Rubicon gold mine, Kundana mining centre

by

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Introduction

The Rubicon open pit mine is located in the Kundana mining centre, about 22 km northwest of Kalgoorlie. The mine exposes mafic volcanic rocks of the Grants Patch Group and sedimentary rocks of the Black Flag Group in the Ora Banda Domain. Mineralization is hosted in a 0.5–0.8 m-thick laminated quartz vein along a mafic–sedimentary rock contact. Grants Patch Group mafic rocks in the hangingwall are intensely sheared, with partitioned high-strain zones that trend at a low angle to the main ore vein. Sedimentary rocks in the footwall are folded, with penetrative axial plane foliations.

Other vein arrays are associated with the main vein, including flats, footwall stockworks, and splay veins that affect the grade and location of high grade oreshoots. The main vein is best mineralized in areas where it is most disrupted by other vein intersections and microfaulting of the vein fabrics. Foot- and hangingwall veins, and vein stockworks are also potential exploration targets. Shear zones that intersect the main ore vein at an angle produce an intersection lineation plunging steeply south, and could control the geometry and distribution of high grade oreshoots.

Cross faults disrupt the main ore vein, with displacements of up to 11 m in the open pit. These faults have displaced the vein laterally, and can result in a loss of the ore horizon in underground ore drives. A major cross fault (White Foil Fault) produces the greatest offset of the ore vein, whereas several smaller faults have variable displacements and kinematics.

Kundana mining centre

Geology

Hadlow (1990) described the geology of the Kundana mining centre in detail, and much of the local geology presented here is drawn from that study. The location and geology of the mining centre are presented in Figures 1 and 2.

Rock types

The Kundana mining centre covers the interpreted position of the Zuleika Shear Zone and adjacent areas in the Ora Banda and Coolgardie Domains. The eastern part of the area lies on the north-northwesterly trending Kurrawang Syncline, and the western part is on the eastern limb of the south-southeasterly trending Powder Sill Syncline. In the east, the stratigraphy consists of high-Mg basalt and dolerite (Bent Tree Basalt), feldspar-phyric basalt (Victorious Basalt), graphitic black shale, intermediate

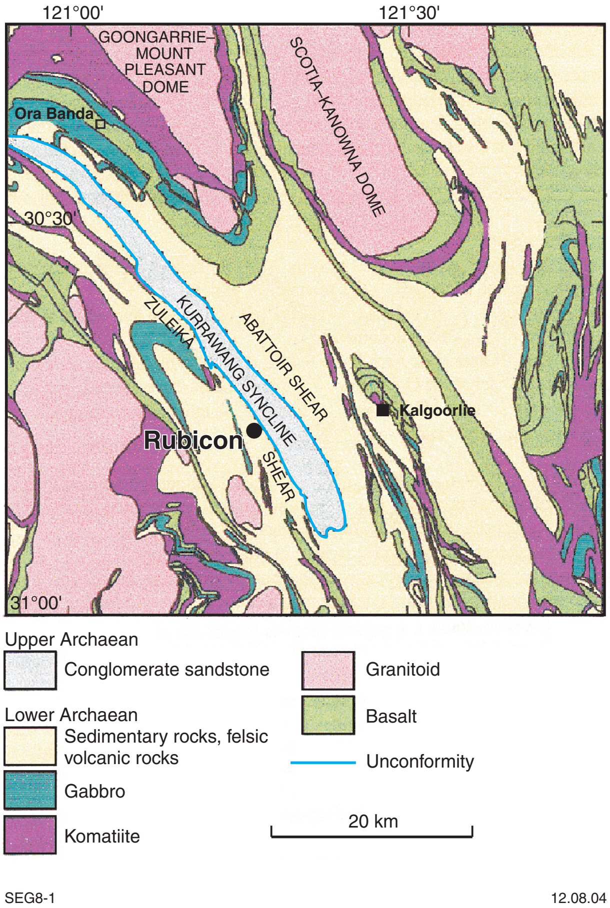

Figure 1. Regional geological setting of the Rubicon gold mine (after Goleby et al., 2000)

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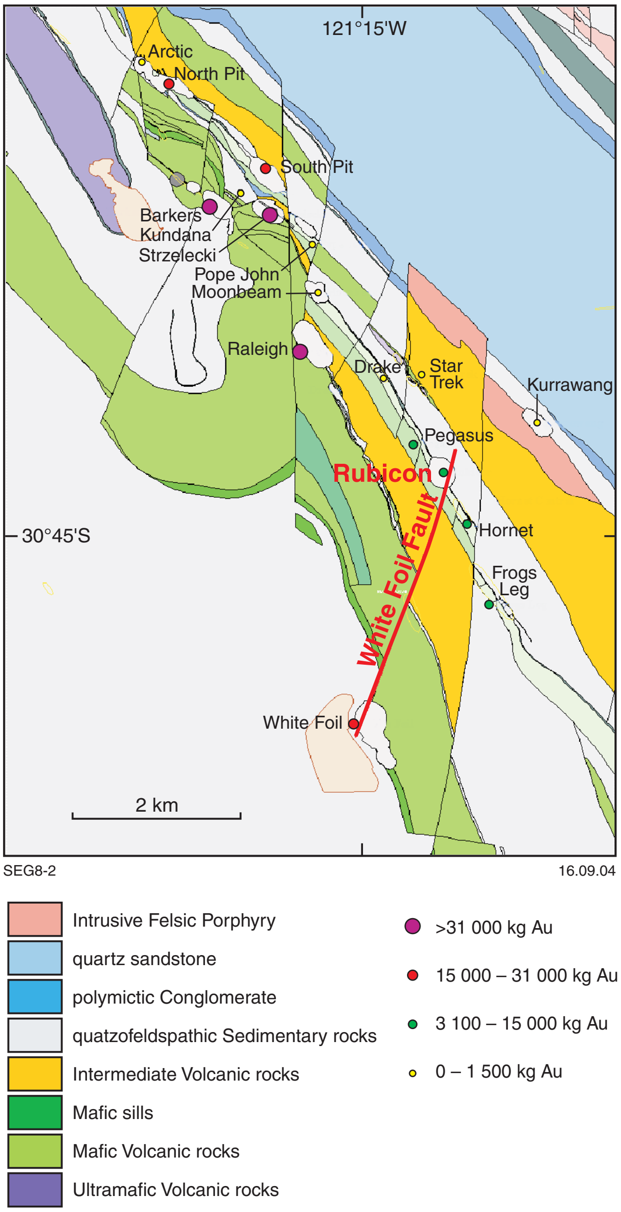

Figure 2. Local geological setting of the Rubicon mine

volcaniclastic rocks, dolerite sills, and polymictic conglomerate (Kurrawang Formation). This sequence contrasts with komatiite, felsic sedimentary rocks of the Spargoville Formation, and the layered, differentiated Powder Sill dolerite in the west. Graphitic shales and andesite–dolerite contacts are of particular interest since they are the primary sites hosting laminated auriferous quartz veins. Shear reactivation of the stratigraphic contacts produced strike-persistent shear zones that localized hydrothermal fluids.

Structure

Rocks in the Kundana mining centre record three main deformation events including folding, shearing, and brittle faulting. Folding in the eastern part of the area produced a slightly overturned sequence, which was interpreted as an isoclinal anticline between the Powder Sill and Kurrawang Synclines (Hadlow, 1990). A small but important northerly plunging anticline at the eastern extension of the Powder Sill could have formed a rigid body that affected the subsequent partitioning of strain during the regional shortening. Ductile shearing produced partitioned zones of flattening and simple shear strain with a dominantly down-dip stretching lineation. Plagioclase phenocrysts in the Victorious Basalt are stretched into rodlike shapes, with axial ratios up to 7:1, and X>>Y=Z indicating an apparent constriction. Exposures in the Arctic open pit show elongation in the XY and XZ planes, whereas the phenocrysts exhibit orthorhombic symmetry in the YZ plane. The orientation of the Zuleika Shear Zone is variable about the vertical, and most exposures show a steep dip, which varies from vertical in the North pit to mostly easterly dipping in the Kundana north outcrops. Reverse kinematics is suggested by asymmetric boudinage of syntectonic quartz veins in a westerly dipping foliation viewed in plan section. The stretching lineation is subparallel to the fold axes of open-tight chevron folds in metasedimentary rocks that also plunge steeply north (interpreted F_2).

Gold deposits

Gold mineralization at Kundana comprises quartz veins that were emplaced into several graphitic shale horizons and along lithological contacts. The deposits are discussed in detail by Lea (1998) and only pertinent structural features are discussed below. The Kundana mines contribute significantly to the total gold endowment of the region, with an estimated historic production plus resources of about 217 t. This endowment is contained within three large deposits — Strzelecki (1.8 Moz), Barkers (0.9 Moz), and Raleigh (0.9 Moz) — and many other smaller deposits, including South pit (0.7 Moz) and North pit (0.5 Moz). The Strzelecki and Barkers orebodies are well developed, and provide clear information on the timing and control of gold mineralization within sheared rock contacts.

Vein thickness and geometry

Veins in the Strzelecki and Barkers orebodies trend about 65°/220° (strike 310°). Underground mine geologists have indicated that the ore grade decreases where the strike orientation of the vein moves away from this trend toward 300°. Small kinks in the vein localize high-grade portions and thick vein intersections. As shown in Figure 3, the thickest portions of the veins form semicontinuous steeply (60°–65°) southeast-pitching pipes where the vein is >0.5 m thick.

Vein kinematics

Veins in the Kundana mines display a well developed, shallowly north-plunging slip lineation that is manifested as slickenside grooving on the vein surface. At one locality underground at the Barkers mine, this lineation pitches 25°–35°N in the plane of the vein, and this orientation is observed throughout the mines (Fig. 3). The slip vector of the veins is about orthogonal to the trend of the thickest

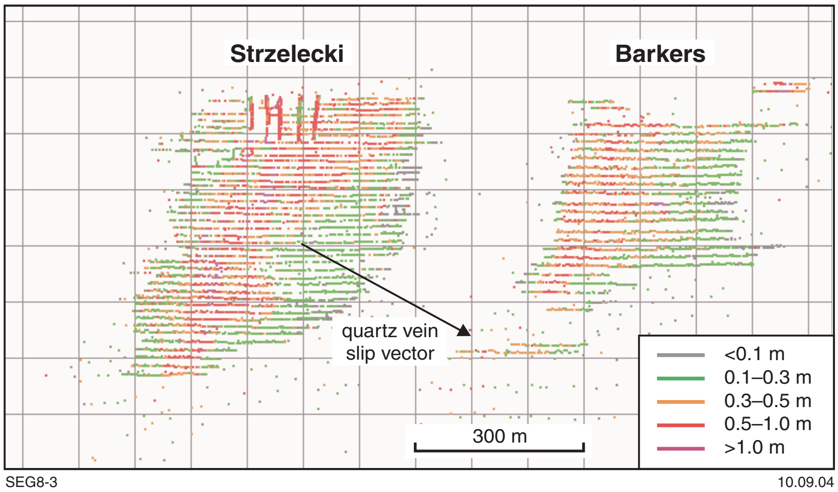

Figure 3. Plot showing variation of vein thickness (m) for the Strzelecki and Barkers orebodies

portion of the veins, suggesting that most quartz veins were emplaced with oblique movement sense (Fig. 3). Dilation and high-grade development at kinks where the vein orientation changes from 300° to 310° suggest a dextral movement sense during the vein formation. However, the sense of offset is equivocal, and clear kinematic indicators are lacking (Hadlow, 1990). Preferential opening along the fault produced a dilational jog and probably facilitated thick quartz precipitation at 90° to the slip vector, with minor development of breccia and fault cataclasite typical of extremely high fluid pressures (Sibson, 1987).

Gold distribution

The distribution of gold grade is erratic in the Barkers and Strzelecki veins (Fig. 4), and, whereas the very high grades apparently show no direct relationship to vein thickness, the presence of gold grades >10 g/t correlates with a vein thickness of >0.1 m. There are small, localized, very high grade shoots with steep to vertical northerly pitches (Fig. 4) in the extreme northern and southern ends of both orebodies. This orientation of the highest grades does not appearto be related to the ductile shearing even though the high grades are subparallel to the principal stretching lineation in the Zuleika Shear Zone. In several areas in the Barkers mine, small thin shear bands transgress the laminations within the ore vein, suggesting a later timing for the shear bands. Microstructural analysis confirms the siting of gold in these early and late shear laminations, and reveals crucial timing relationships for the vein emplacement, ductile shearing, and ore deposition.

Importantly, the orebodies do not occur within the Zuleika Shear Zone, but are totally contained within

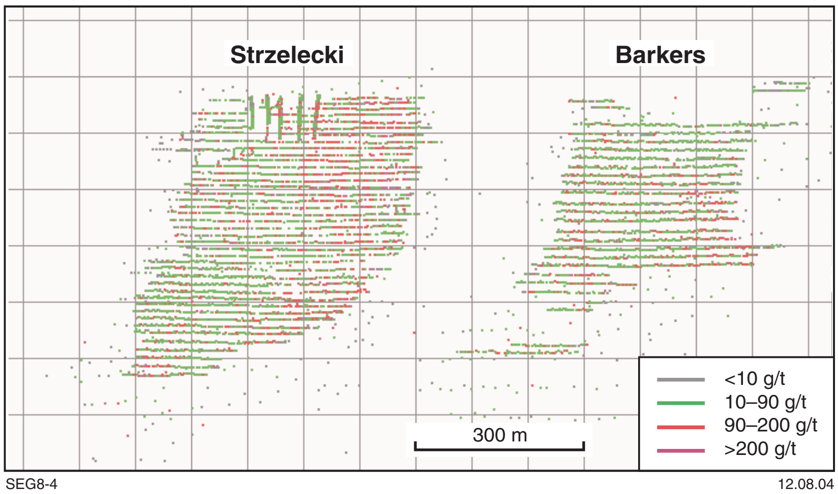

Figure 4. Plot showing variation of gold grade (g/t Au) for the Strzelecki and Barkers orebodies

andesite–dolerite contacts in the wallrocks of the shear zone (Barkers and Strzelecki) or graphitic shales very close to the shear zone (South and North pits). This distinction may seem irrelevant, but the vein kinematics and emplacement geometry (Barkers and Strzelecki) indicate that mineralization either pre- or postdates the ductile shearing. Also, the orientation of the Zuleika Shear Zone is subvertical to easterly dipping, whereas the andesite–dolerite contacts dip moderately southwest. Clearly, the stratigraphic horizons would have failed in a ductile fashion during reactivation (e.g. enforced shearing; Robert et al., 1994), and the emplacement of veins during such movements would have produced the characteristic brittle–ductile deformation style. The South and North orebodies could have had a closer relationship to the Zuleika Shear Zone since they are developed in veins on sheared black shale contacts near the high strain zone. The orebodies are therefore located in structures that almost certainly failed during the ductile deformation, yet this early failure was not necessarily related to their formation. The lack of coincidence between the thickest portions of the veins and the highest grade areas indicates that some other factor controlled the location of the high grade oreshoots. Later shear laminations that crosscut the veins could provide this connection.

Hadlow (1990) advanced an alternative hypothesis, observing that the highest grade portions of the South pit were located where 345°–350°-trending intense foliation zones intersected the main vein or contact. These foliation zones appear to be approximately axial planar to shallowly south-plunging tight to isoclinal folds in the wallrocks of the South pit (Fig. 5). The folds in this exposure are developed in black shale and chert, and plunge 20°→150°. This fold orientation is parallel to the regional F_2 folds, and the folds are the same generation as those observed in the Arctic open pit that plunge steeply north near the Zuleika Shear Zone. From these observations, it is interpreted that the east-northeast–west-southwest shortening of D_2 produced upright F_2 folds that were progressively rotated into parallelism with the principal extension direction of the finite strain ellipsoid as strain was partitioned into ductile shear zones. These folds could have induced anisotropy at the mine scale, localizing the high grade oreshoots in the veins. At a regional scale, the small anticline in the Powder Sill could have induced the anisotropy that altered regional strain and fluid flow patterns, and focused fluids into the actively deforming black shale horizons.

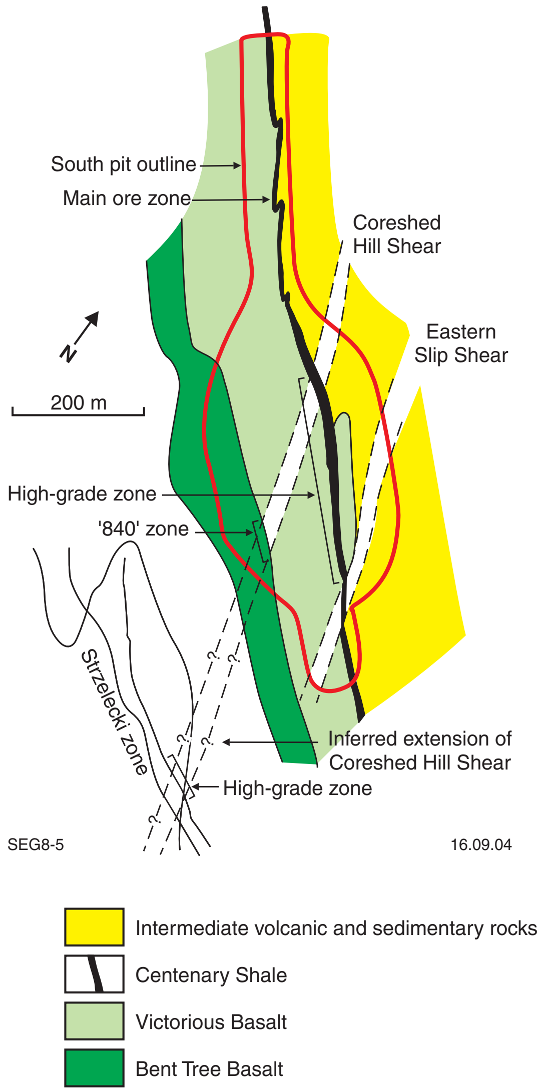

Figure 5. Schematic diagram of the South pit showing the intersection geometry of the Coreshed Hill Shear with the main ore zone, producing a localized high-grade shoot. Diagram oriented to local grid (from Hadlow, 1990)

Rubicon mine geological setting

Stratigraphy

The stratigraphy preserved at Rubicon (Table 1) represents a transition from mafic volcanism to sedimentation and felsic–intermediate volcanism. Formations exposed in the mine include the Bent Tree and Victorious Basalts of the Grants Patch Group, and the Centenary Shale and Spargoville Formation turbidites of the Black Flag Group. Strata of intermediate composition present in the Spargoville Formation are interpreted as crystal and lapilli tuffs since they grade into adjacent metasedimentary rocks. Major bedding contacts dip steeply to the west (Fig. 6), indicating that the stratigraphic sequence is slightly overturned, with Victorious Basalt geometrically overlying the Black Flag succession.

Bent Tree Basalt

The Bent Tree Basalt is not well exposed in the mine, but is present in the upper reaches of the western wall of the pit. The contact with Victorious Basalt is planar and intensely sheared, locally with dismembered slices of the Centenary Shale (also known as K2 black shale horizon) along the contact. The Bent Tree Basalt is massive, pillowed tholeiitic basalt that is locally doleritic with flow layering.

Table 1. Stratigraphic correlation of rock successions across tectonostratigraphic domains of the Kalgoorlie Terrane (modified from Swager et al., 1990). The red boxes show the sections of regional stratigraphy from Ora Banda and Coolgardie Domains exposed in the Rubicon mine

Stratigraphic succession	Characteristic rock types	Ora Banda Domain	Kambalda Domain	Coolgardie Domain	Boorara Domain
Polymictic conglomerate unit	Polymictic conglomerate, immature sandstone: coarse trough cross beds, graded beds	Kurrawang Formation	Merougil Conglomerate	Absent	Absent
Felsic volcanic and sedimentary unit	Felsic volcaniclaastic sedimentary rocks, ranging from coarse-clastic sandstone to interbedded sandstone or siltstone. Rhyolite to dacite, locally andesite; lava, tuff, agglomerate	BLACK FLAG GROUP: Pipeline Andesite; Orinda Sill; Ora Banda Sill	BLACK FLAG GROUP: Junction Dolerite; Condenser Dolerite; Golden Mile Dolerite; Triumph Gabbro	BLACK FLAG GROUP: White Flag Formation; Powder Sill; Spargoville Formation	Felsic unit, volcanic and sedimentary rocks
Upper basalt unit	High-Mg and tholeiitic basalt; massive, pillowed, and vesicular lavas	GRANTS PATCH GROUP: Victorious Basalt; Bent Tree Basalt; Mt Pleasant Sill; Mt Ellis Sill or Enterprise Dolerite	KALGOORLIE GROUP: Paringa Basalt; Defiance Dolerite; Williamstown Dolerite	COOLGARDIE GROUP: Absent or thin and discontinuous	Absent or thin and discontinuous
Komatiite unit	High-Mg basalt at top then thin komatiite flows with minor interflow sedimentary beds, overlying thicker komatiite flows and/or massive olivine adcumulate	LINGER AND DIE GROUP: Big Dick Basalt; Siberia Komatiite; Walter Williams Formation	Devon Consols Basalt; Kambalda Komatiite	Hampton Formation	Highway ultramafics
Lower basalt unit	Thoeliitic and high-Mg basalt flows, subaqueous	POLE GROUP: Missouri Basalt; Wongi Basalt	Lunnon Basalt	Golden Bar Sill; Burbanks Formation; Three Mile Sill	Scotia Basalt
References		Witt (1987, 1994) Gregory (1998) Harrison (1983,1984, 1987)	Roberts (1988) Woodall (1965) Langsford (1989) Cowden and Archibald (1991)	Hunter (1983)	Christie (1975) Witt (1994)

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Victorious Basalt

The Victorious Basalt is a distinctive regional marker unit of plagioclase-phyric tholeiitic basalt. The rock is distinguished by coarse phenocrysts of white plagioclase (up to 6 cm in diameter) in a dark basaltic groundmass (Fig. 7), and forms a uniform layer up to 100 m thick. Locally, the unit is pillowed with internal igneous flow layering. The upper contact of Victorious Basalt forms the major ore horizon in the mine. The basalt at this contact is sheared, with intense ductile strains recorded by stretched phenocrysts. Other significant shear zones throughout the unit anastomose and link with heterogeneous strain distribution. These shear zones are chlorite rich near the main lode, but contain no significant mineralization.

Centenary Shale (K2)

The Centenary Shale forms a regionally continuous unit, typically 1.5 m thick but up to 10 m thick in places (Fig. 8). The shale is a carbonaceous sedimentary horizon, locally discontinuous, that is replaced by disseminated

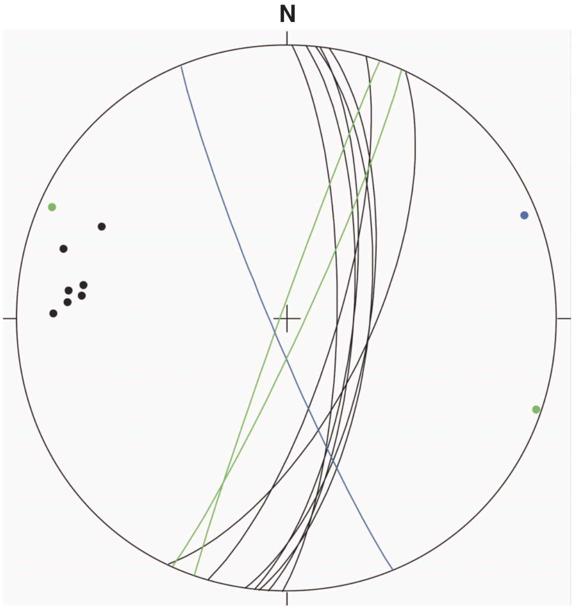

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Figure 6. Stereogram of bedding measurements at Rubicon. Black = S_0 in sedimentary rocks; green = Victorious Basalt – sedimentary rock contact; blue = Victorious Basalt – Centenary Shale contact

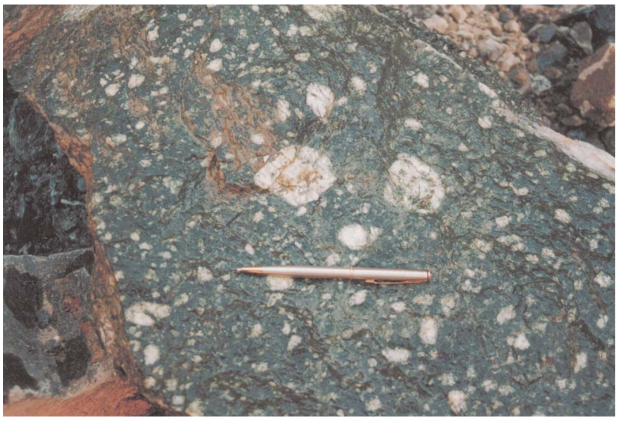

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Figure 7. Plagioclase megagrysts in porphyritic Victorious Basalt

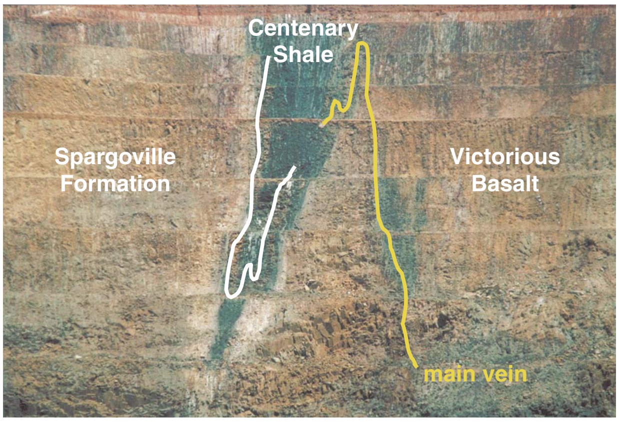

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Figure 8. Infold of Centenary Shale in the footwall of the main stratigraphic contact. The wedge of black shale is within turbidites and contains a section of folded cherty siliceous material that could include fragments of the main vein. The structure is similar to a geometry described in the South Pit by Hadlow (1990)

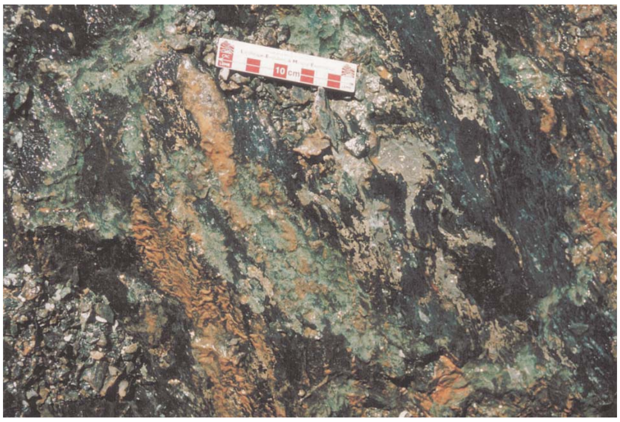

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Figure 9. Detail of the chaotic internal structure of intensely sheared and chloritized Centenary Shale near the main vein

arsenopyrite, pyrrhotite, and biotite with extensive quartz–pyrite vein emplacement, and chlorite alteration near the vein (Fig. 9).

Sections through the shale show discrete thrust faults with mesoscale hangingwall anticlines in pyritic and sedimentary layering, indicating significant thrust movement on the shale. The folds have a penetrative axial planar cleavage, and this cleavage is deformed locally by a spaced crenulation cleavage. Core intersections show layers of pyrite folded and dismembered within an intensely sheared shale matrix. Stacked cross sections show the complexly folded and sheared shale that is locally dismembered and discontinuous on the scale of tens of metres (Fig. 10). This erratic distribution must be carefully considered when extrapolating between intersections of the shale in exploration drill-holes.

Spargoville Formation

Spargoville Formation rocks at Rubicon are mostly fine-grained psammopelites, now quartz–chlorite and quartz–biotite schists that are relicts of original finely bedded turbidites; the turbidites also contain rare horizons of black shale (Figs 11 and 12). Primary textures are locally preserved, with graded bedding and scour-and-fill structures. The fine grained rocks also have interbedded crystal-rich tuffs, with plagioclase–hornblende composition, that appear to be intermediate flow rocks in hand specimen, but are polymictic and gradational in contact with the psammopelites, indicating a sedimentary origin (Fig. 13).

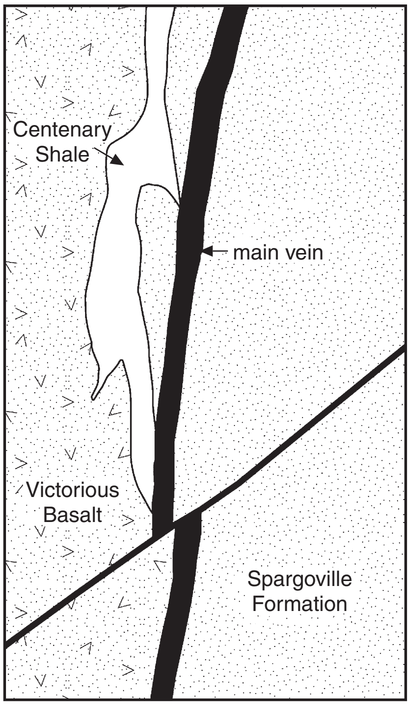

Figure 10. Schematic cross section (looking north) at 5732N (mine grid)

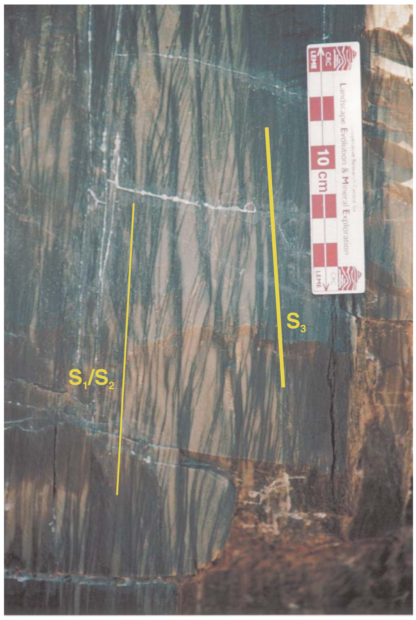

Figure 12. S_1 and S_2 fabrics display minor angular discordance, even using a hand lens, but are cut and reoriented by the S_3 shear bands, which also displace the fold limbs in S_0

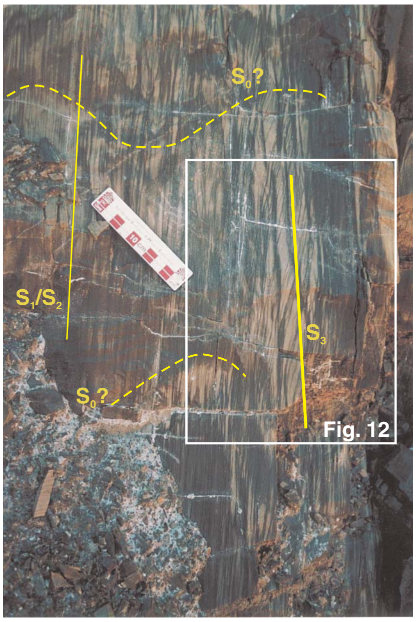

Figure 11. Cleaved metasedimentary rocks with ?bedding S_0 folded into upright folds with S_1/S_2 axial planar cleavage and a later overprinting S_3 discrete shear fabric. Bedding is defined by compositional layers in the rock, possibly remnants of quartz- and mica-rich bedding

Figure 13. Folded carbonate–quartz vein with S_1 axial planar foliation and sericite–carbonate alteration halo. Note the necking and boudinage of the vein in the limbs of the microfold. The polymictic host rock is clastic and of volcaniclastic or ?sedimentary origin; view to the south

Structural geology

Folds

Mesoscopic folds are present but poorly preserved within metasedimentary rocks near the contact with Victorious Basalt. Intrafolial, isoclinal folds indicate significant transposition of bedding into parallelism with the S_1 cleavage, indicating a high degree of shortening of the sequence. These folds, developed on a centimetre scale, are the only folds evident in the pit, with the exception of a large infold of Centenary Shale within the Spargoville Formation turbidites. Mine-scale folding is suggested by folded foliations in the southern pit wall. Cleavage–fold relationships indicate that the mesoscale folding is probably representative of the regional-scale structure.

Foliation

Two main foliations are present in the Rubicon pit. The observations below refer mainly to sedimentary rocks of the Black Flag Group, since the foliation is pervasive in these rocks. The two foliations in the sedimentary rocks are closely related in orientation but have significantly different morphologies. Discrete high-strain zones locally disturb foliations in the Victorious Basalt.

S_1–S_2

S_1 is a continuous cleavage defined by slivers of biotite or chlorite in the psammopelites (Figs 11 and 12). The foliation is penetrative at all scales and defines the gross rock structure where intensely developed, locally forming a slaty cleavage. S_2 is a discrete cleavage that overprints S_1 but, due to the closeness of orientations between the two foliations, does not crenulate S_1. The rocks have a banded appearance in areas where S_2 is well developed, which, on closer inspection, is defined by discrete laminae of biotite or chlorite spaced at about 1–5 mm, at a small angle to S_1. S_2 could represent a stronger partitioning of strain that overprints S_1. The similar orientations of S_1 and S_2 are common throughout the district (Fig. 14), but the two foliations are distinguished by their morphologies.

Shear zones

High strain zones

Several significant high-strain zones are localized within the Victorious Basalt. These zones anastomose and vary from 1 to 20 m in thickness. The shear zones trend 66°/030° on average (Fig. 15), intersecting the main ore contact at an angle of about 20°. This relationship is also observed in diamond drillcore where the immediate wallrocks of the ore zone are sheared, but the shear foliation has an angular relationship with the ore vein: the ore vein cuts the foliation (Fig. 16). These hanging- and footwall shear zones appear to control the emplacement of splay veins that are well mineralized, and their presence in the Rubicon pit where high grades are localized in the main lode is similar to a relationship observed in the South pit by Hadlow (1990).

Shear zones in the Victorious Basalt have strong, steeply north-plunging stretching lineations with an average plunge of 66°→360° defined by elongate plagioclase phenocrysts and mica films on the surface of the foliation (Fig. 17). In one exposure, the S–C fabric relationships indicate a dextral-normal movement sense on the shear zone. Veins within these shear zones are sheared and boudinaged within the ductile fabric, which wraps vein boudin terminations.

Stretched plagioclase phenocrysts have no consistent asymmetry, but are typical of a bulk flattening with ellipsoids in all XYZ sections. Towards the margins of these shear zones, lens-shaped lithons of Victorious Basalt are surrounded by intensely sheared rock as the shear zone tapers into massive basalt. Sheared zones are overprinted by a flat vein array that persists throughout the pit.

Shear vein arrays

Several shear vein arrays are mapped in the open pit (Figs 18 and 19). The arrays have classic sigmoid geometries forming stacked veins sets along a shear plane. The vein tips preserve the original opening orientation of the cracks and the direction of σ_1, but, with subsequent shearing, the central portion of the veins has been

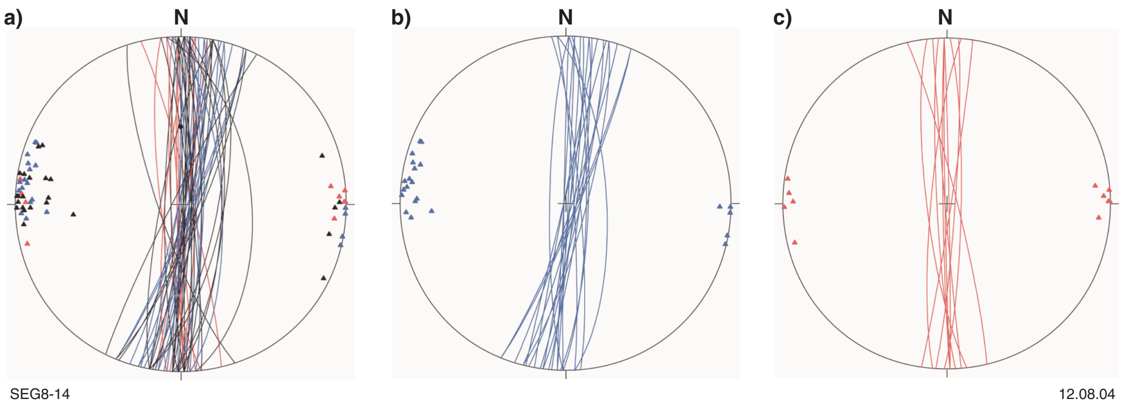

Figure 14. Stereograms showing: a) all foliations; b) S_1 penetrative cleavage; and c) S_2 spaced cleavage. Black = foliation; blue = S_1; red = S_2

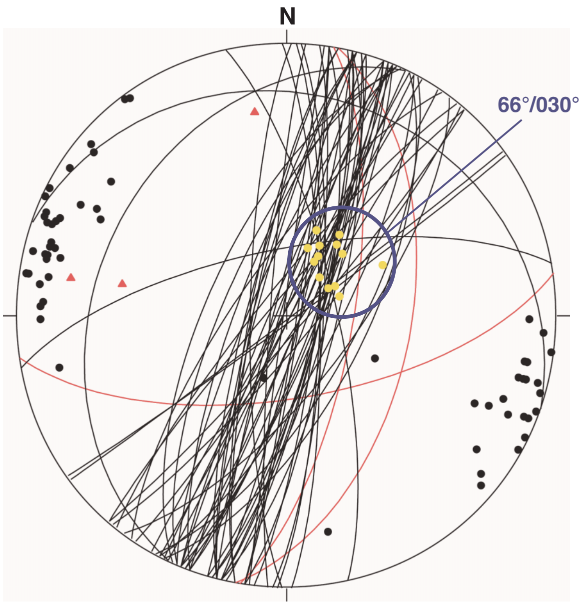

Figure 15. Stereogram of shear zones measured in the Rubicon pit. The shear zones have a mean orientation of 84°/107°, with strong steeply northeast-plunging stretching lineations (yellow dots) that trend 66°→030° on average

Figure 16. Margin of the main vein against sheared, chloritic, and pyritic Centenary Shale

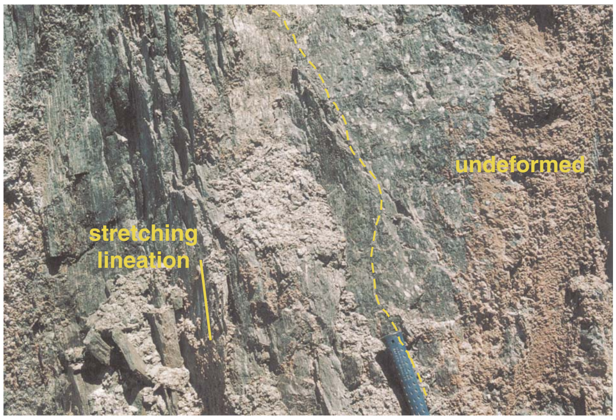

Figure 17. Intense ductile shear zone in Victorious Basalt. Hammer handle delineates the margin of the shear zone with undeformed porphyritic basalt, showing the highly partitioned nature of the strain. A strong steeply north-pitching stretching lineation is visible on the shear surface

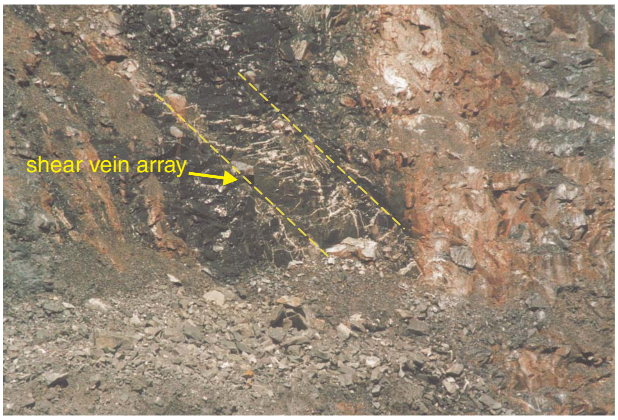

Figure 18. Shear vein array developed in metasedimentary rocks; the veins are sigmoid in the plane of the wall, hence the view is oblique to the shear plane. The vein geometries indicate a sinistral shear sense in a subvertical plane striking 080°; view to the southeast; field of view about 5 m

progressively reoriented. Geometric analysis of shear vein arrays allows the shear sense to be determined at the time of deformation of the vein array. Shear vein arrays developed in turbidites in the footwall of the White Foil Fault display a conjugate geometry indicating formation during east–west shortening, which matches that predicted for the formation of the White Foil Fault. The veins are quartz–tourmaline–biotite–pyrite veins, with strong, narrow carbonate–muscovite alteration halos and sigmoid geometry. A small shear vein array in the hangingwall of the orebody deforms the late low-angle vein and fracture set, with a top-to-the-southeast normal shear sense (Fig. 19). This array distorts both the upright shear foliation, and flat veins that crosscut the foliation.

Cross faults

One major cross fault and several minor faults crosscut the ore horizon at high angles. The major cross fault is interpreted, from aeromagnetic imagery (Figs 2 and 20), to be the strike extension of the White Foil Fault.

The White Foil Fault is a zone of brittle–ductile deformation up to 6 m wide, with about 11 m of apparent dextral offset of the main ore horizon in plan view. Apparent offset at the mine is significantly less than the offset of stratigraphy at the camp scale, which is up to several hundred metres, and this indicates a variable displacement along the strike extent of the White Foil Fault (Fig. 2). The offset is sharp and apparently brittle, whereas internally the fault contains a ductile foliation in stretched phenocryst basalt. The mine geologist has confirmed that the fault is not mineralized, and forms a

Figure 19. Shear zone deforming flat veins in the Victorious Basalt. The flat veins dip to the south, and are deformed by a shallowly north-dipping shear zone with reverse shear sense; view to the west; field of view about 3 m. The shearing could be a continuation of the same shortening event that led to vein formation

'dead zone' in the ore blocks, hence its timing is probably late with respect to mineralization.

The kinematics is difficult to determine, but the internal foliation contains a lineation pitching 55°→045° and defined by stretched plagioclase phenocrysts. This stretching lineation appears to be developed mostly on S-foliations within the fault, and may not be indicative of the movement vector. Veins and exposed C-planes of the fault have a shallowly east-pitching slickenside and mica lineations that probably indicate the true movement sense. Several cross faults oriented parallel to the White Foil Fault affect the ore. These faults have both sinistral and dextral apparent offsets in plan view, but their offsets are of the order of 1–2 m, indicating that they are not significant at the drive scale.

Rubicon mineralization

Main vein

The main vein at Rubicon is a laminated shear vein up to 1.2 m thick, but is generally 0.3–0.8 m in thickness (Fig. 21). The vein dips west and is locally overturned to the east, but maintains a very steep dip of 75–85° (Fig. 22). The foliation in the wallrocks is typically truncated against the vein, but in places the foliation bends into the vein with a reverse deflection sense (Fig. 16). The main vein has laminated margins, with that on the vein footwall being wider and more intense than shear laminations on the hangingwall (Fig. 23).

The ore zone comprises the vein, and mineralized footwall stockwork veins and breccia zones, producing a total width of up to 5 m (Fig. 24). Black shale in contact with the main vein is intensely altered to green chlorite with abundant disseminated, fine-grained pyrite and coarse-grained arsenopyrite. The vein contains coarse-grained disseminated galena, sphalerite, scheelite, and gold. Arsenopyrite in the vein is usually contained within black shale slices that have spalled from the wallrocks during vein formation. The sulfide species (arsenopyrite) reflects the highly reducing nature of the carbonaceous shale, rather than the presence of a distinct ore fluid.

Folding, conjugate microfaulting, and stylolitization deform laminations in the vein. In polished slabs, the gold is located along all of these microstructures, but particularly along those that disrupt laminations, indicating a late timing for gold precipitation (i.e. post vein formation).

Other veins

Several other vein sets are present in the Rubicon pit, including footwall stockwork veins, shear vein arrays, splay veins, and wallrock veins. Shear vein arrays are discussed above (see **Shear zones**).

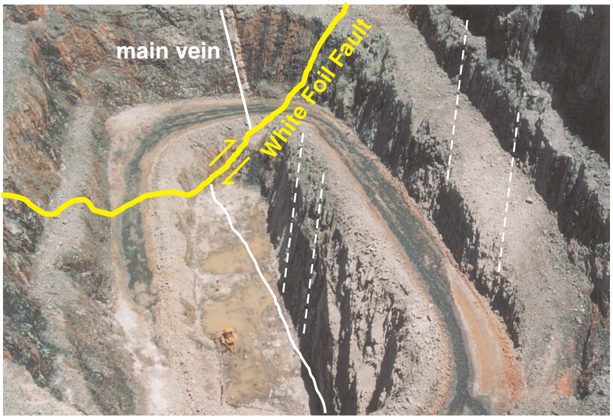

Figure 20. Location of the White Foil Fault at the southern end of the pit. Note the angular relationship between hangingwall shear zones (delineated by white dashes) in the Victorious Basalt and the main vein

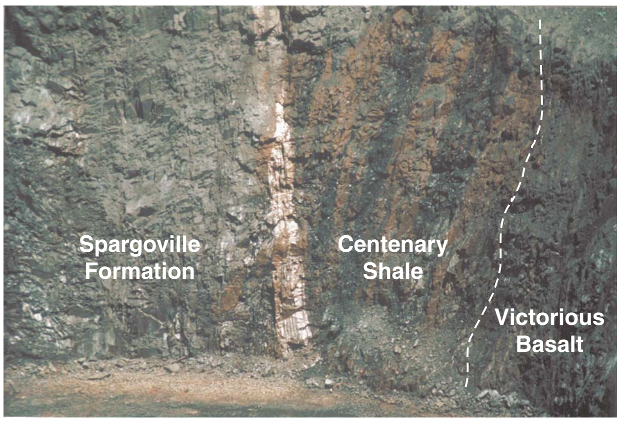

Figure 21. Main vein at the contact between Centenary Shale and Spargoville Formation sedimentary rocks; view to the south; field of view about 10 m

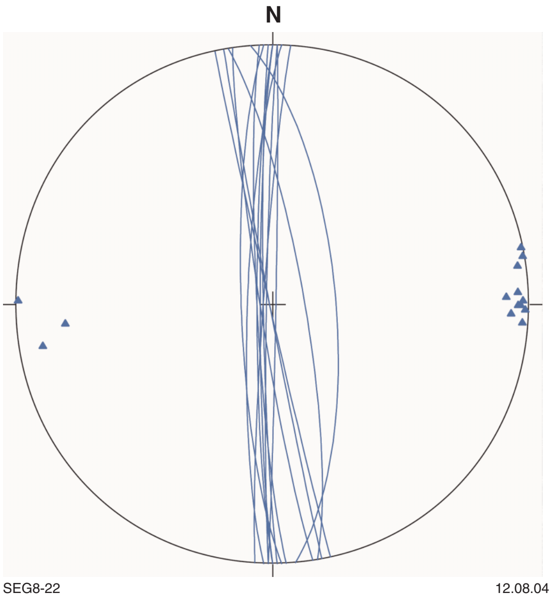

Figure 22. Stereogram showing the steep westerly orientation of main vein contacts

Figure 23. Laminated main vein. The dark banding is sheared spalls from the Centenary Shale wallrocks included in the quartz vein

Figure 24. Stockwork veins (delineated by yellow lines) in the footwall of the Rubicon main vein. Most veins dip steeply east with an angular discordance against the main vein; view to the north; field of view about 6 m

Stockwork veins

Stockwork veins are generally developed in the footwall of the main vein, with several well-defined average orientations (Fig. 25), and comprise crack-fill type veins (with little or no internal structure) and laminated shear veins. Footwall stockwork veins in drillhole URD044 are distributed over 25 m in three main clusters of gold-bearing veins, with a common intersection point of 14°→173° (Fig. 25).

Each cluster represents one of the three main ore-stage orientations, but the recorded veins have mineral assemblages typical of the post-ore stage veins, which are quartz–tourmaline(–actinolite). Throughout the stockwork, the highest gold grades are associated with quartz–tourmaline veins. Hence, there could be more than one phase of tourmaline vein emplacement; i.e. an early stage with gold, and a later stage postdating gold (Fig. 26).

The common intersection point of these three vein sets plunges at about 90° to the average stretching lineation of ductile shear zones in the pit. This relationship suggests that mineralization was synchronous with the shearing that disrupted the main Rubicon ore vein, and generated mineralized footwall stockworks. Such an interpretation fits with observations of the main vein being best mineralized where it is most disrupted at both macro- and microscales. Hence, stockwork formation in the footwall and mineralization was broadly synchronous with the main ore stage at Rubicon.

Flat veins

A significant array of flat veins is present in both the hanging- and footwalls of the Rubicon main vein (Figs 27

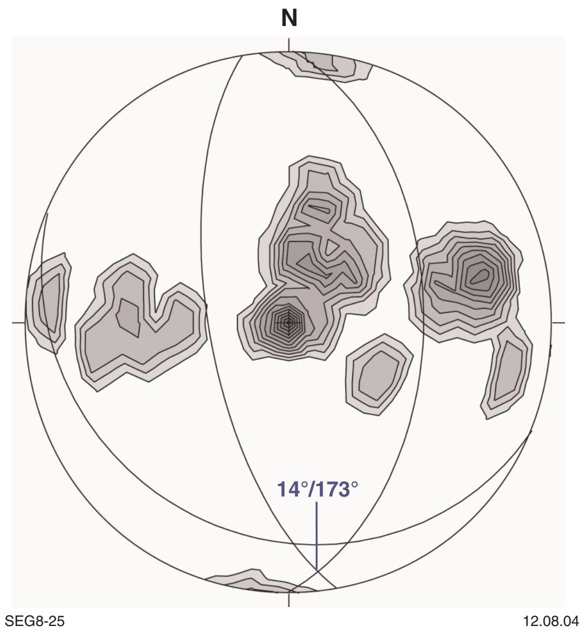

Figure 25. Contoured stereogram of footwall stockwork veins from drillhole URD044 showing a common intersection direction of 14°→173°

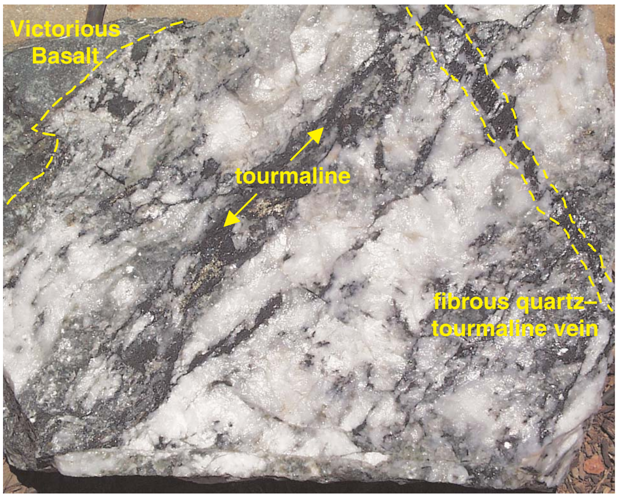

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Figure 26. Slab of main vein showing extensive tourmaline replacement of laminations, and late fibrous quartz–tourmaline veins that cut the main vein fabric at a high angle

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Figure 28. Flat veins in Victorious Basalt, spaced at 0.5–1 m; view to the west; field of view about 10 m

and 28). The veins are 0.5–50 mm thick and are crack-fill type, with no evidence of crack-seal texture or lamination. Flat veins form a well-defined set dipping 22°/240°, and have a geometric relationship typical of vein systems hosted by reverse faults. These veins are part of the main ore stage generation containing quartz–tourmaline–?K-feldspar.

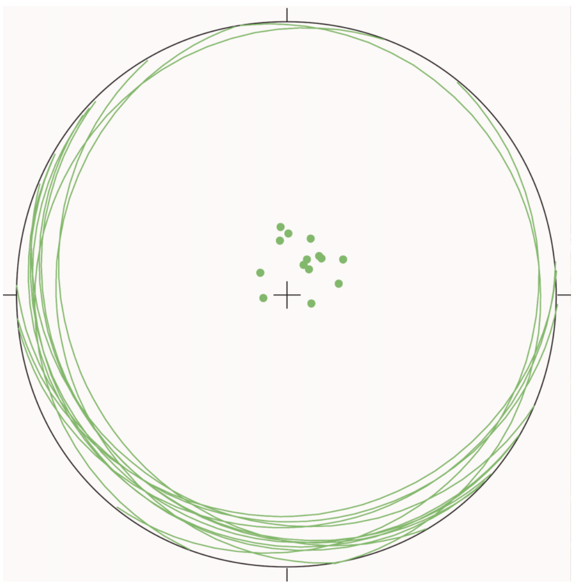

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Figure 27. Stereogram showing the shallowly southward dip of flat veins in the wallrocks of the Rubicon main vein

Splay veins

Splay veins are developed mostly in the hangingwall of the main vein. They are shear laminated at 10–20 cm in thickness, and splay into the main vein at a small angle (10°–20°). Splay veins are well mineralized and effectively widen the ore zone over small distances.

Wallrock veins

Other wallrock veins include the many shear vein arrays throughout the pit and several thin but remarkably continuous veins that traverse the western wall within Victorious Basalt. Reports from the mining crew indicate some visible gold in these veins, but they are volumetrically minor and do not form mineable ore zones.

Summary

Having multiple vein types and orientations at Rubicon results in a situation where the main laminated vein is not the only ore zone of interest in the system. As a consequence, the ore zone is up to several metres wider than the laminated vein, particularly in areas where splay veins intersect the main vein, or where footwall stockworks are particularly dense. A shallow southerly plunge of the footwall stockwork intersection results in a subhorizontal oreshoot that should be investigated for exploration potential underground away from the main ore horizon. Exploration drilling indicates that these oreshoots have a small to moderate size (i.e. less than 80 × 80 m).

Structural timing and interpretation

The timing and paragenetic history suggest continuous regional shortening and vein deformation, punctuated by episodes of fluid overpressure. Kinematic interpretations do not indicate major reorientations of the principal shortening direction between deformation phases. It is possible that earlier formed structures were reactivated at each successive phase of regional shortening because the shortening direction was apparently consistent: this reactivation could include foliation reactivation, fold tightening, and fault or shear reactivation, and further vein deformation.

Summary and conclusions

The location of the main Rubicon ore vein was controlled by a complex sequence of events. Significant shortening of the rock sequence and deformation of the K2 black shale horizon pre-dates emplacement of the main vein. Subsequent deformation of the vein appears to coincide with the mineralization events in several stages. Strain partitioning and fabric intersection appear to be major controls on the preparation of the ore structures and subsequent location of high grade oreshoots. Cross faults have a late timing, lack gold and alteration, and probably had no significant influence on the location of the main vein.

Stratigraphic facing indicates an overall eastward-younging, slightly overturned sequence in the Rubicon pit. The Victorious and Bent Tree Basalts are significantly thinner in this exposure than elsewhere in the Ora Banda Domain: thin stratigraphic units could reflect structural thinning or original unit thickness at the basin margin. Infolded black shale and chert structures are common in the location of ore zones along the K2 horizon. These infolds appear to coincide with the intersection of high strain zones in the wallrocks with the K2 horizon. It is unclear whether the infolds are produced by strain partitioning in areas where rigid chert bands are present along the K2, or at the shear intersections. Alternatively, the shear zones could have been localized where the infolds cause perturbations in the regional strain field. It is possible that these structures were also instrumental in localizing the later cross faults.

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