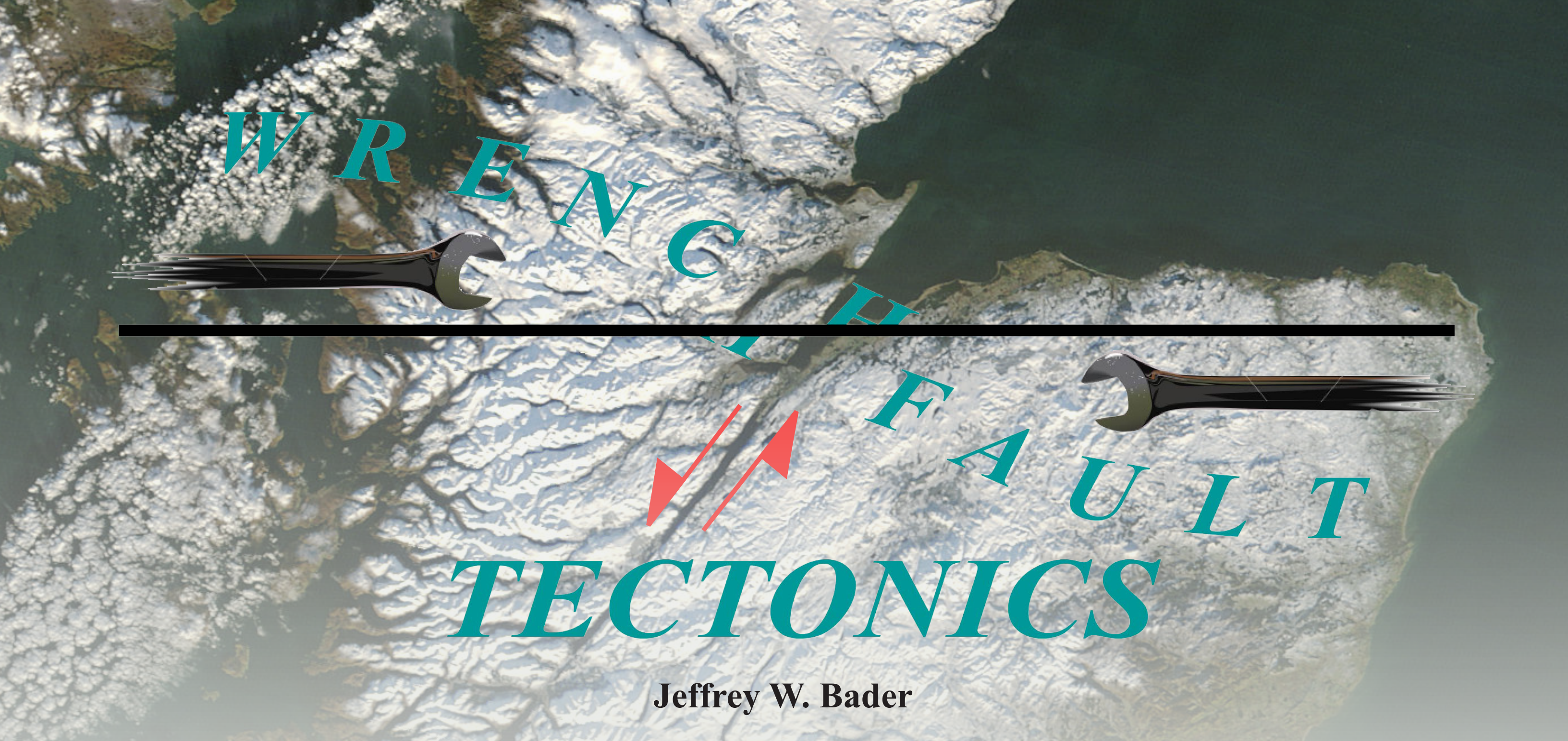

WRENCH FAULT TECTONICS

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Introduction

A fault is defined as a surface where one set of rock has slid past another (Fig. 1). Major faults within the crust of Earth are the result of plate tectonic forces, with the largest generally at, or near, plate boundaries (e.g., San Andreas fault). The fault "plane" represents the actual fracture surface between the rock masses. Because larger faults generally do not consist of a single clean fracture, the term "fault zone" is often used for the area of deformation associated with the main fault. Friction, rigidity, and irregularities of the rock units often prevent smooth, gradual movement along the fault plane and at times there is no movement whatsoever, causing increased stress that eventually must be released. Therefore, fault development is episodic, and slip occurs when stress, built up along the "stuck" portion(s) of the fault or fault zone, is alleviated. Released energy from active fault rupture may cause earthquakes, most of which are too small to feel. However, many faults within the crust are not active and may not have been active for millions or even billions of years, such as in the continental interior of North Dakota. These faults are generally "rooted" in older igneous and metamorphic rocks (basement) that underlie sedimentary rocks. The larger of these may be very old plate boundaries or sutures that have been amalgamated and reactivated as intracratonic fault zones within tectonic plates that have grown through geologic time.

Once rock is stressed, associated strain (deformation) will occur. Strain may occur either cumulatively or instantaneously, depending on the ability of the rock to flow. The lower crust and mantle of Earth are more ductile (plastic) and will accumulate strain more gradually and generally deform by shearing, unless stresses are significant; whereas, the brittle middle- to upper-crust will deform through instantaneous fracture. This instant stress release results in motion along a fault defined as "slip" (Fig. 1). The sense of slip is defined by the relative movement of geologic markers (piercing point) on either side of the fault plane, and/or by actual "scratches"

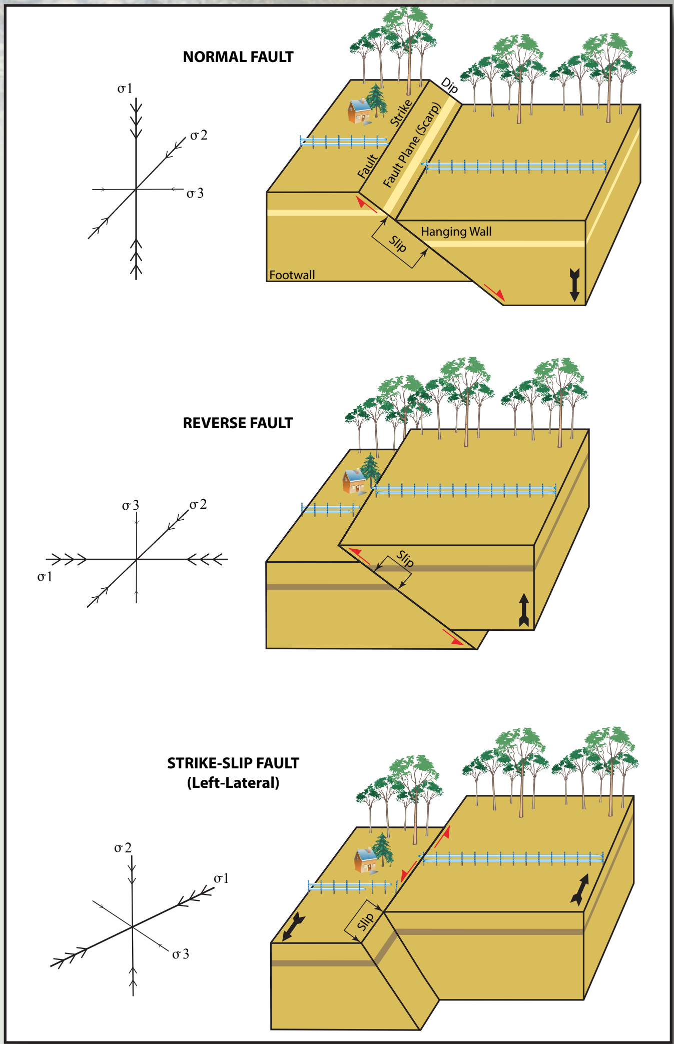


Figure 1. Block diagrams of dip-slip and strike-slip faults. σ = sigma.

(slickenlines) gouged on the fault plane during fault movement. The two sides of a non-vertical fault plane are referred to as the hanging wall (above) and footwall (below).

Faults are commonly mapped both at the surface (geologic maps) and in the subsurface (geologic cross-sections). They are mapped and categorized based on the actual direction of slip as shown on Figure 1. These are: 1) dip-slip faults (normal and reverse) where movement is parallel to the dip of the fault plane; 2) strike-slip faults where movement is parallel to the strike of the fault; and 3) oblique-slip faults where movement includes components of both dip- and strike-slip.

Types of Faults

When rocks are deformed, we may define the stress directions; one is vertical (perpendicular to the surface of Earth) and the other two are horizontal (parallel to the surface of Earth), creating a stress ellipsoid (Fig. 1). The long axis of the ellipsoid defines the maximum stress and the short axes represent the minimum stress, with an intermediate stress between the two end-points. Faults may be further classified based on the stress ellipsoid as shown on Figure 1.

Normal Faults

For a normal fault, sigma 1 ($\sigma 1$), or the maximum stress, is vertical and the minimum stress ($\sigma 3$) is in the horizontal plane (Fig. 1). This results in the hanging wall moving down relative to the footwall. Normal faults are the result of tensional stresses in the crust.

Reverse Faults

For a reverse fault, $\sigma 1$ (maximum stress) is horizontal and $\sigma 3$ (minimum stress) is in the vertical plane (Fig. 1). This results in the hanging wall moving up relative to the footwall. Reverse faults are the result of horizontal stresses in the crust.

Strike-slip Faults

For strike-slip faults, the fault plane is very steep or vertical. Maximum and minimum stresses ($\sigma 1$ and $\sigma 3$) are both in the horizontal plane (Figs. 1 and 2). This results in the hanging wall moving laterally (shearing stresses), relative to the footwall. Strike-slip faults may thus be explained in terms of "shear" with end-members being pure shear (non-rotational) and simple shear (rotational) (Figs. 2A and 2B). Wrench faults or transcurrent faults are a type of strike-slip fault, as are tear faults and transform faults (plate boundary where strike-slip faults connect offset spreading

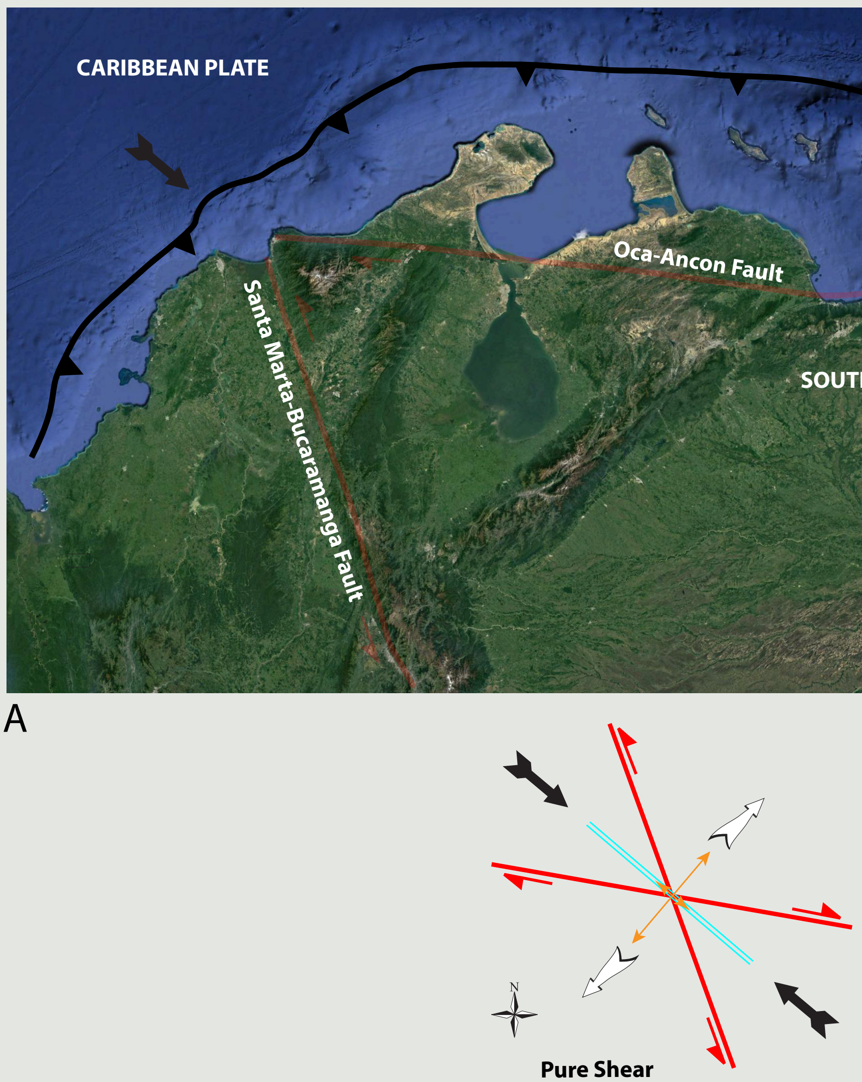
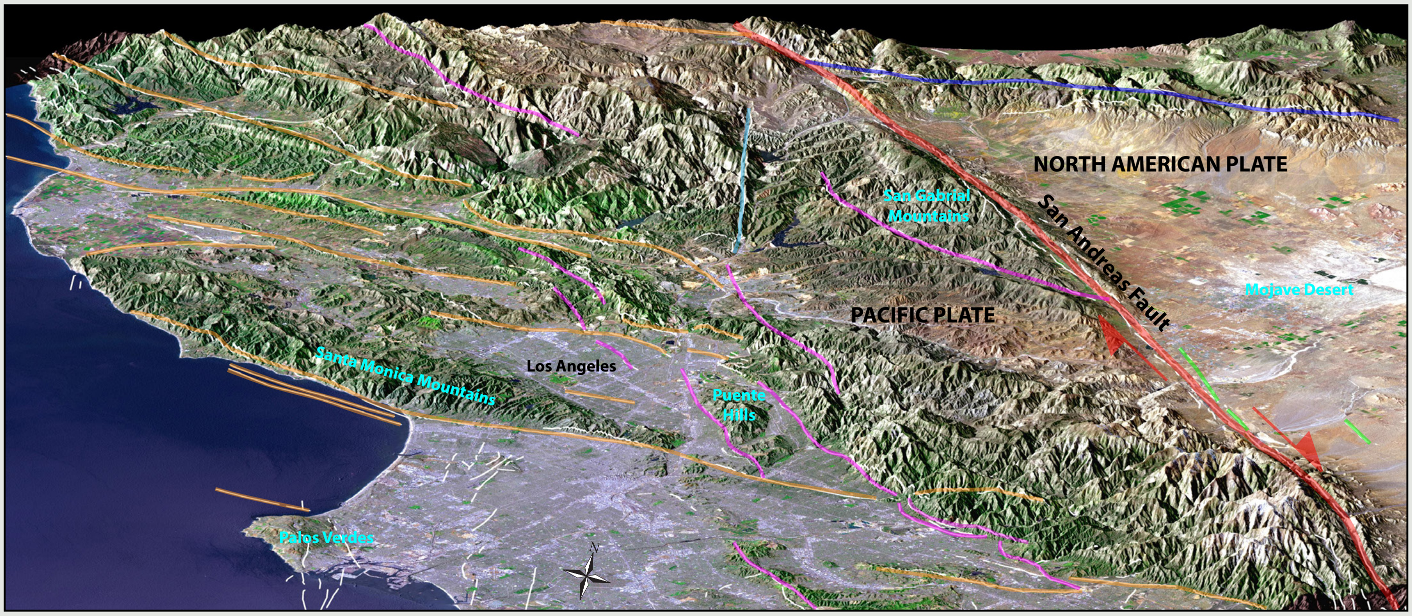


Figure 2. Geometry of structures formed during pure shear (A) at an active convergent plate boundary (northern Andes, South America) and simple shear (B) at an active transform plate boundary (San Andreas Fault, California). Modified from Sylvester, 1988.



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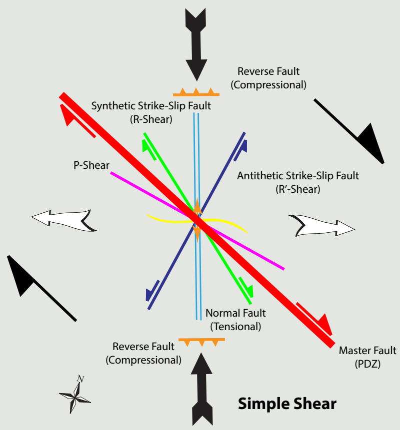

centers at divergent plate boundaries). They may be either left-lateral (sinistral) or right-lateral (dextral) in sense of displacement (Fig. 1). Some faults may be both a transform and wrench fault, such as the San Andreas Fault of California (Fig. 2B).

Wrench faults, by definition, have the following attributes:

- Lateral-slip evidence (often not easily discerned);
- Involve basement rocks (thick-skinned) on a regional/continental scale (versus tear faults which are thin-skinned/sedimentary cover faults of limited extent);
- Vertical or very steep fault plane;
- Associated with complex, but predictable, rectilinear deformation zones of subsidiary faults and en échelon folds, especially in the sedimentary cover above the basement-rooted wrench fault.

Wrench faults may initially form in basement rocks as conjugate pairs during pure shear (Fig. 2A). These types of compressional faults are developed at convergent (collisional) plate boundaries and are presently forming in China as a result of collision between the Asian and Indian Plates along the Himalayan mountain front. Conjugate shears can also form at convergent plate boundaries (subduction zones), as observed along the northern coast of South America (Fig. 2A), where compression related to SE-directed subduction of the Caribbean Plate beneath the South American Plate has fractured the craton along two major strike-slip fault zones. However, development and more importantly, evolution of conjugate shears, can best be explained using a simple shear model (Fig. 2B), because, by definition, wrench faults are older structures rooted in basement rocks that are commonly buried by younger sedimentary cover and reactivated as simple shears throughout geologic time. It is the reactivation process that makes wrench faults very important in the development of sedimentary basins and petroleum accumulation, where the term "wrench" fault became popular (Moody and Hill, 1956; Wilcox et al., 1973). This was especially so in southern California in the mid-1900s. In the cores of continents, these faults are billions of years old and are generally inactive today. However, wrench faults at the edges of present-day plate boundaries may be much younger (millions of years old), exposed at the surface, and currently active (e.g., San Andreas Fault; Fig. 2B).

Figure 3A shows sinistral simple-shear deformation of a circle into an ellipse. The strain ellipse for this type of simple shear is shown as Figure 3B for comparison. The strain ellipse may be used to identify subsidiary structures based on the predictable pattern of deformation observed in wrench fault zones. Subsidiary structures that can form in the sedimentary cover above a basement-rooted wrench fault therefore include en échelon folds, en échelon Riedel shears (R shear-synthetic and R' shear-antithetic), P-shears, en échelon normal faults, and as wrenching proceeds, the master wrench fault or wrench-fault zone that may break through the sedimentary cover to the surface (Figs. 2B and 3B). Figure 4 shows a simple basement-rooted sinistral wrench fault and development of en échelon synthetic strike-slip faults (R shears) in the sedimentary cover along with corresponding strain ellipse, for comparison.

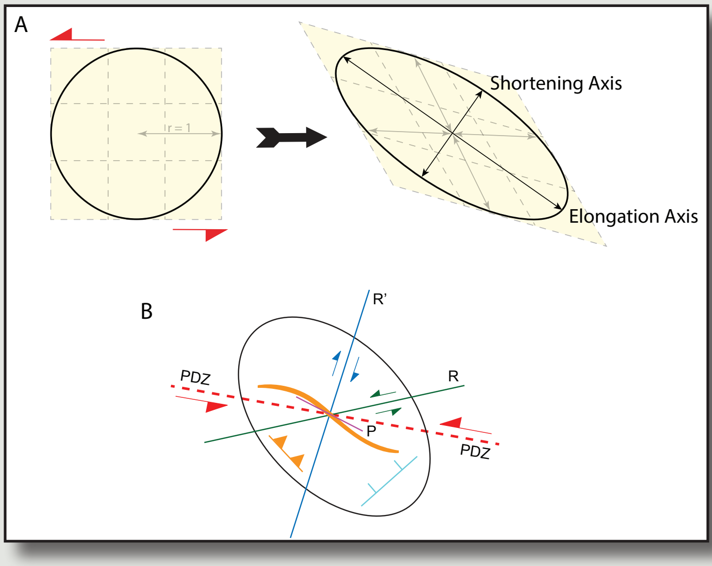

Figure 3. (A) Homogeneous, left-lateral (sinistral) deformation of a circle into an ellipse. (B) Strain ellipse for a sinistral simple shear showing: 1) bearing of hypothetical buried, basement-rooted master fault (dashed red line); and 2) bearing and type of potential subsidiary structures (faults and folds) expected to form in the sedimentary cover above the basement-rooted master fault. **PDZ**–Principal displacement zone, **P–P**-shear, **R–**Synthetic Riedel shear, **R'**–Antithetic Riedel shear, **Sawteeth**–Thrust/reverse fault, **Barbs**–Normal fault, **Curvilinear Trace**–Fold.

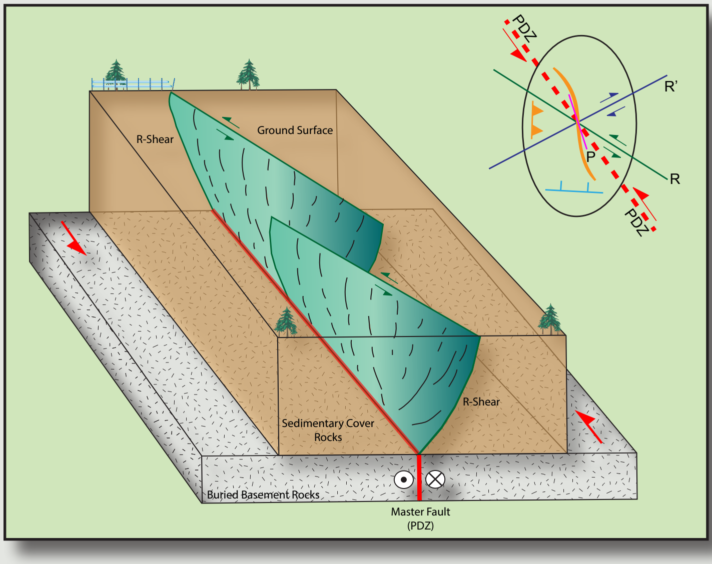

Figure 4. Block diagram of basement-rooted sinistral wrench fault and strain ellipse for comparison showing development of curvilinear and propeller-shaped R-shears in the sedimentary cover. See Figure 3 for abbreviations and strain ellipse designations.

Identifying Wrench Faults

Lateral slip on wrench faults is very difficult to discern and faults are generally buried beneath thousands of feet of sedimentary cover, precluding examination of the fault plane for kinematic (slip) indicators. Seismic data may not reveal these faults in the subsurface because stratigraphic markers may show little offset after fault movement. Therefore, other means are necessary to help identify, and at least semi-quantify wrench-fault deformation.

Surface/Aeromagnetic/Gravity Mapping

Wrench faults are more easily identified if exposed at the surface where the fault plane and deformed rocks may indicate lateral movement, such as along the San Andreas Fault zone. In the subsurface, aeromagnetic (Sims et al., 2004) and gravity maps (Fig. 5) may be used to identify sharp discontinuities in basement rocks that may be faults, and if seismic data is available, these discontinuities may be examined in cross-section. However, all of these data are rarely available, and even if so, evidence of lateral movement is generally not discernable, even at the surface. Therefore, for basement-rooted wrench faults, deformation of the sedimentary cover provides important information that may be used to identify wrench fault zones.

Deformation of Sedimentary Cover: An Example of a Buried Wrench Fault

The Cat Creek fault zone of east-central Montana is an excellent example of a buried Precambrian (billions of years old) wrench fault that was reactivated during the Laramide orogeny (~70-40 million years ago). Movement on this fault in the Laramide deformed several thousand feet of sedimentary cover rocks, some of which are now exposed at the surface (Nelson, 1993).

The fault zone is characterized at the surface by a set of well-developed en échelon normal faults that are present across a rectilinear deformation zone of approximately 200 km (125 mi). Along this trend, several curvilinear (reverse-S shape) anticlines are oriented northwest to southeast across and lateral to the fault zone (Dobbin and Erdmann, 1955; Vuke et al., 2007). These features are very indicative of sinistral movement on a basement-rooted wrench fault based on comparison with the strain ellipse for a sinistral system. Several other rectilinear fault zones are also present across eastern Montana and combined, these deformation zones collectively define the Central Montana uplift (Bader, 2019a).

Importance of Wrench Faults

The Cat Creek fault was reactivated as a left-lateral oblique-slip fault during the Laramide orogeny (Nelson, 1993; Bader, 2019a). Oil production is from structural traps found in northwest-trending en échelon domes/anticlines created from interpreted

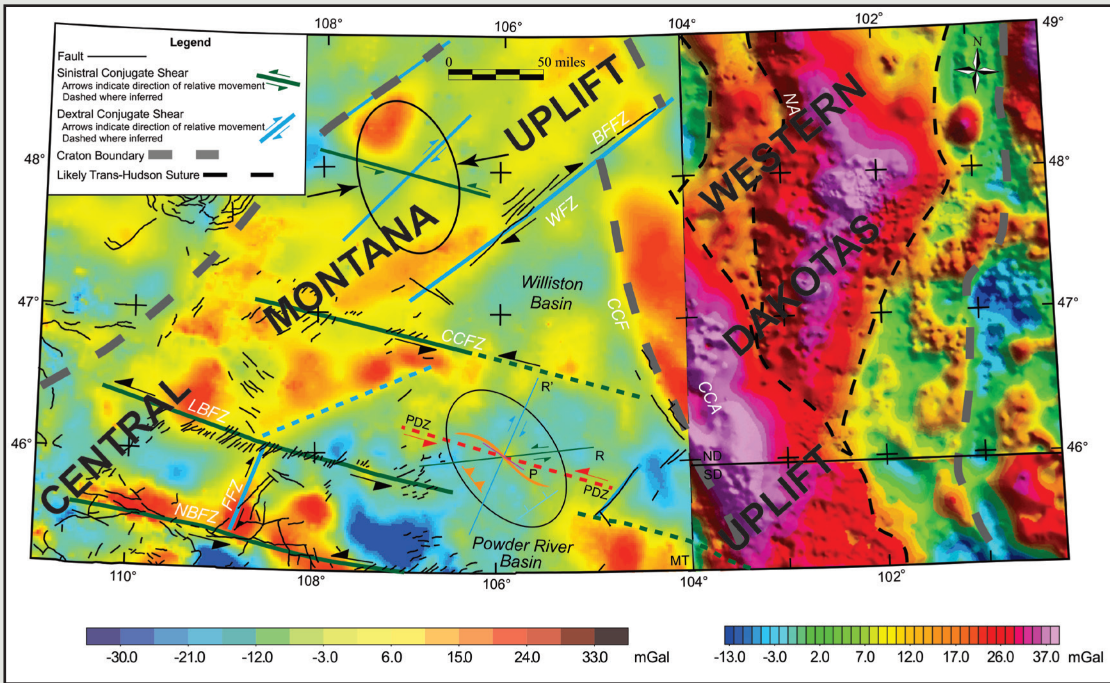

Figure 5. Isostatic residual gravity map of eastern Montana and western North and South Dakota (USGS, 2019) superimposed with pure-shear interpretation for development of conjugate pairs in Precambrian basement rocks of the northeast Wyoming Province. **BFFZ**–Brockton-Froid fault zone, **CCA**–Cedar Creek anticline, **CCF**–Cedar Creek fault, **CCFZ**–Cat Creek fault zone, **FFZ**–Fromberg fault zone, **LBFZ**–Lake Basin fault zone, **MT**–Montana, **NA**–Nesson anticline, **NBFZ**–Nye-Bowler fault zone, **WFZ**–Weldon fault zone. Modified from Bader (2019a).

Laramide left-lateral slip along the Cat Creek fault. Oil fields along the San Andreas Fault are related to right-lateral motion that has also formed traps for petroleum accumulation. Therefore, wrench faults have been, and will be, important for the oil and gas industry.

So, could wrench faults be present in the Williston Basin of North Dakota? Bader (2019b) has shown that several north-south (N-S) zones of potential basement weakness in the form of Precambrian sutures and faults are likely present across western North Dakota. Bader (2018) also has shown that petroleum accumulations in the Devonian Birdbear Formation may be related to development of en échelon folds of a N-S-trending wrench fault in western North Dakota. This suggests that N-S zones of potential basement weakness in western North Dakota may have been reactivated as wrench faults during the Laramide orogeny and/or older Phanerozoic deformational events, forming similar structural traps as observed in eastern Montana. Unfortunately, these structures may be more difficult to discern at the surface because nearly two-thirds of North Dakota is covered by geologically recent glacial deposits, and Paleogene and older sedimentary rocks of the southwestern portion of the state may not have been affected as significantly by Phanerozoic tectonism. Deformation may also be difficult to recognize in outcrop for the “softer” Cretaceous and Paleogene units of western North Dakota as they are likely weathered and/or poorly exposed. Nonetheless, discovery of wrench faults at depth may potentially lead to significant hydrocarbon accumulations in areas where zones of basement weakness can be identified in the Williston Basin of North Dakota.

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