RECORD OF MULTI-SCALE HYDROTHERMAL FLUID PATHWAYS CONTROLLED BY A TRANSTENSIONAL FAULT NETWORK: INSIGHT FROM THE NORTHERN NEVADA RIFT

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ABSTRACT

The fossilized northern Nevada rift (NNR) presents a unique opportunity to investigate multi-scale fault network controls on hydrothermal fluid pathways of low-sulfidation epithermal systems. Evidence suggests that structural controls at all scales directly influenced when and where a series of genetically related Au-Ag epithermal deposits formed within the rift. Field observations indicate the southern half of the NNR formed a series of five half graben basins, aligned on a 340° trending axis. All basins have ~340° striking, E-dipping, boundary fault systems on their western margins. E-dipping boundary faults work in concert with incipient, parallel, W-dipping boundary faults on the eastern basin margins. W- and E-dipping dip-slip boundary faults commonly display apparent dextral offset, are linked by ~50°-70° striking dip-slip faults that frequently display sinistral offset. Collectively, the faults accommodated asymmetrically subsiding blocks to form volcanic depocenters and the basin architecture suggest extension occurred with a slight dextral motion across the ~40 km-wide NNR, consistent with the expected motions of coevally forming structures in a Riedel shear model. The Mule Canyon and Fire Creek deposits are located in similar structural settings in horse blocks bound by the primary boundary fault in the hanging wall and its conjugate on the footwall. Mechanically the conjugate normal faults form subvertical Riedel shear zones that focused hydrothermal fluid flow. Geometries of dike swarms and veins at both deposits suggest that linkages between conjugate normal faults, manifested as surficial relay-ramps, serve as high flux fluid conduits. Steeply plunging ore shoots and kinematic indicators at Fire Creek suggest dip-slip motion on faults formed plunging Riedel shear fabric that channelled fluid flow along individual vein systems. Observations of coseismic deposition of Au-Ag-bearing bands within veins, suggest that fault kinematics and resulting shear fabric were essential in channelizing the flow of Au-Ag-bearing fluids to the epithermal environment at all scales. Results from this study suggest that the fractal nature of shear fabrics may play a key role in understanding the dynamic interaction of structural development, seismicity and fluid flow in extensional environments.

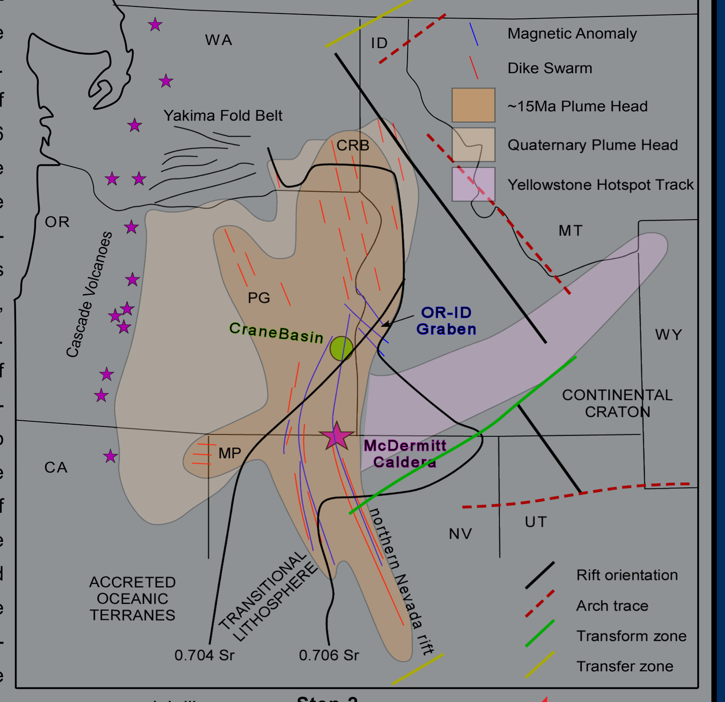
Keywords, Riedel shear, low-sulfidation epithermal, fractal, mineralizing system, coseismic

INTRODUCTION

NW USA Neogene geology is a combination of magmatism-volcanism in relation to plate margin tectonics. Three components are of interests, 1) Sublithospheric migration of the Yellowstone hot spot (YHS) mantle plume thermally weakening the crust, 2) Plate margin tectonics along the San Andreas system causing stress partitioning through the interior of western North America, 3) Predictive structural geometries associated with Riedel shear mechanics and their resulting influence on fluid migration.

Yellowstone Hot Spot - Fossilized Rift System

Figure 1 Right, Regional map of northwestern United States displaying the main components of the Yellowstone hot spot & northern Nevada rift system. Major features are the interpreted rifted margin of the North American craton represented by the 0.706 Sr line, first eruptive center of the Yellowstone hotspot (McDermitt caldera), the interpreted plume sub-lithosphere spreading paths and resulting surface expressions as dike swarms and eruptions (Columbia River Basalts - CRB, Picture Gorge - PG, Modoc Plateau - MP and northern Nevada rift). Structural lineaments represented by blue lines of magnetic anomalies (Ponce, 2002). Major tectono-volcanic structural features are the Oregon-Idaho Graben (OIG) which is associated with the Crane Basin. Interpreted Proterozoic rifted margin of Laurentia (0.6 - 0.8 Ga) after Lund (2008). Base map modified from Camp and Ross (2004) and mantleplume.org. Below, sequential steps of the early stages of hotspot related active rift development that were fossilized during the mid Miocene after Sengor (1995). Step 1 is lithospheric doming and axial volcanism, step 2 by ~120° spaced axial dike swarms and early rift faulting, and step 3 by bi- or tri-axial rift valley formation.



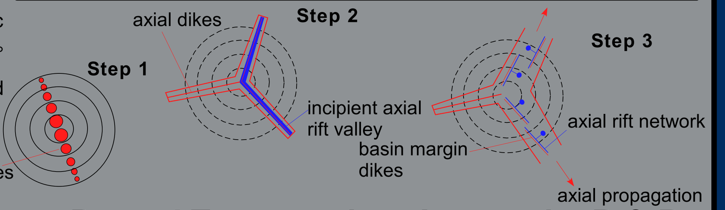
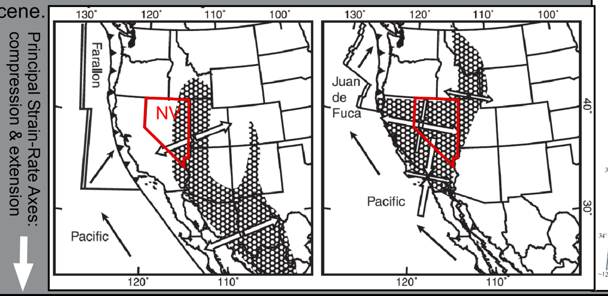


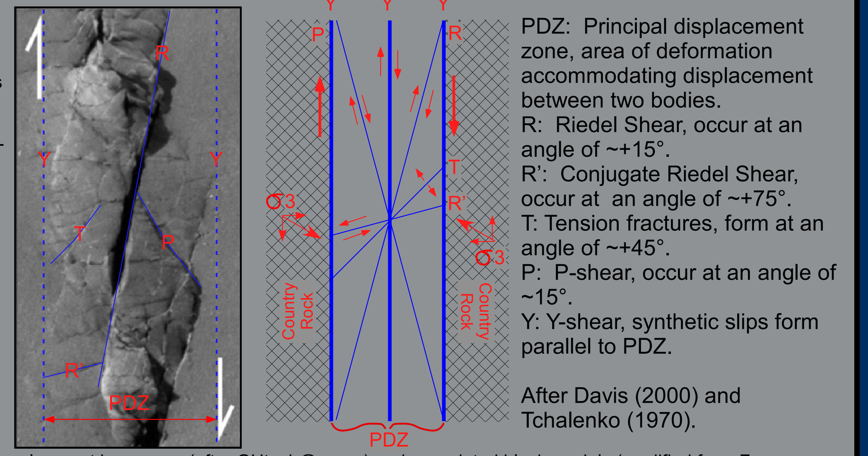
Plate Margin Stress Partitioning - Dextral Transtension Across the B & R

Figure 2 Right, horizontal vectors of GPS stations in western USA from EarthScope's Plate Boundary Observatory network (unavco.org). Motions indicate a continually decreasing northwestern motion from the San Andreas inwards across the Basin and Range (B&R) until Idaho. Decreasing velocities would result that would result in a dextral-sense stress across laterally adjacent terrains. Bottom, time slice map of Basin & Range extension at 22 Ma and 0 Ma after Bird (2002). Significant increase occurs during mid-Miocene.



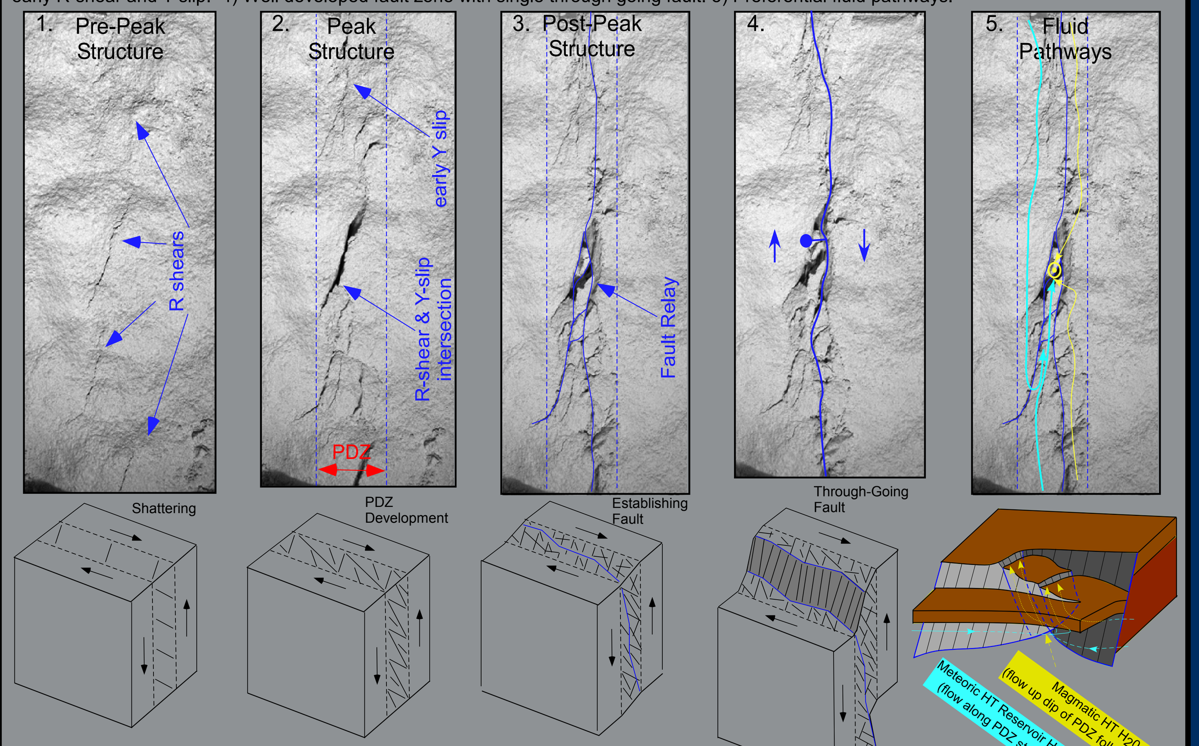
Riedel Shear Mechanics and Controls on Fluid Migration

Figure 3 Riedel shear outline. Left: plan view of clay Riedel dextral shear model with all related internal structures developed. Right: components of a Riedel shear defined. Opposite orientation of internal structures to be developed in a sinistral shear system. Key take-aways are that Riedel shear systems coevally form related structures in predictable orientations of faults at all scales and types, be it normal, dip-slip or reverse and fault relays nucleate upon the intersections of early structures.



PDZ: Principal displacement zone, area of deformation accommodating displacement between two bodies.
R: Riedel Shear, occur at an angle of ~+15°.
R': Conjugate Riedel Shear, occur at an angle of ~+75°.
T: Tension fractures, form at an angle of ~+45°.
P: P-shear, occur at an angle of ~-15°.
Y: Y-shear, synthetic slips form parallel to PDZ.
After Davis (2000) and Tchalenko (1970).

Figure 4 Time series of Riedel shear development in gypsum (after GUtech@oman) and associated block models (modified from Fesson, 2010). 1) Initial shattering of medium to form minimal displacement Riedel shears. 2) Initial linking of shears by Y-slips, and development of a clear PDZ. 3) Forming a through going fault through linkage via connection of individual faults by a relay nucleated at the intersection of an early R-shear and Y-slip. 4) Well developed fault zone with single through going fault. 5) Preferential fluid pathways.



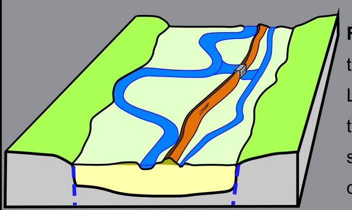
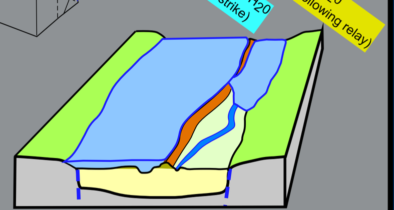


Figure 5 Fluid flow analogy, left, river floodplain contains all downstream flow akin to PDZ of shear zone. Levee system segregates flow to either side akin to a through-going fault slip. Right, lock along levee is passageway to funnel flow from one side of levee to the other akin to a fault relay in a PDZ.



PROBLEM STATEMENT

* Close time-space association between the northern Nevada rift (NNR) and low-sulfidation epithermal deposits.
* Mechanism(s) by which the NNR's development on a multiple scales influenced where and when individual low-sulfidation epithermal deposits formed has not been determined.

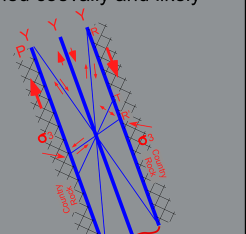
1) Is there a multi-scale structural architecture related to crustal-scale tectonics that is identifiable and documentable? 2) Does the structural architecture influence hydrothermal convection and the time-space relationships where epithermal deposits form?

HYPOTHESIS

This study hypothesizes that predictable controls on fluid migration caused by shear zone geometries influence all scales of hydrothermal fluid flow, extending from the crustral-scale down to the individual vein-scale. The root cause for shear zone geometries is thought to be heightened dextral transtensional deformation across the NNR region during the mid Miocene. This heightened activity was driven by thermal weakening of the crust enabling plate boundary stresses to rapidly form a linear rift basin system during a ~2Myr period that was subsequently fossilized. This study hypothesizes that rift architecture consist of multiple fault fabrics, at orientations that relate to predictable dextral Riedel shear geometries, that formed coevally and likely influenced hydrothermal fluid pathways.

Hypothesized geometries:

PDZ: ~340° orientation of axis of rift system subparallel to plate margin
Y: ~340° orientation of Y-shears, synthetic slips that form major basin bounding faults on western and eastern margins.
R: ~0° orientation of Riedel shears, tforms secondary faults linking Y-slips
T: ~20-30° orientation of tension fractures, forms secondary faults
R': ~50-70° orientation of conjugate Riedel shears, forms primary basin bounding faults at northern and southern margins with apparent sinistral offset.
P: ~300-320° orientation of P-shears, forms secondary faults linking Y-slips.



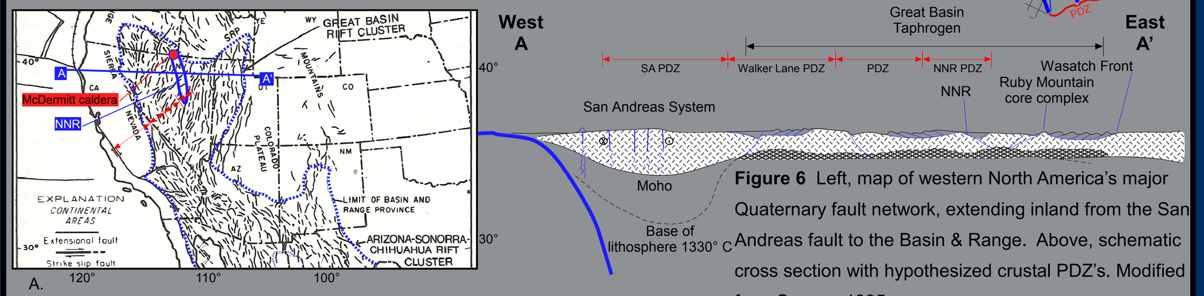


Figure 6 Left, map of western North America's major Quaternary fault network, extending inland from the San Andreas fault to the Basin & Range. Above, schematic cross section with hypothesized crustal PDZ's. Modified from Sengor, 1995.

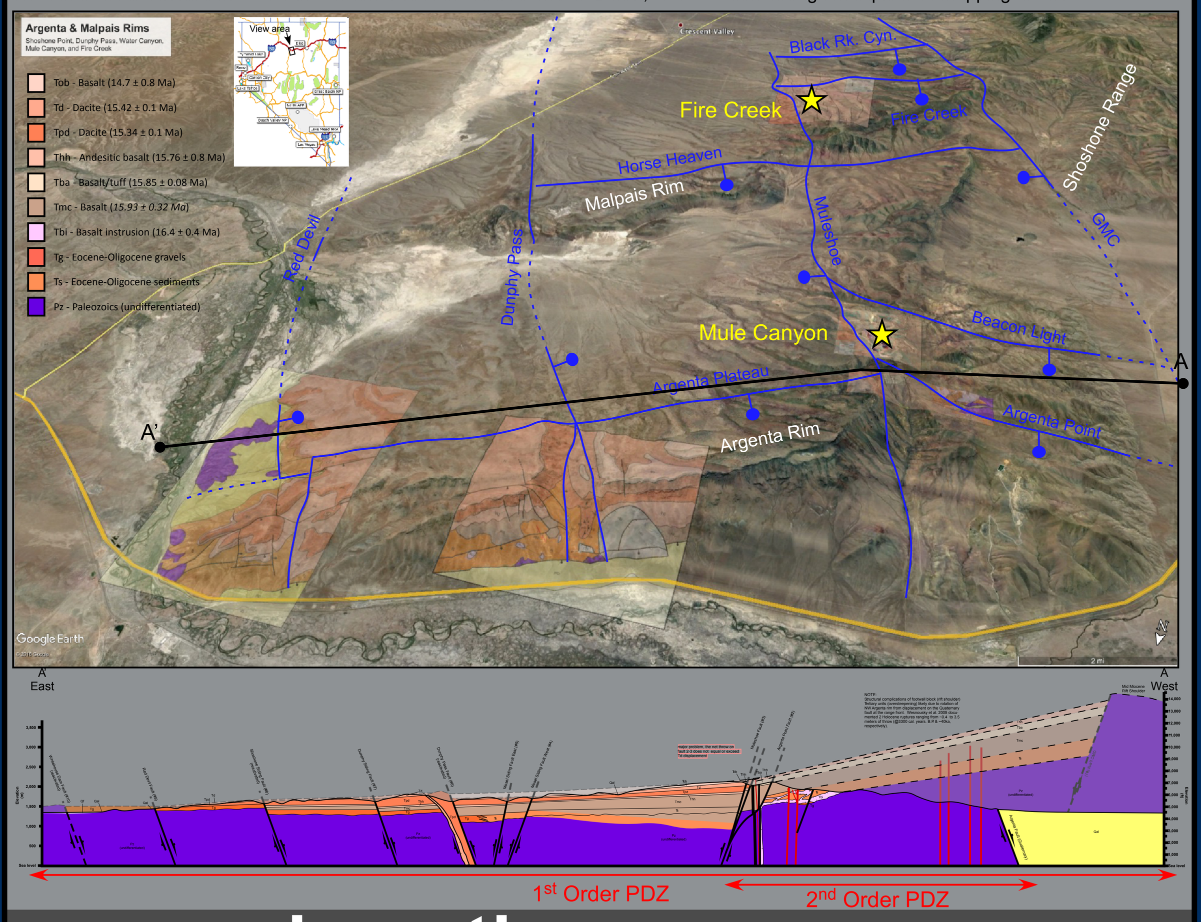
FIELD EVIDENCE

Field mapping has yielded previously unrecognized geometries of Miocene-age growth faults whose coeval formation supports the hypothesis of a crustal-scale Riedel shear formed by dextral transtension:
*** Fault geometries of NNR southern basins contain primary ~340° east and west boundary faults (GMC, Mule Canyon, Dunphy Pass, & Red Devil).**
*** Basins contain primary ~060°-070° north and south boundary faults (Argenta Plateau, Horse Heaven, Fire Creek, & Black Rock Canyon.**
*** Basins contain secondary ~300°-320° (Argenta Point & Beacon Light faults) & 0°-020° faults that often serve as relays linking 340° oriented structures. These are frequently the preferred pathways for epithermal veins.**

When all the structures, with both variable displacements and shear zone widths are aggregated into a comprehensive NNR architecture, they form a multi-scale spectrum of Riedel shear zones. We have grouped fault zones into the following terms describing the width of their respective PDZ's; 1st Order (100-10kms), 2nd Order (10-1kms), 3rd Order (1km-100m), 4th Order (100m-10m), 5th Order (10m-1m), 6th Order (cm's), & 7th Order (mm's).

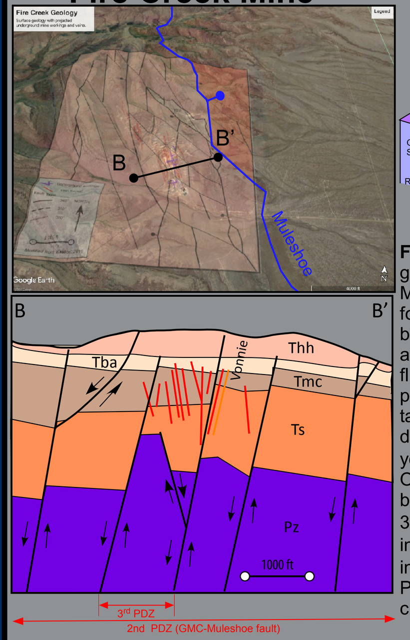
1st to 2nd ORDER PDZ

Figure 7 Oblique view to the southeast of the field area with the primary basin bounding faults. Multiple orientations of coevally forming structures indicate a dextral sense of transtension across the NNR corridor. Below, cross section through multiple field mapping areas.



2nd to 4th ORDER PDZ

Fire Creek Mine



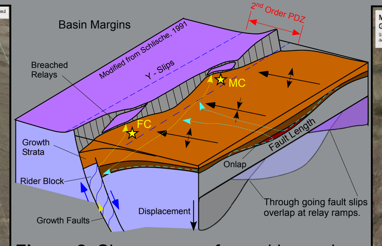
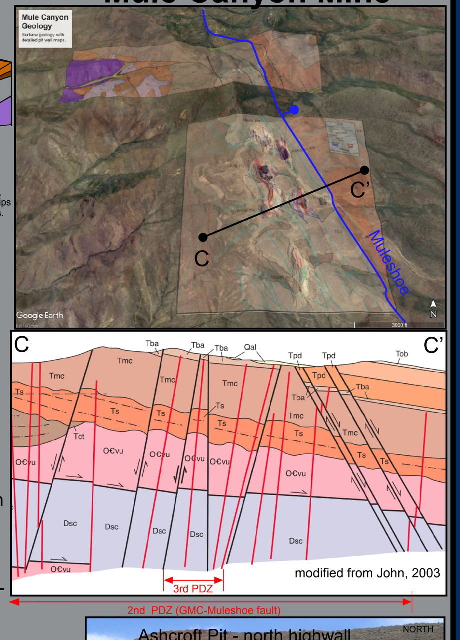
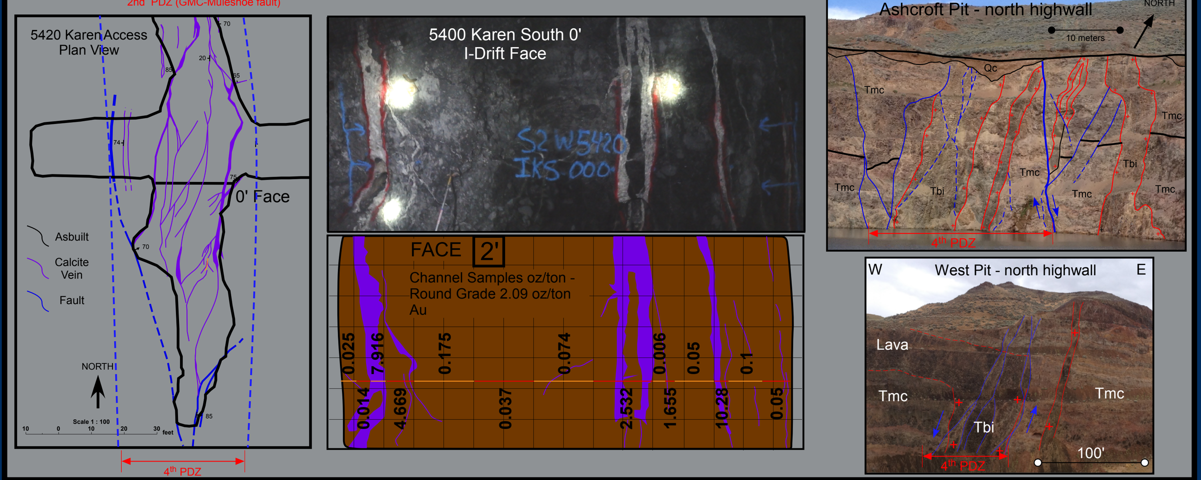


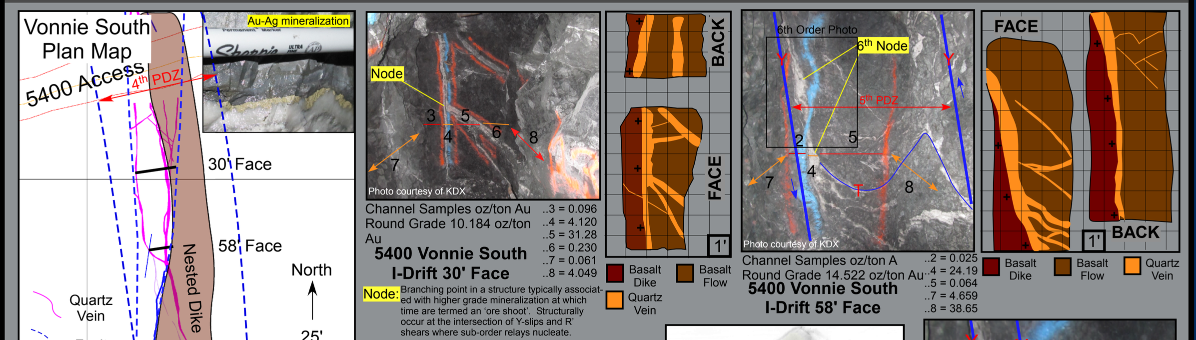
Figure 8 Shears zones formed by conjugate basin bounding faults (e.g. GMC and Muleshoe faults) where Riedel shears form antithetic faults in horse block (rider block at western basin margin) that serve as conduits for ascending hydrothermal fluids to cross between the maximum displacement faults that are likely the deep taps for mineral bearing fluids. Field evidence suggest the location of Mule Canyon and Fire Creek were controlled by 2nd Order Riedel shears. Individual veins at both sites are compartmentalized between 3rd Order PDZs, with each vein representing 3rd Order Riedel shears. Upon close inspection veins form individual 4th Order PDZ's controlling fluid migration on an outcrop scale.

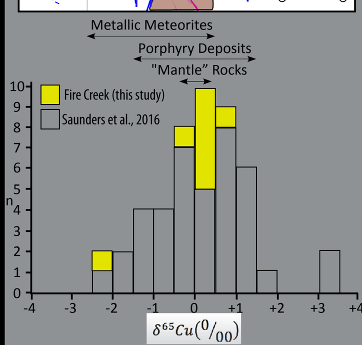
Mule Canyon Mine





4th to 7th ORDER PDZ





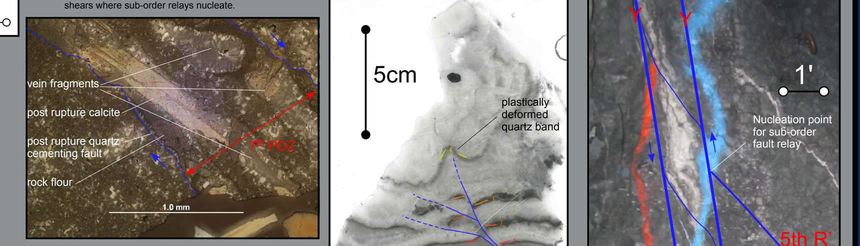
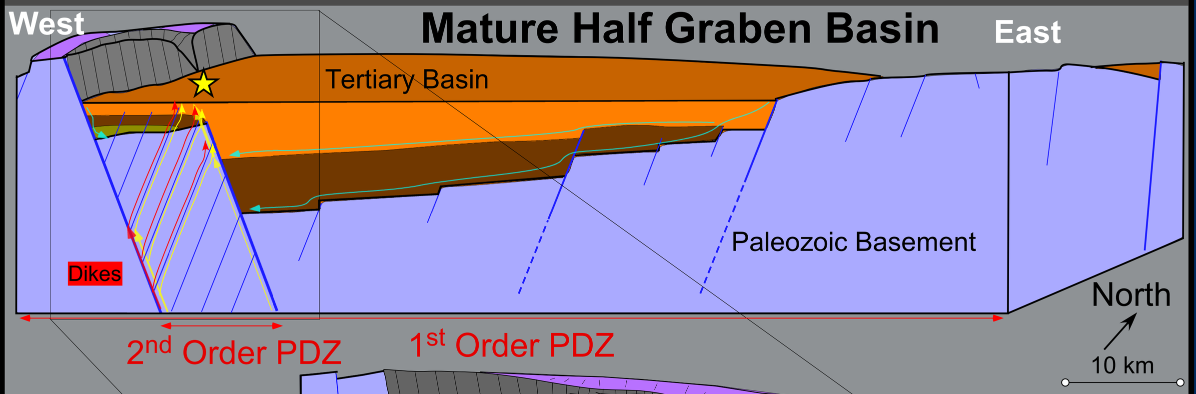


Figure 9 Shear zones from the outcrop- to photomicrograph scale that influence fluid pathways.
The Vonnie vein at Fire Creek jointly exploits a <10 meter displacement fault with a nested dike system. Vein structure and texture reflects coseismic formation from the 5th Order to the 7th Order scale. Cu isotopic studies with colloidal textures strongly indicate mantle sourcing of Au-Ag.

CONCEPTUAL MODEL



Basin Margins

Hydrothermal Fluid Pathways
Meteoric Fluid Pathways

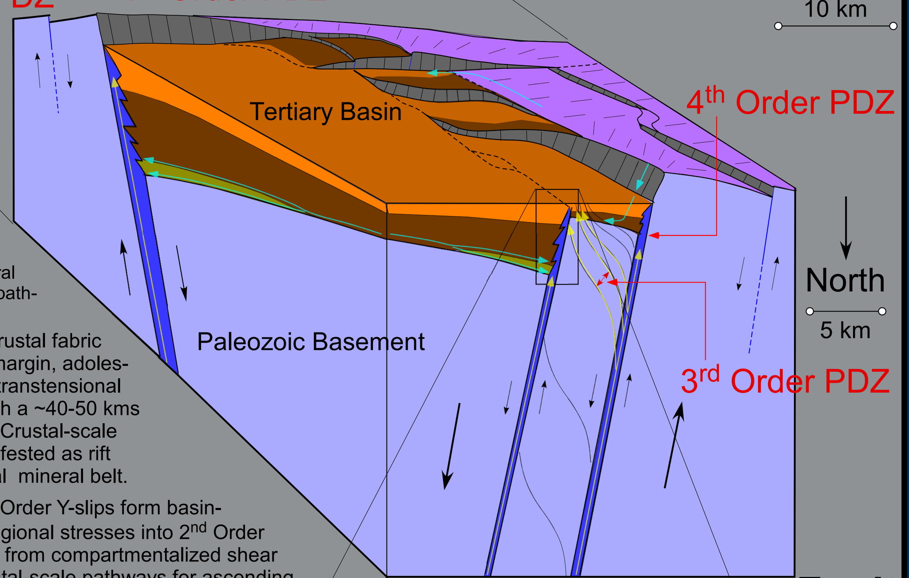


Figure 10 Transtensional structural model and resulting inferred fluid pathways

1st Order PDZ (100-10km): Crustal fabric inherited from Proterozoic rift margin, adolescent development of a dextral transtensional margin. Forms elastic block with a ~40-50 kms wide PDZ and >500 kms long. Crustal-scale fluid conduits formed and manifested as rift basins, that create a epithermal mineral belt.

2nd Order PDZ (10-1km): 1st Order Y-slips form basin-bounding faults that partition regional stresses into 2nd Order PDZs. Where conjugated they from compartmentalized shear zones that are the primary crustal-scale pathways for ascending hydrothermal fluids creating epithermal mineral districts.

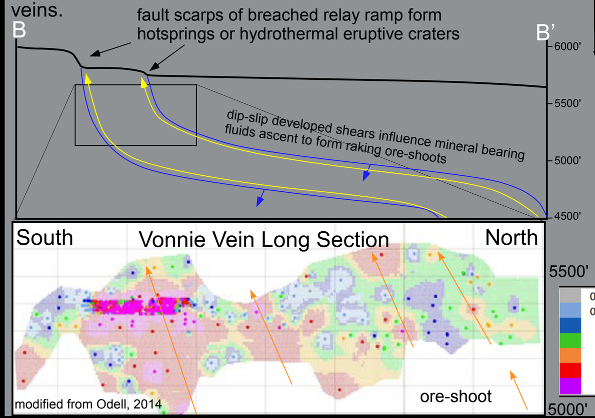
3rd Order PDZ (1km-100m): R and R' shears within 2nd Order PDZ's are manifested as conjugate antithetic faults on rider blocks that further partition stress in 3rd Order PDZs. These structures create fluid conduits on the deposit scale.

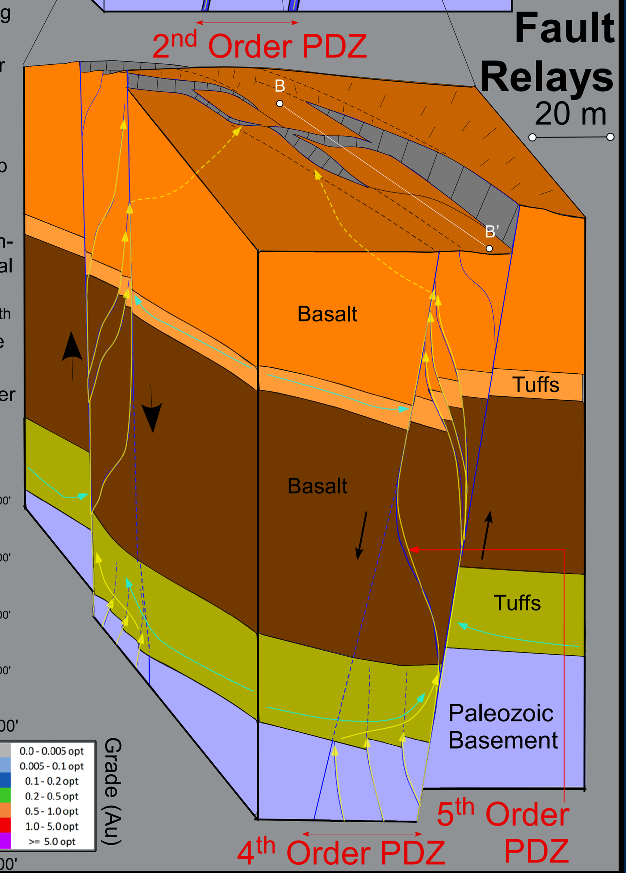
4th Order PDZ (100m-10m): Individual fault zones on the map or outcrop scale that control fluid pathways on a pit or stope scale.

5th Order PDZ (10m-1m): Formed by individual fault slips within a 4th Order PDZ that often or controls for fluids on a individual vein scale.

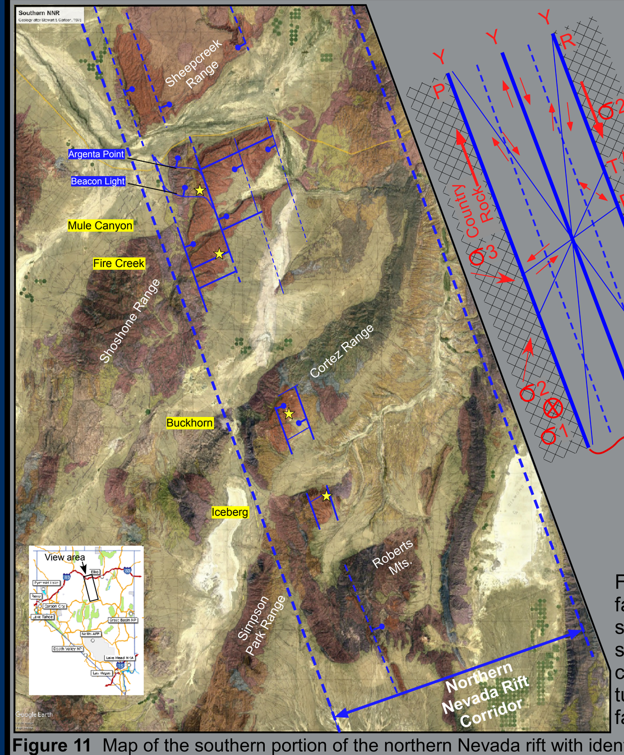
6th Order PDZ (cm): Formed by synthetic Y-slips internal to 5th Order PDZs that create high-flux fluid pathways on a vein scale and high-grade nodes.

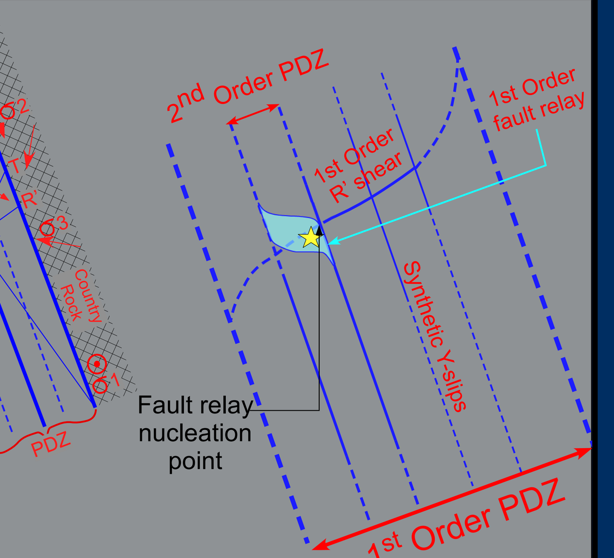
7th Order PDZ (mm): Riedel shear fabric internal to a 6th Order PDZ forms micro-faults on the 7th Order scale whose displacement is preserved in the multi-stage growth of collorm bands in veins.





"The Fire Creek Fractal" GLOBAL EXPLORATION IMPLICATIONS





Fundamentals of brittle rock mechanics influence the structural fabric from the crustal scale down to the microscopic. At each stage a repeating pattern of intersections between R- and R'-shears with Y-slips nucleates fault relays, the structural high-flux conduits that enable fluid migration across through-going structures. By documenting and interpreting the fractal Riedel shear fabric one can infer where fluids will travel through the crust.

Figure 11 Map of the southern portion of the northern Nevada rift with identifiable major structures controlling basin subsidence during the mid Miocene. Coevally active structures are interpreted to be the manifestation of a rift-scale transtensional shear zone that influenced not only the formation of the basins but also the ascent of magma and hydrothermal fluids. Right, proposed mechanism controlling the location of the Mule Canyon low-sulfidation deposit.

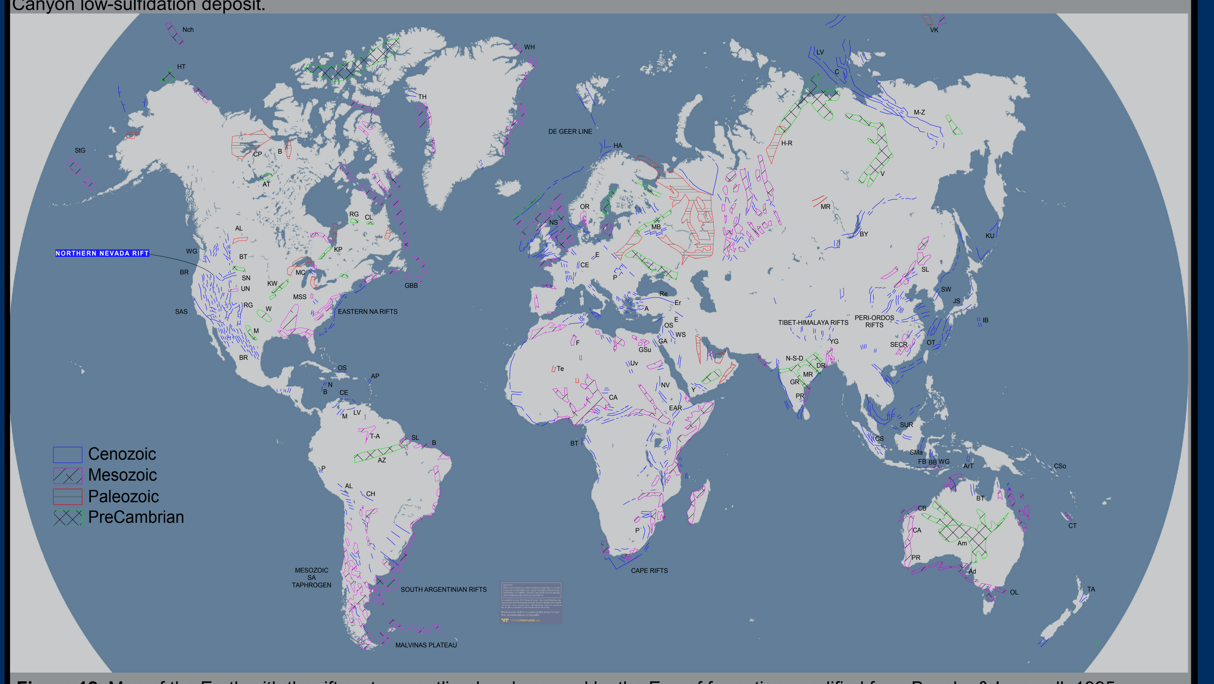


Figure 12 Map of the Earth with the rift systems outlined and grouped by the Eon of formation, modified form Bugsby & Ingersoll, 1995.

DISCUSSION

Field documentation of basins, growth fault networks and low-sulfidation epithermal deposits within the southern portion of the NNR suggest that the hydrothermal fluids exploited a multi-scalar Riedel shear structural fabric. Evidence suggest that hydrothermal fluids are channelized within PDZ's (of all scales) by through going structures which act as barriers. The migrating hydrothermal fluids take advantage of fault relays between through going structures to migrate across. By identifying the volumes of rock that host fault relays (at all scales) one can vector to the highest flux pathways of fluid migration. In the epithermal environment these are often the host to either ancient low-sulfidation deposits or modern geothermal reservoirs.

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