The significance of the early deformation architecture in localizing "Carlin-like" gold mineralisation at the Jianchaling Gold deposit, Shaanxi province, Peoples Republic of China

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Abstract. The Jianchaling (JCL) deposit is located on the northern edge of the South China Craton and is separated from the North China Craton by the ESE-WNW trending Qinling-Dabie orogenic belt. A recent structural geology study established a new deformation framework for the local mine area. Structural controls on the distribution of Carlin-style mineralisation developed during early ductile deformation that preceded gold mineralisation. Early ductile deformation saw the rotation of early shallow dipping thrust faults to upright attitudes during regional folding. Subsequent extension or gravitational collapse folded bedding and the F_1^{45} fault asymmetrically about shallow dipping axial planes, whereby one limb maintained a shallow north dip. These deformation events produced the critical structural architecture for the gold mineralising event. "Carlin type" gold mineralisation was synchronous with late reverse movement along the F_1^{45} fault that locally brecciated the shallow north dipping "heterogeneities" in the F_1^{45} fault geometry. These heterogeneities were a product of early folding of the F_1^{45} fault. The shallow dipping heterogeneities provided the zones of maximum dilation and fracture during the gold mineralising stage, resulting in shallow plunging ore shoots. Steeply plunging ore shoots developed at the intersections of cross cutting gold stage NW and NE striking faults with the ESE striking F_1^{45} fault.

The Jianchaling mine provides an example where the early deformation history was vital to developing "traps" for mineralisation. In the absence of early recumbent folding, only small, steeply plunging ore shoots would have developed along the F_1^{45} fault.

Keywords. China, Jianchaling, structure, Carlin type, cleavage asymmetry

1 Introduction

The Jianchaling (JCL) gold mine is located along the southern border of the Qinling-Dabei orogenic belt, and on the northern edge of the South Chian Craton in southwest Shaanxi Province of the Peoples Republic of China. It is the first mine designed, constructed, financed and operated to western standards in China, with a pre-mined resource of 1.6 Mt @ 9.85 g/t gold (Vielreicher et al., 2003; Erceg et al., 2004). An ongoing drilling program is currently looking to expand the resource of the nearby Zhangjianshan (ZJS) deposit, as reserves at JCL are almost exhausted.

In the mine region, gold is located at the contact of Proterozoic ultramafic and dolomite units that are separated by steeply dipping ESE-WNW trending faults. Within the Jianchaling mine, the most voluminous zone of gold mineralisation occurs along shallow north dipping portions of the ESE trending F_1^{45} fault; where the bulk of gold mineralisation is hosted within the footwall ultramafic sequence with minor occurrences of economic gold in the hanging wall dolomite sequence. Gold mineralisation is submicron sized and generally occurs in arsenic-rich rims of finely disseminated sulfides, particularly pyrite, and is constrained within dark grey dolomite-quartz-pyrite alteration selvedge's in veins and fractures that have formed late in the deformation history. The strong element association of the Au-As-Hg and the alteration and mineralisation assemblages led Erceg et al. (2004), to classify the deposit as "Carlin type".

Two types of ore shoots are found within the deposit. The most voluminous high-grade ore domains are shallow ESE plunging ore shoots that are located along shallow north dipping portions of the F_1^{45} fault. Thinner by volume are ore domains that occur at intersections of steeply dipping NW-SE to NE-SW trending faults with the F_1^{45} fault. These ore shoots typically have steep east plunges, as the F_1^{45} fault has a steep NNE dip.

JCL and ZJS are both structurally controlled "Carlin-type" gold deposits, where gold is sub-micron sized and generally occurs in arsenic-rich rims of finely disseminated pyrite crystals. To optimize exploration programs, a joint study with staff from Sino Gold and SRK Consulting was initiated to identify testable structural models for the localisation of mineralisation in the Sino Gold mine lease and exploration licence areas.

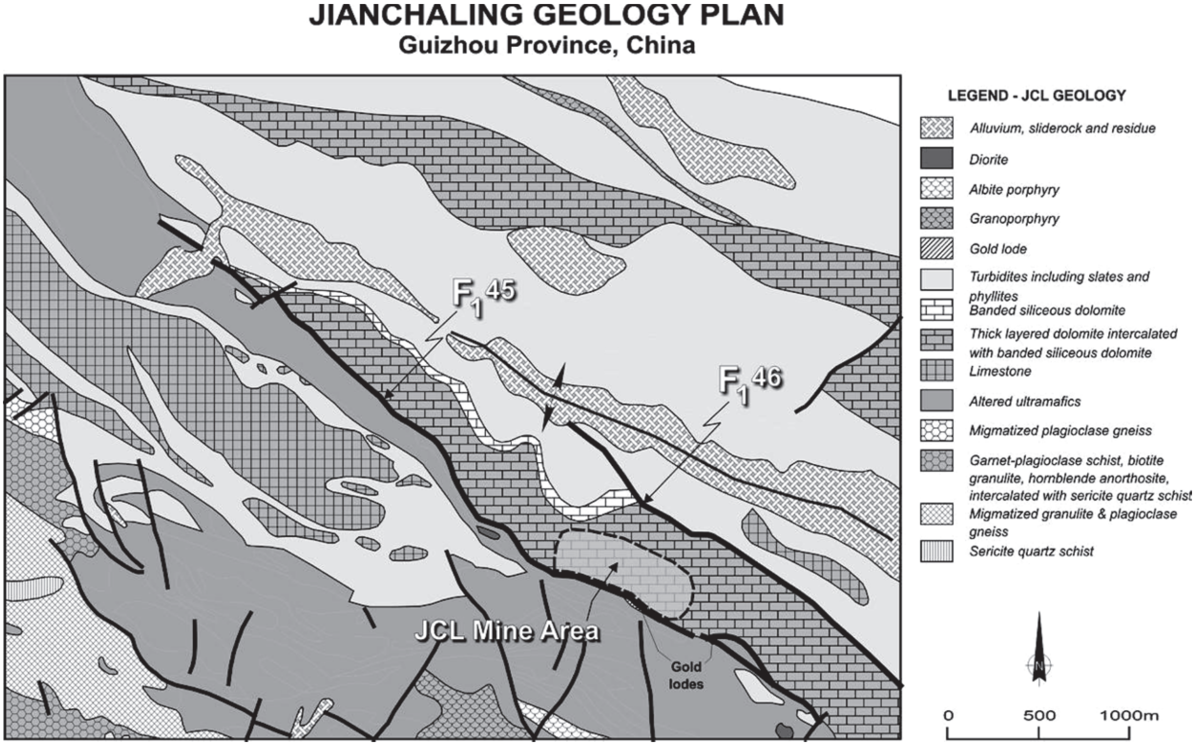

Figure 1: Geology map of the Jianchaling deposit area. Highlighted on the map is the location of the JCL mine area, the F_1^{45} and F_1^{46} faults and the anticline in the hanging wall of the F_1^{46} fault. The F_1^{45} fault continues along strike for another 2km to the ESE of the edge of the map

2 Local geology and geometry of the deposit

Gold mineralisation at the Jianchaling deposit is hosted in the steeply north dipping F_1^{45} fault and it is the most prominent fault in the mine area. The F_1^{45} fault separates metasedimentary rocks in the hanging wall from metamorphosed ultramafic (dunite, harzburgite - Vielreicher 2001) rocks in the footwall, and can be traced along strike for about 5.5km (Fig. 1). The ultramafic footwall rocks consist of variably metasomatised serpentinites and gabbroic rocks (Vielreicher et al. 2003), and are believed to be mid to late Proterozoic in age. The serpentinized footwall sequence adjacent to the F_1^{45} fault has been primarily altered to fine grain talc schists, talc-magnesite schists, or massive magnesite rocks with minor quartz-carbonate alteration The footwall ultramafics were overlain by a hanging wall sequence that consists of highly fractured, weakly metamorphosed, recrystallised, massive to well bedded limestone and dolomite. Adjacent to the F_1^{45} fault, the carbonate rocks are highly fractured and recrystallised, with variable amounts of silicification. To the north, the hanging wall carbonates are separated from a thick sequence of phyllites and graphitic slates by a steep ESE striking fault, referred to as the F_1^{46} fault.

Bedding is generally steeply north dipping and it is sub-parallel to the F_1^{45} fault geometry. Within the main ore zone at JCL, the F_1^{45} fault and bedding have been rotated asymmetrically to shallow north-northeast dips. In long section the main ore zone has a shallow plunge along strike that is intersected by both steep NE and NW striking faults that are SE and NE dipping respectively. The intersections of these faults produce moderate to steep east pitching ore shoots. However along the main ore zone, there are NE to NW striking faults that dip shallowly from the NW to SE, cross cut the F_1^{45} fault and locally have increased volumes of ore in the footwall of these faults. Displacement along the cross cutting NE and NW faults is usually small with the majority offsets less than 15m.

Whilst the minor shallow faults (or splays) locally produce shallow plunging ore domains, the overall shallow geometry of the main ore zone is continuous for more than 500m along strike (Fig. 2). In cross section the main ore zone ranges up to 100m wide along the shallow north-dipping portion of the fault, in areas where shallow north dipping faults are absent. Therefore the overall shallow north dipping ore geometry along the F_1^{45} fault must be a product of deformation that preceded mineralisation. Thus to understand the localisation of ore along the F_1^{45} fault, necessitated an investigation into the deformation events that initiated the fault and subsequently modified its shape.

3 Summary of the deformation history

Structural mapping of the surface and underground exposures, as well as logging of drill core, provided a new deformation framework of the local mine area. Extensional deformation in the time period between the mid to late Proterozoic saw the extrusion of the footwall ultramafics, which precipitated sub-economic nickel mineralisation. Circulation of seafloor hydrothermal fluids synchronous with the extrusion serpentinised the ultramafic rocks. This was followed by the deposition of the hanging wall sequences of the Duan Tou Yan formation in a progressively deepening ocean.

Compressional deformation (D_1) which was approximately N-S directed, affected these sequences late in the Phanerozoic by initiating thrusting along ESE striking faults, including the F_1^{45} fault. Regional upright folding followed during approximately NNE-SSW bulk shortening (D_2). During D_2, bedding and ESE striking faults within the mine area were rotated from shallow to steep dips. This deformation event records near peak metamorphic conditions and produced the dominant differentiated crenulation cleavage in the region. Reverse faulting along the ESE striking faults late in D_2 enhanced the penetration of CO_2 rich fluids that metasomatised both the ultramafic and sedimentary sequences. Recumbent folding during D_3 locally rotated bedding and early deformation fabrics and faults from steep to shallow dips. Deformation during D_3 is possibly the consequence of orogenic collapse of the orogen between shifts in the direction of bulk shortening. Strain was accommodated along the F_1^{45} fault by folding during D_3 rather than by shearing, and deflected the geometry of portions of the fault from steep to shallow dips. NE over SW displacement was recorded by bedding, the S_2 foliation and the folded portions of the F_1^{45} fault. Folding of the F_1^{45} fault created heterogeneities in the average fault dip that focussed deformation and mineralisation during D_4.

Renewed horizontally directed NE-SW shortening transpired during D_4. Exhumation of the rocks during D_3 had elevated the rock package to higher crustal levels, where brittle deformation dominated. Reactivated sinistral reverse (mostly reverse) faulting along the ESE striking F_1^{45} fault saw strain accommodated across shallow dipping portions of the fault by fracture and brecciation. Enhanced fluid flux in to these zones of brecciation advanced the precipitation of gold. Reactivated reverse shear along the long limbs of the folded fault propagated new hanging wall faults. Steep NW striking mostly reverse faults disrupted the F_1^{45} faults and locally precipitated narrow, steep plunging ore shoots.

Small offsets (<10m) of the F_1^{45} fault along steep NNE and NNW striking faults post date gold mineralisation during D_5. Bulk shortening during this phase of deformation was E-W directed whereby only minor fractures and faults developed.

4 Significance of early ductile deformation to mineralisation

The early ductile deformation at Jianchaling has controlled the architecture of the F_1^{45} fault for later gold mineralisation. A key to recognising the importance of the early ductile deformation was found in the differentiation asymmetry of cleavage in phyllites and slates found in the hanging wall of the F_1^{46} fault, which is located parallel to and north of the F_1^{45} fault. The hanging wall of the F_1^{46} fault hosts an anticline where on the northern side of the anticline, the differentiated cleavage S_2 is steeper than bedding and is sub-parallel to the axial plane. Vergence from both the differentiation asymmetry and bedding cleavage relationships indicates an anticline to the south. On the southern limb of the anticline, the S_2 cleavage has a shallower dip than bedding and the differentiation asymmetry indicates a syncline to the north. This indicates that the S_2 cleavage was not axial planar to the hanging wall fold and that the geometric relationship is only possibly if the S_2 differentiated cleavage has been folded with bedding. Asymmetries from weaker fabrics developed during D_3 and D_4 suggest that folding in the hanging wall of the F_1^{46} fault was a two-stage process. Initially steeply dipping beds and cleavage were rotated to shallower dips during D_3, which then exposed both bedding and cleavage to upright folding during D_4.

Deformation in the hanging wall carbonate rocks could not be accommodated by folding in the same way as the 'weaker' phyllites and slates within the hanging wall of the F_1^{46} fault during D_4. Instead, deformation was effectively partitioned coarsely between the two steeply dipping ESE striking faults during D_4 and was mostly accommodated by reactivation of these faults. This partitioning of strain was crucial in localising brecciation along the F_1^{45} fault during mineralisation.

Reactivation of the F_1^{45} fault, however, was not enough to localise of economic gold mineralisation. It was the shear of the irregular geometries within the gross F_1^{45} fault shape during reactivation that allowed mineralisation to be localised into an economic gold deposit. The geometry of the F_1^{45} fault has followed a similar path to bedding in the hanging wall phyllites. After initial thrusting, the F_1^{45} fault rotated to a steep north dip during regional upright folding, where the regional fold axis is located more than a kilometre to the SSW of the mine. Ductile deformation during D_3 folded the F_1^{45} fault about shallow dipping axial planes with a NE over SW sense of shear. These folded portions of the F_1^{45} fault are heterogeneities within the gross fault geometry that enabled fracturing and brecciation to be localised during reactivation of the F_1^{45} fault during D_4. Shallow dipping splay faults initiated along the folded portions of the F_1^{45} fault to accommodate the mostly reverse movement of the F_1^{45} fault.

Consistent shallow southwest dipping sheeted mineralised veins/fractures sets developed in response to the movement along these splays and the F_1^{45} fault. In contrast, steep NW striking reverse faults that intersect the F_1^{45} fault and were active during gold mineralisation (Vielreicher et al. 2003) produced steeply plunging but thin ore zones. In the absence of the heterogeneities along the F_1^{45} fault that developed during D_3 folding; only thin, steeply plunging, sub-economic mineralised zones could form. Therefore the deformation during both D_2 and D_3 has been crucial to creating heterogeneities along the F_1^{45} fault that subsequently localised gold mineralisation.

5 Conclusion

Transporting metals in a hydrothermal system typically requires large fluid fluxes due to the low solubility of metals. The percolation of a significant volume of fluid to precipitate an ore deposit requires enhanced permeability particularly in low permeable rocks. Fractured rocks in fault zones create zones of high permeability for hydrothermal fluids to flow. However, the fault zone must be *active,* as any precipitation of minerals from the hydrothermal fluid, such as quartz, will reduce the fault zones permeability. Heterogeneities within active fault zones are locations where rock fracture intensifies, as the rock has to accommodate deformation around the heterogeneity. Zones of intense fracture or brecciation increase fluid flow into these zones and the enhanced porosity locally reduces the fluid pressure and thereby promotes mineral precipitation. The Jianchaling deposit is an excellent example where the early ductile deformation was critical in developing heterogeneities within the F_1^{45} fault that subsequently localised gold mineralisation. Gold mineralisation has developed late in the deformation history and has "Carlin like" affinities, with strong element associations of the Au-As-Hg as well as the alteration and mineralisation assemblages. However without the structural "traps" that developed during early ductile deformation, gold mineralisation at the JCL deposit, "Carlin-like" or otherwise, would have only developed smaller ore bodies.

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