Structural architecture and relative timing of Fimiston gold mineralization at the Golden Mile deposit, Kalgoorlie

by

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Introduction

The giant Archean Golden Mile gold deposit, which contains over 60 million ounces (Moz) of gold, is located in the southern part of the Archean Norseman–Wiluna greenstone belt, part of the Yilgarn Craton of Western Australia. It is situated on the outskirts of the city of Kalgoorlie. The Golden Mile has been in near-continuous production since the initial discovery of gold in 1893. It has produced over 50 Moz of gold, and the current Super Pit operation still hosts over 12 Moz of gold reserves. Over 10 Moz of gold were produced between 1894 and 1909, with the all-time peak year of production being 1903, when 1.2 Moz of gold was produced at an average grade of 41 g/t Au (Woodall, 1965; Clout et al., 1990). By 1912, the deepest shaft on the Golden Mile was the main shaft of the Boulder Consolidated Gold Mine, already 27 levels deep (-823 m). This led Larcombe (1912) to write that, 'In view of these facts the necessity for a detailed geological examination of the belt, coupled with an exact deciphering of the underground structure, becomes at once evident, for one of the necessary consequence of mining is the destruction of the evidence as to the origin and relation of the ore deposits'.

Historically, numerous mining companies, controlling a patchwork of separate small mining leases, operated several underground operations on the Golden Mile deposit. Operating leases on the Golden Mile were progressively amalgamated through the years until, in 1989, Kalgoorlie Consolidated Gold Mines (KCGM), a current joint venture between Barrick Gold Corporation and Newmont Gold, emerged as the sole owner of the Golden Mile and Mount Charlotte deposits. Underground gold mining effectively ceased in 1990 at the Golden Mile, and current mining operations consist of large scale open-pit mining extending over the entire Golden Mile deposit, complemented by underground mining of the Mount Charlotte deposit. The Super Pit operation recovers gold mostly from low-grade alteration selvedges along mined-out lodes, pillars, and portions of lodes that were uneconomic for underground mining. Underground access on the Golden Mile was maintained until the end of 2003.

The scope of the field trip at the Golden Mile will depend on the progress of mining. The nature and scale of the mining operation at the Golden Mile makes it difficult to visit specific sites of interest in the pit. The visit will probably comprise an overview of the Golden Mile geology from an observation bay near the top of the pit. This will be complemented by a review of drillcore documenting the main mineralization and alteration styles. Nonetheless, this field guide presents detailed mapping of localities in the pit and underground, which are now mined out or inaccessible. The field guide has focused on the documentation of the structural architecture and relative timing of gold emplacement at the Golden Mile, based on field relationships established through underground and pit mapping. More comprehensive overviews of the Golden Mile geology include Travis et al. (1971), Clout et al. (1990), and Bateman et al. (2001).

Structural architecture

Stratigraphy

A good understanding of the host stratigraphy is critical to better define the structural architecture of the Golden Mile deposit. The major and trace element geochemistry of the Paringa Basalt and Golden Mile Dolerite is used in three ways to define the structural architecture:

1. Consistent geochemical fractionation trends within the Paringa Basalt and individual units of the layered Golden Mile Dolerite are used as younging indicators.
2. Major faults are documented by offsets in the fractionation trend of the Paringa Basalt.
3. Early synvolcanic faults are interpreted by abrupt changes in the thickness and composition of the Paringa Basalt and Golden Mile Dolerite.

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The Paringa Basalt sequence consists of a 400–700 m-thick accumulation of basaltic flows grading from a high magnesium basalt with ubiquitous variolitic and local spinifex textures at the base, to a gradually more fractionated tholeiitic basalt (Bateman et al., 2001). The upper portion of the Paringa Basalt is characterized by pillow and flow breccia textures, with a general increase of interflow sedimentary rocks. The Paringa Basalt displays a gradual fractionation trend with increasingly more evolved compositions towards the stratigraphic top, characterized by increasing Zr, TiO_2, Al_2O_3, V, and Fe_2O_3 contents, and decreasing MgO, Ni, and Cr contents (Fig. 1). The top 50–100 m section of the Paringa Basalt sequence consists of a high Fe tholeiite in sharp contact with the underlying tholeiitic basalt. It is characterized by high contents of TiO_2, Fe_2O_3, Zr, and P_2O_5, and very low MgO, Ni, and Cr contents. The high Fe tholeiite constitutes an important marker of the stratigraphic top of the Paringa Basalt sequence: this unit itself displays a normal fractionation trend.

The Golden Mile Dolerite is a differentiated layered gabbroic sill about 700 m thick. The intrusion has been subdivided into ten units based on petrographic and geochemical characteristics (Travis et al., 1971). Units 1 and 10 form the basal and upper chill margins, respectively. Units 2 and 3, the basal cumulate units, display very high Cr, Ni, and MgO contents with a decreasing trend upward into the intrusion. Units 4 and 5 consist of medium-grained subophitic gabbro with a generally flat geochemical pattern. Units 6, 7, and 8 are magnetite-rich (10–15 wt % magnetite), and unit 6 displays a very strong enrichment in elements with strong partition coefficients into magnetite, such as V, Cr, Ni, and Cu. These elements are, in turn, strongly depleted in units 7 and 8. Units 6 and 7 display gradual enrichment trends in Zr, TiO_2, and Fe_2O_3 towards unit 8. Unit 8, the granophyric unit, is characterized by high SiO_2, Zr, TiO_2, P_2O_5, and Fe_2O_3 contents. Unit 9 displays a gradual fractionation trend characterized by higher Zr, V, and TiO_2 contents, and lower Cr, Ni, and MgO contents towards the contact with unit 8.

The Golden Mile Dolerite displays important lateral variations in terms of thickness, internal magmatic layering, and geochemistry. The Golden Mile Dolerite on the easterly dipping limb of the upright northwesterly trending Kalgoorlie Anticline is significantly thinner (200 m) than on the westerly dipping limb (700 m), and displays a gradual fractionation trend without the formation of magmatic layering (Figs 2 and 3). The fractionation trend in the thin Golden Mile Dolerite is

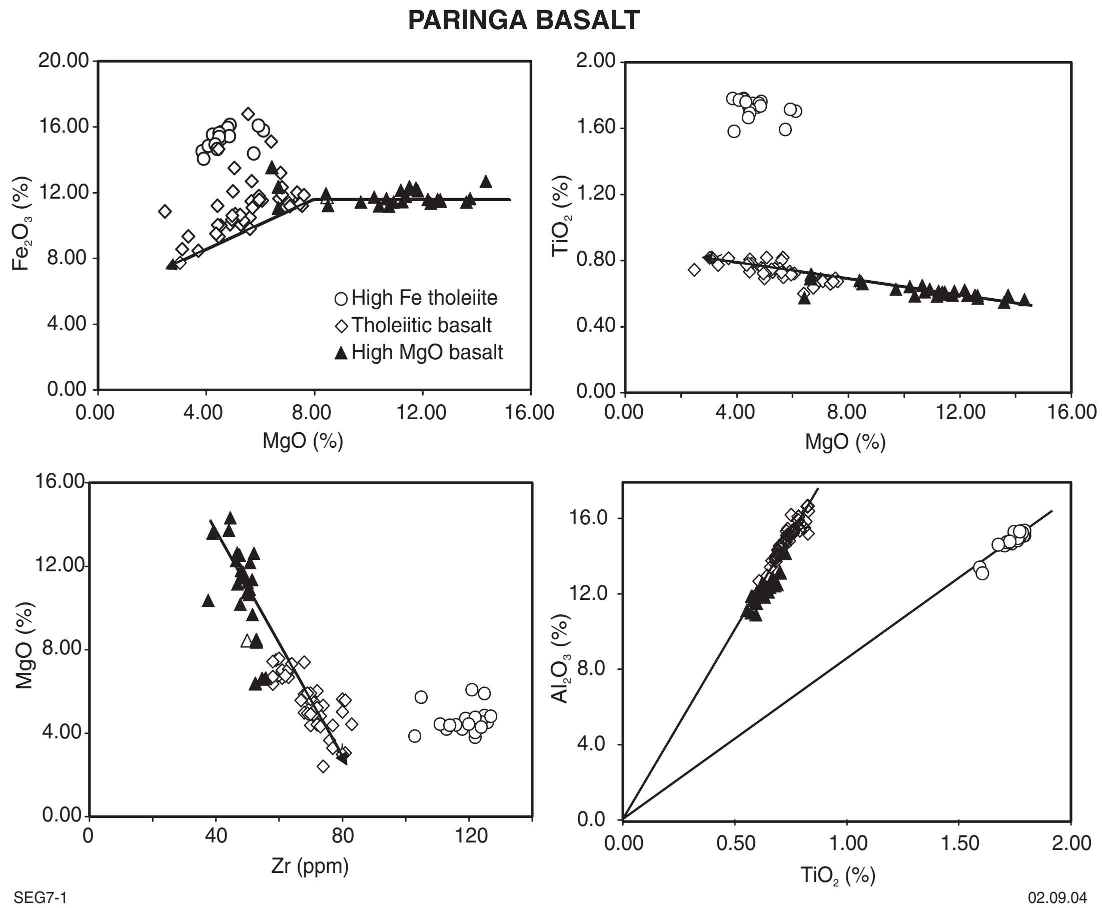

Figure 1. Geochemical variation diagrams of the Paringa Basalt highlighting the progressive fractionation trend from the high MgO basalt at the bottom of the Paringa Basalt sequence to the more fractionated tholeiitic basalts higher in the stratigraphy, and the high Fe tholeiite marker unit at the top of the Paringa Basalt sequence

indicative of a younging direction to the east, which is consistent with the interpretation of this thinner dolerite being on the easterly dipping limb of the Kalgoorlie Anticline. The chemostratigraphy of the underlying Paringa Basalt also supports this interpretation.

South of the Eastern Lode System, the Golden Mile Dolerite is slightly thinner (500 m) and displays less well developed internal magmatic layering, with significantly less abundant magnetite in units 6, 7, and 8. This transition is gradual and not associated with the Adelaide Fault (Travis et al., 1971). In turns, this confirms the equivalence of the Golden Mile and Aberdare Dolerites across the late stage Adelaide Fault (Clout, 1989).

Structure

The continuity of the Golden Mile Dolerite south of the Adelaide Fault establishes the regional continuity of the north-northwesterly trending, upright, and shallowly south plunging Kalgoorlie Syncline–Anticline pair (Fig. 1), which dominates the structural architecture of the Golden Mile (Woodall, 1965; Travis et al., 1971). The Kalgoorlie Syncline is an asymmetric fold, with the western limb being subvertical whereas the eastern limb dips at 30° to the west. Geochemical studies have further highlighted a consistent internal chemostratigraphy in the Paringa Basalt, which provides an additional marker for precisely locating the Kalgoorlie Anticline. The anticline plunges at about 20° south, which results in progressively older units being exposed along its axis towards the northwest. The Golden Mile Fault, a steeply west-dipping normal fault with substantial displacement, offsets the hinge of the Kalgoorlie Syncline (Woodall, 1965). The Golden Mile Fault forms the eastern contact between a narrow band of Black Flag Group (mudstone–sandstone), and the Golden Mile Dolerite to the east (Figs 2 and 3). The western contact of the Black Flag Group with the Golden Mile Dolerite is intrusive, as indicated by the wide chill margin within the dolerite. The Black Flag Group is itself intruded by numerous feldspar porphyry dykes.

There is a parasitic syncline–anticline fold pair on the western limb of the Kalgoorlie Anticline within the Golden Mile area (Figs 1 and 2). The Paringa Anticline and the Brownhill Syncline are at the northern end of the deposit. The Brownhill Syncline correlates with the Lake View Syncline at the southern end of the deposit (Gustafson and Miller, 1937). The Golden Mile Fault truncates the Brownhill Syncline – Paringa Anticline fold pair, indicating that initiation of the Golden Mile Fault postdates development of the Kalgoorlie Syncline–Anticline pair (Figs 1 and 2). This relationship does not support the interpretation of the Golden Mile Fault as a thrust and the Kalgoorlie anticline as an overturned hangingwall anticline (Swager, 1989).

A regional, steeply west-dipping, north-northwesterly oriented foliation (N140°/80°W) overprints the Kalgoorlie Syncline–Anticline pair and smaller subsidiary folds. This is well documented in the southern part of the Super Pit

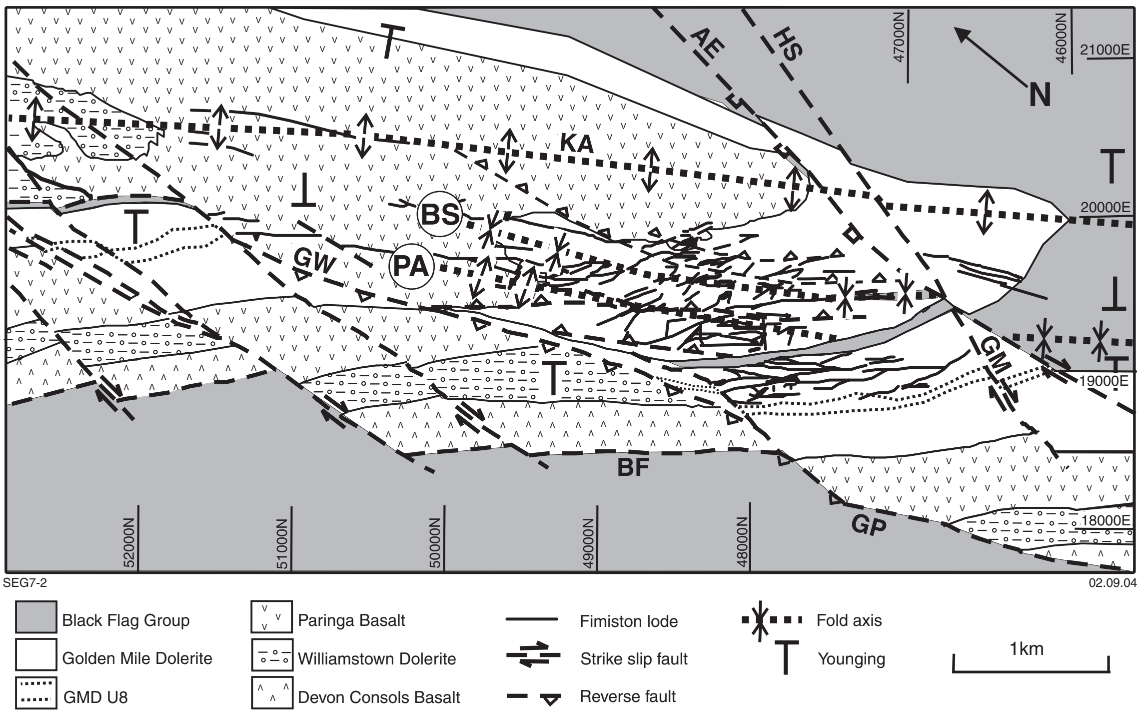

Figure 2 . Map of Golden Mile deposit area, modified after Bateman (2001), Clout (1989), and Gustafson and Miller (1937). AE = Adelaide Fault, BF = Boulder Fault, BS = Brown Hill Syncline, GM = Golden Mile Fault, GMD U8 = Golden Mile Dolerite unit 8, GP = Golden Pike Fault, GW = Golden Mile Dolerite 'wedge', KA = Kalgoorlie Anticline, KF = Kalgoorlie Fault, HS = Hannan Star Fault, PA = Paringa Anticline. Note that a local grid is used

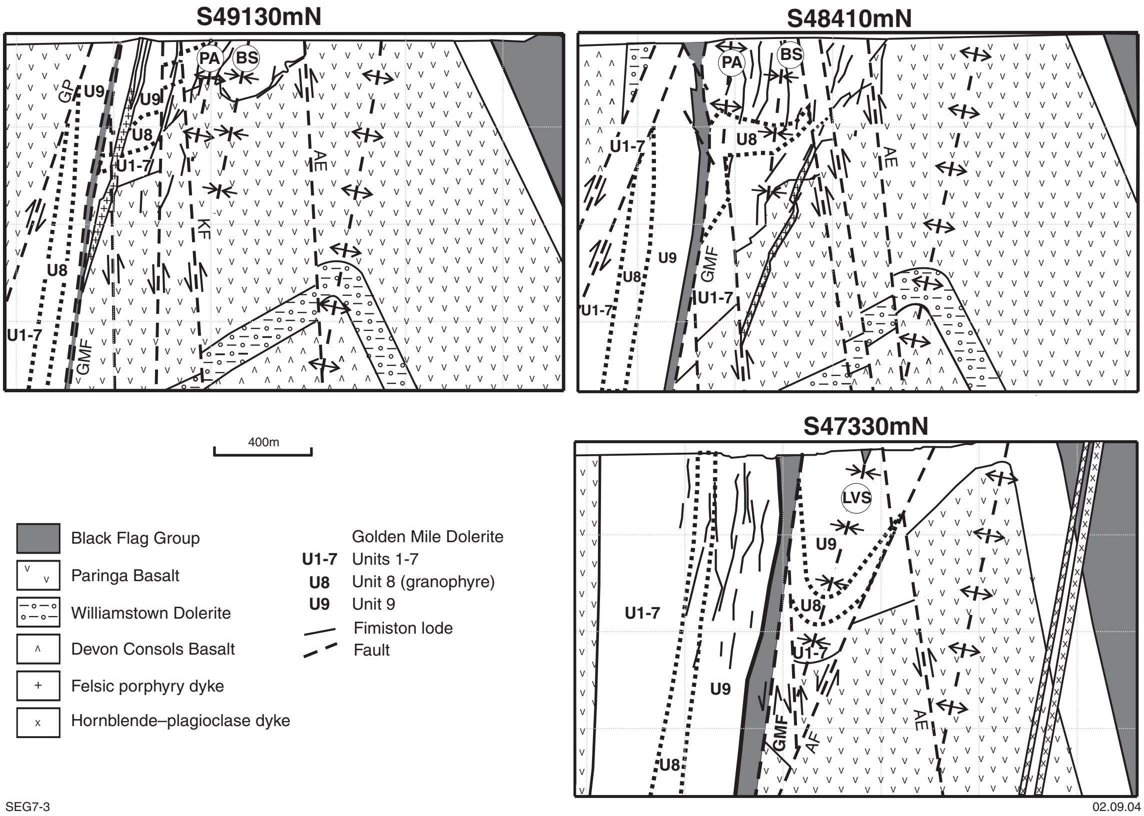

Figure 3. Geological cross sections, oriented local grid east–west looking local grid north, interpreted from compilation, relogging, and geochemical data. Abbreviations as for Figure 2, plus LVS = Lake View Syncline

where the Lake View syncline is exposed in the pit wall (Fig. 4). In that location, interbedded mudstone and siltstones of the Black Flag Group define a tight syncline. Individual beds within the Black Flag Group can be traced continuously across the hinge of the syncline. The upper chill margin of the Golden Mile Dolerite (unit 10) underlies the Black Flag Group. The syncline is also well documented within the underlying Golden Mile Dolerite. The reversal of younging direction in the Golden Mile Dolerite, from the western to the eastern hinge of the fold, is indicated by a reversal of the geochemical fractionation trends within unit 9. In the pit wall exposure of the Lake View Syncline, the regional north-northwesterly trending foliation cuts both limbs of the fold with the same anti-clockwise discordant relationship, indicating that the fabric postdates the fold.

Relative timing relationships

A swarm of feldspar porphyry dykes, centered on the deposit, transects both limbs of the Kalgoorlie fold pair, indicating the dykes were emplaced after this regional folding event and most likely in an upright position (Fig. 2; Golding, 1978; Mueller et al., 1988).

The dykes are, in turn, overprinted by the regional north-northwesterly trending foliation. The feldspar porphyry dykes are also overprinted by Fimiston-style gold mineralization, consisting of narrow vertically and laterally extensive lodes (up to 1200 m vertically and 1000 m along strike) of carbonate–quartz–pyrite wallrock disseminations, accompanied by variably developed carbonate–quartz–pyrite breccias and quartz veinlets. The feldspar porphyry dykes and Fimiston lodes are spatially associated and share three common orientations, historically known as Main (N140°/80°W), Caunter (N115°/65°W), and Cross (N050°/85°N–S). Hornblende porphyry dykes, of alkaline affinity, are also present and share the same orientations. These hornblende porphyry dykes crosscut the feldspar porphyry dykes and, locally, clearly cut the Fimiston lodes.

The north-northwesterly trending regional foliation is preferentially developed within weak layers such as mudstone beds and sericite-rich Fimiston lode selvedges. The constant orientation of the north-northwesterly trending foliation in lode selvedges across a wide range of lode orientations, including the northeasterly trending Cross Lodes and the shallowly dipping Caunter Lodes, provides clear evidence that the foliation overprints the lode selvedges, rather than being related to shearing synchronous with lode formation (Clout, 1989; Swager, 1989). The north-northwesterly trending regional foliation is also axial planar to small-scale buckle folds of Fimiston veins, and dykes, which is consistent with their east-northeast–west-southwest bulk shortening.

The stratigraphy, porphyry dykes, and Fimiston lodes are offset by a network of north-northwesterly trending reverse shear zones comprising a dominant steeply northeasterly dipping and steeply southwesterly dipping sets. The shear zones are particularly abundant in the Eastern Lode System (Figs 1 and 2). The Kalgoorlie Fault, one of the most extensive shear zones of this set, displays a 175 m reverse offset of the stratigraphy, feldspar porphyry dykes, and Fimiston lodes. The Fimiston lodes are commonly transposed within these shear zones, and the shears typically contain boudins of lode material. A conjugate network of shallowly dipping shear zones commonly postdates the steep reverse shear zones (Wells, 1964). These two sets of shear zones are reactivated by a later dextral strike-slip transcurrent deformation event, as indicated by ubiquitous shallowly plunging mineral lineations and slickensides within fault planes (Finucane, 1941).

The Adelaide Fault is a regional-scale, south-southeasterly trending, steeply west-dipping dextral fault, which terminates in the southern part of the Eastern Lode System in a south-southwesterly trending releasing bend that dips 70° west (Fig. 1). In the releasing bend, the fault displays a normal movement with an offset of about 300 m. The Australia East Fault, a steeply east-dipping reverse fault offsetting the Fimiston Lodes, is itself crosscut and offset by the Adelaide Fault (Fig. 2). Late northerly to north-northeasterly trending steeply dipping dextral faults form the latest set of faults at the Golden Mile. The Hannans Star Fault dextrally offsets the Morrisson lode, part of the Western Lode System, by about 40 m. The Hannans Star Fault also offsets the Adelaide Fault.

Quartz–carbonate veins and breccias, typical of the Mount Charlotte vein style mineralization, are associated with both late steeply dipping, and shallowly dipping reverse fault sets. The veins and breccia cut the Fimiston lodes, and contain fragments of these lodes with randomly oriented, foliated, sericite alteration selvedges. This implies that these late veins and some of the shallowly dipping and steeply dipping reverse faults postdate the north-northwesterly trending regional foliation.

A small wedge of Golden Mile Dolerite west of the Golden Pike Fault displays a geochemical signature similar to the thin, 200 m-thick Golden Mile Dolerite on the eastern limb of the Kalgoorlie Anticline and south of the Adelaide Fault (Figs 1 and 2). The thinner Golden Mile Dolerite is fractionated but does not display the magmatic layering typical of the thicker Golden Mile Dolerite (Travis et al., 1971). This suggests that the Golden Pike Fault influenced emplacement of the Golden Mile Dolerite and is an early structure, albeit reactivated by later deformation events. In turn, it is possible that the early

Figure 4. Wall at the southern end of the Super Pit, looking south. Black Flag Group (dark) forms the core of the Lake View Syncline flanked on either side by Golden Mile Dolerite (orangish-brown). The north-northwesterly trend of the regional foliation is highlighted (S_2) and clearly overprints the syncline

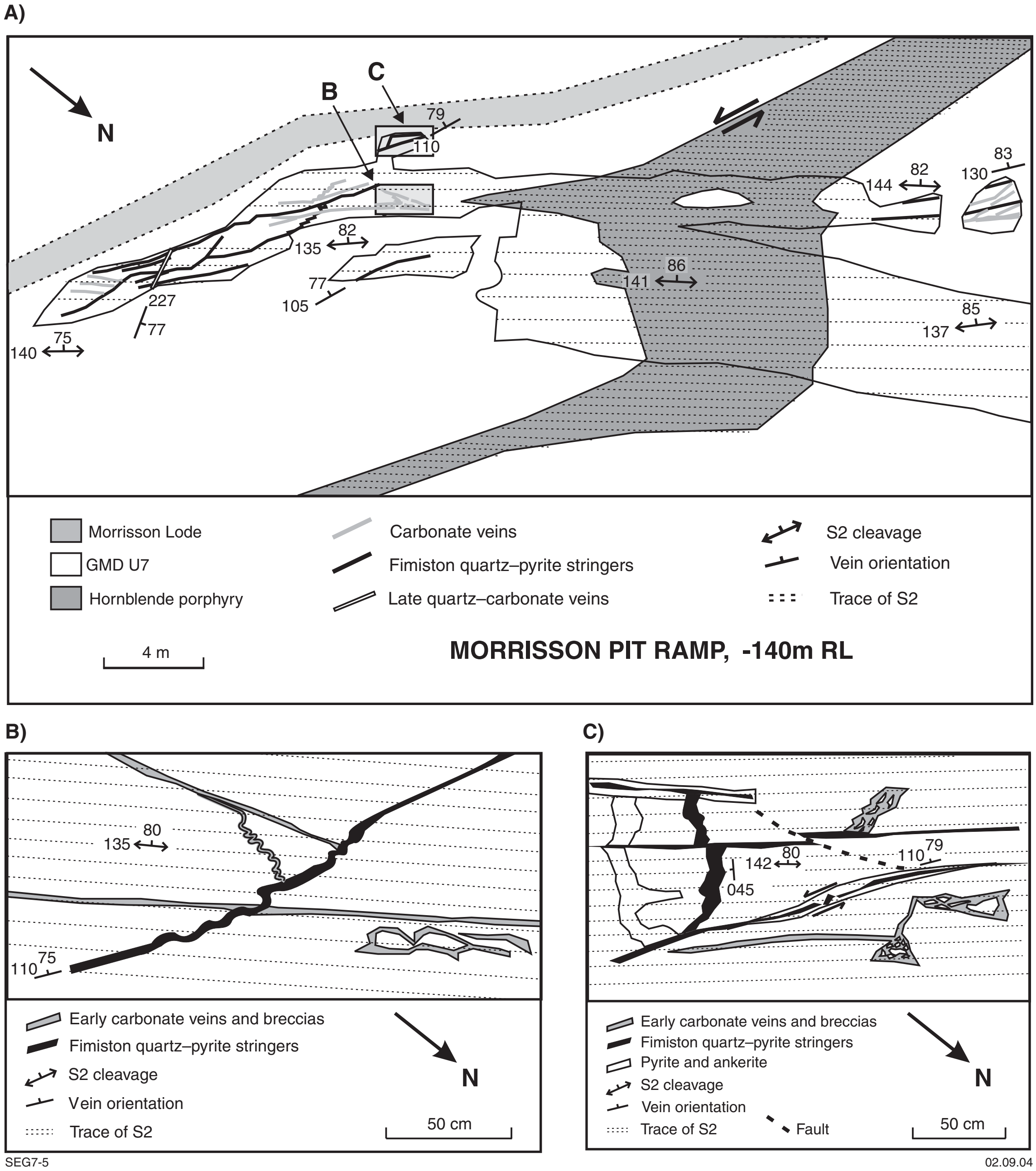

Figure 5. Detailed map of the northern margin of the Morrisson lode, at the bottom and middle of the Morrisson pit. The lode is situated in the southern part of the Western Lode System

Golden Pike Fault had a major control on the localization of the Golden Mile deposit by setting up a favourable geometry.

Field documentation

Some of the key field relationships and structural observations synthesized above are illustrated by a detailed map of the eastern margin of the Morrisson lode within the Morrisson pit (Fig. 5) and an underground sketch of the Black Flag Group between the Western and Eastern Lode Systems (Fig. 6).

Morrisson lode

The Morrisson lode map documents the northeastern margin of the Morrisson lode, located along the ramp towards the bottom of the Morrisson pit, within the southern part of the Western Lode System. The detailed map area contains abundant small Fimiston quartz (–carbonate–pyrite) stringers hosted within unit 7 of the Golden Mile Dolerite, along the northeastern margin of the Morrisson lode (Fig. 5).

A hornblende porphyry dyke is strongly sericite–carbonate altered and overprinted by a penetrative foliation. This foliation is much less well developed within the more competent unit 7. The foliation is axial planar to an S-shaped fold within the hornblende porphyry dyke. The southern margin of the dyke displays a steeply dipping sinistral fault, as indicated by slickensides and mineral lineations plunging shallowly southeast that are observed just west of the map area. The folding, sinistral faulting, and pervasive foliation developed in the strongly sericitized hornblende porphyry dyke are consistent with the transposition of a weak layer affected by bulk shortening directed east-northeast–west-southwest (Poulsen and Robert, 1990; Hanmer and Passchier, 1991).

The Fimiston quartz stringers crosscut carbonate veins and carbonate breccias within unit 7, indicating a phase of carbonate alteration pre-dating the main phase of Fimiston gold mineralization (Bartram, 1969). The Fimiston stringers display the three main orientations of lodes observed at the Golden Mile (Main, Caunter, and Cross), suggesting that the three orientations of ore zones are contemporaneous.

Figure 5B documents a Fimiston quartz stringer crosscutting carbonate veinlets. The Fimiston quartz stringer, oriented at N110°, displays S-shaped buckle folds, whereas the carbonate stringer, oriented at N020°, at a sharp angle to the S_2 foliation, displays Z-shaped buckle folding. This is consistent with a moderate bulk shortening directed east-northeast–west-southwest (Ramsay, 1983).

Figure 5C documents Fimiston quartz stringers in the three main orientations typical of Golden Mile lodes. The Fimiston quartz stringers have pyritic selvedges and crosscut early carbonate breccias. The quartz stringer oriented parallel to the Cross Lode orientation displays buckle folds consistent with weak bulk shortening. The Caunter-oriented quartz stringer displays a minor sinistral shearing, as the pyritic selvedge acted as a less competent layer compared to the quartz stringer. These features are consistent with a weak component of east-northeast–west-southwest bulk shortening associated with the north-northwesterly trending regional foliation.

A small Mount Charlotte-style quartz–carbonate vein in the southeastern part of the map area clearly crosscuts Fimiston quartz stringers. Furthermore, although the vein is almost orthogonal to the S_2 foliation, it does not display any folding, suggesting that its emplacement postdated the bulk shortening event associated with the S_2 foliation.

Black Flag Group

Figure 6 represents the western wall of an underground drive on the 20 level (-667 m) cutting through the Black Flag Group between the Western and Eastern Lode Systems. The section presented is along the western margin of the Black Flag Group.

The Black Flag Group consists of well-bedded mudstone and fine-grained sandstones, and has well developed foliation oriented at N145°/65°W. The bedding planes are subvertical, with graded bedding and crossbedding indicating a younging direction to the east. Small-scale folds of the bedding planes are axial planar to the north-northwesterly oriented foliation planes, and the fold axes plunge shallowly.

A feldspar porphyry dyke along the western end of the drive displays a very irregular contact with the Black Flag Group and is clearly discordant to the bedding planes. The dyke contains 5–10% plagioclase and hornblende phenocrysts, as well as quartz-filled vesicles, within a fine-

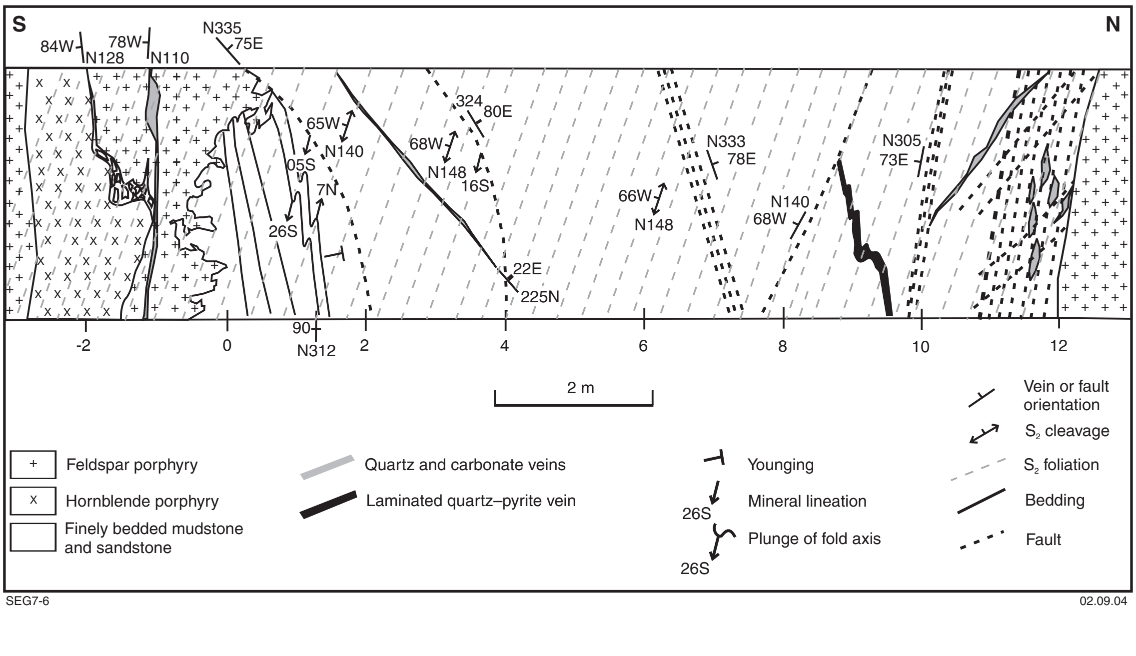

Figure 6. Sketch of underground drive northeast of the Chaffers shaft on level 20 (-667 m RL). Western end of the Black Flag Group separating the Western and Eastern Lode Systems, view of the west wall of the drive, which is oriented north–south

grained quartzofeldspathic groundmass overprinted by a sericite–carbonate assemblage. A hornblende porphyry dyke transects the feldspar porphyry dyke, clearly establishing the relative chronology of dyke emplacement. The hornblende porphyry dyke contains about 20% coarse-grained hornblende phenocrysts, and is also overprinted by intense sericite–carbonate alteration.

Towards the eastern end of the section, there is a small laminated quartz–carbonate vein with pyrite concentrated along the selvedges. Such veins are characteristic of the late stage of the Fimiston ore paragenesis. The vein displays buckle folds that are axial planar to the north-northwesterly trending foliation planes, consistent with bulk shortening associated with the foliation.

The Black Flag Group is cut by several narrow steeply easterly and westerly dipping oblique faults. The faults have a component of reverse offset, but display shallowly plunging mineral lineations and slickensides, which are generally well developed within the sedimentary rocks, and indicate a dextral component of movement. They are interpreted to be reverse faults with a late component of dextral movement, and offset the laminated Fimiston quartz–carbonate vein and feldspar porphyry dykes.

A few coarse-grained carbonate veins and quartz veins within the Black Flag Group, although at sharp angle to the foliation, do not display any buckle folds, and locally crosscut steeply dipping fault planes, such as shown in the eastern portion of Figure 6. These veins are interpreted to be late stage, postdating the north-northwesterly trending foliation, and are probably associated with the late, steeply dipping, oblique faults.

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