

RELATIONSHIPS BETWEEN VEINING AND FAULTING AT TOADSTOOL GEOLOGIC PARK, NW NEBRASKA

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Abstract: A suite of veins and normal faults are well exposed in the badlands of Toadstool Geologic Park, and are being mapped into a GIS database as an undergraduate research exercise. Many gradations between smaller tensile veins and larger faults occur. At horizontal lengths > ca. 10 m slip is often evident along vein walls or along calcite median zones. Fault surfaces commonly change laterally into vein tips, steepening as they do so. Other fault tips transition into an echelon vein arrays. Fault zones are segmented into individual fault surfaces that link via tip curls. The same geometry is observed with the veins. Most faults have a zoned vein in their core. Both faults and veins are associated with wall rock alteration. These relationships, plus common orientations, indicate the faulting and veining are part of one deformation event. Similar veins and faults occur 30 miles to the W and are known from the Big Badlands (S.D.), indicating a more regional extent. Assuming these geometries represent brittle structures arrested at different stages of development, the following model for vein-to-fault evolution is proposed. Failure starts as a vertical tensile feature with local fluid migration depositing silica gels. Once the tensile fracture achieves a critical length, normal slip nucleates on the vein surface or along a calcite interior, producing striae or slickensides, respectively. Despite a sub-vertical orientation the vein surface may be weak enough to resolve sufficient shear stress to slip in the extensional regime. Continued vertical shear propagation at the fracture margin is in a mixed mode along a dipping surface, while horizontally is along a sub-vertical tensile surface. Brecciation, veining, and wall rock alteration with continued slip causes fault zone widening. What determines the threshold for shear to initiate on the veins is presently uncertain. The vein-to-fault transition eventually causes local strain hardening (by dilation and fluid pressure decrease, and/or mineralization), eventual strain migration, and a more distributed strain pattern.



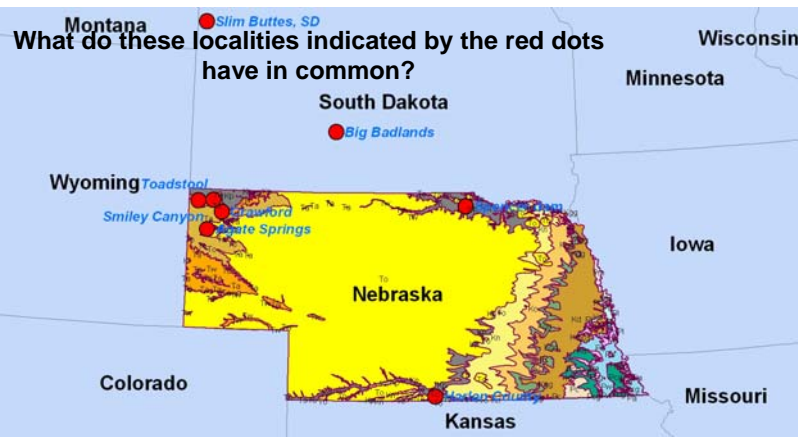
Above: Depicted is the Toadstool fault, the largest and best known fault in the area. **Right:** A small chalcodony vein. **Below:** A typical small scale normal fault with grey chalcodony vein fill along its length. The vein fill causes the faults to erode as small ridges, and fault features can be examined in detail.



Background information: Stratigraphic units involved in ascending order are: Cretaceous Pierre Shale, and the Chadron and Brule Formations of the White River Group. The stratigraphy has been recently redefined by Terry & LaGarry (1998). Several lines of evidence indicate that the deformation is Arikarean in age. This implies that deformation was shallow, perhaps < 1 km.

Quick summary on vein-fault propagation literature:

The literature on models for fault growth and propagation has burgeoned. Early models stressed linkage of pre-existing or precursory structures, with tensile fractures such as veins providing an example of the later (review by Crider & Peacock, 2004). They also recognized that propagation mechanisms vary along the fault margin dependent on the orientation of the slip vector relative to the margin (similar to screw and edge dislocations). In one common model, tensile fractures and/or other features that form due to stress concentrations at the fault tip represent a 'process' zone. Linkage of tip structures with continued strain occurs and the fault tip migrates through its precursory process zone (e.g. Marchal et al., 2003). In addition, faults can join to form a longer, segmented fault system when 2 separate fault tips enter each other's area of stress influence and link through a relay zone. D'Alessio & Martel (2004) consider how barriers to fault growth influence fault terminations and tip structures. In this case tip structures may reflect fault growth arrest. Walsh et al. (2003), stressing the importance of a 3-D perspective, contrast isolated (similar to the model described above) vs. coherent fault models (where fault segments "are kinematically interrelated from their initiation"). Toadstool provides an opportunity to explore the utility of some of these models.

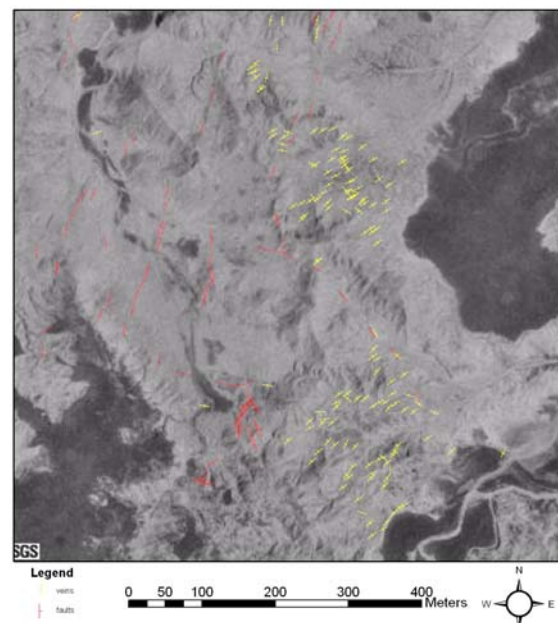
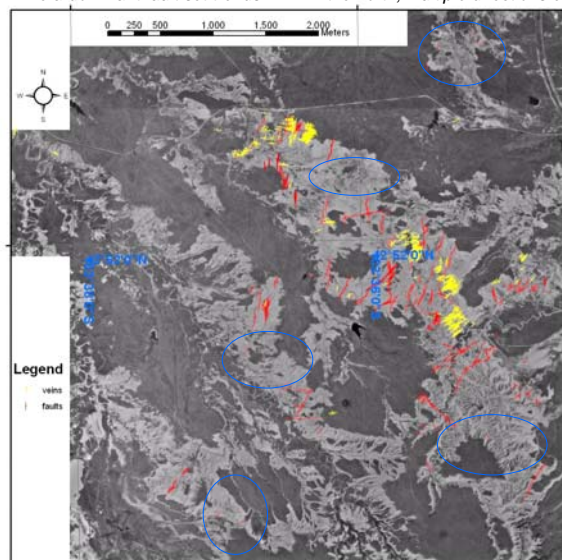


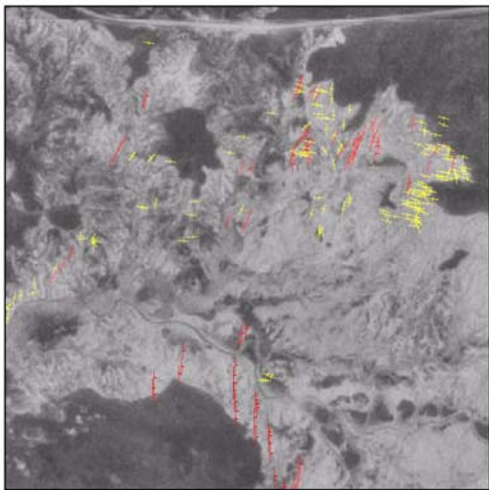
Below: GIS plot of fault and vein strikes in the Toadstool area. USGS airphotos with 2m per pixel resolution provide base map. Elliptical areas represent areas where faults exist but have not been mapped yet. Significant faulting occurs outside this area, especially to the south. Note that the veins occur in distinct concentrations (informally called patches). While a dominant fault set trends NNE in the north, multiple directions exist.

Below: Close up of two vein (in yellow) fields showing a dominant N60E direction, oblique to the adjacent fault. Longer veins often have striae and/or slickensides indicating some slip (Tegels, 2003), but offset of strata is not evident. Note how the southern vein patch truncates against the fault. Vein orientations near the fault change.

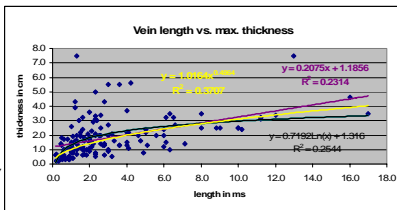
Description of the Toadstool GIS mapping project: We are building a GIS data base of features related to deformation in the Toadstool, Nebraska area. Layers include fault attributes, vein attributes, fracture density, sandstone channel positions, paleocurrent directions, USGS air photos, 10m USGS DEMs, and north central U.S. deformation localities (e.g. above map). Fault and vein attributes include orientations, thicknesses, fault throws, types of mineralization, and types of structures and or textures. More than 1200 GPS localities with attribute information have been entered for the Toadstool area so far, and there is potential for several times this amount of data (i.e. mapping is far from complete). Objectives of the project are to: a) investigate fault-vein propagation mechanics, b) explore fault and vein scaling relationships, c) possibly constrain fluid flow patterns, d) constrain the regional strain pattern and place in a context of intraplate strain history and deformation mechanisms, e) to explore the utility of GIS in investigating the above, and to give undergraduates research experiences (all but the first author are undergraduate students). We intend to study other localities (e.g. S. D. Big Badlands) in a similar way. This poster is a progress report focusing on fault-vein relationships seen at Toadstool.

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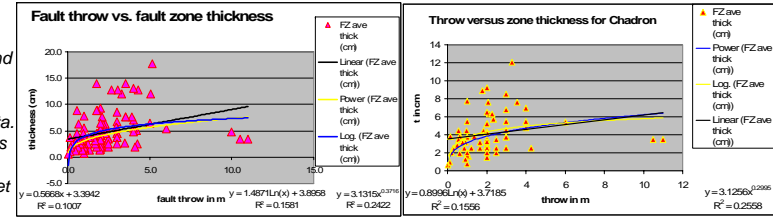




Right: A weak relationship exists between vein length and thickness (Tegels, 2003). Subdividing by vein orientation does not improve the relationships significantly. The majority of the data comes from one vein patch.



Right: Scaling relationships between throw and fault zone thickness are not evident in this data. Such relationships have been found elsewhere (Bonnet & others, 2001).

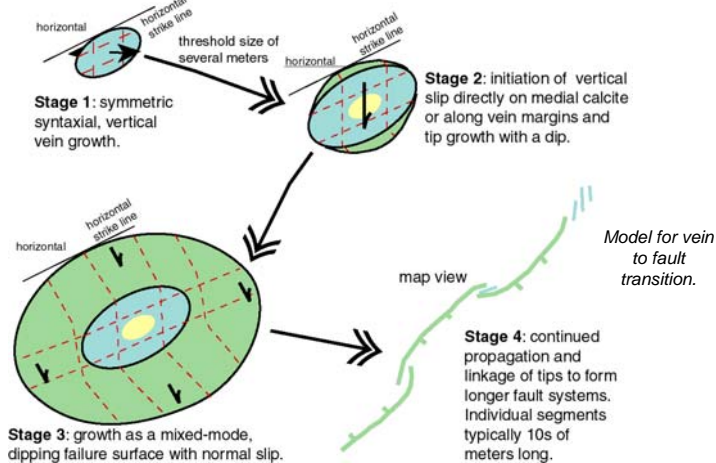


Above: A tip of a normal fault ending in an echelon array of zoned chalcodony veins (red dashes).



Above: A normal fault with striae on a chalcodony vein surface that bends into a subvertical position. Is rotation responsible or does this reflect the fracture growth pattern.

Right: Dip-slip striae on a dilational chalcodony vein surface. Note mechanical pencil for scale. Dilational vein material isn't localized just at releasing jogs or bends, but characterizes the length of the fault, suggesting a mixed-mode propagation mechanism for the fracture.



Conclusions:

- A complex, distributed, strain pattern characterizes the area.
- Fault and vein formation was coeval.
- Veins occur in distinct concentrations or 'patches'; faults and channel sands influence vein distribution. Chalcodony veins are vertically constrained to the Chadron Formation.
- Tip curls indicate that vein and fault tips commonly 'communicated', and influenced each other's propagation.
- Slip initiates directly on vein surfaces at a threshold size.
- Slip may have nucleated on the veins because of a low strength character.
- Relict structures along the fault length expected from migrating tip process zones are uncommon, suggesting fault tip structures are unique to late stage fault growth and termination (barrier effect), or due to fault linkage.
- Faults propagated as mixed mode surfaces.
- As faults propagate into different mechanical units propagation mechanisms may change. In the case of Toadstool, veins played an important precursory role in the Chadron formation, but less so in the overlying Brule.
- Fault segmentation and other patterns can be documented and explored in a GIS environment, which is also conducive to exploring this intraplate strain.

References:

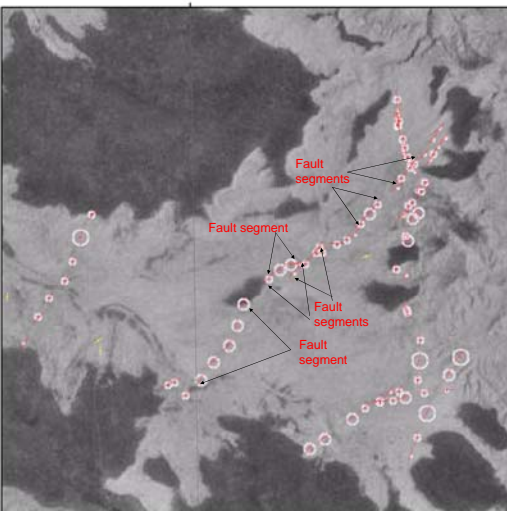
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Above: GIS plot showing a dominant vein set perpendicular to the dominant fault set, and subordinate vein set parallel to the faults, and spatially associated with the faults. Note also the different orientation of the dominant vein compared to the previous map. Strain patterns seem to be domainal in the study area. Faults and veins exist in the middle portion of the map here, but have not been mapped yet.



Left: Strong tip curl of chalcodony veins.

Below: GIS plot of several faults with graduated symbols representing fault zone thickness. Patterns noted in the field, such as fault bends, overlaps, tip curls and splays, are replicated here, indicating GPS accuracy is adequate to capture fault geometry at this scale. Fault zone thickness decreases from the middle of a segment towards linked ends of the segment.



Above: Tip curls linking an echelon tension chalcodony veins. Tip curling may reflect either greater fracture roughness or smaller differential stresses (Renshaw & Pollard, 1994). Smaller differential stresses would be expected given the shallow crustal level of faulting and the relatively weak character of the strata.



Above: Multiple directions of chalcodony veins, with a bend in the main vein that may reflect the influence from the tip of the vein above.