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Gold mineral systems in the Tanami region

New insights from NTGS–AGSO research

AS Wygralak, TP Mernagh, G Fraser, DL Huston, G Denton, B McInnes, A Crispe & L Vandenberg

Prelminary results of a joint NTGS–AGSO research program to document gold deposits of the Tanami region in the Northern Territory raise important new questions regarding ore genesis. Deposits in the Dead Bullock Soak and The Granites goldfields are related to regional D_5 or D_6 structural events. The ore fluids were low to moderate salinity (4–10 eq wt % NaCl), moderate to high temperature (260–460°C) and gas-rich. Ore deposition occurred at depths of three to eight kilometres. In contrast, ore fluids in the Tanami goldfield (also related to D_5 structures) were low temperature (120–220°C) with minor CO_2, and ore deposition occurred at depths of less than 1.5 kilometres. Preliminary $^{40}Ar/^{39}Ar$ studies of biotite tentatively suggest that mineralisation at Callie occurred at 1720–1700 Ma. Lead isotope data indicate that the Pb in the deposits was not derived solely from nearby granites. In the Dead Bullock Soak and The Granites goldfields, O and H isotopic data are consistent with either a metamorphic or magmatic origin for the ore fluids; in the Tanami district these data require an additional meteoric fluid input. These results illustrate the complexity of gold mineralisation in the Tanami region, and raise important questions about the origin and timing of these deposits.

The Tanami region, located 600 kilometres north-west of Alice Springs, is one of the most important new gold provinces in Australia. It straddles the Northern Territory–Western Australian border along the southern margin of the Palaeoproterozoic North Australian Craton. The Tanami region contains more than 50 gold occurrences including three established goldfields (Dead Bullock Soak, The Granites and Tanami), as well as several significant gold prospects (Groundrush, Titania, Crusade, Coyote and Kookaburra). The region has produced 4.5 Moz Au. The remaining resource is 8.4 Moz (260 t) Au, but this figure is steadily growing because of extensive exploration.

Outcrop in the area is sparse (5%), requiring the development and fine-tuning of new geophysical and geochemical techniques to allow the detection of 'blind' gold mineralisation under the regolith cover. Understandably, successful explorers safeguard their methodology and data to maintain their perceived competitive advantage. This has resulted in a lack of a regional understanding of geological factors controlling mineralisation.

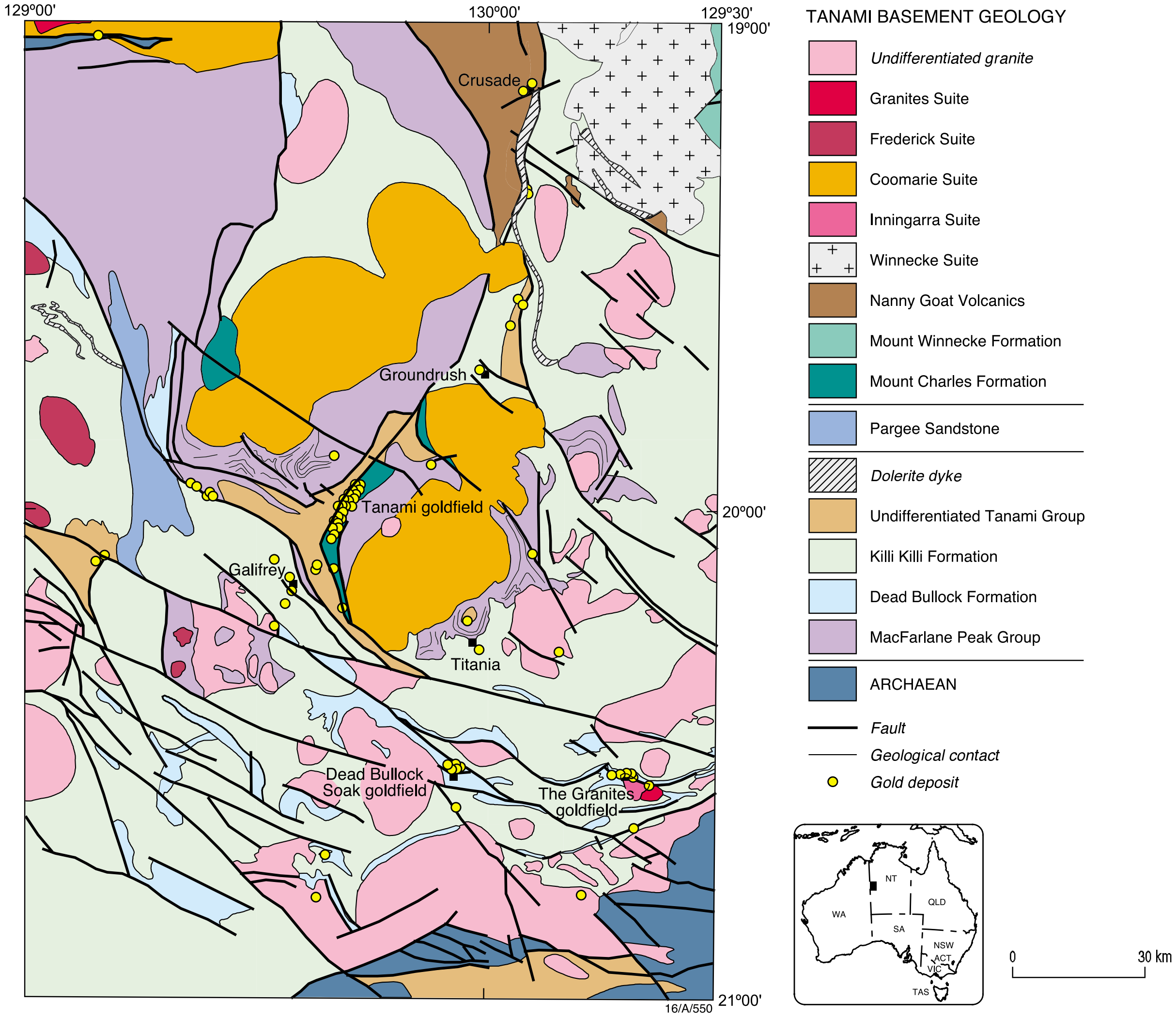
Being aware of this problem and recognising the economic importance of the Tanami region, the Northern Territory Geological Survey invited the Australian Geological Survey Organisation to commence a joint National Geoscience Agreement project in 1999. The purpose was to study hydrothermal systems and develop models that facilitate mineral exploration.

Regional geology

Recent stratigraphic[1], structural[2] and igneous[3] studies indicate that the Tanami region has a similar geological history to the Pine Creek Orogen, Tennant Creek Province and eastern Halls Creek Orogen of Western Australia (Eastern Lamboo Complex).

The oldest Tanami rocks are isolated inliers of Archaean gneiss and schist such as the Billabong complex (60 km east of The Granites mine; figure 1), and the Browns Range Metamorphics (southern flank of Browns Range Dome[4]). SHRIMP based U-Pb zircon geochronology indicates protolith ages around 2510 Ma and high-grade metamorphism at 1882 Ma.[4] The 1882 Ma event is assigned to the Barramundi Orogeny in the Pine Creek Orogen. It is the maximum age for rift initiation, basin formation and deposition of the overlying orogenic sequences.

Figure 1. Geology of the Tanami region with the location of gold occurrences



These orogenic sequences comprise the multiply deformed volcanics and sediments of MacFarlane Peak and Tanami Groups. The MacFarlane Peak Group consists of mafic volcanics, turbiditic sandstone, siltstone and minor calc-silicate. The Tanami Group comprises basal quartzite, the Dead Bullock Formation—which consists of carbonaceous siltstone, graphitic shale, minor iron-rich BIF and chert—and the turbiditic Killi Killi Formation. Dolerite sills intrude both MacFarlane Peak and Tanami Groups and predate deformation. The Tanami Group signifies rapid marine transgression, then deep marine starved sedimentation, followed by rapid prograding wedge sedimentation.

Tanami Group sedimentation is terminated by the onset of the Tanami Orogenic Event (TOE) between 1848 and 1825 Ma.[2] Recent geochronological evidence (detrital zircons as young as 1815 Ma in the Killi Killi Formation) suggests that this event is younger than the previously accepted age of the Barramundi Orogeny. The TOE involved multiple deformation (D_{1-3}) and syn to post D_1 greenschist to amphibolite facies metamorphism (M_1). The TOE is probably equivalent to the Eastern Halls Creek Orogeny, which was related to the collision of the North Australian and Kimberley Cratons at around 1835 Ma.[5,6] The Pargee Sandstone, a coarse siliciclastic molasse, unconformably overlies the Killi Killi Formation and represents a sub-basin formed during the TOE.

The period immediately after the TOE is characterised by D_4 extensional rifting, sedimentation, felsic volcanism and granite intrusion. Aeromagnetics indicate that intercalated basalt and turbidite of the Mount Charles Formation lie above deformed MacFarlane Peak and Tanami Groups.[7,8] Geochemistry indicates a continental rift setting for Mount Charles basalt.[9] The age of Mount Charles Formation is poorly constrained, but it is intruded by Coomarie Suite aplite dykes dated at 1824±12 Ma (AGSO OZCHRON). Extrusion of the Mount Winnecke Group felsic volcanics during D_4 rifting (1825–1815 Ma) is also coincident with widespread granite intrusion. Five granite suites have been identified: Winnecke Suite, Frederick Suite, Inningarra Suite, Coomarie Suite, and The Granites Suite.[3] Most granites are I-type with similar characteristics to those in the Halls Creek Orogen. D_5 faults formed after emplacement of the Winnecke, Fredrick, Inningarra and Coomarie granite suites.

Peneplanation of the Tanami basement and deposition of the Birrindudu Group siliciclastic platform cover sequence occurred sometime after intrusion of the Granites Suite (post 1800 Ma). Regional correlation with the Tomkinson Creek Group and Upper Wauchope subgroup in the Davenport Province and Tennant Inlier suggests a 1790–1760 Ma age.

Younger Proterozoic sequences include the Redcliff Pound Group, Antrim Plateau Volcanics, and siliciclastics of the overlying Lucas Formation, Pedestal Beds and Larranganni Beds. Redcliff Pound Group quartz arenite loosely correlates with the Amadeus Basin Heavitree Quartzite.[10]

D_6 faults cut all earlier generations of structures and are mainly defined from aeromagnetics.

Deposit geology

The Dead Bullock Soak (DBS) goldfield is the largest goldfield in the Tanami region, with a total resource of 6.3 Moz Au. Stratabound mineralisation is hosted in carbonaceous siltstone, iron-rich rocks and chert of the Dead Bullock Formation, which have been metamorphosed to greenschist facies. Although most deposits are hosted by BIF (e.g., Villa, Dead Bullock Ridge and Triumph Hill), by far the largest deposit, Callie (3.9 Moz), is hosted by carbon-rich siltstone at a stratigraphically lower position. All deposits occur in an east plunging anticlinorium (figure 2a). Unlike other goldfields in the Tanami region, there is not a close spatial association between gold mineralisation and granitoids.

The BIF-hosted deposits are localised in iron-rich parts of the Orac and Schist Hill formations (local mine terms) in the upper part of the local stratigraphy (part of Dead Bullock Formation). The iron-rich units have an amphibolite-chlorite±sulfide±magnetite assemblage. Although the distribution of the iron-rich units is a first-order control on mineralisation, high grade shoots are localised in zones of parasitic folds or structural thickening.[11]

Mineralisation in the Callie deposit is localised in F_1 fold closures and is controlled by the intersection of a corridor of D_6 veining and carbonaceous rocks (figure 2b). Hydrothermal alteration varies with depth in the mine; biotite assemblages at depth give way to chlorite at shallower levels. However, the ore is uniformly associated with decarbonised zones within the originally carbonaceous siltstone. Callie mineralisation consists largely (70%) of free gold and minor auriferous arsenopyrite.

The Granites goldfield (figure 3), which has a total resource of 1.6 Moz Au, comprises stratabound mineralisation within intensely folded, amphibolite facies iron-rich rocks of the Dead Bullock Formation. The host unit to the ore is amphibole-garnet-magnetite schist with up to 15 per cent sulfides (pyrrhotite, pyrite, arsenopyrite and chalcopyrite).

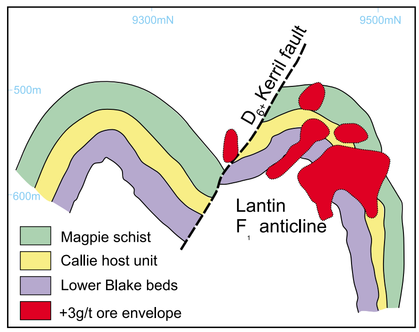


Figure 2b. A cross-section of Callie in Dead Bullock Soak

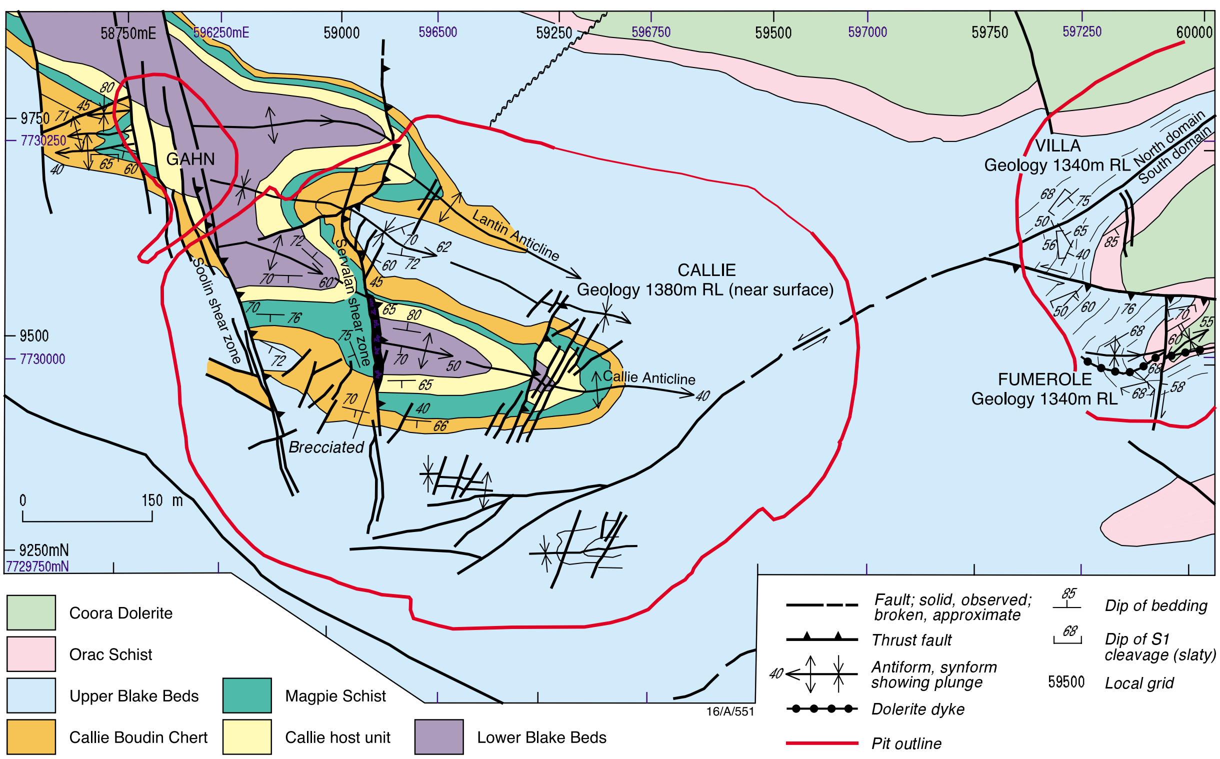
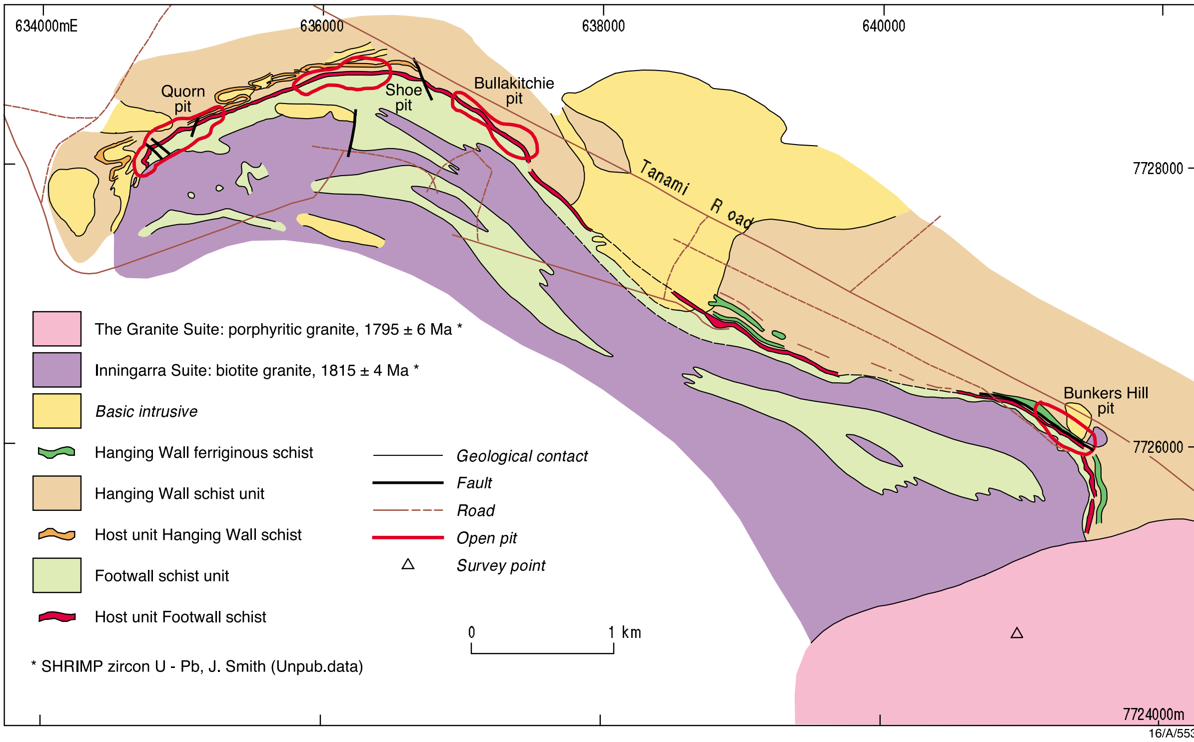


Figure 2a. Geology of Dead Bullock Soak (DBS) goldfield

Figure 3. Geology of The Granites goldfield



Although the orebodies are broadly tabular and steeply pitching, lenticular ore shoots are also present. At East Bullakitchie deposit, these ore shoots follow a prominent fold plunge.[12] Gold occurs in disseminated sulfides (arsenopyrite, pyrrhotite, pyrite), and is also associated with quartz-carbonate veining. Unlike the DBS goldfield, there is a close spatial association of mineralisation and granites. Inningarra and The Granites granite suites (1815±4 and 1795±5 Ma respectively) lie in close proximity to mineralisation. The geometry of the host sequence is related to D_5 deformation, which occurred in the interval between the Inningarra and The Granites granite intrusions.

The Tanami goldfield (figure 4), which has a total resource of 2.1 Moz Au, consists of quartz veins hosted by weakly deformed basalt and medium- to coarse-grained clastic sediments of the Mount Charles Formation. These units exhibit little metamorphism (sub-greenschist facies).

Mineralisation is controlled by three sets of D_5 faults striking 350–010º, 020–040º and 060–080º, and dipping east and south-east. The quartz veins are associated with an inner sericite-quartz-carbonate-pyrite alteration zone (within one meter of lodes) and an outer chlorite-carbonate zone (to 20 m).[13] Feldspar is locally a gangue mineral in the auriferous veins. Gold occurs in

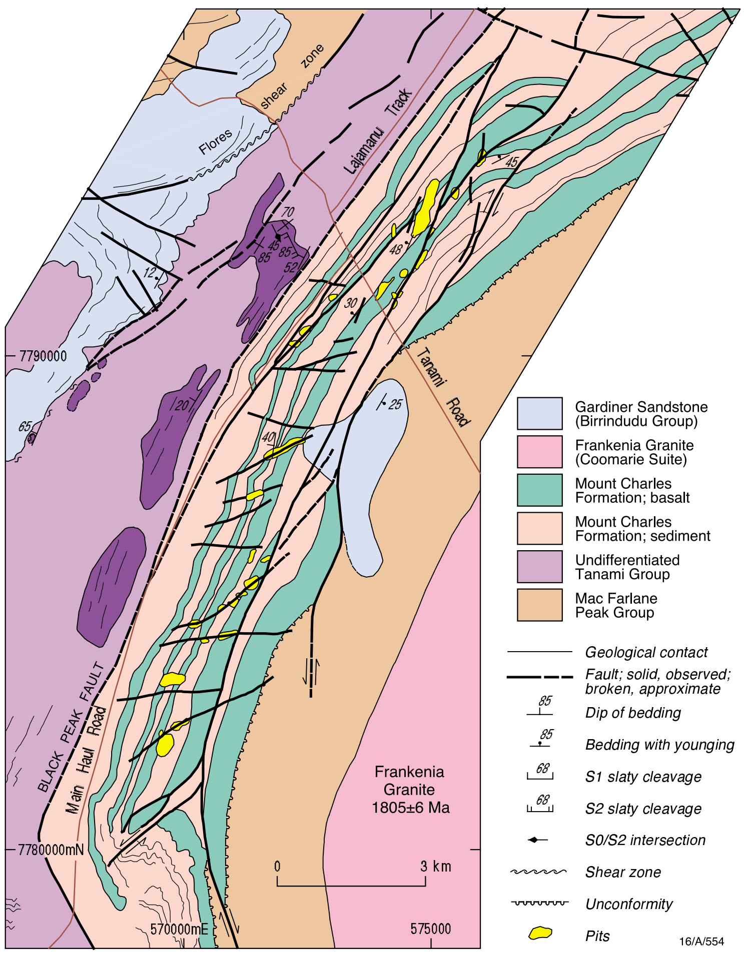


Figure 4. Geology of Tanami goldfield

sulfides (pyrite, arsenopyrite and pyrrhotite). Vein textures such as colloform banding indicate high-level mineralisation. Like The Granites goldfield, there is a spatial relationship with the Coomarie and Frankenia granites (1815±4 Ma and 1805±6 Ma respectively). This association has been used to infer a genetic link with the granites, either directly through a magmatic-hydrothermal origin of the fluids, or indirectly through contact metamorphic fluids.[13]

The Groundrush prospect (resource 0.7 Moz Au) is characterised by dolerite-hosted quartz vein mineralisation adjacent to a chilled margin of the Groundrush (Talbot South) granite dated at 1812±5 Ma. The majority of the ore is free gold, but some auriferous arsenopyrite is also present. The orebody is open at depth. Mineralisation and deformation relationships remain to be determined.

The Titania (Oberon) prospect (resource 0.48 Moz Au) is hosted by turbidites in extensively folded, lower greenschist facies Killi Killi Formation. The ore bodies are structurally controlled by D_5 structures and are localised in anticlinal closures. Like Callie, mineralisation appears to be controlled by the amount of carbon in the host rock. Ore minerals include arsenopyrite, pyrite and free gold.

The Crusade prospect (resource 0.1 Moz Au) contains quartz vein mineralisation associated with a faulted rhyolite-basalt contact within the Nanny Goat Volcanics. The location of auriferous quartz veins is controlled by reverse thrusting related to D_5 deformation. A significant part of the ore comprises free gold.

Little public information is available on the Coyote and Kookaburra prospects that lie on the Western Australian side of the border, although they are currently being evaluated.

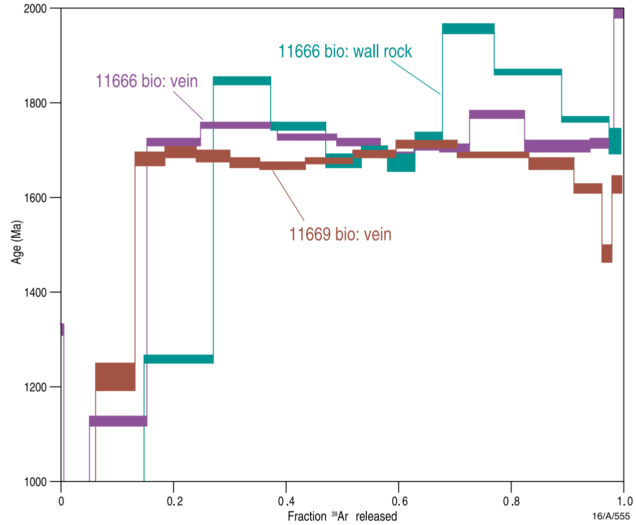
Age of mineralisation

Considerable uncertainty surrounds the age of gold mineralisation. The spatial relationship between mineralisation and granitoids (many of which are now dated) has led to proposed genetic links between granitoid intrusion and mineralisation; a postulation that remains to be further tested. In contrast, Callie is not obviously spatially related to granitoid, raising questions about any genetic role of granitoid in gold mineralising events.

A pilot $^{40}Ar/^{39}Ar$ study has been conducted to assess the potential of this method for improving age constraints on mineralisation. Samples for $^{40}Ar/^{39}Ar$ analysis were selected after petrographic examination that showed a variety of mineral phases and textures, including multiple vein generations. Interpretation of geochronological results is critical to understanding these geological relationships.

Wall-rock biotite of an ore-stage vein from Callie (sample 11666) yields a discordant spectrum with ages of less than 1000 Ma from the first two steps, giving way to ages between 1680 and 1950 Ma for the final 70 per cent of the gas release (figure 5a). The older part of the age spectrum exhibits an age peak at around 1850 Ma. Subsequent steps yield progressively younger ages leading to a relatively flat portion of the age spectrum at 1700±20 Ma between 47 and 67 per cent of the gas release. The spectrum then rises to a maximum age of 1950 Ma before progressively 'younging' to around 1700 Ma. Coarse, unfoliated biotite from the vein margins in the same sample yields a relatively flat age spectrum in which all but two steps over approximately 80 per cent of the gas release, give ages between 1690 and 1730

5a.



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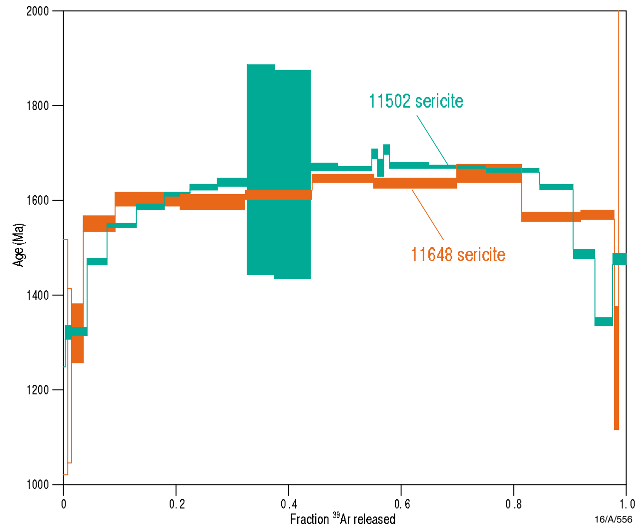

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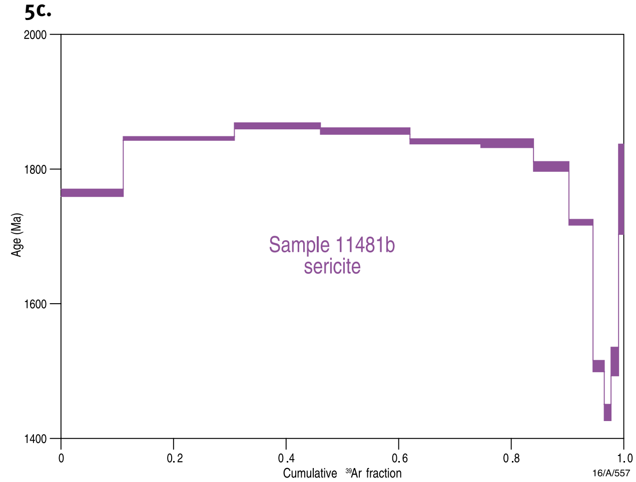
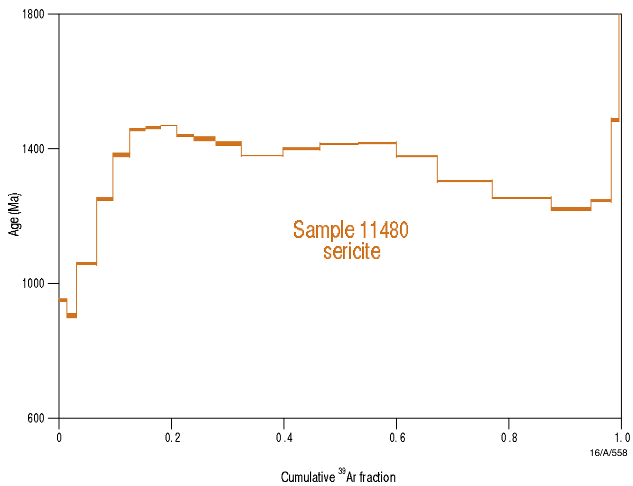


Figure 5. $^{40}Ar/^{39}Ar$ age spectra from gold deposits in the Tanami region: **a.** biotite age spectra from Callie deposit; **b.** sericite age spectra from the Galifrey (11648) and Titania (11502) deposits; **c.** sericite age spectrum from the Carbine deposit; **d.** sericite age spectra from the Callie deposit

5d.



Ma. The exceptions are two steps with slightly older apparent ages of 1752 and 1774 Ma (figure 5a).

Another biotite sample (11669) from ore-stage quartz vein at Callie returned relatively flat spectrum, with 70 per cent of the gas release yielding ages in the range 1666 to 1711 Ma (figure 5a). A sample of mixed, fine sericite and coarser muscovite associated with an auriferous vein from Callie (sample 11480) returned a discordant age spectrum. It rose from initial ages of 900 Ma to a maximum age of 1450 Ma at about 20 per cent of the gas release, followed by progressively younger ages spanning a range to around 1200 Ma (figure 5d). The non-ideal behaviour of this age spectrum is suggestive of ^{39}Ar recoil during irradiation, making interpretation problematic.

Hydrothermal sericite from the Carbine deposit (Tanami goldfield, sample 11481) yields an age spectrum in which 75 per cent of the gas yields ages between 1840 and 1865 Ma, before exhibiting considerably younger ages of 1500 Ma in the final few per cent of gas release (figure 5c). The convex upwards shape of this spectrum may also be indicative of ^{39}Ar recoil—a possibility supported by the total gas age of 1810 Ma, which is slightly older than the conventional K/Ar age of 1772±20 Ma.

Sericite sample (11502) from Titania yields an age spectrum that rises gradually from initial ages around 1200 Ma to a flat section in which 60 per cent of the gas gives ages between 1660 and 1710 Ma (figure 5b).

Hydrothermal sericite from the ore zone at the Galifrey prospect (Tanami goldfield, sample 11648) yields an age spectrum which rises initially from 1200 Ma to a flat section, in which 60 per cent of the gas release yields ages between 1600 and 1660 Ma (figure 5b).

The three biotite-age spectra from the Callie deposit are plotted together in figure 5a. The two vein-biotite samples yield very similar age spectra with most of the gas having apparent ages in the range 1670 to 1720 Ma. Textural evidence clearly suggests that these biotites crystallised synchronously with the quartz veins in which they are hosted. This in turn is interpreted as synchronous with ore mineralisation. With typical values for argon closure in biotite around 300°C, and evidence from fluid inclusions that suggests temperatures in the quartz veins exceeded 300°C (see below), the biotite ages presented here should be regarded as minimum ages for the timing of ore mineralisation. However, ambient country-rock temperature before vein formation and mineralisation, at the estimated depth of between three and six kilometres, is likely to have been considerably less than the biotite closure temperature (assuming near-surface geothermal gradients of less than 50°C/km). If mineralisation was relatively localised, the thermal effects could have been relatively short-lived—especially as maximum vein-formation temperatures were probably in the range 310–330°C. Given these considerations, the argon ages preserved in biotite give a close estimate of the timing of vein crystallisation and associated gold mineralisation.

The age spectra from Titania and Galifrey (two deposits 50 km apart) are remarkably similar in form and age, but their ages are 50 to 100 Ma younger than those derived from Callie biotites. These younger ages could represent cooling and isotopic closure ages of sericite significantly later than ore mineralisation.

In summary, the limited amount of ^{40}Ar/^{39}Ar data currently available is consistent with at least some of the Tanami gold mineralisation significantly post-dating the TOE in the region. In the case of the Callie deposit, the data may suggest a link with the Strangways Event (1720–1730 Ma[14]) that was responsible for widespread deformation and metamorphism in the Arunta Province to the south-east of the Tanami region.

Fluid inclusions studies

The physico-chemical character of the ore-bearing fluids has been investigated by microthermometric and laser Raman microprobe analysis of fluid inclusions.

At Callie the ore-stage, gas-rich, fluid inclusions homogenise over a temperature range of 310–330ºC and have salinities of 7–9 wt % NaCl eq. The laser Raman microprobe did not detect any CH_4 in these inclusions, but both CO_2-rich and N_2-rich inclusions are present. Two-phase aqueous inclusions also coexist with the gas-rich fluid inclusions and homogenise over the range 220–360ºC. Their salinities range from 8–22 wt % NaCl eq. The estimated depth of formation of the gas-rich inclusions is 3.2–5.8 kilometres.

The Granites goldfield contains abundant CO_2-bearing, primary fluid inclusions with salinities ranging from 4–8 wt % NaCl eq. Although most inclusions are CO_2-rich, laser Raman microprobe analysis has shown that the vapour phase of some inclusions contains CO_2 and up to 73 mole % N_2, while others contained CO_2, small quantities of N_2, and up to 50 mole % CH_4. This indicates significant local variations in fluid composition. Some inclusions homogenised to the vapour phase. The majority, however, homogenised to a liquid over the range of 260–300°C. Two-phase aqueous inclusions are also present in lesser amounts and they coexist with the CO_2-bearing inclusions. The aqueous inclusions have salinities ranging between 18 and 20 wt % NaCl eq and homogenise to the liquid phase over the range 240–260°C. The estimated depth of formation for the above inclusions range from 3.8–7.5 kilometres.

Rare, primary, CO_2-rich fluid inclusions are found in a few deposits in the Tanami goldfield, but two-phase aqueous inclusions are the dominant type. No gases have been detected in the vapour phase of these inclusions. They can be grouped into three populations: (i) relatively saline inclusions with 18–23 wt % NaCl eq; (ii) moderately saline inclusions with 11–17 wt % NaCl eq; and (iii) low-salinity inclusions with 0–10 wt % NaCl eq.

Only type iii, low-salinity inclusions are associated with mineralisation. Necking down of inclusions has caused a wide spread in homogenisation temperatures, but there is a distinct mode at 160ºC. Depth estimations for the aqueous inclusions range between 0.4 and 0.8 kilometres. It is estimated that the CO_2-rich inclusions formed between 1.3 and 1.5 kilometres. These shallow depths are consistent with a number of high-level features (comb quartz and chalcedonic textures).

Ore-stage fluid inclusions from the Groundrush deposit have a distinctly different character. The inclusion population is dominated by high-temperature, gas-rich inclusions. These inclusions homogenised over a temperature range of 220–460ºC with a mode at 420ºC. Their salinity ranged between 4–10 wt % NaCl eq. Laser Raman microprobe analysis indicates that the vapour phase is typically dominated by methane with lesser amounts of CO_2. The estimated depth of formation of these inclusions ranges between 5.5 and 8.3 kilometres.

Figure 6 summarises physico-chemical properties of fluid inclusions from the above deposits. Groundrush appears to have formed at the greatest depths and has the most reduced (CH_4-rich) fluids. The Granites goldfield and the Callie deposit formed at shallower depths. The Granites fluids were CO_2 rich, but variable in N_2 and CH_4. The Callie fluids show only small variations in temperature and salinity and are more oxidised with only CO_2 and N_2 being detected. The Tanami deposits appear to have formed at the shallowest levels and are dominated by low-salinity aqueous fluids, although some CO_2-bearing fluids have also been detected.

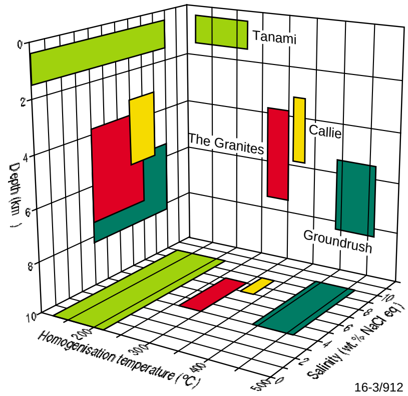


Figure 6. Summary of physico-chemical properties of ore-stage fluids at Callie, The Granites, Groundrush and Tanami corridor deposits

Source of metals

$\delta^{18}O$ values calculated for ore fluids using mean temperatures obtained from fluid inclusions and $\delta^{18}O$ values of quartz are 5.9±2.0 ‰ at Callie, 4.6±2.0 ‰ at The Granites, and range from 1.0 to 5.0 ‰ at the Tanami goldfield. The relevant fluid inclusion δD values are -85‰ to -58‰ (median -72‰)at Callie, -71‰ at The Granites and -69‰ to -37‰ (median -52‰) at the Tanami goldfield. The corresponding mean fluid inclusion $\delta^{13}C$ values are -6.2‰ at Callie and -8.1‰ at The Granites. There was insufficient CO_2 to measure $\delta^{13}C$ values at the Tanami goldfield.

The above data indicate involvement, at the ore stage, of metamorphic or magmatic fluid at Callie and The Granites, and a notably different exchanged meteoric fluid at the Tanami goldfield.

Further information on the provenance of metal-bearing fluids was obtained by comparing lead isotope ratios of hydrothermal K-spar and auriferous sulfides with lead isotope ratios of K-spar from granites spatially associated with mineralisation. The results obtained to date (figure 7) indicate that the initial lead isotopic ratios of sulfides from The Granites goldfield, Tanami goldfield and Groundrush deposit probably were similar to each other. They are significantly different, however, to the initial ratios of the granites as determined from K-feldspar separates. The initial ratio of the Groundrush granite is unique compared with the other granites. It may be indicative of derivation by partial melting of Archaean basement. Dolerite hosting the Groundrush deposit has lead isotopic values similar to the sulfides. However it is unclear whether this feature is primary, or if the isotopic ratios were re-equilibrated by subsequent hydrothermal activity.

A combination of stable isotope data and lead isotopic ratios—as well as significantly younger Ar-Ar ages of ore-related minerals, when compared with the age of granitic intrusions—suggest that these intrusions were not the source of ore-bearing fluids.

Tanami region gold mineral system

Results of this study indicate that gold deposits of the Tanami region are suprisingly diverse, with some being basalt and dolerite hosted, some in BIF, and some being sediment hosted. Moreover, fluid inclusion data suggest that the four main deposits all formed at different depths with Groundrush being the deepest and the Tanami deposits being the shallowest (figure 8, page 14). Hydrogen and oxygen isotope data are consistent with either a magmatic or metamorphic origin for the ore fluids, but the Pb isotope data show that the Pb in these deposits was not derived from a magmatic source.

Despite the evident differences these deposits have similarities, particularly Callie, Groundrush and The Granites. Most importantly, ore fluids have salinities less than or equal to 10 wt.% NaCl eq, and are CO_2-rich. The Tanami fluids differ in that they are not as CO_2-rich, consisting mostly of aqueous inclusions indicative of high-level fluid mixing. The composition of these fluids bears some similarities to the fluid chemistry of Archaean lode gold deposits[15] that have mainly mixed aqueous-carbonic fluids with some moderate- to low-salinity aqueous inclusions. Fluid salinities in the Tanami deposits, however, lie in the upper range of those reported from Archaean gold deposits. Groundrush and Callie have greater levels of CH_4 and N_2, respectively, than that commonly observed in Archaean gold deposits. In this respect the fluid chemistry of these deposits appears to be more closely related to that reported for turbidite-hosted gold deposits.[16]

Figure 8 presents a preliminary gold system model based on these and other data for the entire Tanami region. The project's data conflicts in terms of the role of granites in the mineral system. Although there is a strong spatial association among deposits in the Tanami and The Granites goldfields and at Groundrush, Pb-isotope and $^{40}Ar/^{39}Ar$ data presented herein are not consistent with a direct genetic link between granite intrusion and mineralisation.

The Tanami goldfield has the most suggestive evidence for a role for granites. These deposits are located within a corridor between two granite domes, and the $^{40}Ar/^{39}Ar$ data overlap the age of intrusion of one of these granites. These granites may have acted as either a heat engine or focused fluid flow within the Tanami corridor. Other deposits such as Callie do not have a close spatial association with granites, and the $^{40}Ar/^{39}Ar$ age data do not accord with the time of granite intrusion. Given these uncertainties, the role of granites in the mineralising event is an open question.

Structural evidence[2] shows that D_5 or D_6 shear zones are important controls on gold mineralisation within the region. These structures facilitated regional fluid flow into deposition sites. Fluid flow was assisted by brittle failure and brecciation of competent rocks (e.g., Tanami), the formation of dilatant zones (e.g., The Granites) and the existence of structural corridors (e.g., Callie).

Alteration assemblages vary as a consequence of host lithology and also temperature and depth of mineralisation. The variety of host lithologies for these deposits suggests that different precipitation mechanisms may have operated in different areas. Desulfidation of ore-bearing fluids during interaction with Fe-rich host rocks may have led to Au precipitation at Groundrush and The Granites. A more complex mechanism may have been responsible for the sediment-hosted Callie deposit. In this case, relatively oxidising fluids reacted with graphitic sediments, reducing the fluid, decarbonising the rock, and producing CO_2 gas. H_2S was also partitioned into the gas phase, destabilising the gold bisulphide complexes and precipitating gold. Finally, gold was remobilised by later fluids that concentrated it near the top of decarbonised zones in a process analogous to ‘zone refining’ in volcanic-hosted massive sulfide deposits. Structural thickening during F_1 folding at Callie may have enhanced this process by preparing a thicker zone of reactive rock. Fluid-inclusion data from the Tanami goldfield suggest that the ore-bearing fluids mixed with a localised brine, and Au precipitation resulted from mixing and cooling processes.

The data suggest that a number of processes formed gold deposits in the Tanami region. This directly has resulted in a diversity of ore deposit characteristics. Consideration of this diversity, from a mineral systems perspective, highlights the likelihood that undiscovered gold deposits in the Tanami region will have a large range of characteristics and that mineral deposition can occur in a number of different host lithologies. Current evidence indicates that D_5 and D_6 structures should be the favoured targets for future exploration.

Future research

Results of this joint NTGS–AGSO research program raise more questions than they answer. To address these questions, the following research programs will be undertaken over the next year:

- further direct dating of mineralisation (including possibly dating zircon in late ore-stage veins);
- further lead isotope work;
- a more extensive program by AGSO on Western Australian prospects (e.g., Coyote) to detect any regional changes in the age and character of mineralisation; and
- extension of work to the Birrindudu area (quartz-Au veins in the Winnecke Granophyre).

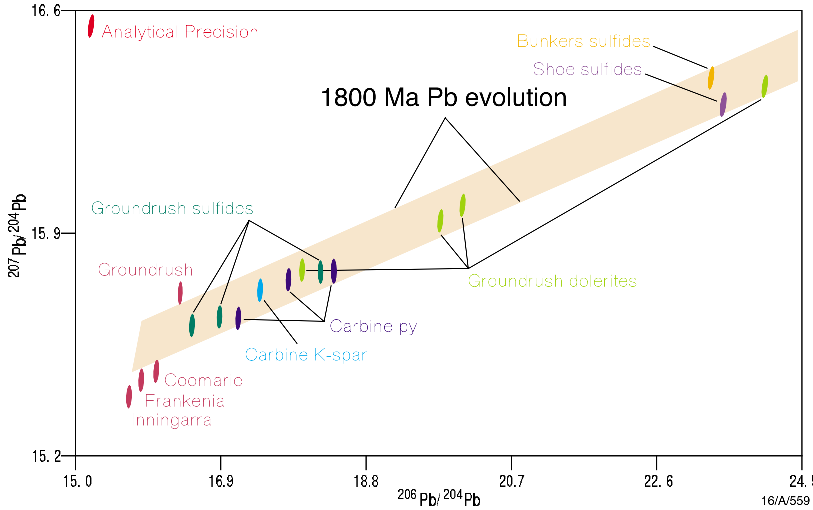


Figure 7. $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ ratios of hydrothermal ore-related minerals, granites (Coomarie, Frankenia, Inningarra, Groundrush) and Groundrush dolerite

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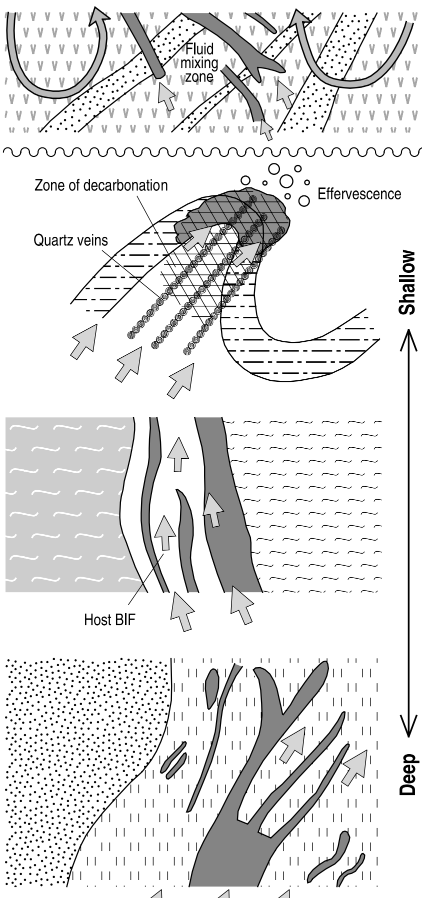

DEPOSIT	FLUID CONDITIONS	FLUID TRANSPORT/ ORE CONTROLS	VEIN ASSEMBLAGE/ ALTERATION	DEPOSITIONAL MECHANISM
TANAMI 0.4 - 1.5 km	120 - 220 °C 0 - 10 wt.% NaCl eq Minor CO_2 content	Brittle faulting in basalt and sediments.	VEINS: qtz±ser±ank±py±chl ±sp±aspy±cpy ALTERATION: (1) ser+qtz±carb±py (inner zone) (2) chl+carb (outer zone)	Fluid mixing between low salinity, CO_2-bearing fluid and localised brine.
CALLIE 3.2 - 5.8 km	310 - 330 °C 7 - 9 wt.% NaCl eq $CO_2 \pm N_2$	Sheeted quartz veins within a 'structural corridor'. Grade increases where there are high angle intersections between quartz veins and bedding planes. Increased porosity in zones of decarbonation.	VEINS: Originally qtz+feld(±biot±epid) but extensively recrystallised. ALTERATION: (1) cc±chl±qtz±py (upper levels) (2) chl±tit±ru (mid levels) (3) biot±il±epid±po(lower levels)	(1)Reduction and/or effervescence of ore-bearing fluids from interaction with graphitic host rock (2) Zone refining to concentrate gold near the top of the decarbonised zone
THE GRANITES 3.8 - 7.5 km	260 - 300 °C 4 - 8 wt.% NaCl eq $CO_2 \pm N_2 \pm CH_4$	Dilatant zones formed during folding in banded iron formation. Amphibolite grade host rocks adjacent to granite intrusions.	VEINS: (1) qtz±aspy±po±py (2) cc±diop (3) qtz+cc (4) clz±qtz±diop±cc ALTERATION: (1) hbl(±cum±epid±chl) (2) diop±clz±hbl±feld±qtz (3) hbl±diop±clz±feld±qtz (4) hbl±tit±qtz±feld±il	Desulfidation of ore-fluids during interaction with BIF host unit.
GROUNDRUSH 5.5 - 8.3 km	390 - 460 °C 4 - 10 wt.% NaCl eq $CH_4 \pm C_2O$	Quartz veining and brecciation in dolerite.	VEINS: qtz±carb±py±po±aspy ALTERATION: Not determined	Desulfidation of auriferous fluids during interaction with host rocks.

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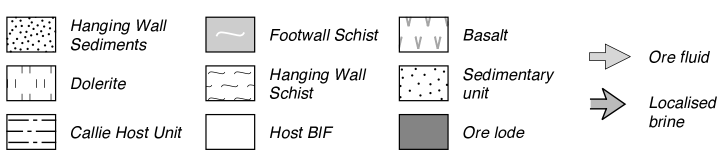

ser - sericite, qtz - quartz, feld - feldspar, carb - carbonate, cc- calcite, ank - ankerite, py - pyrite, cpy - chalcopyrite, sp - sphalerite, chl - chlorite, hbl - hornblende, clz - clinozoisite, cum - cummingtonite, diop - diopside, po - pyrrhotite, aspy - arsenopyrite, lo - loellingite, tit - titanite, ru - rutile, biot - biotite, il - ilmenite, epid - epidote

Figure 8. Schematic diagram showing fluid-system model for the Tanami region