.89 Ga has been proposed (Lehtonen et. al. 1998). Possible D3 deformation ages include 1.89 to 1.88 Ga (for CLGB deformation, Sorjonen-Ward et al. 1997); 1.88 Ga (for similar structures adjacent to the CLGB, Wikström et al. 1996); 1.90–1.85 Ga and 1.84–1.80 Ga (for successive movements on the Koliari Shear Zone, a strike-slip shear zone similar in orientation to CLGB D3 shear zones but located at the western
Table 2. Key deformation events, inferred $\sigma_1$ directions and/or tectonic transport directions of these events, and typical strike orientations of the structures generated

<table>
<thead>
<tr>
<th>Major deformation phase</th>
<th>Regional $\sigma_1$ direction or tectonic transport direction</th>
<th>Strike of key structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_1/D_2$</td>
<td>N-NE transport in south</td>
<td>Sirkka Line, containing E-striking to NW-striking segments. NW-striking sections may reflect later deformation of the Sirkka Line</td>
</tr>
<tr>
<td></td>
<td>S-SW transport in north</td>
<td>NW-striking margin thrusts at the northeastern CLGB/Lapland Granulite Belt contact</td>
</tr>
<tr>
<td>$D_3$</td>
<td>Generally NW-SE to NE-SW $\sigma_1$ (oldest to youngest movements respectively), but variably modified by local conditions</td>
<td>E.g., N- to NE-striking Kiistala Shear Zone. $D_3$ shears are most likely to have more variable strikes south of the Sirkka Line, and WNW- to NW-striking $D_3$ structures are common in this area</td>
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</table>

margin of the CLGB, Berthelsen & Marker 1986; not shown in Fig. 1), and a minimum age of 1.77 Ga (for an undeformed felsic dyke intruding $D_1/D_2$ thrust related folds within the CLGB (Väisänen 2002)). Post-collisional Nattanen-type granites (Fig. 1) cut by $D_3$ faults also have an age of 1.77 Ga (Lehtonen et al. 1998), providing a minimum age for $D_3$ and a maximum age for $D_2$. Estimated age ranges for mineralisation based on the isotopic composition of lead in sulfides include 1.99–1.87 Ga for mineralisation in the Saattopora area; 1.89–1.85 Ga for mineralisation in the Soretiavuoma, Kiistala (Suurikuusikko) and Iso-Kuotko areas; and 1.85–1.82 Ga for mineralisation in the Pahtavaara area (Mänttäri 1995; locations in Fig. 1). The resolution offered by the available age dates for mineralisation is

Table 3. Summary of available dates and timing relationships between CLGB deposition, deformation, metamorphic, and mineralising events. Plotted date ranges include error bars. Only post-tectonic intrusions (1.77 Ga Nattanen granites) have been included due to their relevance to age dates, but pre- and syn-tectonic intrusions are also present within CLGB stratigraphy. Data sources: columns 1, 2 and 3 Lehtonen et al. 1998; column 4 (date ranges left to right, exact values quoted previously in text) Sorjonen-Ward et al 1997, Wikstöm et al. 1996, Berthelsen and Marker 1986, maximum age Väisänen et al. 2002; column 5 Mänttäri 1995, ranges left to right for Saattopora (1.990–1.870 Ga), Soretiavuoma North/Kiistala/Kuotko (1.890–1.852 Ga), and Pahtavaara (1.850–1.820 Ga) areas respectively

<table>
<thead>
<tr>
<th>Age -Ga</th>
<th>Host rock deposition phase</th>
<th>$D_1/D_2$</th>
<th>$D_3$</th>
<th>$D_4$</th>
<th>Mineralisation (Pb-sulfide age range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.70</td>
<td>Post-tectonic intrusions</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1.80</td>
<td>Foreland basin</td>
<td>Maximum $D_1/D_2$ age 1.89 Ga</td>
<td>Minimum $D_1$ age 1.77 Ga</td>
<td>Possible $D_3$ ages</td>
<td></td>
</tr>
<tr>
<td>1.90</td>
<td>Collision</td>
<td></td>
<td></td>
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<tr>
<td>2.00</td>
<td>Opening ocean basin</td>
<td></td>
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<tr>
<td>2.10</td>
<td>Cratonic/cratonic margin phase</td>
<td></td>
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<tr>
<td>2.20</td>
<td>Intra-cratonic rifting 2.5-2.2 Ga</td>
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</table>
insufficient and requires better paragenetic constraint. More analyses of the dominant gold-bearing sulfide phases and alteration minerals at individual occurrences are needed to constrain the absolute age(s) of mineralisation.

Peak regional metamorphism in areas containing gold occurrences also requires further constraint, but results to date suggest that peak metamorphism began during D$_1$/D$_2$ thrusting in some areas (Hölttä et al., this volume). Table 3 presents a brief timeline of CLGB events as constrained from available age dates. This data, though insufficient, suggests a late orogenic timing for gold mineralisation.

### STRUCTURAL CONTROLS ON MINERALISATION

A clear regional spatial relationship exists between shear zones and mineralised sites within the CLGB (Fig. 2). Gold occurrences at Saattopora, Sirkka, Soretialehto and Soretiavuoma North are located on or immediately adjacent to Sirkka Line structures, and at least 12 other gold occurrences are located within 3 kilometres of the Sirkka Line (Eilu 1999). A significant spatial relationship between regional lineaments such as the Sirkka Line and gold has also been reported for other orogenic gold districts (e.g., Eisenlohr et al. 1989).

The Suurikuusikko and Iso-Kuotko occurrences occur on D$_3$ shear zones. The Pahtavaara, Kaaresselkä and Isomaa gold occurrences also coincide with shear zones with interpreted strike-slip movements, although whether these features represent shear zones generated or reactivated during D$_3$ is less clear. The Loukinen occurrence is spatially associated with both the Sirkka Line and an intersecting D$_3$ shear zone. The task for this project and for exploration within the CLGB is to understand the causes and practical implications of these spatial correlations.

#### Deposits spatially associated with the Sirkka Line

**Saattopora**

The Saattopora deposit (Figs. 1 & 2) is on an E- to ESE-striking section of the Sirkka Line, and provides a good introduction to the complexities of dealing with Sirkka Line-associated deposits. D$_3$ structures are not obvious on regional map sheets of the immediate area of Saattopora, or clearly seen in regional aeromagnetic images. It might therefore be assumed that the location of Saattopora is wholly influenced by Sirkka Line structures, but in detail this connection is not so clear.

Surface Sirkka Line structures at Saattopora are sub-vertical, as are the Sirkka Line aeromagnetic features in the immediate area (Airo M-L., pers. com. 2001), unlike the moderately south-dipping structures that would be expected in a simple thrust zone. The envelope of intense albite alteration associated with and containing the Saattopora ore lodes strikes parallel to the Sirkka Line, but dips steeply to the north (Korvuo 1997; Fig. 3). This distribution of alteration may reflect a preferentially altered stratigraphic unit that obtained its current strike during thrusting, but the dip of the zone is opposite to that expected within a simple thrust-interlayered stratigraphy.

A detailed alteration and deformation history exists at Saattopora, with an early carbonate-dominated (low-iron carbonate) alteration phase overprinted by the strongly albitised envelope to ore-bearing veins (Fig. 3), followed by further carbonate (high-iron carbonate) alteration hosting gold mineralisation. In order of formation, a NWW- to NW-striking foliation, E-verging and N- to NNW-verging folds, and a NE-striking cleavage all predate mineralisation and have variable timing with respect to alteration events. Gold occurs in late, brittle carbonate-rich veins, and in associated breccia zones in the immediate wall rock of the veins. These veins have several orientations but are usually vertical, very planar N-S-striking veins approximately orthogonal to Sirkka Line structures in the area. The veins are not fibrous and their mechanism of formation is not certain. Gold-bearing veins are not deformed at a macroscopic scale, and appear to be the youngest structural feature observed at Saattopora.

Most features within this complex deformation sequence cannot be fully explained by a simple, causative relationship between N- to NE-directed D$_1$/D$_2$ thrust-related deformation and mineralisation. As is evident from the numerous broken and displaced Sirkka Line segments visible in Figure 2, Sirkka Line thrusts have undergone significant post-thrusting deformation and/or reactivation. This and the complex nature of deformation at Saattopora, compared to the undeformed nature of ore veins, suggest that the veins were emplaced after most of the deformation and support a D$_3$ timing for mineralisation.
Sirkka (Sirkka Kaivos)

Mineralisation at Sirkka also has a close spatial association with the Sirkka Line (Figs. 1 & 2). An obvious characteristic here and at other locations along the Sirkka Line is an intense cleavage that gives rocks a banded appearance. This fabric is well developed in meta-sedimentary and meta-basic host rocks, has an E-W to NW-SE strike and moderate to steep dip, and is interpreted as an early deformation feature associated with Sirkka Line thrusting. Evidence for gold-rich mineralisation clearly synchronous with or pre-dating this fabric has not been found at any location during this research. At Sirkka, mineralised quartz-carbonate-sulfide breccias containing gold as inclusions within gersdorffite and arsenopyrite (Vesanto 1978) post-date this fabric, as does the associated pervasive carbonate alteration of host rocks, implying that mineralisation post-dates D₁/D₂ thrusting.

Gold is also present in veins within Kumpu Group sediments (Hugg R., pers. com. 2003) deposited during the late collisional to early foreland basin stage of CLGB evolution, and which unconformably overlie the ore-host sequence at Sirkka. These veins are similar in composition to mineralised breccias at Sirkka, and may provide further evidence for mineralisation post-dating thrusting if belonging to the same phase of mineralisation.

Loukinen

East of Saattopora and Sirkka, the Loukinen occurrence (Figs. 1, 2, & 4), provides a clear example of the role of D₃ strike-slip shear zones in influencing deposit location within D₁/D₂ deformation zones. Loukinen is located on an E- to ESE-striking section of the Sirkka Line that contains several gold occurrences. Limited interpretive modelling of drill core data suggests the envelope of mineralised zones is steeply dipping, and strikes approximately parallel to the trend of the Sirkka Line (Keinänen V., pers. com. 2001). However, available surface exposures provide evidence constraining mineralised breccias to intersection points between the Sirkka Line and N- to NNE-striking D₃ dextral strike-slip shear zones (Figs. 4a & 4c). Gold at Loukinen occurs as free gold, or in pyrite and gersdorffite.
Fig. 4. Simplified interpretation of features present in aeromagnetic images (a) in the vicinity of the Loukinen, Soretiavuoma North, and Soretialehto prospects (circled). A similar interpretation to that shown in Figure 4a, covering an area further north and including the Suurikuusikko property (b). Figures 4a and 4b are designed to highlight the location of prospects relative to major faults. Simplified map of surface exposure at the Loukinen prospect (c), showing the presence of N- to NNE-striking shears associated with graphitic alteration and brecciated zones. Example of Loukinen ore (d; Dark aversin fig a + b = magnetic high)
(as inclusions or within the lattice; Eilu 1999) within graphitic quartz-sulfide breccia zones generated by movement on these \( D_3 \) shears.

**Soretialehto and Soretiauva North**

Southeast of Loukinen, Sirkka Line structures bend to strike NW and decrease in dip (Airo M-L. pers. com. 2001; Figs. 1 & 2). This bend in the Sirkka Line has been interpreted to result from deformation (folding and shearing) of this zone during the rotation of the CLGB associated with \( D_3 \) (Ward et al. 1989). More information is required to establish whether the current orientation of this bend relates totally to \( D_3 \) deformation, to a combination of \( D_3 \) deformation and pre-\( D_3 \) events, or preserves an original thrust segment orientation \( \pm \) syn-thrusting deformation.

Common in parts of this area are rocks with intense potassic alteration. Ultramafic protoliths have been variably altered to fuchsite-carbonate-rich assemblages. The timing of this alteration event relative to early Sirkka Line movements is unclear. However, the distribution of alteration visible in drill core from this area indicates that it is more sporadic than would be expected if it were a syn-depositional alteration event. Some gold deposition has accompanied this alteration event, with altered rocks outside concentrated occurrences having gold grades averaging up to 0.5 ppm (Pekkala & Puustinen 1978). Higher grade mineralisation in these rocks is restricted to zones cross-cutting the altered hosts, but it is not clear if the background and high gold grades represent discrete mineralisation phases, or stages of the same event.

Elevated gold grades at the Soretialehto occurrence (Figs. 1 & 2) occur adjacent to a contact between fuchsite-carbonate-altered meta-komatiites and sericitised and carbonate-altered graphitic phyllite. At Soretialehto, gold occurs in pyrite within quartz-carbonate-rich breccia zones cutting the altered komatiites, and in pyrite or as free gold within later planar quartz-carbonate extensional veins. Apart from some evidence for early E-W compression, fabrics at this site strike NE, and are overprinted by mineralised breccia zones bound by N- to NE-striking shear zones. These shear zones experienced strike-slip movements, with variable displacement senses indicated. The gold-bearing veins are not folded and have a similar orientation to mineralised veins at Saattopora, striking N to NNE. No NW-striking fabrics paralleling the orientation of the Sirkka Line in this area were seen at Soretialehto.

The nearby Soretiauva North occurrence (Figs. 1, 2, & 5) occurs along a similar NW-striking lithological contact as Soretialehto, but the meta-komatititic host rocks here do not appear to show the extreme potassic alteration expressed as fuchsite-rich rocks at Soretialehto. An early WNW- to NW-striking folded fabric (local \( S_1 \)) is the oldest structural feature preserved. This fabric appears to reflect non-coaxial strain, with a poorly preserved \( S_2 \) fabric indicating strike-slip movement evident in some samples. The nature of this fabric suggests an association with the strike-slip dominated \( D_3 \) phase of deformation. What remains to be established is whether \( S_1 \) initially developed during \( D_1 \), or was a fabric produced in association with \( D_1/D_2 \) thrusting that was later sheared (perhaps during the folding seen at this site). \( S_1 \) is approximately parallel to the Sirkka Line, but resolving the cause of the Sirkka Line orientation here is also required before the origins of this local \( S_1 \) can be understood.

Folds of \( S_1 \) have sub-vertical axial planes striking NE, and axes typically plunging ~45° NE. An axial-planar, NE-striking crenulation cleavage is associated with these folds, and numerous quartz-carbonate shear veins with similar orientations to the crenulation cleavage cut the limbs and hinges of the folds. Pervasive iron-rich carbonate alteration occurred pre- to syn-vein formation, and intensifies at the margins of veined zones and sections of tighter folding.

Folded \( S_1 \) and the crenulation cleavage are in turn are cut by a series of NW- and NE-striking shears, followed by or synchronous with NNE- to N-striking shears. These are strike-slip shears, with movement lineations pitching less than 20°. The dominant movement sense is ambiguous, with both sinistral and dextral senses observed for all shear zone orientations, and no clear timing relationships observed between the two senses of movement. Gold-bearing quartz-carbonate-sulfide infill zones have developed within these shears. The highest gold grade in outcrop at Soretiauva North occurs at the intersection points between the shear zones labelled a and b in Figure 5.

The inferred \( \sigma_1 \) direction associated with folding at Soretiauva North is approximately NW-SE. Such a compression orientation is similar to that required to dilate the section of the Sirkka Line hosting Soretialehto, Soretiauva North, and other occurrences, as it is approximately parallel to the NW-strike of this zone (Fig. 1). The map of altered lithologies in Figure 5 also suggests a widening of the altered zone around Soretiauva North in NW-striking sections, and the simplified envelopes of gold-bearing zones (veins and breccias) are consistent with the orientation of failure zones predicted to result from dilation of this zone, either as internal breccia zones or breccias associated with shearing at the margins of a dilated zone.

At least the NW-striking mineralised shear zones
Structural controls on GOLD mineralisation in the Central Lapland Greenstone Belt

at Soretiavuoma North fit the above suggestion, with shears in other orientations possible relating to these NW-striking shears, or to other D₃ shear zones in the immediate area. The strike of late shear zones associated with mineralisation at Soretialehto and Soretiavuoma North most resemble the orientation of D₃ shear zones north of the Sirkka Line, including the N- to NE-trending Kiistala Shear Zone hosting the Suurikuusikko deposit. The Kiistala Shear Zone potentially intersects the Sirkka Line near both Soretialehto and Soretiavuoma North (although its exact southern termination point is unclear), further supporting the existence of D₃ deformation in this area.

In the case of the Kiistala Shear Zone, D₃ is expressed as a distinct shear zone, but at Soretialehto and Soretiavuoma North D₃ may be expressed either as re-use of earlier structures and/or an overprinting of early features by D₃ deformation. As at the previous occurrences described, complex post-thrusting deformation is again suggested by the features present at Soretialehto and Soretiavuoma North, making a D₁/D₂ timing for mineralisation unlikely.

**Deposits spatially associated with strike-slip shear zones in the south and southeastern CLGB**

The deformation history of the southern and southeastern CLGB is clearly complex (Fig. 2) and remains to be investigated in detail. However, mineralisation at these sites shows similar features to the other occurrences discussed so far. In each case, mineralisation is spatially constrained to strike-slip shear zones, and occurs late in the sequence of deformation and alteration events recorded for each occurrence.

**Isomaa**

At Isomaa (Figs. 1 & 2), an auriferous quartz-pyrite breccia occurs near an E-striking bend of a NE-striking shear zone interpreted from surface mapping. It is likely that the breccia occurs within this shear but this could not be proven from current surface exposures. The shear zone bend is defined by intensely sheared
quartz-tourmaline-sericite-sulfide altered host rocks, and is also mineralised. Recorded movements on this shear zone were dextral strike-slip on a sub-horizontal elongation lineation, and the locations of mineralisation are consistent with deposition in a dilatant zone generated by movement on this shear zone. The mineralised breccia is paragenetically late and only partially deformed, probably by later movement on the host shear zone. The relationship of this shear zone to Sirkka Line structures is not known.

**Kaaresselkä**

The Kaaresselkä area (Figs. 1, 2, & 6) contains several gold occurrences, and the timing of mineralisation at each is the same relative to the local deformation sequence. No concrete evidence for N-NE-directed thrust-related deformation was encountered during mapping, but several fabrics older than the mineralised structures exist. It is possible but not demonstrable due to lack of outcrop that one of these older fabrics may relate to early thrusting, and the Kaaresselkä area lies near a complex WNW-striking southeastern continuation of the Sirkka Line (Figs. 1 & 2).

Gold occurs as free gold or within pyrite and chalcopyrite (as lattice substitutions; Eilu 1999) in intensely foliated zones associated with WNW-striking, steep-to vertically-dipping sinistral strike-slip shear zones; and in late NE-striking, steep- to vertically-dipping brittle carbonate-rich veins. Both features cut all earlier fabrics, and are not themselves deformed apart from minor displacement by late faults. Pervasive carbonate alteration is also associated with mineralisation.

Mineralised sites and NW- to WNW-striking shear zones in the area are concentrated within a steeper western limb section of a fold (sketched in detail in Fig. 6, and evident in Fig. 2). These shears may have been initiated on this limb in response to fold tightening, but the timing of this folding relative to D₃ is not clear. Mineralised shears at Kaaresselkä have a similar orientation to Sirkka Line thrust remnants in this area, but the movements immediately pre- to syn-mineralisation are clearly strike-slip. This and the generally undeformed nature of ore hosting structures suggest a connection between mineralisation and D₃ deformation.

**Pahtavaara**

The Pahtavaara occurrence (Figs. 1 & 2) is also in a structurally complicated location. Units of the Sattasvaara komatiite complex host the deposit, and extension-related structures associated with the evolution of this complex are likely to have provided an

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Fig. 6. Aeromagnetic image of the Kaaresselkä area (a). Equivalent faults in surface exposures have sub-vertical to vertical dips. Gold-bearing carbonate-rich veins cutting sheared quartzite (b; pencil is approximately five centimetres long). Sheared ore host (c). Gold occurs in sulfides overprinting the dark shear fabric and augen-shaped clasts. In detail the shear fabric displays an s-c fabric (sketch) indicative of sinistral fault movement (figure width on short side is three centimetres)
inherent crustal weakness utilised by later deformation events. This complex is interpreted to have formed in an E-striking rift system, the products of which now lie in an E-striking, refolded syncline (Räsänen 1999). Rifts and shear zones striking ENE and NE also existed during deposition (Saverrikko 1985). The northern and western margins of the complex are described as intensely folded and overthrust (Räsänen 1999), and geophysical data suggests that the northern contact may be a reverse fault (Lehtonen et al. 1998).

A NE-striking cleavage, followed by an ENE-striking cleavage occur in this area, and an E-striking shear zone generating a segregation layering overprints both. In the area of most intense shearing, two types of mineralised structures occur. The oldest hosts the A-type (higher grade) mineralisation, which occurs within a series of E-striking alteration zones dipping 70° to 80° N (Korkiakoski & Kilpelä 1997). Gold-bearing, irregularly oriented barite-carbonate-quartz veins and infill breccias cut biotite-talc altered rock and tremolite-altered rock within these zones. The overprinting, lower-grade B-type mineralisation within the same alteration zones is hosted by a series of NNW-striking quartz-dominated veins and less abundant E-striking veins of the same composition (Niiranen K., pers. com. 2001). Gold in both mineralisation types occurs as discrete native grains at the grain boundaries of silicates and along micro-fracture surfaces (Korkiakoski & Kilpelä 1997), suggesting paragenetically late mineralisation. It is not certain if the two mineralisation phases are parts of the same fluid event.

Shear sense on the host shear zone is unknown, but the relatively regular repetition of NW-to NNW-striking B-ore veins suggests a dextral sense if the stress field generating the host shear also produced these veins. A NW-SE σ3, for the Sattavaara area was also suggested from a study of magnetic lineaments, the results of which also indicate dextral movement on several NW- to WNW-striking lineaments in the area (Airo 1990). Sorjonen-Ward et al. (1992) suggested that the shear zone hosting Pahtavaara evolved as a high-strain zone during reorientation of a regional strike-slip foliation (D3). The timing of mineralisation and nature of the host shear zone suggest that Pahtavaara mineralisation was a late (D3) event in a zone with a long history of deformation and alteration. However, an earlier timing for gold mineralization (even potential formation during a sea floor alteration phase) cannot be excluded for this deposit (Korkiakoski 1992).

**D3 shear-shear hosted deposits north of the Sirkka Line**

Occurrences associated with strike-slip shear zones north of the Sirkka Line have relatively clearer and less complex settings than those further south. Discrete N- to NE-striking D3 strike-slip shears are the dominant tectonic feature north of the Sirkka Line, where the voluminous Kittilä Group rocks provide a large volume of relatively homogenous stratigraphy. The extent of discrete D3 shear zones into areas south of the Sirkka Line is not clear although, as discussed above, strike-slip shears or movements on shear zones are present there as well.

**Suurikuusikko**

Suurikuusikko, the largest known gold resource in the CLGB, is hosted by a shear zone similar in orientation to that which truncates the Sirkka Line at Loukinen (Figs. 1, 2 & 4). Suurikuusikko occurs within a mostly N-striking segment of an otherwise NE-striking D3 structure (the Kiistala Shear Zone). All parts of this N-striking shear segment (and associated NE-striking segments to the south) are mineralised where drilled to date (~2001; along a strike length of 5.5 kilometres).

The Kiistala Shear Zone has a complex movement history, with the youngest D3 movements recording dextral strike-slip shearing. Early folding, a sub-regional NW-striking shear fabric, and sinistral movements on the Kiistala Shear Zone all pre-date the latest shear movements. A direct correlation appears to exist between the intensity of shearing within the Kiistala Shear Zone and the amount of gold-bearing arsenopyrite present. As with mineralisation at Loukinen, ‘graphitic’ alteration also accompanies intense shearing and mineralisation at Suurikuusikko. Intense albite and carbonate alteration is also present in ore zones, decreasing sharply away from intensely deformed zones. Gold occurs as inclusions and lattice substitutions (Chernet et al. 1999) within arsenopyrite (73.2%) and as inclusions in pyrite (22.7%), with the remainder as free gold (Kojonen & Johanson 1999). Gold-bearing arsenopyrite and pyrite occur disseminated on microfractures, shear fabrics, and stylolitic features, all spatially bound between N- to NE-striking sections of the Kiistala Shear Zone.

Known ore zones at Suurikuusikko plunge moderately north, but the mechanisms controlling this plunge are not completely resolved. Ore zones are likely to occupy high strain zones generated during D3 shearing on the Kiistala Shear Zone, although
other factors including preferential host lithologies, and shear zone/lithological contacts also influence the location and orientation of ore lodes. A more detailed discussion of Suurikuusikko is given by Patison et al. (this volume).

**Iso-Kuotko**

The Kiistala Shear Zone can be followed north until it joins others at a complex intersection of shear zones. The Iso-Kuotko occurrences lie close to the junction of these shears (Fig. 7). All of these shear zones are likely to be D$_3$ in age, but have not been studied in exposures with the exception of the Kiistala Shear Zone. The NE-trending shear zone shown in Figure 7 continues to the NE, causing sinistral displacement of D$_1$/D$_2$ structures at the Lapland Granulite Belt/CLGB contact (Fig. 1), indicating a D$_3$ age for this structure.

Several phases of mineralisation have been reported at Iso-Kuotko, all of which overprint a series NW-striking fabrics evident in surface exposures. However, considering paragenetic and compositional similarities evident in all mineralised sections of drill core, it is likely that these ‘phases’ indicate that a series of structures have been utilized or generated by one mineralising event. Most mineralisation occurs in identical quartz-carbonate-sulfide veins and associated breccia zones, with over 60% of gold occurring as free gold between the grain boundaries of the vein and breccia minerals. (Härkönen et al. 2001). The first phase is reported occurring within a shear fabric dipping approximately 45° NE and containing parallel gold-bearing veins (Härkönen et al. 2001). Subsequent mineralisation phases include shear-hosted sub-vertical NW- and N-striking veins (Härkönen et al. 2001). Shear senses in outcrops indicate dextral strike-slip movement on some host shears.

The NW-striking shear-related mineralised structures are likely to relate to the NW-striking shear zone in the area seen in Figure 7. The N-striking veins are contained within shear zones of the same orientation to the Kiistala Shear Zone in the Suurikuusikko area immediately south of Iso-Kuotko. Apart from the ore veins and breccias described above, disseminated arsenopyrite is also present at Iso-Kuotko. These disseminations are more like Suurikuusikko mineralisation than the Iso-Kuotko ore veins and breccias, but the gold-bearing potential of disseminations needs further testing. The timing of all shears in the Iso-Kuotko area, and the undeformed nature of ore-bearing veins and breccias support a D$_3$ age for mineralisation in this area.

![Fig. 7. Simplified map showing the location of prospects at Iso-Kuotko (after Härkönen and Keinänen 1988, and Sorjonen-Ward et al. 1992)](image-url)
These examples provide a good introduction to the structural characteristics of CLGB gold occurrences. Clearly much work remains to be done to fully understand many aspects of deformation and mineralisation within the CLGB. However, several useful findings have emerged form this work to date, and these are reviewed below.

**1. Strike-slip shear zones are prospective for mineralisation throughout the CLGB**

From the summary of key gold-bearing structures presented in Table 4, it is clear that shear zones with strike-slip displacements are the most common host structures for gold occurrences, a correlation that exists throughout the CLGB. However, the complexity of this correlation varies.

Occurrences hosted by strike-slip shear zones away from the Sirkka Line, such as Suurikuusikko and Iso-Kuotko, provide clear examples of this correlation. These occurrences are also within sections of fairly uniform (dominantly mafic volcanic rocks) stratigraphy. However, among other features, the localised effects of lithological variations, of intersecting structures, and of early structures in constraining mineralisation to particular sites needs to be investigated further to aid identification of the most favourable locations for mineralisation within these long host shears.

Areas south of the Sirkka Line and in the south-eastern CLGB are the most complicated to interpret. The mix of lithologies (Fig. 1), and the variety and abundance of deformation features present here (Fig. 2) make these areas substantially more heterogeneous than areas north of the Sirkka Line. Occurrences such as Isomaa, Karesselkä and Pahtavaara indicate that $D_3$ strike-slip shear movement is also associated with mineralisation in these areas. However, at some of these occurrences (e.g., Karesselkä), the orientation of strike-slip shear zones may be partially inherited from the orientation of pre-$D_3$ deformation zones. Similarities in occurrence-specific paragenetic events that can be correlated between most of the occur-

<table>
<thead>
<tr>
<th>Occurrence</th>
<th>Dominant strike of closest pre-syn D1/D2 deformation feature</th>
<th>Post D1-D2 feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saattopora</td>
<td>E to ESE (Sirkka Line)</td>
<td>Strike of mineralised shear zone and displacement sense (where known)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike of mineralised veins and type (where clear)</td>
</tr>
<tr>
<td>Sirkka (Kaivos)</td>
<td>E (Sirkka Line)</td>
<td>Breccia zone(s) of unclear strike</td>
</tr>
<tr>
<td>Loukinen</td>
<td>E (Sirkka Line)</td>
<td>N to NNE Mineralised breccias within dextral strike-slip shear zone(s)</td>
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<td></td>
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<tr>
<td>Soretialahti</td>
<td>NW (Sirkka Line)</td>
<td>N to NE Mineralised breccias within strike-slip shear zones</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N to NNE Mineralised extensional or hybrid veins cutting mineralised breccias</td>
</tr>
<tr>
<td>Soretiavuoma</td>
<td>NW (Sirkka Line)</td>
<td>NW to N and NE Mineralised shear infill within dextral + sinistral strike-slip shear zones</td>
</tr>
<tr>
<td>North</td>
<td></td>
<td>–</td>
</tr>
<tr>
<td>Isomaa</td>
<td>Multiple</td>
<td>NE Mineralised infill within a dextral strike-slip shear zone</td>
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<tr>
<td></td>
<td></td>
<td>–</td>
</tr>
<tr>
<td>Karesselkä</td>
<td>WNW (Sirkka Line – very fragmented)</td>
<td>WNW Disseminated mineralisation within sinistral strike-slip shear zone(s)</td>
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<tr>
<td></td>
<td></td>
<td>NE</td>
</tr>
<tr>
<td>Pahtavaara</td>
<td>E-striking rift? Pre-D1</td>
<td>Mineralised breccia within sub-vertical shear zone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NW Mineralised veins cutting shear-related breccia</td>
</tr>
<tr>
<td>Suurikuusikko</td>
<td>n/a?</td>
<td>N-NE Disseminated, fabric and micro-veinlet hosted mineralisation within a strike-slip shear zone with early sinistral and late dextral movements</td>
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<tr>
<td>Iso-Kuotko</td>
<td>n/a?</td>
<td>NW and N Shear infill and breccias/shear veining associated with dextral (exclusively?) strike-slip shears</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NW and N Mineralised shear veins synchronous with shear zones</td>
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</table>
references reviewed here, regardless of location, suggest that strike-slip shear movements in southern areas are likely to be the same age as D$_3$ shearing north of the Sirkka Line.

2. **The Sirkka Line is a prospective area, but has a more complicated relationship to mineralisation than might be assumed from the spatial association between gold occurrences and Sirkka Line structures**

Sirkka Line structures represent the major zone of prolonged deformation within the CLGB. Through its role in aligning volcanic-dominated mafic rocks to the north against a sediment-rich sequence to the south, the Sirkka Line also generates the major stratigraphic and litho-chemical boundary in the area containing most gold occurrences. These two factors alone are enough to increase the likely prospectivity of areas proximal to the Sirkka Line. Highly deformed zones, and the most deformed areas within these (e.g., fault jogs and splays), are widely acknowledged as the most likely sites for concentrating mineralising fluids (e.g., Cox et al. 2001).

However, occurrences coinciding with the Sirkka Line demonstrate that while it is in general a prospective zone, care must be taken to understand the more detailed events constraining mineralisation to specific locations. This is essential because mineralisation appears to post-date the D$_1$/D$_2$ structures which dominate these areas. For example, despite the Sirkka Line-parallel alteration envelopes associated with mineralisation at the Loukinen, Saattopora and Sirkka occurrences, the N- to NE-striking strike-slip shear zones containing mineralised breccias at Loukinen clearly suggests that D$_3$ structures determined the final location of mineralisation at this occurrence. Additional timing criteria at Saattopora and Sirkka (as discussed) also indicate a post-D$_1$/D$_3$ age for mineralisation.

The Soretiavuoma North occurrence also provides some evidence for reactivation of D$_2$/D$_3$ segments of the Sirkka Line during D$_3$. Like Karesselkä, this occurrence is associated with strike-slip shearing that lies parallel to pre-existing structures evident in regional aeromagnetic images that are within or near the Sirkka Line. Regardless of whether these occurrences are or are not hosted by reactivated Sirkka Line segments, the late timing of mineralisation supports a post-D$_1$/D$_2$ age for mineralisation.

The focusing of fluids into pre-existing, localised irregularities (structural or lithological) during later deformation events, and an association between reactivation of earlier structures and mineralisation have been documented as common occurrences in similar deformed belts elsewhere (e.g., Colvine 1989; Vearncombe et al. 1989; Groves et al. 2000). The potential for such events is high in areas of Sirkka Line deformation, and these are critical questions to consider when exploring within these areas in order to determine which zones were more favourable for mineralisation during D$_3$.

3. **Most gold occurrences studied were generated during D$_3$**

The relative timing of mineralisation and deformation features reviewed here indicates that gold occurrences throughout the CLGB region are typically related to D$_3$ events, the Pahtavaara deposit being a possible exception. D$_3$ deformation also appears to have coincided with the general CLGB-wide evolution from ductile to brittle deformation conditions. Post-D$_3$ ductile deformation events were not documented during this work, and D$_3$ strike-slip shears are typically the last major deformation features observed in the local deformation sequences established at individual gold occurrences. Low-displacement D$_1$ brittle faults were occasionally present, but these have little impact on mineralised structures.

Mineralised strike-slip shears are often associated with semi-synchronous brittle deformation products, which are also mineralised (e.g., mineralised shears and veins at Karesselkä – Fig. 6; and at Soretialehto). These veins are similar in composition to the ore breccias they crosscut, and/or to proximal alteration mineralogy relating to the shear-associated mineralisation at these sites. Mineralised veins at these occurrences are also very planar and undeformed. These points suggest that these examples of vein-hosted gold mineralisation are products of the late stages of D$_3$. The loose cluster of Pb-sulfide ages shown in Table 3 are reasonably consistent with the timing of D$_3$, and favours mineralisation that is synchronous with or immediately post-dating the convergent margin phase of CLGB development.

There is much scope for reviewing the observations and ideas presented here by applying theoretical concepts proposed for structurally controlled gold deposits. More information and interpretations are required regarding the impact of regional and local scale stress and fluid pressure variations, fluid-chemical histories, and the effects of pre-existing structural and lithological variations in localising deposits. These and other factors have been identified as determining sites most likely to become mineralised. (e.g., Cox et al. 2001). **Such a review was not the purpose of this paper, but understanding how structural features associated with CLGB gold mineralisation have acted**
as fluid transporting and focusing mechanisms is an overall aim of this research project. The results of investigations using whole-rock geochemistry, stable isotopes, fluid inclusions and other relevant techniques are being added to the initial observations presented here to address some of these questions.

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