

# Stratigraphy of the Proterozoic Revett Formation and Its Control on Ag-Pb-Zn Vein Mineralization in the Coeur d'Alene District, Idaho

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## Abstract

The Proterozoic Revett Formation hosts most of the mesothermal Ag-Pb-Zn vein ore in the Coeur d'Alene district of northern Idaho. Although it had long been recognized that stratigraphy plays a fundamental role in determining where veins produce ore, the stratigraphy of the Revett Formation and its relationships to veins remained poorly known for most of the first 100 yr of mining in this district.

In northern Idaho and western Montana, the Revett Formation contains informal lower, middle, and upper members. In the Coeur d'Alene district, most ore production south of the regionally significant Osburn fault came from the upper Revett Formation, and north of the fault, most production came from the upper and lower Revett Formation. Where vein structures intersect favorable strata, the veins contain rich ore; where vein structures cross unfavorable strata, they are poorly mineralized or barren. Quartzite is the most favorable host rock for base metal veins, and silicified blocky siltite is the most favorable host rock for silver veins. Both rock types are abundant in the Revett Formation, which accounts for the disproportionately large production from this unit. In the western portion of the Belt Supergroup, ore deposit types correlate with regional-scale thickness changes in the Revett Formation: sediment-hosted stratiform copper mineralization occurs in thin Revett Formation, whereas Coeur d'Alene veins occur in thick Revett Formation. Base metal veins in the Coeur d'Alene district occur in relatively thick, chemically reduced, relatively coarse grained Revett Formation, whereas silver veins occur in, or marginal to, areas with less thick, locally oxidized, relatively fine grained Revett Formation, demonstrating that district-scale metal zonation correlates with district-scale facies and thickness changes.

The upper, middle, and lower Revett Formation thicken considerably southward across the Osburn fault, with the upper Revett showing over an order of magnitude thickness increase. Changes in thickness of the Revett Formation across the Osburn fault reflect a major, down-to-the-south, crustal-scale fault that was active during sedimentation and was periodically reactivated during the structural and metallogenic history of the district. We suggest that this fault and changes in stratigraphic thickness helped control fluid flow within and beyond the Coeur d'Alene district during mineralization events. Stratigraphic thickness and facies changes in the Revett Formation are greatest and most abrupt in the Coeur d'Alene district, indicating that this area was structurally complex during sedimentation. Presumably, this early structural complexity also enhanced subsequent Ag-Pb-Zn mesothermal vein formation.

## Introduction

THE COEUR D'ALENE mining district of northern Idaho is the second largest producer of silver in the world, having produced over 34,000 metric tons (t) of silver, together with 7.2 million metric tons (Mt) of lead and 2.8 Mt of zinc (Long, 1998). Although structurally controlled, the veins in the Coeur d'Alene district are profoundly influenced by stratigraphy. The host rocks for these veins are Middle Proterozoic metasedimentary rocks of the Belt Supergroup, and one unit, the Revett Formation, hosted approximately 70 percent of the ore that has been produced from the district (extrapolated from data in Mitchell and Bennett, 1983). This paper builds on a U.S. Geological Survey Open-File Report (Mauk, 2002), which archives detailed stratigraphic information from many localities throughout the Coeur d'Alene district and documents abrupt and major changes in stratigraphic thicknesses, sedimentary facies, and redox states of the metasedimentary rocks in the district. In this paper, we summarize these

changes and then discuss how these changes have significant implications for mine, district and regional structural geology and mapping, basin architecture, district-scale fluid flow, alteration halos, district-scale metal zonation, and regional metallogeny.

## Regional Geology

Metasedimentary rocks of the Middle Proterozoic Belt Supergroup crop out over much of eastern Washington, northern Idaho, western Montana, and southeastern British Columbia (Fig. 1). The Belt Supergroup contains four major stratigraphic divisions: the lower Belt, the Ravalli Group, the middle Belt carbonate interval, and the Missoula Group (Harrison, 1972; Fig. 2). In much of western Montana and northern Idaho, the Burke, Revett, and St. Regis Formations form the Ravalli Group, and their type areas are in or near the Coeur d'Alene mining district. Ravalli Group rocks have been interpreted as having formed in several depositional environments, including deltaic (Boyce, 1973), turbiditic (Hrubar, 1971, 1973), alluvial fan (White and Winston, 1982), sheet

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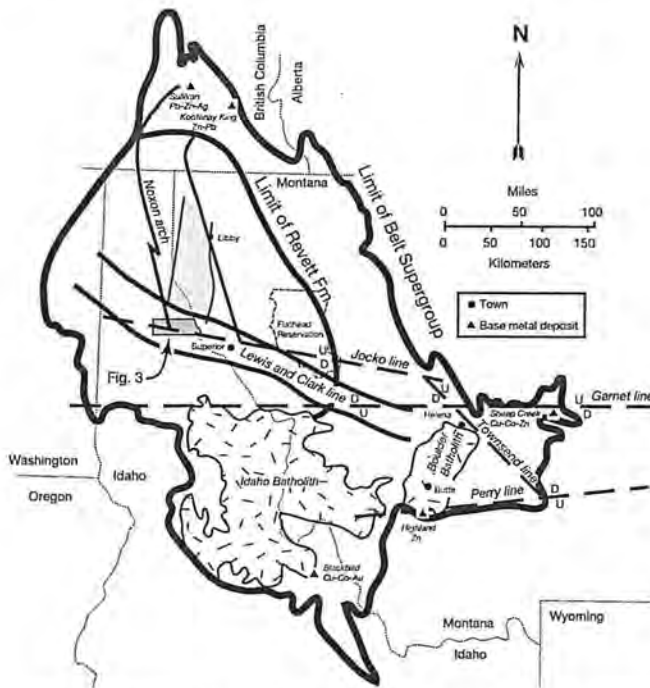


FIG. 1. Map showing location of Belt terrane (heavy bold line), western Montana copper sulfide belt (lightly stippled), Coeur d'Alene mining district (dark stipple), base metal deposits in the lower Belt (triangles), inferred Proterozoic structures (medium lines), limit of the Revett Formation (bold line), and outline of the Flathead Reservation (dashed line). The Lewis and Clark line is a 50-km-wide zone with abundant faults, whereas the Jocko line is a proposed down-to-the-south Proterozoic fault. Compiled from Hobbs et al. (1965), Harrison (1972, 1974), Harrison et al. (1974), Winston (1986, 2000), and White (2000).

floods on alluvial aprons (Winston, 2000), alluvial and/or fluvial with a marine influence (Luepke and Lyons, 2001), and beach, nearshore slope, and subtidal channel environments (Hayes and Einaudi, 1986). The Revett Formation was deposited between approximately 1468 Ma, the age of the underlying lower Belt (Anderson and Davis, 1995) and 1454 Ma, the age of the overlying middle Belt carbonate (Evans et al., 2000).

The Belt terrane has had a long history of deformation, ranging from synsedimentary faulting to Tertiary extension. Most workers agree that the Belt Supergroup experienced syndepositional faulting, but some disagree about the location of these inferred Proterozoic faults. Some workers maintain that this faulting was localized along the Lewis and Clark line, a 50-km-wide zone with abundant faults that extends across much of the Belt terrane (Fig. 1; e.g., Hobbs et al., 1965; Harrison et al., 1974; White, 2000). In contrast, Winston (1986, 2000) suggested that Proterozoic synsedimentary faults cut the Belt basin into at least five crustal blocks, with differential subsidence producing subbasins that now have strata with different thicknesses (Fig. 1). Harrison (1972) reported a large area along the northern Idaho-Montana border where Belt strata are significantly thinned and called this feature the post-Ravalli dome. White (2000) concluded that the dome is elongated in a north-south direction and suggested this feature be renamed the Noxon arch.

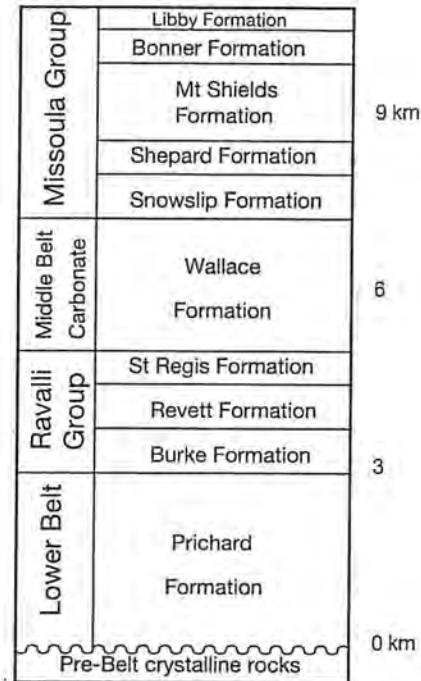


FIG. 2. Stratigraphic subdivisions and approximate thicknesses of the Belt Supergroup in the central and western portion of the Belt terrane.

The Belt terrane was affected by the East Kootenay orogeny at <1370 Ma, which produced gentle warping and cleavage of Belt Supergroup rocks (McMechan and Price, 1982) and perhaps also a regional magmatic-thermal event that affected rocks throughout the Belt terrane (Doughty and Chamberlain, 1996). During the Mesozoic to early Tertiary, the Belt terrane underwent compressional faulting and batholith intrusion (Harrison et al., 1980). The Cretaceous Idaho batholith lies south of the Lewis and Clark line and Coeur d'Alene district and extends within 65 km of the district, with its metamorphic border zone reaching as close as 22 km from some veins. Although the Lewis and Clark line undoubtedly contains older structural elements, it is defined primarily by Cretaceous or younger reverse, normal, and strike-slip faults (White, 1998a).

The Belt Supergroup contains the following three important classes of ore deposits.

1. The lower Belt, which hosts the synsedimentary sediment-hosted massive sulfide deposits, including the 1450 to 1470 Ma Sullivan deposit (Jiang et al., 2000).

2. The Revett Formation, which hosts diagenetic sediment-hosted stratiform copper mineralization, including the Troy (Spar Lake) deposit (Hayes and Einaudi, 1986). These deposits occur in the western Montana copper sulfide belt (Fig. 1), which extends into the northern part of the Coeur d'Alene district at the Snowstorm mine, Missoula tunnel, Military Gulch, and Blossom Lakes (Fig. 3).

3. The epigenetic veins in the lower Belt and Ravalli Group in the Coeur d'Alene district, which have been classified as Ag-Pb-Zn veins in clastic metasedimentary terranes

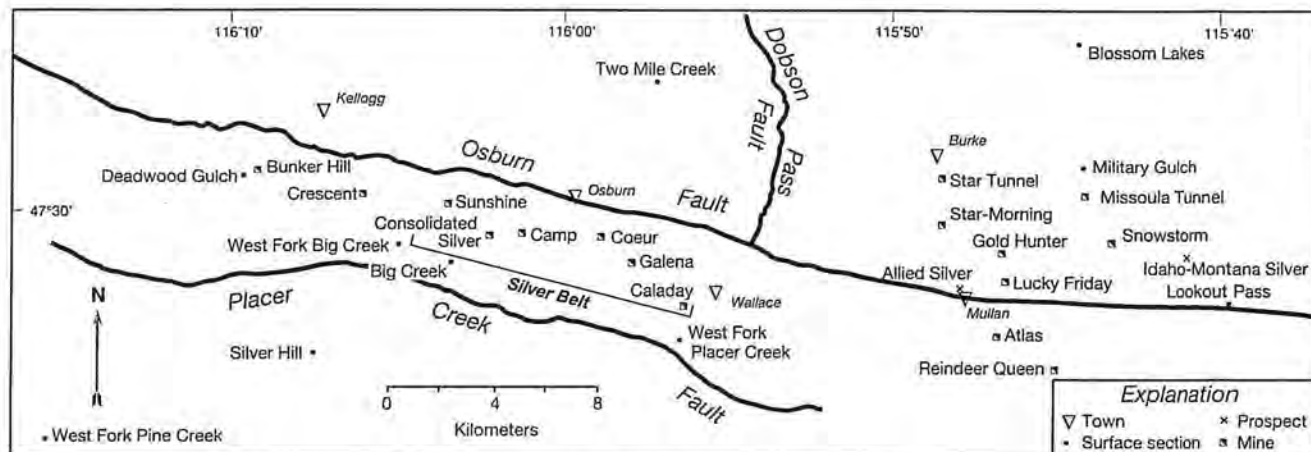


FIG. 3. Location of measured sections in the Coeur d'Alene mining district. Major faults redrawn from Gott and Cathrall (1980). The Snowstorm and Missoula Tunnel deposits, and the Military Gulch and Blossom Lakes sections contain sediment-hosted stratiform copper mineralization. All other deposits are Ag-Pb-Zn epigenetic veins.

(Beaudoin and Sangster, 1992). The debate concerning the age of the veins is summarized below, but the veins clearly postdate sedimentation, diagenesis, major folds, and some, but not all faults.

### Geology of the Coeur d'Alene district

#### District geology

The Coeur d'Alene district lies at the junction of the Lewis and Clark line and the Noxon arch (Harrison et al., 1974; White, 2000). Rocks in the district have undergone strong folding and faulting. The largest fault in the district is the Osburn fault, which bisects the district, has 20 to 30 km of post-ore right-lateral strike-slip offset, and is part of the regional-scale Lewis and Clark line (Fig. 3; Hobbs et al., 1965; Bennett and Venkatakrishnan, 1982). The structural history of the district is complex, with five episodes of deformation that post-date sedimentation (Wavra et al., 1994; White, 1998a). In addition, many workers have advocated syndepositional faulting along the Lewis and Clark line (e.g., Hobbs et al., 1965; Harrison, 1972; Chevillon, 1977) or along a Proterozoic synsedimentary fault called the Jocko line (Fig. 1; Winston 1986, 2000).

Wavra et al. (1994) concluded that deformation associated with mineralization at the Sunshine mine was dip-slip along high-angle structures during a tectonic metamorphic event that preceded strike-slip offset along the Osburn fault. They suggested that this event may be related to emplacement of the Idaho batholith and/or docking of the Wallowa terrane.

#### Veins and alteration

The Coeur d'Alene district has well-developed district-scale zonation of metals in its veins. All of the significant ore deposits in the district lie within 12 well-defined, nearly straight, parallel to subparallel mineral belts that mostly trend N 65° W. Some belts are base metal rich, and other belts are silver rich (Fryklund, 1964; Crosby, 1984). The 8-km-long Silver Belt, located south of the Osburn fault, contains several

silver-rich mines, including the Crescent, Sunshine, Consolidated Silver, Coeur, and Galena (Fig. 3). The Sunshine mine alone produced over 10,000 t of silver (Wavra et al., 1994), more silver than the Comstock Lode. The Silver Belt is flanked to the west by the Bunker Hill mine, which primarily produced lead and zinc, and to the east by a number of properties that produced minor base metals. Similarly, north of the Osburn fault, silver-rich deposits pass westward to base metal-rich deposits (Fryklund, 1964; Bennett and Venkatakrishnan, 1982).

Veins in the Coeur d'Alene district are commonly less than 4 m wide, with dip extents that are normally several times their strike lengths. Strike lengths commonly exceed 300 m and dip extents may exceed 1,000 m (Fryklund, 1964; Wavra et al., 1994). Veins are typically zinc and lead or silver rich and commonly contain 350 to 850 ppm Ag (10–25 oz/t), 7 to 14 percent Pb, and 4 to 8 percent Zn. Both base metal and silver veins contain massive siderite and quartz in highly variable proportions. Base metal veins have galena and sphalerite as their dominant ore minerals, whereas silver veins contain argentiferous tetrahedrite with minor amounts of galena, sphalerite, chalcocopyrite, and boulangerite. Individual orebodies show a relative absence of mineral zonation (e.g., Leach et al., 1988).

The Coeur d'Alene district contains three main types of alteration: hydrothermally bleached zones, carbonate zonation, and sulfide alteration. Early workers in the Coeur d'Alene district noted that many veins occur in rocks that are gray or purple elsewhere but have been altered to some shade of green with an overall lighter hue, called "bleached" rocks (e.g., Shenon and McConnell, 1939; Mitcham, 1952). Weis (1964) demonstrated that the bleached appearance of the rocks was due to lack of pigments hematite. Bleached zones were reported to follow structural features, including faults, shear zones, cleavage, and the crumpled flanks of folds (Shenon and McConnell, 1939; Sorenson, 1951) and occur almost exclusively adjacent to economic parts of veins or surround large clusters of sulfide-bearing veins.

Productive veins in the Coeur d'Alene district are enclosed by zones of disseminated siderite that locally extend up to hundreds of meters into the surrounding wall rocks (Gitlin, 1986). The siderite zones pass outward to ankerite plus calcite zones that may also be hundreds of meters wide. The regionally dominant carbonate is ankerite, which extends beyond the mineralized area in the district (White, 1998b). Alteration zones that contain low-grade disseminated galena, sphalerite, tetrahedrite, arsenopyrite, or pyrite surround many of the veins in the district. The sulfides fill microfractures and have replaced disseminated carbonate (Leach et al., 1988) and quartz grains (Reid, 1982).

#### *Fluid inclusions and geochemistry*

Fluid inclusion analyses indicate that ore formed at approximately 250° to 350°C at pressures from 1 to 3 kbars, corresponding to a minimum burial of 3.5 to 10 km under lithostatic pressure (Leach et al., 1988). Ore formed from complex CO<sub>2</sub>-CH<sub>4</sub>-C<sub>n</sub>H<sub>m</sub>-N<sub>2</sub>-H<sub>2</sub>O-NaCl fluids; base metal veins formed from fluids that were rich in methane and light hydrocarbons, whereas silver veins formed from CO<sub>2</sub>-rich fluids (Leach et al., 1988). Large veins show only minor mineral and element zonation and no significant changes in the P-T-X of their fluid inclusions. Taken together, the data suggest that the veins formed from metamorphic fluids, although the cause of fluid migration and the mechanism(s) of ore deposition are unknown (Leach et al., 1988).

Criss and Fleck (1990) show a zone of steep <sup>18</sup>O gradients in Belt Supergroup rocks north of the Idaho batholith that they interpreted to reflect large-scale metamorphic-hydrothermal fluid flow. Oxygen isotope compositions of vein material from the Coeur d'Alene district are consistent with precipitation from metamorphic fluids that had equilibrated with Belt Supergroup metasedimentary rocks (Constantopoulos and Larson, 1991; Constantopoulos, 1994; Eaton et al., 1995). However, wide variations in δD<sub>H<sub>2</sub>O</sub> values of -18 to -105 per mil from inclusion fluids from vein quartz have also been interpreted as indicating that meteoric water was locally involved in vein formation (Constantopoulos and Larson, 1991). Alternatively, we suggest that the strongly depleted δD values may indicate that inclusion fluids contained abundant methane or derived their low δD values from exchange with methane and light hydrocarbons (Arehart et al., 1990).

The timing of vein formation in the Coeur d'Alene district is very controversial. Lead isotopes, Sr isotopes, and K-Ar and <sup>40</sup>Ar/<sup>39</sup>Ar ages are consistent with two ages of mineralization: Proterozoic formation of base metal veins and Mesozoic to Cenozoic formation of silver-rich veins (Leach et al., 1988, 1998; Rosenberg and Larson, 2000). Other workers argue that all veins formed during the Mesozoic to Cenozoic, based on structural relationships (White, 1998a) and Sr isotopes (e.g., Eaton et al., 1995; Criss and Eaton, 1998; Fleck et al., 2002).

#### **Methods**

Results presented here were obtained during a district-wide investigation of the stratigraphy of the Revett Formation that included describing over 13 km of drill core and stratigraphic sections. Outcrop and underground stratigraphic sections were measured using a Jacob's staff and described at a

scale of 1:120 (1 in = 10 ft). Drill core was also logged at a scale of 1:120. Individual stratigraphic sections (plotted at a scale of 1:1200) and additional correlation diagrams are shown in Mauk (2002). Stratigraphic sections from the Bunker Hill, Crescent, and Lucky Friday mines are based largely on unpublished data from B.G. White; the derivation of these sections is discussed more thoroughly in Mauk (2002). Figure 3 shows the location of sections included in this study.

#### **Rock Types in the Revett Formation**

The Revett Formation in the Coeur d'Alene district contains six rock types: vitreous quartzite, subvitreous quartzite, sericitic quartzite, blocky siltite, argillaceous siltite, and thin-bedded argillite. Mauk (2002) describes these rock types and provides color photographs of field occurrences; these rock types represent a continuum of hardness, grain size, sorting, and bed thickness (Table 1). Winston (1986, 2000) presented an alternative classification scheme that is based on sedimentary structures, grain size, and inferred original mineral composition (Table 1).

Rocks in the Revett Formation that contain chemically oxidized iron in the form of hematite or magnetite are generally lavender to gray. Winston (1978, 1986) has shown that red beds of the Missoula Group generally contain sedimentary structures that indicate subaerial deposition, such as desiccation cracks and mud chips. In many places, this is also true of the Revett and St. Regis Formations. Elsewhere, however, light green to gray beds contain magnetite, indicating an intermediate oxidation state; some of these rocks might have been deposited subaerially.

The Revett and St. Regis Formations also contain rocks that are green, lack hematite and magnetite, and lack sedimentary structures indicative of subaerial exposure. We refer to these rocks as chemically reduced. Their green color is due to phengitic illite, which hosts ferrous iron, although additional iron occurs in some rocks as pyrite, ankerite, siderite, and/or chlorite. The mineralogy and sedimentary structures of these rocks are consistent with deposition and/or diagenesis in a subaqueous, chemically reduced environment.

#### **Stratigraphy of the Revett Formation**

##### *Previous work*

Most of the previous stratigraphic work in the Coeur d'Alene district focused on map-scale problems, such as how to define mappable units in the Belt Supergroup (e.g., Lindgren, 1904; Ransome and Calkins, 1908; Hobbs et al., 1965). The first detailed stratigraphic study of the Revett Formation in the Coeur d'Alene district was in the vicinity of the Bunker Hill mine; it identified and informally named lower, middle, and upper members of the Revett Formation (Fig. 4; White et al., 1977; White and Winston, 1982). The lower member consists of thick units of sericitic, subvitreous, and vitreous quartzite that alternate with thinner units of siltite. The middle Revett is dominated by argillaceous and/or blocky siltite, although quartzite and thin-bedded argillite are locally important constituents. The upper member contains sequences of quartzite that alternate with sequences of siltite and/or thin-bedded argillite.

TABLE 1. Properties of the Rock Types of the Revett and Lower St. Regis Formations

Rock type	Color	Hardness	Grain size	Sorting	Bed thickness	Sedimentary structures	Sediment type of Winston (1986, 2000)
Vitreous quartzite	White, light gray	Very hard	Medium sand, fine sand	Very well, well	0.3-2 m avg 0.6-1 m	Cross-strata, flat laminations	Crossbedded sand Flat-laminated sand
Subvitreous quartzite	Light gray, light green, tan	Very hard	Medium sand, fine sand, very fine sand	Well	0.3-2 m avg 0.6-1 m	Cross-strata, flat laminations, ripple cross-laminae, hummocky cross-stratification?	Crossbedded sand Flat-laminated sand
Sericitic quartzite	Light green, tan, lavender	Hard, moderately hard	Fine sand, very fine sand	Well moderately	0.3-1.7 m avg 0.5-1 m	Flat laminations, ripple cross-laminae	Flat-laminated sand
Blocky siltite	Green, light green, tan, lavender	Moderately hard, soft	Silt, very fine sand	Moderately	5-25 cm avg 18 cm	Ripple cross-laminae, flat laminations, massive	Not represented
Argillaceous siltite	Green, light green, tan, lavender	Soft	Silt, very fine sand, clay	Moderately, poorly	0.75-5 cm	Lenticular bedding, wavy bedding, parallel bedding, synaeresis cracks, mud skins, mud chips, graded beds, flaser bedding	Discontinuous layer
Thin-bedded argillite	Lavender	Soft	Silt, very fine sand, clay	Moderately, poorly	0.75-10 cm	Sedimentary couplets, wavy bedding, lenticular bedding, parallel bedding, graded bedding, synaeresis cracks, desiccation cracks, mud chips	Mudcracked even couplet, mudcracked even couplet, mudcracked lenticular couplet, mudcracked mud, uncracked lenticular couplet, undulating couplet, pinch-and-swell couplet

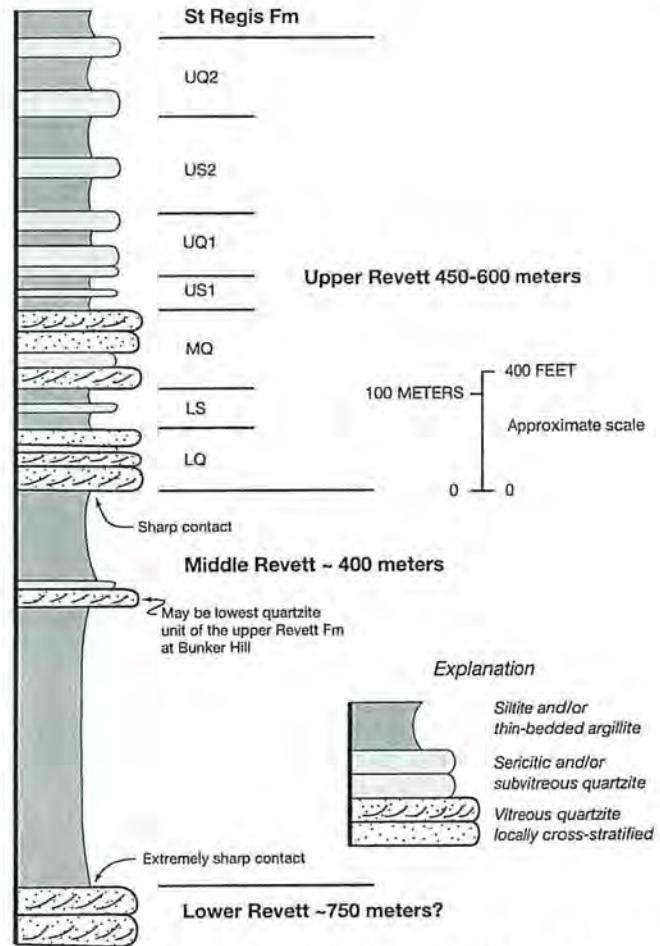


FIG. 4. Generalized stratigraphic section of part of the Revett Formation south of the Osburn fault, showing stratigraphic subdivisions in the upper Revett Formation. Legend for stratigraphic units: LQ = lower quartzite, LS = lower siltite, MQ = middle quartzite, US1 = first upper siltite, UQ1 = first upper quartzite, US2 = second upper siltite, UQ2 = second upper quartzite.

Several theses have addressed the stratigraphy of the Revett Formation (Hrabar, 1971; Bowden, 1977; Wingerter, 1982; Alleman, 1983; Hayes, 1983; Mauk, 1983; Cronin, 1988). Many of these included stratigraphic descriptions from one or more localities in the Coeur d'Alene district, but none of these studies included work in any of the mines. This study, and the underpinning work of Mauk (2002), is the first comprehensive attempt to document the stratigraphy of the Revett Formation throughout the entire Coeur d'Alene mining district, using surface, underground, and drill core exposures.

In this study, we place the top of the Revett Formation at the top of the highest coset (pair) of thick sets of quartzite, as suggested by Hayes (1983). Unfortunately, Hayes' (1983) definition cannot be used to place the Burke-Revett boundary, because sequences of thick-bedded quartzite occur within the upper member of the Burke Formation (Mauk, 1983). Generally, this contact is placed where thinner-bedded, sericitic quartzite of the Burke Formation passes up to the

thicker bedded, vitreous to subvitreous, more commonly cross-stratified quartzite of the Revett Formation.

*Stratigraphic correlations*

All stratigraphic correlations in the Belt Supergroup are lithostratigraphic, because chronostratigraphic units, such as tephra, have not yet been identified and correlated in widely separated exposures. This limits the scope and extent of all stratigraphic studies, but lithostratigraphic correlations nonetheless provide a powerful and commonly under-utilized tool for many types of work in the Belt Supergroup.

In this study, we established stratigraphic correlations using several criteria. We anticipated that thick sequences of quartzite would be relatively continuous, although they might change thickness or character from place to place. We used the general nature of the upper, middle, and lower Revett Formation to help place measured sequences into a broad context. For example, a section that consists of packages of quartzite that alternate with packets of siltite would be placed into the upper Revett Formation, whereas a section that contains mostly siltite or argillite would be classified as middle Revett. The Revett-St. Regis contact and the sharp contact between the lower and middle Revett also provided useful datums that are traceable over large areas.

In stratigraphic studies, it is critically important to identify and quantify fault offsets. Fortunately, the Coeur d'Alene district has excellent geologic maps (Hobbs et al., 1965), and mine workings have been thoroughly mapped by mine geologists. We relied on the published geologic maps to provide information on surface faults and on the unpublished mine

maps for underground work and core logging. Significant faults and structures were noted, and where possible, we attempted to assess their offsets. In some cases, we were able to greatly refine prior interpretations.

*Stratigraphy of the Revett Formation south of the Osburn fault*

The Revett Formation is much thicker south of the Osburn fault than to the north of this fault. Most veins occur in the upper Revett Formation south of the Osburn fault, so the upper Revett is well exposed in many mines, and we have documented its stratigraphy in detail. In contrast, the middle and lower Revett Formation generally occur at great depth or distant from mine workings in the mineral belts south of the Osburn fault. Consequently, few workings have penetrated these units and their stratigraphy is less well known.

*Stratigraphy of the upper Revett Formation:* The upper Revett Formation contains seven informal subunits south of the Osburn fault (Fig. 4): lower quartzite (LQ), lower siltite (LS), middle quartzite (MQ), first upper siltite (US1), first upper quartzite (UQ1), second upper siltite (US2), and second upper quartzite (UQ2). Figures 5, 6, and 7 show thickness, facies, and redox changes within the upper Revett Formation south of the Osburn fault. Figure 5 shows correlations among mines in the back panel and correlations among surface sections in the front panel. Figure 7 is a correlation diagram only, with no map scale, which extends the back panel of Figure 5 east to the Reindeer Queen stratigraphic section.

In the Silver Belt, the upper Revett is 450 to 500 m thick and has two distinct facies changes. (1) The upper Revett

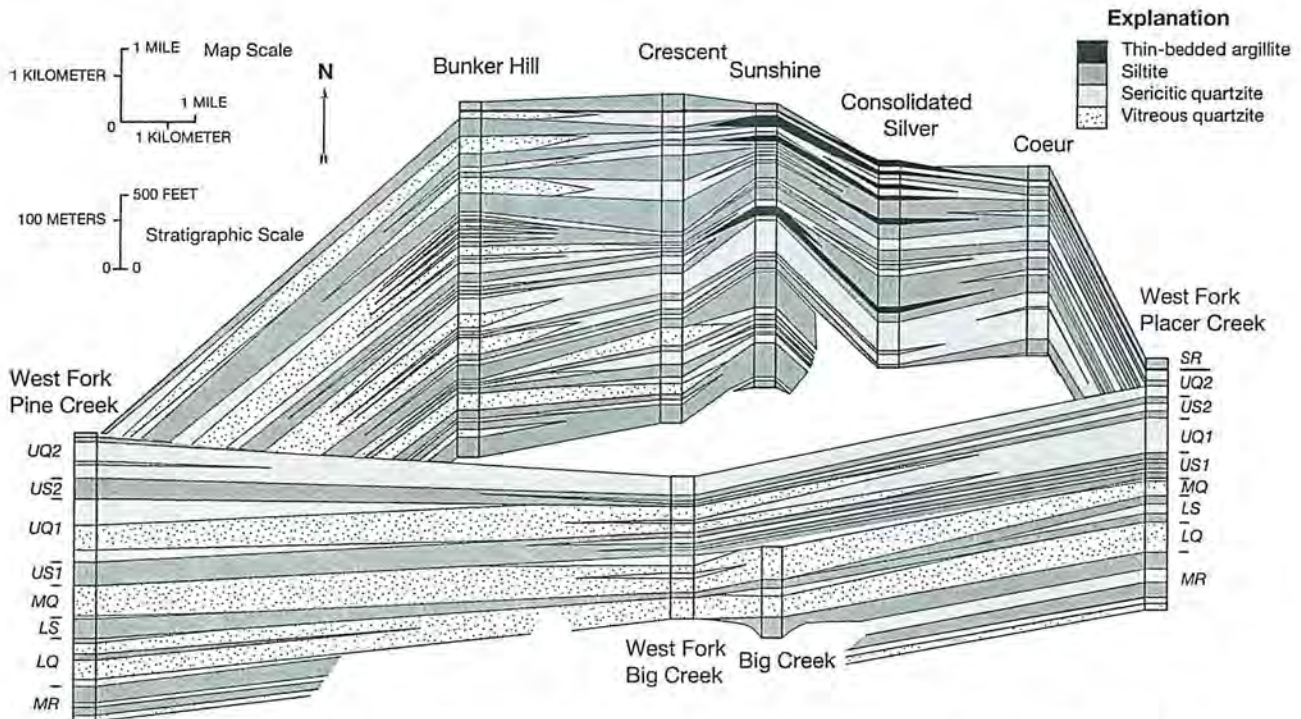


FIG. 5. Generalized fence diagram showing stratigraphic and facies relationships in the upper Revett Formation south of the Osburn fault. MR = middle Revett Formation; SR = St. Regis Formation; UQ2, US2, UQ1, US1, MQ, LS, and LQ are subdivisions of the upper Revett Formation, as shown in Figure 4.

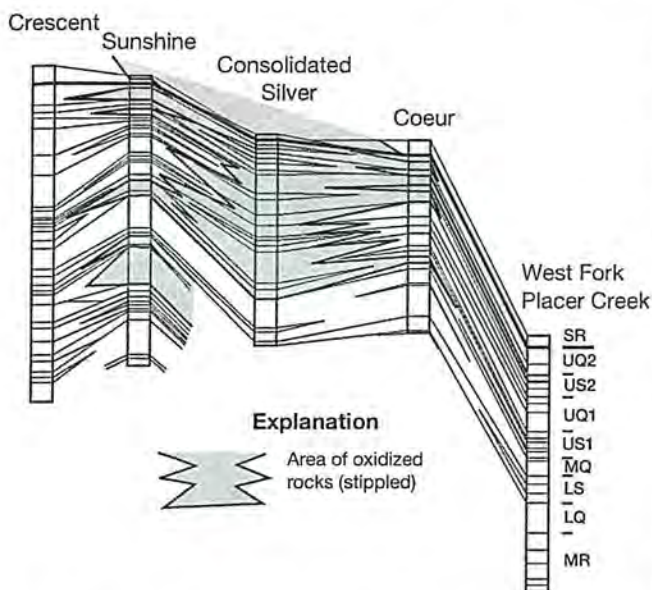


FIG. 6. Generalized fence diagram showing strata that are commonly chemically oxidized in the upper Revett Formation south of the Osburn fault. Legend for stratigraphic units as given in Figure 4.

finer from the east and west toward the middle of the Silver Belt by the addition of siltite, thin-bedded argillite, and sericitic quartzite at the expense of vitreous and subvitreous quartzite (Figs. 5, 7). Significantly, the Sunshine and Consolidated Silver mines contain substantial packages of thin-bedded argillite within the upper Revett Formation. (2) The upper Revett fines to the north in the Silver Belt in a similar manner.

West of the Silver Belt, the upper Revett thickens to over 600 m at the Bunker Hill mine. The stratigraphy in the Crescent mine is transitional between that exposed at Bunker Hill and

the Silver Belt because, although the upper Revett is over 600 m thick, most of the quartzite is sericitic or subvitreous. The upper Revett also thickens to the east of the Silver Belt, to reach over 550 m in the Reindeer Queen area (Fig. 7).

Color and oxidation state in the upper Revett Formation also change significantly south of the Osburn fault. Where hydrothermal bleaching is absent, the contact between chemically oxidized lavender strata and chemically reduced green to gray strata generally lies near the base of the lowest unit of thin-bedded argillite (Figs. 6, 7). Above this, rocks are commonly oxidized, but reduced strata locally form a significant or even predominant portion of the section. At the Bunker Hill and Crescent mines in the west, the upper Revett is entirely reduced, and it consists of quartzite and siltite (Fig. 6). However eastward, toward the center of the Silver Belt, argillite beds come in lower in the section, oxidized beds increase at the expense of reduced beds, and lavender rocks occur in the first upper siltite at the Coeur, Consolidated Silver, and Sunshine mines (Fig. 6).

**Stratigraphy of the middle Revett Formation:** At the West Fork of Pine Creek and in the Big Creek area the middle Revett is 400 to 450 m thick, and a diamond drill hole at the Consolidated Silver mine penetrated 430 m (stratigraphic thickness) of middle Revett (Mauk, 2002). The drill core shows that the middle Revett may contain an upper unit that is dominated by siltite and a lower unit that contains significant amounts of quartzite.

**Stratigraphy of the lower Revett Formation:** At Silver Hill, the lower Revett may be approximately 740 m thick (Mauk, 2002). Exposures from several localities south of the Osburn fault indicate that the lower Revett has more quartzite and less siltite than the upper Revett, and the lower Revett has a higher percentage of vitreous and subvitreous quartzite than the upper Revett. The top of the lower Revett appears to contain the most vitreous quartzite in the entire Revett Formation south of the Osburn fault.

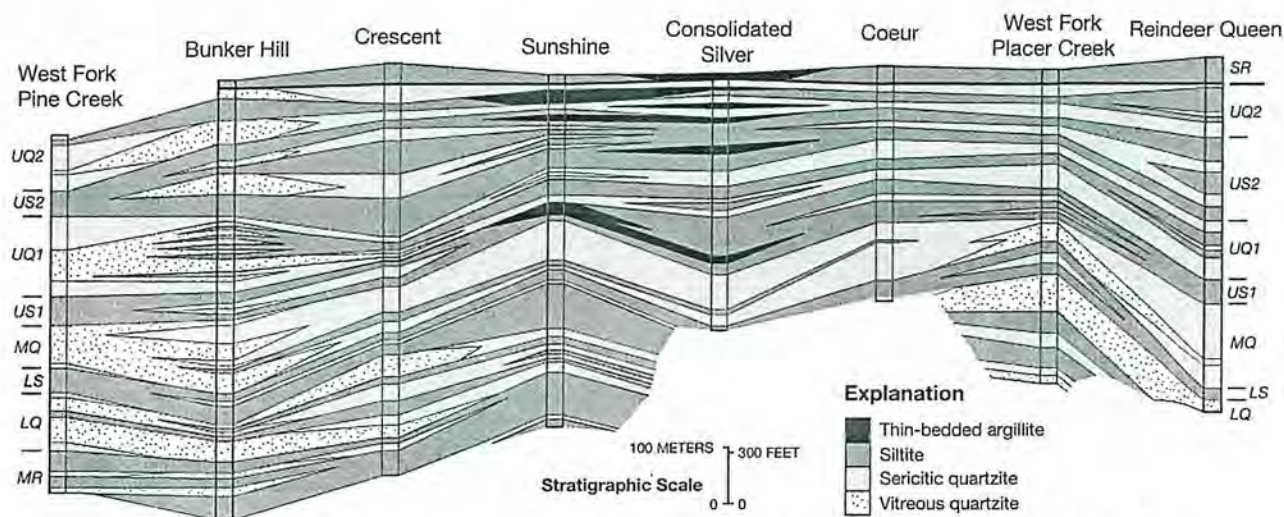


FIG. 7. Generalized stratigraphic correlation diagram for the upper Revett Formation south of the Osburn fault. MR = middle Revett Formation; SR = St. Regis Formation; UQ2, US2, UQ1, US1, MQ, LS, and LQ are subdivisions of the upper Revett Formation, as shown in Figure 4. This is a correlation diagram only, with no map scale, drawn to show stratigraphic and facies changes from west to east in the area south of the Osburn fault.

### Stratigraphy of the Revett Formation north of the Osburn fault

North of the Osburn fault, the Revett Formation has much thinner stratigraphic units than south of the fault. North of the fault, there is 45 to 120 m of upper Revett, 60 to 120 m of middle Revett, and approximately 450 m of lower Revett (Fig. 8).

**Stratigraphy of the upper Revett Formation:** The upper Revett Formation north of the Osburn fault contains five distinct informal subunits: lower quartzite (LQ), lower siltite (LS), middle quartzite (MQ), upper siltite (US), and upper quartzite (UQ; Figs. 8, 9; Hayes and Einaudi, 1986). These subunits occur widely throughout northern Idaho and

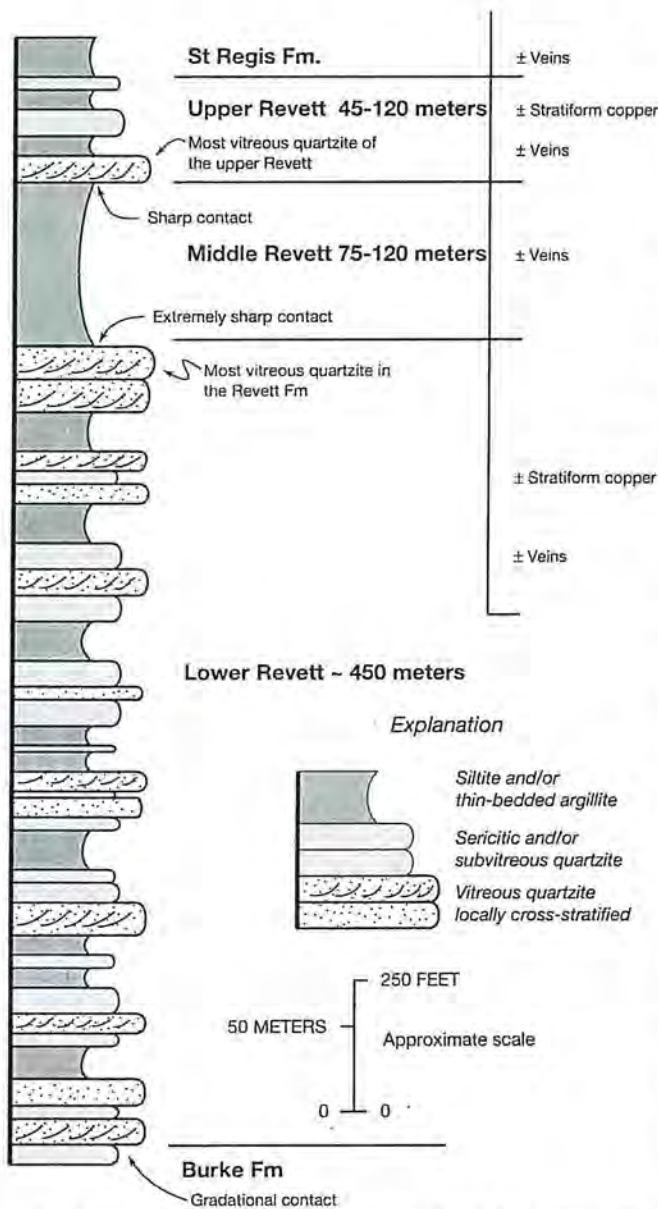


FIG. 8. Generalized stratigraphic section of the Revett Formation north of the Osburn fault.

western Montana, where the upper Revett is commonly 60 to 90 m thick (White et al., 1984; Hayes and Einaudi, 1986).

The upper Revett Formation is approximately 120 m thick at the Two Mile Creek, Allied Silver, Lucky Friday, and Idaho-Montana Silver properties (Fig. 9). These atypically thick sections contrast markedly with the 45 m of upper Revett at Military Gulch and with the more typical thicknesses of 60 to 90 m of upper Revett elsewhere in northern Idaho and western Montana.

The entire upper Revett Formation is chemically reduced at the Two Mile Creek, Allied Silver, Lucky Friday, and Military Gulch localities. However, at the Idaho-Montana Silver property, the top 15 m of the upper Revett contains magnetite and therefore is chemically oxidized.

**Stratigraphy of the middle Revett Formation:** In most places in western Montana and northern Idaho, the middle Revett ranges from 90 to 150 m thick and is dominated by siltite (White, 2000; Fig. 8). However, thin-bedded argillite and quartzite are locally important in the Coeur d'Alene district and elsewhere. For example, at the Lucky Friday mine and the Allied Silver property, quartzite commonly occurs in the middle Revett, whereas the middle Revett locally contains thin-bedded argillite at the Idaho-Montana Silver property (Fig. 9).

In the Coeur d'Alene district, north of the Osburn fault, the middle Revett is approximately 120 m thick at the Lucky Friday, Allied Silver, Two Mile Creek, and Idaho-Montana Silver properties, which is slightly greater than the average thickness elsewhere in northern Idaho and western Montana. At Military Gulch, however, the middle Revett has thinned to approximately 60 m.

The middle Revett contains only chemically reduced strata at the Lucky Friday, Allied Silver, and Two Mile Creek properties. At the Military Gulch and Idaho-Montana Silver localities, however, the middle Revett contains significant lavender- or magnetite-bearing, chemically oxidized intervals.

**Stratigraphy of the lower Revett Formation:** The lower Revett is typically 400 to 450 m thick in western Montana and northern Idaho and consists of thick intervals of quartzite with thinner intervals of siltite (Fig. 8). At Two Mile Creek and Blossom Lakes, the lower Revett coarsens upward from mostly sericitic quartzite at the base, to mostly subvitreous quartzite in the middle, to large, bold cliffs of vitreous quartzite at the top. In some places north of the Osburn fault, the lower Revett has been mapped as the entire Revett, and the middle and upper Revett have been included in the St. Regis Formation.

### Paleocurrent directions in the Revett Formation

Some quartzite units contain cross-stratification, which most commonly occurs as tabular sets of planar cross-strata with angular to tangential bases, although lenticular sets of trough cross-strata occur locally. Sets range from 0.3 to 1.8 m thick but most are 0.5 to 1.0 m thick. Paleocurrent directions from underground and surface exposures in the Coeur d'Alene district show predominantly north- to northeast-trending paleocurrent directions (Fig. 10), which, as discussed below, have implications for basin architecture and also for district-scale structural reconstructions.

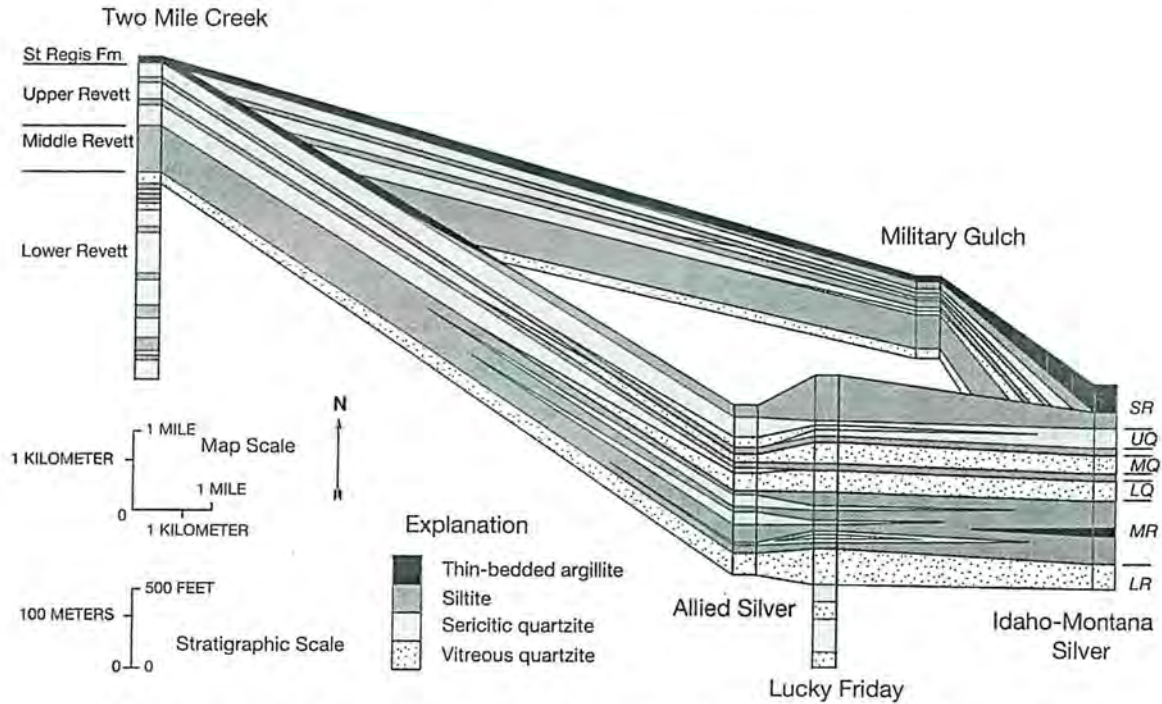


FIG. 9. Generalized fence diagram showing stratigraphic and facies relationships in the upper Revett Formation north of the Osburn fault. Stratigraphic subdivisions of the upper Revett are the same as shown in Figure 8. Map and stratigraphic scales are the same as in Figure 5.

Discussion

The stratigraphic relationships presented above, when integrated with other information, have important implications for understanding mine, local, and regional geology, the location of veins in the Coeur d'Alene district, district-scale fluid flow, alteration halos, basin architecture, district-scale metal

zonation, and regional metallogeny. These features are discussed separately below.

District and regional stratigraphy

Several criteria have been used to identify the contact between the Revett and St. Regis Formations, including the

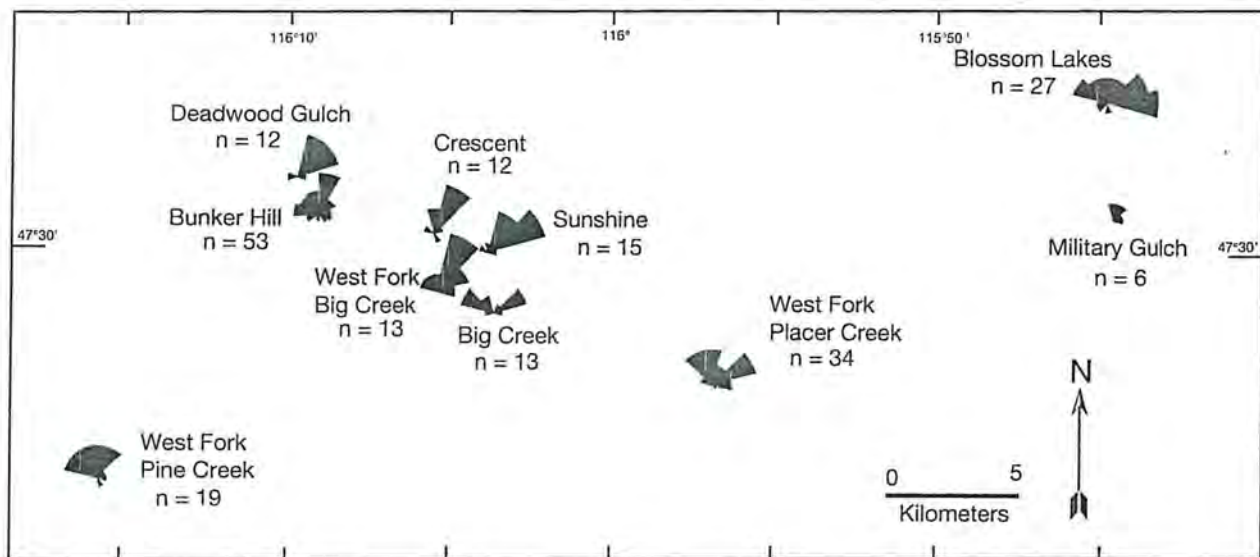


FIG. 10. Map showing paleocurrent rose diagrams from the Revett Formation in the Coeur d'Alene district. Compiled from data and diagrams in Mauk (2002).

presence of crossbedded quartzite (e.g., Harrison and Jobin, 1963; Bowden, 1977), the presence of siltite to argillite couplets and abundant mud chips as marking the base of the St. Regis Formation (e.g., White and Winston, 1982; Alleman, 1983), and placing the top of the Revett at the top of the highest coset of thick sets of quartzite (e.g. Hayes, 1983; Mauk, 2002). Our work indicates that the only regionally consistent stratigraphic criterion is the position of the highest coset of thick sets of quartzite, due to the lack of crossbedding in some quartzite units and the variable occurrence of thin-bedded argillite at various stratigraphic horizons within the Revett and St. Regis Formations.

Recognition that the upper Revett consists of alternating packages of quartzite and siltite and/or thin-bedded argillite changed the recognition of stratigraphic units in the Coeur d'Alene district. Early workers tended to see the Revett-St. Regis contact as upwardly transitional from massive quartzite of the Revett Formation through interstratified quartzite and siltite until typical St. Regis Formation siltite and argillite were encountered. This interval was referred to as the Revett-St. Regis transition zone. It was believed to vary in thickness throughout the district, but it was never precisely defined, and nowhere was it accurately measured. The term was loosely applied to stratigraphic intervals that contain lithologies characteristic of the Revett and St. Regis Formations, but the term had different meaning for different workers; it was mapped differently from mine to mine, and even within individual mines, depending on exposure or personal preferences. We recommend abandoning the term Revett-St. Regis transition zone and advocate the use of the criteria of Hayes (1983) to define the Revett-St. Regis contact, as described above.

The upper Revett in the Silver Belt has dramatic facies changes, so it is easy to see how the idea of a Revett-St. Regis transition zone could vary from mine to mine (Figs. 5, 7) or even within different areas of the same mine. The correlations shown in Figures 5 and 7 demonstrate that quartzite is a more reliable indicator of stratigraphic position than the presence of argillite. Similarly, chemically oxidized units and thin-bedded argillite occur at various stratigraphic levels in the Revett Formation throughout the Coeur d'Alene district (Figs. 5-6, 9), indicating that their presence is not a reliable indicator of stratigraphic contacts.

Thicknesses of Revett Formation units are dramatically different on opposite sides of the Osburn fault; some units show over one order of magnitude change in thickness. Correlations of the upper, middle, and lower Revett across the Osburn fault might be regarded as tenuous, particularly in the absence of traceable marker beds or unconformities in the Ravalli Group. However, three lines of evidence suggest that our correlations of the upper, middle, and lower Revett across the Osburn fault are valid.

1. Lithostratigraphic sequences within the three members of the Revett Formation are similar on both sides of the Osburn fault.

2. The uppermost quartzite of the lower Revett is the cleanest, most vitreous quartzite in the entire Revett Formation on both sides of the Osburn fault.

3. The contact between the middle and lower Revett is extremely sharp on both sides of the Osburn fault. In some

places, such as Military Gulch, this contact is clearly an erosional unconformity. If this proves to be a widespread unconformity, it would strengthen correlations on a regional scale. However, this hypothesis needs further testing.

Based on stratigraphic thickness and facies changes within the Revett Formation, the Coeur d'Alene mining district can be subdivided into four blocks: the Bunker Hill, Silver Belt, Lucky Friday, and western Montana copper sulfide belt blocks (Fig. 11). The thickness of the upper Revett varies from 450 to 500 m in the Silver Belt, to over 600 m in the Bunker Hill block, to 120 m in the Lucky Friday block, and to 45 to 90 m in the western Montana copper sulfide belt block.

Recognition of lithostratigraphic sequences in these four blocks facilitates both local mapping and regional correlations, providing improved information about fault offsets and which units are preferred ore hosts. In some places, the Revett Formation has been misidentified. For example, our work indicates that in the vicinity of the West Fork of Pine Creek on the Twin Craggs quadrangle, Campbell and Good (1963) mapped the middle Revett Formation as the Burke Formation.

#### *Stratigraphic control of orebodies in the Coeur d'Alene district*

We have documented the relationships between stratigraphy and orebodies at the Bunker Hill, Crescent, Sunshine, Consolidated Silver, Coeur, Galena-Caladay, Dayrock, Star, and Lucky Friday mines in the Coeur d'Alene district. These studies clearly show that ore deposition favored certain strata. However, due to the complex nature of the relationships among stratigraphy, structure, and vein grades, it is difficult to document, constrain, and portray these relationships. Consequently, we present here only the few examples from our work where relationships are relatively well known from detailed mapping and core logging.

Most orebodies change thickness or grade where the wall rocks enclosing the veins change to a markedly different lithology. Both base metal and silver veins containing either quartz- or siderite-dominated gangue are affected. Where veins enter an unfavorable lithology, most thin and do not lose grade but some lose grade and do not thin.

In many places, the host rocks that have enhanced or inhibited vein development are distinct and mappable on scales that leave no doubt about the influence of strata on vein quality. Many orebodies are entirely confined to narrow packages of strata and abruptly become uneconomic at boundaries of contrasting lithologic units.

Quartzite is generally the most favorable host rock for base metal veins. Siltite, especially silicified blocky siltite, is the most favorable host rock for silver veins. Argillite and argillaceous siltite are generally not favorable host rocks for either type of vein. However, there are notable exceptions as well as local instances where veins became unproductive in strata that elsewhere host rich ore. The following examples illustrate these observations.

Veins that strike across mineral belts, such as the Lucky Friday (Fig. 12A), or that intersect bedding at a high angle, such as the Star, are less sensitive to lithologic changes than veins that cross the strike of bedding at a low angle. However,

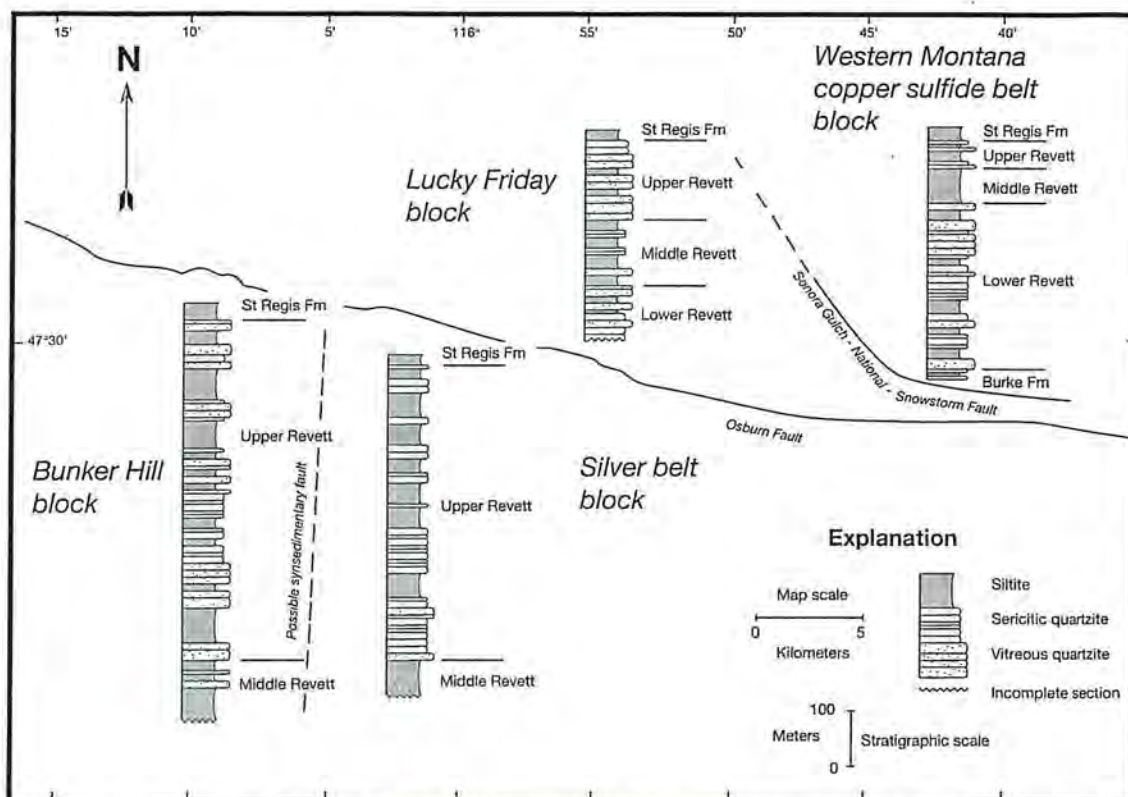


FIG. 11. Generalized stratigraphic sections for parts of the Revett Formation in the Coeur d'Alene district.

one or more of the boundaries of the former orebodies commonly follow the intersection of the vein with bedding and generally coincide with an abrupt change to argillaceous siltite.

Where it was discovered in surface outcrops, the Lucky Friday base metal vein was within argillaceous siltite of the lower St. Regis Formation (Fig. 12A). In the St. Regis, the deposit is a narrow quartz vein with a short strike length and low lead grades. However, the vein thickens and lengthens rapidly along strike at the 2,000-ft level, where the structure passes into the massive vitreous quartzite that marks the abrupt top of the Revett. At greater depth, the vein thins, its strike length shortens, and it becomes more shootlike where it passes through the argillaceous siltite and sericitic quartzite of the middle Revett. Yet deeper, the vein reenters the vitreous quartzite of the lower member and has the same strike length, continuity, width, and grade as in the upper Revett. Recent mining continued in the lower Revett.

The Star-Morning vein, the largest single orebody in the district, spanned the entire Revett Formation. As the vein passed downsection through a transition to the underlying Burke Formation, pyrite became prominent and "panels" dominated by either pyrite or sphalerite lay parallel to the intersection of strata and vein (M. Hutchenson, pers. commun., 1984). As a result of decreased zinc grade, the vein became uneconomic along a line that closely approximates the Revett-Burke boundary. The vein was apparently mined for tens of meters upsection into strata mapped as lower St.

Regis, but neither the character of the vein nor the local upper Revett and St. Regis strata at this location are known to us.

White (1976) represented the veins of the Bunker Hill mine on an "orebody/stratigraphy diagram" (Fig. 13). This diagram shows the host strata for each vein by mine level. Because most strata strike northwest and dip steeply, the diagram resembles a northeast-trending vertical longitudinal projection. Most orebodies lie within a 400-m-thick interval of strata extending from the bottom of the middle quartzite through a quartzite unit in the second upper siltite. Orebodies that appear narrow are northwest-striking veins, whereas northeast-striking veins appear to be broad on this projection. For the northeast-striking veins, most boundaries that are not parallel to strata are faults. Many individual orebodies parallel strata, and large, fault-bounded veins typically have at least one margin that parallels strata. Some veins, such as the Lower Tallon, Newgard, Stanley, and Guy, lie entirely within narrow quartzite units. Others extend across numerous stratigraphic units, but ultimately terminate along a stratigraphic contact. No significant amount of ore has been found in either the middle or lower Revett, but known ore-bearing structures have not been explored in the lower Revett. Bunker Hill veins strongly favor vitreous and sericitic quartzite in the upper Revett.

At the Galena mine, the Silver vein and many other veins are best developed in silicified, blocky siltite (Fig. 12B). The Silver vein, which produced more than 3,000 t of silver, is

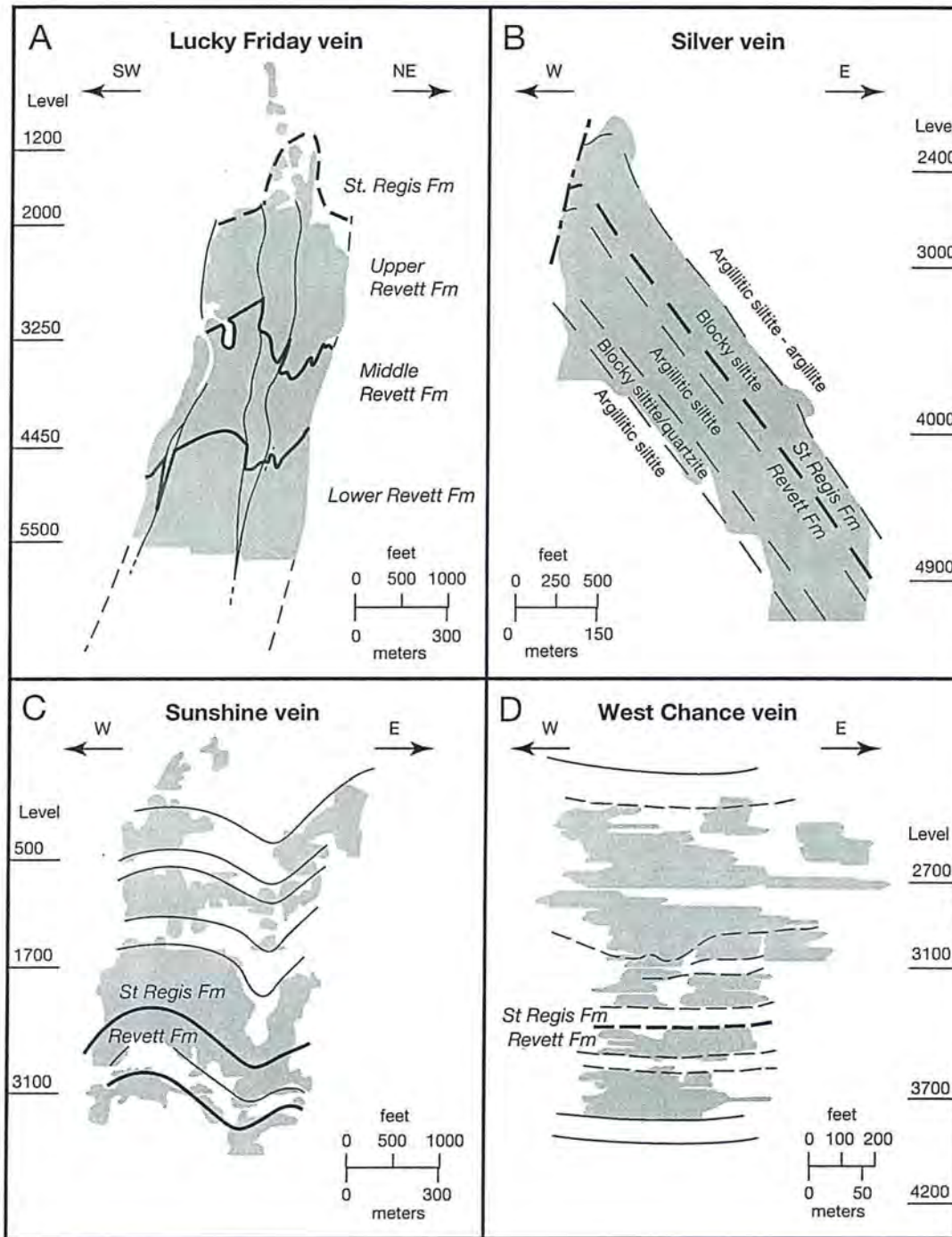


FIG. 12. Vertical longitudinal projections of four major veins in the Coeur d'Alene district. Shaded areas have been mined. Dashed and solid lines identify lithologic boundaries in wall rocks. See text for discussion. A. Lucky Friday vein. Subvertical solid lines are faults that cut the Lucky Friday vein and its enclosing stratigraphy. B. Silver vein in the Galena mine. C. Sunshine vein. D. West Chance vein in the Sunshine mine.

economic but weaker in interstratified argillaceous siltite. However, upper and lower boundaries are sharply defined by contacts with argillite. Thick vitreous or sericitic quartzite units in the southeastern part of the Galena mine host little ore.

In the northwestern part of the Galena mine, and at the Coeur mine 1.5 km to the west, the strata that host the Silver vein orebody are only locally silicified and host almost no ore. Instead, the orebodies are contained in strata characterized by thick-bedded sericitic quartzite, indicating that favored

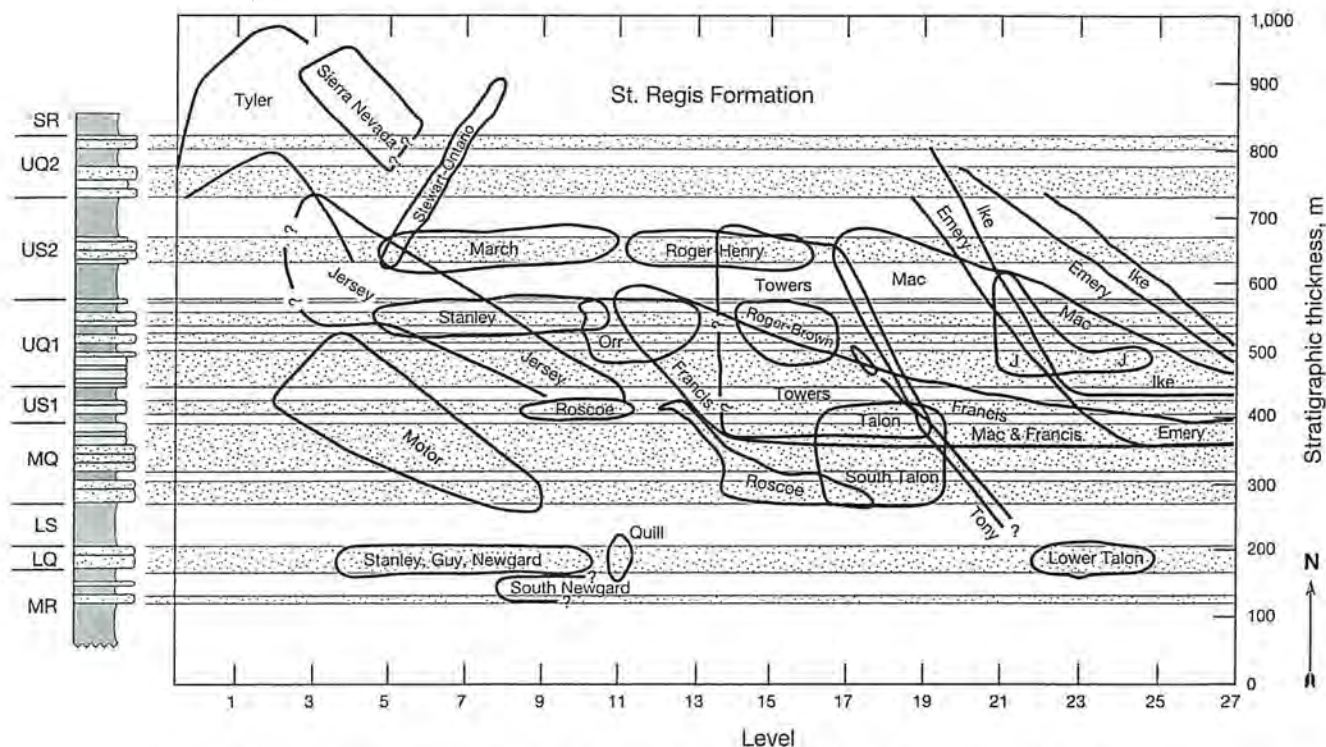


FIG. 13. Stratigraphic position of individual orebodies at the Bunker Hill mine. The diagram compiles data from various fault blocks and superposes them against stratigraphy and mine level. Because bedding dips vertically, the result is a pseudo-longitudinal projection looking parallel to bedding. The Bunker Hill upper Revett stratigraphy is displayed on the left side of the diagram and is extended across the diagram to the right or downward. Strata face north, so that the part of the diagram labeled St. Regis Formation lies toward the north. The diagram is best viewed by turning the left side upward, which provides a west-looking projection. Redrawn from White (1976). Legend for rock types as given in Figure 4.

host rocks for veins can change significantly over very short distances.

Figure 14 shows the stratigraphic position of four separate veins at the Sunshine mine, and Figure 12C-D shows longitudinal projections of two of the important veins. The Sunshine vein, which also produced over 3,000 t of silver, neatly traces favorable strata around several large folds truncated by the vein (Fig. 12C). The vein was many meters wide and of bonanza grade where the vein occurs in thick-bedded blocky siltite just above the 1700 level but became narrower, lower in grade, and locally uneconomic in other strata. The orebody largely dies out below the contact with a 20-m-thick interval of argillaceous siltite. Yet deeper, where the minor fault that hosts the vein passes into massive quartzite, it contains only small amounts of ore, although similar quartzite is strongly favored by many other veins in the district, such as those at the Bunker Hill and Lucky Friday mines.

Two hundred meters into the structural hanging wall of the Sunshine vein, the Copper vein reaches its greatest thickness and grade in the same quartzite unit that hosts the minor ore of the deepest extent of the Sunshine vein. Upward, the Copper vein abruptly tops out just below a contact with argillaceous siltite but does not reappear in a higher quartzite or in any of the strata that host the Sunshine vein, even though the structure that hosts the Copper vein continues through these higher strata.

The West Chance vein of the Sunshine mine also passes through numerous lithologic units (Fig. 12D). Like the Sunshine vein, the West Chance vein is widest and richest in blocky siltite and uneconomic where it passes downward into argillite. Also like the Sunshine vein, it does not contain ore where it intersects massive sericitic and vitreous quartzite at depth.

White (1998b) suggested that the distribution of metals in veins and the wall-rock alteration associated with individual veins are best accounted for by the upward and outward movement of mineralizing fluids within the vein structures and where rising ore fluids encountered specific, locally favorable strata. The main control on favorability of strata may have been rheology. Quartzite and blocky siltite were most likely to deform in a brittle manner during vein formation, thereby preserving openings for hydrothermal fluids, whereas argillite and argillaceous siltite deformed in a ductile manner, thereby sealing possible vein conduits. We cannot explain why quartzite is the preferred host for base metal veins, and silicified blocky siltite is the preferred host for silver veins, but we note that these rock types differ in their competency, chemistry, hydrology, thermal, and chemical properties, and these are likely important factors in controlling the ore distribution.

Several explanations for stratigraphic ore control have been proposed. Reid et al. (1975) noted that changes in the strike and/or dip of individual veins and vein structures commonly

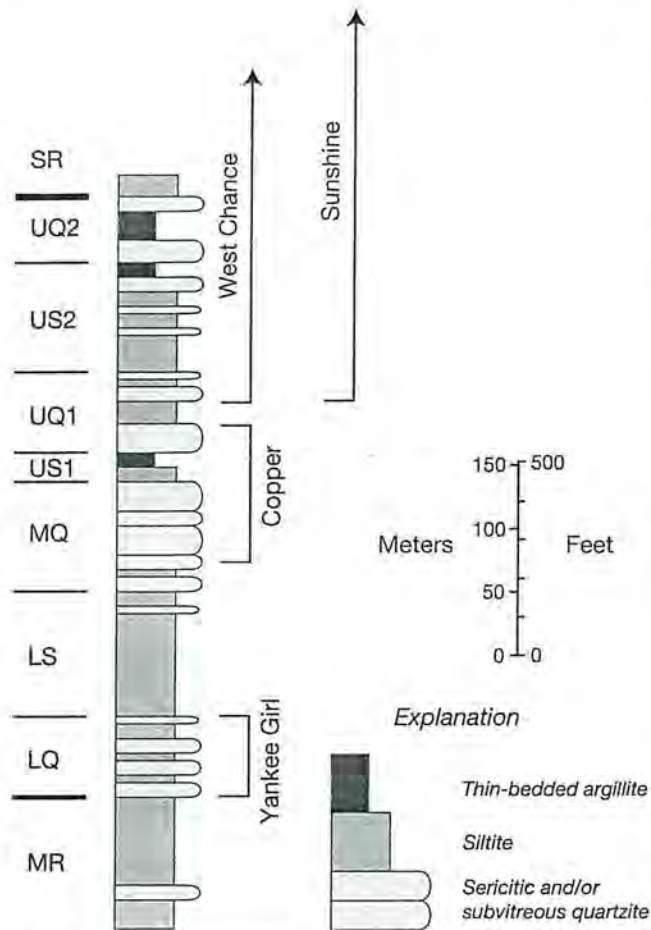


FIG. 14. Generalized stratigraphic section of the upper Revett at the Sunshine mine, showing stratigraphic position of several orebodies. The Sunshine vein made significant ore from the top of the St. Regis Formation to unsilicified argillaceous siltite in the middle of UQ1. The West Chance vein bottomed at the same stratigraphic position but did not extend as high as the Sunshine. The Copper vein topped out at the upper contact of quartzite lower in UQ1 and its ore shoot narrowed downward in MQ quartzite. The Yankee Girl orebody was economic in sericitic quartzite but uneconomic in vitreous quartzite within LQ. Legend for stratigraphic units as given in Figure 4.

correspond to lithologic changes. They suggested that stratigraphically controlled vein widening was mechanical and that slip on veins created open spaces as a result of these deflections.

Farmin (1982) suggested that quartzite may have supplied quartz to the adjacent veins. Subsequent replacement of the quartz by sulfides could account for the observed lithologic control. We note that the textures of sulfides such as tetrahedrite often mimic distinctive quartz textures, even in siderite-dominant veins, suggesting that sulfide was deposited by replacement of the quartz.

#### *Color and oxidation state of the Revett Formation, and the recognition of alteration halos*

In many places, the contact between chemically reduced strata and overlying chemically oxidized strata closely follows the base of the lowest interval of thin-bedded argillite and

crosscuts stratigraphy on a regional to local scale, such as in the Silver Belt south of the Osburn fault (Fig. 6). North of the Osburn fault, a tongue of oxidized strata occurs in the middle Revett at the Idaho-Montana Silver property and at Military Gulch. Thus, much of the Revett Formation in the Coeur d'Alene district was chemically reduced during sedimentation and/or diagenesis, but other intervals were chemically oxidized.

In addition, many places in the Coeur d'Alene district contain strata that are lavender where unaltered but have been hydrothermally bleached to light green adjacent to veins (Mitcham, 1952; Weis, 1964). In exploration, it is important to distinguish between diagenetically reduced rocks, which are not necessarily spatially associated with veins, and hydrothermally bleached rocks, which form alteration halos around veins. Documentation of hydrothermal bleaching requires detecting color changes within specific strata, from greenish colors close to faults, fractures, and veins, to lavender hues away from mineralized zones. In rocks that were reduced diagenetically prior to mineralization, other mineralogical and/or geochemical indicators, such as carbonate and sulfide minerals (White, 1998b; Strand et al., 2001), must be identified to highlight alteration.

#### *District-scale metal zonation*

The district-scale metal zonation of Coeur d'Alene veins coincides with significant changes in the Revett Formation on both sides of the Osburn fault. South of the Osburn fault, the upper Revett Formation in the Silver Belt contains thick intervals of chemically oxidized rocks, but the rocks of the upper Revett to the east, west, and south of the Silver Belt are largely to totally chemically reduced (Fig. 6). In addition, the upper Revett is thinner and finer grained in the Silver Belt than elsewhere south of the Osburn fault. North of the Osburn fault, the Lucky Friday mine contains significant silver vein mineralization and borders an area to the east where the middle Revett contains chemically oxidized strata at the Idaho-Montana silver property. West of the Lucky Friday mine, the Revett Formation is chemically reduced, and base metal veins occur in the Revett Formation. Therefore, on the district scale, base metal veins, which contain fluid inclusions with abundant methane and light hydrocarbons (Leach et al., 1988), occur in the diagenetically reduced Revett Formation. In contrast, silver veins, which formed from CO<sub>2</sub>-rich fluids (Leach et al., 1988), occur in, or marginal to, areas with the highest concentrations of the oxidized Revett Formation.

The pronounced difference in the age and style of mineralization between the veins of the Coeur d'Alene district and the sediment-hosted stratiform copper mineralization of the western Montana copper sulfide belt coincides with a dramatic thinning of the Revett Formation. Thick sections of the Revett Formation in the Lucky Friday, Bunker Hill, and Silver Belt blocks host epigenetic veins, whereas thin Revett strata in the western Montana copper sulfide belt host diagenetic stratiform mineralization (Fig. 11).

Therefore, district-scale variations in thickness, facies, and redox states of the Revett Formation can help to evaluate the prospectivity of an area for base metal or silver veins or for sediment-hosted stratiform copper mineralization. Base metal veins occur in thicker, relatively coarse grained, diagenetically

reduced Revett Formation, silver veins occur in thinner, relatively fine grained, locally oxidized Revett Formation, and sediment-hosted stratiform copper orebodies occur at diagenetic redox boundaries (Hayes, 1990) in very thin Revett Formation.

#### *Basin architecture*

The four lithostratigraphic blocks in the Coeur d'Alene district (Fig. 11) may be bounded by synsedimentary faults, although structural juxtaposition, time-transgressive units, or differential compaction may account for some of the observed thickness changes. The largest and most abrupt thickness changes occur across the Osburn fault, coinciding with the location of the Jocko line Proterozoic growth fault (Winston, 1986, 2000) or a structure of the Lewis and Clark line (e.g., Hobbs et al., 1965; Harrison, 1972; White, 2000). Structural reconstructions of the Coeur d'Alene district that omit synsedimentary faulting (Hobbs et al., 1965; Hobbs and Fryklund, 1968; Bennett and Venkatakrishnan, 1982) cannot explain these large and abrupt thickness changes. Instead, we interpret these thickness changes as reflecting a major, down-to-the-south, crustal-scale fault that was active during sedimentation and that was periodically reactivated during the structural and metallogenic history of the district.

Other workers have presented evidence consistent with synsedimentary faulting in the Coeur d'Alene district and elsewhere in the western portion of the Belt terrane. Chevillon (1977) concluded that breccias and soft-sediment deformation at the Atlas mine reflect Proterozoic tectonism along a fault at, or near, the current location of the Osburn fault. East of the Coeur d'Alene district, Alleman (1983) documented significant thickness changes within the Revett Formation across the Jocko line. On the Flathead Reservation in western Montana, the lower, middle, and upper Revett are 750, 450, and 470 m thick, respectively, south of the Jocko line (Mauk, 1983; White et al., 1984; Ryan and Buckley, 1998). These thicknesses are strikingly similar to those in the Silver Belt. North of the Jocko line on the Flathead Reservation, the Revett Formation thins to a more typical total thickness of approximately 1,000 m (Mauk, 1983; Ryan and Buckley, 1998). At the Nancy Lee mine near Superior, Montana, the Revett Formation is also very thick. The above thicknesses are consistent with the proposed offset across Winston's (1986, 2000) Jocko line, but we are not aware of similar thickness changes across the Lewis and Clark line to the east of the Coeur d'Alene district. On balance, therefore, the available data from the Revett Formation support the Jocko line as the most likely down-to-the-south Proterozoic synsedimentary fault in the region.

South of the Osburn fault, no known large structure separates the Bunker Hill and Silver Belt blocks, although a synsedimentary fault may have separated these areas during deposition of the Revett Formation. North of the Osburn fault, the Lucky Friday block and western Montana copper sulfide belt may be separated by the Snowstorm-National-Sonora Gulch fault system, which may follow the trace of a Proterozoic synsedimentary fault (T.S. Hayes, pers. commun., 1985).

Regional cross-strata data from the Revett Formation north and east of the Coeur d'Alene district record north to northeast paleocurrent directions (Hrubar, 1971; Bowden, 1977;

Hayes, 1983; Mauk, 1983; Ryan and Buckley, 1998), and those within the Coeur d'Alene district continue this trend (Fig. 10). The paleocurrent data show no evidence for southward sediment transport during sedimentation. Therefore, if the Jocko line was an active down-to-the-south fault during sedimentation, the fault appears to have had little or no topographic relief, indicating that on average, sedimentation rate exceeded the rate of offset across the fault. Furthermore, the consistency of the paleocurrent data suggest that structural blocks within the Coeur d'Alene district have not been significantly rotated, as advocated by Hobbs and Fryklund (1968), who proposed approximately 45° of counterclockwise rotation of the Silver Belt (see also White, 1998a).

#### *Regional and district-scale fluid flow*

Sediment-hosted stratiform copper deposits, including those of the Belt Supergroup, formed from basinal fluids during diagenesis (e.g., Hayes and Einaudi, 1986; Brown, 1997). Their formation required focusing of hydrothermal fluids, and stratigraphic thinning provides one effective focusing mechanism (e.g., White, 1971; Swenson and Person, 2000). Regional thinning of the Revett Formation over the Noxon arch may have been a dominant control on the location of the western Montana copper sulfide belt. However, local thinning of the Revett Formation would have resulted in an especially favorable environment in the Coeur d'Alene district, where remarkable and sudden thickness changes occur. We propose that, on a regional scale, diagenetic fluids were expelled from deeper and thicker strata to the west and east of the Noxon arch, and that these fluids migrated into the western Montana copper sulfide belt, where they formed sediment-hosted stratiform copper mineralization (Fig. 1). In the Coeur d'Alene district, however, we suggest that diagenetic fluids were expelled from deeper and thicker strata south of the western Montana copper sulfide belt block, and that they migrated northward to contribute to sediment-hosted stratiform copper mineralization. Unusually high grade ore at the Snowstorm mine (Fig. 3) may reflect pronounced focusing of fluids as a result of abrupt changes in stratigraphic thicknesses in the Coeur d'Alene district.

One of the longstanding questions about the Coeur d'Alene district is why hydrothermal fluids produced so much ore in the district and not elsewhere in the Belt Supergroup. Most workers agree that the Coeur d'Alene veins formed from metamorphic fluids. One of the difficulties in explaining the formation of metamorphic vein deposits is how to generate the large volumes of fluid that are required, particularly if a block of crust is old and has previously undergone burial metamorphism like the Belt Supergroup (e.g., Maxwell and Hower, 1967), which must significantly dehydrate the block of crust. Recent work in the Australian lode gold deposits suggests that crustal underplating may be an efficient way to drive large-scale fluid circulation (Kerrick et al., 2000). The Belt Supergroup may have experienced significant underplating during the East Kootenay orogeny at <1370 Ma (McMechan and Price, 1982; Doughty and Chamberlain, 1996) and the area was unquestionably profoundly affected by the intrusion of the Idaho batholith (Fig. 1). We agree with Criss and Fleck (1990) that a zone of steep <sup>18</sup>O gradients in Belt Supergroup rocks north of the Idaho batholith reflects

large-scale flow of metamorphic hydrothermal fluids. This high-gradient zone does not parallel the northern border of the batholith but instead partly coincides with the Lewis and Clark line (Criss and Fleck, 1990).

Furthermore, our results support previous interpretations that the Coeur d'Alene district sits astride a major crustal fault that has been recurrently active during and after sedimentation (e.g., White, 2000, and references therein; Winston, 2000), and our data suggest that other synsedimentary faults may also occur in the district. We propose that the Jocko line in the Coeur d'Alene district acted as a regionally significant, down-to-the-south, crustal-scale fault that formed a hydrologic barrier to northward-flowing metamorphic hydrothermal fluids, deflecting flow upward and into associated second- and third-order faults in the Coeur d'Alene district. Steep  $^{18}\text{O}$  gradients (Criss and Fleck, 1990) most likely represent focused flow along these faults and greatly diminished fluid flow to the north, due in large part to major changes in stratigraphic thickness across the Jocko line. The abrupt northward thinning of stratigraphic units across the Jocko line indicates that northward-flowing fluids would be focused by stratigraphic thinning, whereas southward-flowing fluids would dissipate as they crossed the Jocko line.

The Coeur d'Alene district may be unique within the Belt basin because it straddles a crustal-scale fault that has been recurrently active since sedimentation, and because it is within reach of metamorphic fluids that were expelled from the crust during the formation and intrusion of the Cretaceous Idaho batholith and possibly during the Proterozoic East Kootenay orogeny. Batholith intrusion and/or magma underplating associated with orogeny mobilized the tremendous volumes of fluid that were required to form such a large ore district; crustal-scale faults and significant changes in stratigraphic thickness helped focus these fluids, and second- and third-order faults within the district provided hydrothermal conduits so the fluids could deposit ore.

### Conclusions

We have established a district-wide stratigraphic framework for the Revett Formation that can be used at the mine, district, and regional scale to improve geologic mapping, structural assessment, and exploration for ore. Where vein structures intersect favorable strata, they produce rich ore; where structures cross unfavorable strata, they are poorly mineralized or barren. Veins that strike across bedding at a high angle are less sensitive to lithologic changes than veins that cross the strike of bedding at a low angle. The most favorable host rock for base metal veins in the Coeur d'Alene district is quartzite, and silicified blocky siltite is the most favorable host rock for silver veins.

Southward thickening in the lower, middle, and upper Revett Formation reflects a major, down-to-the-south, crustal-scale fault that was active during sedimentation and that was periodically reactivated during the structural and metallogenic history of the district. Stratigraphic thickness and facies changes in the Revett Formation in the Coeur d'Alene district are greater and more abrupt than anywhere else in the Belt Supergroup, indicating that this area was structurally complex during sedimentation. This structural complexity most likely

contributed to the area being a favorable site for later epigenetic mesothermal ore deposition.

Significant changes in the redox state of the Revett Formation are inherited from the depositional environment and subsequent diagenesis. In addition, some rocks are hydrothermally bleached on a more local scale. Although this work highlights the importance of distinguishing between diagenetically reduced rocks, which are not necessarily prospective for ore, and hydrothermal bleaching, which is strongly prospective for ore, it remains for future workers to identify criteria to distinguish between these two types of bleaching.

District-scale metal zonation correlates with district-scale facies and thickness changes in the Revett Formation. Base metal veins occur in chemically reduced, relatively thick Revett Formation, whereas silver veins occur in, or marginal to, areas with locally oxidized, less thick Revett Formation. Regional-scale metallogenic provinces correlate with regional-scale thickness changes in the Revett Formation. Diagenetically formed sediment-hosted stratiform copper mineralization occurs where the Revett Formation is thinnest, whereas epigenetic Coeur d'Alene veins occur where the Revett Formation is significantly thicker. The results of this study underscore the importance of regionally significant, long-lived, crustal-scale faults in controlling Ag-Pb-Zn veins in clastic metasedimentary terranes (e.g., Beaudoin and Sangster, 1992) by providing compelling evidence that the Osburn fault coincides with a Proterozoic structure that profoundly influenced sedimentation of the Revett Formation.

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