Polyphase Folding in the Keno Hill Ag-Pb-Zn Mining District, Yukon, Canada

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Summary

The Keno Hill Ag-Pb-Zn mining district of the central Yukon, Canada, is described as a fault-controlled, vein-hosted deposit located within deformed and imbricated rocks of the Selwyn Basin. Detailed structural mapping of abandoned open pit mines and the actively mined Bellekeno underground deposit has identified at least three discrete episodes of ductile to brittle-ductile deformation in the region including a previously undocumented, early phase of folding.

F_1 and F_2 folds are tight to isoclinal, north verging and coaxial. Spatial distribution of $F_{1\text{-}2}$ fold interference patterns suggests that F_1 and F_2 folds are related to discrete episodes of thrust-related deformation. Early thrust-related folds are modified by broad, open to locally tight and polyclinal, S-SE plunging F_3 folds that are associated with sinistral oblique fault development and base-metal mineralization. This was followed by a final phase of brittle, dextral transcurrent deformation.

The greatest structural complexity is observed to the west of the district, where $F_{1\text{-}2\text{-}3}$ fold interference patterns are observed proximal to D_3 and D_4 faults and a rheological contrast appears to have permitted F_3 fold tightening. It is thought that the localised structural complexity may be in part due to the area's proximity to a major F_3 fold hinge.

Introduction

The Keno Hill Ag-Pb-Zn mining district of the central Yukon is a historic region approximately 350 km north of Whitehorse that has been actively mined and studied for close to 100 years (Cathro, 2006) and is currently being explored and developed by Alexco Resource Corp. The district is located in, and dominated by, rocks of the Selwyn Basin, including deformed and imbricated sedimentary rocks and Triassic meta-gabbros and meta-diorites. The district comprises several fault-controlled, vein-type silver-rich base-metal deposits that are typically hosted in the Mississippian Keno Hill Quartzite (Lynch, 1989) within the Tombstone thrust sheet (Fig. 1). Emplacement of meta-mafic bodies has been dated at 232 +1.5/-1.2 Ma (U-Pb baddeleyite) in the Ogilvie Range, west of the mining district (Mortensen and Thompson, 1990). Mair et al. (2006) proposed the cessation of ductile deformation by 104 to 100 Ma ($^{40}Ar/^{39}Ar$ muscovite) with the earliest age of deformation constrained by a Late Jurassic age for the youngest deformed sedimentary rocks in the region, while Sinclair et al. (1980) retrieved a K-Ar (whole rock) age for mineralization of 87 ± 3 Ma.

The Tombstone thrust sheet is bounded above and below by the Tombstone and Robert Service thrusts, respectively. Tombstone thrust-related deformation of rocks in the hanging wall of the Robert Service thrust indicates that displacement along the Robert Service thrust initiated prior to Upper Jurassic, northwest translation of strata along the Tombstone thrust (pers. comm., D. Murphy, 2009). Deformation associated with thrust faulting produced highly strained and transposed strata and is believed to have generated the lower to middle greenschist-grade metamorphism that is observed across the area. The regional foliation is a compositional layering that is thought to be an intense differentiation cleavage formed during thrust related folding and re-folding of primary bedding and associated shearing between compositional layers.

High resolution structural mapping of abandoned open pit mines and the actively mined Bellekeno underground deposit was conducted between 2008 and 2009 and has identified at least three episodes of ductile to brittle-ductile deformation followed by a later period of brittle, dextral transcurrent fault propagation.

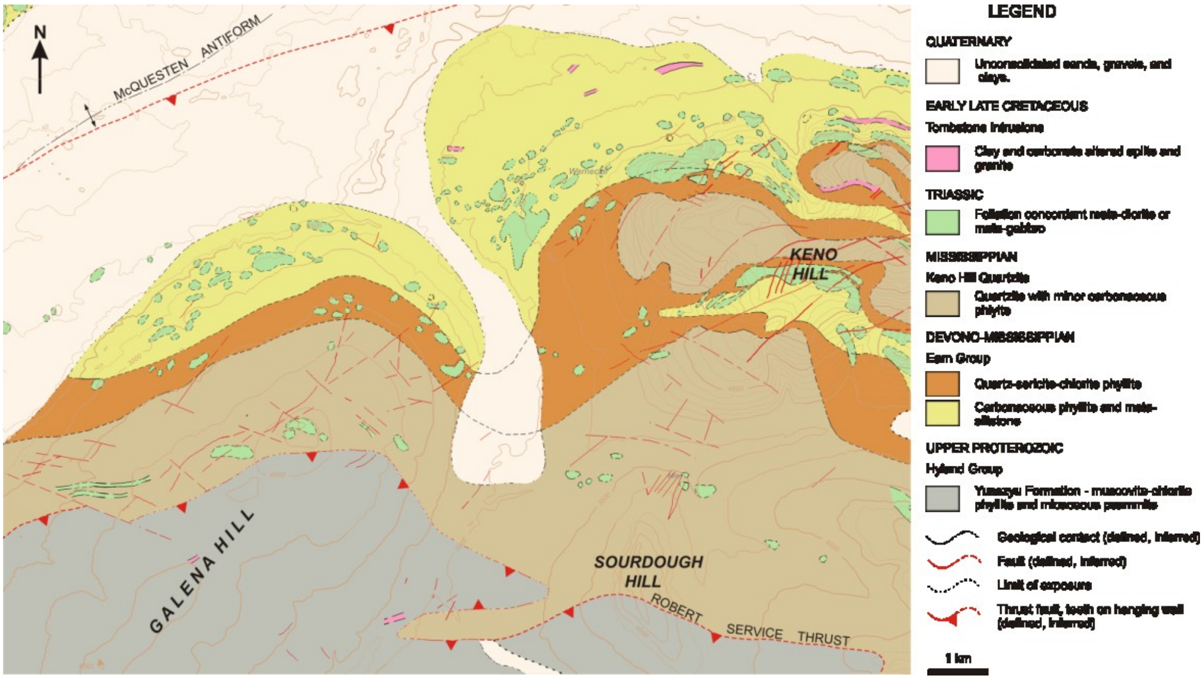

Figure 1. Simplified geological map of the Keno Hill Ag-Pb-Zn mining district (modified after Murphy and Roots, 1997).

Results

Two phases of sub-coaxial, tight to isoclinal folds are observed from micro- to meso-scale in the district and are related to movement along the Robert Service and Tombstone thrusts. These thrust-related folds typically plunge shallowly E-W and have axial surfaces parallel to the primary regional foliation that generally dips approximately 25˚ S–SSE. The earliest identified phase of folding (F_1) is most evident at structurally higher levels, near the Silver King deposit, to the west of the district, and proximal to the transition between the Keno Hill Quartzite and the overlying Upper Schist unit. At this locality up to 30 cm thick isoclinally folded packages of quartzite are clearly re-folded by tight to isoclinal, north-verging F_2 folds (Fig. 2). Elsewhere, evidence for F_1 folding is sporadic and commonly limited to micro-scale, intrafolial folding of deformation fabrics.

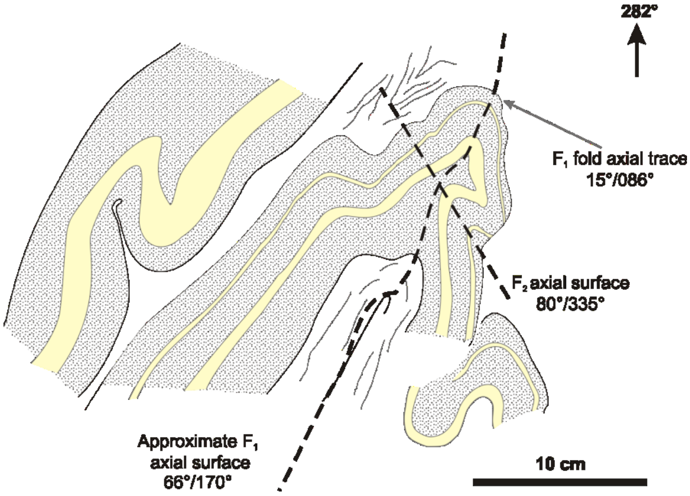

Figure 2. Sketch of F_1 - F_2 fold interference pattern at Galena Creek. UTM: 0471915 mE, 7085382 mN.

F_2 folding is evident across the district at meso-scale and forms tight to isoclinal, recumbent to rarely upright structures. It is observed within all units in the district, except the late-stage, cross-cutting felsic dykes of the Tombstone suite. F_2 folding most commonly appears as intrafolial folds within thin (1 – 20 cm) schistose layers that are interleaved with thicker quartzite layers. The shallowly plunging E-W modification of F_2 fold axes is attributed to subsequent deformation and the development of moderate to shallow, S-SE plunging F_3 folds (Fig. 3).

Subsequent to thrust-related folding a rotation of the σ_1 far-field stress from approximately N-S to NE-SW produced oblique sinistral faults with associated base-metal mineralization, minor, late-stage, antithetically oriented, oblique dextral faults and F_3 fold development. Typically F_3 folds are manifested as broad, open to warped, shallow to moderate, S-SE plunging structures with steep dipping (approximately 80˚) hinge surfaces. In the Bellekeno underground workings, F_3 folds are commonly associated with axial surface-parallel mode I-II fracture hosted quartz (with minor pyrite and siderite) veins, stockworks, schistose upwellings and extensive boudinage. Axial surface-parallel veins commonly occur within thick (0.4 – 1 m) quartzite packages and terminate against thin schistose layers.

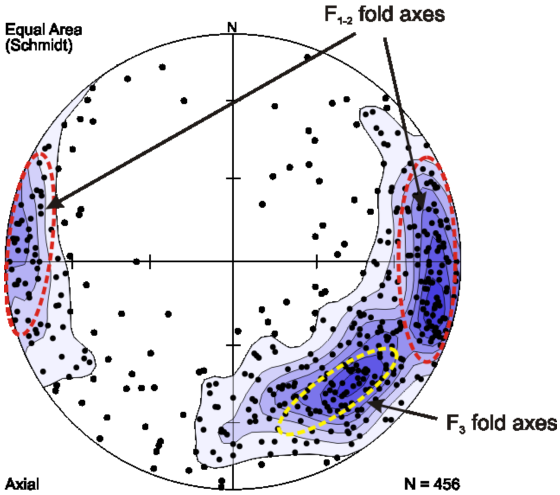

Figure 3. Density contoured lower hemisphere projection of fold axes in the Keno Hill Ag-Pb-Zn mining district. F_1 and F_2 fold axes plunge shallowly E-W; F_3 fold axes plunge shallow to moderately S - SSE.

Locally F_3 folds appear tight and in the Bermingham open pit mine chevron and polyclinal F_3 folds are developed proximal to the cross-cutting (D_4?) Mastiff fault within an approximately 40 m thick package of graphitic schist. It is thought that the incompetency of the schist relative to the quartzite allowed for fold tightening and that the resultant structural weakness through the hinge of the chevron folds permitted subsequent development of the right-stepping Mastiff fault. Elsewhere, in the Bermingham West open pit mine, 1 cm amplitude, intrafolial, chevron folds in sericitic and graphitic schist layers indicate that foliation parallel slip occurred during F_3 fold formation (Fig. 4).

Discussion

Despite a sub-coaxial relationship between F_1 and F_2 folds, the relative abundance of F_1 folds at high structural levels, close to the top of the Keno Hill Quartzite, suggests that F_1 folds represent an early, discrete phase of deformation and are not the result of an extended phase of thrusting and imbrication associated with F_2 formation. Thrusting and deformation associated with the Robert Service thrust is believed to have initiated earlier than that associated with the Tombstone thrust and as such may have been related to the formation of the earliest phase of folding. Subsequent isoclinal folds may be related to the northwest translation of strata associated with development of the Tombstone thrust. Both F_1 and F_2 fold axes are modified by typically broad, open, S-SE plunging F_3 folds that are associated with sinistral oblique fault development and base-metal mineralization. Fold interference patterns and fault relationships are very complex proximal to the Bermingham open pit mine, and simpler along strike, proximal to the Hector-Calumet deposit. It is thought that this is due to their relative proximity to major F_3 fold terminations. The Bermingham deposit is thought to be located within or near a major F_3 fold hinge, whereas the Hector-Calumet deposit is believed to be located within the limb of a major fold.

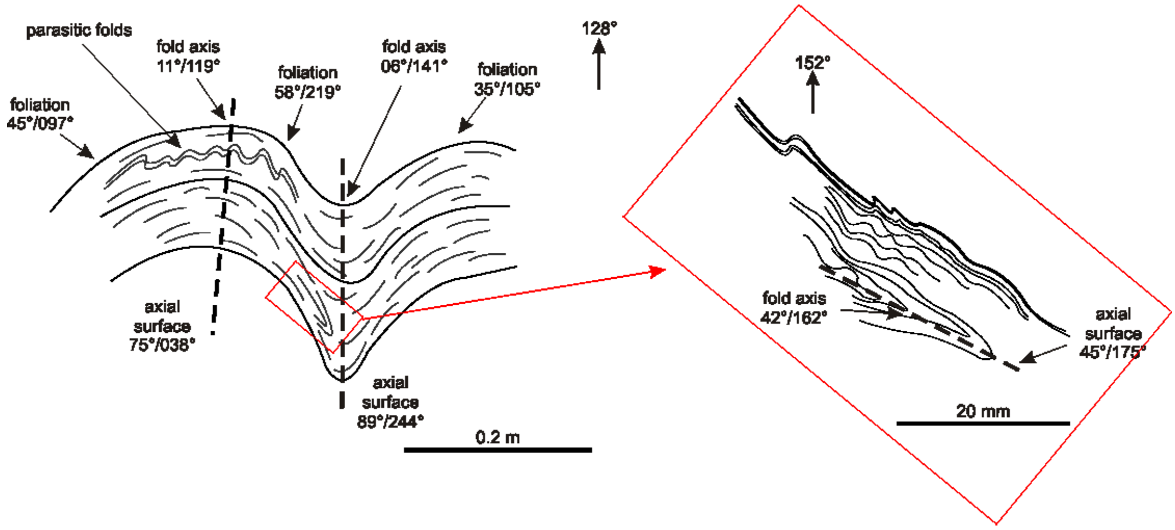

Figure 4. Field sketch of F_2 - F_3 fold interference patterns in the Bermingham West open pit mine (sub-vertical exposure).

Acknowledgements

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