Fracture and fault patterns associated with basement-cored anticlines: The example of Teapot Dome, Wyoming

Scott P. Cooper, Laurel B. Goodwin, and John C. Lorenz

ABSTRACT

Teapot Dome is an asymmetric, doubly plunging, basement-cored, Laramide-age anticline. Most of the fractures, deformation bands, and faults at Teapot Dome are interpreted to have formed during contemporaneous longitudinal and transverse stretching of the sedimentary cover over a basement-involved thrust. Strain was accommodated by fractures, deformation bands, and normal and normal-oblique faults that strike both parallel and perpendicular to the fold hinge. The fracture and fault patterns at Teapot Dome are distinctly different from those formed within anticlines associated with thin-skinned thrust systems. The inferred fracture-influenced permeability anisotropy of thick-skinned systems is therefore distinct from that of thin-skinned systems. We propose that Teapot Dome is a good analog for similar basement-involved, thrust-generated anticlines.

INTRODUCTION

Basement-cored anticlines across the Rocky Mountain region have been hydrocarbon-exploration targets since the turn of the last century. Structures of this type are also found in many other areas of the world (e.g., DeSitter, 1964; Harding and Lowell, 1979). Examination of natural fracture and fault patterns in outcrops of the Mesaverde Formation at Teapot Dome, Wyoming, was undertaken to develop a better understanding of the influence of lithology and structural position on the development of these features. This study also provides insight into controls on deformation of a heterogeneous sequence of clastic sedimentary rocks in a basement-cored anticline. We show that these features have predictable

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orientations with regard to large-scale structures. Specifically, vertical extension fractures, shear fractures, deformation bands, and normal and normal-oblique faults are parallel or perpendicular to the fold hinge. Similarities exist between the patterns observed at Teapot Dome and those described or postulated by DeSitter (1956), Murray (1967), Simon et al. (1988), Garrett and Lorenz (1990), Engelder et al. (1997), Unruh and Twiss (1998) and Hennings et al. (1998, 2000). The orientations of two primary fracture sets predicted by one of the most widely used conceptual models in the petroleum industry (i.e., Stearns and Friedman, 1972) are significantly different from those observed at Teapot Dome. These differences highlight the importance of using a conceptual model analogous (i.e., with mechanically similar stratigraphic units and which formed under a similar tectonic regime) to a specific petroleum reservoir for analysis and prediction of fracture-influenced permeability anisotropy.

GEOLOGIC REVIEW: TEAPOT DOME

Teapot Dome is located in central Wyoming, near the southwestern edge of the Powder River Basin (Figure 1). It was established as a Naval Petroleum Reserve (NPR 3) by President Wilson in 1915 (Curry, 1977; Doll et al., 1995), with production initiated in October 1922 (Trexel, 1930). Teapot Dome is one of several structural hydrocarbon traps along the western margin of the Powder River Basin. It is part of a larger Laramide structural complex, comprising three or more north-south–trending anticlines in addition to Teapot Dome (Doelger et al., 1993; Gay, 1999).

A basement-involved thrust that terminates upward within the sedimentary section of this doubly plunging anticline is evident in three-dimensional (3-D) seismic data (Figure 2) (J. LeBeau, 1996, personal communication; Cooper et al., 2003). Normal and normal-oblique faults that strike predominantly perpendicular to the curvilinear fold hinge are common along the eastern limb (Olsen et al., 1993; Doll et al., 1995). Mesaverde Formation sandstones and shales are exposed along the western, eastern, and southern limbs of the anticline (Figure 1). Maximum dips along the western limb are near 30°, whereas dips along the eastern limb range from 7 to 14°.

Stratigraphy

The Mesaverde Formation has been subdivided into members at Teapot Dome. The Teapot Sandstone Member overlies the Parkman Sandstone Member with an intervening layer of marine shale (Wegemann, 1918; Thom and Spieker, 1931). This relationship suggests sea regression during the deposition of the Parkman Sandstone Member, followed by a brief transgression, and then regression during the deposition of the Teapot Sandstone Member (Weimer, 1960; Zapp and Cobban, 1962; Gill and Cobban, 1966). An unconformity at the base of the Teapot Sandstone Member represents

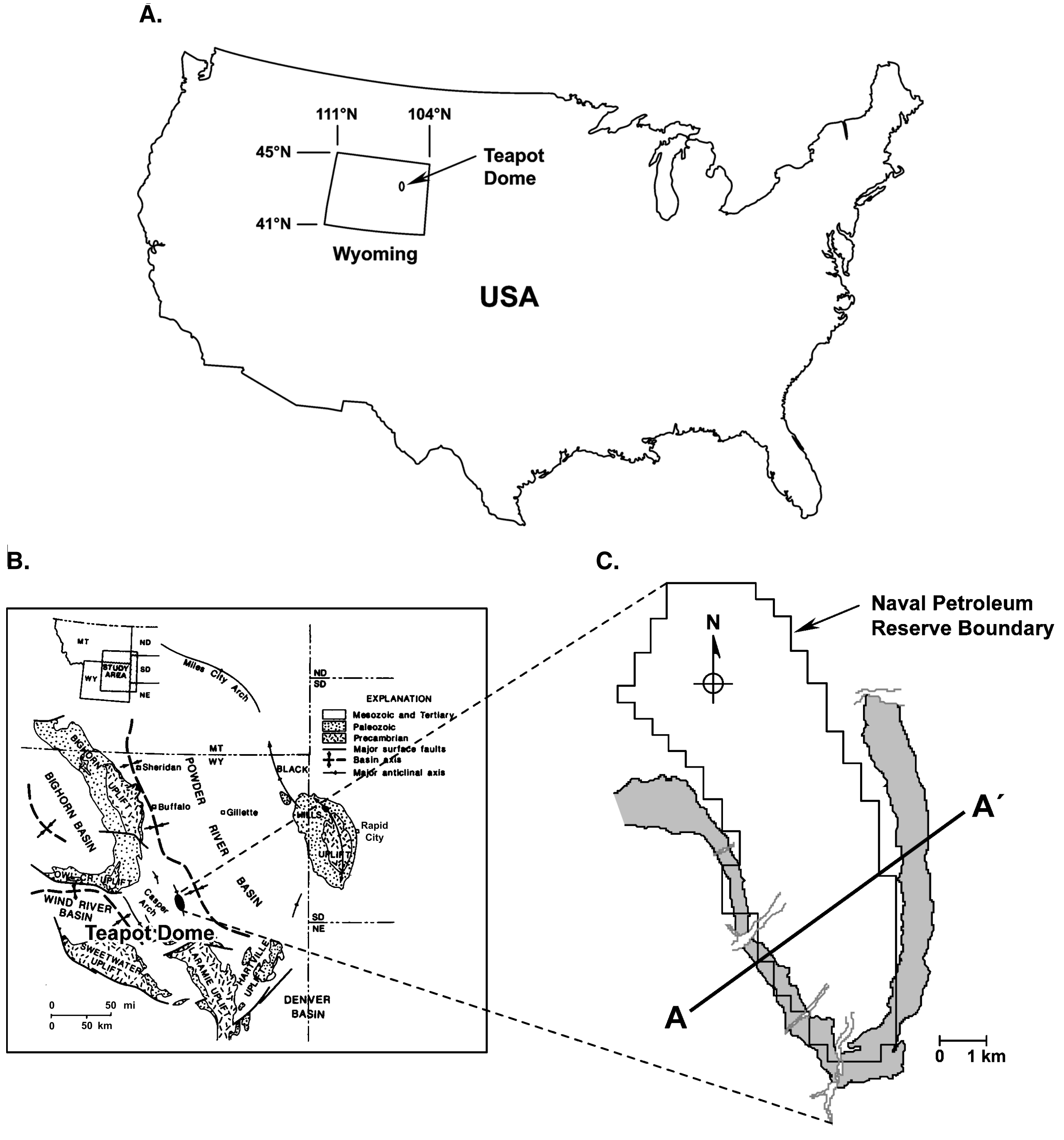


Figure 1. (A) Location of Teapot Dome. (B) Map view of Teapot Dome relative to the Powder River Basin and surrounding Laramide uplifts (modified from Fox et al., 1991). (C) Map view of Teapot Dome illustrating Mesaverde Formation outcrops and location of seismic profile AA′ shown in Figure 2 (modified from Cooper et al., 2003). See Figures 7 and 8 for latitude and longitude.

probable subaerial exposure and erosion associated with relative sea level change driven by regional tectonism (Gill and Cobban, 1966; Weimer, 1984; Merewether, 1990; Martinsen et al., 1993). Fractures in the Parkman Sandstone Member are the principal focus of this study.

Previous Work

A major set of faults and fractures striking perpendicular to the hinge of the anticline and a secondary set parallel to the fold hinge were described and attributed to extension across the fold by Thom and

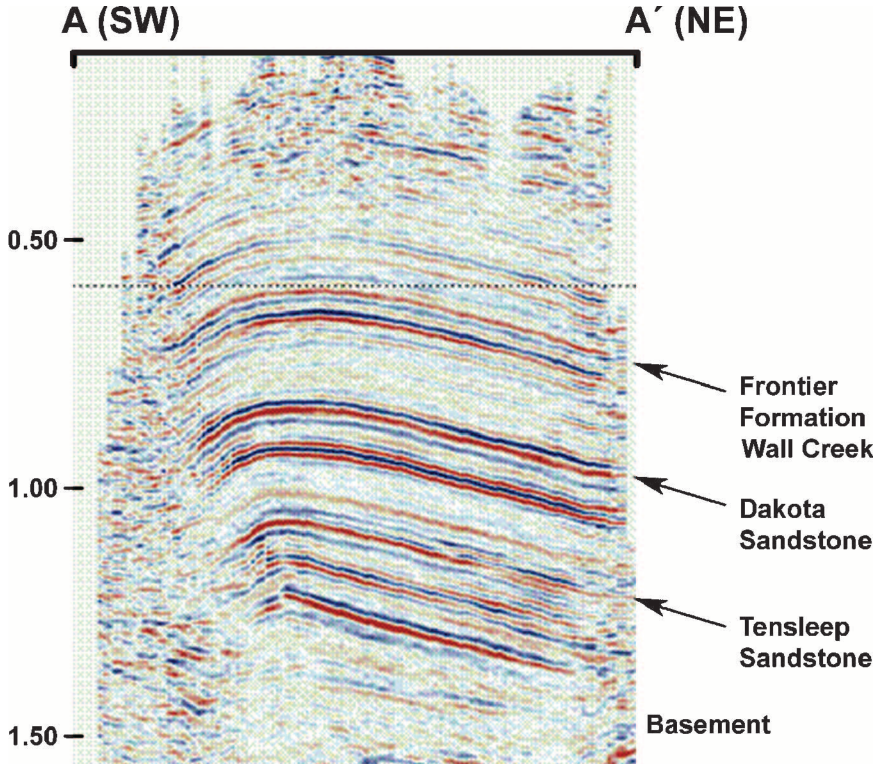


Figure 2. Seismic cross section through Teapot Dome, two-way traveltime in seconds (see Figure 1 for location and Figure 4 for surface to basement stratigraphic section). The west-vergent, basement-cored thrust tips out within the lower Paleozoic section; the basement sedimentary contact is a relatively poor reflector (B. Hart, 2005, personal communication; M. Milliken, 2005, personal communication; U.S. Department of Energy seismic data).

Spieker (1931). Doll et al. (1995) inferred three primary fracture directions in the subsurface from steam flood response data: (1) perpendicular to the fold hinge, (2) N65°W, and (3) parallel to the hinge. Using surface hydrocarbon, E_h, pH, soil electrical conductivity, iodine, and bacteria data, Fausnaugh and LeBeau (1997) observed permeability trends inferred to be controlled by northeast-striking fractures and faults.

REVIEW OF FRACTURE-FOLD RELATIONSHIPS

Numerous authors have described preferred fracture orientations in other folds associated with both thin-skinned and thick-skinned, basement-cored thrusts. Fracture orientations differ with fold type, as indicated below, but are notably similar in each category.

Fractures in Folds Associated with Thin-Skinned Thrusts

Stearns and Friedman (1972) proposed a conceptual model of fracture-fold relationships based on five fracture sets associated with the Teton anticlines in northwestern Montana (Stearns, 1964, 1967; Friedman and Stearns, 1971; Sinclair, 1980). The Teton anticlines are part of a thrust sheet confined within the sedimentary section. The larger, westernmost anticline is hereafter referred to as the Teton anticline. The two fracture sets determined to be sufficiently common for incorporation into their generalized fracture model include both extension and conjugate shear fractures (Figure 3). Stearns and Friedman (1972) suggested that these fracture sets resulted from folding because of their consistent orientations with respect to bedding and the anticlinal structure. They proposed that the fractures accommodated bedding-parallel shortening across the fold. A third set of fractures was interpreted as accommodating extension because of bending and extension of the formations across the anticline (Stearns, 1964).

Cooper (1992) used core analysis along with wellbore image and sonic logs to analyze subsurface fractures associated with both a fault-bend fold and a fault-propagation fold in the foothills of the Canadian Rocky Mountains. The extension and conjugate shear fractures described by Cooper correspond to the two dominant fracture sets of Stearns and Friedman (1972).

Berry et al. (1996) also record extension fractures similar to those described by Stearns and Friedman (1972) at the Palm Valley anticline in the Amadeus

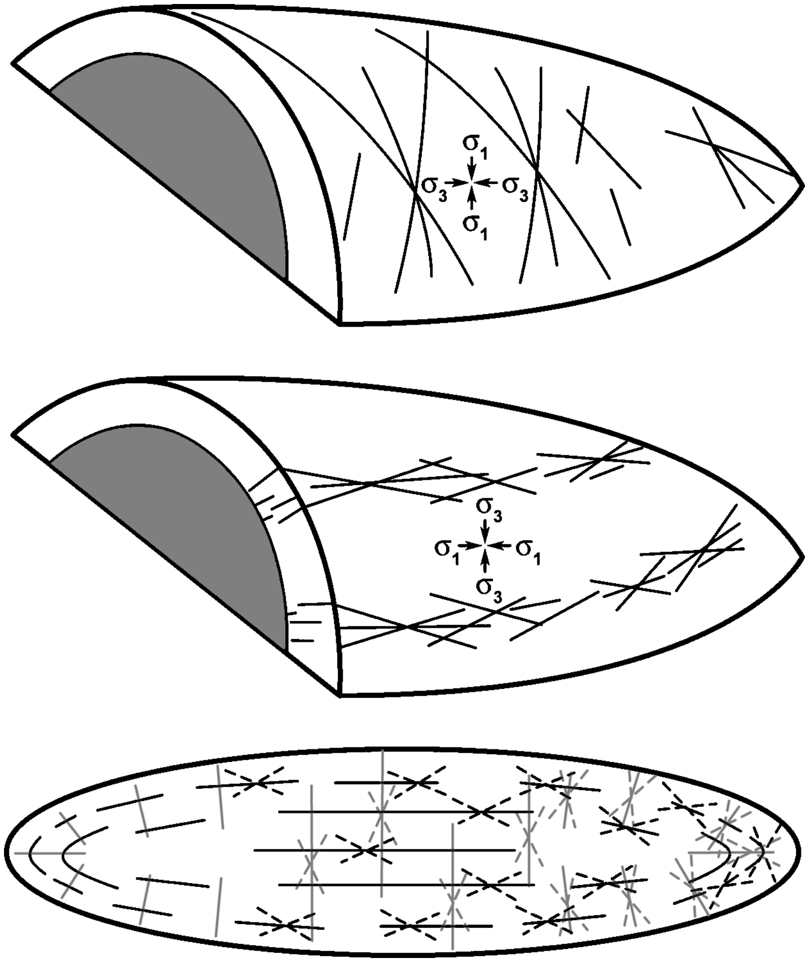


Figure 3. Stearns and Friedman (1972) model of primary fracture sets associated with folding. In both sets, the intermediate principal stress (σ_2) is inferred to be normal to bedding, and the maximum (σ_1) and minimum (σ_3) principal stresses are inferred to lie within the bedding plane. The inferred directions of maximum and minimum principal stresses are different for each fracture set. The lower diagram is a plan view of the fracture sets with conjugate shear fractures shown as dashed lines and extension fractures as solid lines. The two fracture sets are delineated by shading in the lower diagram, with upper-diagram fractures colored gray and middle-diagram fractures colored black. Conjugate fractures are not shown on the left side of the plan-view diagram to emphasize orientation in the extension fractures. The two fracture sets are reprinted from Stearns and Friedman (1972) with permission from AAPG.

Basin of central Australia. Their fold-related fracture-trajectory map shows extension fracture sets that vary in orientation with respect to the fold. These fractures correspond to the fracture sets described by Stearns and Friedman (1972) (Figure 3).

Fractures in Folds Associated with Strata Overlying Deep-Seated Thrusts

DeSitter (1956) documented normal faults parallel to fold hinges in several anticlines (Kettleman Hills, California; Quitman oil field, Texas; Sand Draw oil field, Wyoming; La Paz oil field, Maracaibo district, Venezuela) and attributed them to tension in the upper arc or crest of a doubly plunging anticline. Normal faults roughly perpendicular to the fold hinges at the same locations were attributed to tension resulting from 3-D closure (DeSitter, 1956). Engelder et al. (1997) documented similar faults at Elk Basin anticline in the Bighorn Basin of Wyoming. This basement-cored, doubly plunging, breached anticline has dips in excess of 30° on the forelimb and up to 23° on the backlimb. The anticline strikes roughly north-northwest and is cut by several normal-oblique, northeast-striking, hinge-perpendicular faults. Fractures strike roughly parallel to the hinge throughout the fold. Fractures striking roughly perpendicular to the fold hinge are composed of two basic types: (1) those with trace lengths extending several meters and (2) those that terminate at intersections with hinge-parallel fractures.

Three joint sets have been described within Frontier Formation sandstones at Oil Mountain, approximately 30 mi (48 km) west of Casper, Wyoming (Hennings et al., 1998, 2000). Oil Mountain is a northwest-striking, doubly plunging, breached anticline. It is unique in this category because it is interpreted to have thrust faults in the Mesozoic section that are related to deeper basement thrusts. A fracture set parallel to the fold hinge at Oil Mountain is interpreted as a preexisting regional set due to its presence in Frontier Formation pavements away from the fold. A northeast-striking set, roughly perpendicular to the northwest-striking set, is attributed to the folding process. The third set is north-northwest to north-northeast striking and is oblique to the fold hinge and the other two fracture sets.

The consensus of these studies is that fracture and fault sets oriented parallel and perpendicular to the fold hinge are typical. Our work supports these observations and, more specifically, details the contemporaneous nature of thrusting, folding, and fracture formation in beds overlying a deep-seated thrust.

CONTROLS ON FAULT AND FRACTURE DISTRIBUTION AND ORIENTATION: TEAPOT DOME

Lithology

We have divided the Parkman Sandstone Member of the Mesaverde Formation into five units on the basis of lithology, depositional environment, and mechanical properties (Figure 4). From oldest to youngest, these are shallow-marine, interbedded sandstones and shales (unit 1), shoreface and beach sandstone (unit 2),

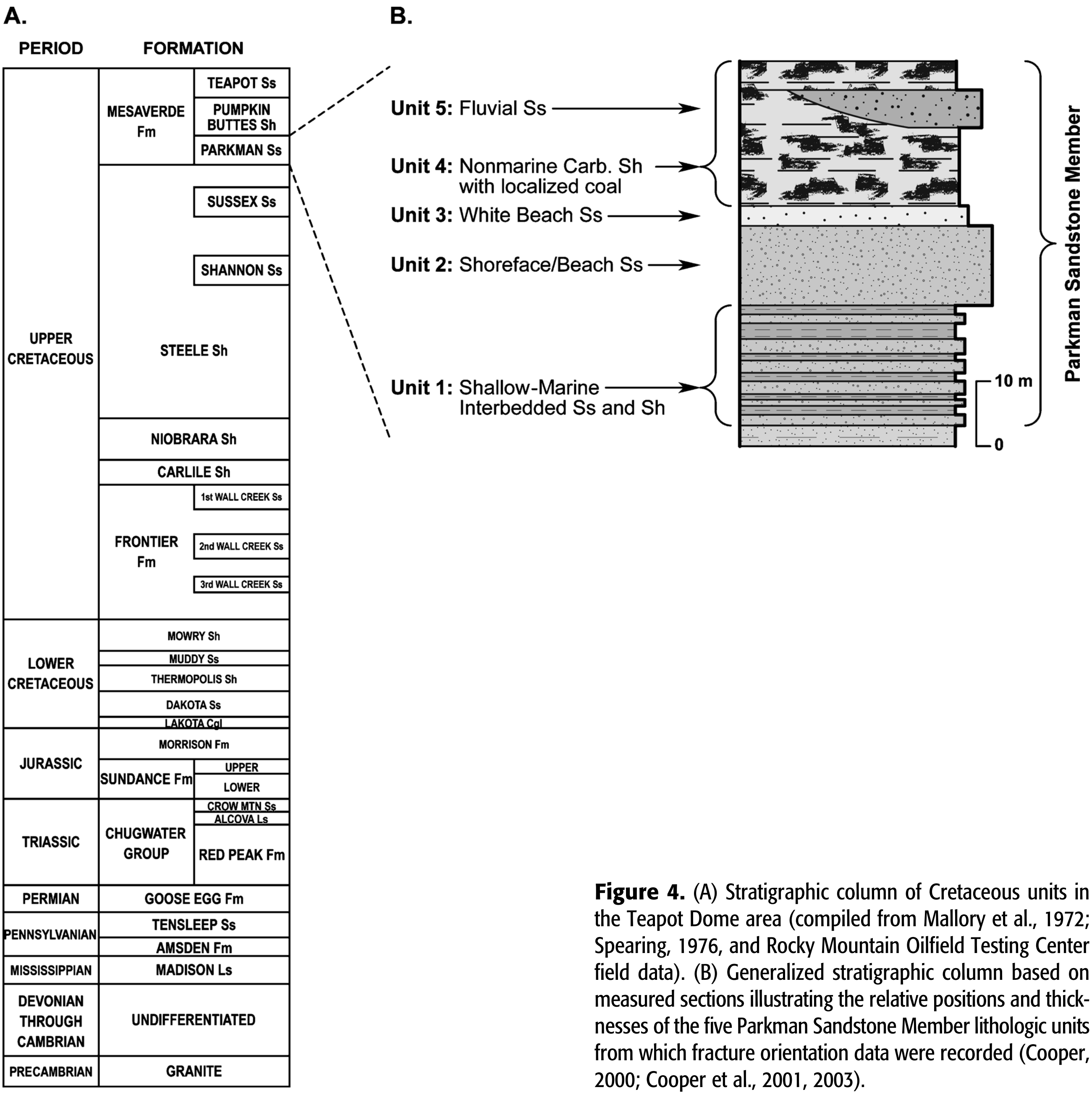


Figure 4. (A) Stratigraphic column of Cretaceous units in the Teapot Dome area (compiled from Mallory et al., 1972; Spearing, 1976, and Rocky Mountain Oilfield Testing Center field data). (B) Generalized stratigraphic column based on measured sections illustrating the relative positions and thicknesses of the five Parkman Sandstone Member lithologic units from which fracture orientation data were recorded (Cooper, 2000; Cooper et al., 2001, 2003).

white beach sandstone (unit 3), nonmarine carbonaceous shale (unit 4), and lenticular fluvial sandstones in the carbonaceous shale unit (unit 5). Key observations and justifications for interpretations of depositional environments in this progradational sequence are summarized by Cooper (2000) and Cooper et al. (2001).

Unit 1 consists of interbedded shales and very fine-grained, shallow-marine sandstones and ranges in thickness from 10 to 20 m (33 to 66 ft), with individual bed thicknesses from 2 to 150 cm (0.8 to 59 in.).

The fine-grained shoreface sandstone unit (unit 2) has an average thickness of 15–20 m (49–66 ft).

The white, fine- to medium-grained beach sandstone unit (unit 3) is distinctive because of its snowy white color, higher porosity, and less extensive cementation than any of the other sandstones. This unit ranges in thickness from 0 to 4.5 m (0 to 14 ft), with an average thickness of 2 m (6.6 ft).

The nonmarine carbonaceous shale (unit 4) averages 40 m (131 ft) in thickness and is locally interbedded with thin coals. A distinctive dark gray color, generally weathered, and very fine grain size (clay and silt) characterize this unit.

Laterally discontinuous (over tens of meters), poorly sorted, medium-grained, lenticular fluvial sandstones (unit 5) are located within the carbonaceous shale unit (unit 4). Individual fluvial sandstone beds range between 1 and 6 m (3.3 and 19 ft) in thickness.

Faults

Two dominant sets of faults are observed in the field area. The first set consists of northeast- and southwest-dipping, normal conjugate faults that strike subparallel to the fold hinge. These occur primarily along the southern hinge of the anticline, where curvature is at a maximum (Figure 5). The second set includes northeast-striking normal and normal-oblique faults that dip to the northwest and southwest. These are common along the eastern limb. Most terminate before intersecting the western limb; displacements therefore decrease to the southwest across the fold. A normal component of displacement is recorded by stratigraphic separation, whereas the strike-slip component is inferred from slickenlines with rakes of 20–35° on three fault surfaces. The sense of slip for all three faults, based on slickenline orientation and separation, is oblique right lateral. The faults are generally perpendicular to the fold hinge, even where it bends, and are characterized by vertical separations that vary across the fold. The largest offsets, up to 40 m (131 ft), are observed on the eastern limb. The few hinge-perpendicular faults exposed on the western limb have vertical separations of 0.5–1 m (1.6–3.3 ft). Although continuous exposure is not available around the dome, these hinge-perpendicular faults appear to be most common near the crest or culmination of the fold.

Two faults near the apex of the anticline, observed in seismic reflection profiles from the Rocky Mountain Oilfield Testing Center, can be projected across the anticline into valleys along the western limb. Individual segments of the western limb, separated by these valleys, display different bedding and fracture orientations. In each segment, the strike of one primary fracture set roughly parallels the strike of bedding. These valleys are therefore interpreted to be fault controlled. Valley trends suggest that the faults belong to the northeast-striking fault set.

Two interpretations of the continuity of northeast-striking faults across the anticline are possible. One is that the faults coalesce from east to west. The second is that only a few faults have lateral extents long enough to intersect the western limb; others tip out within the anticline. This latter interpretation is preferred, based on surface measurements and available subsurface two-dimensional and 3-D seismic data and reservoir maps.

Faults in well-cemented sandstones typically have damage zones characterized by high fracture density. The fractures generally strike parallel to the faults. Where a given fault continues into the high-porosity, poorly cemented sandstones of the white beach facies (unit 3), it is expressed as a broader zone of subparallel deformation bands instead of fractures.

Deformation bands also commonly occur as conjugate pairs near the southern and southwestern exposures of the anticline and as deformation-band shear zones in other areas. The conjugate pairs are oriented such that there is a vertical bisector to the acute angle between a given pair (Figure 6). The deformation bands strike parallel to the primary fracture orientations recorded at Teapot Dome, which suggests a genetic relationship. Where displacement can be constrained, individual bands have generally indiscernible to 3 cm (1.2 in.) of normal separation. Separation across compound (up to 20) deformation bands ranges from indiscernible to approximately 20 cm (8 in.).

Fractures

Three throughgoing fracture sets were documented at Teapot Dome. One consists of fractures striking oblique to the fold hinge. A second set strikes subparallel

Figure 5. Located on the fold hinge in the downplunge area at the southern end of the anticline, these normal conjugate faults and fractures strike parallel to the fold hinge and have a vertical bisector to the acute angle. Vertical separations are typically small (0–30 cm; 0–12 in.).

to the fold hinge. The third fracture set is roughly perpendicular to the fold hinge. Forty-four percent of the 1413 fractures measured during this study are parallel to the fold hinge, 32% are perpendicular to the fold hinge, and 24% are oblique to the fold hinge. The two youngest (age is determined by fracture-abutting relationships and detailed later in this section) of the throughgoing fracture sets strike parallel to the two fault sets described previously. Most of the fractures are bed-normal extension fractures. Locally, these are replaced by conjugate shear fractures of the same strike and with a near-vertical bisector to the acute angle.

The hinge-perpendicular fracture set (Figure 7) was documented at 35 out of the 90 sites where fracture measurements were taken around the anticline. Six additional sites exhibit hinge-perpendicular deformation bands, but no fractures.

The hinge-parallel fracture set (Figure 8) was documented at 51 sites. Six additional sites exhibit hinge-parallel deformation bands, but no fractures of similar orientation. Figure 9 summarizes the fracture set orientations. A complete index of all fracture, deformation band, fault, and lithologic data for each site is provided in Cooper (2000).

Outcrops of the fold hinge are generally absent due to erosion of the fold core. Where a part of the hinge crops out near the southern exposure of the dome, an increase in density of fractures not related to faults is evident relative to the eastern and western limbs. This is evidenced by eight sites on the southern hinge of the anticline with a mean fracture spacing of 34.7 cm (13.6 in.) (n = 71), compared to ten sites on the fold limb with a mean fracture spacing of 57.3 cm (22.5 in.) (n = 78).

Where pavement surfaces are large enough, both hinge-parallel and hinge-perpendicular fractures can be seen to extend up to 100 m (330 ft) in trace length. Where fractures intersect, they typically meet at abutting

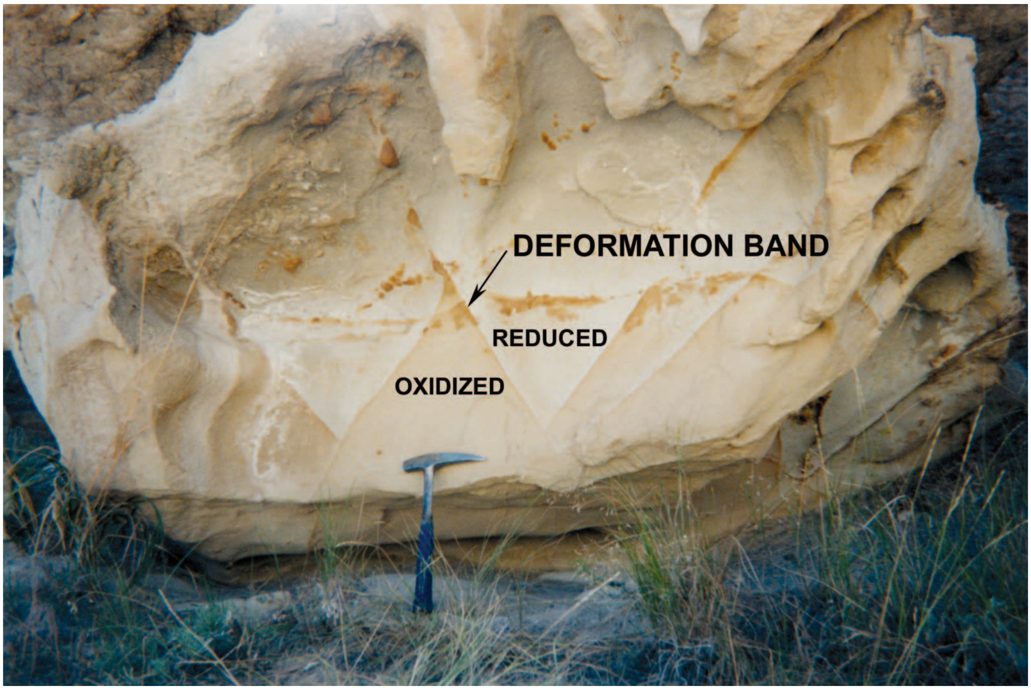


Figure 6. Conjugate deformation bands with a vertical bisector to the acute angle. Note the reduced iron above the deformation bands and the oxidized iron below, which indicate that the deformation bands are permeability barriers.

T intersections. The fracture that does not terminate at such intersections is interpreted to be the oldest, as younger fractures would terminate at a preexisting discontinuity. Locally, hinge-parallel fractures can terminate against hinge-perpendicular fractures, or hinge-perpendicular fractures can terminate at intersections with hinge-parallel fractures, and both abutting relationships can be seen in the same outcrop, indicating that the fracture sets were formed at nearly the same time.

The set of fractures that strikes obliquely to the fold hinge (typically northwest to west-northwest) is found at 28 sites around the fold and is equally distributed among the various lithologic units. This is the oldest set of fractures relative to the other throughgoing fracture sets as determined by abutting relationships. Data collected in unfolded strata at a distance from Teapot Dome show that fractures with a similar strike are present throughout the region (Figure 10), suggesting that a regional set of fractures existed before the formation of the Teapot Dome.

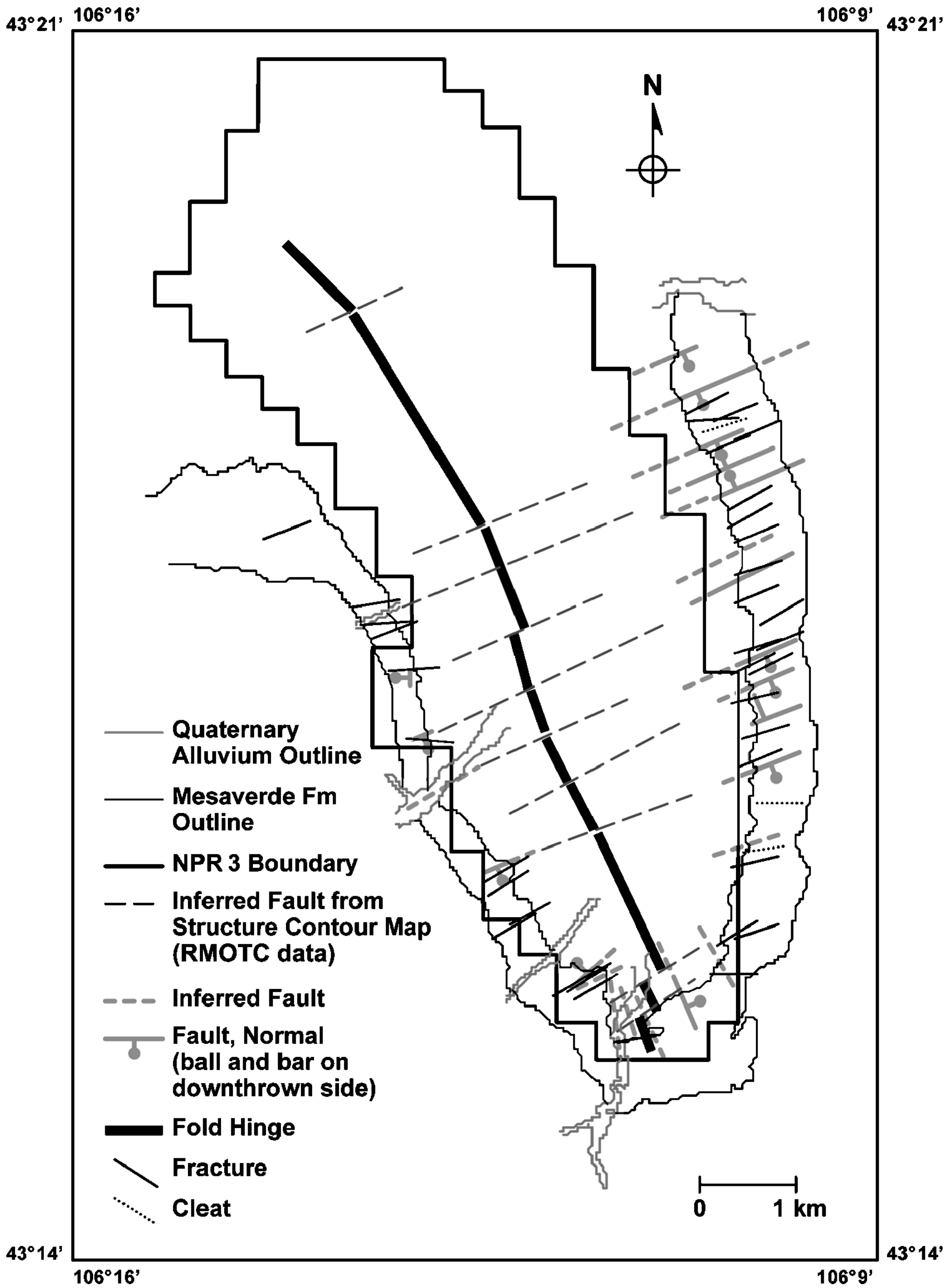
Mineralization

Faults and associated fractures are variably cemented. Fractures at 38 out of 90 sites around Teapot Dome were mineralized with calcite and/or iron oxides. Iron oxide mineralization was evidenced by iron staining, both on the fracture surface and at some distance (1–4 cm; 0.4–1.6 in.) into the matrix from the fracture. Some of the compound fault planes at Teapot Dome are heavily cemented and more erosion resistant than adjacent strata and, therefore, tend to stand out as erosion-resistant ridges or spurs up to 10 m (33 ft) high and 50 m (164 ft) long, projecting out toward the center of the dome. Poorly cemented or uncemented faults, in contrast, weather into gullies and valleys. The degree of cementation of individual structures varies abruptly within the study area. In one area, a well-cemented fault is located just 50 m (164 ft) from a highly weathered fault that is inferred to have little or no cement.

Deformation of High-Porosity Sandstone

Deformation bands accommodate strain in high-porosity sandstones at Teapot Dome. This is caused by rock strength, which decreases in a nonlinear fashion with increasing porosity (Price, 1966; Dunn et al., 1973; Hoshino, 1974), and by the differential stress required for failure at the transition between brittle faulting and cataclastic flow. At pressures below the brittle-ductile transition zone, failure in high-porosity sandstones occurs through dilatancy, followed by grain fragmentation and pore collapse. In the transition zone, shear bands dominate. Failure may be localized within narrow (typically <2-mm [<0.08-in.]-wide) bands that accommodate displacements of a few millimeters to centimeters and have along-strike lengths from a few centimeters to

Figure 7. Map of faults and representative hinge-perpendicular fractures at Teapot Dome. A higher density of these structures exists on the eastern backlimb of the fold (modified from Cooper et al., 2001, 2003). RMOTC = Rocky Mountain Oilfield Testing Center.



tens of meters (Engelder, 1974; Aydin, 1978; Jamison and Stearns, 1982; Wong et al., 1992, 1997; Antonellini and Aydin, 1994; Antonellini et al., 1994; Wong, 1998; Davis, 1999; Olsson et al., 2004). These small-displacement faults are referred to as deformation bands (e.g., Aydin, 1978).

At Teapot Dome, 1-mm (0.04-in.)-wide deformation bands are common in the high-porosity, poorly cemented sandstones of the unit 3 white beach facies. The deformation bands are composed of sand grains that are both smaller in size and more angular than the surrounding rock. Point counts from samples collected at two locations indicate that undeformed unit 3 sandstone has a mean porosity of 38% at one site and 41% at the second site. Point counts in the same thin sections indicate that mean porosity in deformation bands at both sites is 5%, a nearly 10-fold reduction in porosity from the matrix. Undifferentiated clay-size material, derived from comminuted lithic grains, is abundant within the deformation bands but absent from the matrix.

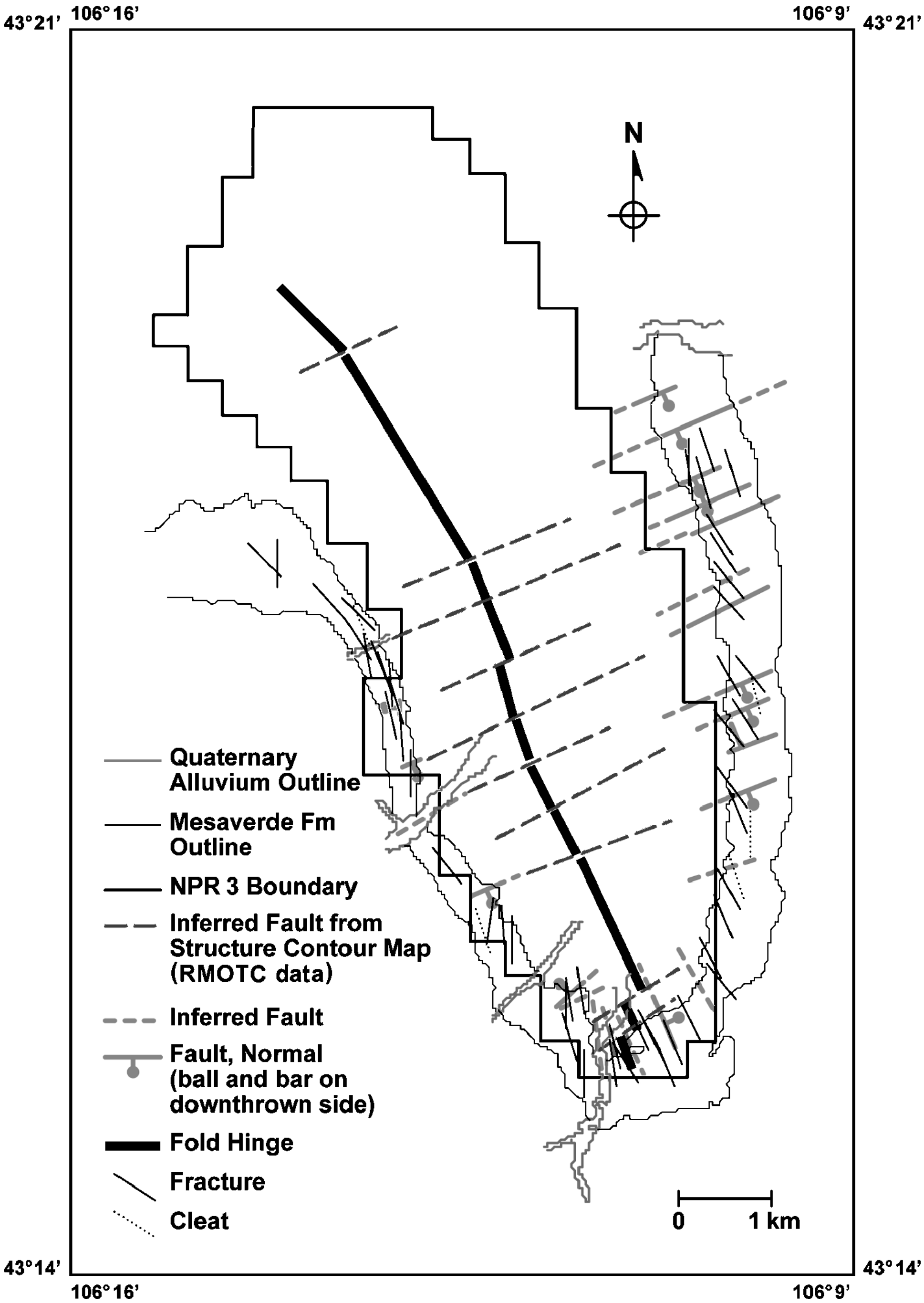
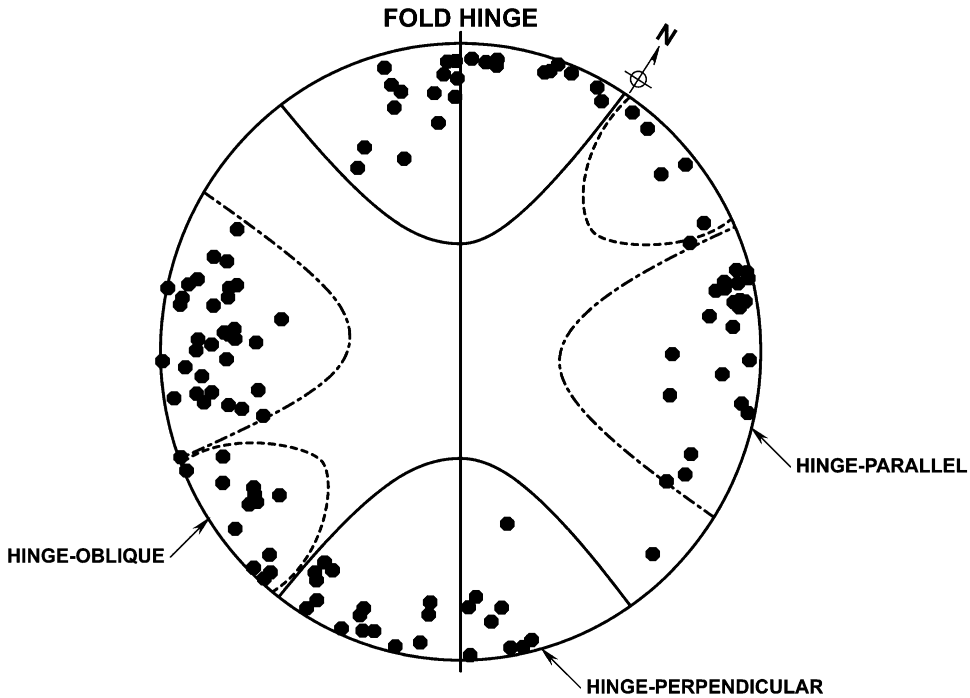


Figure 8. Map of faults and representative hinge-parallel fractures at Teapot Dome. Faults of this orientation are generally confined to the limited exposures of the fold hinge at the southern end of the anticline (modified from Cooper et al., 2001, 2003).

Deformation bands at one site are composed of 30% clay-size material on average, whereas deformation bands at the other site have an average of 23% of this material. At both sites, deformation bands have no measurable cement content. Iron oxide and chert cements constitute less than 1% of the matrix.

Field observations of differential iron staining, presumably related to fluid flow, indicate that iron may be reduced on one side of a deformation band, but oxidized on the other (Figure 6). It is evident from petrographic study that deformation bands have a lower porosity relative to the surrounding matrix because of grain-size reduction and pore collapse. These observations suggest that deformation bands are at least partial barriers to fluid flow. Deformation bands were also found to strike parallel to the fracture sets at Teapot Dome, suggesting that they formed at the same time and under similar conditions as the fractures.

Figure 9. Lower-hemisphere equal-area net plot, normalized to the fold hinge, of poles to 129 representative throughgoing fractures from 90 sites at Teapot Dome. Each measurement is representative of the average local patterns at a given outcrop. Fractures are considered hinge-parallel if they strike ±20° from the hinge; hinge-perpendicular fractures strike 90 ± 20° from the hinge.



DISCUSSION

Structures observed within the Cretaceous Mesaverde Formation at Teapot Dome include extension fractures, conjugate shear fractures with normal displacement, deformation bands, hinge-parallel normal faults, and hinge-perpendicular normal-oblique faults. The dominant fracture sets strike parallel to subparallel to the fault sets. Most of the fractures are bed-normal extension fractures. These observations agree, in general, with those made previously by Thom and Spieker (1931). In addition, we have documented fractures oblique to the fold hinge. Fisher and Wilkerson (2000) suggested that hinge-oblique fractures could be formed in a fold associated with basement-involved thrusting. Because such fractures form early in the folding process, they can predate the other fracture sets and still be related to folding. However, at Teapot Dome, the hinge-oblique fractures are not only older than the other fracture sets, but they are also similar in strike to fractures found throughout the region, suggesting that they are unrelated to folding (Figure 10) and may be a preexisting regional fracture set.

In contrast, hinge-parallel and hinge-perpendicular fractures, deformation bands, and faults are interpreted to be broadly contemporaneous with basement-involved thrusting and folding at Teapot Dome. This interpretation is based on several observations. First, fracture-abutting relationships indicate that the two fracture sets were broadly contemporaneous. Second, the dominant fracture sets strike roughly parallel and perpendicular to the fold hinge, suggesting that they are related to the folding event. In addition, the fracture sets are both parallel to and spatially related to the fault sets. The northeast-striking faults are oriented roughly perpendicular to the fold hinge, even where the hinge axis bends, and die out toward the western limb of the anticline, suggesting that they are related to differential movement across individual basement fault blocks.

Seismic data show that a basement-involved blind thrust terminates within the lower Paleozoic section. Using coseismic displacements after the Northridge earthquake of 1994 and inversion of kinematic data from basement-involved anticlines (Wise and Obi, 1992; Narr, 1993; Varga, 1993) to interpret the principal strain-rate axes in a blind thrust, Unruh and Twiss (1998) determined that horizontal shortening occurred perpendicular to the fold hinge, and maximum lengthening was horizontal and parallel to the fold hinge. These results are consistent with our observations. Specifically, hinge-perpendicular fractures and faults record extension parallel to the hinge of Teapot Dome. The fold itself evidences shortening normal to the hinge at the basement level, with extension in the same direction in the overlying strata caused by folding and/or stretching over the rising thrust front. Extension of the strata during folding was accommodated by hinge-parallel fractures

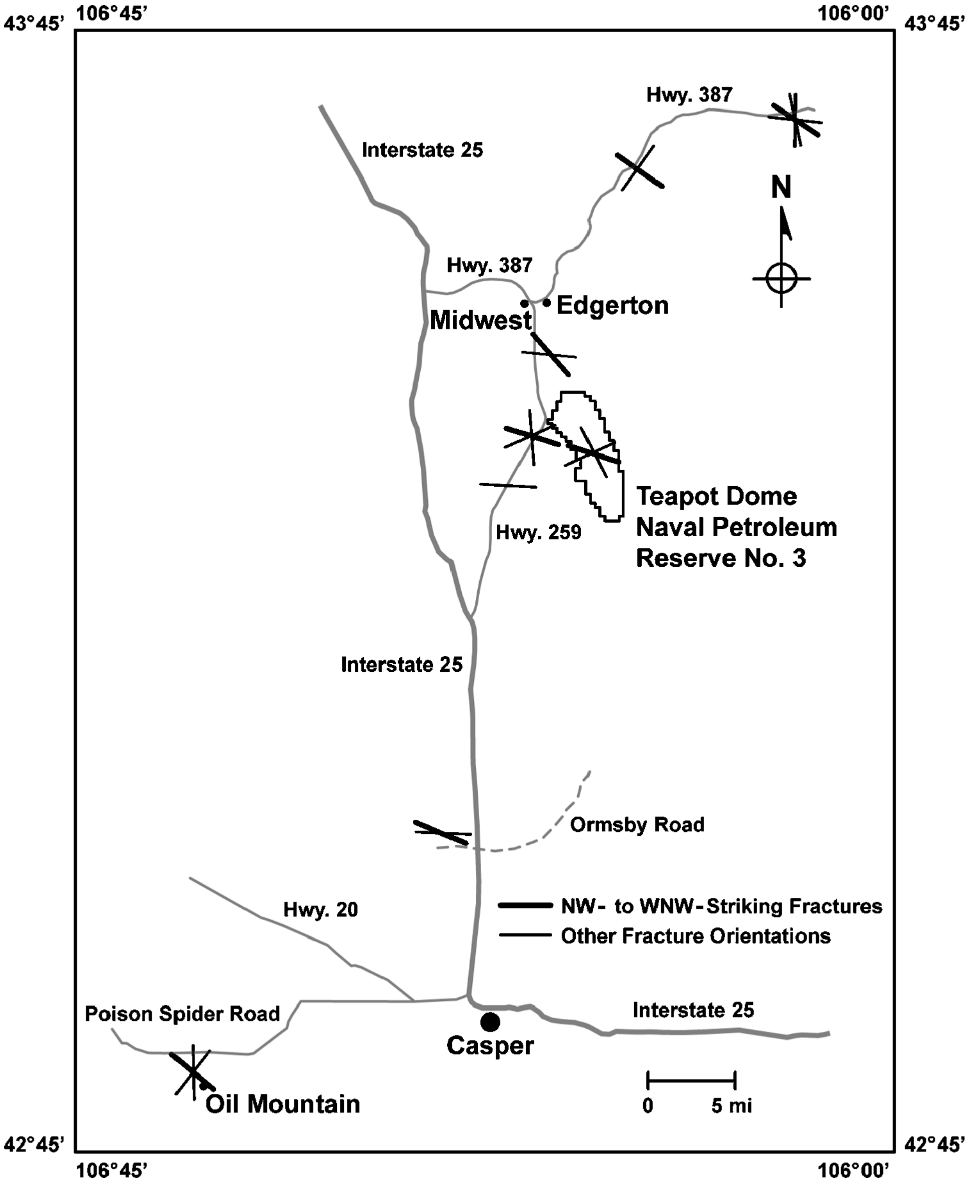


Figure 10. Representative fracture data from locations in the vicinity of Teapot Dome. Oil Mountain data are from Hennings et al. (1998, 2000). The northwest-striking fracture set is inferred to be an older regional fracture set due to abutting relationships at the Teapot Dome and its regional extent.

and faults. The normal faults, extension fractures, and conjugate shear fractures parallel to the fold hinge are interpreted to have accommodated extension related to bending of the brittle beds. The normal-oblique movement recorded on some of the northeast-striking faults indicates that they may have a transfer fault component related to differential movement across individual segments of the basement-cored thrust.

The orientations of faults and fractures at Teapot Dome are similar to those documented by DeSitter (1956), Murray (1967), Simon et al. (1988), Garrett and Lorenz (1990), Lorenz (1997), Engelder et al. (1997), and Hennings et al. (1998, 2000). In most of these studies, the fractures and/or faults striking parallel or perpendicular to the fold hinge were attributed to the folding process. The structures described by Engelder et al. (1997) at Elk Basin anticline are perhaps most similar to those at Teapot Dome. Two fracture sets, one parallel and the other perpendicular to the fold hinge, were documented. At Elk Basin anticline, as at Teapot Dome, there is a higher percentage of hinge-parallel fractures than hinge-perpendicular fractures. Moreover, hinge-perpendicular fractures were the throughgoing set in a few areas but terminate against hinge-parallel fractures in other areas, similar to Teapot Dome.

Structures at Oil Mountain, in central Wyoming, that are similar to those at Teapot Dome include fractures striking both parallel and perpendicular to the fold hinge and an increase in fracture density in the southern plunging region of the hinge (Hennings et al., 1998, 2000). Although the hinge-parallel fractures at Oil Mountain were interpreted to predate folding, this set is subparallel to, and thus may be, the same regional fracture set that predates folding at Teapot Dome. The age relationship between hinge-parallel fracturing and fold formation at Oil Mountain is therefore ambiguous. Fracture density in the southern hinge at Oil Mountain is greater than at the Teapot Dome hinge, possibly because Oil Mountain is a tighter fold as evidenced by the overturned forelimb.

Simon et al. (1988) deformed semibrittle clay cake over an expanding balloon, creating a dome and two orthogonal sets of fractures. One set was parallel to the long axis of the dome; the second was perpendicular to that axis. The deep-seated thrust at Teapot Dome acted in a similar fashion, forcing the overlying strata to bend and extend both parallel and perpendicular to the fold hinge. We infer that normal-oblique faulting accommodated differences in along-strike displacement (i.e., these structures acted as transfer faults in the underlying thrust).

3-D Conceptual Model of Fractures in Strata within Basement-Cored Anticlines

The observed fracture trends and interpreted genetic relationships from Teapot Dome and similar folds form the foundation of our conceptual model of fault and fracture development in an anticline above a basement-cored thrust (Figure 11). The fracture set determined to predate folding at Teapot Dome is not incorporated into this conceptual model as it did not form as a response to folding and because preexisting regional fracture sets will vary in orientation with location.

A comparison between this and the earlier conceptual model that describes fracturing associated with folding (Figure 3) (Stearns and Friedman, 1972) shows significant differences as well as some similarities in fracture patterns. Conjugate shear fractures at Teton anticline are oriented such that the bisector of the acute angle is parallel to the plane of bedding, whereas at Teapot Dome, conjugate fractures and conjugate deformation bands have a vertical bisector to the acute angle. Shear fractures therefore obliquely transect the Teton anticline but strike either parallel or perpendicular to the fold hinge at Teapot Dome. Bedding-perpendicular extension fractures in both anticlines strike parallel and perpendicular to the fold hinge in the vicinity of the fold culmination. However, near the downplunge parts of the fold hinge, where bedding strike is not parallel to the trend of the fold hinge, differences in extension fracture patterns between the two types of anticlines are apparent. One major difference is that the fracture sets at the Teton anticline remain parallel to bedding strike and, thus, change orientation with respect to the fold hinge, whereas the fracture sets at Teapot Dome are everywhere parallel and perpendicular to the fold hinge.

These two anticlines are distinctly different both in terms of the depth of the thrust relative to the fractured strata and in the type of folding process. Teapot

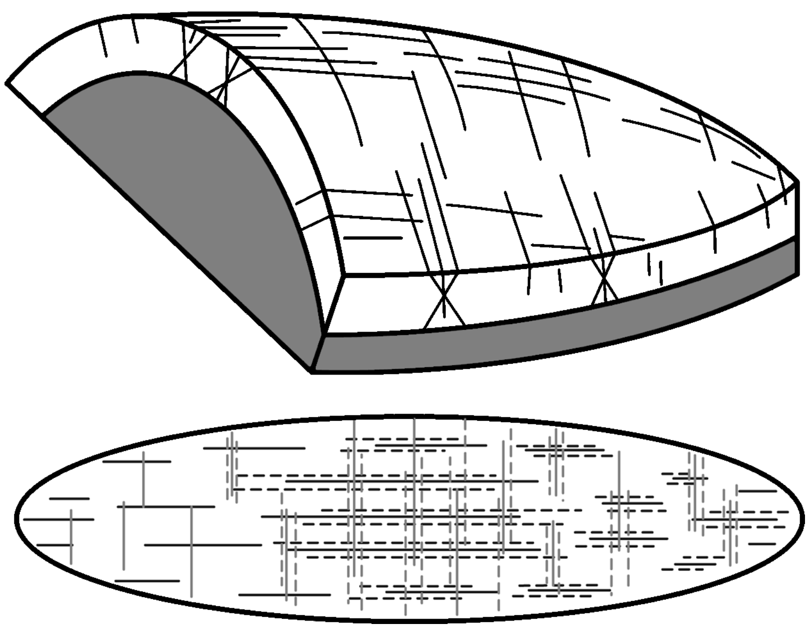


Figure 11. Conceptual 3-D model of fracture patterns developed at Teapot Dome. Conjugate shear fractures and faults are shown with dashed lines and eliminated on the left side of the plan-view diagram to highlight the orientation of extension fractures (upper diagram modified from Cooper et al., 2001, 2003). Hinge-perpendicular fractures are gray, and hinge-parallel fractures are black in the lower diagram.

Dome is situated above a deep-seated, basement-cored thrust. The sedimentary layers are interpreted to be essentially draped over the thrust, with the fold forming passively in response to faulting. Lengthening in the area of flexure (drape) over the deep-seated thrust is evidenced by conjugate fractures and faults with a vertical bisector to the acute angle. Folds that have fracture patterns similar to those at Teapot Dome will be those associated with similar deep-seated blind thrusts.

In contrast, the Teton anticline is cored by a thin-skinned thrust that propagated through the sedimentary section. As described by Sinclair (1980), the Teton anticlines, separated by an unfaulted syncline, are essentially buckle folds over a thin-skinned thrust. In this case, folding was driven by bedding-parallel shortening as evidenced by conjugate shear fractures with a bedding-parallel bisector to the acute angle. Similar relationships have been observed in fault-propagation and fault-bend folds in the foothills of the Canadian Rockies (Cooper, 1992) and the Palm Valley fold in central Australia (Berry et al., 1996).

Stearns (1964) also observed a hinge-parallel conjugate fracture set with a vertical bisector to the acute angle at Teton anticline, which was not considered a dominant fracture set by Stearns and Friedman (1972) and was believed to accommodate folding. However, this is a significant set of fractures at Teapot Dome and is incorporated as such in the generic model.

Fluid-Flow Implications

Fractures, deformation bands, and faults have been shown to increase or decrease permeability in certain directions and, thus, introduce permeability anisotropy and heterogeneity (Elkins and Skov, 1960; Rice, 1983; Nelson, 1985; Lorenz and Finley, 1989, 1991; Fassett, 1991; Teufel and Farrell, 1992; Caine et al., 1996; Rawling et al., 2001; Sternlof et al., 2004). Reasonable predictions of permeability anisotropy require an understanding of controls on the distribution and orientation of these features.

As previously described, depending on the lithology of the faulted rock unit, a single fault at Teapot Dome can be expressed as either a zone of deformation bands (partial barriers to flow) or a fault with a primary slip plane and an associated fracture zone (a possible fluid pathway), depending on the porosity and degree of cementation of the host rock. However, in both units with deformation-band faults and units with fracture-based faults, maximum permeability would be parallel to fault strike. In the former, fluid flow would be mostly confined to the matrix. In the latter, fluid flow would occur preferentially along fractures as long as they remained unmineralized. Therefore, in low-permeability rocks, fractures will be the primary pathways for fluid flow. In contrast, in the high-porosity sandstones that host deformation bands, the matrix will provide the main pathway for fluid flow. Relatively well-cemented, low-porosity sandstones typically do not make a better reservoir than poorly cemented, high-porosity sandstones. However, it is apparent from this study that natural fracturing will help increase production in more brittle sandstones, whereas deformation bands may hinder production in high-porosity sandstones.

Fracture patterns typical of basement-cored anticlines have numerous implications (Figure 11). Because the dominant set of throughgoing fractures is parallel to the fold hinge, significant permeability anisotropy is expected, with maximum permeability generally parallel to the fold hinge across the entire anticline. Areas of greatest change in dip of bedding (i.e., the fold hinge) are areas of increased fracture density, with fractures generally parallel to the fold hinge (Figure 12). This increase in fracture density near the hinge of the anticline should be associated with an increase in both permeability and permeability anisotropy.

Northeast-striking normal faults and associated fractures may locally result in maximum permeability perpendicular to the fold hinge. This will most likely be at the crest of the fold, where northeast-striking faults are numerous. However, even in the crest, the areas between northeast-striking faults can be dominated by hinge-parallel fractures. Therefore, the location of a specific well and its proximity to a fault zone will determine the orientation of the maximum permeability. Intersections of hinge-perpendicular with hinge-parallel faults and associated fractures should be areas of enhanced permeability, where increased interconnectivity may allow for locally increased production (Figure 12). The permeability anisotropy will depend on the number of faults and fractures of each set and degree of connectivity and will thus vary from site to site.

Studies of steam flood response at Teapot Dome by Doll et al. (1995) support permeability trends that are parallel and perpendicular to the fold hinge. The hinge-perpendicular permeability trend is further supported by the Fausnaugh and LeBeau (1997) Teapot Dome study. Garfield et al. (1992) document permeability anisotropy related to fracturing at Little Sand Draw field that is hinge-perpendicular. Whereas the authors infer a different model for fracture formation

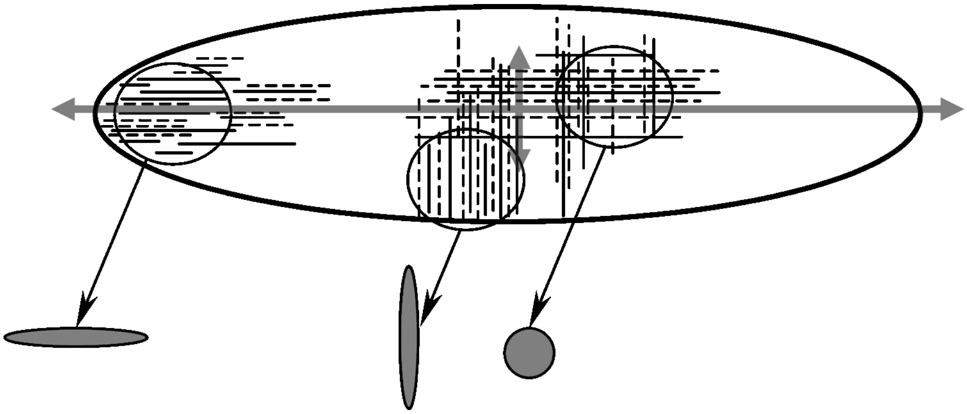


Figure 12. Plan view of conceptual model of permeability domains related to intersecting or relatively nonintersecting fracture patterns along a Teapot Dome–type anticline. These domains will change across the anticline. Conjugate shear fractures are shown with dashed lines, and excess fractures are eliminated to highlight the fractures at specific areas. Potential drainage ellipses are shown outside the anticline. Areas of nonintersecting fractures show drainage ellipses that parallel the fracture orientations. Areas with numerous intersections should have near-circular drainage patterns. These patterns are supported by the Doll et al. (1995) steam flood data.

(i.e., Stearns and Friedman, 1972), the observed fracture system would also fit the Teapot Dome model.

A preexisting fracture set oblique to the fold hinge (N65°W) is also present at Teapot Dome. This regional fracture set is also locally important: it provides the most significant flow directionality with respect to water response and rapid oil response during steam flooding (Doll et al., 1995) in the east-central part of the anticline.

Highly mineralized fractures and faults will reduce the overall permeability within a volume of rock. Most of the fractures and faults at Teapot Dome, however, are relatively unmineralized; areas of moderate mineralization were observed only locally.

CONCLUSIONS

Fractures, deformation bands, and faults associated with folding of the Cretaceous Mesaverde Formation at Teapot Dome are arranged in patterns related to structural position. Fracture density increases near faults. Conjugate fractures and deformation bands, with a vertical bisector to the acute angle, and normal faults striking subparallel to the axis of the anticline are common in the exposed hinge of the anticline. Northeast-striking normal-oblique faults and associated fractures are generally perpendicular to the fold hinge and are more closely spaced near the crest of the dome. Extension fractures and faults that parallel the fold hinge are more closely spaced near the hinge.

The fractures, deformation bands, and fold are interpreted to have formed in a dynamic interactive system driven by displacement on the basement-involved thrust fault. Variable displacement along the thrust front was accommodated by transfer faults (the northeast-striking normal-oblique faults) roughly perpendicular to the thrust fault and fold hinge. These faults also accommodated a component of extension associated with the bending of beds from the topographically higher crest to the lower northern and southern areas of plunge. Hinge-parallel normal faults that are roughly parallel to the thrust fault also accommodated a component of extension perpendicular to the fold hinge.

In the absence of significant subsurface data, a data set built from observations of outcropping strata, lithologically analogous to subsurface reservoir rocks, may allow a first-order determination of key features (i.e., fractures, faults, and deformation bands) likely present in the subsurface, including their spacing and influence on permeability and fluid flow. Our conceptual model of fault and fracture distribution in basement-involved anticlines is consistent with observations made previously at Teapot Dome and other similar structures. This model is significantly different from Stearns and Friedman's (1972) conceptual model, which has been widely applied to all anticlines regardless of the folding process. We propose that our model is best applied to basement-cored structures, whereas the Stearns and Friedman (1972) model is a better analog for folds developed above thin-skinned thrusts that formed in response to layer-parallel compression. In other words, fracture analogs are best applied with knowledge of the tectonic setting of the structure of interest. Using the wrong model can result in a poorly designed secondary recovery system, wherein early breakouts in unexpected directions can occur, and production is not optimized.

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