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Kinematic History of the Boulder-Lefroy Shear Zone System and Controls on Associated Gold Mineralization, Yilgarn Craton, Western Australia

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Abstract

The Boulder-Lefroy shear zone, developed in the ca. 2.7 to 2.65 Ga Archean greenstone sequence of the Kalgoorlie terrane in the Yilgarn craton, is remarkable for the number and importance of gold deposits it hosts. These include, from south to north, the following gold districts (with tons of contained Au): St Ives (253 t), Hampton-Boulder-Jubilee (123 t), Golden Mile (1,821 t) plus Mount Charlotte (219 t), and Paddington-Broad Arrow (112 t). Detailed structural studies reveal that the shear zone system developed in two main stages, the first related to a phase of north-northwest–south-southeast–trending folding and thrusting (regional D_2) and the second related to sinistral shearing (regional D_3) that reactivated and linked the preexisting north-north-west–south-southeast–trending network of thrust planes. Sinistral movement resulted in only limited displacement (less than 12 km) and evolved from ductile shearing in broad zone toward semibrittle shearing along narrow planes (regional D_4). The structures suggest a temporal evolution from crustal thickening during D_2 through lateral escape during D_3 to the development of brittle structures during D_4.

The Fimiston and Oroya lodes at the Golden Mile in Kalgoorlie are also exceptional in their gold endowment and associated alteration and were most likely developed during D_2. All other deposits along the shear zone system were formed within 25 m.y. of the Fimiston and Oroya lodes, late in the tectonic history of the terrane, either during D_3 or D_4. Intense mineralization within and around the shear zone resulted from multiscale focusing of mineralizing fluids. At a regional scale, fluids were focused into the shear zone system and its large anticlines which expose deeper mafic and ultramafic rocks. At a local scale, fluids were further focused into structural pathways resulting from strain-induced permeability in rocks with contrasting rheology.

Introduction

The Archean Yilgarn block of Western Australia is one of the major gold provinces on Earth, with the Golden Mile and Mount Charlotte gold deposits at Kalgoorlie alone having produced 1 percent of the worlds total gold production (Bateman et al., 2001). The major gold deposits in the Yilgarn block, including those at Kalgoorlie, are structurally controlled, and several lie in the immediate vicinity of the Boulder-Lefroy shear zone (BLSZ; Fig. 1). Understanding the relationship between this shear zone system and gold mineralization has been the subject of major scientific and exploration efforts (Weinberg et al., 2004), yielding many important exploration models which are today applied worldwide. Whereas a number of published and unpublished studies detail parts of the Boulder-Lefroy shear zone system, this paper systematically covers the structural evolution of the system as recorded within the gold deposits.

The north-northwest–trending Boulder-Lefroy shear zone is a major shear zone, over 200 km in length, located within the greenstone sequence of the Kalgoorlie terrane in the southern part of the 600-km-long Norseman-Wiluna belt, one of four Yilgarn provinces (Gee, 1979). This belt of metamorphosed rocks is characterized by abundant tholeiites and komatiites, overlain by felsic volcanic and sedimentary rocks and intruded by granitic rocks. This broad stratigraphy is summarized in Table 1. The shear zone can be traced from the Paddington gold mine, north of Kalgoorlie, to south of Kambalda (e.g., Gemuts and Theron, 1975; Griffin, 1990). Whereas its trend is parallel to the main regional fabric, its main trace is relatively poorly defined because of lack of exposure combined with a number of strands and splays (e.g., Griffin, 1990, and maps in Keats, 1987). Many authors separate the Boulder shear zone, to the north, from the Lefroy shear zone to the south (e.g., Swager, 1989a).

Interpretations of the sense of movement in the Boulder-Lefroy shear zone vary widely, inferred from large-scale features of the shear system or observed directly where the shear zone is exposed. Swager (1989a) interpreted the Boulder-Lefroy shear zone as a major sinistral wrench structure as evidenced by the 12-km apparent sinistral displacement of geo-

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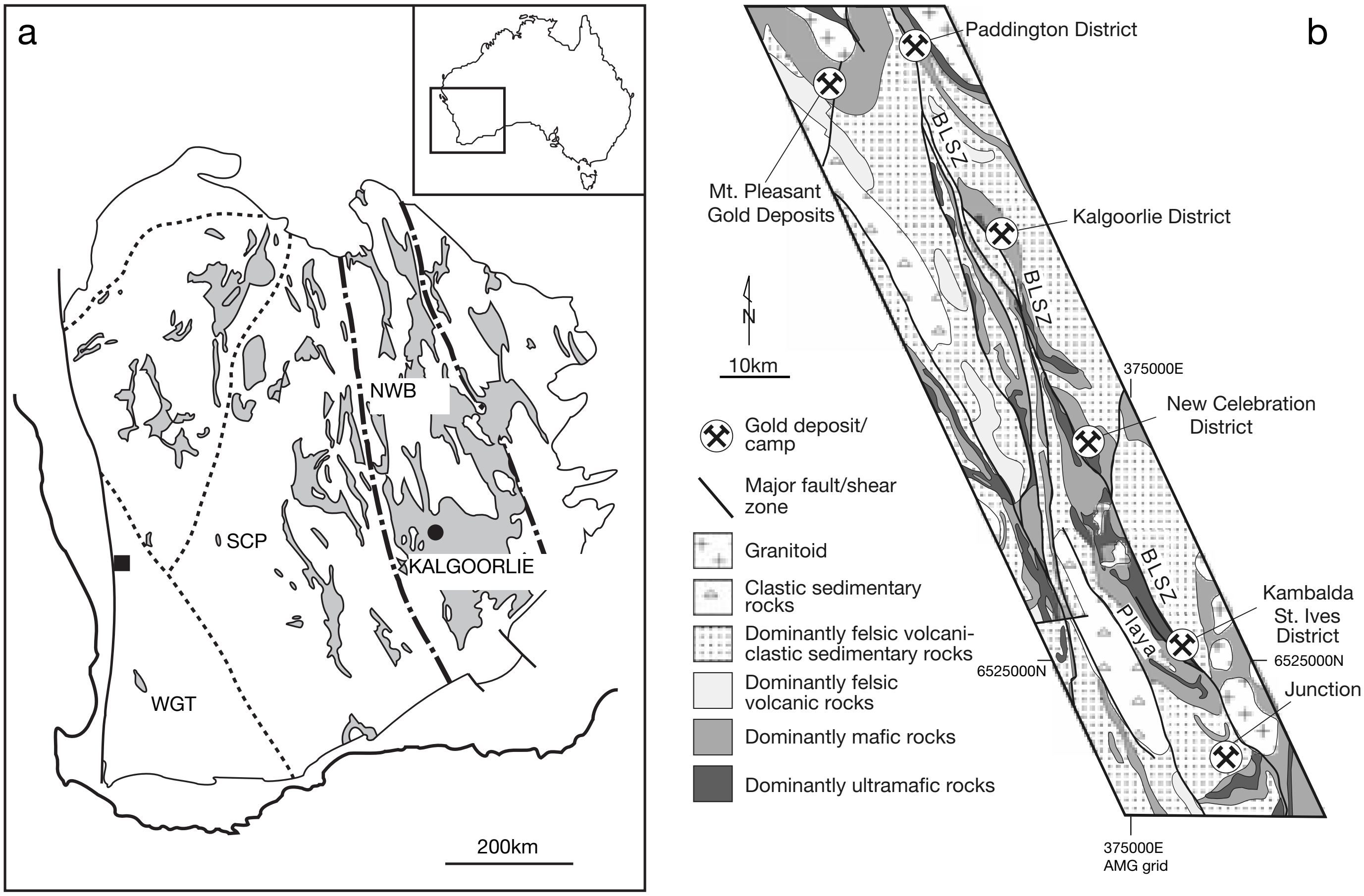


FIG. 1. (a). Location of the Yilgarn craton in Australia and a map of the craton indicating the position of the Norseman-Wiluna belt (NWB) limited by two thick north-northwest–south-southeast–trending dashed lines (redrawn from Phillips et al., 1996). (b) Schematic map of the Boulder-Lefroy shear zone (BLSZ) and surrounding geology and important gold camps. The Playa shear zone in the Kambalda-Saint Ives district is indicated.

logic markers (Langsford, 1989), the north-south–trending en echelon folds along parts of the shear zone, and the sigmoidal, en echelon distribution of north-south–trending dextral shear zones in the Kalgoorlie district. An important reverse sense of shear also has been interpreted from seismic lines (Goleby et al., 2000) and confirmed by field observation (Boulter et al., 1987; Copeland et al., 1998; Ridley and Mengler, 2000). Other authors recognized oblique-sinistral movement in the system (e.g., Swager, 1989a, 1991; Witt, 1991; Nguyen et al., 1998, p. 1627) as well as dextral movement (Mueller et al., 1988).

The shear zone and its immediate surroundings host four major gold districts with more than 100 t of total gold each. From north to south these are (Fig. 1) the Paddington, Kalgoorlie, New Celebration (also known as the Hampton-Boulder-White Hope district), and Kambalda-Saint Ives districts. North of Paddington, the Boulder-Lefroy shear zone merges with the Boorara shear zone to form the Bardoc tectonic zone, where gold endowment of major districts generally only reaches ~10 t Au or one order of magnitude less than districts along the Boulder-Lefroy shear zone. Interestingly, the Boorara shear zone, parallel to and immediately east of the Boulder-Lefroy shear zone, has only sparse and significantly smaller gold deposits, although it is a major structure.

This paper derives the history of deformation of the shear zone system from the study of limited exposures and open pits, starting with a review of the regional deformation phases recorded in the Kalgoorlie-Kambalda area, then describing gold distribution and the structural evolution of three major mining districts. These are the New Celebration district in the center, the Kambalda-Saint Ives district in the south, and the Kalgoorlie district in the north. New data are presented for the New Celebration and Kambalda-Saint Ives districts.

Deformation History

The deformation history of the Norseman-Wiluna belt is generally divided into four main shortening phases, D_1 to D_4 (Table 2; e.g., Archibald et al., 1978; Platt et al., 1978; Witt and Swager, 1989; Swager et al., 1992, 1997). D_1 comprises the earliest recognizable structures. In the Kalgoorlie terrane, D_1 is described as a major north-directed thrusting phase, with recumbent folding and large-scale stratigraphic repetition (Archibald, 1979; Martyn, 1987; Vearncombe et al., 1989; Witt and Swager, 1989; Swager and Griffin, 1990; Swager et al., 1992; Knight et al., 1993). Sequence repetition is particularly evident where the lower mafic-ultramafic stratigraphy

TABLE 1. Suggested Stratigraphic Correlations between the Three Gold Districts along the Boulder-Lefroy Shear Zones

Kalgoorlie (Swager, 1989a)	New Celebration (Langsford, 1989)	Kambalda-Saint Ives (Watchorn, 1998)
Black Flag Group, felsic volcanic and sedimentary succession >1 km thick, upward coarsening 2676 ± 4 Ma	Black Flag Group	Black Flag Group
Golden Mile dolerites, differentiated into 10 units; competent granophyric unit 8, with abundant plagioclase and quartz, hosts gold	Triumph Gabbro, ~ 600 m	Condenser and Junction Dolerites
Kalgoorlie Group		
Paringa basalt, 1,000 to 1,500 m, siliceous, high Mg basalt, variolitic and pillowed and numerous chert interflows (2690 ± 5 Ma)	Kyarra Basalt	Paringa Basalt
Williamstown dolerite, up to 300 m; in situ fractionation at the base of the Paringa Basalt	Pernatty Dolerite, 300 to 500 m, basal cumulate pyroxenite	Defiance Dolerite
Kapai slate, persistent 5- to 25-m marker horizon varying from pyritic graphitic slate to magnetite-bearing laminated chert (2692 ± 4 Ma)	Kapai Slate	Kapai Slate
Devon Consols basalt, 60 to 100 m, high Mg variolitic basalt (2693 ± 30 Ma)	Mutooroo Basalt, 100 to 200 m	Devon Consols Basalt
Hannan's Lake serpentinite, 800 to 1,200 m, serpentinized ultramafic lavas, spinifex and cumulate textures; nickel orebodies at lower contact; grade upward to high Mg basalts (2709 ± 4 Ma)	Kambalda Komatiite	Kambalda komatiite (also known as Tripod Hill Fm.)
		Lunnon Basalt, >2,000 m, thin flows of uncontaminated pillowed tholeiites, with thin interflow sediments (2720 Ma)

has been uplifted and exposed at the margins of granitic domes (e.g., Dunnsville dome, Swager, 1989b; Widgiemooltha dome, Griffin, 1990).

A major change in the shortening direction took place and initiated a second major deformation which gave rise to the dominant north-northwest–south-southeast fabric. This change took place at ca. 2655 to 2650 Ma (Weinberg et al., 2003, see also Davis, in press) as inferred from the age of sedimentation of the Kurrawang sequence that was folded by this event (Krapez et al., 2000). This event lasted 20 to 30 m.y. defining the late Archean Kalgoorlie orogen (Weinberg et al., 2003) and was associated with relatively small exposed volumes of the 2,650- to 2,630-m.y. low Ca and alkaline granites, as well as major gold mineralization (the third tectonothermal event of Smithies and Champion, 1999). This deformation comprises the three distinct phases known regionally as D_2-D_4.

D_2 was a crustal thickening event characterized by thrusting and folding, which gave rise to the regionally dominant north-northwest-south-southeast–trending fabric (Table 2; Archibald et al., 1978; Platt et al., 1978; Witt and Swager, 1989; Swager and Griffin, 1990). This phase was followed by D_3 and D_4, two strike-slip faulting events, which gave rise to conjugate sets of ductile shear zones and brittle faults,

TABLE 2. Summary of Structures and Their Relative Timing

	D_1 crustal thickening north-directed thrusts	$D_{1(local)}$	D_2 crustal thickening Boulder-Leroy shear zone stage 1	D_3 lateral escape Boulder-Leroy shear zone stage 2	D_4 brittle reactivation
Kalgoorlie		Golden Mile fault, (east side-up); Kalgoorlie anticline (recumbent fold); Fimiston lodes	North-northwest–trending thrusts, (west side-up); north-northwest–trending folds and foliation; Oroya lodes	Sinistral on north-northwest planes; tightening of D_2 folds; dextral north-trending en echelon shear zones	Brittle (semibrittle) reactivation of early shear zones Mt. Charlotte-style gold
New Celebration			North-northwest–trending, steepened thrusts; gently plunging boudin axes	Sinistral reactivation; dextral north-south Pisces shear zone; gold deposition, syntectonic pyrite	Gold deposition?
Kambalda-Saint Ives goldfields	North-directed thrusts and north-verging recumbent hanging-wall folds (e.g., Tramways, Foster, Republican thrusts)		Folding of D_1 structures; north-northwest–trending foliation, upright gentle folds	West-northwest–directed thrusts; north-northeast–trending dikes; sinistral, north-northwest–trending shear zones; gold deposition	Normal and dextral reactivation of D_3 shear zones

respectively, and D_3 was associated also with en echelon north-south–trending folds (Witt and Swager, 1989; Swager and Griffin, 1990). D_3 and D_4 define a phase of lateral crustal escape, and the transition from D_2 to D_3-D_4 was most likely continuous and a result of the crust having reached its maximum sustainable thickness during D_2 (Weinberg et al., 2003).

The literature has focused mostly on the sinistral character of D_3, as a result of a historical focus on the major northwest- and north-northwest–trending shear zones of the Kalgoorlie region (e.g., Langsford, 1989; Swager, 1989a, Hunter, 1993). It is clear, however, that D_3 also comprises important north-south and north-northeast–trending dextral shear zones (e.g., Platt et al., 1978; Skwarnecki, 1987; Hammond and Nisbet, 1992).

The last deformation phase, D_4, is the subject of some disagreement and much misunderstanding. Some authors used the term to include all north-south or north-northeast–trending dextral shear zones, neglecting the fact that some of them are ductile shear zones and most likely conjugate to the sinistral north-northwest–trending shear zones. Mueller et al. (1988), on the other hand, suggested that deformation patterns in the Kalgoorlie area resulted from a dextral wrenching event, which overprinted an earlier sinistral wrenching (D_3). Ridley and Mengler (2000) used the term to define continued regional shortening leading to a brittle reactivation of the dextral and ductile D_3, north-northeast-south-southwest– and north-south–trending shear zones in the Kalgoorlie district. A more general definition of D_4, and the one used here, is that it comprises a brittle or semibrittle conjugate pair of faults: a dextral north-northeast-south-southwest– and a sinistral east-southeast–west-northwest–trending set. This pair developed as a result of the same strain axes system as D_3 but possibly in a lower temperature, higher crustal-level environment. These faults are visible in aeromagnetic imagery as lineaments cutting through most lithologies but are particularly well expressed in the more competent granitic bodies.

Gold Distribution and Timing of Gold Mineralization

The distribution of gold deposits along the Boulder-Lefroy shear zone follows a remarkable pattern (Fig. 2) where the major mining districts characterized by peaks in gold endowment are spaced 30 to 40 km apart with intervening regions having virtually no significant gold concentrations (Weinberg et al., 2004). Interestingly, the more endowed a district is, the less endowed are the adjacent zones along strike. Gold distribution also coincides with the exposure of regionally important anticlinal cores at the Kalgoorlie, New Celebration, and Kambalda-Saint Ives districts.

The timing of gold mineralization and the origin of mineralizing fluids in the Yilgarn craton are subjects of much discussion (e.g., Groves, 1993). Detailed studies suggest that a major phase of gold mineralization took place late in the tectonic evolution of the craton, either during D_3 or D_4 (Mueller et al., 1988; Vearncombe et al., 1989; Clout et al., 1990; Groves et al., 1990, 2000; Ridley and Mengler, 2000). This is supported by published age determinations, which mostly constrain mineralization to ca. 2640 to 2625 Ma (e.g., Groves et al., 1995, 2000; Yeats et al., 1999). There is, nevertheless, some evidence that gold mineralization may have been more protracted, starting earlier, possibly at ca. 2660 Ma (Yeats et al., 1999), with a number of gold deposits in the Norseman-Wiluna belt being demonstrably multiply deformed and arguably deposited during early folding and thrusting events (e.g., Coolgardie, Knight et al., 2000; Tower Hill deposit, Witt, 2001; Mulgarrie, Davis et al., 2001). Most importantly, the Kalgoorlie gold district, the largest of them all, has had multiple gold mineralizing events (e.g., the Golden Mile Fimiston- and Oroya-style and Mount Charlotte deposits at Kalgoorlie: e.g., Clout et al., 1990; Kent and McDougall, 1995; Ridley and Mengler, 2000), suggesting a protracted mineralization history (Bateman et al., 2001).

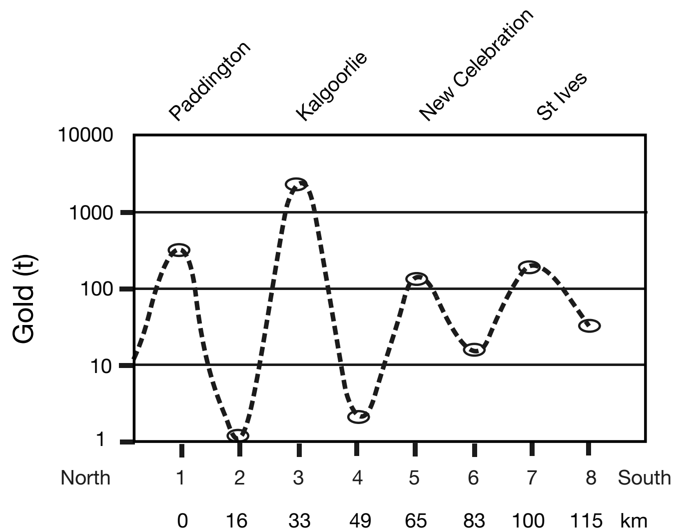


FIG. 2. Gold endowment (log-scale) along the Boulder Lefroy shear zone plotted from Paddington in the north to Saint Ives in the south (modified from Weinberg et al., 2004). Gold endowment was measured in boxes 17 ± 2 km long and 10 km wide, centered at the Boulder-Lefroy shear zone and aligned parallel to it, covering its length from north of Paddington to south of Saint Ives. Endowment includes all gold produced and known reserves within each box. Gold peaks occur at regular intervals of approximately 35 ± 5 km. Each peak is followed by gold-poor areas (troughs). Note that box 7, corresponding to Saint Ives, does not include the gold at Junction, which is plotted in box 8.

New Celebration District

The New Celebration district (Langsford, 1989; Griffin, 1990; Fig. 3) is located in the central region of the Boulder-Lefroy shear zone and has a total gold endowment of >100 t. This district is discussed first because the Boulder-Lefroy shear zone is exposed in some of the mines, and it best illustrates the findings of this study.

The dominant geologic structures at New Celebration are the Celebration and Resolution anticlines (Fig. 3), which expose a sequence of mafic and ultramafic rocks in their core, intruded by a number of granitic dikes (porphyries) and differentiated dolerite sills, and overlain by the felsic volcaniclastic rocks of the Black Flag Group. The exposed stratigraphy is similar to that of the neighboring areas (Table 1; Griffin, 1990). The Boulder-Lefroy shear zone truncates the folds, and the main gold deposits at New Celebration (Fig. 3) tend to occur within or immediately adjacent to the Boulder-Lefroy shear zone (Norris, 1990; Copeland et al., 1998). The

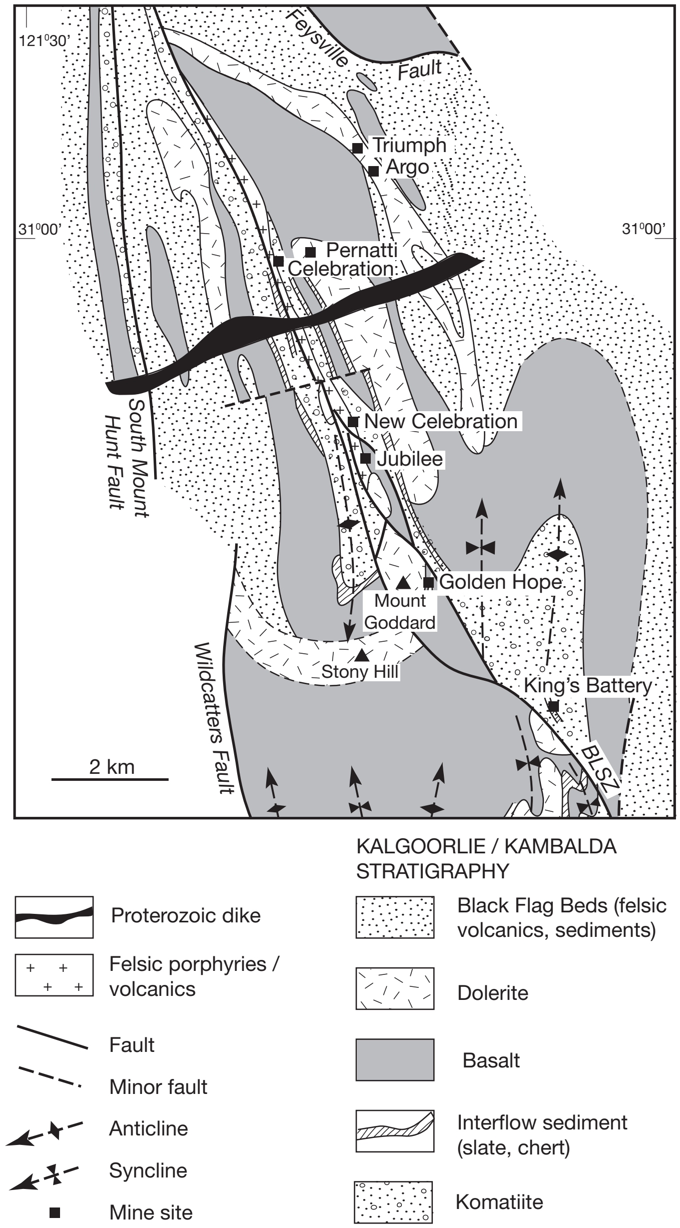


FIG. 3. Geologic map of the New Celebration district, showing the Celebration and Resolution anticlines and important deposits (redrawn from Swager, 1989a). Maximum displacement in this part of the Boulder Lefroy shear zone (BLSZ) has been determined by the apparent displacement of the Triumph Dolerite.

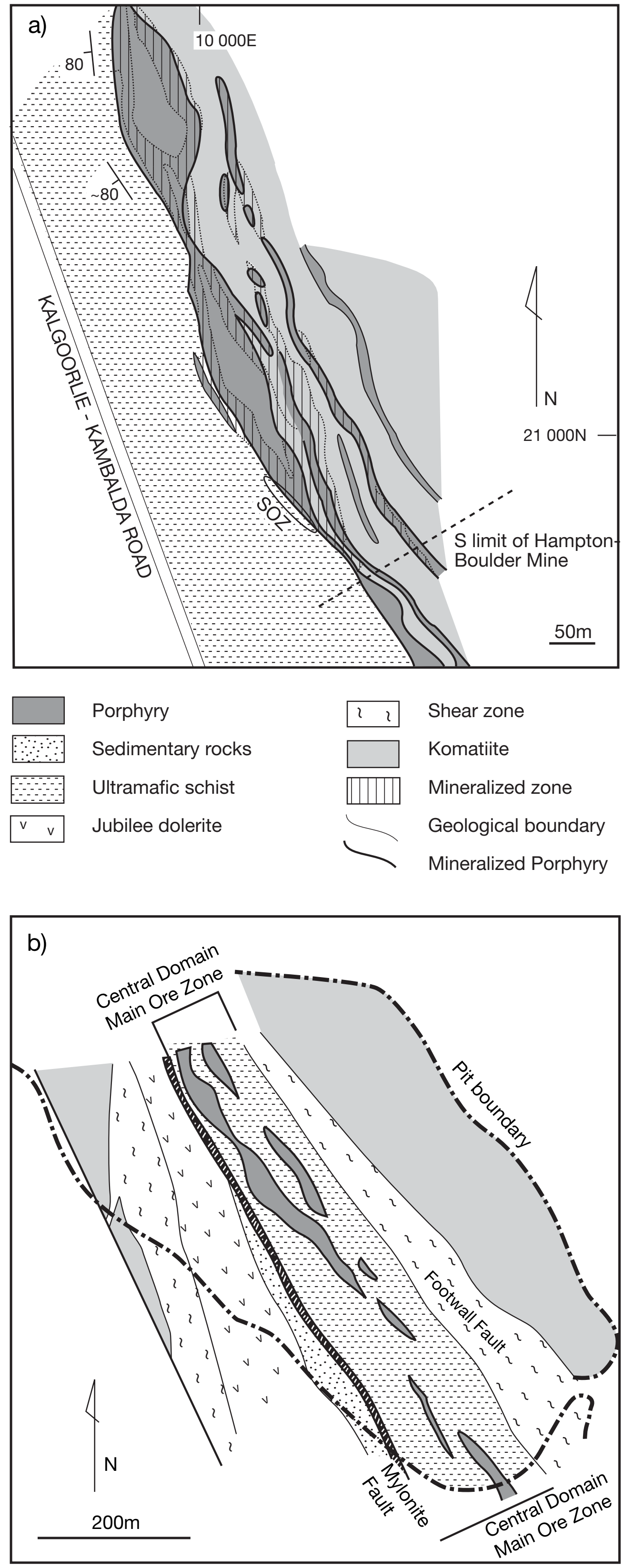


FIG. 4. (a). Geologic map of the Hampton-Boulder pit, showing the boudinaged, wide porphyry hosting the mineralization (redrawn from Norris, 1990). (b). Geologic map of the Jubilee pit (redrawn from Copeland et al., 1998).

Hampton-Boulder and/or Jubilee mines and the well-exposed King's Battery area are the main focus of the study below.

Previous studies

Hampton-Boulder and Jubilee form a 1-km-long, continuous open pit and together have produced 45 t of gold, with 78 t remaining (above 0.5 g/t; S. Devlin, pers. commun., 2001). The main feature of these deposits is that they lie within the Boulder-Lefroy shear zone at the contact between schistose country rocks and a boudinaged porphyry (granitic) dike (Fig. 4; Norris, 1990; Williams, 1994; Copeland et al., 1998; Dielemans, 2000). A zone of intense shearing, up to 100 m wide, dips steeply west and defines the Boulder-Lefroy shear zone (Norris, 1990). Mineralization is controlled by a boudinaged quartz-feldspar porphyry, more than 1 km long and up to 80 m wide, which also dips steeply west and separates a mafic hanging wall from an ultramafic footwall (see Copeland et al., 1998, for detailed stratigraphy at the Jubilee mine). Major gold mineralization is related to stockworks of quartz-carbonate-pyrite veinlets along both contacts of the fractured porphyry, producing a series of tabular, steeply west-dipping ore zones (Griffin, 1990).

The most detailed structural study of Hampton-Boulder focused on the underground mine at the Southern ore zone (Dielemans, 2000; see also Williams, 1994), a very rich ore zone at the southern end of the Hampton-Boulder gold deposit. Dielemans (2000) described a penetrative mylonitic foliation, which transposed original rock contacts and strikes on average N 40° W/82° W. He noticed a gradual change in foliation orientation from northwesterly at the Southern ore zone, to nearly northerly at the northern end of the deposit. This change is accompanied by a similar change in the orientation of the main porphyry dike (the northern boudin in Fig. 4). This earlier penetrative foliation is overprinted by what Dielemans (2000) described as anastomosing shear planes, with glistening surfaces, spaced >10 cm and striking between N 40° W and N-S and dipping 70° to 90° W.

A large number of lineation types were determined by Dielemans (2000) and may be divided into three main groups: (1) boudin axes commonly plunging gently south, (2) a gently to moderately southeast-plunging mineral and stretching lineation, and (3) a steeply northwest-plunging lineation (crenulation, mineral, and stretching lineations). In the absence of indicators, Dielemans (2000) assumed dominant sinistral movement (following Langsford, 1989) and interpreted the southeast-plunging lineation as the movement direction, and the almost perpendicular, steep northwest-plunging crenulation lineation to represent the intermediate stress axis. Dielemans (2000) documented carbonate fibers which had grown perpendicular to pyrite faces within the ore and parallel to the southeast-plunging lineation, indicating that pyrite, and possibly gold, deposition took place either during or before sinistral shearing.

Mueller et al. (1988) described the structures at Hampton-Boulder, in which pods of schist preserve kinematic indicators showing sinistral sense, wrapped by an anastomosing shear fabric containing kinematic indicators with a dextral sense and mineral lineations plunging 20 south-southeast. This dextral sense of shearing was not confirmed in this study.

At the Jubilee mine, lying immediately south of Hampton-Boulder's tenement boundary in Figure 4, mineralization is bound by the Mylonite fault in the west and the Footwall shear in the east (Fig. 4b). Gold occurs as 2- to 20-μm grains in pyrite in quartz-carbonate veins in schistose rocks that are intruded by intermediate to felsic and semiconcordant porphyry dikes in between the Mylonite fault and the Footwall shear (Copeland et al., 1998). The main orebody has a strike length of 800 m and an average width of approximately 40 m. Gold distribution is strongly influenced by rock type, and the highest grades are developed around intermediate porphyries, but felsic porphyries and dolerites are also mineralized.

Copeland et al. (1998) concluded that the Boulder-Lefroy shear zone at Jubilee is a system of anastomosing shear zones, including the two bounding faults, and characterized by horizontal shortening and a strong vertical extension component, as indicated by downdip lineation, flat-lying quartz veins, and subhorizontal boudin axis. These shear zones have transected the hinge of a large-scale anticline, as inferred from opposite younging orientations on either side. Copeland et al. (1998) concluded further that the structures at Jubilee are inconsistent with the interpretation that the Boulder-Lefroy shear zone is a major wrench system but rather suggest that the structures represent either a steepened thrust or a ramp connecting with deeper thrusts.

Hampton-Boulder and/or Jubilee

The continuous Hampton-Boulder and/or Jubilee open pit is now closed and most parts are inaccessible. Our description below is limited to the northern and eastern walls of the Hampton-Boulder pit and to the southern wall of the Jubilee pit.

The northern wall of Hampton-Boulder is a zone of intense shearing with penetrative and steep mylonitic foliation (N05° W/80° W; Fig. 5a) and approximately downdip mineral and stretching lineation (Fig. 6a), exposed in the pit over more than 50 m across strike. Moderately dipping, narrow thrust planes, with a strike parallel to the main foliation, such as that formed around the margins of a folded porphyry (Fig. 7) are interpreted to be related to the main deformation in this zone. This is because the main deformation zone, the thrust planes and the folded porphyry, all accommodate the same strain characterized by horizontal shortening perpendicular to the dominant foliation and vertical extension.

Two sinistral strike-slip shear zones are exposed on the eastern wall of the pit (Fig. 5b). They are parallel to the main N05W trend of the area and are 2- to 3-m-wide zones of intensely sheared chlorite-talc-biotite schist, with gently north- and south-plunging mineral and stretching lineations (Figs. 5b, 6a). The sinistral sense of shear is deduced from S-C fabrics that are clearly defined microscopically and by the asymmetry of mesoscopic weathered fish-shaped blocks. At the margins of these late shear zones, sinistral shearing gives rise to anastomosing foliation around less deformed pods preserving the older downdip lineation. The anastomosing planes glisten due to oriented phyllosilicates (mostly chlorite, but also talc and biotite).

A dextral sense was documented along two narrow shear zones oriented north-northeast. These planes are curved and merge into the north-northwest–trending sinistral shear planes. Their physical links and general mineralogical similarity suggest that the dextral shear zones are conjugates to the dominant sinistral shear planes.

The southern wall at Jubilee exposes meter- to decameter-scale bands of intense shearing over 100 m wide, characterized by mylonitic rocks (Fig. 8a), intercalated with less deformed bands. The average foliation at Jubilee strikes toward N 25° W/75° W, whereas foliation at Hampton-Boulder strikes N 05° W/80° W (Fig. 6). Shear zones are characterized by downdip stretching lineation (Fig. 6b). A range of structures was documented within the mylonitic bands or in less sheared areas such as narrow reverse north-northwest–trending faults (sense of shear derived from S-C fabric, tails around

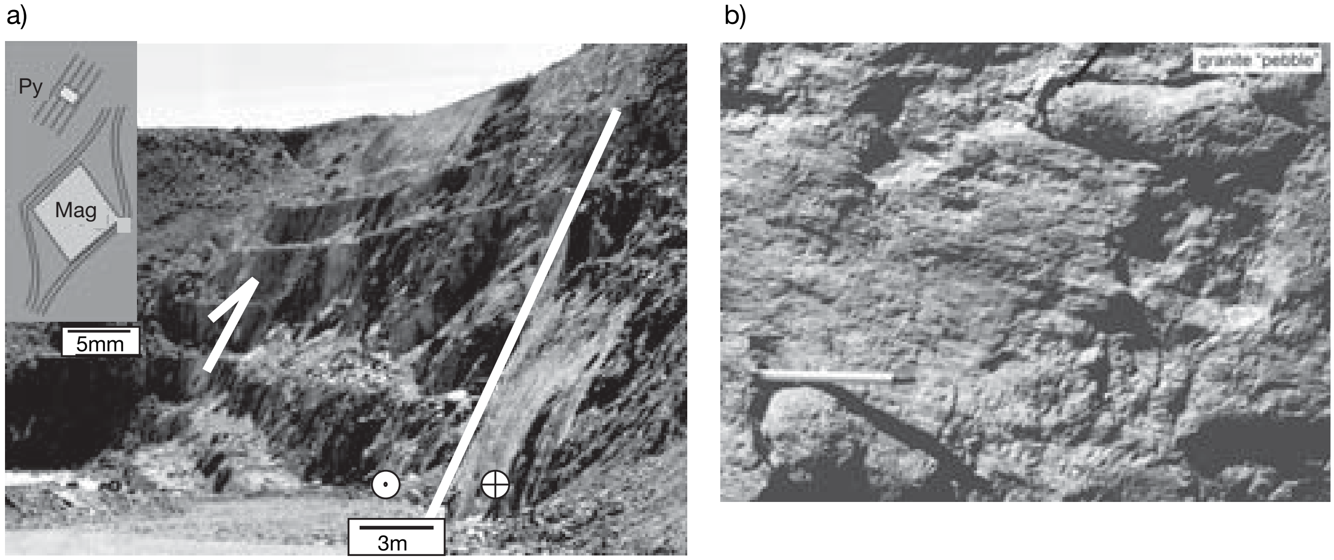


FIG. 5. (a). The northern wall of the Hampton-Boulder open pit. On the western side, intense foliation and downdip lineation defines a steep reverse shear zone with a dominant west side-up sense. On the eastern side, a 3-m-wide sinistral shear zone with gently plunging lineation cuts the reverse shear zone. Person for scale on the footwall of the reverse shear zone. Insert shows schematically the relationship between magnetite and pyrite and the foliation within the reverse shear zone. (b) South-southeast–plunging stretching lineation and striae on sinistral shear zones on the eastern wall of the Hampton-Boulder pit. Elongated "pebbles" of granite, up to 10 cm long and oriented parallel to the lineation, are shear-disrupted granitic dikes.

clasts, meter-scale marker displacement), boudins with gently plunging axis, and tight to isoclinal folds (Fig. 8b). As at Hampton-Boulder, all these structures collectively define an east-northeast–west-southwest–shortening axis and a vertical extension axis. In contrast to Hampton Boulder, there is no evidence for strike-slip reactivation.

King's Battery

An extensive exposure of the Boulder-Lefroy shear zone away from major mineralization is located at the historical site of King's Battery, 6 km south-southeast of Hampton-Boulder and/or Jubilee (Fig. 3). The area mainly comprises north-northwest–trending sheared mafic and ultramafic volcanic rocks, a 3- to 5-m-thick black slate (known as the Kapai Slate,

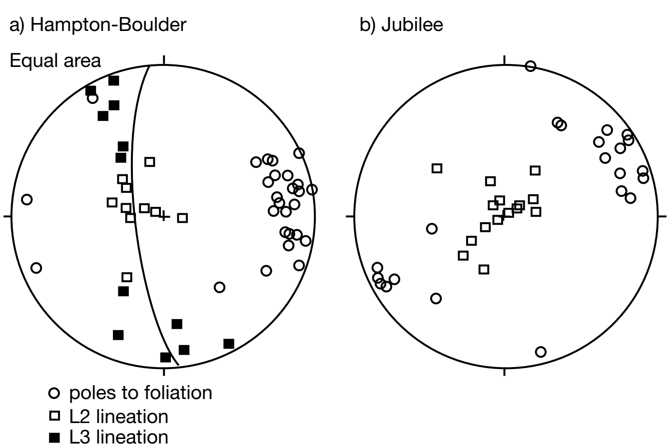


FIG. 6. Lower hemisphere equal area stereonet projection. (a). Structural elements from the Hampton-Boulder mine. Mineral and stretching lineation on reverse shear zones (open squares), and on sinistral shear zones (black squares); poles to foliation (black lozenges); great circle indicates the best-fit foliation plane striking N05° W/80° W. (b). Same for Jubilee. Notice the absence of strike-slip motion, which would be indicated by gently plunging lineations (i.e., close to the margins of the stereonet). Best-fit foliation strikes N 25° W/75° W.

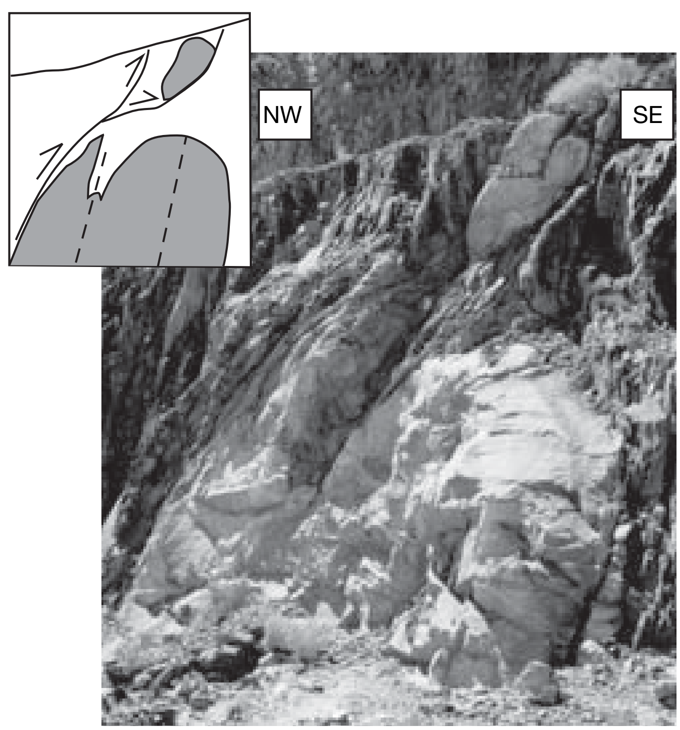
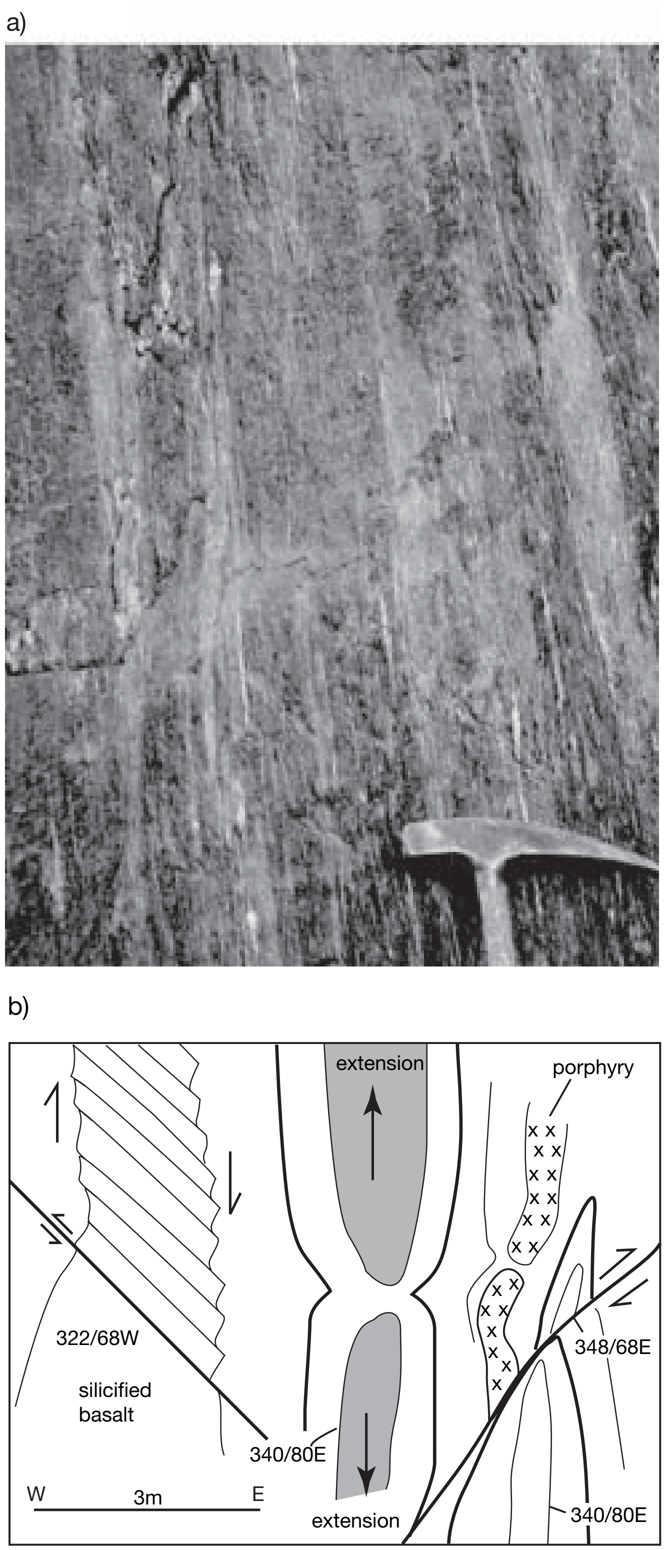


FIG. 7. Tightly folded granite within chlorite schist, associated with a north-northwest–trending reverse fault which displaces part of the granite to the east as indicated by the arrows. Photograph taken from the eastern wall of the Hampton-Boulder pit. Image is 5 m high.

now altered to black chert), a gabbroic intrusion, and a number of quartz veins and porphyry (granitic) dikes. King's Battery is located on the eastern limb of the large-scale Resolution anticline (Fig. 3), which has an axial trace trending north-northeast and was interpreted to represent a D_3 fold related to sinistral shearing (Swager and Griffin, 1990; Fig. 3).



This area has two different deformation zones. The western deformation zone is characterized by intensely strained ultramafic rocks (talc + carbonate ± chlorite schist) at least 100 m wide (western boundary unconstrained) and has a general attitude of N 40° W/80° W. A stretching lineation defined by elongate carbonate porphyroblasts in the ultramafic rocks plunges steeply southeast (typically 145°/70°), subparallel to a mineral lineation in mafic schists. S-C fabrics and drag fold asymmetry indicate west-side down normal sense of movement on steep planes.

The eastern shear zone is distributed over a width of approximately 200 m and partitioned preferentially into mafic schists. The zone strikes approximately N 20° to 30° W and has a well-defined parallel foliation and a gently north-plunging stretching lineation, defined by elongated pyrite agglomerates, strained reduction spots, stretched clasts and striations. Well-developed S-C fabric in the coarser grained units consistently indicates sinistral shear sense with an east-side down component, and this is confirmed in thin section, where chlorite wraps around coarse tremolite grains with consistent sinistral stepping. There is no unequivocal evidence for the relative timing of the two shear zones. Most rock types, including rocks within both deformation zones, record a late, overprinting, steeply dipping, pervasive foliation trending toward N 10° E.

Interpretation

The Boulder-Lefroy shear zone as exposed in the Hampton-Boulder and Jubilee pits is characterized by an early phase of deformation which gave rise to the observed 100-m-wide zone of intense deformation, with downdip mineral and stretching lineation. Combined with boudins, tight to isoclinal folds and north-northwest–trending, moderately to steeply dipping thrusts, these structures accommodated horizontal east-northeast–west-southwest–shortening and vertical extension (Copeland et al., 1998). These structures are all interpreted to represent the expression of the regional D_2 deformation phase, as this was responsible for crustal thickening and gave rise to the dominant north-northwest–trending fabric.

This early deformation was overprinted at Hampton-Boulder (including the Southern ore zone) by sinistral strike-slip movement. The direction of the maximum shortening strain

FIG. 8. (a). Strongly foliated mylonitic gabbro defining the Boulder Lefroy shear zone at Jubilee. The photograph is of a vertical wall, perpendicular to the foliation planes, showing elongated and disrupted carbonate and quartz veins. Outside the mylonitic zone, the gabbro is coarse grained and the veins are wider and crosscut a much weaker foliation. (b). Schematic line drawing of structures documented within an intensely sheared zone within a schist on a vertical exposure at Jubilee (drawn to scale based on a photograph) showing (1) boudinaged granite dike or competent mafic bands within the schist with gently plunging axes (middle and right-hand side), (2) a west-dipping reverse fault displacing the hinge zone of a tight fold with axial planar foliation parallel to the main foliation within the shear zone (lower right-hand side), (3) silicified basalt depicting a bookshelf-style deformation on narrow, east-dipping reverse planes accommodating west side-up deformation (left-hand side). All structures combined accommodated vertical stretching and horizontal shortening in the direction perpendicular to the dominant 340°/80° E foliation.

axis during this phase was west-northwest–east-southeast, implying a local clockwise rotation in relationship to earlier deformation. This event is related to the regional D_3 phase, as this was responsible for regional-scale sinistral shearing in north-northwest–trending shear zones.

The structures described by Dielemans (2000) at the Southern ore zone are reinterpreted here on the basis of the findings presented above. The early penetrative foliation described at the Southern ore zone corresponds to the dominant mylonitic foliation in Hampton-Boulder and Jubilee, where it is associated with a steep lineation, and the anastomosing shear planes that Dielemans (2000) described correspond to similar anastomosing planes on the sinistral shear zones at Hampton-Boulder. The moderately southeast-plunging mineral lineation and the steep northwest-plunging mineral and stretching lineation at the Southern ore zone correspond to the lineations documented on the sinistral and reverse shear zones, respectively. Thus, rather than representing a single sinistral shearing, as interpreted by Dielemans (2000), the structures are a result of D_2 and D_3, and the calcite fibers on pyrite grains within the ore zone grew during D_3, indicating that pyrite was present during that phase.

The structures documented at King's Battery could be interpreted in the light of the structures at the Hampton-Boulder and/or Jubilee mines. The western deformation zone at King's Battery is interpreted to have resulted from intense flattening deformation developed as part of the regional D_2 shortening and represents a rotated reverse shear zone, as there is no associated evidence for an extensional deformation phase (gently dipping foliation and axial planes of folds or moderately dipping normal faults). The sinistral shear zones are interpreted to postdate the D_2 structures and to have developed during D_3, although no timing relationships were documented. The late, pervasive, N 10° E-trending foliation is interpreted to represent the axial planar foliation of the Resolution anticline, in which case this would be a late-developed D_3 fold (Swager and Griffin, 1990). Alternatively, this foliation could be related to a north-northeast–trending dextral shear zone (possibly D_4, Fig. 3) located immediately to the east of King's Battery.

Timing of mineralization

In the northern wall of Hampton-Boulder, ultramafic rocks displaying a steep lineation contain grains of chromite rimmed by magnetite and grains of pyrite. Magnetite and/or chromite grains commonly deflect the S_2 foliation and are elongated along the foliation, indicating their presence during shearing. This contrasts with smaller euhedral pyrite grains that do not deflect the fabric (Fig. 9a), suggesting that they overprint S_2 foliation. Figure 9b shows that gold is related to these pyrite grains and is also late. Similar relationships could not be determined in samples from within the D_3 sinistral shear zones because of the small size of the pyrite grains. These limited observations are in accordance with the conclusions of Copeland et al. (1998) that gold mineralization is late in the metamorphic-structural sequence as it is associated with retrogression assemblages. This is also in accord with Witt (1993), who considered that microstructures and larger scale relationships, such as vein orientations and steeply plunging porphyry boudins, suggested left-lateral strike-slip movement during gold mineralization and therefore argued for a syn-D_3 mineralization.

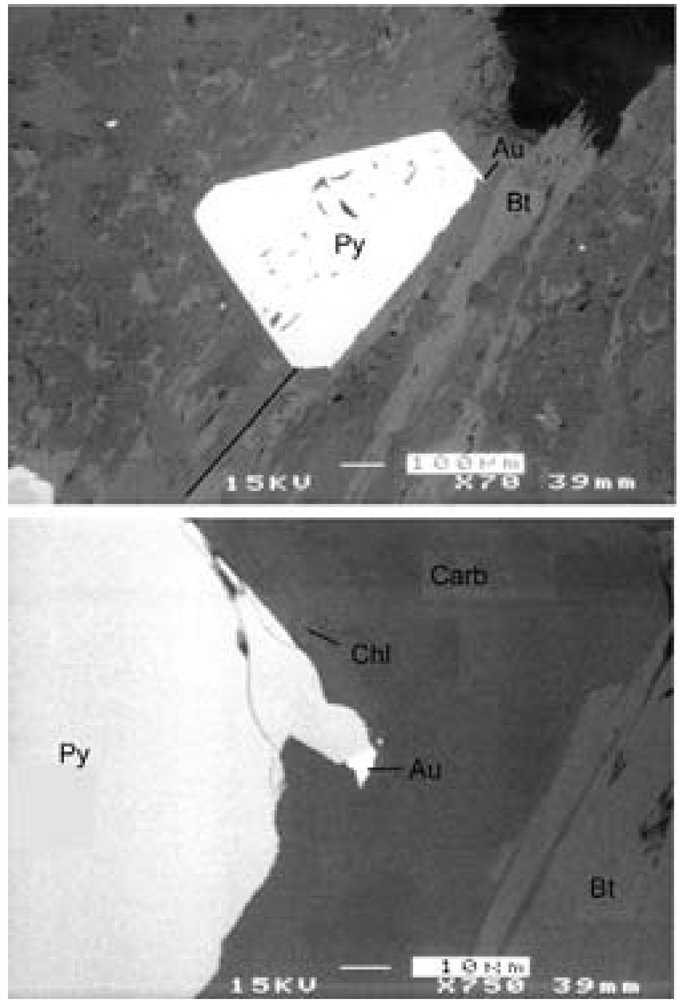


FIG. 9. Scanning electron microscope (SEM) image of ultramafic schist collected from within the early, steep, reverse D_2 shear zone, at the north face of the Hampton-Boulder pit. The thin section was cut perpendicular to foliation (N 15° W/80° W) and parallel to lineation (S/70°). a) Coarse euhedral pyrite grain in a zone of talc-chlorite-carbonate-biotite alteration. The foliation (marked by a thin black line) is unaffected by the pyrite grain, suggesting that the pyrite grain grew over a preexisting fabric. This is typical of all pyrite grains observed in this rock and contrasts with magnetite grains which deflect the foliation. The pyrite grain has a protrusion on its upper right side (b) which shows a bleb of gold in contact with the pyrite suggesting that, like pyrite, gold postdated D_2.

In summary, the structures documented in this district suggest a change from a D_2 horizontal shortening and vertical extension event giving rise to the dominant north-northwest–trending fabric, to a D_3 north-northwest–trending sinistral shearing. The narrow widths of strike slip shear zones suggest a modest amount of sinistral movement, in accordance with regional estimates of no more than 12-km apparent displacement (Langford, 1989). Although north-northeast–trending dextral shear zones were documented at Hampton-Boulder, kinematic indicators do not confirm early reports of important dextral shear parallel to the Boulder-Lefroy shear zone in this district (e.g., Mueller et al., 1988).

The width and intensity of D_2 structures suggest that this was an important deformation phase in the early stages of the Boulder-Lefroy shear zone and of the Kalgoorlie orogen.

Kambalda- Saint Ives Goldfield

Like the New Celebration district, the main geologic feature of this southern district is a regional-scale anticlinal dome, known as the Kambalda anticline, cut by regional shear zones (Fig. 10). The Kambalda-Saint Ives goldfield has a number of large gold and nickel deposits associated with metamorphosed Archean mafic-ultramafic volcanic and intrusive rocks and sedimentary rocks.

Previous studies

Gold deposits in the district are mainly disseminated in shear zones or hosted by quartz veins or breccia, localized within low-displacement reverse shear zones, up to 1,000 m long (Nguyen et al., 1998) with maximum displacement of up to a few hundred meters (e.g., Repulse fault: Watchorn, 1998). Many of the mineralized shear zones are developed in local structures adjacent to much larger north-northwest–trending regional shear zones, such as the Playa shear zone, to which they are interpreted to be kinematically related (e.g., Roberts and Elias, 1990; Nguyen et al., 1998). The Boulder-Lefroy shear zone is the major regional fault, and is considered to be the first-order structure from which the second-order Playa shear zone splays. The latter is the largest shear zone in the immediate vicinity of many gold deposits in the area and extends for about 10 to 15 km south of the Kambalda dome (Fig. 10).

Apart from the north-northwest–trending shear zones, the broader area south of Kambalda township is characterized by important and well-defined east-northeast–west-southwest–striking D_1 thrusts (Archibald, 1979) such as the Foster, Tramways, and Republican thrusts (Fig. 10; Swager and Griffin, 1990; Swager et al., 1992). The Tramways thrust has an inferred movement of south-over-north (Swager and Griffin, 1990) and is associated with a recumbent north-northwest–verging, east-northeast–trending, large-scale fold defined by the Tramways greenstones (Gresham and Loftus Hill, 1981; Griffin, 1990; R. Perriam, pers. commun., 2001). These early structures were later folded by D_2, leading to north-northwest–trending, upright, open folds, possibly associated with north-northwest–trending shear zones (see Griffin, 1990, table 18). M. A. Bennet (unpub. technical report 005, St Ives project R525, Western Mining Corporation, 1995) ascribed the framework of reverse faults to D_2, and these were later reactivated by D_3.

D_3 in Kambalda was different from that of the other districts in that it gave rise not only to steep strike-slip shear zones but also small-scale thrusts on the limbs and hinge of the open D_2 folds. Figure 11 summarizes the structural evolution of D_3 according to Bennet (1995). The different structures grouped under this same deformation phase require a continuous west-northwest–east-southeast σ_1 and a temporal switching of the other two stress axes. This stress system gave rise to a finite three-dimensional oblate strain ellipsoid characterized by a west-northwest–east-southeast maximum shortening axis and two extensional axes (i.e., a vertical axis related to thrusting and another oriented north-northeast–south-southwest related to strike-slip motion). The very last deformation event of this major deformation phase requires that a weakened west-northwest–east-southeast main stress axis became σ_3.

In general agreement with Bennet (1995), a study at Revenge (Nguyen et al., 1998) concluded that the structures, and their kinematic indicators related to gold mineralization, suggest a stress system with a gently plunging east-southeast σ_1 during mineralization (Fig. 11). Nguyen et al. (1998) defined two main types of shear zones: northwest-trending, subvertical first- and second-order regional shear zones, such as the Boulder-Lefroy and Playa shear zones, and smaller, more localized, east- and west-dipping mineralized shear zones. Watchorn (1998) grouped the deposits according to the mineralized structures: those where gold is hosted by 2- to 10-m-wide thrust zones, trending north or northwest and dipping moderately either east or west (e.g., Revenge, Defiance); and those hosted by steep north-northwest–trending fault zones (e.g., Britannia, Sirius).

Many authors concluded that gold mineralization took place during D_3 (e.g., Roberts and Elias, 1990; Bennet, 1995, Nguyen et al., 1998; Watchorn, 1998). Compston et al. (1986) concluded that gold was emplaced following the peak of metamorphism at 2660 Ma, and Watchorn (1998) concluded that mineralization took place after D_2 upright folding, in broad agreement with Bennet (1995). The age of retrograde carbonation at Victory was determined by U-Pb dating of rutile at 2627 ± 7 Ma (Clark, 1987). These carbonated rocks are overprinted by metasomatic alteration associated with gold, and mineral fabrics associated with this later alteration indicate gold deposition during and after shearing (Clark, 1987). The last episode of mineralization associated with nonfoliated biotite overprinting all D_3 fabrics at Victory was dated at 2601 ± 3 Ma (^{40}Ar-^{39}Ar age for metasomatic biotite, Clark, 1987). However, Snee et al. (2003) indicated that the decay constant used for calculation of the ^{40}Ar-^{39}Ar date should be corrected, yielding ages that are approximately 1 percent older and therefore indistinguishable from the U-Pb date. The U-Pb date is similar to the inferred mineralization age of 2631 ± 9 Ma determined by Nguyen (1997) at Revenge by means of U-Pb SHRIMP dating of hydrothermal monazite from gold-bearing, quartz-pyrite veins and also to dates determined for mineralization at Kalgoorlie (e.g., 2638 ± 6 Ma Oroya shoot: McNaughton et al., 2005).

Structural analysis

The Kambalda-Saint Ives goldfield differs from New Celebration in that many controlling shear zones are moderately dipping (Fig. 12). The attitudes of the gently dipping shear zones exposed in North Orchin, Victory-Defiance, and Repulse are plotted in Figure 13a, together with their south or southeast gently plunging mineral and stretching lineation, which coincide with the orientation of regionally dominant mineral lineations (R. Perriam, pers. commun., 2001). Structural analysis of data collected as part of this study in the North Orchin, Victory-Defiance, Britannia, and Sirius open pits is here compared with data for Revenge (Nguyen et al., 1998) and with the structural evolution proposed by Bennet (1995). As in previous studies in the region, the structural information is first separated into that related to gently dipping structures and that from steep structures.

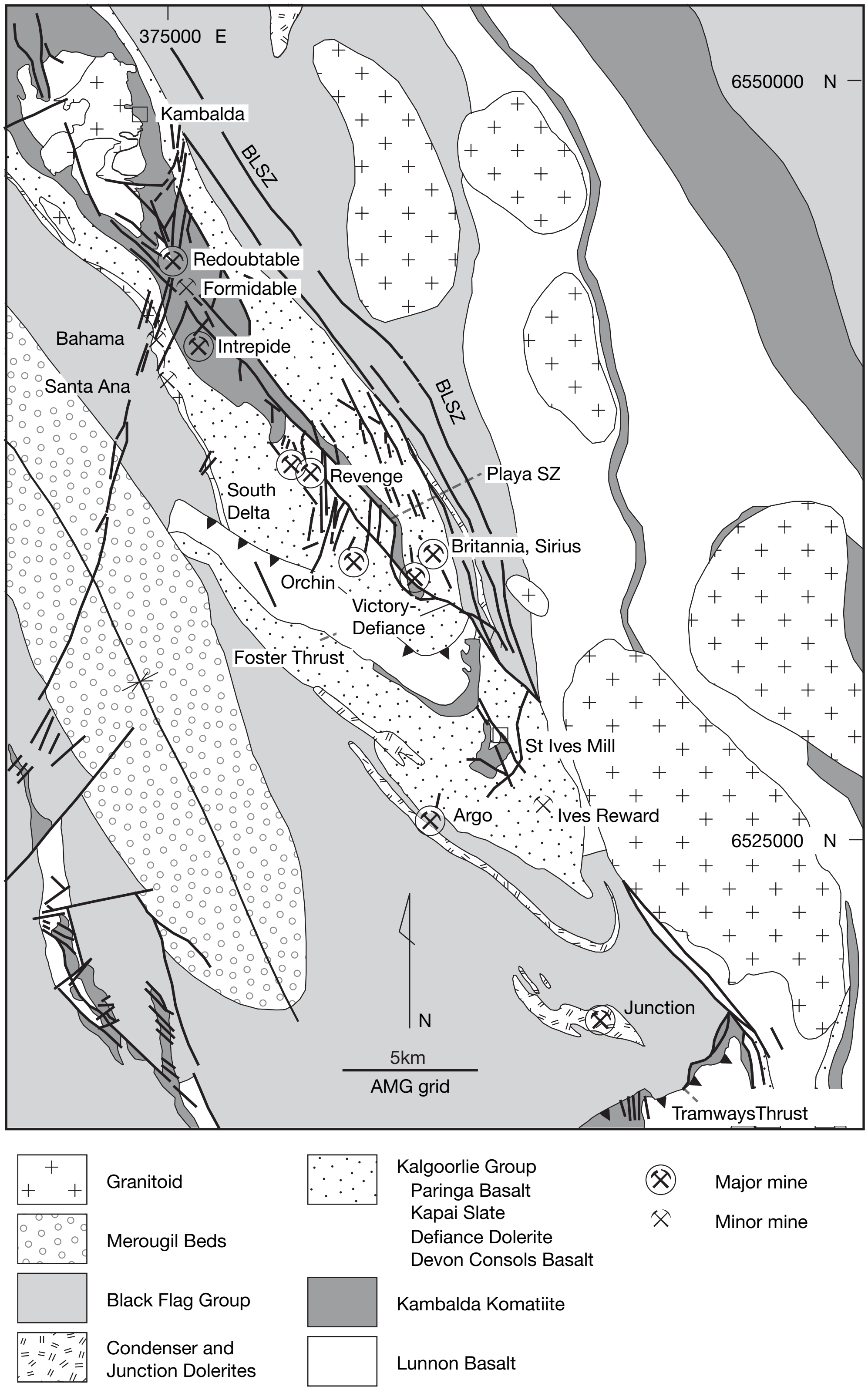


FIG. 10. Geology of the Kambalda area redrawn by S. Hagemann from Watchorn (1998). The Repulse shear zone links with the Playa shear zone and is the small curved fault that runs through the Victory deposit.

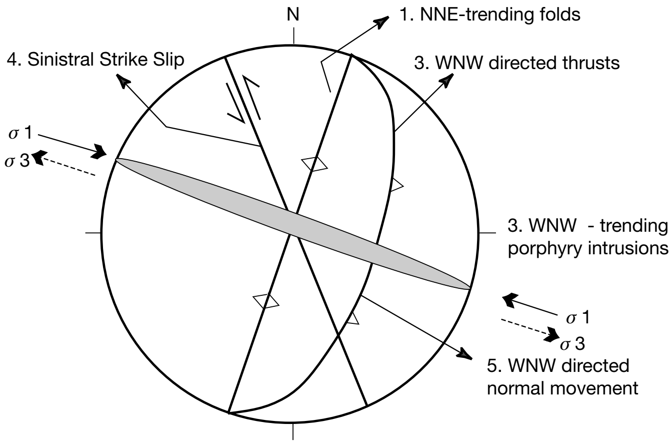


FIG. 11. Schematic stereonet projection of the structures developed during D_3 at the Kambalda-Saint Ives district, according to Bennet (1995), and interpreted orientation of the maximum shortening axis. 1 = early folding along north-northeast axes, refolding a north-northwest fold to give rise to domal structures; 2 = west-northwest–striking, steeply dipping porphyry dikes cut north-northeast–trending folds; 3 = west-northwest–directed thrusts (such as the Defiance C32 and C33 in Victory-Defiance, Revenge N01, and Orchin shear zones; Fig. 10) cut these dikes and some of them host gold mineralization which is contemporaneous to shearing (Nicholson, 1995); 4 = preexisting north-northwest–striking, D_2 shear zones such as Repulse, Britannia, and Sirius faults are reactivated; 5 = the final stage of D_3 is normal dip-slip movement in a west-northwest–east-southeast direction. Structures 1 to 4 are all related to the same west-northwest–east-southeast maximum shortening axis (z) but 5 requires a change to west-northwest–east-southeast x strain axis (dashed arrow).

Gold in North Orchin is hosted by the NS/45°–50° E A2 shear zone. The asymmetry of fibrous tails around pyrite grains (Nicholson, 1995), subhorizontal quartz veins, asymmetric folds, and S-C fabric within the A2 shear zone all indicate a reverse sense of movement. Bands, 2 cm wide with a normal sense of shear (S-C fabric), overprint the early reverse structures (also noted by Bennet, 1995, as late D_3 event). Minor isoclinal folds have inclined axial planes, parallel to foliation within the thrust, and a gently plunging fold axis toward N 20° E nearly parallel to localized crenulation lineation within the thrust (N 30° E/10°; Fig. 13a). These isoclinal folds and crenulation are interpreted to be related to the thrusts, as these structures indicate northeast-southwest shortening.

FIG. 12. Gently dipping, sheared contact between carbonaceous, pyritic Kapai Slate above and basalt below, at the North Orchin mine (Fig. 10).

The Victory and Defiance orebodies are separated by the Repulse shear zone. This shear zone is part of a group of listric faults that splay from a common sole thrust at depth, which in turn seems to splay off the steeply dipping Playa fault (Nguyen et al., 1998, fig. 6). The Repulse shear zone has a combined sinistral and reverse displacement of 300 to 600 m in a west-northwest direction, as defined by marker offsets (Bennet, 1995). Where exposed in the pit, the shear zone is approximately 50 cm wide, strikes N 22° W/45° E, with a stretching lineation plunging 130°/25° and S-C fabric which confirms the sinistral-reverse sense.

Despite differences in attitude of the shear zones in both the North Orchin and Victory-Defiance mines and a thrust plane mapped in the Britannia pit, stretching lineations are roughly parallel and nearly perpendicular to the fold and/or crenulation axes (Fig. 13a). Together with their sense of shear, the orientation and kinematics of the structures suggest a subhorizontal, west-northwest–east-southeast–trending, maximum shortening strain axis (z) and a vertical maximum extension axis (x). This is similar to the conclusions of Bennet (1995) and Nguyen et al. (1998).

The attitudes of the steep shear zones in Britannia and Sirius and that of the Playa shear zone (from Nguyen et al., 1998) are plotted together with the documented stretching lineations in Figure 13b. The shear zones investigated at the Britannia and Sirius deposits have steep dips and sinistral strike-slip shear sense. Their strike and dip change with depth and distance from the pits and are interpreted as listric faults related to the Repulse shear zone described above (Watchorn, 1998; Fig. 10). The exposures at Britannia reveal the main, steep mineralized shear zone, striking N 30° W/80° E, and subhorizontal mineral lineations and kinematic indicators (S-C fabric), indicating sinistral sense of shear. This shear zone cuts across 20- to 30-cm-wide, older, gently dipping shear zones (N 50° W/25° SW, plotted in Fig. 13a), with parallel quartz veins in their cores and drag folds on their margins that define reverse movement. These older shear zones have a similar orientation to the west-dipping shear zones described at Revenge (Nguyen et al., 1998), including the presence of quartz veins in their cores. At Sirius, the main shear zone strikes N 20° W/70° E and has subhorizontal mineral lineations and S-C fabrics, indicating sinistral sense of shear. Evidence for older deformation is preserved between anastomosing strike-slip planes associated with alteration, as a steep mineral lineation in unaltered basalt, and is in accordance with the interpretation of E. Baltis (pers. commun., 2001) that the Sirius shear zone initially formed as a reverse fault, linked at depth to the Repulse thrust. This interpretation is also supported by the listric geometry of the Britannia and Sirius shear zones, which suggests that they started out as reverse faults and not as strike-slip faults which more commonly have steep attitudes.

Assuming that the inferred strain axes are parallel to stress axes, the method of Fry (1992) for determining maximum shear orientation on any given plane is applicable. All recorded mineral lineations and senses of shear in North Orchin, Victory-Defiance, and Britannia may be explained by

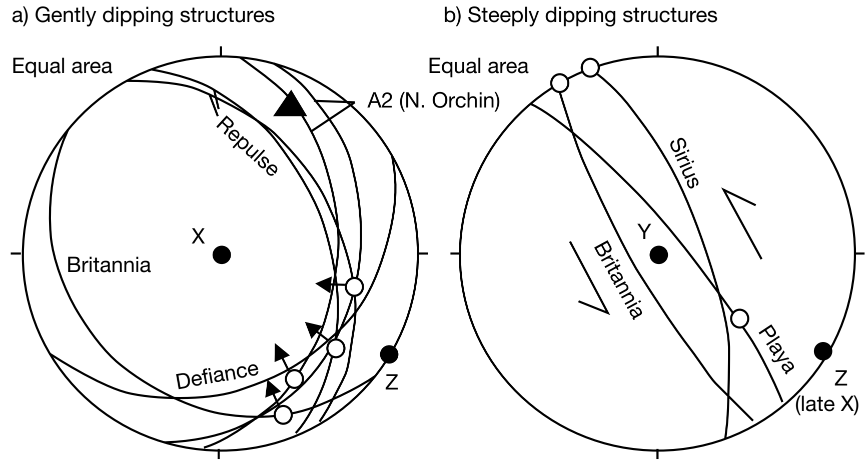


FIG. 13. (a). Lower hemisphere equal area stereonet projection of major gently dipping structures from the North Orchin (A2 shear zone), Victory-Defiance (Defiance and Repulse shear zones), and Britannia deposits, as well as stretching and mineral lineations (dots in great circles). Arrows on dots correspond to the documented reverse movement direction; black triangle corresponds to the orientation of D_3 fold axes and crenulation lineation. (b). Major steeply dipping shear zones at Playa (from Nguyen et al., 1998), Britannia, and Sirius. Dots correspond to stretching and mineral lineations, and arrows indicate inferred sinistral shear sense. Interpreted orientations of the strain axes are indicated.

a nearly uniaxial compression. Using Fry (1992), the mineral lineations and kinematics associated with the steep shear zones mapped at Britannia and Sirius (Fig. 13b) can be explained by the same stress system. However, the same system does not give rise to the moderate southeast-plunging lineation on the Playa shear zone (Fig. 13b).

Within the sinistral shear zone at Sirius, a narrow band (~20 cm wide) with dextral S-C fabric was found. Also within the A2 thrust plane at Orchin, a decimeter-scale band within the thrust plane has S-C fabric, indicating normal sense of movement. Such movements had previously been recorded by mining personnel (Bennet, 1995; E. Baltis pers. commun., 2001) and suggest a relaxation of the maximum stress axis after thrusting and sinistral shearing (as indicated in Fig. 11).

Interpretation

The structures described in this section focus on the well-exposed open pits related to gold deposits formed in the vicinity of the Boulder-Lefroy shear zone. The Boulder-Lefroy shear zone itself is very poorly exposed in this area, so the evolution of the system can only be understood through the structural record documented in the open pits. In addition, many other gold deposits in the district have not been considered in this study, and the five deposits that were studied in detail may not provide a complete view of its deposits. Nevertheless, the observations in this study support Bennet's (1995) conclusion that thrust planes and strike-slip faults belong to the same deformation phase, which overprints earlier formed north-northwest–trending open folds. The open north-northwest–trending large-scale folds represent the regional D_2 and resulted from a compressional deformation regime with vertical extension and the maximum shortening strain axis, z, oriented east-northeast–west-southwest. The broadly northwest-directed thrusts that reactivate the limbs and hinges of these earlier folds represent D_3 structures (Fig. 13a), which also include the associated steep sinistral shear zones (Fig. 13b) and a number of other structures detailed in Figure 11. As in the New Celebration district, the change from D_2 to D_3 is associated with a clockwise rotation of the maximum shortening strain axis, z, from east-northeast–west-southwest to east-southeast–west-northwest. The fact that thrusts are associated with strike-slip shear zones during D_3 is a result of strain partitioning of an oblate strain with important components of vertical and horizontal extension. In this context, gold mineralization started during D_3, as indicated by the strong control of D_3 steeply dipping sinistral shear zones and gently dipping thrust structures on gold mineralization, dated at ca. 2630 Ma (Clark, 1987).

Kalgoorlie District

The Kalgoorlie district lies approximately 40 km north-northwest along the Boulder-Lefroy shear zone from New Celebration. The Boulder-Lefroy shear zone is the major through-going shear zone in the district, and the deposits lie 1 to 2 km west of the shear zone and are associated with a regional antiform. It is the most endowed region in the Yilgarn craton with respect to gold. A number of workers have described the gold mineralizations and the structural evolution of the district (e.g., Phillips, 1986; Boulter et al., 1987; Mueller et al., 1988; Swager, 1989a; Clout et al., 1990; Phillips et al., 1996; Scott, 1997; Ridley and Mengler, 2000), but there is limited agreement on the sequence of events, characterization of regional deformation phases, or the timing of mineralization (summarized in Keats, 1987).

The Golden Mile, the most important deposit, is a sheared, intensely mineralized system which produced over 90 percent of the total production of the Kalgoorlie district. The remainder came from smaller but significant deposits such as Mount Charlotte, a system of extensional quartz veins (Ridley and Mengler, 2000). Like the other two world-class districts described previously, the Kalgoorlie district is characterized by a large-scale anticline, the Boomerang anticline, which exposes the deeper part of the greenstone stratigraphy (Table 1) and intrusive dolerites (Fig. 14). The anticline is cut by the Boulder-Lefroy shear zone, which places these deeper rocks into contact with Black Flag Group sedimentary rocks. The shape, size, and rock types exposed in the Boomerang anticline are similar to those in the Celebration anticline described above.

The sinistral shear sense on the Boulder-Lefroy shear zone has been inferred by Swager (1989a) from the en echelon distribution of large-scale folds along the shear zone, the asymmetric curving of minor folds, and from marker displacements described herein for New Celebration. However, partly because of poor exposure and partly because of the absence of markers, there is presently no direct evidence of the shear sense on the Boulder-Lefroy shear zone in the Kalgoorlie district. Seismic studies reveal that the district lies atop a large triangular-shaped rock mass bounded by reverse shear zones with opposite dips (Goleby et al., 2002). These listric shear zones sole into a regional-scale detachment plane, which limits the thickness of the greenstone sequence to 5 to 9 km. A seismic reflection profile (line 97AGSK4: Owen et al., 2001) crossed the Boulder-Lefroy shear zone immediately south of the Golden Mile. The image produced is not simply interpreted, given the field relationships observed at the

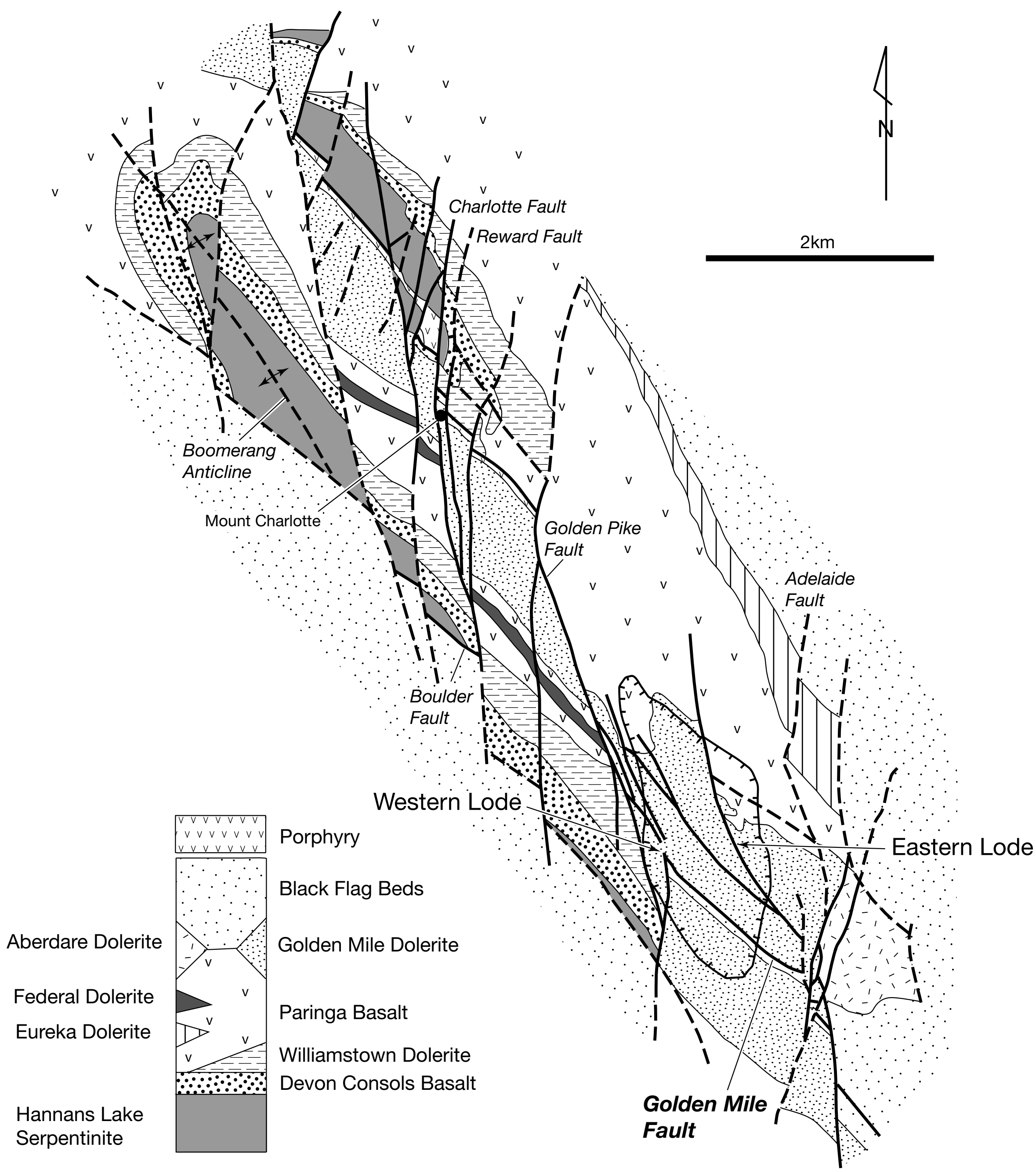


FIG. 14. Geology of the Kalgoorlie district. Map modifed after Clout et al. (1990) and Bateman (2001).

surface. Bateman et al. (2001) concluded that a complex history is implied by the seismic data, with dominant east block-up reverse faults and minor west block-up reverse faults being essentially synchronous in broad terms and part of the D_2 event. The reflector that coincides with the Boulder-Lefroy shear zone at the surface dips west and was interpreted as a thrust with complex relationships with other west- and east-dipping thrusts.

According to Bateman et al. (2001), the earliest recognizable event was thrusting along the Golden Mile fault, ascribed to D_1. This thrust is localized within black shales (Fig. 15), is virtually parallel to bedding, and caused repetition of the greenstone stratigraphy due to east-over-west movement. In this paper this earliest deformation phase is termed $D_{1(local)}$ to emphasize that it might not relate to the regional D_1. Another $D_{1(local)}$ structure is the hanging-wall Kalgoorlie anticline (Bateman et al., 2001), with no equivalent synclinal closure at depth (Mueller et al., 1988; Swager, 1989a; Clout et al., 1990; Bateman et al., 2001). $D_{1(local)}$ structures are disrupted by major D_2 east- and west-dipping shear zones with reverse senses of movement, which include the Boulder-Lefroy shear zone, as suggested by seismic sections and supported by the kinematics of small-scale shear zones with equivalent orientations (e.g., Flanagan fault, Mueller et al., 1988; Clout et al., 1990).

The local D_1 structures of Bateman et al. (2001) are roughly parallel to the regional north-northwest–south-southeast D_2 fabric, and their origin can be interpreted to be related to the regional D_1, rotated during D_2 to their present trend, or to be early D_2 structures, abandoned as they steepened and locked up, and cut by younger gently dipping D_2 thrusts and folds. We suggest that the latter is more likely in view of the steep reverse D_2 structures described in the New Celebration and Kambalda-Saint Ives districts.

$D_{1(local)}$ structures, including the Golden Mile fault, have been folded by the Boomerang anticline, which has been ascribed to both D_2 and D_3 by different workers. Swager (1989a) and Bateman et al. (2001) suggested that the Boomerang anticline is part of D_3 because of its steep (>60°) north-plunging hinge, in contrast to the gently plunging, northwest-trending hinges of D_2 folds, such as the Celebration anticline (Swager, 1989a). A more likely alternative is that both the Boomerang and Celebration anticlines formed during D_2 in association with thrusts and that their different axes resulted from regional variation in attitudes of previously deformed rocks (e.g., $D_{1(local)}$).

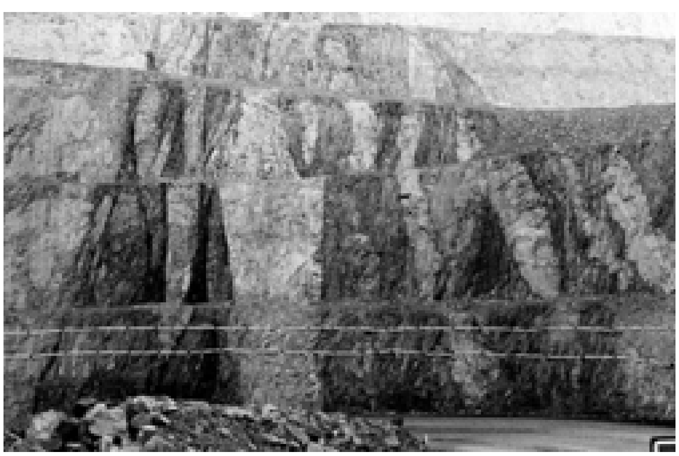


FIG. 15. The Golden Mile fault (see Fig. 14), an early shear zone developed within carbonaceous shale (dark gray) and including numerous felsic lenses altered to quartz, ankerite, and fuchsite (V mica). The latter could represent either disrupted porphyry dikes or slices of volcaniclastic rocks. Dolerite crops out on both sides of the Golden Mile fault. The lowest bench is approximately 20 m high.

As described previously, Swager (1989a) suggested that the Boulder-Lefroy shear zone as a sinistral wrench fault. However, if the Boomerang anticline is part of D_2, there is no direct evidence in Kalgoorlie to support this interpretation. The only local evidence to suggest sinistral shearing is related to a north-south and north-northeast–south-southwest set of ductile, dextral shear zones that segment the anticline (e.g., Mueller et al., 1988). Their en echelon distribution suggests that they are associated with a deeper throughgoing north-northwest–trending sinistral shear zone. These dextral shear zones are interpreted as part of the D_3 event because they clearly overprint earlier D_2 structures and because they were later reactivated by brittle, dextral D_4 faults a few kilometers long, with a few hundred meters of displacement (Ridley and Mengler, 2000). D_4 also gave rise to new north-south–trending, dextral brittle faults.

Mineralization

The Kalgoorlie district is characterized by three different styles of mineralization which have been interpreted to represent a protracted, polyphase mineralization history (Bateman et al., 2001). Most of the gold is in Fimiston-style lodes, the earliest mineralization, which host over 1,000 t of gold. This was closely followed by the deposition of the Oroya-style lodes, which include the Oroya shoot (60 t gold), and the third and last mineralization type known as the Mount Charlotte-style quartz veins which contained 15 t of gold.

Fimiston lodes are hosted by the Golden Mile Dolerite and the Paringa Basalt (Fig. 16). They are individually up to 2 km in length and occur over a total strike length of close to 7 km north-south and 1.3 km in known vertical extent (Bateman et al., 2001). They have a range in attitudes, with the majority striking north-northwest with a steep southwest dip (Clout et al., 1990).

Oroya-style lodes are essentially similar to the Fimiston lodes but characterized by the most intense alteration and mineralization in the district and famous for the intensity of its Au-Te mineralization and "green-leader" alteration with high contents of V in mica and various oxides (Bateman et al., 2000). Structurally, the 1,500-m-long Oroya shoot differs from the Fimiston lodes in that it formed in a dilational jog within shear zones along the contact between the Golden Mile Dolerite and the Paringa Basalt (e.g., Lungan, 1986), whereas Fimiston lodes abut against the shear zones, which host the Oroya shoot (Fig. 16).

Mount Charlotte-style mineralization also occurs in the Golden Mile but typifies the Mount Charlotte and Mount Percy deposits, a few kilometers to the north. This style of mineralization is characterized by strictly dilational quartz vein swarms which clearly crosscut Fimiston-style lodes (e.g., Ridley and Mengler, 2000; Bateman et al., 2001). In the Mount Charlotte and Mount Percy deposits, gold is hosted by

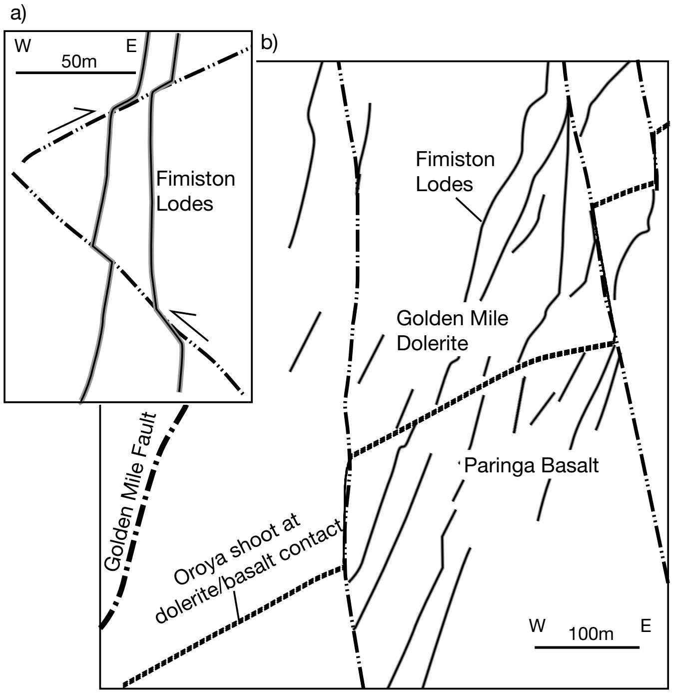


FIG. 16. (a). Fimiston Western lodes (west of the Golden Mile fault) cut across and are displaced by D_2 thrusts. (b). Steep Fimiston Eastern lodes (solid lines east of the Golden Mile fault), abutting against the moderately west dipping Oroya shoot (thick single-dashed line), which is sited at the contact between the Golden Mile Dolerite and the Paringa Basalt. Both the Fimiston lode and the Oroya shoot are cut by steep D_3 faults (double-dashed lines). Figures redrawn from Bateman et al. (2001).

a competent, FeO-rich rock embedded in low competency surroundings (Johnston et al., 1990; Vanderhor and Groves, unpub. report for MERIWA project 195, 1996). The main controlling structures are north-trending D_4 faults, particularly reactivated D_2 faults, known collectively as the Charlotte set (Boulter et al., 1987).

Timing of mineralization

Structural relationships and style of mineralization suggest multiple and protracted gold mineralization events. A number of interpretations have been proposed for the relative timing of the different styles of mineralization. Current controversy centers on the total duration of the mineralization processes and whether the Fimiston lodes and Oroya shoot represent a single or two temporally distinct events.

SHRIMP U-Pb dating of zircons from a lamprophyre dike interpreted to be contemporaneous with the Oroya mineralization yields an age of 2638 ± 6 Ma (McNaughton et al., 2005), which is similar to other ages for the southern Kalgoorlie terrane (Vielreicher et al., 2003). Kent and McDougall (1995) determined ^{40}Ar-^{39}Ar ages on hydrothermal muscovite samples associated with gold systems from both the Mount Charlotte and Golden Mile deposits and published two dates interpreted to represent the time of mineralization, 2602 ± 8 and 2629 ± 9 Ma, respectively. Recent reexamination of the analytical data and the standards used to determine that the younger Ar-Ar age should be corrected upward by ~1 percent to ca. 2630 Ma (Snee et al., 2003). Thus, the development of the Oroya shoot and the Mount Charlotte mineralization can be constrained to within 1 percent or 30 m.y. uncertainty inherent between different age determination methods.

Presently the dating of events allows for multiple and often contradictory interpretations. Recently, Bateman et al. (2001) concluded that the Fimiston lodes were early tectonic breccias and veins that filled open cavities, which were overprinted by foliation in some instances. They argued for a pre- or syn-$D_{1(local)}$ age for the Fimiston lodes based on local structural relationships. A key point in their argument is that, except for mineralized felsic dikes, the Fimiston lodes are overprinted by all other structures, including the Golden Mile fault ($D_{1(local)}$), the D_2 thrusts hosting the Oroya shoot (Fig. 16a), and the D_3-D_4 strike-slip shear zones (Fig. 16b).

The crosscutting relationships in Figure 16b support the argument that the Fimiston lodes and Oroya shoot represent two separate mineralizing events. However, the recognition that the alteration in both is essentially identical and anomalous in terms of Te and Au contents and V micas compared to other deposits in the region supports the argument that they are part of the same mineralizing event. Therefore, the apparent crosscutting relationship may be a consequence of the steep Fimiston lodes not propagating across the thrust plane because of the changes in stress and rheology in the vicinity of the thrust plane. The same D_2 east-northeast–west-southwest–shortening event which produced the Fimiston lodes (e.g., Finucane, 1941) also gave rise to the thrust plane hosting the Oroya shoot. Thus the Fimiston and Oroya lodes most likely were formed during the same mineralization event, in structures developed during the same regional D_2 event, and structures ascribed to $D_{1(local)}$ are, in fact, early D_2 structures. Up to 25 m.y. later (the maximum age difference between the absolute ages), but possibly considerably less, the Mount Charlotte lodes were deposited during D_4.

In the Kalgoorlie district, as in New Celebration, gold deposits lie within a regional-scale anticline developed during the same D_2 event that gave rise to the thrust plane, which defined the Boulder-Lefroy shear zone. In contrast to the other districts, where major gold mineralization took place during D_3, the major Fimiston- and Oroya-style mineralization at Kalgoorlie took place during D_2. Evidence for sinistral D_3 shear zones have not been documented locally at Kalgoorlie, but en echelon, north- or north-northeast–trending, ductile, dextral shear zones (D_3) may be the surficial expression of a deeper sinistral shear zone. These dextral shear zones were later reactivated in a dextral sense in a brittle regime during D_4, which also gave rise to new parallel faults and to Mount Charlotte-style mineralization.

Discussion and Conclusions

Boulder-Lefroy shear zone: A two-stage history

In the New Celebration district, an early stage of development of the Boulder-Lefroy shear zone was characterized by crustal shortening (vertical extension, D_2). D_2 foliations and thrust planes are all steep (>60° dip), suggesting that they might have rotated to these comparatively unfavorable dips for reverse motion on the planes, by considerable penetrative straining. This was followed by a clockwise rotation of the maximum shortening axis from east-northeast–west-southwest to east-southeast–west-northwest and reactivation of early formed and steepened north-northwest–trending thrust planes by sinistral shear zones, associated with dextral shearing on north–north-northeast–trending planes (D_3).

In the Kalgoorlie district, documentation of structure within the Golden Mile together with seismic images supports the interpretation that the Boulder-Lefroy shear zone formed as a thrust plane. The earliest structures recognized in the district ($D_{1(local)}$) represent earlier steepened D_2 and locked-in structures, crosscut by newly formed active, moderately dipping thrust planes such as the one hosting the Oroya shoot (Fig. 16). In both districts the large-scale anticlinal crests exposing deeper rocks are interpreted as part of the crustal shortening phase, D_2. Reactivation of the Boulder-Lefroy shear zone during D_3 has not been documented in the Kalgoorlie district. The ductile, en echelon north-northeast–trending dextral shear zones segmenting the Boulder-Lefroy shear zone and the Boomerang anticline may represent the local expression of D_3. These were reactivated during D_4, which also gave rise to new north-northeast–trending brittle faults.

In the southern district of Kambalda-Saint Ives, it was not possible to determine the nature of the Boulder-Lefroy shear zone, so its history is inferred from the system exposed in the mines. In this district, D_2 gave rise to a south-plunging anticlinal crest characterized by gently dipping limbs. D_3 was expressed by the reactivation of lithological contacts on these gentle D_2 fold limbs and crests, in the form of northwest-directed thrusting, recording a clockwise rotation of the maximum shortening strain axis from east-northeast–west-southwest to southeast-northwest, similar to that recorded in New Celebration.

Based on the evidence presented here and on regional considerations, it is suggested that the Boulder-Lefroy shear zone system developed in two main stages (summarized in Fig. 17 and Table 2). The first stage resulted from D_2 crustal thickening and is defined by a number of north-northwest–south-southeast–trending thrust ramps arranged roughly along strike of the Boulder-Lefroy shear zone, with both east and west dips, as suggested by the seismic image at Kalgoorlie, and possibly linked by transform faults. These thrust planes developed in tandem and interacted with the roughly equidistant, large-scale anticlinal crest exposed in each district. At this stage, the Boulder-Lefroy shear zone was probably not a continuous plane but a system of reverse shear zones, where earlier formed thrust planes steepened with increased strain,

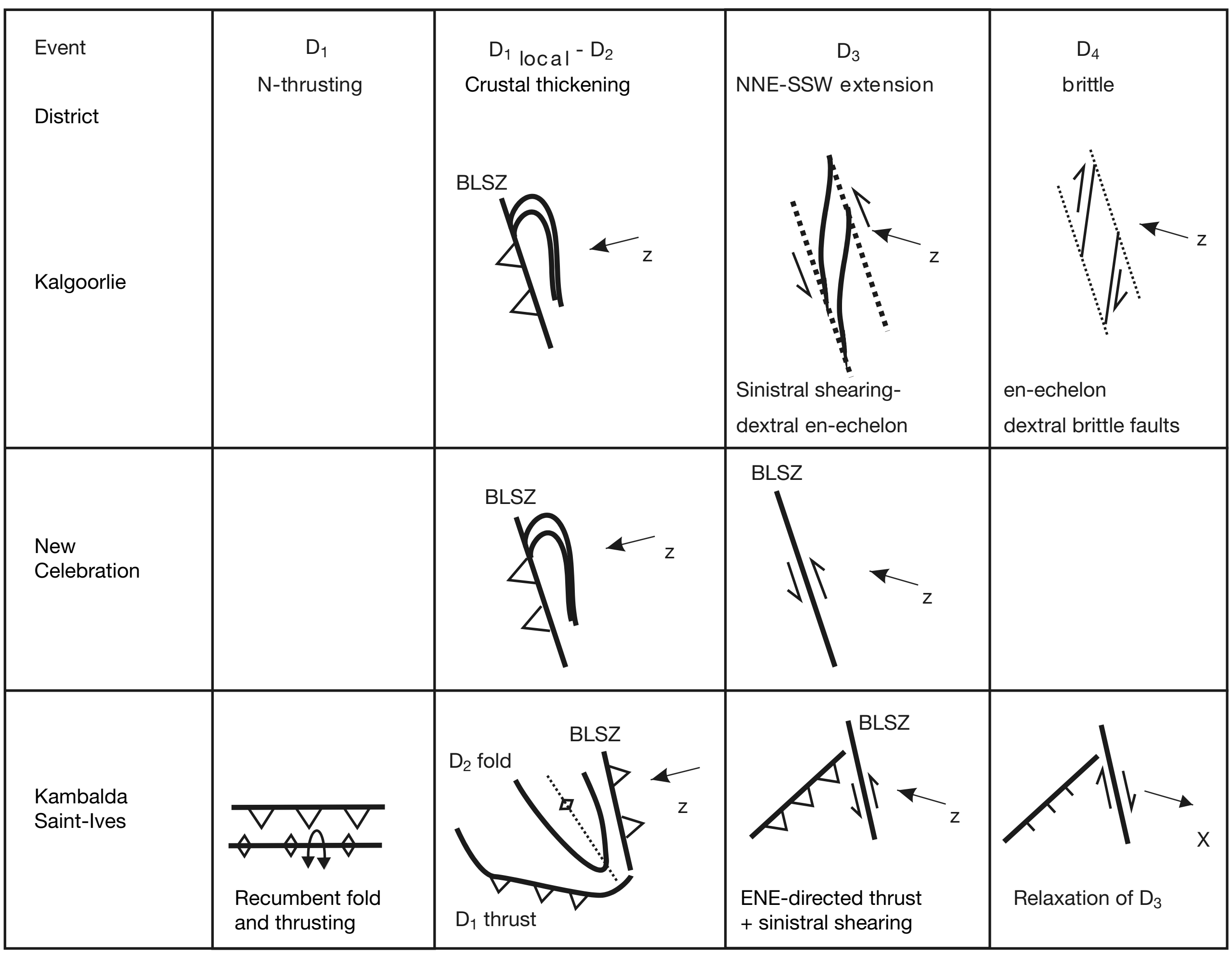


FIG. 17. Summary of the features developed during each major deformation phase in the three gold districts along the Boulder Lefroy shear zone (BLSZ). The maximum shortening and extension axes, z and x, respectively, are indicated.

became locked, and were abandoned as new thrust planes, and associated folds developed.

The second main stage is related to the regional D_3-D_4 deformation phases and is characterized by a reactivation of D_2 reverse shear zones by (1) north-northwest–trending sinistral shear zones at New Celebration with a total sinistral displacement <12 km (e.g., Langsford, 1989; Swager, 1989a), (2) north-northeast–trending dextral en echelon shear zones at Kalgoorlie (with displacements on the order of hundreds of metres), and (3) northwest-directed thrusting on fold limbs (with displacements on the order of hundreds of meters) or steep sinistral shear zones at Kambalda-Saint Ives. D_4 structures are best documented at Kalgoorlie and gave rise to minor but important brittle shearing which led to the Mount Charlotte mineralization (Ridley and Mengler, 2000).

We speculate that many of the thrust planes that formed the early Boulder-Lefroy shear zone underwent reactivation during D_3, as strain weakening and their north-northwest trend make them favorable sites for sinistral shearing during east-southeast–west-northwest–directed shortening. This reactivation may have led to the linking of the thrust planes along strike to form a continuous set of faults and strands. The modest total displacement recorded on the Boulder-Lefroy shear zone and its tortuous trace suggest that the sinistral deformation was not a major phase of wrenching (Wesnousky, 1988), as previously suggested (Swager, 1989a). More likely, the present complexity of the trace of the Boulder-Lefroy shear zone, with its numerous bends and jogs, suggests that the sinistral shear zone grew by the coalescence of early-formed isolated thrust planes.

In accordance with the published literature, D_3 and D_4 remain separate phases because their structures may be discriminated in the field and mark a temporal evolution from ductile to brittle deformation. However, because these two phases are apparently not separated by any significant time gap and indicate constant orientation of strain axes, they should be viewed as different expressions of a single deformation event as the crust cooled or strain rate increased and not as separate tectonic events.

The Larder Lake-Cadillac deformation zone in the southwest Abitibi makes an interesting comparison to the Boulder-Lefroy shear zone in that both developed broadly contemporaneously at greenschist facies conditions and both host world-class gold deposits. The east-west–trending Larder Lake-Cadillac deformation zone is interpreted by Wilkinson et al., (1999) to have represented a zone of bulk axial strain accumulation during north-south–directed shortening and greenschist facies metamorphism. Sectors deviating from that main east-west trend experienced either sinistral or dextral transpression during deformation, depending on their orientation. The next regional deformation event, characterized by northwest-southeast shortening, caused the reactivation of the deformation zone by dextral shearing (Wilkinson et al., 1999). The two deformation phases recorded in the Larder Lake-Cadillac deformation zone are essentially analogous to those recorded in the Boulder-Lefroy shear zone system, except that the latter initiated as a series of discontinuous thrust planes which evolved into a continuous feature through sinistral reactivation. In conclusion, the Boulder-Lefroy shear zone is not a wrench fault but formed by linking earlier formed thrust planes during modest sinistral strike-slip movement.

Fluid focusing

The anomalous endowment of the Boulder-Lefroy shear zone is most likely due to an efficient, multiscale, mechanism of focusing of mineralizing fluids. At the largest scale (10–100 km), the Boulder-Lefroy shear zone system controls gold mineralization. At the scale of 1 to 10 km, the next major control is the cropping-out crests of regional-scale anticlinal structures (see also Goleby et al., 2002) that, in the case of the Boulder-Lefroy shear zone system, form equidistant structures of similar size. At the district scale (1 m to 1 km), fluid focusing and mineralization were controlled by strong rheological contrasts within the volcano-sedimentary sequence. Thus, abundant competent intrusive rocks, such as dolerite (e.g., at the Golden Mile and Mount Charlotte) or granitic rocks (e.g., at Hampton-Boulder and/or Jubilee) within low-competency phyllosilicate-rich rocks, such as talc-chlorite schists abundant along the trend of the Boulder-Lefroy shear zone, provide ideal conditions for focusing of mineralizing fluids.

Timing of gold mineralization

Gold deposition along the Boulder-Lefroy shear zone took place during D_3 (e.g., Saint Ives and New Celebration districts) and D_4 (Mount Charlotte). Whereas detailed geochronology and structural evidence constrain the timing of most deposits along the Boulder-Lefroy shear zone to late in the tectonic history of the Yilgarn craton (2.64–2.63 Ga), there is controversy surrounding the timing of the Fimiston and Oroya lodes at the Golden Mile, by far the largest deposit in the Yilgarn craton. The similarity between the very anomalous alteration patterns of the Fimiston and Oroya lodes suggest the two are part of the same mineralizing event, geochronological and structural relationships suggest that these formed 25 m.y. or less before the Mount Charlotte mineralization style. While gold mineralization is generally late in the tectonic evolution of the belt, current discussion focuses on whether the richest deposit at Kalgoorlie may have had a protracted history.

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