Geochemical controls on high-grade gold mineralisation at the Junction lode-gold deposit, Kambalda, WA

Kate Moran

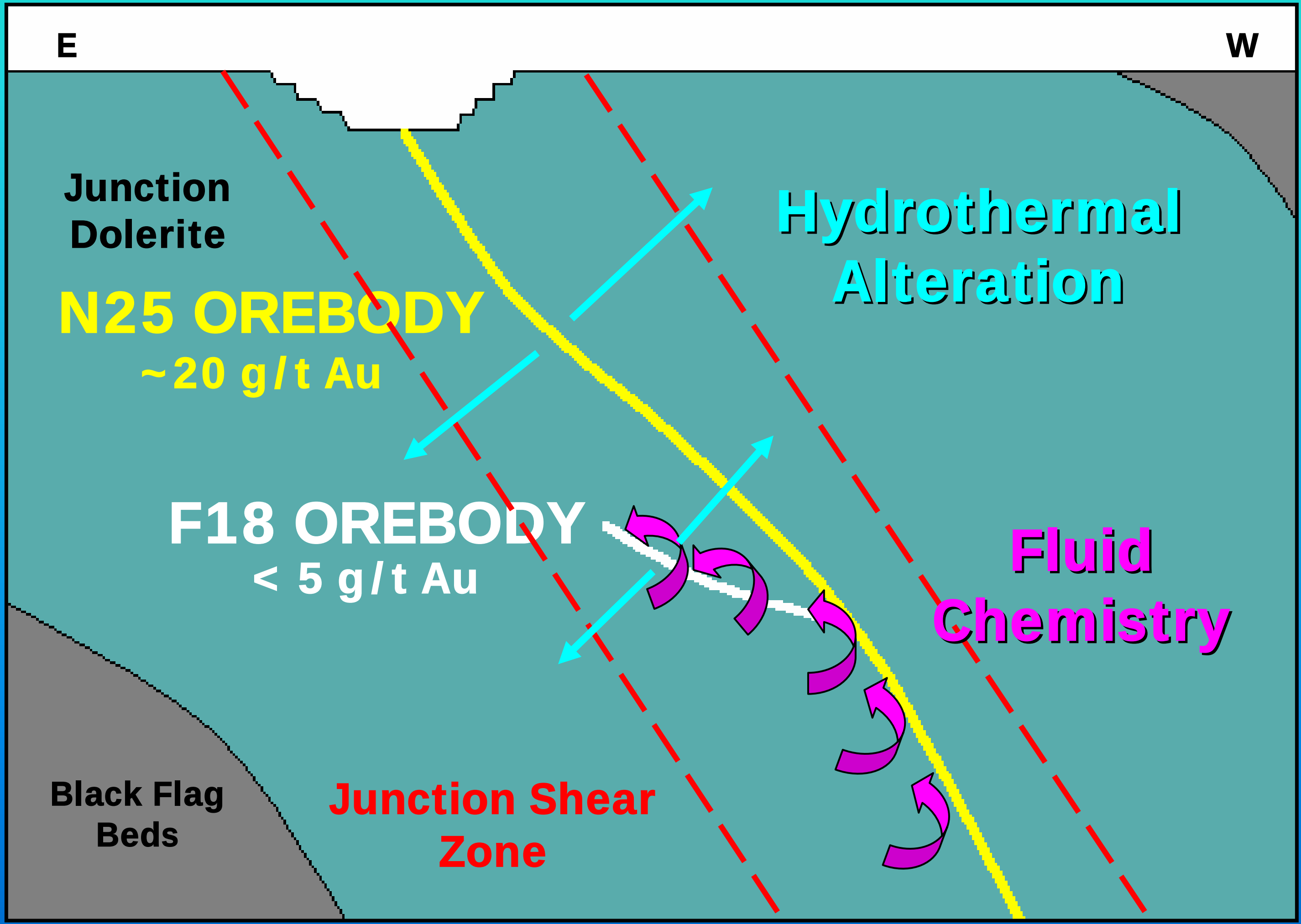
Geology Honours 2003

Supervisors
Steffen Hagemann (UWA, pmd*CRC)
Peter Neumayr (UWA, pmd*CRC)
John Walshe (CSIRO, pmd*CRC)
Bob Morrison (Gold Fields, St Ives)

GOLD FIELDS

THE UNIVERSITY OF WESTERN AUSTRALIA

PROBLEM STATEMENT



Presentation Outline

1. Geological Setting
2. Hydrothermal Alteration
   - Distal, Intermediate, Proximal Zones
3. Gold Mineralisation
4. Fluid Inclusion Study
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   - Microthermometric Results
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5. Depositional Model
   - Hydrothermal Alteration and Fluid Evolution
   - Major Differences and Similarities: N25 and F18
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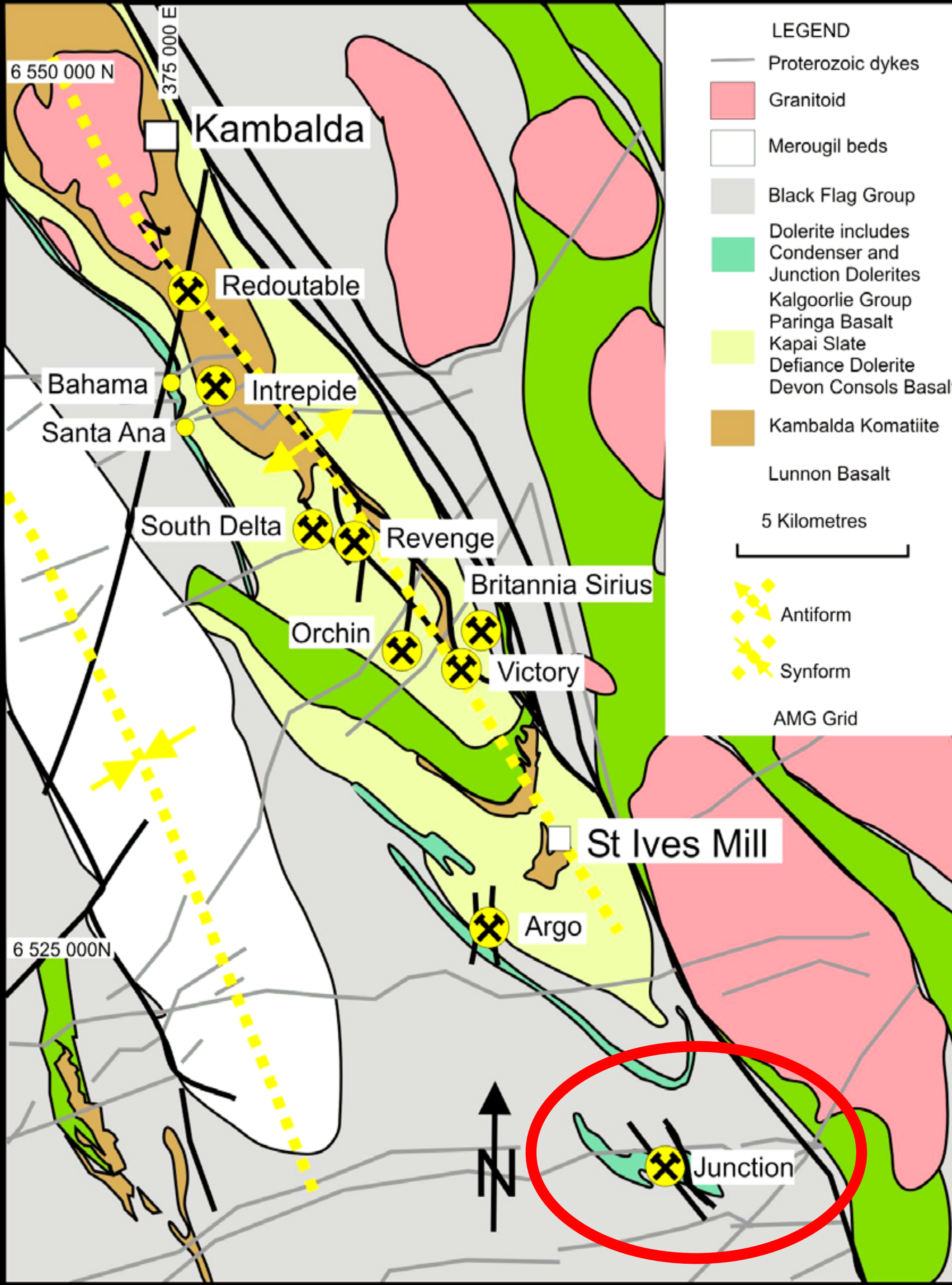
   - Geochemical Controls on Gold Mineralisation
6. Implications for Future Work

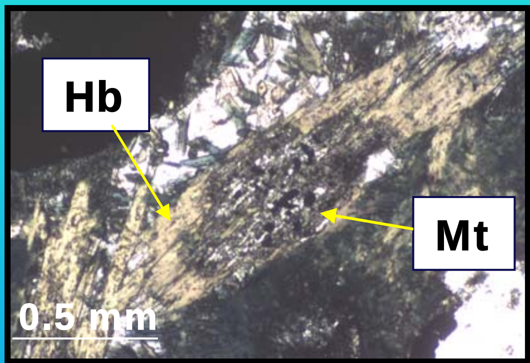


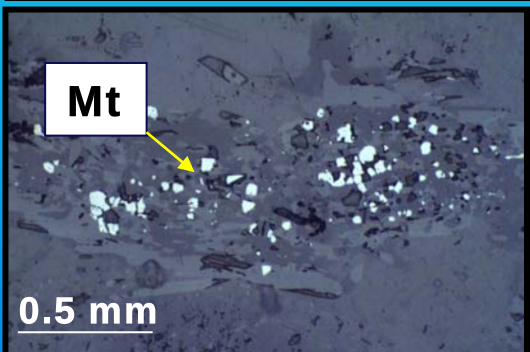
Junction Deposit

- **Orogenic lode-gold deposit within St Ives gold camp**
- **Located in Kambalda Domain of Kalgoorlie Terrane**
- **Hosted by differentiated dolerite sill (Junction Dolerite), structurally controlled by oblique reverse-sinistral shear zone (Junction Shear Zone)**
- **Up to 23 March 2003, total production 8.4Mt @ 6.39g/t for 1.74 Moz**

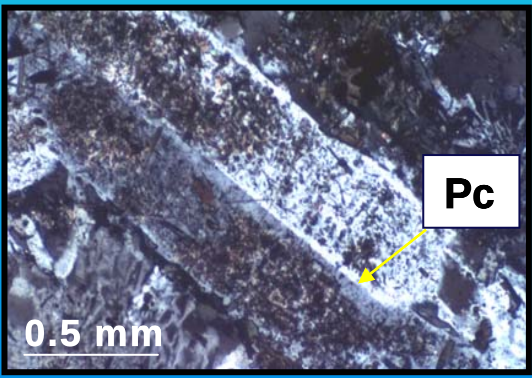
Distal Alteration Zones

Distal Alteration Zones N25 and F18 orebodies: similar





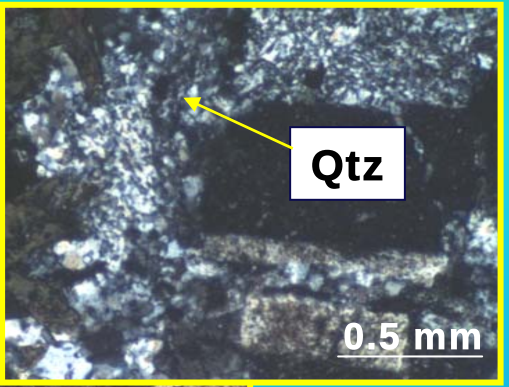
- **Hydrothermal mineral assemblage chlorite–magnetite**
- **Relict metamorphic hornblende and actinolite**
- **Relict igneous plagioclase, quartz and apatite**
- **F18 relict igneous magnetite**
- **N25 hydrothermal skeletal ilmenite replaces igneous magnetite**

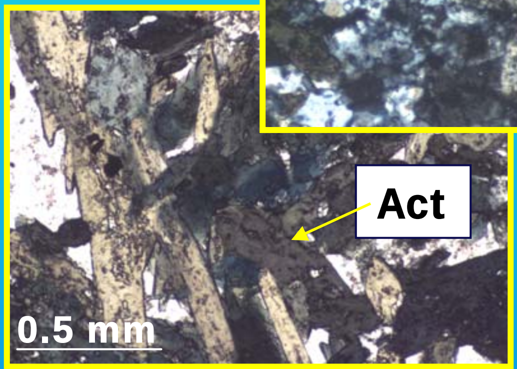


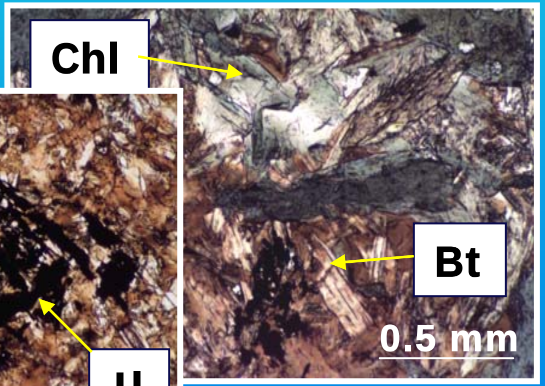
Intermediate Alteration Zones

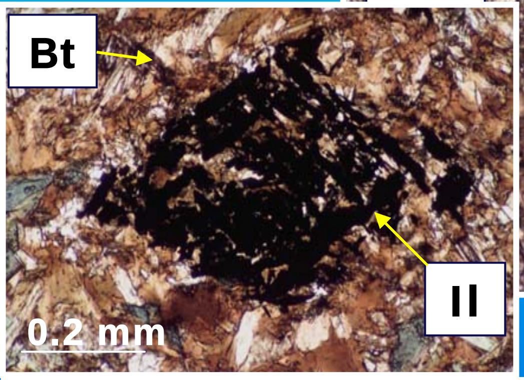
N25

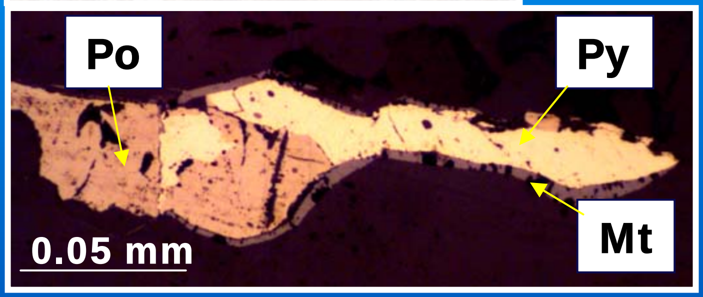
- Hydrothermal mineral assemblage actinolite–quartz–chlorite
- Dominant sulphide and oxide: pyrrhotite, ilmenite
- Moderate foliation







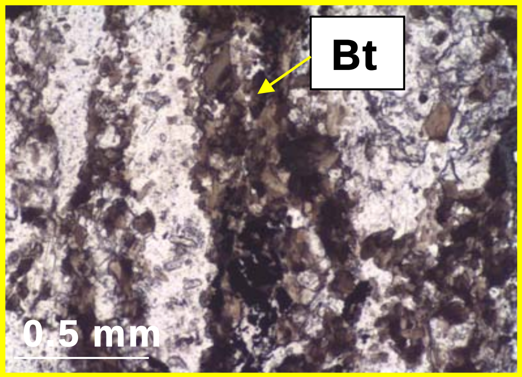


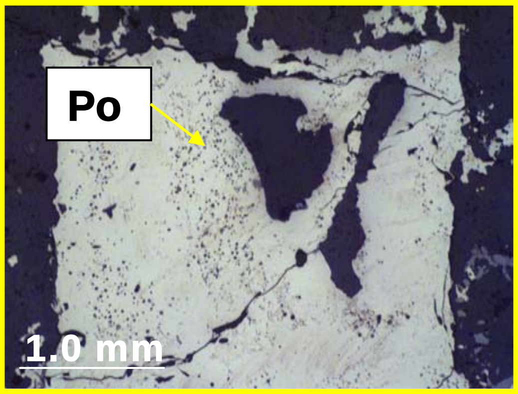


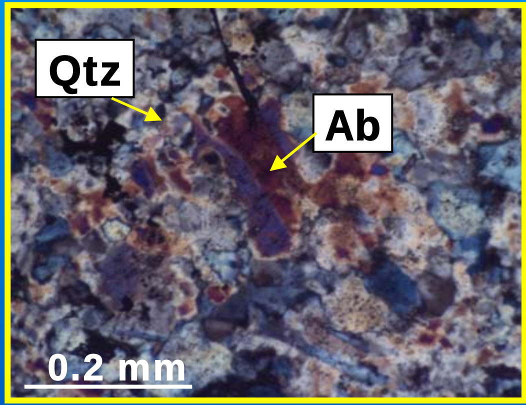
F18

- Hydrothermal mineral assemblage actinolite–quartz–biotite–chlorite
- Dominant sulphide and oxide: pyrite, ilmenite
- Pyrite rimmed by magnetite and contain exsolved pyrrhotite inclusions
- Weak to moderate foliation

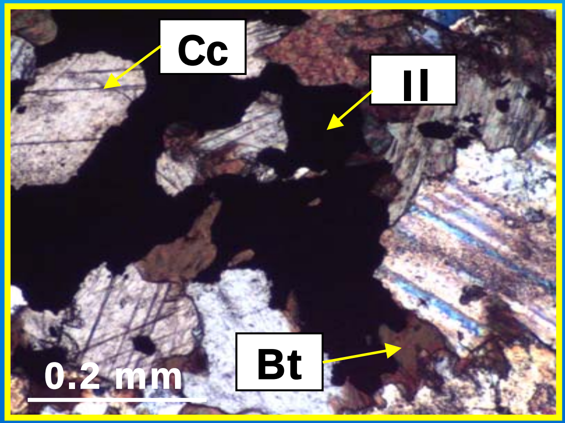
Proximal Alteration Zones: N25 Orebody

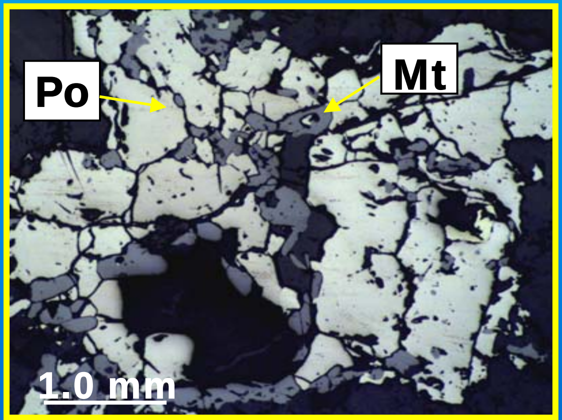






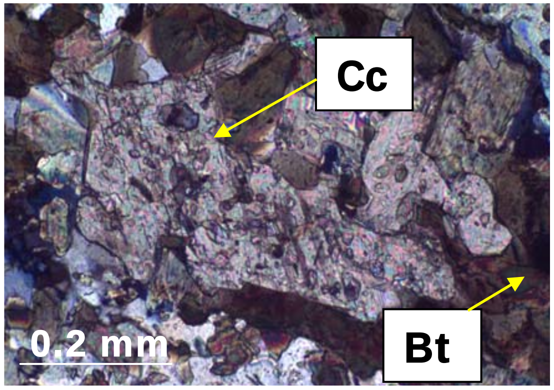
- Hydrothermal mineral assemblages biotite–calcite–pyrrhotite–magnetite–chlorite and albite–quartz
- Dominant sulphide and oxide: pyrrhotite, magnetite
- Strong foliation

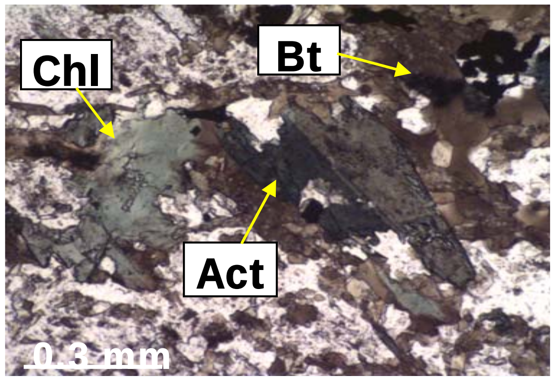


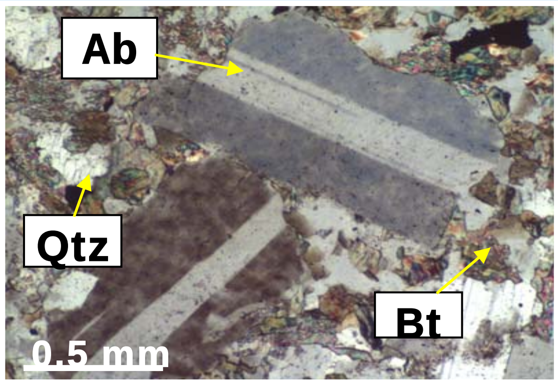


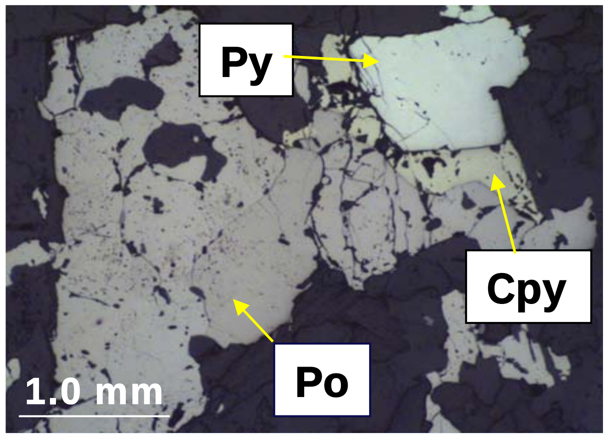
Proximal Alteration Zones: F18 Orebody

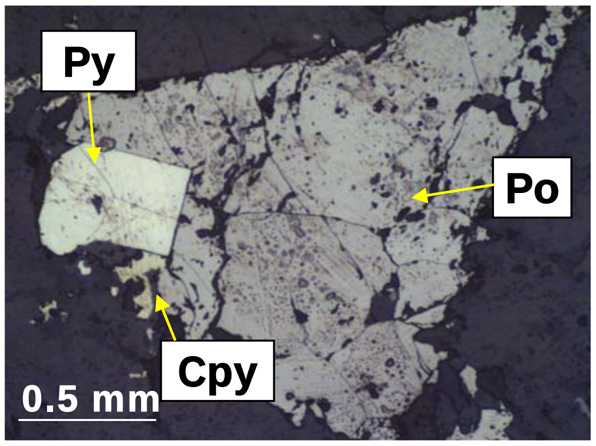
- **Hydrothermal mineral assemblages biotite–calcite–actinolite–chlorite–pyrite–magnetite–pyrrhotite and albite–quartz**
- **Dominant sulphides and oxide: pyrite, pyrrhotite, ilmenite**
- **Strong foliation**









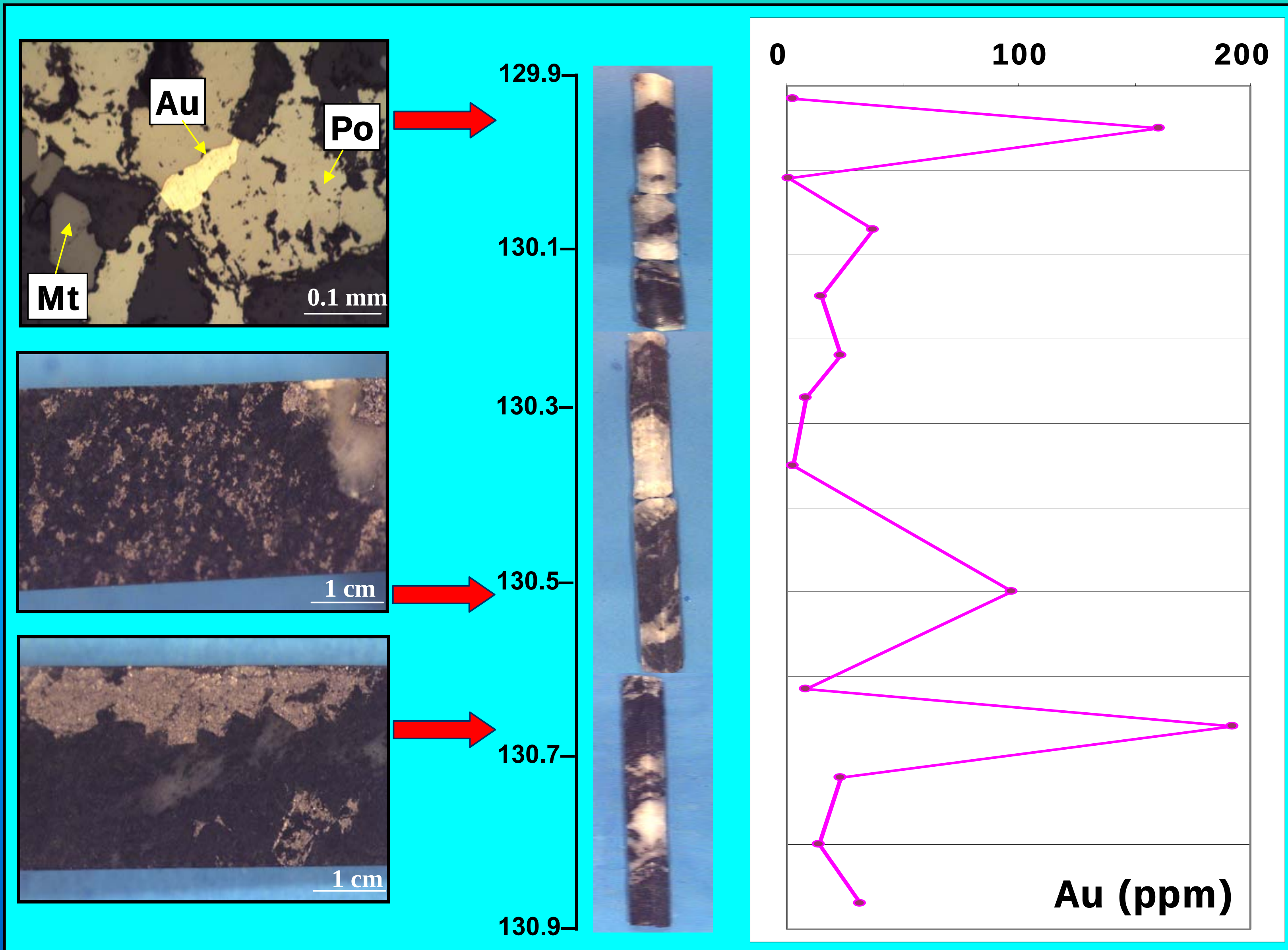


Gold Mineralisation

Ore Zones: Brecciated or strongly foliated to mylonitic rocks within the proximal alteration zones

N25 ORE ZONES	F18 ORE ZONES
Breccia matrix: quartz±albite±calcite	Breccia matrix: albite–carbonate±quartz
Gold: fine-grained (0.01-0.1 mm) subhedral grains in qtz, po, bt, cc, ab, chl, il and mt	Gold: SAME
High abundance pyrrhotite: coarse-grained (3-9 mm) euhedral (~20 vol%)	Low abundance of pyrrhotite (<10 vol%) Pyrite present in ore zones
Albite–quartz present in high-grade zones	Albite–quartz generally absent in proximal alteration
Average gold grades >20 g/t	Average gold grades < 5 g/t

Gold Mineralisation



Fluid Inclusion Study

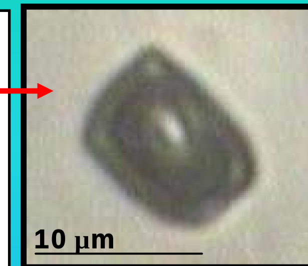
- **Three main stages of vein formation:**
  - **Pre-mineralisation quartz–magnetite–epidote veins**
  - **Syn-mineralisation quartz±albite±calcite veins that are locally brecciated**
  - **Post-mineralisation carbonate veins**

- **Fluid inclusion analyses undertaken on samples from pre-mineralisation veins and syn-mineralisation veins from N25 and F18 orebodies**

- **Fluid inclusions characterised petrographically, microthermometric data collected from ~400 inclusions. Measurements taken on Linkham THMSG 600 heating and freezing stage at the University of Western Australia**

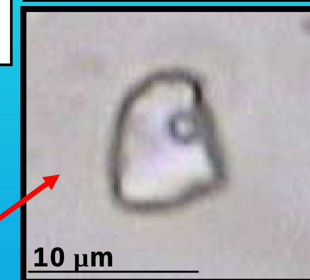
Fluid Inclusion Types

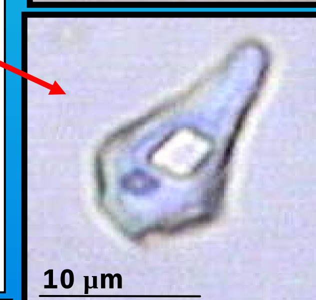
Type 1: CO_2-CH_4



- Mainly water-absent CO_2-CH_4 two-phase (liquid CO_2 and carbonic vapor) inclusions at room temperature
- vapour phase occupies 50-80 vol %

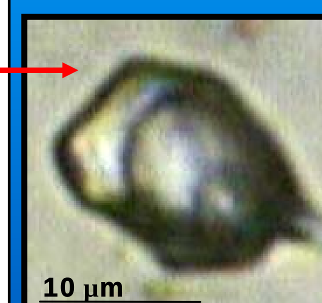
Type 2: H_2O-NaCl-$CaCl_2$ ± daughter minerals





- Two-, three- or poly-phase fluid inclusions (liquid H_2O, vapor H_2O daughter mineral or minerals) at room temperature
- vapour phase occupies 5-10 vol %
- square, colourless daughter crystals (halite, sylvite) 2.5-6.25μm

Type 3: H_2O-CO_2

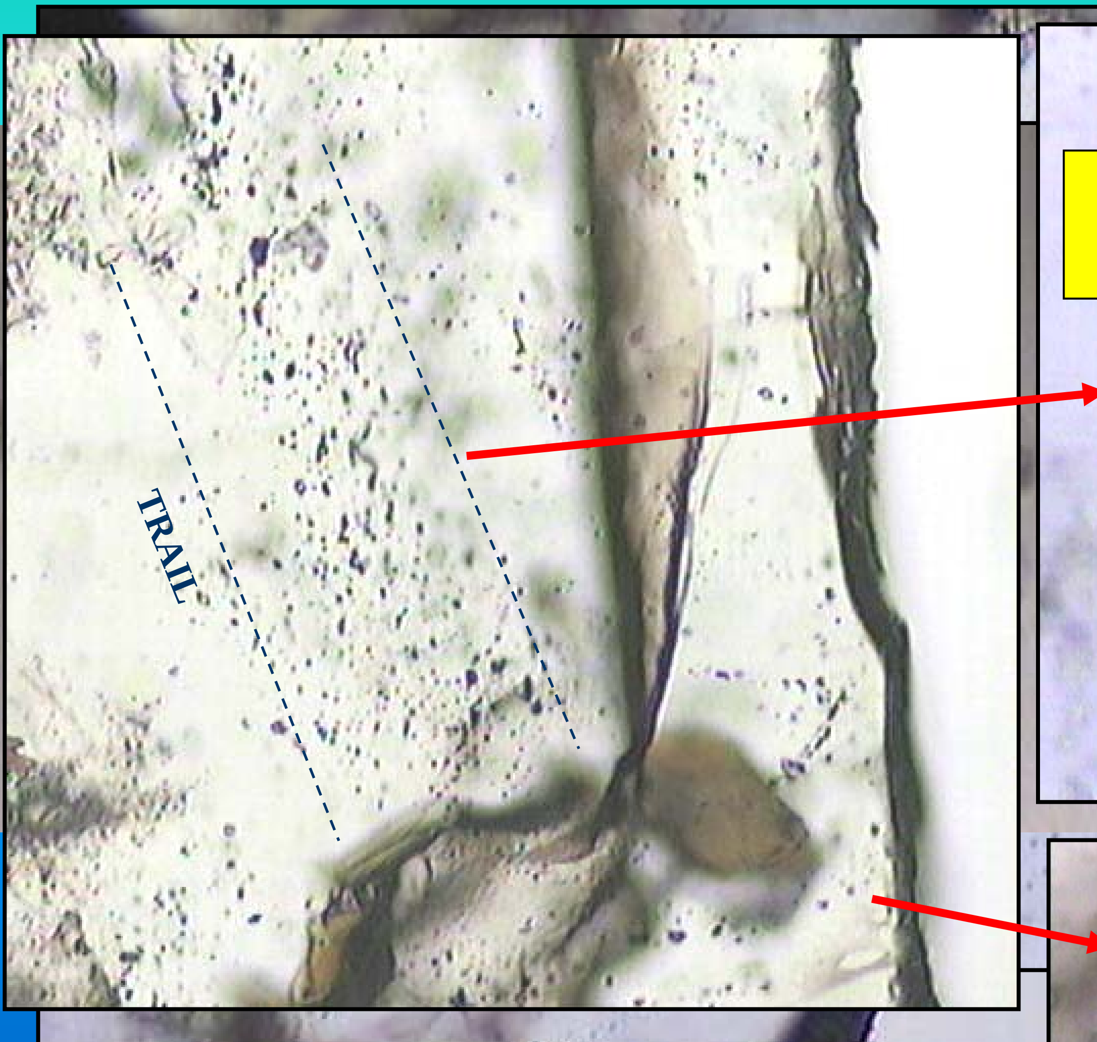


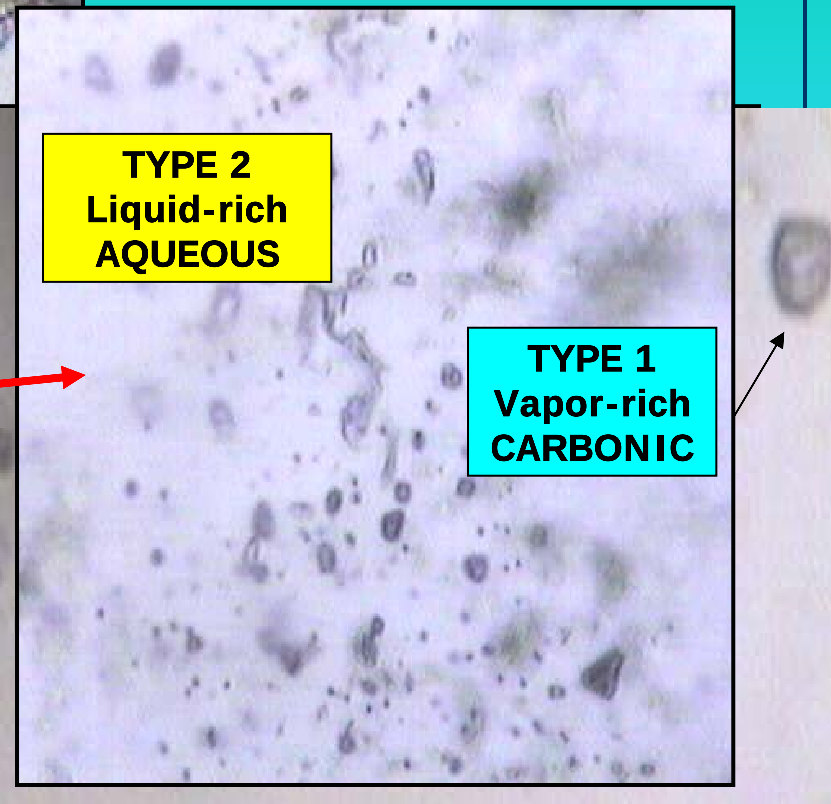
- Three-phase fluid inclusions (liquid H_2O, liquid CO_2, vapor CO_2) at room temperature
- Proportion of CO_2 ranges 30-80 vol %

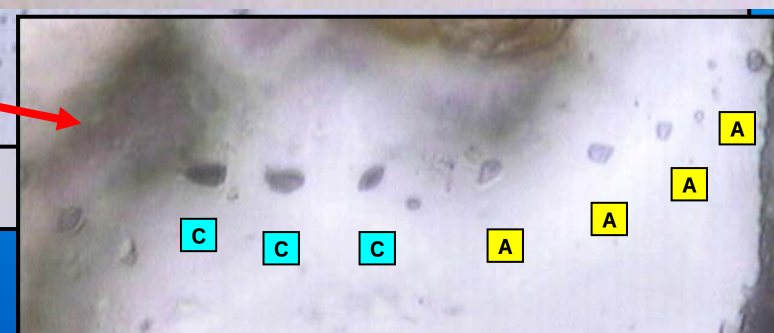
Fluid Inclusion Assemblages

- **Pre-mineralisation Veins**
  Dominantly Type 2 inclusions:
  - Primary to pseudosecondary inclusions, form intragranular trails or clusters
  - Secondary inclusions commonly contain daughter minerals, form intergranular trails
- **Syn-mineralisation Veins: N25 Orebody**
  - Pseudosecondary Type 1 and Type 2 inclusions coexist within intragranular trails
  - Primary Type 3 inclusions from intragranular trails or clusters
  - Pseudosecondary Type 1 and Type 2 inclusions in separate intragranular trails
  - Secondary Type 2 inclusions form intergranular trails
- **Syn-mineralisation Veins: F18 Orebody**
  - Pseudosecondary Type 1 and Type 2 inclusions in separate intragranular trails
  - Secondary Type 2 inclusions form intergranular trails

N25 Syn-Mineralisation Veins

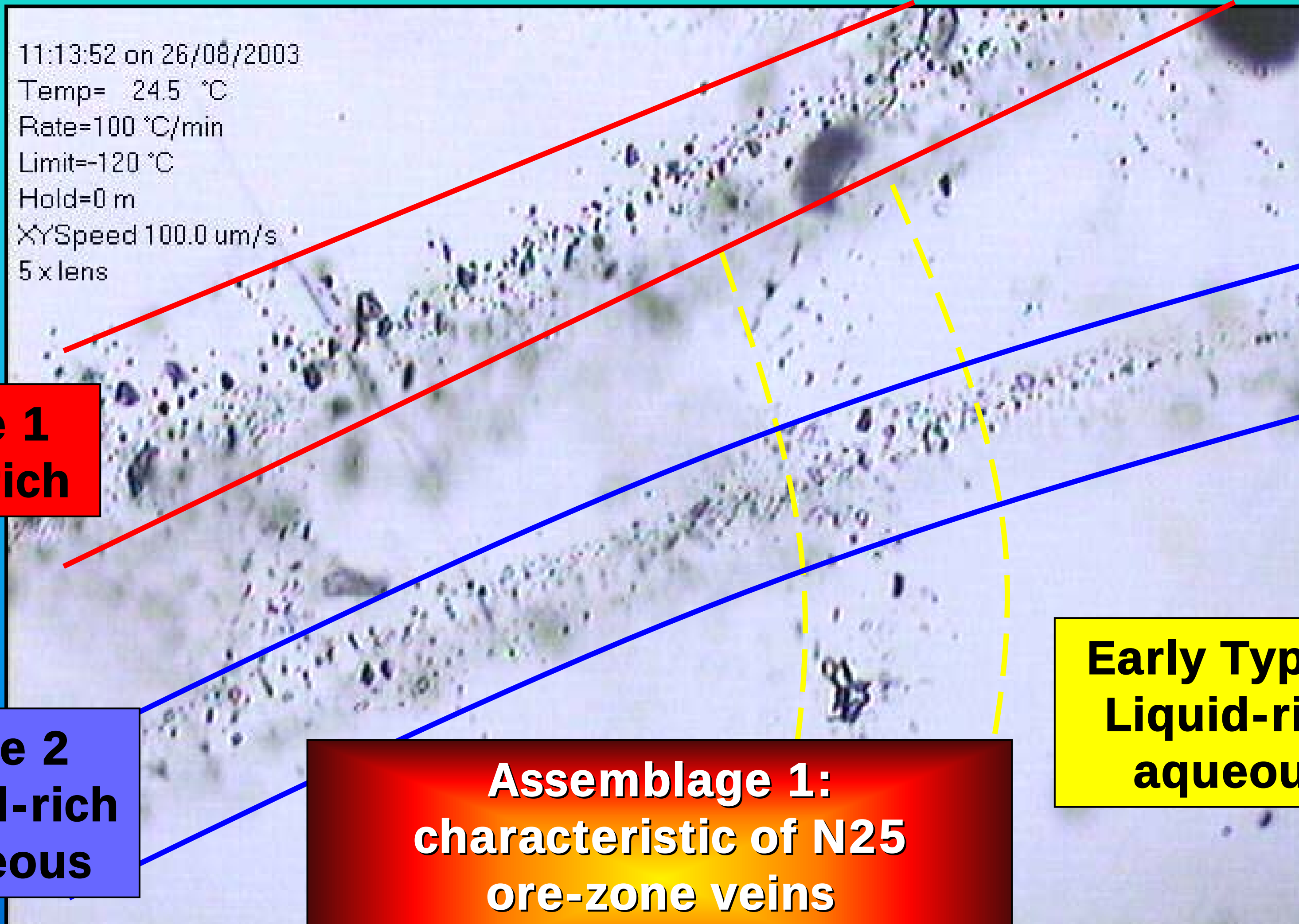






Assemblage 1: Type 1 CO_2-rich and Type 2 liquid-rich aqueous inclusions

F18 Syn-Mineralisation Veins



Type 1 CO_2-rich

Type 2 Liquid-rich aqueous

Early Type 2 Liquid-rich aqueous

Assemblage 1: characteristic of N25 ore-zone veins

NOT OBSERVED in F18

Microthermometric Results

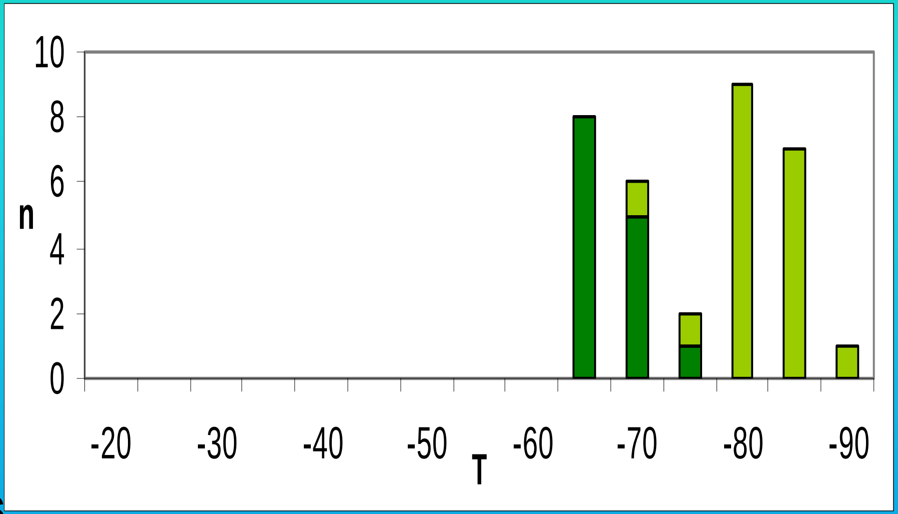
Pre-Mineralisation Veins

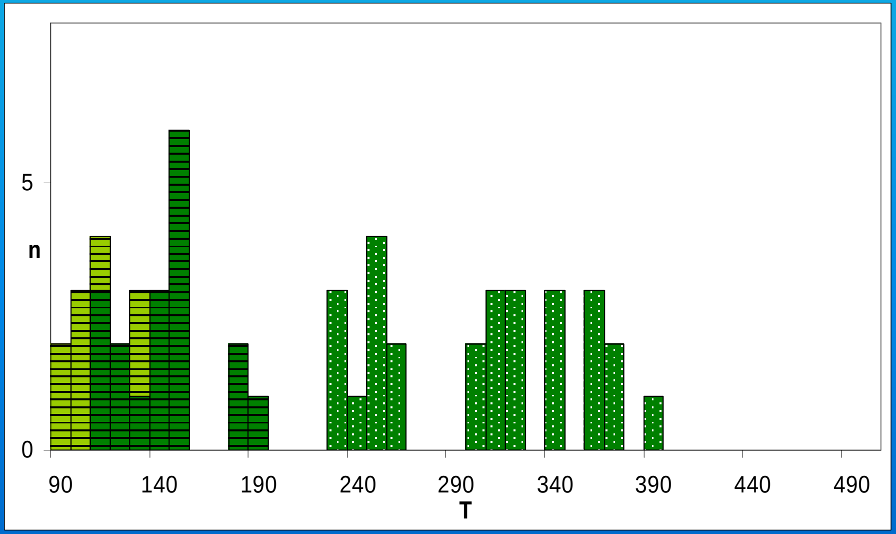
- **Type 2 Liquid-rich Aqueous**
  low eutectic melts
  (-65° to -85°C)
  indicates presence of Ca^{2+}

- **PIXE probe analyses:**
  Ca, K and Cl major components in the fluid as well as Br, Sr Fe, Cu, Zn, As

- **High salinity (12-23 equiv wt % $CaCl_2$)**

- **Homogenisation temperatures: 230° to 390°C**

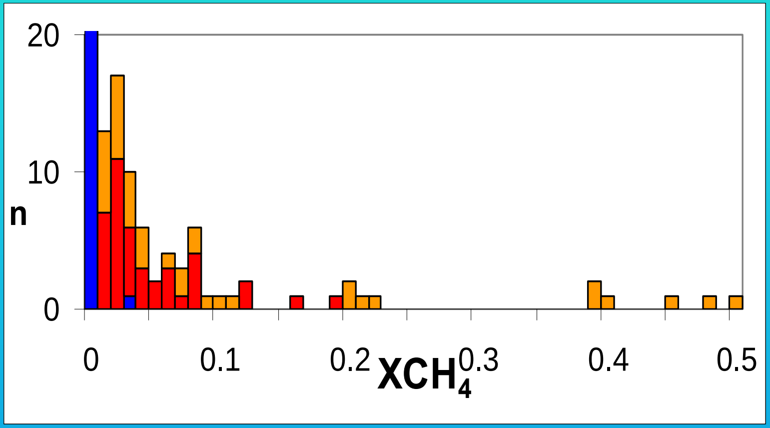


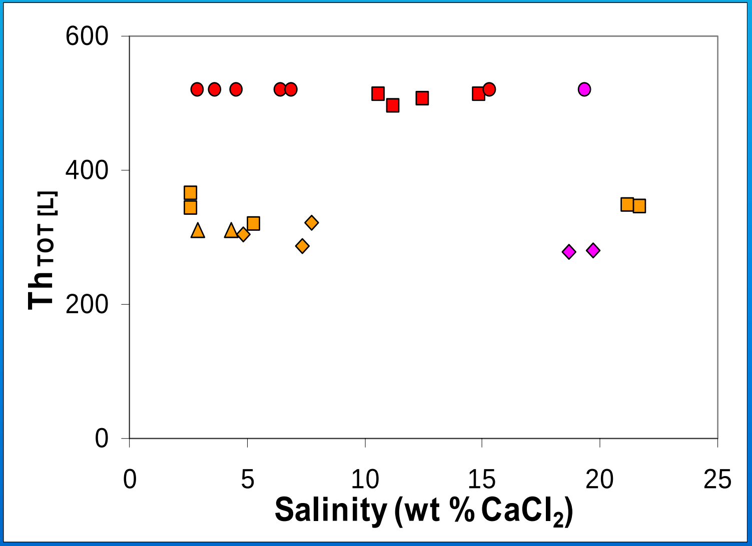


Microthermometric Results

Syn-Mineralisation: N25

- **Type 1 CO_2-rich**
  - Contains small amounts of methane (up to 51 mol % CH_4)
- **Type 2 Liquid-rich Aqueous**
  - High salinity (12-29 equiv wt % $CaCl_2$)
  - Homogenisation temperatures: 300° to 470°C
- **Type 3 H_2O-CO_2**
  - Low salinity (approx 7 equiv wt % NaCl)
  - Contains approx 25 mole percent CO_2
  - Homogenisation temperatures: 311° to >520°C

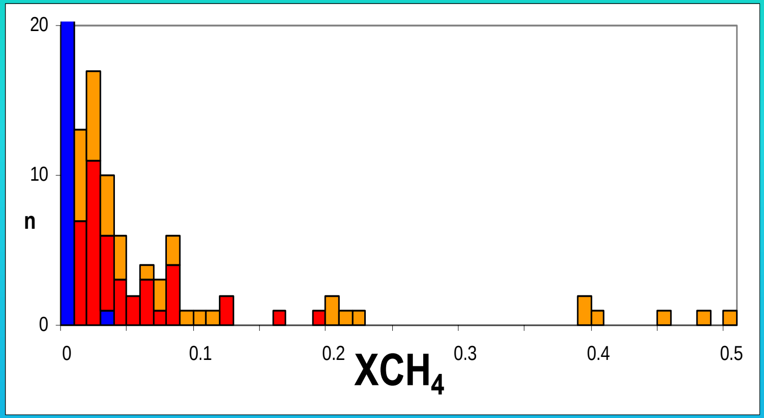




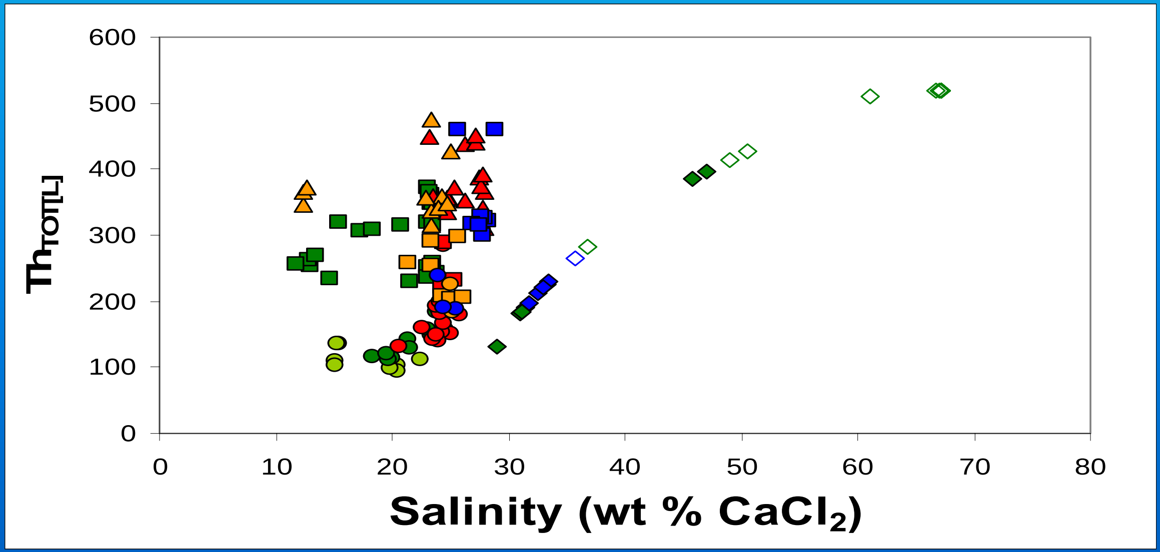
Microthermometric Results

Syn-Mineralisation: F18

- Type 1 CO_2-rich
  - Contains little or no methane (< 1 mol % CH_4)



- Type 2 Liquid-rich Aqueous
  - High salinity (24 to 29 equiv wt % $CaCl_2$)
  - Homogenisation temperatures: 290° to 460°C

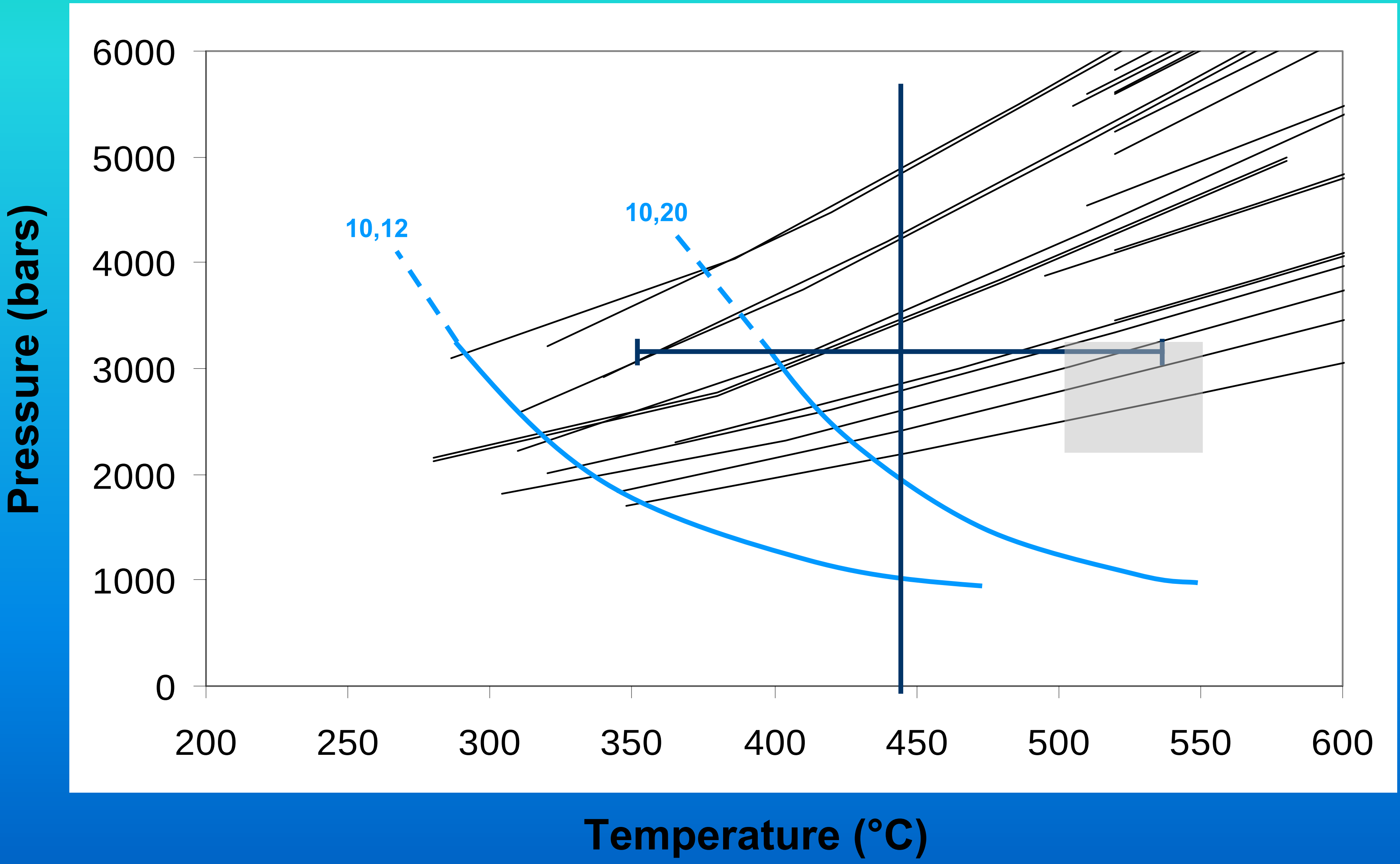


Phase Immiscibility in N25 Orebody

- **Type 1 CO_2-rich and Type 2 liquid-rich aqueous inclusions trapped along the same healed fracture planes - suggests that the two phases are cogenetic and possibly represent trapped immiscible fluids.**
- **Ramboz *et al.* (1982) developed criteria can be used to test if they represent stable immiscible phases:**

1. ***Temporally and spatially related***
2. ***Pairs of liquid- and vapour-rich Type 3 H_2O-CO_2 inclusions homogenise in the same temperature range, to both liquid and vapour***
3. ***Type 3 H_2O-CO_2 fluid inclusions of similar shape and size decrepitated at approx same temperatures***
4. ***Relative concentration of chemical components in the liquid and vapour is appropriate to equilibrium fractionation at Th_{TOT}***

Pressure and Temperature Conditions



Fluid Compositions

Pre-Mineralisation

1. High salinity aqueous fluid (12-23 equiv wt % $CaCl_2$) rich dissolved ions (Ca^{2+} Na^{+} Cl^{-}) poor in volatiles (CO_2)

F18 Syn-Mineralisation

1. High salinity aqueous fluid (24-29 equiv wt % $CaCl_2$) rich dissolved ions (Ca^{2+} Na^{+} Cl^{-}) poor in volatiles (CO_2)

2. Carbonic fluid poor in dissolved ions and rich in CO_2 contains little CH_4 (<0.01 XCH_4)

N25 Syn-Mineralisation

1. High salinity aqueous fluid (12-28 equiv wt % $CaCl_2$) rich dissolved ions (Ca^{2+} Na^{+} Cl^{-}) poor in volatiles (CO_2)

2. Carbonic fluid poor in dissolved ions and rich in CO_2 contains CH_4 (up to 0.51 XCH_4)

3. Low salinity fluid (7 equiv wt % NaCl) contains H_2O, CO_2 and small amounts of Ca, Na, Cl and CH_4

Depositional Model

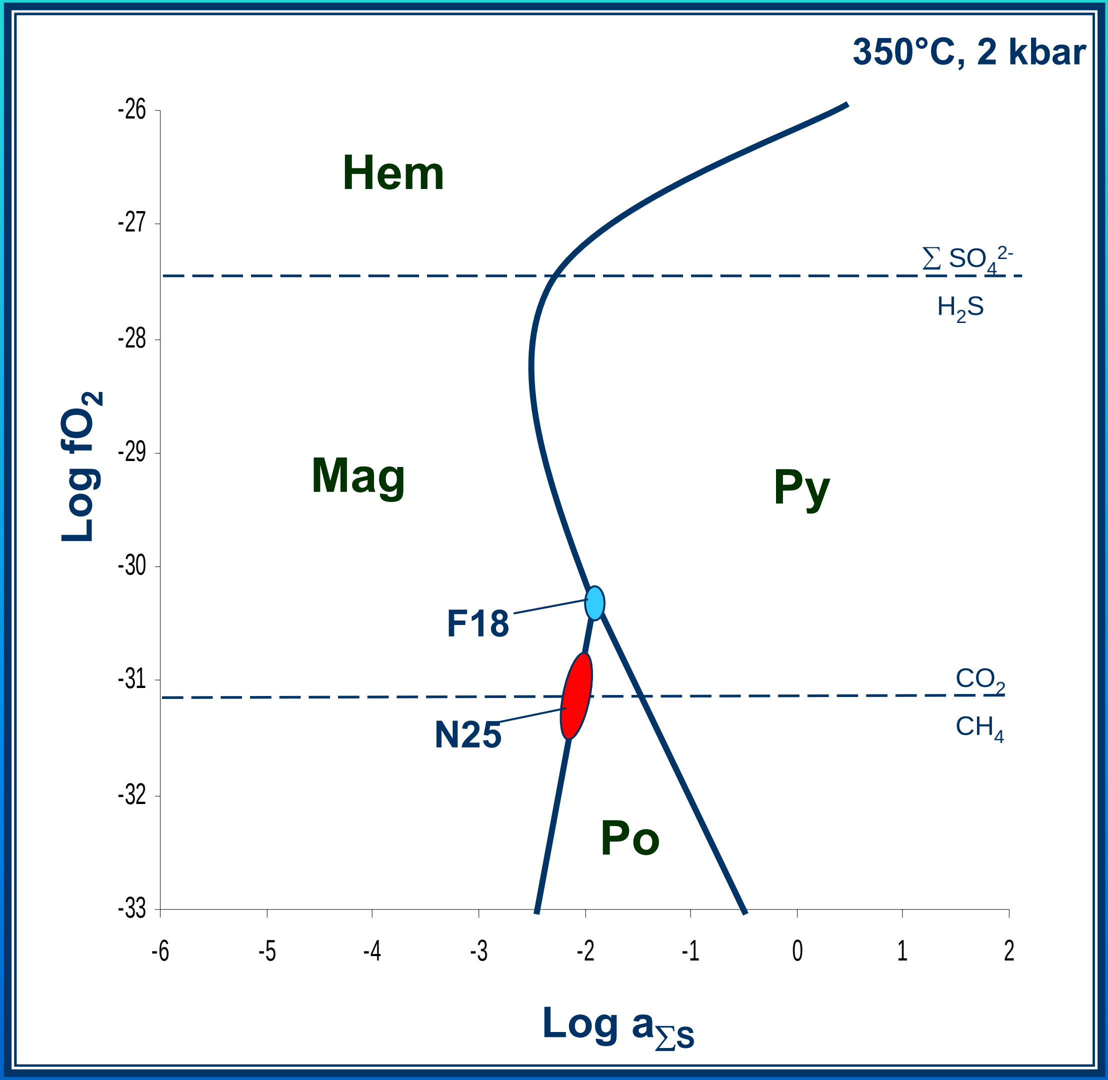
Hydrothermal Alteration Evolution

- Alteration halos adjacent to quartz±albite±calcite veins and breccias in the N25 and F18 orebodies display a lateral zonation and temporal mineral evolution
- Same initial evolution of hydrothermal alteration, similarity of hydrothermal mineral assemblages define the distal (chlorite–magnetite) and intermediate (actinolite–quartz–chlorite±biotite) alteration zones
- Main phase hydrothermal alteration and gold mineralisation formed gold-bearing alteration halos proximal to veins and breccias in N25 and F18 orebodies
- The equilibrium mineral assemblages differ between the two orebodies
  - N25: bt–cc–po–mt–chl and ab–qtz
  - F18: bt–cc–act–chl–py–po–mt and minor ab–qtz

Depositional Model

Hydrothermal Alteration Evolution

- **Variation in proximal ore assemblages - attributed to a difference in oxidation state of the ore fluid**
- **At 350°C and 2 kbar, po–mt in N25 reduced ore fluid compositions, py–po–mt in F18 relatively oxidised conditions**



Depositional Model

Hydrothermal Fluid Evolution

- Type 2 aqueous inclusions dominate pre-mineralisation qtz–mt–ep veins. Evidence for infiltration of high salinity H_2O-$CaCl_2$-NaCl fluid in early stages of hydrothermal alteration

- Fluid inclusion types, occurrences and associations differ in syn-mineralisation veins of N25 and F18
  - Coexisting trails of Type 1 CO_2-rich and Type 2 liquid-rich aqueous inclusions, occurrence of Type 3 H_2O-CO_2 inclusions – exclusive to N25
  - Separate trails of Type 1 CO_2-rich and Type 2 liquid-rich aqueous inclusions – observed in both

- Intergranular trails of secondary Type 2 aqueous inclusions: high salinity, low homogenisation temps in both orebodies – late stage saline fluid unrelated to mineralisation

Depositional Model

Major Similarities and Differences: N25 and F18

Similarities

- **Hosted by Junction Dolerite (Zone 3), metamorphosed upper GSF to lower AF conditions**
- **Structurally controlled by Junction Shear Zone**
- **Same initial evolution of hydrothermal alteration**
- **Syn-mineralisation veins: separate intragranular trails of Type 1 CO_2-rich and Type 2 aqueous inclusions**

Differences

- **Proximal alteration zones differ: py and act in F18**
- **N25: po-mt indicate reduced conditions, F18: py-po-mt indicate relatively oxidised conditions**
- **N25 syn-mineralisation veins: coexisting Type 1 and Type 2 inclusions and occurrence of Type 3 inclusions**
- **Type 1 CO_2-rich inclusions in N25 have higher CH_4 contents compared to same inclusion type in F18**

Depositional Model

Hydrothermal Alteration, Fluid Evolution and Gold Mineralisation Model

Model 1: Phase Separation

- **Unmixing of H_2O-CO_2-NaCl±$CaCl_2$ fluid into CO_2-rich vapour and high-salinity aqueous liquid**
  - **Type 3 H_2O-CO_2: trapped parent fluid**
  - **Coexisting Type 1 CO_2-rich and Type 2 aqueous: insitu phase separation**
  - **Separate trails Type 1 and Type 2: immiscible fluids trapped after phase separation**
- **Drop in fluid pressure associated with fracture propogation could have triggered phase separation in N25 orebody**

Depositional Model

Hydrothermal Alteration, Fluid Evolution and Gold Mineralisation Model

Model 2: Fluid Mixing of Externally Derived Fluids

- Coexisting Type 1 and Type 2 inclusions in N25 can be explained by entrapment of two chemically dissimilar, partly miscible fluids
- Fluid mixing proposed on camp-scale at St Ives (Walshe *et al.*, 2003)
- Fluid mixing seldom confirmed from fluid inclusion studies
- Fluid mixing model can account for higher CH_4 content in Type 1 inclusions N25, assuming two fluids H_2O-CO_2 and CO_2-$CH_4 \pm H_2$

Depositional Model

Hydrothermal Alteration, Fluid Evolution and Gold Mineralisation Model

Model 3: Fluid Mixing of Internally Derived Fluids

- Fluid mixing of a primary, oxidised gold-bearing fluid with more reduced fluid that evolved during wallrock interaction with carbonaceous slates or graphitic shales
- Cf. Cox *et al.* (1995) – Wattle Gully and Uemoto *et al.* (2002) – Golden Crown gold deposits
- At Junction: host dolerite intrusive into Black Flag Group
- Fluid mixing can account for higher CH_4 content in N25, assuming ore fluid responsible for mineralisation equilibrated with Black Flag Beds to higher degree than ore fluid in F18

Geochemical Controls on Au Mineralisation

Two key observations

1. Gold dominantly sited in proximal alteration zones
2. Evidence of phase immiscibility is restricted to syn-mineralisation veins of N25 orebody

- Importance of fluid-wallrock interaction as gold precipitation mechanism in both N25 and F18
- Phase separation adequately explains observed fluid inclusion associations and compositions in N25 orebody
- Fluid inclusion associations in F18 orebody can be explained by either entrapment of two separate fluids, or immsicble fluids that formed during phase separation in N25 orebody, and channelled to F18 orebody

Geochemical Controls on Au Mineralisation

- Evidence **phase separation** restricted to N25 orebody, coincides with **highest gold grades** – important implications for gold precipitation mechanisms at Junction
- Separation of ore fluid into immiscible phases would increase fO_2 and pH, through partioning of volatiles into vapour phase → increase gold undersaturation, whilst decrease in H_2S content of ore fluid → decrease gold solubility: may have triggered precipitation of ore concentrated in high-grade breccias in N25
- However, process of **phase separation** would **increase oxidation state of fluid** – contradicts CH_4 contents in fluid inclusions in syn-mineralisation veins of N25.
- **Addition of CH_4** to ore fluid via interaction with Black Flag Beds or sourced from CH_4-bearing fluid

Implications for Future Work

- Implications for other dolerite-hosted Archean lode-gold deposits, e.g., Argo deposit
- Fluid inclusion study established local variations in fluid compositions and associations are related to hydrothermal alteration mineralogy and structures
  - Compile mineral variations of proximal alteration zones in existing core logs at Junction or Argo to determine which structures contain evidence of more reduced or oxidised fluids
- Further PIXE microprobe, Laser-ICP-MS, isotopic and noble gas analyses on syn-mineralisation fluid inclusions to identify fluid sources
- Carbon isotope (^{13}C) analyses of Type 1 CO_2-rich inclusions in syn-mineralisation veins to determine if CH_4 is sourced from a deep crustal CH_4-rich fluid or via interaction with Black Flag Beds

Summary

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   - Pressure and Temperature of Mineralisation
   - Fluid Compositions
5. Depositional Model
   - Hydrothermal Alteration and Fluid Evolution
   - Major Differences and Similarities: N25 and F18
   - Three models: Phase Separation, Fluid Mixing of Externally Derived Fluids, Fluid Mixing of Internally Derived Fluids
   - Geochemical Controls on Gold Mineralisation
6. Implications for Future Work

Thank you

Any questions?