A thematic issue dedicated to the giant Golden Mile Au-Te deposit, Kalgoorlie, Western Australia

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Received: 12 February 2020 / Accepted: 20 February 2020 / Published online: 9 March 2020
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The Kalgoorlie district in the Archean Yilgarn Craton of Western Australia comprises the Golden Mile (1767 t Au to Dec. 2018), Mt Charlotte (153 t Au) and smaller gold deposits (23 t Au combined; Keats 1987). Kalgoorlie was established in 1893, when Patrick Hannan, Thomas Flanagan and Dan Shea discovered alluvial gold. The Great Boulder Proprietary Ltd. was the first to treat sulfide ore mined below the oxide zone. The high gold grade (Table 1) sparked the sinking of hundreds of shafts on adjacent leases. Underground mining advanced to the 3670 ft (– 1119 m) level of the Chaffer's shaft and lasted until 1992, when operations ceased due to the amalgamation of open cuts into the Fimiston “Super Pit” (Fig. 1).

In the first contribution to this thematic issue, Witt et al. review the subdivision of the Yilgarn Craton into a Paleo- to Mesoarchean proto-craton and the Neoarchean Eastern Goldfields Superterrane, which includes the relatively young (ca. 2.70–2.65 Ga) and juvenile Kalgoorlie-Kurnalpi Rift (KKR). Although the komatiitic rocks in the Kalgoorlie Terrane are likely plume-related, a subduction-zone tectonic setting is interpreted for the KKR, consistent with the long-lived emplacement of enriched volcanic rocks and later intrusions, which cannot be explained by crustal contamination of plume-related ultramafic and mafic magmas. The Golden Mile and other “orogenic” gold deposits in the KKR are subdivided into proximal intrusion-related and distal-source types.

Mueller et al. revise the orogenic, magmatic and metamorphic evolution of the southern Kalgoorlie Terrane. Structural relations and zircon U-Pb ages are used to correlate the

volcano-sedimentary successions and constrain the emplacement of porphyry intrusions and the formation of Cu-Au skarns and mesothermal gold deposits along the Boulder Lefroy-Golden Mile transcurrent fault system. Geochemical and hornblende-apatite electron microprobe data indicate a relationship between anhydrite-bearing gold deposits such as the Golden Mile and late-orogenic, oxidized monzodiorite-suite intrusions of adakitic affinity.

In Mueller, the geometry of the vast network of mineralized shear zones in the Golden Mile is illustrated on level plans and in cross-sections with emphasis on structural data from the Paringa South mine (Part 1). The steeply dipping Fimiston shear zones, centred on the D2 Golden Mile strike-slip fault, are interpreted as Riedel systems formed in the tholeiitic host rocks after D1 folding and greenschist facies metamorphism but prior to the emplacement of granodiorite dykes at ca. 2675 Ma. Wall-rock alteration and gold mineralization were broadly synchronous with the emplacement of diorite dykes at ca. 2663 Ma and took place during alternating D2 strike-slip and D3 shortening, which generated the reverse Oroya fault system. D4 dextral strike-slip faults offset the Golden Mile lodes up to 2 km and control the quartz-vein ore bodies at Mt Charlotte dated at 2651 ± 9 Ma.

Representative ore bodies (lodes) in the Paringa South mine (Part 2) are described in Mueller based on detailed mapping, petrography and whole-rock geochemistry. Fimiston-style phengite-ankerite ore in D2 strike-slip faults replaced propylitic Golden Mile Dolerite (GMD) and contains disseminated magnetite, hematite, auriferous pyrite, minor chalcopyrite and tennantite. Oroya Au-Te ore overprints Fimiston ore in D2 faults but is the only ore in D3 reverse faults, which offset Fimiston lodes up to 50 m. These relationships are interpreted to indicate separate hydrothermal systems. In Oroya ore, early silica-chlorite-siderite replacement (pyrite-arsenopyrite-sphalerite-pyrrhotite) is crosscut by silica-ankerite fill (pyrite-tetrahedrite-tellurides-gold). Mass balance calculations indicate that both fluids introduced CO₂, Ca, K, Rb and Sr but that the Oroya fluid carried higher concentrations of Si, Fe, Ni, V and Te. Barren paragonite-chloritoid

Editorial handling: B. Lehmann

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Table 1 Early production from mines, Western Lodes, Golden Mile

Period	Crude ore (tonnes)	Gold (t)	Grade (g/t)
Great Boulder Proprietary Ltd.			
1895–1902	393,924	23.37	59.33
Golden Horseshoe Estates Com.			
1896–1907	1,415,490	45.60	32.21
Ivanhoe Gold Corporation Ltd.			
1897–1909	1,929,147	41.94	21.74

Data: Krusch 1903, Larcombe 1913

alteration at the southeast margin of the Golden Mile forms a thermal anomaly (405–425 °C) in propylitic GMD (310–340 °C).

Mueller and Muhling document wall-rock alteration and ore mineralogy in the Oroya Shoot, the main D3 ore body (> 62 t Au) in the Paringa South mine (Part 3). The shoot is famous for its telluride-rich ore (120–600 g/t Au) and for its V-rich gangue including nolanite, muscovite, chlorite and tourmaline. Chlorite and arsenopyrite thermometry indicate rapid fluid cooling from 450–400 °C to 340 °C during Stage 1

deposition of silica, chlorite, siderite, dendritic pyrite, chalcopyrite and sphalerite. Stage 2 quartz-ankerite breccia ore is characterized by montbrayite, tellurantimony and free gold. Altaite-tellurium myrmekites are interpreted as melt droplets deposited at > 400 °C. Late covellite and digenite were deposited at low tellurium but high sulfur fugacity. Mass balance calculations based on Oroya ore, and carbon-oxygen isotope data from dolomite in a late-mineralization kersantite dyke, implicate the local monzodiorite plutons as the fluid source.

Mueller et al. constrain the PTX conditions of gold deposition in the ore bodies described in Part 2 of the Paringa South series. The input fluids (PT = 300 MPa, 420 ± 30 °C) cooled to the ambient temperature at 10 km depth (250–300 °C). Fimiston refractory ore (7 g/t Au) formed during the replacement of propylitic chlorite by ankerite, magnetite and pyrite, the latter enclosing micron- to nano-sized gold and Au-Ag tellurides. High-grade Oroya ore (30–120 g/t Au) replaced previously altered ankerite-rich wall rock. Rapid cooling, an acidic fluid pH and the retrograde solubility of ankerite facilitated Stage 1 chalcedony-pyrite replacement. Locally, the fluid was reduced by trapped organic methane. In Oroya Stage 2 pyrite-telluride ± magnetite ore, grains of tellurantimony,

Fig. 1 Looking northwest into the Fimiston “Super Pit” at Kalgoorlie, Western Australia, courtesy of Kalgoorlie Consolidated Gold Mines (website download 2006). In June 2019, the Super Pit was 4.0 km long, 1.5 km wide and up to 620 m deep. The sulfide ore milled in 2018 amounted to 13.2 million metric tons at 1.78 g/t Au head grade including 0.904 million tons at 2.57 g/t Au from the Mt Charlotte underground mine. Gold recovery by cyanide leach after ultra-fine

grinding of the pyrite flotation concentrate was 82–83% (Q4 mine statistics 2018; barrick.com). Dark green propylitic Golden Mile Dolerite is exposed in the southwest wall and central part of the open pit. Light brown Paringa Basalt, altered pervasively to a pre-sulfide sericite-quartz-ankerite assemblage in a broad contact zone, forms the northeast wall of the open pit. Dark red-brown laterite soil extends to about 50 m depth

altaite, calaverite, petzite and montbrayite were deposited at about 400 °C. As fluid temperature and tellurium fugacity declined, native gold, krennerite, coloradoite, melonite, sylvanite and hessite crystallized. Genetic similarities between the Golden Mile and the Miocene Porgera gold deposit are discussed.

Godefroy-Rodriguez et al. present multiple sulfur isotope analyses ($\delta^{34}\text{S}$, $\Delta^{33}\text{S}$, $\Delta^{36}\text{S}$) obtained by secondary ion mass spectrometry (SIMS) in pyrite from the Kapai Slate black shale marker bed, and from Fimiston, Oroya and Mt Charlotte hydrothermal gold ore. The results reveal a very large spread in $\delta^{34}\text{S}$ (−12.6 to +23.5‰) and $\Delta^{33}\text{S}$ values (−1.0 to +1.1‰), caused by oxidized (Fimiston) versus reduced hydrothermal conditions (Oroya, Mt Charlotte) in the case of $\delta^{34}\text{S}$ and by the mixing of crustal- and mantle-derived sulfur in the case of $\Delta^{33}\text{S}$. In $\Delta^{33}\text{S}$ – $\Delta^{36}\text{S}$ space, a regression line of -0.75 ± 0.34 ($r^2 = 0.53$) is fitted to all data, different from the array defined by Archean sedimentary rocks (−0.9 to −1.5; Johnston 2011).

Finally, Godefroy-Rodriguez et al. complement the sulfur isotope data with pyrite trace element analyses using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Syngenetic/diagenetic pyrite from the Kapai Slate is barren of gold consistent with whole-rock assays of ≤ 0.06 g/t. In hydrothermal pyrite, the 75- μm ablation spots detected Au–Ag–Te inclusions and lattice-bound elements (e.g. Ni, Co, As). Linear mixed effects (LME) modelling of the analytical data indicates systematic differences between pyrites co-existing with oxidized and reduced mineral assemblages in Fimiston-, Oroya- and Charlotte-style ore. In combination with metallurgical data, the results suggest that nano-sized inclusions rather than lattice-bound gold are responsible for the low recovery (82–83%) in the Fimiston mill.

A short review of previous research

The discovery of tellurides in Golden Mile ore (Holroyd 1897) stimulated research on ore and gangue mineralogy (Krusch 1901; Lindgren 1906), enhanced and summarized in Simpson and Gibson (1912) and complemented by the studies of Stillwell (1931), Golding (1978) and Shackleton et al. (2003). Fieldwork by the Geological Survey of Western Australia (GSWA) progressed from mining lease mapping on basic geology (Maitland and Campbell 1902) to the documentation of outcrops and mine workings throughout the Kalgoorlie district (Simpson and Gibson 1912; Feldtmann and Farquharson 1913; Feldtmann 1916). The fourth bulletin of the Kalgoorlie series by Feldtmann (about 1928) was never published in print but is available as a free GSWA download (www.dmp.wa.gov.au). Some of his Golden Mile level plans and cross-sections became part of the study of Stillwell (1929), still a valuable source of structural and petrographic information today.

Privately funded studies include those of Krusch (1903), MacLaren and Thomson (1913), Thomson (1913) and Larcombe (1913). The geological maps and sections prepared by MacLaren, “illuminating to those privileged to see them” (Stillwell 1929), remained confidential and only the petrographic work of Thomson was published. Gustafson and Miller (1937) recognized isoclinal folding in the Kalgoorlie district but concluded that the geometry of the Golden Mile lode system ruled out a relationship to folding. They were also the first to infer a granitoid batholith at depth as the source of the porphyry dykes and hydrothermal fluid.

After World War II, structural studies by Finucane (1948), Tomich (1952) and Wells (1964) enhanced our understanding of the Golden Mile. District-scale mapping by Western Mining Corporation (Campbell 1953; Woodall 1965; Travis et al. 1971; Clout et al. 1990) and GSWA geologists (Keats 1987) outlined a complex system of faults transecting the regional folds. The crosscutting relationships and fault geometries were re-interpreted by Mueller et al. (1988), who related the Golden Mile shear zones to sinistral strike-slip on the bounding faults. They also recognized that the Mt Charlotte quartz-vein ore bodies were structurally younger than the Golden Mile deposit. The combination of company and GSWA mapping led to the delineation of the gold-rich Boulder-Lefroy fault system extending more than 100 km in strike (Mueller and Harris 1987; Swager 1989; Swager et al. 1995). The crustal-scale nature of the Boulder-Lefroy and other regional faults became instrumental in the development of the metamorphic hydrothermal model for Archean gold deposits (Phillips 1986; Groves 1993). Aspects of this and other genetic models are reviewed in Hagemann and Cassidy (2000) and in Bateman and Hagemann (2004). The results presented in this thematic issue suggest that the metamorphic fluid model proposed for “orogenic” gold deposits requires modification. The anhydrite-bearing Golden Mile Au–Te deposit may be “orogenic” due to its location in a fold belt but formed by the superposition of two intrusion-related hydrothermal systems: Fimiston and Oroya.

Acknowledgements Both guest editors acknowledge the support of Bernd Lehmann and the manuscript referees, whose input led to substantial improvements: Andrea Agangi, Louis Cabri, David Cooke, Matthias Cornelius, David Craw, Benoit Dubé, Paul Duuring, Max Frenzel, Sue Golding, Chris Hesford, David Huston, Gawen Jenkins, Stephen Kesler, Jochen Kolb, Robert Linnen, Janet Muhling, Juhani Ojala, Caroline Perring, Martin Reich, John Ridley, James Saunders, Gerard Tripp, Walter Witt, Derek Wyman and Jiří Zachariáš.

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