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Syn-Metamorphic Gold Deposits in Amphibolite and Granulite Facies Rocks

by

John Ridley

Institut für Isotopengeologie und mineralische Rohstoffe,
ETH-Zentrum, Sonneggstr. 5, CH-8092, Zürich, Switzerland

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Introduction

Lode- and vein-style gold deposits are a distinct class of hydrothermal ore deposit. The deposits are hosted in metamorphic belts, most commonly in low-pressure facies series belts, are structurally controlled, are typically associated with wallrock sulfidation and carbonation, and are enriched in a distinct suite of elements: Au with Ag, Te, S, As, Bi, Sb, W, K, Cs, Rb and SiO_2, but rarely base metals. From fluid inclusion evidence, a weakly saline, water-rich H_2O-CO_2±CH_4 fluid of near neutral pH was involved in deposit genesis. The dominant cause of gold precipitation is probably destabilisation of gold-bisulfide complexes where sulfide minerals are formed in fluid-wallrock reactions, though phase separation in the mixed aqueous–carbonic fluid may also be influential. FYFE & HENLEY (1973) first suggested derivation of the ore fluid through metamorphic reactions at the greenschist–amphibolite facies transition, but this remains controversial, and orthomagmatic, other metamorphic, and surface-water origins for the fluid have also been proposed (see reviews by KERRICH, 1991; HODGSON, 1993).

The deposits have often been classed as 'mesothermal' because of their association with greenschist-facies metamorphic terrains and the generally inferred conditions of formation at 250 – 400 °C at pressures of 1 – 3 kbar. However, in the Archean Yilgarn Craton in Western Australia, a major gold province which currently provides about 7% of annual gold production, although most gold deposits, including the world-class Kalgoorlie deposits, are hosted in greenschist-facies terrains, about 15% of gold resources are in amphibolite- and granulite-facies terrains. Elsewhere in the world, two of the largest known deposits of Archean age, at Hemlo in the Superior Province of Canada and the Kolar schist belt of India, are in amphibolite-facies terrains, and Phanerozoic deposits include small showings in granulite-facies pelites in Moldanubia (GRUNDMANN et al., 1985). This paper considers the deposits in the higher-temperature terrains of the Yilgarn Craton. From their structural setting, petrology, chemistry and isotope chemistry, it is argued that mineralisation was at high temperature, essentially syn-peak metamorphic. Some implications of this conclusion for ore genesis in metamorphic terrains are discussed.

Lithological and structural setting of deposits in amphibolite- and granulite-facies terrains

The Yilgarn Craton is dominated by late-Archean granitoids, granite-gneisses and greenstone belts, and shows many features typical of Archean cratons, including sub-greenschist to lower-granulite facies low-pressure facies series dynamothermal metamorphism. Amphibolite- and granulite-facies terrains cover about 25% of greenstone belt outcrop (Fig. 1). Within these terrains, deposits are hosted by all major rock types, but dominantly by mafic rocks, ultramafic rocks and banded iron formations (BIF's), and on a mine scale are often very similar to the better known deposits in greenschist-facies terrains.

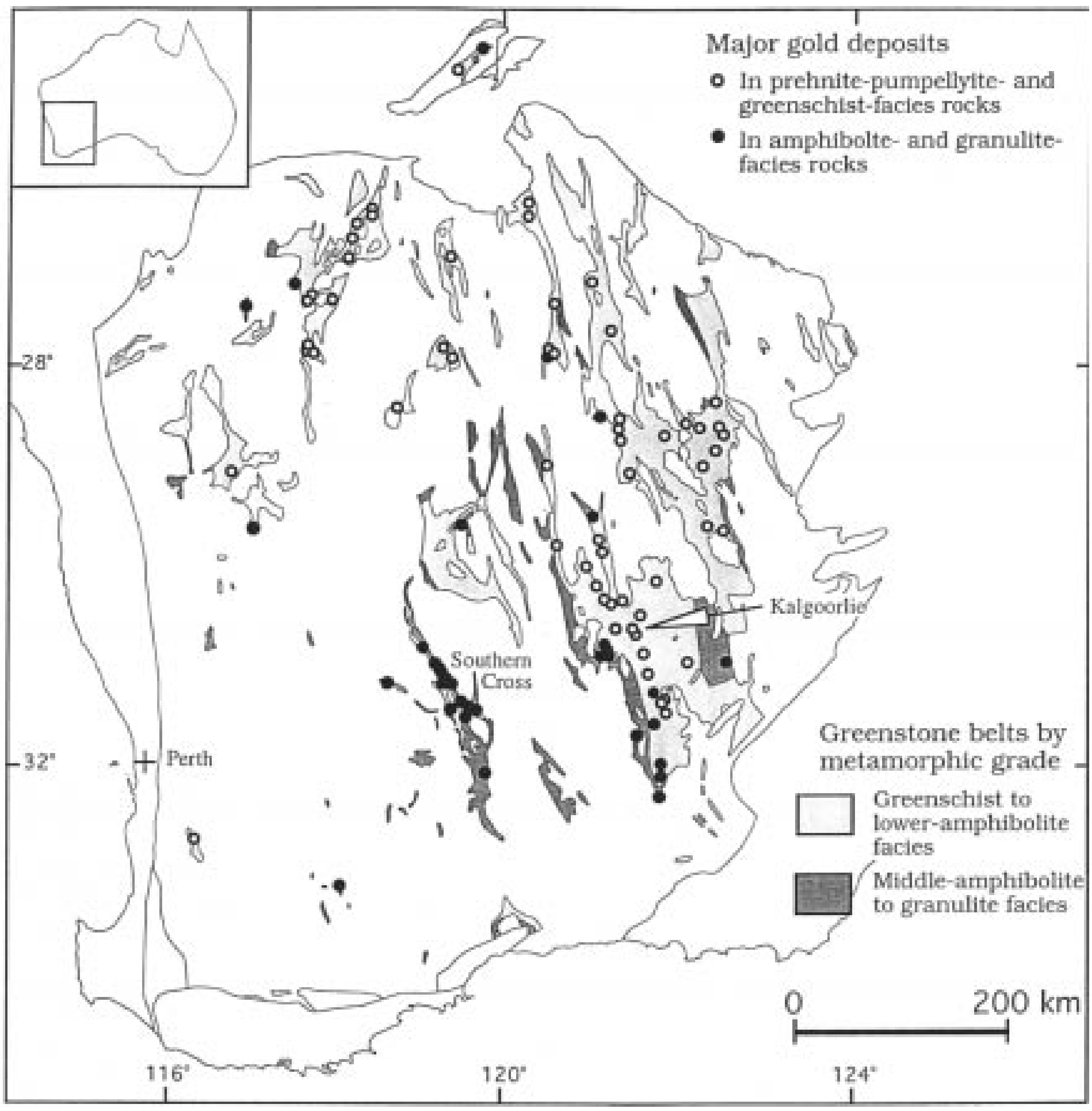

Fig. 1
The Archean Yilgarn Craton of Western Australia showing greenstone belts divided by metamorphic grade (after BINNS et al., 1976) and major gold deposits in hostrocks of different metamorphic grade.

Although all deposits are structurally controlled, the structural styles and lithological and structural settings are various. Broad ductile shear zones are common host structures, and in these ore zones characteristically have multiple, sheeted, relatively thin, foliation-parallel veins. Shear zones may also host disseminated ore associated with foliation parallel and cross-cutting millimetre thick quartz - amphibole - sulfide veinlets. Continuous, massive or laminated quartz–sulfide veins similar to those of shear-zone hosted deposits in greenschist-facies terrains occur where the host structure is a more discrete shear zone. Other deposits are associated with extensional vein stockworks, either in massive hostrocks, or cutting fold-axial planar cleavages and fold-axes in folded competent lithological units.

Deposit geochemistry

Ores from gold deposits in high-temperature terrains in the Yilgarn Block have geochemical compositions generally indistinguishable from those in greenschist-facies terrains. However, typical CO_2 contents of ores in mafic-hosted deposits in lower-amphibolite facies terrains are 3 – 6 wt.% and in higher grade terrains 1 – 2 wt.%, hence significantly lower than the range of 5 – 20 wt.% in greenschist-facies terrains.

Oxygen and carbon isotope compositions of vein quartz and carbonates show no obvious trend with hostrock metamorphic grade, with $\delta^{18}O$ in deposits in amphibolite-facies terrains from 9.3 – 12. ‰ largely overlapping the range from mesothermal deposits (10-15 ‰). Calcite $\delta^{13}C$ ranges from -8.4 to - 0.5‰, with the majority between - 7.5 and -6.0‰, thus also indistinguishable from mesothermal deposits (-8.1 to -2. ‰).

Mineral assemblages

Alteration haloes: Zoned alteration haloes are a feature of lode- and vein gold deposits. Mineral assemblages in the haloes vary systematically with hostrock metamorphic grade. In the higher-grade terrains, haloes formed of high-temperature assemblages extend to between about one metre to several tens of metres from ore (Fig. 2). Biotite, calcic-amphibole and diopsidic clinopyroxene are prominent, especially in intensely altered mafic and ultramafic hostrock, although diopside is absent in deposits in lower-amphibolite facies terrains and generally more abundant at higher hostrock metamorphic grade. Biotite, as fine scattered grains in textural equilibrium with metamorphic minerals is generally the most distal sign of alteration. Other common gangue minerals are plagioclase, K-feldspar, almandine garnet, quartz and calcite. Typically, the alteration minerals are syn- to late-tectonic within the host structures, though in middle-amphibolite facies or higher grade terrains, strongly altered rock may be massive and texturally equilibrated. A sporadic, static overprint of the high-temperature phases by chlorite, sericite, actinolitic amphibole, and carbonate phases is common, but even where strongest, the high-temperature assemblages are abundantly preserved throughout alteration haloes. Altered rock and ore almost invariably contains a few percent modal sulfide, as in mesothermal deposits. In contrast to mesothermal deposits, pyrrhotite rather than pyrite is generally the dominant sulfide phase, with assemblages of major ore minerals in ore zones being one of: (i) pyrrhotite alone; (ii) pyrrhotite - arsenopyrite ± pyrite; (iii) pyrrhotite - arsenopyrite - loellingite, and; (iv) pyrrhotite - pyrite -

chalcopyrite. Galena and sphalerite are relatively common minor ore phases. Tellurides, including hessite, petzite, altaite and Bi-tellurides, occur at some deposits, and are locally associated with high-grade, sulfide-poor ore zones.

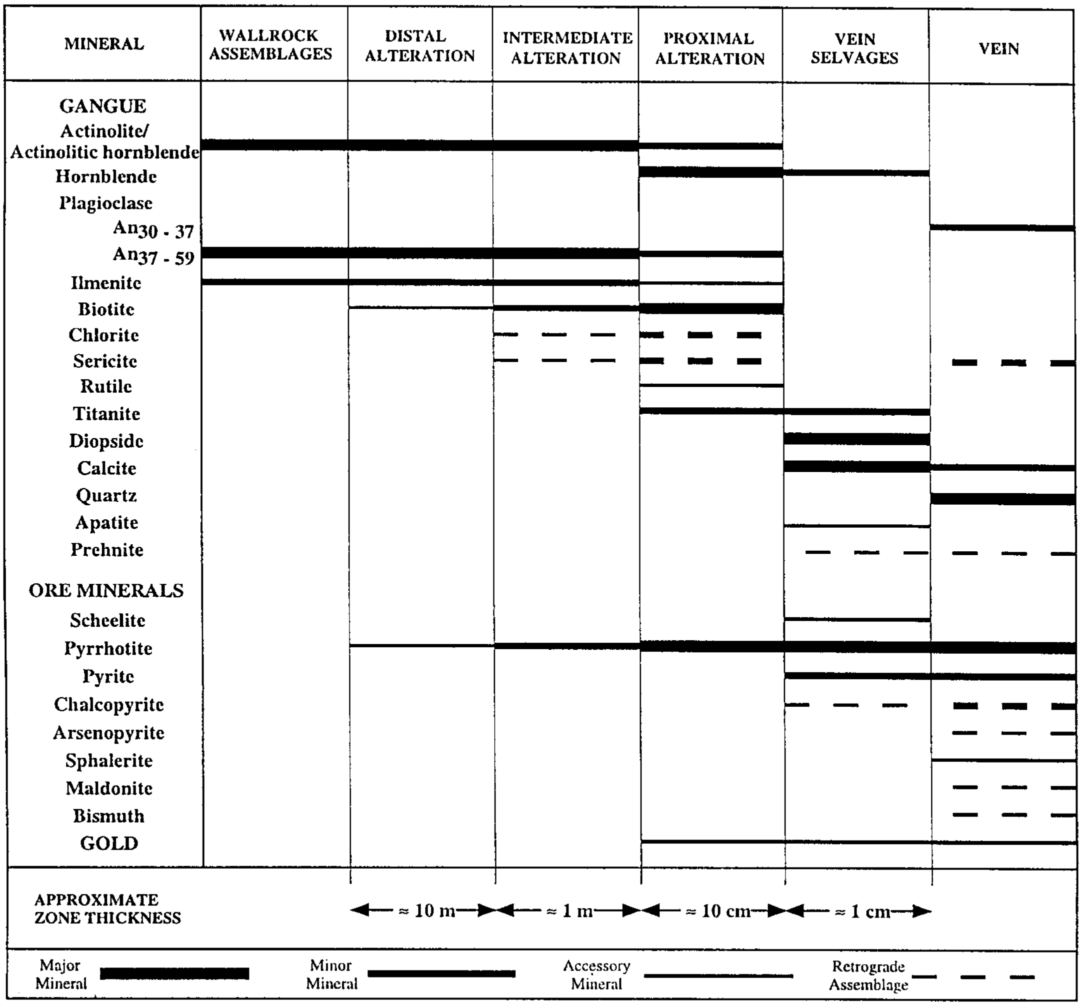

Fig. 2
Ore and alteration minerals in a typical zoned alteration halo of a gold deposit in amphibolite-facies mafic hostrocks, the example of the Hopes Hill deposit, Southern Cross (after, BLOEM, 1994).

Veins: Quartz, diopside, calcic-amphibole, calcite, garnet, biotite and plagioclase are the common gangue phases in veins, with quartz generally dominant, although diopside or calcic-amphibole may be of equal importance in thinner veins, especially in ultramafic hostrocks. Sulfides are a major component in some veins, in places as sulfidic clots up to a few centimetres diameter, but other veins are essentially sulfide-free. Minor vein phases are scheelite, apatite and tourmaline. The veins are typically massive and lack clear internal textures, and vein quartz is granoblastic, either with well-annealed mosaic textures, or mosaics with serrated to irregular grain shapes, hence indicating some strain-induced recrystallisation. Relicts of coarse fibrous vein quartz are preserved at deposits in massive hostrocks. Textures of intense dynamic recrystallisation with elongate polygonal grains are relatively rare. Isolated rosettes of amphibole at vein margins, or more typically, continuous millimetre- to centimetre-thick, mono- or bimineralic vein selvages formed of texturally late clinopyroxene or amphibole with calcite, plagioclase or biotite are a distinct feature of deposits in mafic and ultramafic hostrocks. Around many veins, the vein-selvage is separated from altered wallrock by one or more further thin monomineralic or bimineralic zone. In particular, a clinopyroxene selvage is separated from biotite-altered wallrock by an amphibole, or amphibole-plagioclase zone. Within a few centimetres of a vein there are often alternating lamellae a few millimetres wide of, for instance, biotite- and amphibole-rich rock.

Siting of gold: Gold forms small, high-fineness, 'free' grains in veins or in sulfide-bearing wallrocks. Gold tellurides occur in telluride rich ores, and the gold-bismuth alloy maldonite is present locally in some ores. Native gold occurs as primary irregular inclusions in arsenopyrite or other sulfides, along sulfide grain boundaries, particularly loellingite-arsenopyrite contacts, as clusters of fine grains in gangue phases around sulfides, intergrown with, or as inclusions in, diopside or amphibole in vein selvages, or as clouds of fine-grains intergrown with amphibole in altered wallrock. It is relatively rare as a fracture filling within sulfides. SIMS analysis of NEUMAYR et al. (1993) showed up to 200 ppm Au as submicroscopic particles or as solid solution within loellingite where this phase is present, with coexisting arsenopyrite essentially gold free.

Petrological interpretation of ore and alteration assemblages

The P-T conditions of equilibration of the high-temperature alteration and ore assemblages in most deposits in amphibolite- and granulite-facies terrains in the Yilgarn Craton range from 450 – 700°C at 3 – 5 kbar (Fig. 3a), and are the same as those of peak metamorphism in the surrounding terrain, or up to about 50°C cooler at similar pressures. The different assemblages can be understood in terms of mineral stability with respect at different T at constant X_{CO2} (Fig. 3b). For instance, the stability of diopside relative to carbonates at higher temperatures reflects the reaction Tr + Cal + Qtz = Di. The temperatures and pressures of retrograde overprinting are poorly constrained, and the range of minerals formed suggest that there were probably different phases of overprinting during cooling. The presence of prehnite requires temperatures below 400°C at low X_{CO2}, chlorite geothermometry generally suggests equilibration temperatures of around 300°C.

Although the dominant alteration and sulfide assemblage in ore zones have equilibrated at near peak-metamorphic temperatures, this does not necessarily imply that the gold was introduced at these conditions. Gold introduction may have been post-peak and associated with a retrograde overprint, or pre-peak, and the present observed assemblages the result of subsequent metamorphic recrystallisation of ore (Fig. 3a). These two possibilities are discussed here.

Arguments for and against a significantly retrograde introduction of gold

The presence of sericite, chlorite and carbonate in veins and alteration zones, visible gold in late chlorite and chlorite-calcite filled veinlets and fractures, low temperature ore minerals, e.g. chalcopyrite and maldonite, and compositional equilibration of pyrrhotite and some arsenopyrite at low temperatures, suggest the possibility of hydrothermal gold introduction during retrogression, in a similar fashion as argued for instance by BOIRON et al. (1996) for gold deposits in Hercynian-age orogenic belts in Europe. However, in the Yilgarn Craton lodes, the low temperature overprint is never pervasive through large volumes of rock, and in all deposits, gold is most closely associated with specific high-temperature minerals, for instance as inclusions in amphibole and diopside. An association with late fractures in sulphide phases is rare. Of particular significance is the presence of gold in composite loellingite-arsenopyrite grains both as native gold at loellingite-arsenopyrite interfaces and sub-microscopically within loellingite. Loel ingite was in equilibrium with the high temperature gangue assemblage, but was partially replaced by arsenopyrite before cooling to greenschist facies conditions (T > 450°C, NEUMAYR et al., 1993). Gold is thus in a paragenetically early phase that was stable at high temperatures. It is interpreted that any association of gold with low-temperature minerals in these deposits reflects local remobilisation during retrogression of earlier introduced gold.

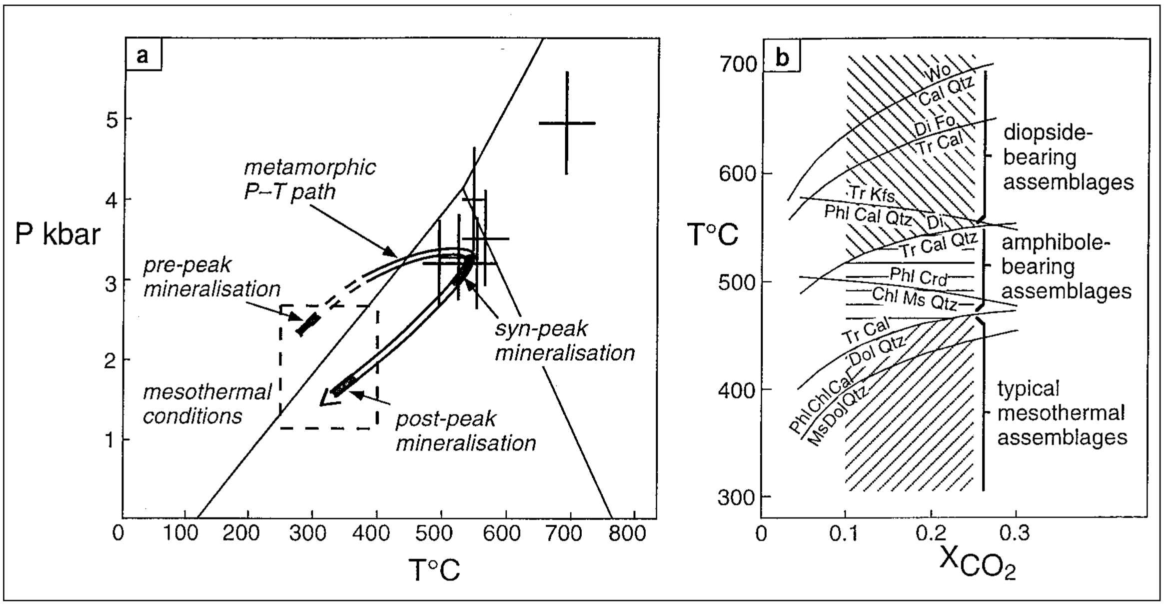

Fig. 3

(a) Crosses show Pressure - Temperature conditions of equilibration of alteration and ore assemblages in various gold deposits in amphibolite- and granulite-facies terrains, (approximate uncertainty of determinations given by size of crosses). For comparison, the typical conditions of formation of mesothermal gold deposits, and the aluminosilicate equilibrium curves are shown. A schematic P–T path for the terrains indicates the three possible timings of gold mineralisation considered here: pre-peak- syn-peak- and post-peak-meatmorphic.

(b) Partial Temperature-XCO_2 diagram showing reactions limiting the stability of common mineral assemblages in alteration zones of gold deposits in greenschist-facies and amphibolite-facies terrains. A fluid XCO_2 of 0.1 - 0.25 is characteristically determined from fluid inclusion studies in mesothermal deposits.

Differentiation between pre- and syn-metamorphic mineralisation

Distinction between pre- and syn-peak metamorphic mineralisation is more difficult. Textural equilibration promoted by high metamorphic temperatures means that reaction textures between metasomatic and metamorphic minerals are rarely preserved and that clear paragenetic sequences can rarely be defined. At the edge of an alteration halo, for instance, ore-related biotite and pyrrhotite form euhedral plates parallel or oblique to the foliation in textural equilibrium with metamorphic minerals, or pyrrhotite may be intergrown with amphibole. Some replacement and inclusion–host textures are evident, but few are diagnostic of the conditions of metasomatism. Gold in diopside or amphibole, for example, could have been first included in ankerite or quartz, and these minerals replaced by the calc-silicate phases during prograde metamorphism. Distinction between pre- and syn-metamorphic mineralisation requires other types of evidence, a number of which are discussed here.

Petrology and petrography of alteration zones: In principle, the thermodynamic variance of assemblages in alteration zones should be diagnostic of the relative timing of alteration and metamorphism (e.g. PHILLIPS, 1985), however, it has proven difficult to distinguish the effects of added components from those of variance. The general increase in the number of phases towards an ore zone (Fig. 2), for instance, biotite + pyrrhotite added to a Hbl - Pl - Ilm ‘amphibolite’ assemblage without the loss of a phase at the edge of a halo, can be interpreted as a result of added components, in this example, K and S, rather than a decrease in variance.

Vein selvages typically have one or two silicate phases and one sulfide phase, thus have high variance, and were likely formed in a high temperature metasomatic event. However, the selvage minerals are texturally late, and as selvage thicknesses are relatively constant within a deposit, irrespective of vein thickness, zones are generally thicker in deposits in middle-amphibolite facies than in lower-amphibolite-facies hostrocks and are of the same order as bimetasomatic zones in lower- to middle-amphibolite facies terrains (e.g. VIDALE, 1969), it is suggested that the selvages are not directly related to mineralisation, but formed bimetasomatically by reaction between calcite in the vein and Qtz - Bt - Pl - Hbl in the proximal alteration assemblage post mineralisation.

Timing relations of alteration, mineralisation, deformation and metamorphism: Textures of veins, ore and alteration minerals are in most deposits syn-tectonic and indicate dynamic crystallisation or recrystallisation at high temperatures, although vein selvages and late vein in some deposits may be essentially undeformed. The host structures were thus last active at high temperatures, and vein formation was most likely during the latest increments of movement along the host shear zone. The lack of specific ore deformation textures such as pressure fibres around pyrite grains, or of crack-seal vein fibre growth, is as expected if there was crystallisation and recrystallisation at high temperatures. Controls on the siting of ore shoots and deposits by late-formed cross structures or irregularities on a host structure, for instance shear bands, or flexures in a host shear zone or host fold-hinge zone, also implies that mineralisation did not pre-date any significant deformation, but was essentially late in the local deformation history.

Stable isotope chemistry of carbonates ore zones: Oxygen isotope data of quartz-diopside and quartz-calcite pairs in veins shows isotopic equilibration at or slightly below peak metamorphic temperatures (Fig. 4a). If the lower carbonate content of ores at higher metamorphic grade is due to prograde decarbonation, a carbon isotope distillation of ^{13}C from ^{12}C of up to a few per mil would have occurred, with the carbonate remaining after decarbonation being isotopically lighter, as is typically recorded in metamorphosed carbonate rocks (VALLEY, 1986). No such trend with metamorphic temperature is recognised in the gold deposits (Fig. 4b).

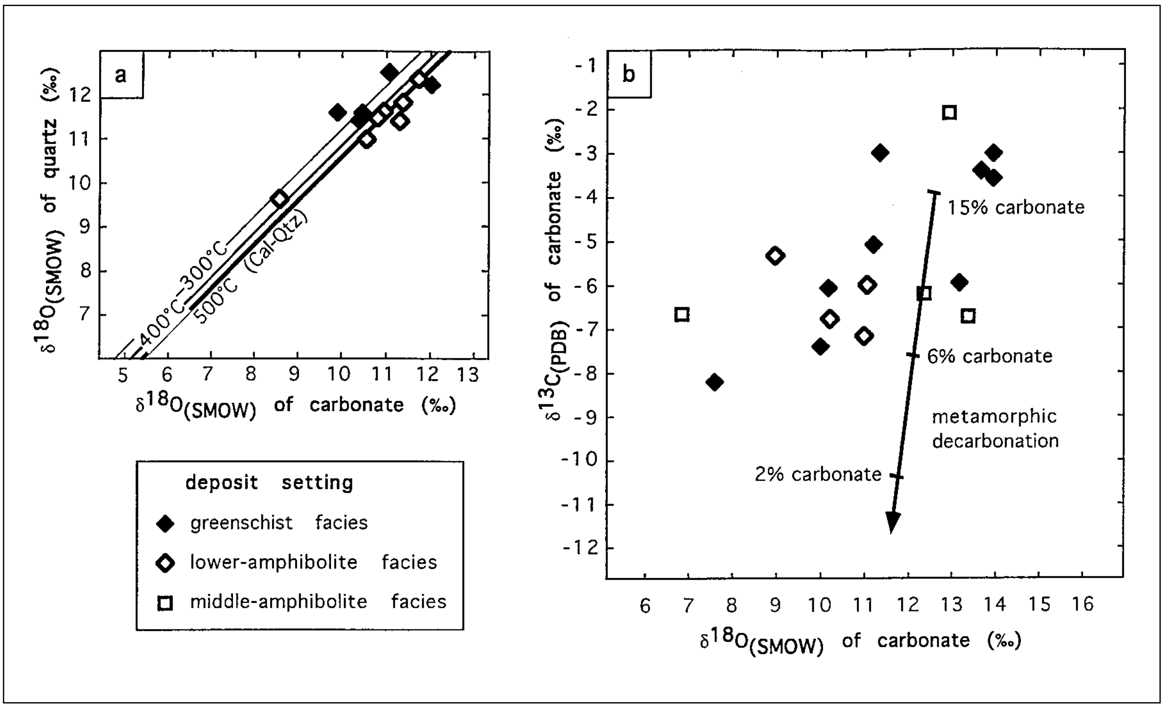

Fig. 4
Carbon and oxygen isotope characteristics of alteration minerals in gold deposits in different metamorphic grade terrains from the Yilgarn Craton.

(a) d18O of coexisting carbonate and quartz showing general isotopic equilibration at peak metamorphic conditions, irrespective of whether these are amphibolite- or greenschist-facies conditions.

(b) d13C - d18O of carbonates from deposits in different grade terrains compared to a theoretical metamorphic decarbonation fractionation trend of a mesothermal ore with initially 15 modal % carbonate heated from middle-greenschist to middle-amphibolite facies conditions.

Discussion and implications

The similar ore geochemistry and isotope chemistry of the deposits in high temperature terrains indicate that they are genetically related to mesothermal deposits. The strongest evidence against post-metamorphic introduction of gold is its occurrence as primary inclusions in, and texturally in equilibrium with, high-temperature minerals, and the association of ore with specific high-temperature alteration assemblages. Evidence against gold introduction significantly before the metamorphic peak are the lack of a decarbonation isotopic signature, and the control of deposit siting in most deposits by structures that formed late in the local deformation and metamorphic history. Taken together, the petrography, geochemistry, structural geology, and stable-isotope chemistry of the gold deposits in higher-grade terrains in the Yilgarn Craton thus are most consistent with mineralisation at high temperatures, approximately synchronous with the peak of metamorphism. Temperatures of gold precipitation were thus in the range 450 - 650°C, possibly up to 700°C, at pressures of 3 - 5 kbar. A similar interpretation has been argued for some deposits in higher-grade metamorphic terrains elsewhere in the world (e.g. ANDREWS et al., 1986), particularly for those in lower-amphibolite facies terrains, but alternative interpretations given for others, with mineralisation during a retrograde, greenschist-facies event being most commonly proposed for deposits in Phanerozoic belts. How widespread gold mineralisation at high temperatures is thus remains to be assessed.

The recognition of mineralisation at relatively high temperatures and pressures has given rise to the 'continuum model' for lode-gold deposits (GROVES et al. 1995), in which it is proposed that gold-bearing fluids are derived from a source below the level of the deposits and gold is precipitated during upward movement through the crust, potentially over a range of depths. Higher S contents of the fluid at higher temperatures mean that gold would be carried at all depths predominantly as a bisulfide complex (RIDLEY et al., 1996), and hence likely precipitated as a result of wallrock reactions. Possible deep fluid sources are from magmas that crystallised at depth, metamorphic dehydration in a subducted slab, or mantle devolatilisation. Metamorphic devolatilisation reactions at the greenschist–amphibolite facies transition or a surface fluid seem ruled out as possible fluid sources.

An implication of a deep fluid source is that many gold deposits, particularly mesothermal deposits in greenschist facies terrains, may have formed several kilometres above the fluid source. The fluid at the deposit may thus have been significantly modified during its passage through the crust and geochemical signatures of its source masked. The fluid in deposits in high-temperature terrains is likely to be closest to its original composition. In this respect, the $\delta^{18}O$ of quartz in the deposits indicates a fluid that at high temperatures would have been in equilibrium with granitoids rather than with greenstone volcanic rocks, and backs up Sr and Pb isotope data (MUELLER et al., 1991; McNAUGHTON et al., 1993) that indicate that the fluid at least interacted with, and is taken as an argument for ore fluid derivation from the granitoid substrate to the host greenstone belts.

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References

ANDREWS, A.J., HUGON, H., DUROCHER, M., CORFU, F., LAVIGNE, M.J. (1986): The anatomy of a gold-bearing greenstone belt: Red Lake, Northwestern Ontario, Canada. - In: MacDONALD, A.J. (Ed.): Gold '86: Konsult International, Toronto, 3-22.

BINNS, R.A., GUNTHORPE, R.J., GROVES, D.I. (1976): Metamorphic patterns and development of greenstone belts in the eastern Yilgarn Block, Western Australia. - In: WINDLEY, B.F. (Ed.): The Early History of the Earth: Wiley, New York, 303-313.

BLOEM, E.J.M. (1994): Structural controls, alteration history and genesis of Archaean gold deposits near Southern Cross, Yilgarn Block, Western Australia. - Unpublished PhD thesis, The University of Western Australia, 181 p.

BOIRON, M.-C., CATHELINEAU, M., BANKS, D.A., YARDLEY, B.W.D., NORONHA, F., MILLER, M.F. (1996): P-T-X conditions of late Hercynian fluid penetration and the origin of granite-hosted gold quartz veins in northwestern Iberia: A multidisciplinary study of fluid inclusions and their chemistry. - Geochimica et Cosmochimica Acta, 60, 43-57.

FYFE, W.S., HENLEY, R.W. (1973): Some thoughts on chemical transport processes, with particular reference to gold. Minerals Science and Engineering. - 5, 295-303.

GROVES, D.I., RIDLEY, J.R., BLOEM, E.J.M., GEBRE-MARIAM, M., HAGEMANN, S.G., HRONSKY, J.M.A., KNIGHT, J.T., McNAUGHTON, N.J., OJALA, V.J., VIELREICHER, R.M., McCUAIG, T.C., HOLYLAND, P.W. (1995): Lode-gold deposits of the Yilgarn Block : Products of Late-Archaean crustal-scale overpressured hydrothermal systems. - Geological Society of London Special Publication, 95, 155-172.

GRUNDMANN, G., LEHRBERGER, G., LAHUSEN, L. (1985): Freigold in Sillimanit-Cordierit-Gneisen des Moldanubikums bei Unterlangau, Oberpfalz. - Fortschritte der Mineralogie, 63 Beiheft, 81.

HODGSON, C.J. (1993): Mesothermal gold deposits. - Geological Association of Canada Special Paper, 40, 635-678.

KERRICH, R. (1991): Mesothermal gold deposits: a critique of genetic hypotheses. - In: ROBERT, F., SHEEHAN, P.A., GREEN. S.B. (Eds.): Greenstone Gold and Crustal Evolution, NUNA Conference Volume: Geological Association of Canada, 13-31.

McNAUGHTON, N.J., GROVES, D.I., WITT, W.K. (1993): The sources of lead in Archaean lode gold deposits of the Menzies-Kalgoorlie-Kambalda region, Yilgarn Block, Western Australia. - Mineralium Deposita, 28, 495-502.

MUELLER, A.G., DE LAETER, J.R., GROVES, D.I. (1991): Strontium isotope systematics of hydrothermal minerals from epigenetic Archean gold deposits in the Yilgarn Block, Western Australia. - Economic Geology, 86, 780-809.

NEUMAYR, P., CABRI, L.J., GROVES, D.I., MIKUCKI, E.J., JACKMAN, J.A. (1993). The mineralogical distribution of gold and relative timing of gold mineralization in two Archean settings of high metamorphic grade in Australia. - Canadian Mineralogist, 31, 711-725.

PHILLIPS, G.N. (1985): Interpretation of Big Bell/Hemlo-type gold deposits: precursors, metamorphism, melting and genetic constraints. - Transactions of the Geological Society of South Africa, 88, 159-173.

RIDLEY, J., MIKUCKI, E.J., GROVES, D.I. (1996): Archean lode-gold deposits: fluid flow and chemical evolution in vertically extensive hydrothermal systems. - Ore Geology Reviews, 10, 279-293.

VALLEY, J.W. (1986): Stable isotope geochemistry of metamorphic rocks. - In: VALLEY, J.W., TAYLOR, H.P.Jr., O'NEIL, J.R. (Eds.): Stable Isotopes in High Temperature Geological Processes: Mineralogical Society of America Reviews in Mineralogy, 16, 445-489.

VIDALE, R. (1969): Metasomatism in a chemical gradient and the formation of calc-silicate bands. - American Journal of Science, 267, 857-874.