UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

ATOMIC SAFETY AND LICENSING BOARD

In the Matter of CROW BUTTE RESOURCES, INC. (Marsland Expansion Area)	Docket No. 40-8943-MLA-2 ASLBP No. 13-926-01-MLA-BD01

Hearing Exhibit

Exhibit Number: OST018-R

Exhibit Title: Maher (2012) Theoretical framework for Great Plains fracture generation - Version 2 - with links text included

Theoretical framework for Great Plains fracture generation - Version 2

Draft (feedback welcome, still very much in revision)

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March 2012

Introduction: This exercise is driven by the multiple working hypotheses. The question is - what are the various geologic events (triggers) and associated mechanisms that can produce or influence fracture patterns and the history of their development in the Great Plains region? The term fracture is meant to be broadly inclusive - including joints, veins, clastic dikes, and faults. The first three are tensile features, often known as mode 1 failure, whereas faults are shear fractures (which have sliding and tearing modes). Some emphasis is put on tensile fractures in this document since joint sets are so ubiquitous in the Great Plains.

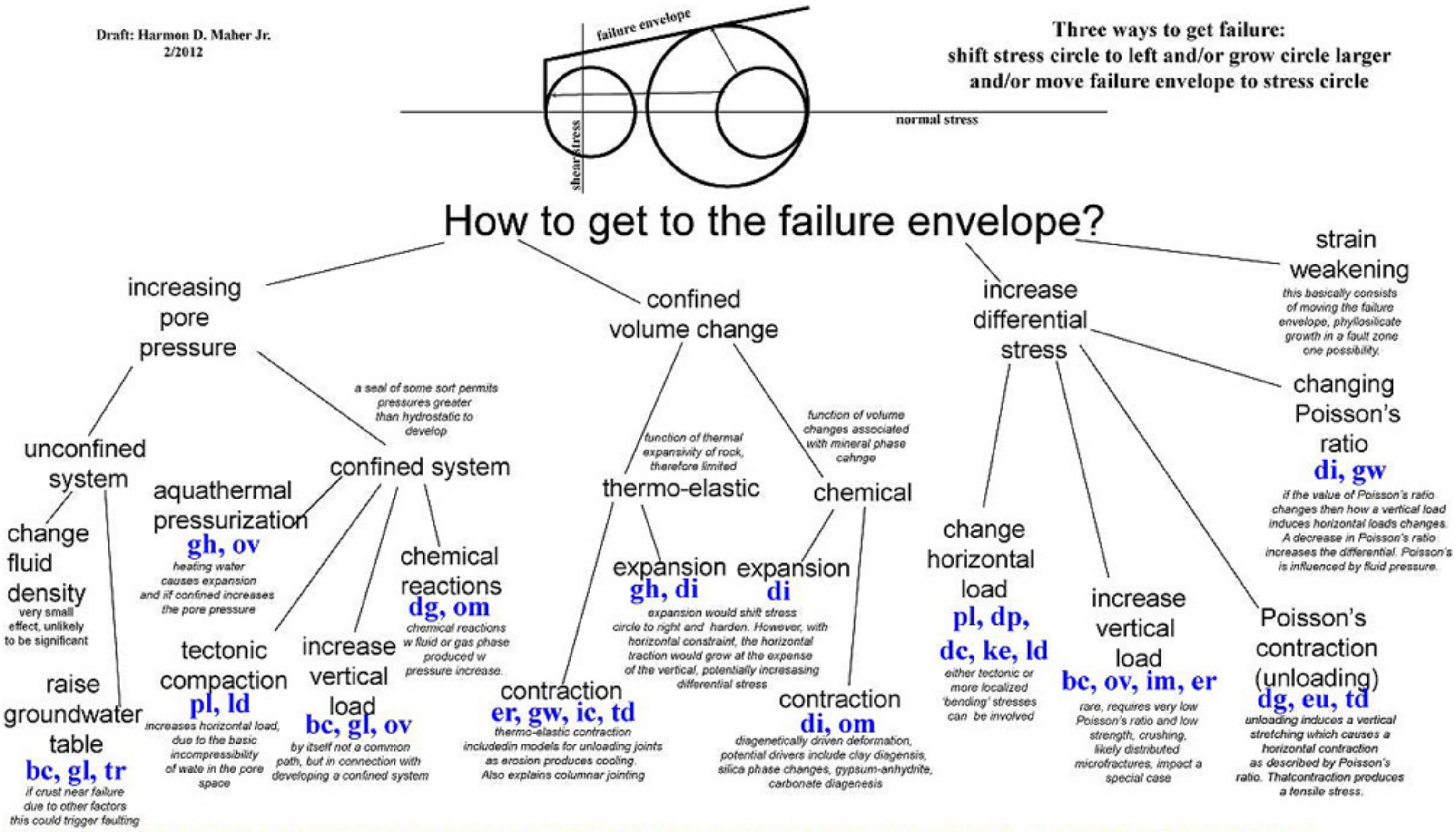
Work from the last decade has brought to light a new suite of brittle failure modes known as deformation bands (e.g. Fossen et al. 2007, Scholz & Siddharthan 2005) that occur in materials with relatively high porosity, such as sandstones and some pyroclastics. Different types of deformation bands are characterized by dilation, by shear, and by compaction, with the existence of hybrids. The primary difference is that tensile and shear fractures are considered surfaces, where as a deformation band is a planar feature with width (and hence has a volume). A related difference is in the tip propagation mechanics. With a deformation band typical linear elastic mechanics do not apply, and instead plastic yielding occurs. It is argued that in some cases deformation bands are precursors to joints and faults. Recent experimental work by Jocund (2011) distinquishes between mode 1 fractures and dilatancy bands, the latter of which is characterized by plumose morphology. Interestingly, Jocund et al. (2011) also found that dilatancy bands can form even with a slightly compressive sigma three. Another important difference between fracturing in porous materials is that typical Mohr Coulomb failure criteria that apply to crystalline materials do not apply. For the time being deformation bands are not considered in this document, but a separate but parallel document is being developed to describe these.

It is important to recognize that the geologic triggering events explored herein are not mutually exclusive and that some temporal and causal linkages are likely between them. It is also certain that the diverse array of fracture systems in the Great Plains are polygenetic. A focus of this document is on establishing criteria that will help generation mechanisms and formation times to be assigned to different fracture sets identified in the Great Plains Fracture Study, and also to better understanding these fractures in a coherent fashion.

Loading paths and geologic triggers: From a mechanical point it makes sense to consider the loading paths that lead to failure (Engelger 1985; Engelder &) as a classification criteria. These loading paths can then be applied to different failure criteria. When trying to understand fractures from a historical and contextual perspective it makes sense to consider geologic events that trigger the fracture formation (e.g. such as differential compaction0. A more sophisticated understanding can be developed by considering both, which this document attempts to do.

Using the Mohr diagram and failure envelopes as an initial guide, three end-member ways to take a stable stress state and have it evolve so that it intersects the failure envelope (with a tensile cutoff included) is to: a) increase deviatoric stress, b) shift the stress circle to the left, c) or shift the Mohr envelope. Naturally, these can be done in tandem. A variety of processes including changing fluid pressures, changing rock stresses, changing elastic material moduli, can produce different loading paths. Figure 1 attempts to capture these possibilities.

The critical loading path can be visualized of as the evolution of the Mohr circle so that it intersects the failure envelope. Therefore, a significant part of modeling loading paths is the form/position of the failure envelope. Failure criteria can be sensitive to loading and environmental conditions. For example, sub-critical fracture growth is where fractures grow more slowly and at differential stress lower than otherwise due to interaction between fluid in the cracks, the rock and the stresses at the tip crack. A fracture tip corrosion and weakening can occur, allowing the fracture to propagate, but since it involves chemical processes (such as diffusion) this process is time dependent. Surface features on tensile fractures are suggested to inform as to the nature of this sub-critical fracture propagation. Jocund et al. (2011) suggest that loading conditions contribute to whether a true mode 1 feature or a dilation band forms. One approach may be to consider that different failure criteria exist for time independent and time dependent failure criteria. One way of thinking of this is that the failure envelope moves and reshapes as a function of the stress evolution and geologic history.



***Triggering geologic events*: bc) burial and compaction, dg) deglaciation, di) diagenesis, dp) diapirism, dc) differential compaction, eu) erosional unloading, er) erosional relief generation, gh) geothermal heating, gl) glaciation, gw) groundwater flow change, ic) igneous cooling, im) impact, ke) karst and/or evaporite dissolution, ld) localized deformation, om) organic maturation, ov) overthrusting, pl) plate boundary forces, td) tectonic denudation .**

Fig. 1: Classification scheme for fractures(tensile and shear) based on possible loading paths, with associated possible geologic events that can theoretically produce that loading path and lead to failure in blue. Some of these loading paths require very specific circumstances and rarely occur, while others are much more common.

Increasing pore pressure and decreasing the effective stress (shifting the Mohr circle to the left) is argued to be a critical process in many loading paths to failure. A question that then arises is what geologic event caused the increase in pore pressure and hence the fracturing? Pore pressure can be greatly increased in confined situations by heating the water, by chemical reactions that produce water (think of baking soda and vinegar in simple play rockets), and by new stresses. In turn a variety of geologic processes can cause the heating, or reactions or new loads that increase the pore pressure. Fig. 1 attempts to capture possibilities, some of which are much more likely than others. **The classification structure for fractures used in this document can be thought of as intersection matrix with hierarchal loading path classification on the one side, and geologic trigger events on the other (e.g. thermal aquapressurization intersecting with intrusion).** An Excel sheet that accompanies this document expands on Figure 1 by listing traits for each of 30 some odd fracture. The hope is that an assemblage of traits is distinctive enough to allow confident assignment to a particular fracture class.

It is important to realize that a geologic event may influence loading paths in multiple ways. For example, a change in the tectonic stress field can both increase the differential stress and increase the pore pressure in confined units. Burial induces a new vertical load, can increase pore pressure in confined systems, can induce diagenesis and produce syneresis, in addition to changing material properties such as Poisson's ratio, and cause slow heating as the geothermal gradient equilibrates with the new sediment. The fracture event itself can change fluid flow paths, reduce pore pressures, changes bulk material properties. These combinations, linkages and feedback guarantee a great diversity of fracture sets and histories. The utility of the classification here is possibly in providing components from which to build a more realistic geologic model for a given fracture set.

The diagram above uses loading paths as a primary consideration. However, most fracture studies occur in a a distinct geologic context. It is therefore more efficient to consider different possible geologic trigger events and the various loading paths they may produce, which is the approach taken below. The following geologic triggers are considered in distinct sections (as individual pdfs), along with sections on potentially diagnostic traits and timing considerations.

A. Distributed juevenile fractures formed by regional tectonic stresses.
B. Neotectonic.
C. Reactivation of underlying, older fracture sets.
D. Tectonic reactivation related.
E. Differential compaction.
F. Topography related subvertical shear fractures.
G. Diagenetically driven deformation.
H. Continental glaciation related.

Part of: Theoretical framework for Great Plains fracture generation - Version 2 Draft (feedback welcome, still very much in revision)
Harmon D. Maher Jr., University of Nebraska at Omaha, April 2012

A. Distributed new fractures formed by regional tectonic stresses.

Sections: introduction to regional tectonic stresses, distributed strain in continental interiors, five sources of information, present day stress fields, GPS geodesy, calcite twin paleo-strain measurements, inferring stress field history from fracture set history, loading paths.

As a good introduction to regional tectonic stresses, the world stress map (URL - http://dc-app3-14.gfz-potsdam.de/) shows consistent maximum horizontal stress tractions in large portions of plate interiors, along with local anomalies. Even a cursory inspection suggests that the larger coherent pattern is aligned with and therefore somehow related to the surrounding plate boundaries. This pattern has been related to how the tectonic boundary forces on the plate margins (e.g. the force associated with spreading ridges or subduction zones) creates an internal stress field, one that penetrates well into plate interiors (e.g. Coblenz & Richardson, 1995). Significantly this suggests that changes in plate margin processes can influence stress-related processes in the plate interior.

There are perhaps two basic manifestations these plate-interior tectonic stresses can have. First, they can produce reactivation of favorably oriented weaknesses (often in the basement), localizing deformation. This could be considered the standard model. The Humboldt fault zone in SE Nebraska, which offsets Paleozoic strata, is underlain by a southern extension of the Precambrian Keweenawan rift. Some late Paleozoic reactivation of the rift may have been related to the Alleghanian orogenesis in the Appalachians (ref). In general, old rifts in particular are thought to be zones of weakness that localize such deformation. This phenomena of reactivation of interior weaknesses is considered in more depth in section D of this document.

While this phenomena can explain localized fracture sets, it can not explain more regionally distributed joint sets or other fracture systems. In addition, a significant portion of earthquake activity in the Great Plains either does not fall on an identified structural weakness, or such weaknesses would be so common that they could be considered distributed at a larger scale of consideration**. It is the more distributed fracture sets formed by these regional, tectonically related stress fields, that do not involve reactivation of previously existing weaknesses that are under consideration here.** The associated strain would need to be quite low (10E-18 to 5 10E-19 s-1 according to Eichbuhl at al. 2010) or episodic. The term juvenile here is meant to indicate that these are new fractures that formed in direct response to the stress field at the time, without previous structure influencing their orientation or development.

In that such fractures involve pristine failure their orientation should be directly related to the causative stress field (e.g. tensile features should be perpendicular to the least principal stress, and the maximum horizontal stress should bisect the acute angle of the conjugate shear planes, and the minimum horizontal stress should bisect the obtuse angle). Whether a feature can be considered distributed or not is in part a function of the scale of observation. Defining the degree of 'destributiveness' would be an interesting endeavor, that would likely lead to a fractal approach. However, so as not to get off track, in this document we are considering larger scales, on the order of counties.

Distributed strain in continental interiors is a debated topic. Evidence exists that continental interiors are critically stressed, meaning that they are relatively close to failure conditions throughout (Zoback et al. 2002). Supporting evidence for this assertion includes distributed seismicity and the general ubiquity of fluid injection related seismicity. Towend and Zoback (2000) in an attempt to explain intraplate regions that are critically stressed and have hydrostatic pore pressures and relatively high permeabilities at a large scale, conclude that: "Continental faulting at a small scale appears necessary to maintain high permeability and low fluid pressures" and argue that “stable intraplate crust is subject to continual small-scale faulting.” Secondary-recovery induced seismicity in southwest Nebraska suggests that locally the rocks are critically stressed there. Distributed faulting could harden the crust by initially producing new fracture networks and relieving pore pressure, thus producing a migrating pattern of deformation as pore pressures change with fault rupture and then fault seal mechanisms. Very low strain rates would favor hardening by allowing time for cementation and other processes to ‘heal’ fractures. Bjorlykke (2001) take exception with the hypothesis of Towend and Zoback (2000), given repeated fault reactivation along certain features. Zoback et al. (2002) suggest that the “current debate over whether intraplate is best viewed in terms of a deforming continuum or as rigid crustal blocks separated by relatively narrow and weak fault zones may be a false dichotomy.” Both persistent activity along some weakness zones, and a more distributed and migratory strain components may exist, and the appropriate question is - what is the mix?

Sandiford (2010), in a wide ranging article that looks at why continents are structured as they are, argues for significant long term internal and distributed strain of the continents (at rates of 10E-17 sec-1). In his model, the state of plate interior stress is driven by the plates gravitational potential energy and plate boundary forcing. Small scale continental interior strain fields oscillate between periods of extension and contraction over a long time period, with an average that is controlled by the long term gravitational potential energy of spreading ridges. This is clearly a model in development, as much is not specified, but is one that addresses some fundamental questions.

In this literature the specific strain mechanisms are left relatively unexplored, with the exception of distributed small scale faulting. Specifically, the role that jointing might play is unmentioned to my knowledge. A joint set with an average width of .1 mm and a spacing of 1 m would represent a strain of .0001. It would then take 10E 13 secs (or some 3 to 4 million years) to form such a joint set at the strain rates suggested by Sandiford (2010). This is a very reasonable time period geologically. Thus, it seems plausible that joint sets could accommodate extensional strains in the brittle upper crust on the order Sandiford describes. On a speculative note, once a joint set exists, it is possible that closing and healing it could produce a similar shortening strain.

If Sandiford is right, then the plates gravitational potential energy is driving the plate interior deformation. However, it is less clear on how or why the fractures would be organized into regional preferred directions. One possibility is that the strain is driven by the gravitational potential energy, but that the plate boundary forces organize its directions inside the plate. This idea, that one phenomena produces the deviatoric stresses that drive fracturing while another component of the stress field organizes it, develops again when we discuss fractures produced by sediment diagenesis below.

In the case of well developed, regionally coherent, fracture sets regional stress fields becomes a default hypothesis for a simple reason. There is no other mechanism that so easily explains the organization of fractures over such a regional (multi-state) scale. It is useful to remember that one must be quite careful in how one defines a fracture set, as a common orientation is not adequate (given process such as reactivation described below).

<u>Five sources of information</u> on stress/strain fields in continental interiors are: 1) theoretical modeling of what interior continental stress fields should be for a given set of assumptions (e.g. plate boundary forces and plate mechanical properties) and using finite element methods, 2) observation of present day stress field patterns and inferences drawn from that , 3) tracking of present day continental interior strain from GPS geodesy and drawing inferences from that, 4) characterization of paleo-strain fields and inference of paleo-stress fields from that, and 5) characterization of distributed fracture patterns and inferences from that. This document briefly discusses possibilities 2 through 5 in the following sections.

<u>Present day stress fields</u> can be inferred from earthquakes (first motion analysis) and a variety of in-situ measurement techniques ( ).   In the southern Great Plains Region a 60 azimuth direction of the maximum horizontal stress traction is evident (Fig. 1). This direction persists throughout the eastern portion of the North American plate, while the western portion shows a much more complex picture. The stress field characterized by the 60 azimuth direction may very well extend into the northern Great Plains, but there is a striking lack of data in this area. A simple expectation would be that vertical joint sets and tensile fractures produced in this field would have a strike of 60 degrees. If they formed in relatively recent times they would be considered neotectonic (Hancock and Engelder, 1989), an origin considered in a separate section below.   There are a variety of fracture sets in the Great Plains that do have this orientation (discussed below). Once again, orientation alone is not enough to assign fractures to a common set.

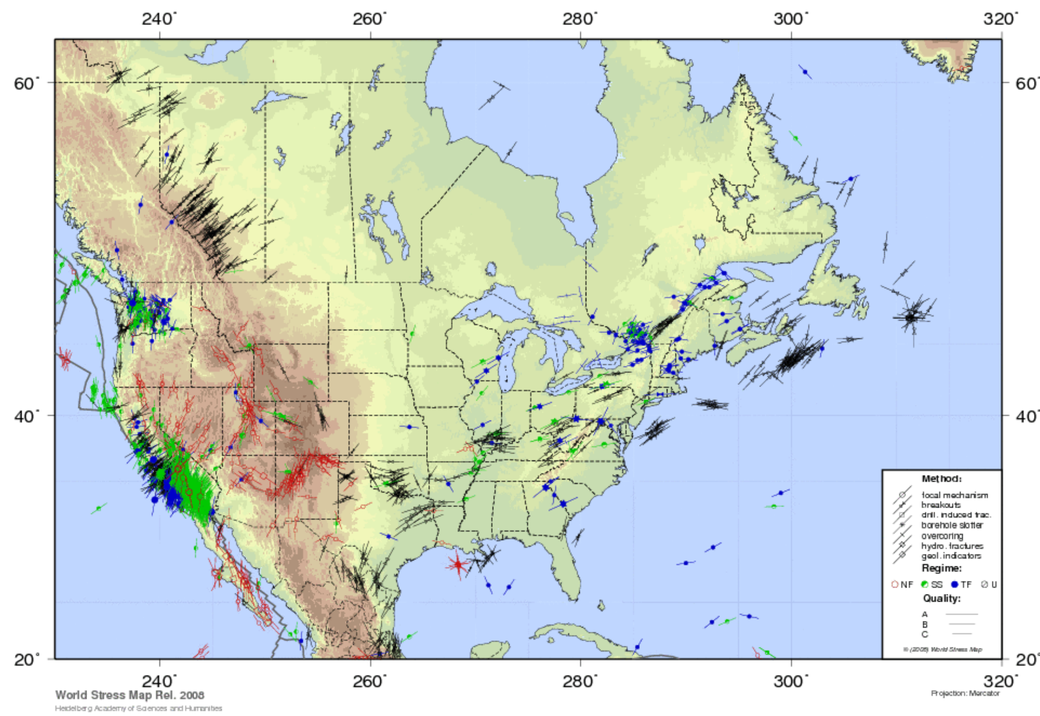


Image from the world stress map showing the horizontal principal stress directions for North America. This would suggest that for east of the Rockies the stress field is fairly homogenous. However, there is a distinct dearth of data for the northern Great Plains, including Nebraska, and the one isolated reading in western Minnnesota has a different orientation. If recent glacial unloading has contributed to the stress field (explored below), then the pattern may be distinctly different in the northern portion.

<u>GPS geodesy</u> has been used to detect distributed strain in continental interiors (e.g. Zhang et al. 2004). Significantly, Wernicke et al. (2000) use GPS data from the Basin and Range area and conclude that "contemporary deformation is quite slow and broadly distributed, rather than being concentrated in the relatively narrow zones of historic earthquakes." More specifically, Berlund et al. 2012 describe how modern distributed strain detected by GPS geodesy in the Rio Grande Rift region extends out into the Great Plains of New Mexico. However, using present day seismic and GPS data to identify more distributed strain can be problematic for several reasons. Such strain is close to or under the threshold of detection by GPS geodesy (Calais et al. 2010). It is also important to separate out transient strain from permanent strain, given the dynamics of large earthquakes.

<u>Calcite twin paleo-strain measurements</u> have provided an opportunity to investigate plate interior stress fields. Using calcite twin paleostress and strain measurements van der Pluijm & others (1997) document pervasive compressive strain associated with both the Sevier and Appalachian orogenies that penetrated for at least several hundred kilometers into the craton, and up to 200 km away from the plate margin. From the strain gradient and the mechanics of the calcite deformational twinning process they are able to detect a stress gradient from the orogenic front into the plate interior.

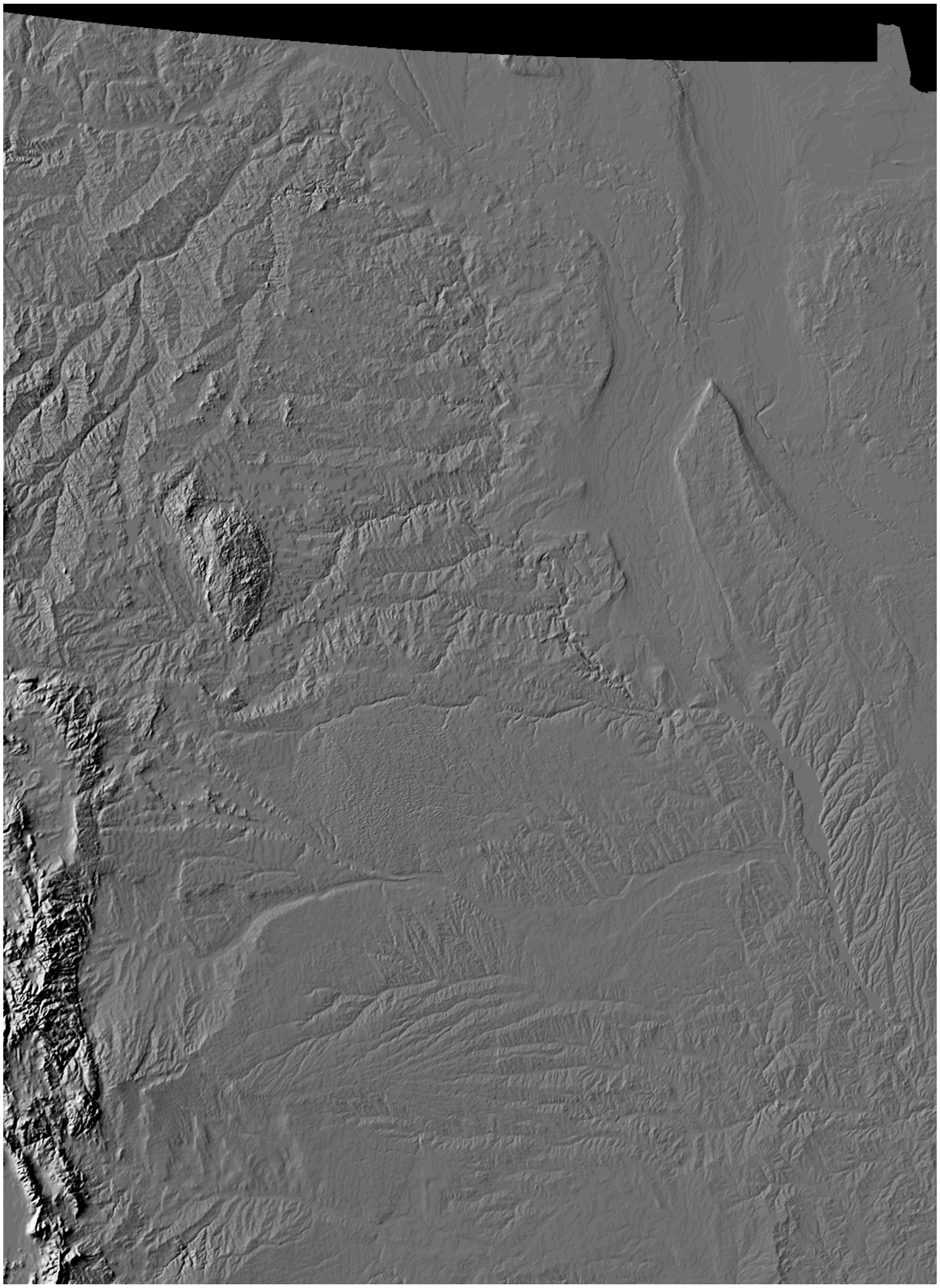
This work clearly demonstrates that plate interior strain and associated stress fields can be tied to plate margin processes where convergent motion is involved. Interestingly, Engelder and Whitaker (2006) describe an ENE striking coal cleat (microjoints) set and corresponding joint set in associated carbonates that is oblique to the orogen. The timing of cleat formation is well constrained. From this they infer the existence of an Appalachian wide stress field for the early phase of Alleghanian oblique convergence. Alleghanian thin-skinned tectonics came afterward and produced a subsequent stress field and associated jointing.

<u>Inferring stress field history from fracture set history</u> is a very common approach in general. Engelder & Whitaker (2006) use cleats in coal (whose age is constrained by their diagenetic origin) and other fracture sets to argue for an early Alleghanian regional stress field now 100 km or more cratonward from the present foreland fold-thrust belt margin that reflected the oblique collision between the continents. Later Alleghanian joint sets reflect the fold-thrust belt development and decoupling. Bosworth et al. (1999) argue in specific that a change in the plate motions between Africa and Europe in the Santonian (Cretaceous) coincided with a deeper, but short lived penetration of deformation and reactivation into the African craton. Other examples exist of where deformation associated with plate convergence can penetrate well into the plate interior. The influence of the India-Asia collision on deformation well into the interior of the Asian plate is particularly complex.

How extensional strain may penetrate into plate interiors is perhaps less clear. Dikes associated with rift magmatism can be particularly useful in unraveling stress field evolution because of the ability to date them. However, they simply constrain the least principal stress traction (as perpendicular to the dike). Conjugate fault sets provide fuller information about the causative stress field, and faulting can often be constrained in timing if there are associated surface deposits, or bracketing relationships with rift related igneous bodies. Using such an approach, Zoback et al. (1981) provided an initial historical framework for the stress field associated with the Basin and Range province, with an earlier period from 20-10Ma, where the minimum horizontal stress was WSW-ENE, and a later phase after 10 Ma in the north was 45 degree clockwise of this earlier direction. Subsequent work has painted an even more complex picture of the regional development of the Basin and Range.

Focusing on fracture systems in Tertiary rocks of the Great Plains, and based on the recognition of Sevier and Alleghanian strain well into the continental interior, the question can be raised as to **whether a counterpart Basin and Range related strain event (or events) and causative stress field exists in the Great Plains**? The change from Laramide and Sevier contraction in western North America to Basin and Range extension could reasonably be expected to influence plate interior stresses. An episode of fracture generation could result as the plate interior equilibrates with its new boundary conditions. This is a primary question driving this project. Rocks are fundamentally weaker in extension than compression, and so extensional forces at a plate margin would be expected to influence interior stresses differently than compressional forces.

There are fracture sets seen at study sites in the Great Plains that are aligned with these Basin and Range directions. Most striking is a series of fracture sets trending NNW-SSE, that may have a very widespread topographic expression (Fig. 2). This direction would be aligned with the earlier Basin and Range stress field. However, it also parallels the Black Hills Laramide trend, and reactivation may also play an important role in the formation of these fracture set. Much more data, and constraints on formation age are needed to assess this idea.



Portion of the USGS Digital Shaded relief image for the northern Great Plains. The Black Hills uplift and the Laramie Mountains are visible. Note the persistent N20W lineament grain that is roughly parallel to the axis of the Black Hills dome. The contrast has been increased in the image to bring out the linear features. Image source: http://pubs.usgs.gov/imap/i2206/. Note that this dominate fracture set is not aligned with the present day stress field.

Loading paths by which regional tectonic stresses can directly induce fracturing include increasing the deviatoric stress and increasing pore pressure through tectonic compaction. However, tectonic stresses may play a contributing role in many other loading paths. For example, the increased pore pressure from tectonic compaction may combine with diagenetic contraction (syneresis) to produce fractures that would not have developed with only one of the two.

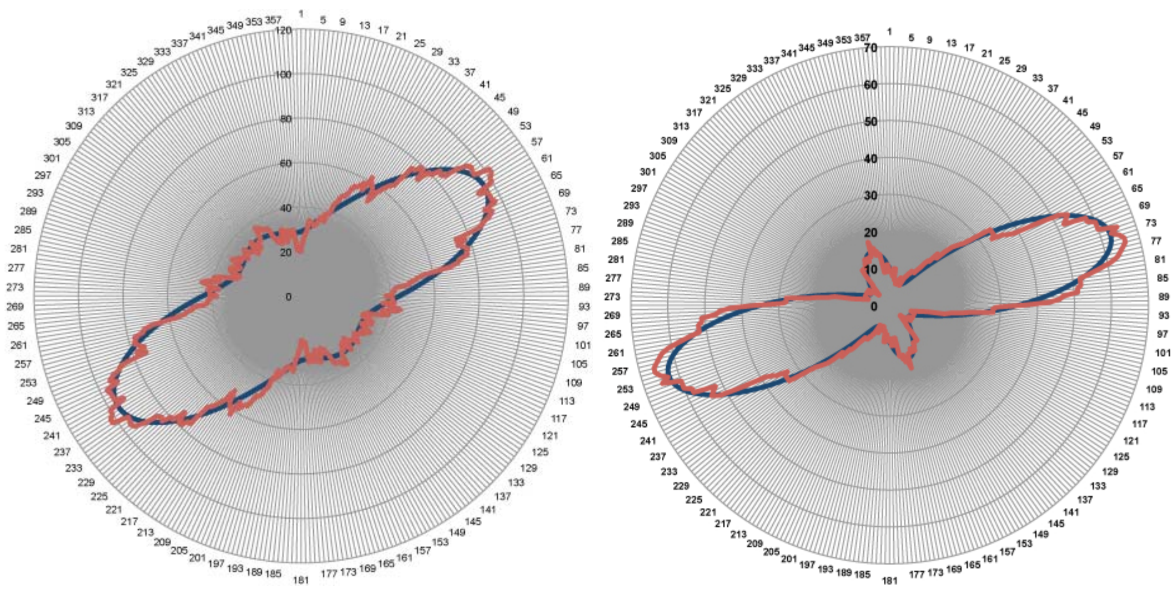
Even if fracturing would have occurred even if there was not a tectonic component, the tectonic stresses may also serve to organize the strike directions of the fractures. A regional stress field could organize the strike orientations of fractures primarily generated by thermoelastic contraction, syneresis or by Poisson's contraction associated with unloading. In this way, orientation patterns can reflect tectonic stresses even when the loading path is not driven by tectonic forces. This is why a simple alignment of fractures with a tectonic direction is inadequate evidence to conclude that tectonic strains were primarily responsible. On the plus side, fracture sets formed by non-tectonic processes (e.g. diagenesis) may still record tectonics stress directions, allowing for more complete models of stress field evolution to be developed.

B. Neotectonic fracture sets

<u>Sections: traits of neotectonic fractures, fracture sets in young loesses, associated loading paths.</u>

<u>Traits of neotectonic fractures</u> are described by Hancock & Engelder (1989) describe neotectonic joints that form in the upper .5 km of the earth's crust aligned with the modern tectonic stress field. These fracture set can be considered as a special case (recently formed) of fractures described above in section A. The examples Hancock and Engelder (1989) studied had some of the following attributes (in no particular order): a) simpler and smooth with occasional plumose structures and arrest marks that suggest vertical propagation, b) a lack of influence by older joint directions, c) large (traversing multiple beds) and slightly dilated, d) vertical orientation or a steeply dipping conjugate set with a small dihedral angle (less than 45 degrees), e) a greater dispersion than older and deeper formed joints.

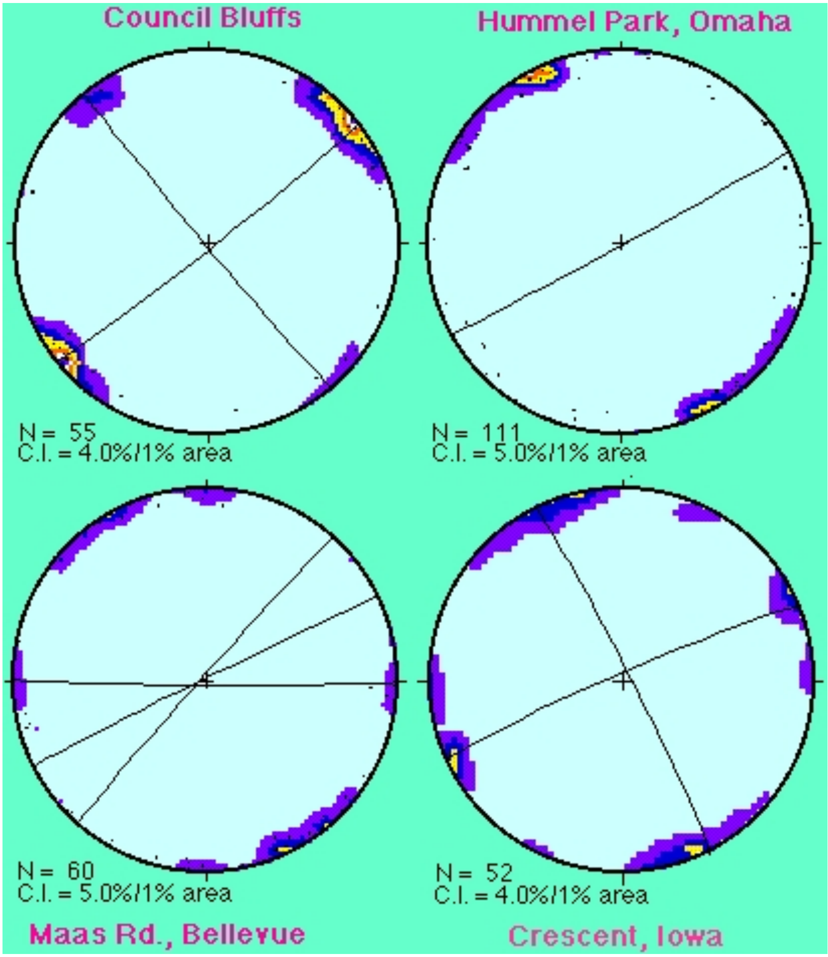
<u>Fracture sets in young loesses</u> in eastern and central Nebraska have consistent orientations with orientations that suggest the possibility of neotectonic joints (Maher et al. 1997, Nanfito et al. 2007). The modern orientation of maximum horizontal stress direction is poorly constrained in Kansas and northwards in the global stress map, but the closest sites would suggest it is oriented roughly 60 azimuth, which is a common direction in the loesses studied. Some of these loesses are younger than 20,000 years and have never been significantly buried. Poisson's ratio for loess is characterized as between .1 and .3, producing a larger deviatoric stress from loading. This is also a function of moisture content (the wetter the higher



These are ray diagram plots of loess fracture strikes from the Hummel Park area in northern Omaha (left, n = 292) and the Crescent, Iowa area (right, n = 128). The red curve is the field data, with each ray value representing the number of readings within in a 30 degree sector centered on the that particular ray, for ray intervals of 1 degree. These types of plots avoid some of the pitfalls associated with rose diagrams. The blue lines represent statistical models developed for each distribution. For the Hummel site the primary model distribution component is a preferred orientation at 59 degrees and a uniform component of 59%. For the Crescent site the primary distribution components are preferred orientations at 72 and 160 degrees azimuth, and a uniform component of 29%. The 160 direction is likely under represented because the outcrop surfaces sampled (road cuts) ran north-south. For more details on the modeling please contact me. Data exists for 11 additional sites.

Image to right is of columnar loess in the Omaha area. Careful inspection shows that the fractures do not have a honeycomb pattern.

Interestingly, an orthogonal fracture set is typical in some loesses, suggesting extension in multiple directions. Often it is not clear that one of the orthogonal directions dominants. Weakly cemented and massive loess deposits seemingly have the appropriate mechanical character to develop neotectonic joints with minimal stress. Their classification as neotectonic is primarily based on their young age and association with the modern stress field. It does not consider the underlying cause of jointing. Loess fractures will be one focused case study for the Great Plains Fracture Study.



To the left are more traditional contoured stereonet plots of poles to loess fractures from four sites in the Omaha area. Note the similarities between the four sites and the orthogonal pattern for the Council Bluff and Crescent, Iowa sites.

Loading paths for these fractures are constrained by their shallow level of formation. Hancock and Engelder (1989) indicate that neotectonic fractures are due to erosional unloading and Poisson's contraction, with thermo-elastic contraction and hydrostatic pore pressures aiding the process. Confined conditions and associated significant elevated pore pressures are unlikely to exist at the shallow conditions.

Some limited erosional unloading has locally occurred in the Great Plains. For example, in the North Platte River valley area, the relief between the valley floor and the preserved gangplank provides a crude estimate of the unloading in the Valley.

Handy & Ferguson (1994) describe a loading path that leads to tensile failure in loess, and conclude: "The vertical sequence of lateral stress from high to low to high again should contribute a tension-induced cleavage if lateral confinement is removed by excavation or erosion. … Loess cleavage appears to result from stress relief and is not a unique directional property of this material."

However, the plots above show a well developed preferred direction where the topographic slope is distinctly oblique to the fracture preferred direction (in the case of Hummer Park the slope is north-south running), suggesting that they are not due to slope unloading.

For the Great Plains loesses erosional unloading has not occurred, and hence inconsistent with Hancock and Engelder's (1989) model. For glacial tills, the unloading possibilities are limited to lodgement tills and melting of overlying glacial ice. This eliminates the possibility of Poisson's contraction, and except for sub-ice water, of significant pore pressure contributions. For tensile fractures, chemically driven contraction (diagenetically driven deformation) or a change in the horizontal load are left by default. However, for loesses it is difficult to identify what diagenetic process could be driving the fracturing. A very low tensile strength coupled with a low Poisson's ratio may be a key factor. Reactivation of underlying fracture systems may also play a role (discussed in the next section).

C. Reactivation of underlying, older fracture sets:

Sections: two mechanisms, evidence for reactivation, loading of overlying strata by the elastic response of an underlying fractured bedrock, role of pore pressure changes, loading paths for reactivation.

Two mechanisms exist for this category: The simplest joint reactivation would consist of additional propagation of the existing fractures. Ostensibly, if a fracture set already exists, then one can expect joint reactivation if they are properly aligned relative to the stress field, and if the appropriate differential stresses exist. This might be recognized by different morphology of propagation features (fractography) along fracture interiors versus margins, or by a consistent bending evolving stress traction directions.

A second and more speculative mechanism comes from role existing fractures play in the material properties of the bulk rock, and hence how the rock body responds to load changes. This may be especially significant where younger and weaker strata exist above a well fractured ‘bedrock’. Stresses may be induced in the overlying rocks due to load changes that induce strain in the underlying fracture rock. This is explained in some more detail below.

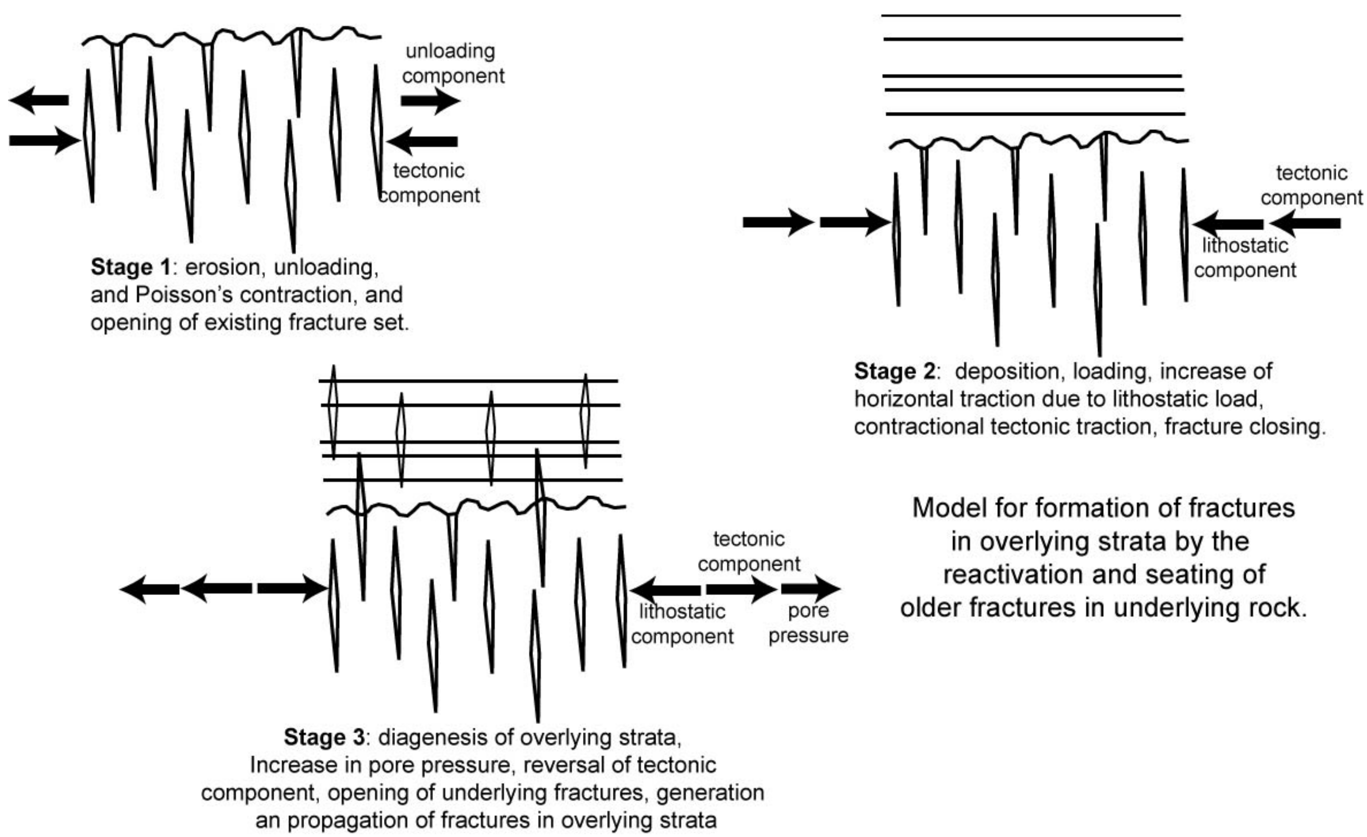


Diagram showing model for how a set of pre-existing fractures gets reactivated to cause new fractures in an overlying sequence. Note that either the new fractures propagate from old ones, or are new and due to the closing/opening of the fractures below.

Evidence for reactivation can be found in fracture sets that truncates at an unconformity is that the fracture set age is bracketed by the age of the strata above and below. However, fracture truncation can also be caused by the unconformity being a mechanical barrier to joint propagation, in which case the fracture set would be younger than the overlying sequence. Additional evidence, such as erosional microrelief associated with the fracture set, or paleoweathering along the fractures is needed to confirm that fractures predate the overlying sequence. These types of relationships are seen with fracture sets in the Brule Formation of the North Platte River valley of Nebraska, that are in unconformable contact with Arikaree Group strata (Scotts Bluff area) or with the Ogallala Group Strata (e.g. at Ash Hollow). Thus, the truncated fracture set predates the unconformity.

Close-up of Brule Formation (more massive, lighter colored strata) and Airkaree Group (better bedded strata) unconformable contact at Courthouse (or is it Jailhouse) rock. Note how the fractures in the Brule Fm. truncate at the contact. However, similar fractures can be seen in a bit higher, and the truncation could be due to the contrast in lithology.

This is the same contact. Note how some of the darker younger sediment above the unconformity fills in fissures aligned with the underlying truncated fractures, suggesting the fractures predated the unconformity. Note also how the fracture on the very right cuts across the contact.

However, some individual fractures with this same direction continue through the unconformity. This indicates that some of the fractures with this orientation postdate the younger strata. The easiest explanation is that the underlying fracture sets have been reactivated. The mechanisms of shear reactivation of joints are well explored in the literature. Mechanisms of tensile reactivation of joints sets are less discussed. The existence of distinct joint sets only 20 degrees apart suggests that the range of alignments where fractures can be reactivated can be narrow.

Expected traits of fracture sets include: a) relatively widespread, developing above the area with the controlling and straining joint system, b) the deeper fractures would have a multistage history of opening and closing (possibly evident in the associated alteration and/or mineralization), and c) propagation directions above the unconformity (as evident plumose structures) should have an upward component.

<u>Loading of overlying strata by the elastic response of an underlying fractured bedrock</u> is a relatively unexplored possibility. Such strains (seating) are important considerations in engineering of dams and reservoirs. The preferred direction of fractures/joints produces a mechanical anisotropy. Therefore, the relationship between the direction of the loading or unloading stresses, the orientation of well developed dominant pre-existing joint sets in the older rocks, and the strain and tensile fracturing in the overlying rocks may be more complex. Specifically the joints will close or open under a new load producing a broadly distributed, but small strain. Theoretically this strain could be transmitted into overlying and attached younger rocks. If a cross-fracture load is relaxed producing extensional strain in the underlying rocks, then depending on the strain and rock strength of the overlying material, tensile fractures could be induced. Note that in this case the fractures in the younger material could be new failures, and not the simple propagation of fractures below into the overlying younger strata. In other words, they could be unconnected to the fractures below. This model requires that the overlying strata be mechanically coupled to the underlying rocks with the fracture set.

The <u>role of pore pressure changes</u> can cause an existing fracture to open or close. A crucial consideration is the rock stresses normal to fracture right at the crack tip versus the opening pore pressure within (Secor, 1965). If the later is sufficiently greater than the former then the tip can open. An additional consideration is that rock-water interactions can cause chemical weakening of the material at the tip, allowing for easier propagation. The fact that some of the Brule fractures can be seen to cross the unconformity indicates that the unconformity is not always a barrier to fracture propagation. After deposition and lithification of the overlying sequence, a change in pore pressure in the underlying sequence could cause the pre-existing fractures to propagate up into the overlying rock. If the overlying unit is fine-grained, then it could provide a seal that would aid in over pressurization of the fluids underneath.

<u>Loading paths for reactivation</u> are potentially complex. A period of uplift and erosion in the absence of a tectonic component could theoretically be expected to produce anisotropic Poisson's contraction in the underlying fracture rocks . A reduction or reversal of a tectonic traction (from compressive to tensile) could also induce joint relaxation and extensional strains in overlying the rocks. On a speculative note, the interval when western North America switched from Laramide related compression to Basin and Range extension, may have been an optimal time for fracture formation by this mechanism (a large scale relaxation).

D: Tectonic reactivation related

Sections: common explanation, linkage between the basement deformation and overlying fracturing in cover strata, interaction between surface sedimentation and basement reactivation, major Precambrian features reactivated in the mid-continent region, loading paths.

A common explanation for localized intraplate fracture systems is often tectonic reactivation (e.g. Werner 1978, Baar and Watney 1991, Carlson, 2007). The fundamental premise is that favorably aligned weaknesses in the Precambrian basement are reactivated to produce fractures in overlying rocks. One of the best examples in the Great Plains region is probably the Colorado lineament (Werner 1978), with Tertiary faulting and seismicity in NE Colorado and NW Nebraska and which follows a Precambrian suture zone. In the case of rifts with significant lenses of mafic volcanics (rift pillows), it has been postulated that the associated density structure produces a local stress field that can localize fracturing and seismicity ( ). **A key trait of fracturing related to basement reactivation is the spatial and kinematic association between the fracture set and an underlying structural feature in the basement**. Verbeek & Grout (1997) argue that for the Colorado plateau cover rocks they can separate out the fractures created by basement faulting, versus a regional pattern uninfluenced by the basement fractures.

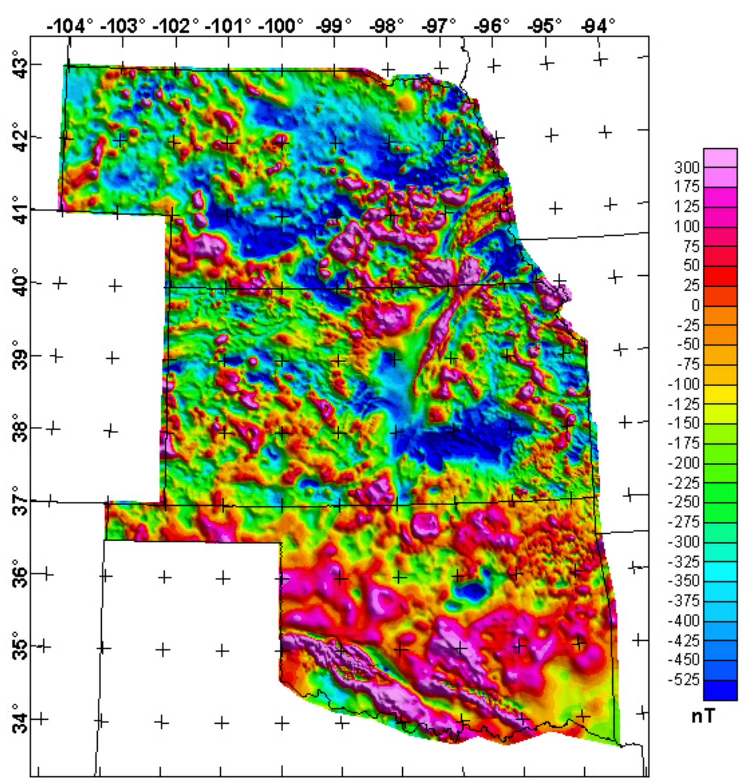
The linkage between the basement deformation and overlying fracturing in cover strata is dependent on kinematics and the nature of the stratigraphy. Given the very different mechanical character of the basement and overlying sediments, and the mechanical variation in the sediments themselves, the relation can be complex. For reactivated faults a tri-shear zone development in the overlying sediment rocks can be expected, especially where salts and shales occur. In a typical tri-shear zone geometry the fault(s) may be quite focused in the basement, and above the strain is distributed across an array of structures in the overlying sediments. Tri-shear zones typically develop for either normal or reverse faults. Both tensile and shear fractures can contribute to the tri-shear zone strain. Theoretically, the thick and very incompetent Pierre shale in particular should have a marked influence on how the strain is distributed at shallow crustal levels in some regions of the Great Plains. It is possible, if not likely, that very gentle monoclines will be expressed on the surface. One example may be the faults and monocline found along the Great Wall in the Big Badlands National Park.

Other linkages may develop. If basement arching or antiformal folding occurs then a simple expectation of aligned crestal fractures in the overlying sedimentary rocks could be predicted. It is also common that an extensional strain occurs parallel to the fold axis, producing a tensile fracture set perpendicular to the fold axis. Wrench reactivation along basement anisotropy is expected to produce an array of overlying en echelon features (Wilcox et al. 1973).

Most longer fault systems are segmented, with along strike changes (along strike slip gradients, bends, relay/transfer zones). Overlying fracture systems should also show corresponding changes along strike. The independent recognition of segmentation of the basement feature that can be associated with changes in overlying fractures systems along strike strengthens the correlation between the two, and likely provides insight into kinematics and deformation mechanics. The segmentation seen associated with the Keweenawan rift would be a large scale example of where such a phenomena may be looked for. To make matters more complicated, the segmented feature may be reactivated in a different kinematic mode from that which produced the original segmentation. For example, the overall Keweenawan rift trend is oblique to the present day maximum horizontal stress in a manner that could produce a dextral shear component.

An interaction between surface sedimentation and basement reactivation may exist if there is a dip slip shear component. This can be very helpful in working out the fracture development history, but caution must be used. An alignment between channels or other sedimentary facies patterns (e.g. thickness changes), and a structural trend can be suggestive that the related structures were active during sedimentation. As one example, at the Rock Bass study site in NW Nebraska, well defined shoe-string channels in the Chadron Formation run parallel to small local faults that also cut the channels. Yet the faults cut chalcedony veins, and belong to a later generation of faulting, that cuts through overlying Brule Fm. strata, clearly postdating significantly the deposition of the Chadron Fm. sediments. Three possible interpretations may exist. First, a coherent faulting episode may span the time from Chadron to Brule Fm. sedimentation and the subsequent diagenesis and formation of the chalcedony veins. A second possibility is that that a fault set produced during Chadron Fm. deposition was reactivated after Brule Fm. deposition, diagenesis and chalcedony vein production. A third possibility, is that the small scale faulting reflects differential compaction around the channel. In general, differential compaction and tectonic reactivation may be easily confused, as differential compaction can also be related to basement topography and related overlying sedimentary facies architecture. Differential compaction as a fracture generation mechanism is discussed in a section below.

<u>Major Precambrian features reactivated in the mid-continent region</u> include: the fore mentioned Colorado Lineament (Werner 1978), the southern extension of the Keweenawan rift in SE Nebraska (the Humboldt fault zone) and NE Kansas, the Chadron and Cambridge arches. The Black Hills, as the easternmost Laramide uplift that impinges on the Great Plains, is a special case, as Wicks et al. (19) explore. In this area, reactivation of Laramide structures is possible.



Aeromag anomaliesfrom USGS site: http://pubs.usgs.gov/ds/2005/138/neksok.html of the 3 states, Nebraska, Kansas and Oklahoma. Note the expression of the Keweenawan rift in SE Nebraska and central Kansas. This is the large feature that underlies the Humboldtfault zone, and has Paleozoic and post Paleozoic fault reactivation.

The critical contribution to the <u>loading path</u> with reactivation is an increase in a subhorizontal stress traction due to underlying deformation of the basement rocks increasing the differential stress. In this case shear fractures could occur. A combination of increased pore pressure, bending stresses in more competent units, unloading and thermal stresses can contribute and also produce tensile fractures.

The discussion of how a regional stress field may organize fracture directions produced by other mechanisms such as diagenetically driven deformation could apply here. A stress field perturbation created by reactivation of basement features could be insufficient to drive the loading path to failure, but could help organize the fracture directions where the significant loading factor may be due to a chemical or thermal contraction.

E. Differential compaction

Sections: potential for compaction, interplay between diagenesis, geometries producing differential compaction, sediment strength and fracture formation, expectations,

For sedimentary rocks differential compaction has been known to produce faulting and fracturing. Perhaps the clearest demonstration of this is the formation of faults and large scale surface fissures when fluid withdrawal (water or hydrocarbons) occurs, sometimes creating an environmental hazard (Jachens & Holzer 1982). Using compaction related fracture patterns on the surface to detect possible structures at depth is a classic exploration strategy in Kansas (Gay, 1989; Merriman, 2005).

The potential for compaction is greatest where a significant amount of fine-grained and organic rich rocks are involved. Compaction can be mechanical (dewatering and grain rearrangement) or chemical (e.g. distributed solution removal, oxidation removal of organics). Salt solution is a special case considered below. In extreme cases organic and/or clay rich sediment can compact two or three fold. Two processes that can induce compaction are vertical loading (by sedimentation) and dewatering.

In the Great Plains the widely distributed Pierre Shale has significant compaction potential, but has a basal geometry and thickness geometry that would not generate much of a differential component (other than around concretions at a small scale). The presence of paleotopography on the basal and internal unconformities and sandstone channels along with an abundance of clay rich lithologies suggests differential compaction is a distinct possibility in White River and Arikaree Groups. The sediments must be lithified enough to have brittle strength and fracture.

Geometries producing differential compaction are diverse. One commonly described geometry is above steeper faults with a dip-slip component, where a proportionally greater amount of finer-grained sediments accumulate on one side and hence more compaction occurs on that side (e.g. with growth faults). Erosional relief on unconformities (paleo-valleys and paleo-highs) can also produce differential compaction in the overlying sediments. Stratigraphic architectures can also drive differential compaction. Above buried reef complexes where the early cementation of the reef rock makes it incompactible, differential compaction can occur. Major channel complexes, which because of their coarser fill, should compact less than the surrounding finer grained rocks, can produce fracture sets through differential compaction.

The interplay between diagenesis, compaction, sediment strength and fracture formation is important to consider. In a simple model as compaction and diagenesis occurs the overlying sediments are unlithified, and do not have sufficient strength to fracture, and instead deform by distributed intergranular processes. In this case, differential compaction related fractures would be uncommon. However, different types of sediments undergo diagenesis (cementation and clay and silica phase changes) at different points in their burial history. Thus, compaction related fractures should be expected in sediments that undergo early diagenesis that overly sediments that undergo late diagenesis and still have compaction potential (under consolidated). Carbonates are known for their early diagenesis, and due to electrostatic forces clay rich sediments start out with enough strength to fracture. The chemical disequilibrium that characterizes volcanic ash rich sediment also produces the possibility of of significant shallow diagenesis especially where silica phases are concerned. Fluid flow conditions and history may be crucial, either promoting or removing cements. In addition, compaction can be delayed if confined conditions makes draining difficult. Fracturing could aid in its dewatering, initiating a feedback loop between dewatering, compaction and fracturing.

A series of expectations can be assembled for such fractures. They should be localized and have a distinct geometric relationship with the underlying structural or sedimentary features across which differential compaction is occurring. They should occur during a period of loading and/or burial that drives the compaction, or substantial lowering of the ground water table (explored below). For tensile features, since they form at a relatively shallow crustal level (upper several kilometers where the majority of compaction occurs) the fracture morphology may be similar to neotectonic joints.

The critical loading paths include bending or shear stresses generated by the differential compaction. Other factors such as pore pressures may contribute, especially since the fine-grained rocks that can produce good seals and over-pressurization also have the greatest compaction potential. As with other potential trigger events, differential compaction related stresses could be insufficient to cause fracturing by themselves, but cause a local anomaly in a regional stress field that organizes fracture orientations produced by other processes such as thermal or chemical contraction.

F. Topography related fractures

Sections: effects of topography, loess fractures, erosion related lateral stress relief, subvertical shear fractures, controversy about shear joints, expected traits,

The loading effects of topography on shallow stresses includes reorientation of principal stresses, and erosional unloading that produced the topography. With a retreating cliff or steep slope the unloading can be horizontal instead of or in addition to vertical unloading. As the topography increases the stress traction parallel to the surface increases, whereas the load perpendicular is close to zero. Mohr criteria would suggest that the resulting tensile fractures would be slope parallel. Spalling off cliff surfaces may form in this way. The erosional unloading will also induce a Poisson's contraction effect, inducing a tensile traction perpendicular to the surface. Exfoliation joints in massive granitic rocks may be explained in this way. In horizontally layered rocks cliffs may form because of the layering and the resulting fractures would be subvertical.

Loess fractures, because of their low strength and association with significant relief (loess bluffs), perhaps have the greatest potential for being driven by topographic processes. In that Brule Formation strata are considered loessal they may also have a similar potential. Maher et al. (1997) and Nanfito et al. (2007) documented multiple regional fracture sets in Nebraska loess. Important traits of these fracture sets is that two or more directions always exist (commonly orthogonal) and that within a county sized area common directions exist from site to site. A fundamental question, in the form of the chicken and egg dilemma, that arises in considering this possibility is whether well developed directional drainage in these sediments is caused by preexisting fractures or are preferred orientations a function of directional direction.

Erosion related lateral stress relief is described by Handy & Ferguson (1994) as the possible cause of loess 'cleavage'. They develop a model where "The distribution of lateral stress vertically in the loess section lends itself to cleavage and spalling as a result of stress relief, as the upper and lower soil expands elastically and places the intermediate soil in tension. (p. 244)" The lower lateral stress is argued to be preserved during burial (sedimentary loading) in the intermediate layer that produces the fracture sets. One clear expectation of such fractures would be that their orientation would be related to slope, with a slope parallel relationship most likely.

However, several aspects of loess fracture systems are inconsistent with this origin. In some cases well developed fracture sets are highly oblique to the modern slope exposure. Multiple and orthogonal directions are also more difficult to explain. Fracture systems that exist in glacial tills are unexplained by this process. Finally, while it is easy to understand how pre-existing fractures could influence drainage development, it is harder to understand how the well developed preferred orientation of drainage formed in the first place if the fractures didn't exist, especially in areas of thick loess development such as the Broken Bow area. One possibility may to look at how the significant paleorelief that the loess is draped over may influence the internal stress distribution.

Shaded relief image showing how the Broken Bow area exhibits well developed directional drainage.

Stereonet of poles to loess fractures from Brokenbow area showing two major directions of fractures, the subordinate of which is parallel to the well developed drainage pattern. Our interpretation is that the topography follows pre-existing fractures and not that the fractures follow topography.

Subvertical shear fractures are described by Price & Cosgrove (1990, 226-237) as forming where a vertical shear stress traction is added to very shallowly dipping (less than a few degrees) clay rich rocks in an otherwise lithostatic stress setting. The subvertical shear fractures can develop due to the local reorientation of the principal stresses. Such sub-vertical shear stresses could be induced by reactivation of a basement fault (e.g. within an overlying tri-shear zone), or could occur due to concentrated differential compaction (e.g. over a buried scarp), or could be topography related. For fracture systems in the Great Plains, the topographic driven fracturing is perhaps the most significant to consider, especially for situations like Scotts Bluff and Pawnee Buttes with significant topography involving clay rich rocks.

Such sub-vertical shear joints could have dips as steep as 85 degrees, and can thus be confused with tensile joints. Recognition criteria would include: a) facets as the fracture refracts through material with a different failure envelope angle, b) an overall smoother character and without typical tensile fracture ornamentation (plumose structures and hack marks), c) a closed character since they are shear fractures and a significant normal stress exists perpendicular to them, and this in turn would prohibit fluid flow related alteration or veining. Price and Cosgrove conclude "that the conditions particularly conducive to the development of vertical shear joints occur in weak rock, not subjected to over-pressure, when at depths of 2-4 km." In the case where these are topography driven an additional expectation might be an asymmetric dip distribution in the direction of the topography.

Significant controversy about shear joints exists in the literature. Part of the controversy concerns the shape of the failure envelope, and specifically the nature of a transition from the tensile cut-off to the failure envelope that describes shear failure. If a smooth curved transition exists, as Koehn et al. (2005) model, hybrid fracture can develop. However, some argue that shear joints can not exist because models suggest that fracture planes with a shear stress on them can not propagate in a planar geometry.

The experimental recent work of Jorend et al. 2012 may provide new insight with respect to shear joints. They experimentally developed joints with plumose structures that were oblique to sigma one, with the obliquity a function of the mean stress value. This suggests that a smooth transition exists and that conjugate shear joints with a small dihedral angle could form. A key argument is that these may initiate as thin deformation bands, which means that the standard models of linear fracture mechanics for tip propagation do not apply, thus negating a major argument against the existence of shear joints. There results would also suggest conjugate fractures may be favored with higher differential stresses and/or depth, where the mean stress value would be higher.

The existence of hybrid or shear joints has two implications for fracture interpretation in the context of the larger study. Since shear fractures can form at an angle to the maximum principal stress, then in the case of shallow conditions and steep slopes the shear fractures produced can be closer to subvertical in orientation. In addition, if the conjugate pair can be established then the direction of all three principal stresses can be estimated.

Expected traits for fractures produced by topographic related stresses include: a) alignment with the slope generating the stresses, b) spatial association with the generating slopes (e.g. diminishment away from slope), c) simple surface morphology of fractures, and d) an intensity related to topographic relief and rock strength.

G. Diagenetically driven deformation:

Sections: primary mechanism, expected traits, Great Plains fracture sets that are diagenetically driven, loading paths.

The primary mechanism for fracturing produced by diagenetic processes is volume loss (syneresis). Literature on polygonal fault systems in marine strata e.g. (Cartwright & Dewhurst 1998, Davies 2005) highlighted the existence of this process. These are stratabound arrays of normal faults with a polygonal map pattern that are centered on fine-grained marine strata, and can be unassociated with other tectonism. They are attributed to sediment volume losses as swelling clays undergo diagenesis and volume reduction. Silica phase changes and maturation of organics may also drive syneresis. Coal cleats are an example of a microfracture set that occurs during thermal maturation (Laubach et al. 1998), and which has been used to track stress field evolution (Engelder and Whitaker, 2006). Laubach et al. (2010) describe structural diagenesis, a relatively new field of study devoted to the interplay between structural processes and diagenesis, with a focus on fracturing.

Expected traits for diagenetically driven include: a) a stratabound distribution, b) association with a host lithology with syneresis potential (especially fine-grained strata with swelling clays), c) association with diagenetic phases and hence formation during burial, and not unloading, and d) a polygonal pattern (either honeycomb or tetragonal) accommodating the horizontal shrinkage. If syneresis occurs in a tectonic stress field, the tectonic stress can organize the fractures into two orthogonal directions, and this can mask the diagenetically driven origin of the fractures.

Great Plains fracture sets that are diagenetically driven include stratabound chalcedony vein horizons and clastic dike arrays within the smectite-rich White River Group sediments (Maher & Shuster, 2012). A combination of a high input of reworked volcanic ash coupled with pedogenesis in these loessal, fine-grained sediments, resulted in strata very rich in smectite. In addition to a stratabound distribution, the chalcedony veins also show significant evidence of vertical shortening, indicating that compaction occurred as they were forming. The silica in the veins is attributed to diagenesis (Lander and Hays,). The generation of fracture avenues could aid fluid flow and associated compaction in these fine-grained sediments. Thus diagenesis, fracture formation, fluid flow and compaction may all be linked through feedback loops.

The strike orientations of the chalcedony veins appear to follow different patterns at different sites. The ambient stress field during syneresis should influence the pattern and the figure below attempts to capture possibilities

Strain ellipses, circular histogram forms, and fracture map patterns for mixes of pure syneresis and horizontal differential stresses strong enough to induce a fracture set.

Another candidate for fracture sets generated by diagenetically driven deformation are the Cretaceous Pierre Shale and Niobrara Chalks. They are fine grained, have significant amount of swelling clays (with local ash layers from eruptions to the west), and often display an array of small normal faults and veins. Studies are ongoing to document these fractures sets and assess their origin.

The primary loading path for these fractures is bulk shrinkage of the materials inducing an isotropic tensile stress. Simple compaction/settling in the vertical direction accommodates the shrinkage in the vertical direction. Therefore, the vertical tractions should remain lithostatic, unless a mechanism produces under-compaction (which has been observed in sediments). However, the tensile shrinkage component will reduce the horizontal stress tractions, increasing the differential stress. Depending on failure criteria, at a shallower depth the tensile cutoff may be reached, while at depth shear fractures may be expected.

Given that mudrocks that undergo the appropriate diagenesis are also generally impermeable, fluid pressures greater than hydrostatic may be generated, and contribute to the loading that produces failures. If the diagenetic reaction also liberates water (as the smectite to illite transformation does), then that could also influence (ostensibly increase) pore pressures.

On the basis of Mohr criteria the regional stress fields may play a role. Diagenetically driven deformation could be favored in extensional terranes as the shrinkage stresses could work in concert with the tectonic traction, increasing the differential stress, while in areas where the tectonic component is compressional they would be opposed and would reduce the differential stress.

H. Continental glaciation related

Sections: mechanisms, relation between glaciations and seismicity, fractures found in glacial till, loading paths.

Mechanisms by which glaciations may influence fracture include isostatic flexuring and the influence of sub-ice fluid pressures. Isostatic flexuring may be produced by other mechanisms, such as erosion, but in the Great Plains area recent glaciations are considered to be more signicant. The possibility that strain related to crustal flexure during glacial unloading and loading may be sufficient to generate bedrock fractures was proposed by Morner (1978). Associated stresses have been modeled by Clark (1982) and found sufficient to induce fracturing. Calais et al (200?, 2006) found that in northern North America consistent GPS detected strain was related to ongoing glacial rebound. A migrating forebulge may be a crucial phenomena, and considering the bulge as producing extension along its crest, the fractures would be expected to be parallel to the forebulge axis. Such fracturing would also be very transitory geologically. During the relaxation of the bulge the stresses and fractures would differ.

Calais et al. (2010) specifically argue that the New Madrid seismicity is a consequence of late-Pleistocene erosion in the northern Mississippi embayment, and is thus a transitory phenomena. Hetzel and Hampel (2005) model how Lake Bonneville fluctuations and associated glacial loading accelerated Wasatch fault movement Utah) in the late Pleistocene and Holocene, and conclude that “Our analysis implies that climate-controlled changes in loads applied to Earth's surface may exert a fundamental control on the slip history of individual normal faults (abstract)”.

The relation between glaciations and seismicity has been explored. Thorson (1996) suggests that glacial processes influenced earthquake activity in the Puget sound area in a method similar to large scale reservoir induced seismicity. This introduces the possibility that recent glaciation reactivated faults in the northern Great Plains area by influencing pore pressures. Naturally, such a phenomena would not be expected in the unglaciated southern areas. Grollimund (2000) investigates the North Sea area looking at the interplay of the regional tectonic stress field, the field due to glacial loading, and pore pressures. They conclude “Analytical and numerical models of plate flexure suggest that these observed lateral stress variations are the result of deglaciation, superimposed on a regional stress field dominated by ridge push. The pore pressure in the northern North Sea roughly follows the stress trend, i.e. high overpressures where horizontal stresses are high … (abstract).” Stewart et al. (2000) provide a review, and one of their conclusions is that glacial loading can generate seismicity hundreds of kilometers from the ice front.

Distinct fractures found in glacial till in the Great Plains exist, but limited analysis has been done on their orientations or origin. Jakobsen & Klint (1999) looked at fractures in lodgement tills in Denmark and found well oriented vertical sets parallel to the ice movement direction. They also note that elsewhere sets perpendicular to the movement also occur. They concluded that those were caused by a combination of subglacial loading. Other fractures present were associated with retreat dessication and freeze-thaw. Wfodarski (2010) also relates fractures in till to shear during subglacial conditions.

Loading paths for fractures associated with glaciations would include elevation of pore pressures underneath the ice and bending stresses associated with lithospheric flexure. As the Grollimund (2000) article demonstrates, it is useful to consider the interplay between the glacial, tectonic and other loading. On a geologic time scale the change in glacial loading can be relatively swift, suggesting that time dependent strength needs to be considered. While not encountered in my literature search yet, the possibility of Poisson’s contraction after unloading of glacial ice may be worth exploring. In the center of an ice sheet where several kilometers of ice may have been removed, the effect could be significant.

Diagnostic traits by which glacial induced fractures can be recognized are not easy to establish. Foremost is a combination of timing (during unloading), spatial association (near the ice margin), and orientation. Flexuring and associated fracturing would be expected to both diminish and migrate inward with time. The sharpest flexure may exist at the forebulge and at the edge of the ice sheet. Orientations parallel or perpendicular to the loading contours could be expected (in the absence of other concurrent factors, such as a tectonic stress field component).

I. Impact related:

Of all the fracture inducing events this one leaves the most distinctive sets of traits. A intensely and chaotically fractured central uplift (if the impact is large enough) with radial and concentric bounding faults, can be surrounded by ring grabens and tilted strata. Overall a radial and concentric fracture pattern defines a bulls eye type pattern. Diapirs can also have this basic geometry, as can some collapse features and volcanic phenomena. In a few rare cases, such as Upheaval dome in Utah, there is debate as to whether a feature is due to impact or diapirism. In practice, associated shatter cones, shock lamellae in quartz, high P impact phases (e.g. stishovite), and other attributes allow impacts to be distinguished from other features. Because of their localized nature and easily recognized character less attention will be paid to them here.

An impact was proposed for near the town of Merna, Nebraska, based on a circular depression, but subsequent research indicated it is a deflation bowl (IANR News, http://ianrnews.unl.edu/static/0111071.shtml). One of the largest impact structures in the Great Plains region is the Manson structure in Iowa, which has no surface manifestation, but is covered by thick glacial tills.

J. Dissolution and collapse related:

Soluble rock types that could produce collapse related deformation includes carbonates and evaporites. Fracturing due to salt flowage is a well documented pheneomena, but is likely limited in the Great Plains as it requires deep enough burial to trigger mobilization. The Paleozoic section in particular has abundant evaporites and carbonates. Karst collapse features are well known and studied.

Fracturing associated with solution would depend on the exact geometry of solution with time. Solution at a point can produce a sinkhole feature. A laterally migrating solution front removing a layer of salt should produce a similar migrating flexure and associated fracture. A more laterally distributed solution could produce a simple lowering. The fractures themselves could enhance fluid flow through the system, aiding the dissolution process.

Up in North Dakota significant salt and associated sinkhole like collapse features exists in the Williston basin (Burke, ??). These features are an important part of the hydrocarbon reservoir architecture.

The Permian basins of west Texas also display collapse features and related deformation. Goldstein and Collins (1984) identify deformation caused by salt dissolution collapse in the Texas panhandle, indicating that "Collapse has resulted in a sequence of deformations including normal faulting, reverse faulting, folding, and veining (abstract)." They also suggested that pre-existing joint sets influenced the dissolution. Dissolution in these cases occurs at multiple stages in the geologic history, producing a corresponding complex history of associated deformation.

There is significant salt in the Kansas subsurface (and perhaps at one time in Nebraska given the saline lakes in the Lincoln area), and there is evidence for at least a significant solution front which could produce local fractures in overlying rocks. Sawin & Buchanan (2002) show a diagram that suggests solution from the top down, but in a very uneven fashion that produced overlying sinkhole collapse, and tapering to the E, in a fashion that could have produced fractures in the overlying rocks (Wellington Formation). In western Kansas a geomorphic feature called Cheyenne Bottoms is attributed to underlying salt dissolution (Keiswetter et al. 1995).

Oldham & Smosna (1996) describe dissolution structures related to Permian evaporites from the Denver Basin in Western Nebraska, including late Cretaceous and or Tertiary dissolution. Oldham's dissertation can be found at the Nebraska Oil and Gas Conservation Commission website
http://nlc1.nlc.state.ne.us/docs/pilot/pubs/NOGCC.html .

K. Changes in geohydrologic regime:

Oil production in southwest Nebraska has triggered minor induced seismicity, a clear reminder that changes in fluid pressure trigger brittle deformation in the Great Plains region. The fundamental cause in this case is typically through a reduction in the effective stress as pore pressures are increased. This phenomena also suggests that the crustal stress state in that area was close to failure, and Towend and Zoback (2000) suggest that much of the cratonic interior is in such a state. Geohydrologic changes could be the final trigger that allows fracturing ultimately caused by differential stresses associated with other phenomena (e.g. far field stresses) to be expressed.

Mechanisms for changing the geohydrologic regime include erosional dissection or depositional loading, or a change in the regional stress field that opens or closes fractures thereby changing hydraulic conductivity, or possibly epei-orogenic tilting. Climatic driven groundwater fluctuations are a possibility, but likely small in their overall effect. Glacial related changes have been discussed, and could be significant.

A speculative model for hydrogeologic regime change in the Great Plains region can be offered. During periods of major deposition ground water elevations would likely increase, enhancing fracture growth through increases in fluid pressures. In addition, compaction, diagenesis and dewatering may be triggered due to the increasing load. During periods of major dissection and unloading, the crust may be expected to harden, as it is partly drained and unloaded, although shallow differential compaction may be locally enhanced due to fluid withdrawal. Such a model would broadly predict that related fracturing would be associated with the deposition of the major Tertiary groups, while the intervening unconformities and associated dissection would be draining events.

Dissection of the gang plank initiated in the Plio-Pleistocene in the western Great Plains, leaving associated gravel deposits like the Broadwater gravels, in an elevated position. McMillan et al (2002) looked at the present gradient versus the paleo-gradient of Ogallala group channel deposits and concluded 680 (plus or minus 200) m uplift had occurred. They estimated that isostatic uplift due to erosional unloading could only produce several hundred meters of uplift, and hence there must be an additional broad uplift component. Karlstom et al. (2011) indicate that mantle driven broad uplift of 500-1000 meters occurred in the Rocky Mountains over the last 10 million years ago. The hydrogeologic consequences of this tilting could be complex, and could be a function of uplift rates. Initial uplift could cause higher relief that could increase pore pressures in deeper artesian aquifers. However, associated erosional dissection would be expected to lead to draining and lowering of the pore pressure in the higher shallow Tertiary units. The magnitude of the reduction would be something less than the amount of relief generated. In western Nebraska the relief can be hundreds of feet. It is worth mentioning that erosional dissection may also create topographic related stresses, generating associated fracturing.

Another candidate for a period of uplift, tilting and associated changes is represented by the White River versus Arikaree Group unconformity. Little information exists constraining this event. Pipey concretions in the Arikaree Group strata in western Nebraska are thought to parallel groundwater flow directions and are consistent with regional flow down slope to the west. It seems likely that periods of sedimentation or dissection are related to the Rocky Mountain uplift history, so that far field changes in the local tectonic stress field, and changes in geohydrologic regime were concurrent, and should be considered together.

L. Criteria diagnostic as to loading triggers:

The attached chart uses a branching classification where the primary class is the loading path that can lead to failure and subclasses consist of geologic trigger events that can produce such a loading paths. Since geologic trigger events can have multiple effects they show up in multiple positions in the chart. For example, erosion can produce a Poisson's contraction and a thermal cooling contraction. Associated with each loading trigger subclass is a list of expected traits.

The listed associated traits will have varying diagnostic utility. For example, a stratabound distribution in fine-grained mudrocks can strongly suggest a diagenetic contraction trigger, whereas a well defined orientation is characteristic of quite a few loading triggers, and is not very diagnostic. With refinement this framework could be used as a scoring rubric to help determine the most likely loading trigger for a given fracture set. In many cases, if enough information is available, the assemblage of traits may be sufficient to assign the causative mechanism(s) with some confidence. Timing is a particular useful diagnostic trait, as is spatial distribution and association. The advantage of this approach is to apply a consistent and sophisticated set of criteria when interpreting fracture set origins. As new literature and understanding develop the classification chart will be amended.

M. Timing of fracture events:

Fracture events are traditionally characterized as difficult to date. Clearly, they form sometime after the host rock developed. For Paleozoic host rocks in the Great Plains that leaves a large window of possibilities. For Pleistocene loesses the term neotectonic fits (Hancock and Engelder,1989), and the age is tightly constrained. However, careful field work in combination with new understanding allows fracture set ages to be much better constrained, and numerous examples exist in the literature where the age of fracture sets has been well constrained (e.g. Engelder & Whitaker 2006, Belayaneh et al. 2007). Three approaches include fracture interplay geometries, relationships across unconformities, associated diagenesis and/or mineralization, and fracture morphology.

Fracture interplay geometries arise from the fact that a pre-existing fracture influences the local stress field, and therefore, the geometry of a growing fracture. Relative timing of fracture sets in a locality can be documented by cross-cutting, truncation, and other geometric patterns. The interpretation that cross joints postdate longitudinal joints is perhaps one of the clearest examples. Tip curvatures and tip outs also can provide relative timing constraints. As a fracture tip migrates towards an area where a pre-existing fracture exists, it can often bend towards a perpendicular relationship and sometimes tip out. Such curvature is also driven by the ambient stress field, and is more common at shallow crustal depths.

Looking at fracture patterns across unconformities can also be instructive. Fracture sets that truncate at the unconformity, and show evidence of influencing the paleo-topography are clearly older. Sometimes enhanced paleo-weathering along fractures in the older underlying rock can also give clear evidence of their age. The unconformable contact between the White River Group (Brule Formation) and overlying Arikaree Group strata shows what appears to be truncation of an older fracture set. However, joint reactivation as described above, can confuse the situation, where some of fractures are reactivated and propagate into overlying younger strata. Therefore, a parallel fracture set in the younger strata could reflect reactivation (and multiple fracture events), and not a younger age for the development of fractures with that orientation in the older sediment.

A variant on this approach, termed paleostress stratigraphy, was described by Teyssier et al. (1995). In Svalbard, Norway, they compared mesoscale fault populations in the various foreland basin formations to look at how the local stress changed with time (due to the evolution of tectonic strain partitioning). The basic assumption is that the lithification is quick enough so that the mesoscale faults broadly reflect contemporaneous stress fields, and that one can backstrip the effect of younger faulting to see past that overprint for the older, underlying units. This approach could possibly be used for tensile features in the three major Tertiary Groups in the Great Plains area, although a large array of data would be needed. Unlike with the mesoscale faults, only part of the stress field would be constrained (sigma three), but this would still be very useful information. Limited initial work has been promising.

The recognition that associated diagenesis and fracture associated mineralization or wall rock alteration can help constrain the timing and conditions is part of a new field of study known as structural diagenesis (e.g. Laubach et al. 2010). If the burial, uplift and fluid flow history is known, the fractures can be placed in this historical context. Chaledony veins and possibly clastic dikes in the White River Group strata of Nebraska and South Dakota are examples (Maher & Shuster 2012). The chalcedony is locally derived from the diagenesis of these volcanic ash rich sediments, and their stratabound character and other traits indicate that syneresis was the loading trigger for their formation. Mineralization and/or associated alteration is not uncommon in the Great Plains rocks.

Fracture surface morphology (fractology has been used as the term of this type of analysis) may also help constrain the conditions of formation. Directions of propagation constrained by the axis of plumose structures may help give a fuller picture of the associated stress state. Engelder (2004) using fracture morphologies documented in ceramics as a guide, distinguishes between a tectonically driven fracture set and a later set driven by hydrocarbon formation. Savalli & Engelder (2005) based on surface features work out three stages in the propagation history of joints in Devonian strata of the Catskill Delta, from critical to subcritical growth.. Weinberger and Bahat (2008) the fracture morphologies of two joint sets in chalks to the stress state and the associated speed of propagation. Basically, fracture surfaces with less relief and simpler plumose structures are thought to propagate more quickly, and at higher differential stresses (often associated with a tectonic stress field), while rougher fracture surfaces with more complicated plumose structures with arrest marks are taken to be indicative of subcritical fracture growth driven by erosional unloading or other lower differential stress loading.

A related question is as to whether fracture development is event driven. An alternate model to distinct regionally coherent events could consist of localized fracture development over a protracted time span due to migrating conditions. The formation of fracture system can be expected to change the bulk rock body properties, both by introducing weakness planes, and by producing a fluid flow network path that can alter pore pressures. A process of local strain hardening by pore pressure reduction associated with develoment of fluid-flow, fracture pathways has been proposed for intraplate faulting by Towend and Zoback (2000).

This is very much a draft copy, a work in progress, and is incomplete and may have significant errors. Any feedback welcome. Please contact me for updates. The organization behind this classification is to consider loading paths that lead to failure, first general, and then more specific. For each loading path geologic events that may trigger such a loading path are then listed. Not included are 7 additional columns that attempt to describe traits in addition to orientation characteristics that characterize each loading path and trigger event combination.

loading path (general)	loading path (specific)	geologic event	explanation	relevant references	orientation characteristics
pore pressure related	aquathermal pressurization	geothermal heating	requires confinement, due to intrusion, thermal expansivity of water > that of rock, hydrothermal brecciation? Heart Mntn?	Engelder 1985; Mcpherson & Garven 1991;	not distinctive, reflective of setting
pore pressure related	aquathermal pressurization	overthrusting	due to disequilibirum heat flow,, limited significance (tectonic compaction likely more significant) but a contributing factor	Gretener, 1981	reflective of stress field producing overthrusting
pore pressure related	aquathermal pressurization	groundwater flow	requires special circumstances, advection in a permeable unit that slowly heats an adjacent confined unit by conduction	undocumented?	not distinctive, reflective of setting
pore pressure related	tectonic compaction	plate boundary forces	requires confined situation, due to basic incmpressibility of water, can be significant in plate interiors	Engelder 1985; Mcpherson & Garven 1991;	horizontal or vertical, tensile strike parallel to sigma one,
pore pressure related	tectonic compaction	diapirism	special circumstance, needs further evaluation of diapirism 'shouldering' vs. uplift , in concert w diapiric rock stress	Nikonau et al. 2012	radial or concentric
pore pressure related	tectonic compaction	localized deformation	reactivation of basement weakness could produce localized convergent contractions	Engelder 1985;	in symmetry with local deformation pattern
pore pressure related	chemical reactions	diagenesis	dehydration reactions can release water, may be significant in water rich clays, function of volume of hydrated mineral versus dehydrated plus water volume	Nadeau et al. 2005;	polygonal to organized by ambient stress field
pore pressure related	chemical reactions	thermal maturation	evidence that overpressures develop from oil/gas development, thermal window	Hansom & Lee (2005)	polygonal to organized by ambient stress field
pore pressure related	increase vertical load	burial and compaction	requires confinement, function of speed of burial, in concert with diagenesis promotes confinement, overpressurization common in seds	Hansom & Lee (2005); MacPherson and Garven 1999	not distinctive, reflective of setting
pore pressure related	increase vertical load	glaciation	glaciation both provides laod and seal, more of a theoretical possibility?	Grollimund & Zoback, 2000	related to glacial loading, in symmetry with forebulge if no other tectonic component
pore pressure related	increase vertical load	overthrusting	site specific (foreland fold-thrust belts), faults as seals versus conduits consideration		reflective of stress field producing overthrusting
confined volume change of solid	thermoelastic contraction	erosion	erosion is associated with cooling as a function of amount removed and time	Engelder 1985;	not distinctive, reflective of setting
confined volume change of solid	thermoelastic contraction	igneous cooling	the potential here is much greater because of greater temperature changes, tensile and not shear fractures	Bergbauer & Marcel 2002; Wright et al. (2011)	in symmetry with igneous body shape, tensile fractures perpendicular to cooling surface
confined volume change of solid	thermoelastic contraction	groundwater flow	very limited possibilities, cold water through hot rocks, in association w hydrothermal circulation assoc with intrusion margins.	Swenson et al. (1995)	determined by cooling geometry, polygonal, but overprint possible
confined volume change of solid	thermoelastic contraction	tectonic denudation	similar and likely in combo w erosion, focused in footwall of thin-skinned rift blocks	undocumented?	vertical tensile, oriented by rift stresses
confined volume change of solid	thermoelastic expansion	geothermal heating	function of T increase, very limited in potential, hardens system, could increase vertical veruss horizontal traction differeence	undocumented? Unlikely	determined by heating geometry, oriented by tectonic stresses
confined volume change of solid	thermoelastic expansion	diagenesis	very limited possibilities, since most diagenetic reactions involve volume loss, salt pans one possibility, shear fractures expected	undocumented?	polygonal to organized by ambient stress field, minimum of two orthogonal directions
confined volume change of solid	chemical contraction	diagenesis	swelling clay diagensesis, silica phase changes, gypsum to anyhydrite are soke possibilities of drivers, polygonal faulting best example	Cartwright and Dewhurst(1994), , Laubach et al. (2010), Maher & Shuster, 2012	polygonal to organized by ambient stress field, minimum of two orthogonal directions

confined volume change of solid	chemical contraction	thermal maturation	coal cleat formation, possibilities for oil shales, likely in concert with pore pressure effects	Laubach et al. 2006; Engelder and Whitaker 2006	polygonal to organized by ambient stress field, minimum of two orthogonal directions
increased differential stress	change horizontal load	plate boundary forces	likely common, distributed likely in concert pore pressure increase	many, Koehn et al. (2005), Engelder & Whitaker (2006)	reflective of tectonic stress field
increased differential stress	change horizontal load	diapirism	complex possibilities, bending & extension of strata overhead, versus lateral shouldering	Marcos (2002)	radial or concentric, or related to diapir geometry
increased differential stress	change horizontal load	differential compaction	production of bending and extensional fractures	Jachens & Holzer (1982)	radial or concentric, or related to geometry of underlying less compactable feature
increased differential stress	change horizontal load	karst &/or evaporite dissolution	collapse related bending stresses, significant local reorientation of principal stress axes	Goldstein and Collins (1984)	radial or concentric or related to collapse geometry
increased differential stress	change horizontal load	localized deformation	complex possibilities, e.g. fracturing associated with folding or tri shear zones, significant reorientation of principal stress axes		aligned with reactivated feature, dominant set parallel
increased differential stress	change horizontal load	glaciation & deglaciation	development of bending stresses due to isostatic lithospheric flexure	Clark (1982), Grollimund (2000)	aligned with flexure axis
increased differential stress	increase vertical load	burial and compaction	very special circumstances hence rare,crushing, favored by low Poisson's ratio, dry conditions, low strength	undocumented?	not distinctive, reflective of setting
increased differential stress	increase vertical load	overthrusting	very special circumstances hence rare,crushing, favored by low Poisson's ratio, dry conditions, low strength	undocumented?	oriented by tectonic stresses
increased differential stress	increase vertical load	erosional relief	In the case of ciffs and steep slopes the vertical load increases while the horizontal does not, increasing the differential stress.	Molnar (2004), Martel (2011)	aligned with cliff
increased differential stress	increase vertical load	impact	complex, but distinctive (e.g. shatter cones), very transient		radial or concentric,
increased differential stress	Poisson's contraction (unloading)	deglaciation	limited in extent by ice density and thickness, can be quick.	Clark (1982)	aligned with glacial loading & forebulge
increased differential stress	Poisson's contraction (unloading)	erosion	significant, a standard component for unloading joints, in concert with thermo-elastic rock cooling	Engelder, 1985	not distinctive, reflective of setting
increased differential stress	Poisson's contraction (unloading)	tectonic denudation	theoretical possibility, relatively unexplored? Potentially significant magnitude	undocumented?	aligned with rift direction
increased differential stress	Changing Poisson's ratio	diagenesis	favored by decrease in Poisson's ratio which increases vertical versus horizontal deviatioric, Poisson's ratio general increases with diagenesis (?) so limited possibilities	unexplored?	not distinctive, reflective of setting
increased differential stress	Changing Poisson's ratio	groundwater flow	water generally increases Poisson's ratio, so drop in groundwater table?	unexplored?	not distinctive, reflective of setting
strain weakening	shifting Mohr failure envelope	deformation	strain weakening		inherited from initial deformation producing strain weakening

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