What controls gold distribution in Archean terranes?

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ABSTRACT

Despite intensive efforts, determination of a predictable pattern of gold distribution to enhance process understanding and simplify exploration has remained elusive. The pattern of gold distribution along the Archean Boulder-Lefroy shear zone in the Yilgarn craton of Western Australia provides insights into gold distribution in one of the world's richest provinces. Four world-class gold deposits, including the giant Golden Mile at Kalgoorlie, are regularly spaced along the shear zone, providing a window into understanding large-scale Archean hydrothermal systems. Relationships among gold endowment, shear-zone trend, and geologic complexity, as measured by fractal dimensions, indicate that (1) ore fluids were focused into those parts of the shear zone with greatest misorientation from the regional trend, which define dilational sites during shearing and became the sites of world-class gold deposits; and (2) the degree of complexity contrast along the shear zone modulated gold endowment.

Keywords: gold, Archean, fractal dimensions, hydrothermal systems, dilational jogs.

INTRODUCTION

Extensive research efforts have been directed toward understanding the regional distribution and endowment of structurally controlled orogenic (mesothermal) lode-gold deposits (Groves et al., 1998, 2000) and their relationship to tectonic setting (Barley et al., 1989). This quest has been driven by academic and industry needs to understand the apparently irregular pattern of distribution of orogenic lode-gold deposits and the complexity of the processes controlling concentrations of gold that are >10,000 times above background levels at specific sites in Earth's crust.

Analysis of geographic information system (GIS) images (Groves et al., 2000) suggests that it is the conjunction of a number of critical factors that controls the formation of world-class orogenic gold deposits. These factors include (1) proximity to crustal-scale shear zones, (2) localized abundance of faults and shear zones both parallel and oblique to these crustal-scale major shear zones in overall low-strain host sequences, (3) proximity of the hinge of regional-scale anticlines, particularly doubly plunging folds, (4) complex lithostratigraphic sequences of varied orientation, (5) presence of small rigid granitic intrusions, (6) host rocks with high total Fe or high Fe/(Fe + Mg) ratios to induce sulfidation and gold precipitation, and (7) preferential formation depths of 5–10 km at temperatures between 300 and 400 °C. Recurring themes are the structural controls on mineralization, particularly shear zones and anticlines, and the complexity of the overall geometry of highly gold-mineralized domains (Groves et al., 1998; Hodgson, 1989; Kerrich, 1986; Sibson et al., 1988).

The continuum model (Groves, 1993) assumes that upwardly advecting gold-mineralizing fluids were potentially widespread in the crust, and that the formation of the gold deposits depended on fluid focusing into crustal-scale, relatively narrow, high-strain and high-permeability structural pathways (Groves et al., 2000; Phillips et al., 1996).

Focused pathways develop preferentially during deformation of areas of geologic complexity. This happens because variety in rheology and variety in the trends of lithological contacts and the trends of both pre-existing and newly formed structures lead to the development of dilational, low mean stress, permeable areas in proximity to contractional, high mean stress, low-permeability areas (Cox, 1999; Holyland and Ojala, 1997; Sibson, 2001). In contrast, areas of relatively simple structure or lithostratigraphy will tend to have slow and diffuse fluid flow during deformation controlled by the rocks' intrinsic permeability, which may be orders of magnitude lower than that of structural pathways (Ingebritsen and Sanford, 1998).

The Boulder-Lefroy shear zone in the Archean Yilgarn craton, Western Australia, presents a rare opportunity to explore controls on gold distribution because (1) its immediate surroundings are anomalously gold endowed, with the giant Golden Mile, which has ~1% of global gold production and several other world-class deposits; (2) it has been intensively explored and has been the focus of much research (reviewed in Weinberg et al., 2004); (3) there is a comprehensive database with gold deposit locations and production data (Townsend et al., 2000); and (4) the distribution of gold camps appears to follow a well-defined pattern of regular spacing. This paper explores the distribution of camps and their endowment within a 5 km buffer zone on either side of the Boulder-Lefroy shear zone (Fig. 1), seeking to understand the controls of gold mineralization. The systematic distribution of gold deposits is described and relationships among gold distribution, structural trends, and geologic complexity are explored.

BOULDER-LEFROY SHEAR ZONE

The Boulder-Lefroy shear zone formed in the Late Archean Kalgoorlie orogen (2655–2625 Ma; Weinberg et al., 2003) and is a >130-km-long structure that merges northward with the Boorara shear zone, giving rise to the poorly endowed Bardoc tectonic zone (the northernmost part of the shear zone in Fig. 1 indicated by the abbreviation BTZ). The shear zone to the south becomes diffuse and its continuation has not been mapped out unambiguously. The average trend of the Boulder-Lefroy shear zone, based on visual estimates, is 155° (i.e., south-southeast), diverging toward 165° in its northern end. It is linked to several splays and cuts across a thick, folded and thrust-faulted sequence of 2.7–2.65 Ga metamorphosed komatiites, basalts, dolerite sills, felsic volcaniclastic rocks, and granitoids of the Kalgoorlie terrane (e.g., Swager, 1989).

The Boulder-Lefroy shear zone underwent three phases of deformation as a result of east-northeast–west-southwest shortening (Swager, 1989; Weinberg et al., 2003, 2004). The shear zone was initially a series of north-northwest–trending thrust planes related to crustal thickening. Thrusting was followed by sinistral ductile shearing, which reactivated and linked the thrust planes, giving rise to the present interconnected and tortuous trace of the shear zone. The final deformation phase, characterized by brittle, dextral-slip, north-northeast–trending faults that cut across the shear zone, may have been continuous with the earlier sinistral shearing (Weinberg et al., 2003).

The Boulder-Lefroy shear zone and its splays control the distribution of gold deposits; one major world-class gold camp, New Cel-

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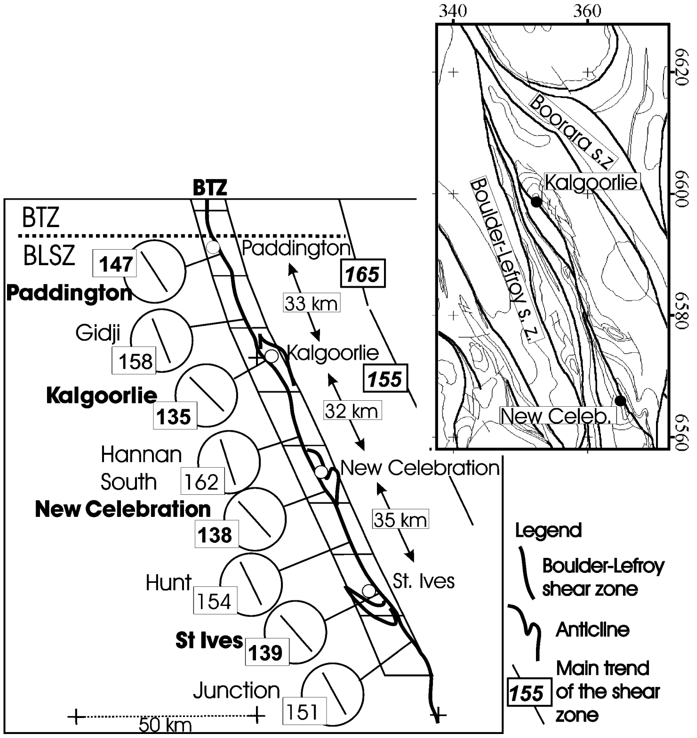

Figure 1. Gold endowment and structural trends of Boulder-Lefroy shear zone (BLSZ). Shear system is redrawn from digital map (inset), showing main gold camps and anticlinal crests, as well as eight boxes (parallelograms) that subdivide shear zone along its length (see Table 1). Boxes vary from 14 to 20 km long (Gidji and Kalgoorlie, respectively) and from 10 to 11.5 km wide. Their length was varied so that each major camp is close to center of its box. Long lines on right side indicate regional trends of BLSZ, including their azimuth values (in degrees), and circles depict most easterly trend of shear zone within each box and trend azimuth (in Fig. 2). North of Paddington, BLSZ ends where it merges with Boorara shear zone (marked schematically in inset) to form Bardoc tectonic zone (BTZ), marked by horizontal dashed line. Inset shows line drawing of geologic features in 1:500,000 digital map (Knox-Robinson et al., 1996) used for fractal-dimension determination (Fig. 3). Thick lines in inset are regional shear zones and fine lines are geological contacts (coordinates in inset are in km; UTM zone 51).

TABLE 1. TRENDS AND TOTAL GOLD IN THE EIGHT AREAS OF THE BOULDER-LEFROY SHEAR ZONE

Gold camp (from N to S)	Regional trend (°)	Easterly trend* (°)	Deviation (°)†	Gold total (t)
1 Paddington	165	147	18	330
2 Gidji	165	158	7	1
3 Kalgoorlie	155	135	20	2500
4 Hannan South	155	162	−7	2
5 New Celebration	155	138	17	130
6 Hunt	155	154	1	15
7 St. Ives	155	139	16	200
8 Junction	155	151	4	32

Note: See Figure 1 for position of the boxes. At Paddington and Gidji, the regional trend is 165°.

*The most easterly trend of the shear zone within the box.

†Deviation is regional trend minus easterly trend.

ebration, is located within the shear zone and three world-class camps are in its immediate vicinity (Fig. 1). Gold mineralization is considered to have been generally structurally and temporally late (Kent et al., 1996; McNaughton et al., 2004), either during sinistral ductile shearing or during the subsequent brittle phase (Groves et al., 2000; Ridley and Mengler, 2000). Some doubt remains with regard to the timing of the different mineralization styles in the giant Golden Mile at Kalgoorlie (discussed in Weinberg et al., 2004).

DIGITAL GEOLOGIC MAP

The digital 1:500,000 Yilgarn craton map used in this study was purposefully prepared with a uniform level of geologic detail (Knox-Robinson et al., 1996). The map is used to determine the fractal dimension of geologic structures, as a means of quantifying geologic complexity in different parts of the terrane, and to avoid bias toward better-mapped regions. Comparison between the GIS map and the original map sources (Knox-Robinson et al., 1996) reveals that the sources have been consistently simplified to obtain a uniform level of geologic detail.

The locations and tonnage of gold deposits are obtained from the Minedex database (Townsend et al., 2000), which includes information on production and remaining resources from historic and recent mines and deposits in the Yilgarn craton. This database is especially important because it allows direct comparisons between geologic complexity and a comprehensive record of the regional distribution of gold endowment. In all cases, estimations of premining resources are used, including remaining gold plus historic and recent production.

GOLD DISTRIBUTION

The Boulder-Lefroy shear zone was divided into eight boxes (parallelograms in Fig. 1; Table 1) in order to study the spatial relationship of gold endowment. The boxes follow the main trend of the shear zone and were designed to emphasize the bimodal distribution of gold endowment along the shear zone. Boxes were approximately centered on the major gold camps, and their length was chosen arbitrarily to half of the distance between them. Gold distribution defines a regular pattern, with four peaks corresponding to the world-class deposits (>100 t contained gold), spaced at intervals of 35 ± 5 km (Figs. 1 and 2), accompanied by four troughs. The richest Kalgoorlie district, which includes the Golden Mile, is followed northward and southward along strike by the two troughs with the lowest endowment (<10 t; Fig. 2). In contrast, the troughs farther away from the Kalgoorlie district and more closely related to other less-endowed gold camps, such as St. Ives, are not as poor as those near the Kalgoorlie district. Thus,

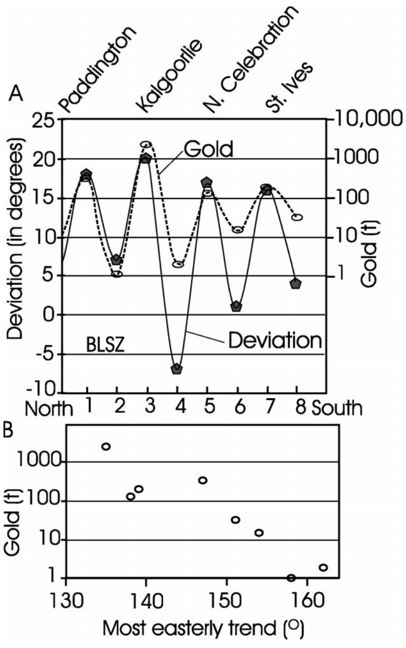

Figure 2. Gold distribution and trend of Boulder-Lefroy shear zone (BLSZ). A: Gold endowment (dashed line with ellipses) within boxes plotted from north to south (from Fig. 1; Table 1). Gold camps alternate with gold-poor zones and coincide with strong counterclockwise deviation (more positive values; solid line with pentagons) of local trend from main trend (155° or 165°; see text and Table 1). B: Absolute value of most easterly trend within each box vs. gold endowment.

the pattern is one in which regularly spaced gold-endowment peaks are proportional to adjacent gold-endowment troughs. This suggests that upward-advecting mineralizing fluids within the shear zone were focused into regularly spaced permeability networks, which captured the fluids that might have otherwise flowed through intervening areas.

In the GIS map, the 155° trend of the Boulder-Lefroy shear zone (or 165° to the north) is an adequate measurement of its attitude because of the flat topography of the area and the subvertical dip of the shear zone, where exposed (Weinberg et al., 2004; Witt, 1993). The most easterly, or counterclockwise, deviation from this main trend, at a kilometer scale, was measured within each box (Fig. 1; Table 1), and the deviation from the main trend of the shear zone was plotted against total gold content (Fig. 2A).

Gold-rich areas are located in boxes with $>10°$ counterclockwise deviation, whereas intervening gold-poor zones are associated with $<10°$ counterclockwise deviation or even clockwise deviation. What is more important is that in all gold camps, the deviation is located in the broad vicinity of the gold deposit. This relationship is reinforced by inspection of more detailed, camp-scale, geologic maps. On these, it is noticeable that in three of the four major gold camps, large deviations coincide with crests of major anticlines (Fig. 1). Gold endowment is related to the absolute value of the most easterly trend of the shear zone, at the kilometer scale, in each box (Fig. 2B).

Considering the overall late history of sinistral motion and gold mineralization, it can be concluded that zones of counterclockwise deviation would have acted as dilational jogs, whereas zones of clockwise deviation provided contraction jogs, and that these jogs provided the first-order control on fluid flux and consequent gold deposition.

FRACTAL DIMENSIONS

Previous studies have determined the fractal dimensions, *D*, of the distribution of ore deposits and fractures and faults (e.g., Blenkinsop and Sanderson, 1999; Carlson, 1991; Roberts et al., 1999) in order to determine whether there is a systematic geographical distribution of deposits in mineral provinces. The fractal dimension of the distribution of structures and lithologic contacts is used here to quantify geologic complexity and relate complexity to gold distribution. *D* was calculated on a 10 km grid covering the Kalgoorlie terrane by using the box-counting method (Mandelbrot, 1983), where lines represent structures and lithologic contacts. A box-counting ArcView script file was developed by using methodology in Hirata (1989), and *D* was calculated for an initial square box 20 km wide and for four levels of halving box width down to 1.25 km (Fig. DR1[1]). This grid was used to determine the fractal dimension within parallelograms lined up along the Boulder-Lefroy shear-zone system.

A parallelogram 12.5 km long and 10 km wide was centered on the northern end of the shear zone, and the value of *D* from the 10 km grid within that parallelogram was used as its typical value. If two grid points fell within the same parallelogram, the average *D* value was used. Gold tonnage of all deposits within the parallelogram was added. The parallelogram was moved southward by half its length, partly overlapping with the previous position, and the process repeated. The procedure applied is simple and designed for application at craton-wide scale followed by focusing into high prospectivity regions. The approach sought to test its usefulness for exploration.

At terrane scale, fractal distribution supports the expectation that gold deposits are concentrated in areas of high geologic complexity or high *D* value (Groves et al., 1998). However, when the *D* value is plotted against gold content along the Boulder-Lefroy shear zone (Fig. 3), the richest Kalgoorlie gold camp is not in an area of highest fractal dimension, but rather in an area of change in complexity, from a low *D* value, related to a monotonous felsic volcaniclastic sequence to the north, to a high *D* value, related to anticlinal crests of greenstones to the south. This same pattern is repeated for the ~200 t gold deposits at Paddington and St. Ives gold camps (Fig. 2). Only the smallest (~130 t gold) New Celebration camp is in an area of high *D* values.

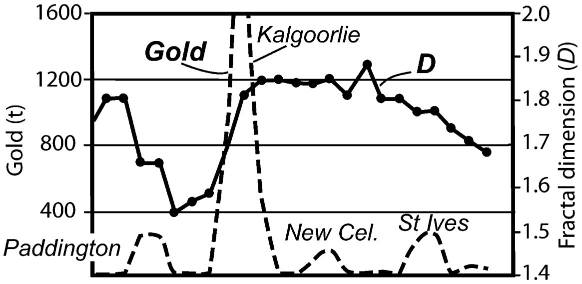

Figure 3. Fractal dimension, *D*, vs. gold. Largest gold camp at Kalgoorlie and Paddington and St. Ives camps coincide with gradients in *D*. Smallest camp at New Celebration is only one that occurs in region of high fractal dimensions.

These relationships suggest that it is the gradient in geologic complexity, rather than the complexity per se, that controls the sites of the largest deposits. Thus, although deviations in the local trend of the Boulder-Lefroy shear zone provide the first-order control on mineralization, gold tonnage is boosted in areas of complexity gradient.

DISCUSSION AND CONCLUSIONS

In this work only structural controls at kilometer scale have been considered. Other variables have been neglected, such as the age of the terrane (Goldfarb et al., 2001) or three-dimensional geometrical aspects. However, the success in accurately accounting for the location of gold camps from map patterns suggests that structural complexity and the most easterly deviation of shear-zone trends at the 1:500,000 scale are reliable guides to deep-sourced fluid pathways. In the broad vicinity of these first-order fluid attractors, fluids are further focused by a number of alternative camp-scale controls that ultimately determine the site of mineralization. Typically these are favorably oriented secondary shear zones, contacts between rocks of contrasting rheology, faults that crosscut older shear zones, folds, or even contractional jogs on seismically active faults (Cox and Ruming, 2004).

The fact that gold distribution in the Boulder-Lefroy shear zone is related to shear-zone trend changes and geometrical complexity, as expressed on 1:500,000 geologic maps, is consistent with conclusions that gold mineralization was late in the structural history of the terrane (Groves et al., 2000). However, the results do not preclude the possibility that areas of initial complexity may have been preferentially reactivated during deformation, thus intermittently focusing mineralizing fluids. In either case, present-day geometry and late shear-zone kinematics provide an accurate guide to the location of world-class gold deposits.

The typical distance of 30–40 km between gold camps along the Boulder-Lefroy shear zone is similar to the typical thickness of continental crust and to the spacing of gold deposits in other parts of the Eastern Goldfields. Such a regular spacing of gold deposits along a single shear zone is rarely replicated elsewhere in nature. It is postulated that the richness of this shear-zone system is a result of the intensive focusing of regional fluids into few dominant pathways defined by regularly spaced dilational jogs. The dominance of a single major control at 30–40 km scale contrasts with other areas in the Yilgarn

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[1] GSA Data Repository item 2004088, Figure DR1, a brief description of the box-counting methodology, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, CO 80301-9140, USA.

craton, e.g., the Bardoc tectonic zone, where a number of alternative controls break the hydrothermal systems into small, irregularly spaced gold deposits. Thus, it is further postulated that dominant fluid pathways spaced every 30–40 km maximize the efficiency of the system and its ability to produce world-class deposits. The next important gold deposit should be 30–40 km south of St. Ives (Fig. 1), wherever the local trend deviates eastward from the main trend of the shear zone. However, the shear zone is poorly defined there.

In conclusion, gold camps along the Boulder-Lefroy shear zone define a systematic pattern of regularly spaced world-class gold deposits between gold-poor zones, with endowment in the gold-rich zones inversely related to that in gold-poor zones. The pattern suggests that the mineralizing hydrothermal systems represented conduits into which fluids were sequestered from surrounding zones. The first-order control on gold distribution was the eastward deviation of the main trend of the shear zone. The world-class deposits coincide with these regularly spaced dilational jogs and associated anticlinal crests, whereas intervening restraining jogs are poorly endowed. Within areas of eastward trend deviation of the shear zone, a number of other controls further focus fluids and determine the site of mineralization. The second-order control modulating gold endowment was geologic complexity; endowment was boosted where there were steep gradients in geologic complexity. It is argued that the Boulder-Lefroy shear zone is well endowed with world-class gold deposits because it is a single, well-defined, crustal-scale shear zone, with widely and regularly spaced dilational jogs, in an otherwise low-permeability greenstone belt. The shear zone thus became the site of highly efficient fluid-focusing pathways.

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