APPLYING STRUCTURAL INTERPRETATION TO THE EXPLORATION OF VEIN AND FAULT HOSTED EPITHERMAL DEPOSITS: IMPLICATIONS FROM ESTABLISHED MINING DISTRICTS

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Initial phases of greenfields and brownfields exploration in epithermal districts often invoke map (plan) vein view interpretation of fault, vein and alteration patterns to identify exploration targets. This two-dimensional approach often results in targeting which assumes a strike-slip setting to vein systems, frequently, and often incorrectly, focusing on interpreted strike-slip dilational jogs or terminations. However, while good examples of strike slip fault hosted veins are apparent mainly in arc-oblique and transtensional fault settings where oreshoots may occur at lateral deflections in a fault-vein system, arc-parallel (arc under extension/retreat) and arc orthogonal (arc under compression) extensional faults are more common hosts to veins where kinematic history of vein-fault systems can be established. Even in first order strike slip/transtensional settings, veins may occupy extensional faults developed obliquely between, or separate from strike slip regional structures so that local orebodies are geometrically controlled by second order normal fault settings (e.g. Comstock, Goldfield).

Veins in epithermal districts typically form late in the history of faults that they occupy, sealing them and often overprinting the fault rock, leaving the offset of lithologic units as the primary indicator of a fault displacement across the vein system. While structurally late, veins typically exhibit evidence for repeated, syn-kinematic episodes of vein formation and brecciation that maintain structural permeability and cyclic fluid flow linked to increments of fault displacement and rupture of hydrothermal seals in the vein system. This allows a field based structural evaluation of vein kinematic evolution and architecture with utilization of fault kinematic indicators, lateral and vertical variations in structural style of fault hosted veins (extensional or fault dominated character), and influence of fault orientation and distribution by host rock rheology and porosity (influence refraction and termination of hosting vein structures). Syn-vein kinematic indicators (oblique cataclastic foliations, Riedel shear fractures) are often preserved in silicified fault rock on vein margins, and form more accurate shear sense indicators than slickensides which are easily reset. Geometry of stress controlled sheeted "stockwork" veins and veinlets which form peripheral to, between, or at tips of fault-hosted veins also provide valuable kinematic information as well as paleostress information, especially in conjunction with internal fault kinematic indicators, and may form bulk oreshoots at predictable lithostructural sites. The mapping and modelling of lithologic marker units is often essential in the tracing, geometrical modeling and determining the relative importance of ore controlling structures, and dilational sites along faults, especially where veins are absent along non-dilational segments of the fault system. Fault character also may vary laterally approaching oreshoots, from entirely cataclastic fill (gouge) through progressively more hydrothermally lithified fault rocks and increasing vein abundance and diminishing fault rocks abundance along the fault trace. These patterns are often coincident with alteration mineral zonation and a mappable increase in the density of extensional "stockwork" veins peripheral to the main structures near oreshoots.

Extensional and extensional-oblique slip fault hosted deposits display different oreshoot geometries at a deposit scale than are apparent in strike slip settings, which with kinematic interpretation result in differing exploration approaches for blind oreshoots along faults and/or beneath high-level alteration zones. Prominent oreshoot controls often are formed early in the fault history during its initial propagation prior to vein development, forming irregularities, deflections and bifurcations in the hosting fault system which later becoming important structural trap sites. These include dilational, and locally contractional steps and bends in strike slip settings. In extensional settings these include extensional relays at fault steps, fault intersections often at curved interacting fault tips, and extensional ramps and relays or jogs at changes in fault dip that are often rheologically controlled (e.g.

Guadalupe/Palmarejo). Lithologically controlled fault refraction often accentuates the shallow dipping nature of long sectional oreshoot bands in many vein extensional fault-vein systems where stratigraphy is also shallowly inclined, especially where coincident with boiling levels in low sulphidation settings (e.g. Kupol, Midas). However, in deposits where rheological contrasts are minor, shallow dipping oreshoots may be influenced more by distance from, and parallel to, the paleosurface. Curved oreshoots on long sectional projection often are elongate but arcuate in near surface, low sulphidation setting, and may correspond with lateral variations in displacement along the hosting extensional faults, conforming with the architecture of the host sequence (e.g. Kupol) and terminating laterally in areas of diminishing displacement at fault tips. Stacked oreshoots may occur where refraction occurs at depth across different units, sometimes resulting in zoned oreshoots which vary in metal content with depth in deeper intermediate sulphidation vein systems. Vein systems may also be constrained below composite rheological and permeability contrasts that are stratigraphically controlled, especially in low displacement, dominantly extensional vein systems (e.g. Hishikari, Hollister, some peripheral vein system at Waihi). Extensional fault relays that may be formed early in faulting history, which are often in plan view mistaken for strike-slip dilational jogs, in near surface low sulphidation settings form sites favourable for the formation of shallow plunging oreshoots at upward-widening horsetail terminations of fault segments that interact with the paleosurface (e.g. Favona, Golden Cross). At greater depths, extensional relays may plunge more steeply where adjacent en echelon fault strands laterally interact without the influence from the paleosurface (e.g. Guanajuato). Where multiple oreshoot controls converge particularly in intermediate sulphidation systems, they may form highly permeable structurally focused sites of intense hydrothermal fluid flow that form oreshoots with exceptionally long dip length (e.g. Martha Hill, Pachuca) which may have restricted lateral dimensions (e.g. Palmarejo Clavos 76). Second order oreshoots internal to the settings described above may include plunges parallel to the syn-mineral slip direction on the controlling structures.

In vein systems formed in nearly pure dip slip faults in young volcanic terrain where stratigraphy is shallow dipping, vein-lithologic intersections and associated rheologically induced fault refraction that forms dilational sites at steep dipping segments may both occur parallel to the σ_2 paleostress orientation. Since this also conforms with the line of intersection of stress controlled extensional vein sets with the principally ore controlling fault-vein systems under ideal conditions, the coincidence of these geometrical associations can result in the potential for highly dilational sites of optimal, initially subhorizontal “stockwork” zones of extensional veins adjacent to the main vein system (e.g. Pachuca; Guadalupe at Palmarejo).

Porous sequences dominated by poorly lithified volcaniclastic rocks may have less focused fluid flow, and faults may dissipate in less lithified horizons or not continuously propagate. Where developed in such settings, fault surfaces can behave as impermeable features of fine-grained cataclastic fill (e.g. Taupo Volcanic Zone), in contrast to their structurally permeability in competent flow- or intrusion dominated settings where active fault strands and fracture networks in surrounding damage zone promote syntectonic, cyclic structural permeability. In these settings, adularia-quartz alteration in low sulphidation settings and vuggy silica in high sulphidation settings can increase rheological competency and promote late formation of structurally controlled, higher grade veins that may be superimposed on earlier disseminated mineralization styles (e.g. Round Mountain, Goldfield, Ohakuri, Hycroft).

Settings and kinematic architecture of vein systems in long lived epithermal metallogenic belts may evolve with arc stress state and resultant evolving fault patterns. Where associated with regional faults, veins may inherit older fault geometry which formed under different paleostress conditions (e.g. Guanajuato, Midas), making establishment of the fault-vein evolutionary history an important contributor to understanding camp scale targeting. At a district scale, veins may be linked to hydrothermal centers formed along regional fault sets, resulting in vein formation along parallel faults outward from the hydrothermal center, often associated with small late, fault controlled felsic or intermediate volcanic flow domes and dykes sets. However, some districts form elliptical zones of parallel or branching veins which are localized along faults that are not linked to regional fault zones, although they may conform to regional fault orientations outside the mining districts. In such districts, controlling networks of parallel sets of faults may exhibit greatest displacement in the central, best mineralized portions of the district, with fault displacement dissipating laterally. This may suggest local control to fault propagation, potentially in response to volume changes in an underlying magma chamber that could also be genetically related to the hydrothermal system.

Distinguishing syn- and pre-vein faults is also essential in appropriate targeting and the recognition of which structures may overprint and offset veins, rather than host them. District scale tilting often by post-mineral regional faulting, can be implied by implied by inclined syn- or near coeval volcanic stratigraphy, tilted textural metal and alteration zonation, or inclination of stratified vein sediment style vein-fill breccias that are common in some vein systems. Recognition of post-mineral tilting can also aid in both in the assessment of local late fault effects and interpretation of relative depth position across the district.

Collective integration of the tectonic setting of epithermal districts and high level alteration zones with fault evolution, kinematic history and architecture in epithermal districts may consequently aid in the identification of new undiscovered deposits and near mine oreshoots. Such a largely traditional structurally based field approach is crucial in the refinement of GIS and remote sensing interpretations that dominate current exploration philosophy, and underscores the need to target based on more than unconstrained map based vein-fault patterns, particularly in the deposit scale extensional settings that characterize most epithermal districts.