Controls on Gold Endowment: Shear Zone Comparison

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Summary

Field observations suggest that a variety of rock types provides a positive environment for gold deposition, because it provides local zones of dilation as a result of competency contrast, as well as chemical gradients to trigger gold deposition. Field observations, supported by theoretical arguments suggest that competency contrast is strongest at greenschist facies temperatures and decreases at amphibolite facies. This is because at greenschist facies phyllosilicate-rich rocks flow viscously, while coexisting quartz- or feldspar-dominated rocks tend to behave in a brittle fashion. Greenschist facies gold deposits in the Norseman-Wiluna Belt provide numerous examples of this contrast, where granite dykes or dolerite sills are intensely fractured while surrounding talc-schist is strongly sheared.

It is in fact this contrast in behaviour and strength at greenschist facies that ultimately leads to gold deposits because such competency contrasts give rise to local strain incompatibility, and rock rotation during shearing, increasing permeability in dilational zones, particularly close to contacts, and focusing mineralizing fluid flow. At amphibolite facies, by contrast, phyllosilicate schists may be strengthened in comparison to other rocks by the growth of amphiboles and feldspars, or grain size coarsening; while quartz- and feldspar-dominated rocks are weakened and start flowing as ductile materials (e.g. Tullis and Yund 1987). Thus, relatively weak schists may become strong amphibolites, while strong granites and dolerites are weakened by temperature rises. Decreased competency contrast then leads to poorly developed fluid pathways, unfocused fluid flow and impoverished gold deposits.

Three shear zones of regional significance and contrasting gold endowment were previously detailed: the Boulder-Lefroy (BLSZ), the Zuleika (ZSZ) and the Ida Shear Zones (ISZ). This section compares them, focusing particularly on the controls on gold mineralization. The main differences between the shear zones, with direct bearing on gold endowment, are their metamorphic facies, variety of rock types, and shear zone orientation.

The most endowed shear zone (BLSZ) strikes between N20º-30ºW, and cuts through a rich variety of greenschist facies rock types, folded into relatively broad antiforms with good ability to focus fluid flow. The Zuleika Shear Zone, has intermediate gold endowment, and has

many intermediate features between the BLSZ and the ISZ. It has a variety of rock types along its length, but these are very tightly folded in the vicinity of the shear zone (reducing fluid focusing ability). Metamorphic temperatures, though varied along strike, are higher than that at the BLSZ, straddling the boundary between greenschist and amphibolite facies. This leads to lower competency contrasts, with negative effects on gold mineralization. The strike of the ZSZ is curved, varying from a similar strike to the BLSZ in the south, where the larger deposits are (e.g. Cave Rocks and Kundana), to a more westerly strike in the north, with a decrease in the size of deposits (Bullant and Ant Hill). Finally, the least endowed of the three shear zones, the Ida Shear Zone runs parallel to regionally continuous layers, which define a synform within a relatively narrow corridor of strongly attenuated layers of monotonous, amphibolite facies mafic-ultramafic rocks enclosed between more competent granitic batholiths, striking approximately N10-20W. Poor gold endowment results from the combined effects of low competency contrasts, strongly attenuated layers with little variation in attitude due to strong flattening, and amphibolite facies metamorphism.

Introduction

In sections 2.3 to 2.5 our study of the Ida, Zuleika and Boulder-Lefroy Shear Zones have been fully described. Fig. 2.6.1 summarizes our findings regarding shear zone kinematics as described in previous sections and compares them with previous interpretations. Detailed comparison will be carried out in Peter van der Borgh's thesis. In this section, the shear zones will be compared (Table 1) focusing on the influences of different shear zone characteristics on gold endowment.

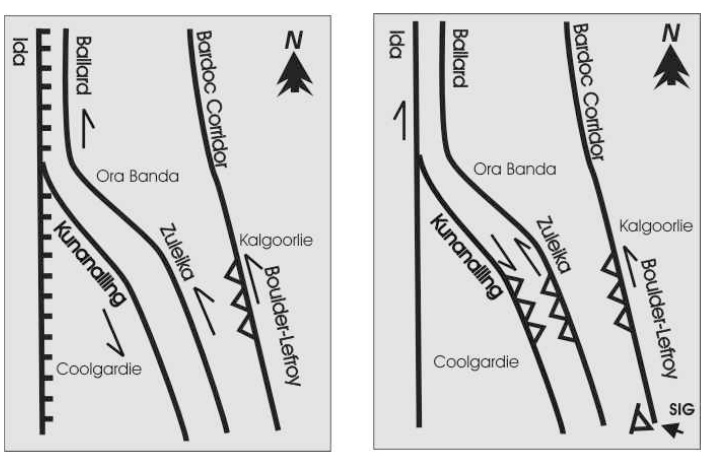

Fig. 2.6.1. a) Kinematics of major shear zones in the Kalgoorlie Terrane as previously reported (Hunter 1993, Swager 1989; Swager et al 1997); b) revised kinematics as detailed in this report and derived from mine-scale structural analyses. The Boulder-Lefroy Shear Zone has a composite history of thrusting and sinistral strike slip. Opposite thrusting directions at Kundana and Kunanalling suggest a pop-up structure. The Ida Shear Zone has a persistent gently

plunging lineation but ambiguous sense of shear due to intense flattening and no evidence for normal faulting.

Spatial distribution of lithologies and variety in contact and structure orientation generally provide a positive environment for gold mineralization. This is because complexity provides increased possibilities of fluid focusing as a result of geometries and variety in rock permeability and strengths, plus it provides a number of possible local chemical gradients that may saturate gold in the fluids. Our efforts to quantify complexity through fractal dimensions will be described in Section 3, here we focus first on the distribution of lithologies around the three shear zones, and subsequently we focus on the role of competency contrast on gold mineralization in creating zones of dilation and focusing fluids.

Competency Contrast

The role of competency contrast in gold mineralization is to increase rock permeability and focus fluid flow. Competency contrast results in strong variations in stress and strain gradients leading to heterogeneous flow close to lithological contacts, fracturing of competent rocks, development of strain shadows, boudin necks or the opening of foliation in incompetent rocks through rotation. In other words, competency contrast disturbs regional stresses giving rise to local zones of dilation and fluid focusing at or close to contacts.

Empirically, it was found that extreme competency contrast between rock types plays a very important role in gold deposition, with a majority of gold deposits in the Norseman-Wiluna Belt having within the mineralized structure either a strongly competent rock (e.g. porphyry dyke, dolerite/gabbro) or an obviously weak, low viscosity schist (e.g. talc schist, shale).

The importance of extreme competency contrast for mineralization should not be underestimated. A simple count of the number of deposits containing sheared ultramafic rocks in contact with more competent rocks in the immediate vicinity of gold mineralization yielded that >60% have ultramafic schist recorded as either the footwall or hangingwall to ore, while <20% record ultramafic as the principal host (n=68). This number increases further when incompetent shales are also counted. Similarly, competent granitic intrusions are so common in gold deposits of the Yilgarn that even a possible genetic relationship to gold has been proposed. In our view their role of either ultramafic rocks or granitic rocks in the mineralization is unrelated to the origin of fluids or gold, but directly related to the origin of high permeability pathways and fluid focusing.

Metamorphic facies has an important effect in decreasing the relative competency contrast of rocks. This is due to the combined effects of the marked weakening of quartz- and plagioclase-dominated rocks (such as granites and dolerites/gabbros) as temperatures rise from 300 ºC to 500ºC; and the strengthening of schists by the metamorphism of phyllosilicate minerals into amphibole or plagioclase rocks. The strengthening of ultramafic rocks may be exemplified by comparing the highly sheared and stretched ultramafic rocks common in greenschist facies deposits, with boudinaged layers of ultramafic rocks in amphibolite facies exposures (Fig. 2.6.2; e.g. at Chadwin, northern ZSZ; Iguana, ISZ).

Thus, we argue further that the reduced endowment of regions dominated by amphibolite facies rocks may be directly related to decreased competency contrasts leading to more homogeneous flow, with decreased opportunity for the creation of high permeability dilational zones during deformation.

Fig. 2.6.2. Boudinaged narrow layer of ultramafic rock within amphibolite at Iguana on the immediate vicinity of the ISZ.

Lithological Complexity

The ISZ is the least endowed of the three shear zones (Table 2.6.1). It runs parallel to a relatively simple and continuous stratigraphic sequence, composed of monotonous mafic and ultramafic rocks. The stratigraphy is highly attenuated through intensive flattening, so that at the scale of regional maps, complexities are erased (Fig. 2.6.3a). Also through intense flattening, any primary angular discordances have been rotated towards parallelism with the regional trend. In contrast, the Zuleika and Boulder-Lefroy Shear Zones have a wide variety of lithologies in its surroundings, and there are both jogs along strike, plus a number of internal angular discordances, such as caused by cross-cutting intrusions, and folds cut by shear zones.

While all three shear zones have numerous granitic dykes (porphyries) and differentiated mafic sills, the sills are more voluminous and locally fractured and brecciated in the vicinity of the ZSZ and BLSZ, and smaller and sheared along the ISZ. Another significant difference is the lack of carbonate alteration along the ISZ in contrast to extensive alteration along the BLSZ. This difference could be an effect of the higher temperatures of metamorphism and alteration within the Ida Corridor and the decreased stability fields of carbonate minerals in equilibrium with basalts and metamorphic fluids.

In contrast to the ISZ, the better endowed shear zones include significant volumes of volcano-sedimentary rocks (Black Flag Group or Kurrawang Sequence) in their vicinity or within the shear zone. As discussed in Section 3, the presence of sedimentary rocks could conceivably be related to gold endowment if they have lower bulk permeability than other rock types. Black Flag Group rocks bound one side of the BLSZ through most of its length, and also crops out immediately north of Kalgoorlie along strike of the BLSZ. If these sedimentary rocks acted as low permeability seals for rising fluids, they would have focused more fluids towards the high permeability neighbouring BLSZ. For the case of Black Flag rocks along strike of the shear zone, lower permeability of the shear zone within these rocks could conceivably have caused deflection of fluids towards other high permeability zones within the shear zone further focusing regional fluids.

Metamorphic facies

Amphibolite facies rocks worldwide tend to be less prospective for gold than greenschist facies rocks (Phillips et al. 1996). This difference is likely to be a compounded result of 1) leaching of gold during prograde metamorphism, 2) less favourable P-T conditions for gold saturation, 3) less voluminous fluids (Powell et al. 1991) and 4) lower rock permeability with increasing depth (Manning and Ingebritsen 1999). To this list, we added above the more homogeneous rock flow at amphibolite facies temperatures as a result of decreased competency and behaviour contrast.

Ultramafic Rocks

Despite the relatively low volumes of komatiites and other ultramafic rocks in the terrane as a percentage of the total, their presence increases in the vicinity of the ZSZ and BLSZ (Fig. 2.6.4). At greenschist facies conditions ultramafic rocks are generally metamorphosed to talc-chlorite schists or serpentinites, both very weak rocks, which tend to focus strain. The abundance of ultramafic rocks along the trace of the shear zones probably results from a combination of strain partitioning to these rocks and them being tectonically emplaced as wedges along the shear zone.

We postulated above that ultramafic rocks, by their low viscosity compared to other rocks at greenschist facies, plays an active role in gold deposition through creating strain gradients and zones of dilation and increased permeability. This very same conclusion can be derived from Figure 2.6.3 which suggests that ultramafic rocks localize shear zones, which in turn localize regional fluid flow and gold mineralization.

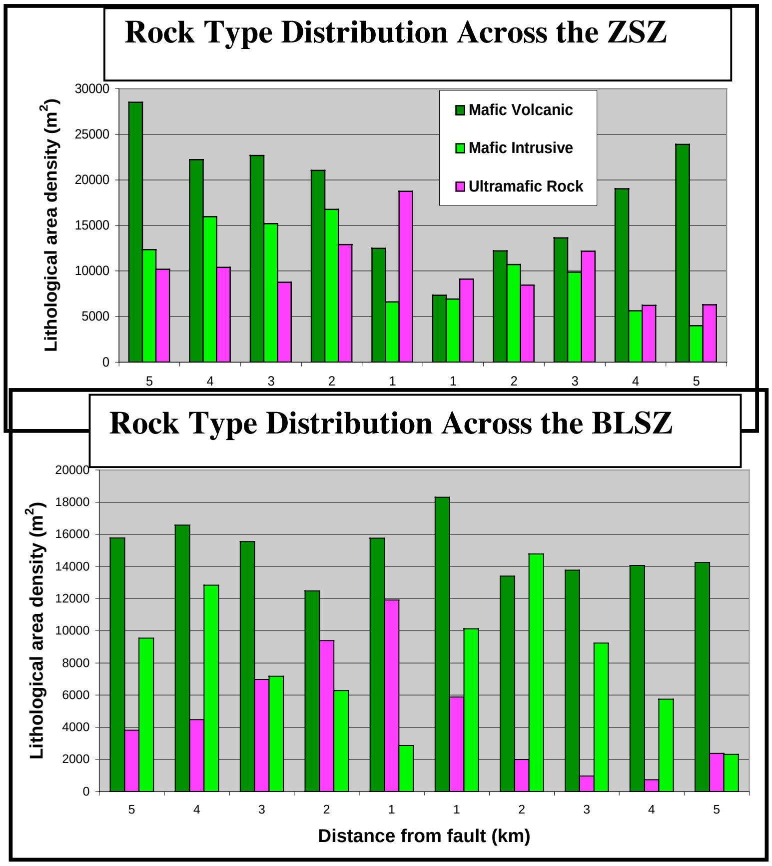

Fig. 2.6.4. Diagrams indicating the increased ultramafic rocks (purple bars) towards the centre of the Zuleika and Boulder-Lefroy Shear Zones at the expense of mafic rock types. Surface area of each rock type is plotted against distance from the shear zone, measured along the length of the shear zone. Felsic rocks have been omitted. Shear zones were either localized by ultramafic rocks, or ultramafic rocks represent tectonically slivers along shear zones.

Role of Folds

Another significant difference between the three shear zones is that the BLSZ cuts across regional, broad antiforms as exemplified by the Boomerang and Celebration Anticlines, while the ISZ runs parallel to the regional foliation and lithological contacts, and the strata in its vicinity defines a tight syncline of strongly attenuated layers. The ZSZ at Kundana defines a zone of intense fold tightening and attenuation of the stratigraphic sequence which defines the Powder Syncline to the west. A similar fold tightening has been observed on the Kunanalling Shear Zone to the west of the Powder Sill Syncline.

If, as it seems likely, antiformal fold closures provide fluid traps for mineralizing fluids and help focus regional mineralization, broad anticlines, cut by a zone of intense shearing such as in Kalgoorlie might play an important role in fluid flow, while tight anticlines like in Kundana will have a much reduced ability to disturb and focus regional hydrothermal fluids. Synforms/synclines, such as along the ISZ, might have no significant ability to focus fluid.

Shear Zone Orientation

A study of the gold content along the BLSZ as a function of its orientation, using geological maps at a scale of 1:1 000 000, found no obvious relationship between the two (Section 3.1). This could mean either that there is no such a relationship, or most likely that the relationship is hidden at larger scales and to be found in more detailed maps.

The Zuleika Shear Zone provides a good example of the controls of orientation on mineralization. Deposits along the ZSZ are generally smaller than those along the BLSZ, as a result of a number of factors. However, deposits along the ZSZ north of Kundana (Zuleika N), where the shear zone trends predominantly N50^{o}W, are generally small (~1 t Au), whereas from Kundana to the south (Zuleika S), where the shear zone trends N20^{o}-30^{o}W, roughly parallel to the BLSZ, the deposits are larger (see Witt, 1993) (Kundana, >150 t Au total, Cave Rocks, 20 t gold total (Watchorn 1998).

If it is assumed purely empirically that the general orientation of the BLSZ is positive for gold mineralization than the Zuleika N is oriented less favourably, by contrast to the richer Zuleika S, which is parallel to the BLSZ. Furthermore, the Zuleika N seems to lack important bodies of competent rock such as dolerite bodies and porphyry intrusions, which are generally relatively small (e.g. Ant Hill, Witt, 1993, p.6-7), while the Zuleika S, in contrast, has larger dolerite sills (such as at Cave Rocks and close to Kundana). Thus, the Zuleika N is unlikely to yield large deposits, except perhaps at intersections with cross cutting, dilatant N-S and NNE-SSW striking shear zones, while the Zuleika S has a generally more favourable orientation and competent rocks to perturb flow.

The poorly endowed Ida Shear Zone is a good example of a regionally persistent orientation, with relatively little perturbation of rock flow during deformation. The strike or the Ida Shear Zone is nearly perpendicular to the regional axis of maximum shortening which trends ENE-WSW, and being a narrow corridor between more competent batholiths, the belt underwent intensive flattening. Because of the high temperature during deformation and reduced competency contrast, layer attenuation and rotation of angular discordant bodies into parallelism with the regional trend, took place without much flow perturbation and few opportunities for dilation zones to focus regional hydrothermal fluids. Once a narrow, strongly stretched belt developed any subsequent deformation was relatively homogeneous with relatively little perturbation of the regional stresses (Fig. 2.6.5). Nevertheless, mineralization developed in those places where competency contrast existed and gave rise to flow perturbation and zones of dilation. Examples are the surroundings of the Central Granite Batholith indentor (Riverina area; described in Section 2.5) and the mineralization in boudin necks at Iguana.

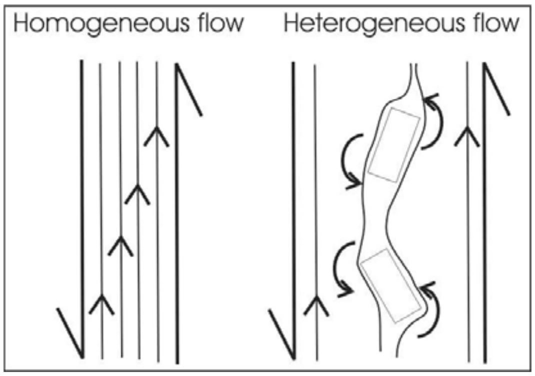

Fig. 2.6.5. Homogeneous flow such as envisaged for the ISZ, and heterogeneous flow, more likely to have taken place along greenschist facies shear zones. Irregular, randomly distributed competent bodies (rectangles) lead to a perturbation of rock flow and rotation of lithological contacts or foliation to dilational (NE-SW) and compressional (NW-SE) orientations, leading to fluid focusing.

Conclusions

Different gold endowment of the three shear zones is related to the combined effects of: *a*) extreme competency contrasts; *b*) degree of straining of the rock package, such as exemplified by the attenuation of the stratigraphy at the Ida Shear Zone (a function of *a*, *c* and *d*); *c*) metamorphic facies, particularly its role in controlling competency contrast; *d*) variety of orientation of lithological contacts and structures giving rise to zones of dilation (function of *b*).

The difference between a rich and a poor shear zone is primarily the result of rock flow disturbance (or stress disturbance) during deformation. In a hypothetical system of perfectly homogeneous, parallel rock flow during deformation, hydrothermal fluid flow will be dispersed through the system and mineralization will not take place. In contrast, in a system where rock flow is perturbed everywhere by the presence of rigid bodies of complex geometry, centers of dilation (divergent flow) and of compression (convergent flow) will develop, leading to fluid focusing and mineralization at dilational spots (Fig. 2.6.5).

Based on these insights we conclude that highly sheared zones, flowing with little perturbation, and including highly attenuated/sheared rocks, with little angular discordance, and including rocks metamorphosed at amphibolite facies, should be assigned low exploration priority. On the other hand, greenschist facies shear zones with varied orientation of lithological contacts and structures, varied lithologies, and close to regional seals, should be assigned highest priorities. The use of fractal dimensions as detailed in *Section 3* should greatly assist the process of quantifying the degree of terrane complexity.