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Tectonic setting and characteristics of natural fractures in Mesaverde and Dakota reservoirs of the San Juan Basin

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Abstract

The Cretaceous strata that fill the San Juan Basin of northwestern New Mexico and southwestern Colorado were shortened in a generally north-south to north northeast-south southwest direction during the Laramide orogeny. This shortening was the result of compression of the strata between southward indentation of the San Juan uplift at the north edge of the basin and northward to northeastward indentation of the Zuni uplift from the south. Right-lateral strike-slip motion was concentrated at the eastern and western margins of the basin to form the Hogback monocline and the Nacimiento uplift at the same time. Small amounts of shear may have occurred along pre-existing basement faults within the basin as well. Vertical extension fractures, striking north-south to north northeast-south southwest (parallel to the Laramide maximum horizontal compressive stress) with local variations, formed in both Mesaverde and Dakota sandstones under this system, and are found in outcrops and in the subsurface. The less-mature Mesaverde sandstones typically contain relatively long and irregular vertical extension fractures, whereas the underlying quartzitic Dakota sandstones contain more numerous, shorter, sub-parallel, closely spaced extension fractures. Conjugate shear fractures in several orientations are also present locally in Dakota strata.

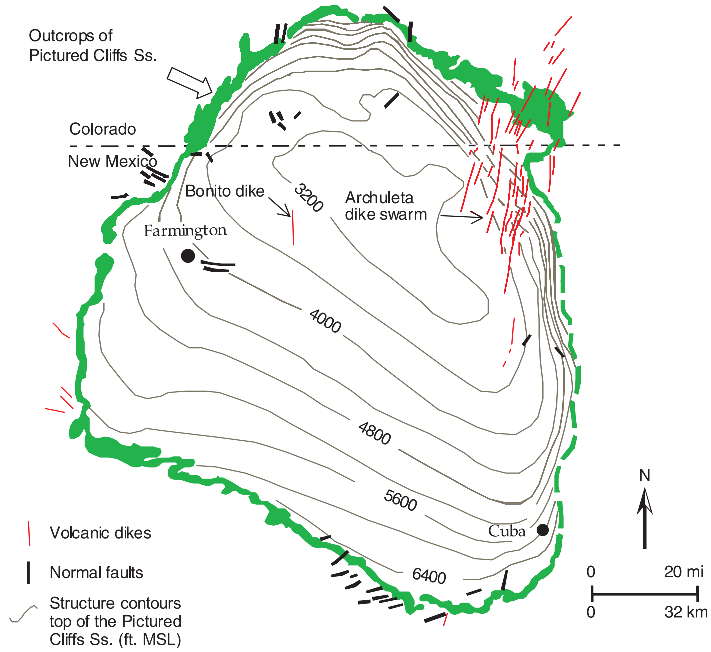

FIGURE 1—Structure contour map of the inner or central section of the San Juan Basin. Contours are drawn on the top of the Upper Cretaceous Pictured Cliffs Sandstone, which overlies the Mesaverde Group. The basin is asymmetric with the northwest trending synclinal hinge near the northern edge of the basin.

Introduction

This paper has two objectives: 1) to provide a brief characterization of natural fractures that control the production of natural gas from sandstone reservoirs in Mesaverde and Dakota strata in the San Juan Basin, and 2) to reconstruct a plausible tectonic framework for the genesis of these fractures. The tectonic model presented here provides a basis for the extrapolation of fracture characteristics from outcrops and core to the subsurface and for the prediction of fracture characteristics in the subsurface. This paper is a shortened version of the report containing more of the supporting data (Lorenz and Cooper, 2001). Copies of the longer report can be obtained directly from the authors or are available from the U.S. Department of Commerce, National Technical Information Service, Springfield, VA, or online at www.osti.gov/bridge.

Most of the published tectonic reconstructions of the San Juan Basin area focus on one or two of the structural elements that bound the basin. Those that examine the entire basin (e.g., Kelley, 1957; Fassett, 1991; Laubach and Tremain, 1994) are primarily descriptive rather than attempting to interpret the kinematics of the important structures. We have re-examined the basic structural building blocks of the basin and have constructed an unconventional but plausible tectonic scenario for the post-Jurassic structural history of the San Juan Basin. Because the impetus behind this study was hydrocarbon reservoir characterization, our tectonic scenario was constructed to provide a framework that would explain the observed outcrop and subsurface natural fracture characteristics and that would permit a basic level of subsurface fracture prediction. Thus the paper presented below is an inversion of the normal procedure wherein fractures would be used as kinematic indicators and as first-level data in the reconstruction of a tectonic history. Nevertheless, fracture evidence and tectonic reconstruction are mutually supporting, and converge on the same conclusion that would have resulted from a more standard approach to the problem.

Location and general geology

The San Juan Basin of northwestern New Mexico and southwestern Colorado is asymmetric, and has strata dipping gently to the north and northeast toward the off-center synclinal hinge located near the Colorado–New Mexico state line (Fig. 1).

Most of the hydrocarbon production from the San Juan Basin comes from an inner zone, approximately delineated by the outcrop belt of the Upper Cretaceous Pictured Cliffs Sandstone and separated from the peripheral areas by a relatively continuous hogback nearly 400 km (154 mi) long, consisting of gently dipping to near-vertical strata. As described below, however, despite the apparent continuity of this feature, this hogback does not have a common mechanical origin along its entire length. Lower Cretaceous strata crop out at the margins of the San Juan Basin and extend into the subsurface to depths as great as 2,000 m (6,562 ft), where they have been penetrated by thousands of natural-gas wells.

Significant thicknesses of overburden strata were stripped from the surface of the basin in post-Cretaceous time. As much as

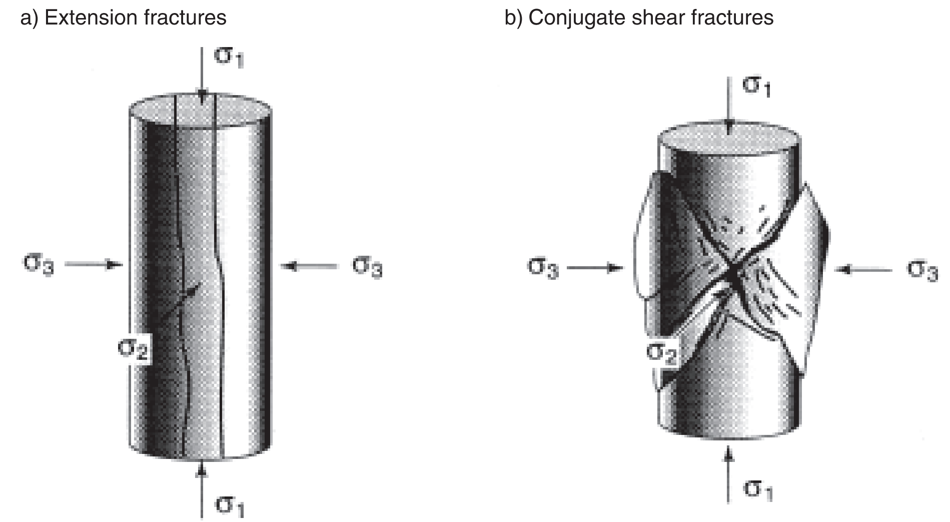

FIGURE 2—Extension and conjugate shear fractures as observed and created in laboratory compression tests (σ_1—maximum principal stress; σ_2— intermediate principal stress; σ_3—minimum principal stress; modified from Weijermars, 1997).

2,500 m (8,202 ft) of overburden may have been removed from northern parts of the basin (Bond, 1984). The previous deep burial and resulting high overburden stress accounts for horizontal stylolites that are locally common in Dakota sandstone cores.

Fracture terminology

For simplicity, breaks in rock will be described as either extension fractures or shear fractures within this paper, consistent with the terminology used within the petroleum industry. Extension fractures (also termed joints, or tensile fractures or dilation fractures or Mode I fractures: Pollard and Aydin, 1988) have displacements perpendicular to the fracture surfaces. Shear fractures have some displacement parallel to the fracture surface (also termed Mode II or Mode III fractures depending on displacement relative to the fracture front: Pollard and Aydin, 1988). Both extension and shear fractures can be formed in laboratory compression tests with specific orientations with respect to the applied stress. Extension fractures form perpendicular to the least compressive stress (σ_3), parallel to maximum compressive stress (σ_1), and bisect the acute angle between the conjugate shear fractures (Peng and Johnson, 1972; Long et al., 1997; Fig. 2).

Previous work

Published structural studies associated with the San Juan Basin focus on the specific tectonic elements bounding the basin (e.g., the Nacimiento uplift: Woodward, 1987; Baltz, 1967), or deal with the basin as a sub-unit within the Colorado Plateau (e.g., Chapin and Cather, 1981; Cather, 1999). Taylor and Huffman (1988, 1998) published several seismic sections across the monoclines that bound the inner basin; these sections suggest locally significant thrust indentation and overhang at the basin margins. Erslev (2001) and Cather (1999) interpret the structure of the Nacimiento uplift on the eastern margin of the San Juan Basin in the context of overall Laramide kinematics.

Previous studies of natural fractures and coal cleats in the San Juan Basin are primarily descriptive and concentrate on outcrops of Mesaverde strata (e.g., Whitehead, 1997; Tremain et al., 1991; Laubach, 1992). These studies suggest a demarcation in surface fracture domains that is approximately coincident with the New Mexico–Colorado border. This demarcation was not apparent during the course of this study, perhaps because this study concentrated on the oldest fractures present in the outcrops, those most likely to be present in the subsurface rather than fractures related to folding and uplift. Whitehead (1997) even suggests that many of the fractures in outcrops, particularly on the Chaco slope area, were caused entirely by surficial, valley-wall gravitational processes. In addition, Condon (1997) reports that the average strike of face cleats in coals at the northern margin of the San Juan Basin is not only oblique to fractures in associated sandstones but that the cleat and fracture strikes rotate in opposite directions along strike. Therefore the coal cleats in these strata may have had a separate origin from the fractures in sandstones addressed here, accounting for some of the discrepancies in orientation data between this study and earlier studies. A multi-stage, multi-directional tectonic origin for faulting and fracturing in this area is suggested by Ruf (2000) and Erslev (1997). Ruf (2000) describes a regional fracture set in the northern San Juan Basin as striking from north northwest to north northeast but relates their formation to post-Laramide extension. Our work suggests this fracture set is part of the regional, early Laramide fracture system.

Kelley (1957) and Kelley and Clinton (1960) note several domains of relatively uniform fracture strikes in the San Juan Basin as part of their broad-scale aerial-photo study of fractures on the Colorado Plateau. However, the scale of their study did not permit detailed examination and assessment of the fractures at ground level, and subsequent investigators have not recognized these domains.

Previous subsurface studies infer the presence of fractures in Cretaceous San Juan Basin reservoirs based on several indirect criteria including association with faults recognized on seismic data (e.g., TerBest, 1997; DuChene, 1989) and anomalous production rates (e.g., Emmendorfer, 1992; Gorham et al., 1979; London, 1972; Ouenes et al., 1998). Fracturing is typically assumed to have been caused, or at least enhanced, by flexures. Actual subsurface fracture data are rare, although Ortega and Marrett (2000) publish subsurface fracture data for the Mesaverde for three wells in the central part of the basin indicating a dominate north-south-striking fracture set, and Lorenz et al. (1999) present a preliminary synthesis of the tectonic framework of the basin based on wellbore-image logs and measured fracture characteristics in 32 Dakota cores. The interpretations herein build on the conclusions of Lorenz et al. (1999), expanding them to encompass Mesaverde reservoirs.

Tectonic setting

The inner part of the San Juan Basin appears to be relatively structureless, with low-amplitude flexures and gentle regional dips. However, the basin is underlain by a Proterozoic crystalline basement with many ancient and locally reactivated faults trending northeast-southwest and northwest-southeast (Taylor and Huffman, 1998). These faults may have been important controls on the fracture patterns in the overlying strata, but we suggest here that the tectonic features surrounding the basin provided the main controls in forming the pervasive, regional fracture pattern.

The principal tectonic features bounding the San Juan Basin are the San Juan uplift or dome to the north, the Zuni uplift to the south, the Defiance uplift and Hogback monocline to the west, the Nacimiento uplift to the southeast, and the Archuleta anticlinorium to the northeast (Fig. 3). These structures were largely formed during the Laramide orogeny (Kirk and Condon, 1986), although many of them had attained some structural expression during earlier tectonic events, and some were reactivated during Tertiary Rio Grande rifting (Kelley, 1957; Slack and Campbell, 1976; Woodward, 1987).

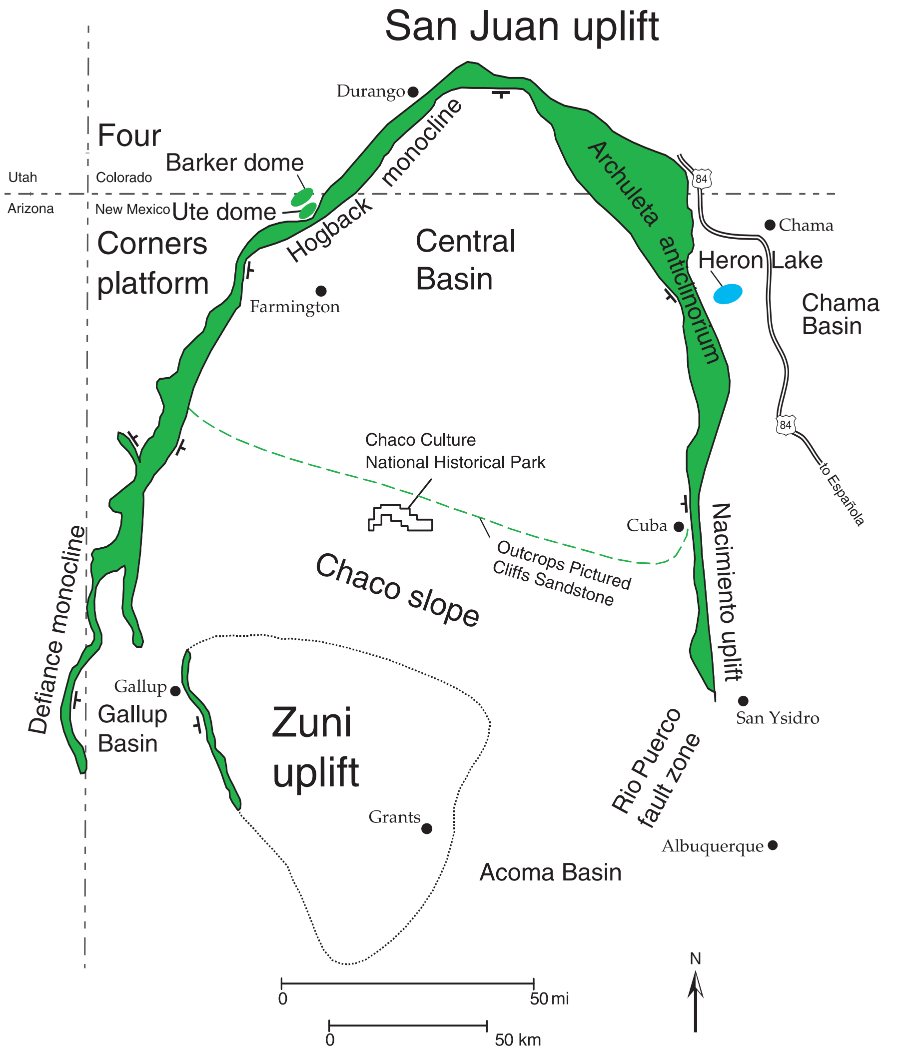

FIGURE 3—Index map showing the structural elements of the San Juan Basin. Areas of steep dip (monoclines) are shown in green with the direction of dip indicated by strike and dip tic marks; long dashed line separates the Chaco slope from the Central Basin and is drawn approximately where the Upper Cretaceous Pictured Cliffs Sandstone is subaerially exposed (modified from Fassett, 1989).

Northern and southern margins of the basin

The Chaco slope is the seemingly passive structural transition between the Zuni uplift and the inner basin. It is an area of relatively gentle homoclinal dip to the north and northeast, but includes broad folds and significant fault zones. The Zuni uplift has deceptively low topographic relief, but in fact there is over 4,000 m (13,000 ft) of structural relief between the crest of this northwest-striking asymmetric structure and the deepest part of the San Juan Basin to the north (Kelley, 1956, 1963; Woodward and Callender, 1977).

The Zuni uplift has had a complex tectonic history, going back to late Paleozoic time (Jentgen, 1977). Chamberlin and Anderson (1989) suggest that the present configuration of the Zuni uplift/Chaco slope complex is the result of Laramide indentation-extrusion tectonics. As the Zuni block was pushed northward and northeastward into the San Juan Basin, large slivers of strata were shoved laterally to the east and west along strike-slip faults. A northeastward indentation stress array is also suggested by the fault pattern northeast of the uplift (Fig. 4). As much as 5 km (3 mi) of left-lateral slip is suggested along escape faults on the western margin of the Zuni uplift (Chamberlin and Anderson, 1989), a rough indication of the order of magnitude of indentation.

On the opposite side of the basin, the San Juan uplift, approximately 100 km (62 mi) in diameter, lies immediately north of the Hogback monocline. It has been obscured by the superimposed Tertiary San Juan volcanic complex. Kelley notes, as far back as 1957, that the floor of the San Juan Basin "is tilted northward and its deepest part generally adjoins the greater uplift in the San Juan dome as though they were counterparts of a single mechanism at depth" (Kelley, 1957, p. 49), and we suggest that there is a direct mechanical relationship between the two as there is between Laramide block-thrust uplifts and basins throughout the rest of the Rocky Mountain region.

Precambrian rocks within the San Juan uplift are at least 4,300 m (14,108 ft) above sea level creating approximately 6,100 m (20,013 ft) of structural relief between the top of the uplift and the deepest parts of the adjacent basin. Much of the difference (3,500 m; 11,482 ft) is taken up across the short distance spanned by the Hogback monocline where it marks the northern border with the San Juan Basin. Moreover, although poorly exposed, small east-west striking, southward-verging thrust faults have been mapped in the surface on the southern side of the San Juan uplift. Larger, south-vergent thrusts have been documented in the subsurface along and south of the Hogback monocline (Taylor and Huffman, 1988, 1998; Huffman and Taylor, 1999). This suggests that the basin and uplift are tectonically/structurally linked. The fracture data presented below are, in fact, compatible with a model wherein the San Juan uplift was thrust southward into the San Juan Basin.

Eastern and western margins of the basin

The Defiance uplift bounds much of the western side of the San Juan Basin and consists of a north-striking asymmetric block with the steepest limb forming the Defiance monocline on its eastern edge. The sinuosity of the monocline is due to several southeast-plunging anticlinal and synclinal cross-folds, giving the Defiance monocline an en echelon character and suggesting approximately 13 km (8 mi) of right-lateral wrench faulting at depth (Kelley, 1967; Woodward and Callender, 1977).

Northward, the Defiance monocline steps to the east to become the steeply dipping Hogback monocline west and northwest of Farmington (Fig. 3). The Hogback monocline has a complex history stretching back to Paleozoic time, and seismic lines show a downward-flattening, west-dipping fault with both normal and reverse senses of motion depending on the age of offset (Taylor and Huffman, 1988). The present down-to-the-east offset of 1,200 m (3,937 ft) is commonly inferred to have occurred during eastward- to southeastward-directed thrusting in Laramide time. Huffman and Taylor (1999) suggest, however, that this persistent zone of structural weakness has also accommodated right-lateral Laramide shear, similar to the Defiance monocline, and this is our preferred interpretation.

The Hogback monocline bends northeastward north of Farmington, where it is interrupted by several re-entrant anticlines and domes such as Ute dome and Barker dome. These small basement-block uplifts suggest volume constraints during right-lateral transpression along en echelon basement faults (e.g., Ralser and Hart, 1999; Hart et al., 1999).

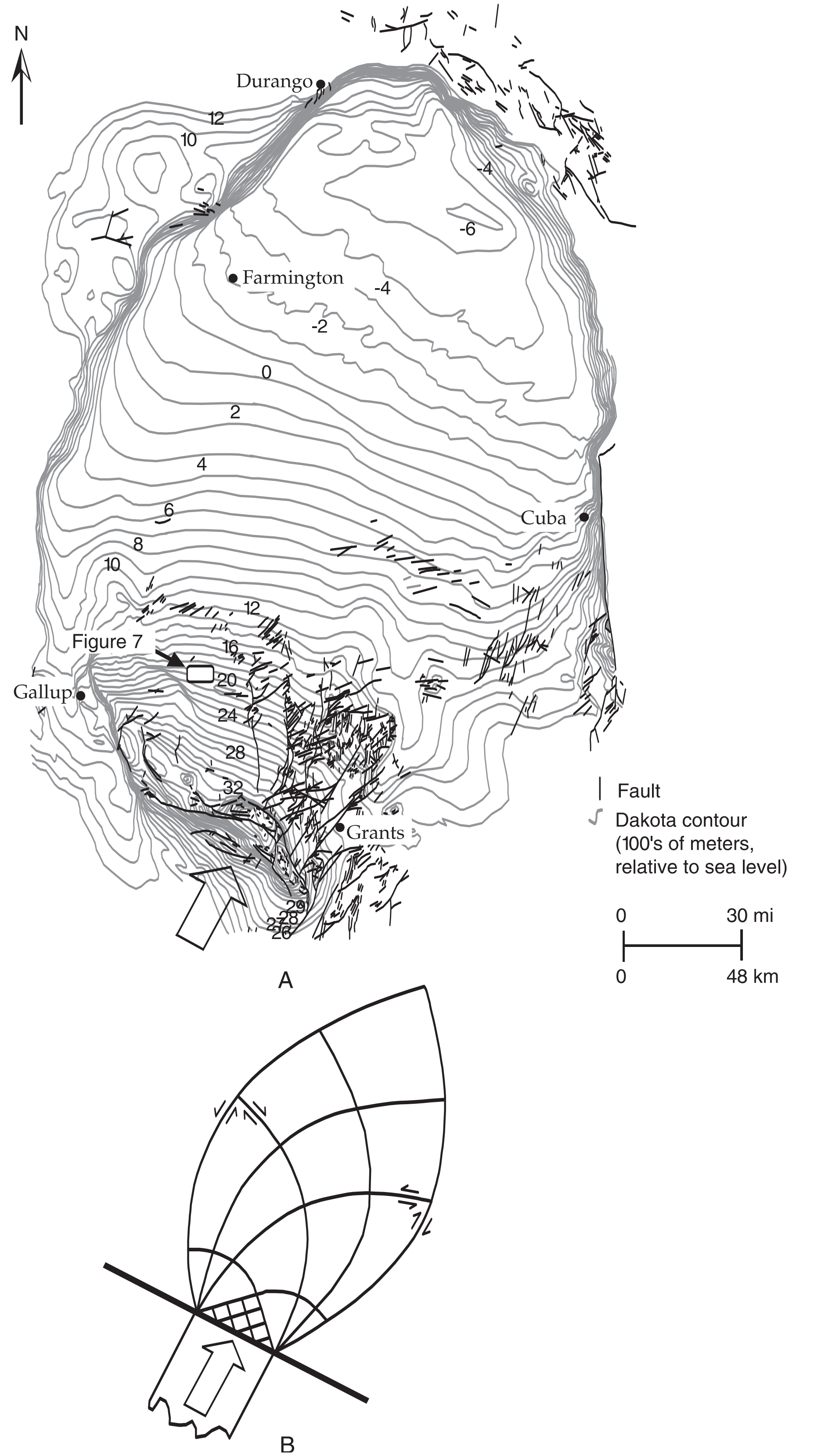

FIGURE 4—**A**) Structure map of the San Juan Basin, contours drawn on the base of the Dakota Sandstone with intervals of meters x 100 relative to mean sea level. Contours are extrapolated in the area of the Zuni Mountains due to erosion (modified after Thaden and Zech, 1986). Faults (shown in black) along the southern margin of the basin are oriented in an array that resembles an ideal slip-line field shown in (**B**) below it. Many of the mapped faults show evidence of strike-slip offset. Large arrow indicates direction of indentation. **B**) Plane-strain slip-line field for an indenter into a finite plastic medium. Arrow indicates direction of indentation (after Tapponnier and Molnar, 1976). The slip-line field will change with boundary conditions and indenter shape (Tapponnier and Molnar, 1976; Molnar and Tapponnier, 1977; Tapponnier et al., 1986).

To the east Huffman and Taylor (1999) present seismic cross sections that suggest inward-directed, sled-runner type thrust planes in front of the Hogback monocline along the Archuleta anticlinorium. However, these structures may also be interpreted as flower structures along right-lateral wrench faults (Taylor and Huffman, 1999; Huffman and Taylor, 2001). Southward along this eastern basin margin, the Nacimiento uplift was formed by a series of north-striking, tilted Precambrian blocks at the southeastern edge of the San Juan Basin, where 3,000 m (9,842 ft) of total structural relief separates the uplift from the adjacent basin.

The Laramide history of the Nacimiento uplift has been interpreted in different ways. Early interpretations (Renick, 1931) were that the uplift was a westward overthrust. Further mapping suggested that an early phase of right-lateral offset of 3–5 km (2–3 mi) formed the north northwest-south southeast striking en echelon folds along the western margin of the uplift (Baltz, 1967; Woodward et al., 1972, 1992). Right-lateral offset along this eastern margin of the basin as great as 20–33 km (12–20.5 mi) is interpreted by Cather (1999).

This early tectonic phase was followed by transpressive, right-lateral wrench faulting during later Laramide time, leading to local overthrusting westward into the basin (Woodward et al., 1972; Baltz, 1978; Woodward, 1983, 1987). Pollock et al. (1998) and Erslev (2001) recently revived the interpretation that most of the offset along this fault front was west-directed thrust motion, and that strike-slip offset of Laramide age was minor. The uplift was reactivated during late Tertiary time in association with extensional faulting along the Rio Grande rift (Kelley, 1957; Woodward, 1987).

There is a structural transition from the southern end of the Nacimiento uplift into the northeast-striking normal faults of the Rio Puerco fault zone. Slack and Campbell (1976) and Slack (1973) suggest this fault zone was the result of right-lateral wrench movement with an offset of less than 2.5 km (1.5 mi). The fault zone has been related to right-lateral Laramide deformation induced by north-northeast directed, regional horizontal compression (Slack and Campbell, 1976).

Tectonic features summary

The loosely connected segments of the Hogback are not the record of a single structural noose constricting the basin with radial, inward-directed thrusting around the edges of the basin. Rather, the Hogback monocline and Nacimiento fault are the aligned expression of en echelon basement fault segments that accommodated some degree of right-lateral, strike-slip offset on the eastern and western margins of the basin, combined with southward-vergent thrust faulting from the San

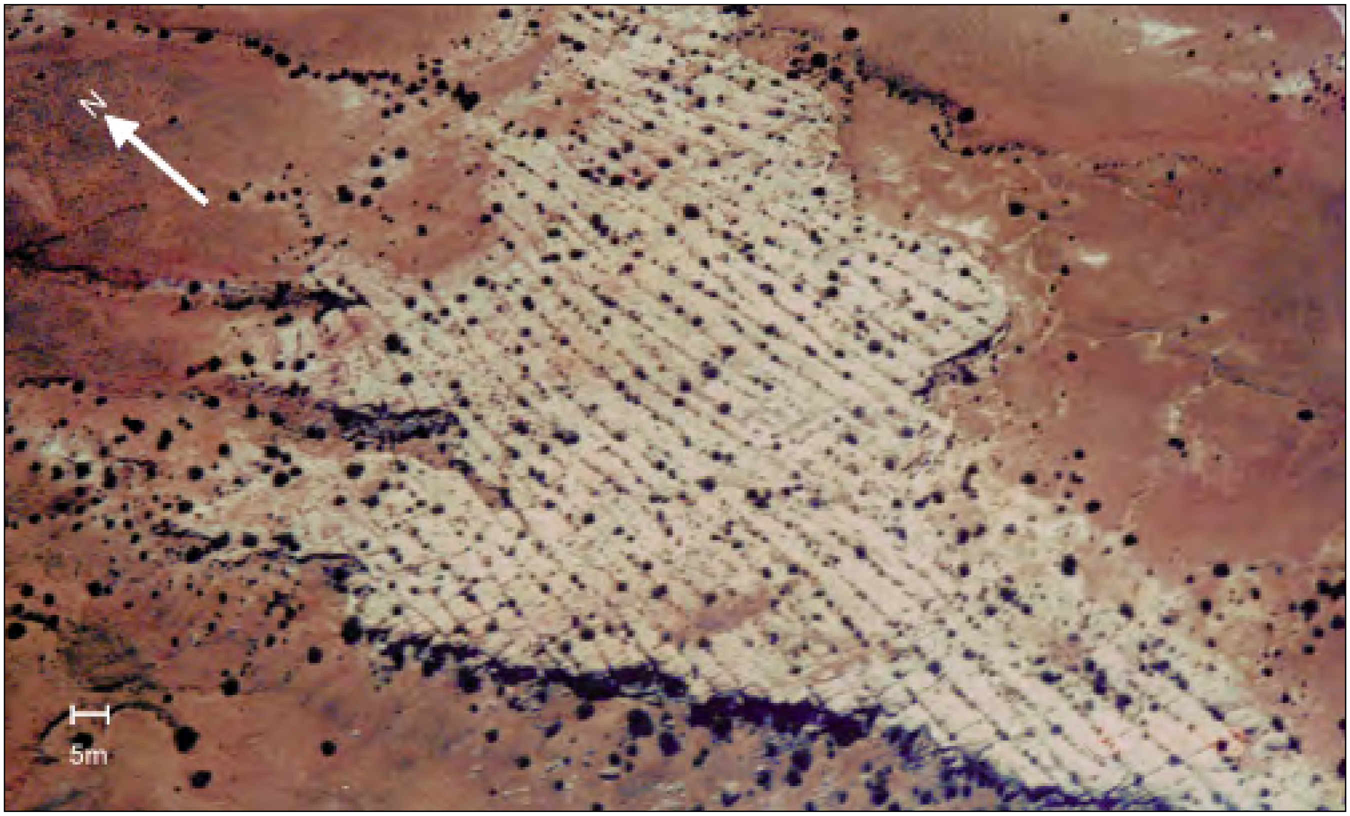

FIGURE 5—Regional extension fractures striking approximately north northeast in early Tertiary rocks southwest of Cuba, New Mexico.

Juan uplift area at the northern margin of the basin. The alignment and connection of these structures into a relatively continuous curvilinear feature that outlines the more stable basement underlying the Central Basin is coincidental.

Outcrop fracture descriptions

The earliest fractures (based on crosscutting relationships) seen in outcrops around the basin typically strike from north-south to north northeast-south southwest. Secondary, local fracture systems associated with local structures are commonly superimposed onto the early fractures, and may even be more numerous or dominant in some outcrops to the point where they obscure the early fracture set. Whereas the secondary fracture sets are typically related to the local structure, the earlier formed, regional Laramide-age fractures consistently strike from north-south to north northeast-south southwest throughout the basin (Figs. 5 and 6). More complete outcrop fracture descriptions are given in Lorenz and Cooper (2001).

The fractured Mesaverde and Dakota reservoirs described here are typically very fine to fine-grained and reasonably well sorted sandstones. Compositionally, the Mesaverde sandstones are relatively immature, whereas Dakota sandstones are mature to quartzitic. The Dakota sandstones are well cemented with siliceous cement except where bioturbation mixed clays into the sandstones before cementation. Mesaverde sandstones are less well cemented, typically with authigenic clay and calcite. This difference in original and diagenetic composition resulted in significantly different mechanical properties (relatively ductile Mesaverde sandstones vs. relatively brittle Dakota sandstones), and thus the two intervals have different fracture characteristics despite having been exposed to the same stress system. Fractures in the immature Mesaverde sandstones typically formed as relatively long, irregular extension fractures, whereas the quartzitic Dakota sandstones contain more numerous but shorter and more closely spaced extension fractures. Many of the Dakota intervals also contain conjugate shear-fracture pairs described in detail below.

Fractures at the northern and southern margins

The oldest, through-going fracture patterns in Dakota and Mesaverde strata at the southern margin of the San Juan Basin most commonly have north northeast-south southwest strikes that are consistent over tens of square miles (Gilkey, 1953; Gilkey and Duschatko, 1953; Santos, 1966; Maxwell, 1976; Kirk and Zech, 1984; Kirk and Sullivan, 1987; Robertson, 1990a, 1990b; Hallett et al., 1999; Fig. 7). Fractures to the northwest of the Zuni uplift have a more north-northwesterly strike. To the north, Point Lookout sandstones of the Mesaverde Group at Chaco Canyon National Historical Park contain younger fracture patterns that appear to have been influenced by the same local structure that created the local east-west trending canyon, but the north-south fracture pattern is still present in the background.

A similar suite of approximately north-south striking, bed-normal extension fractures occurs in the tilted Dakota and Mesaverde sandstones at the north rim of the basin. (All fracture strikes are presented here with bedding rotated back to the horizontal.) Condon (1988, 1997; pers. comm. 1999) mapped fracture strikes around this northern edge of the basin, reporting that the average strike of the earliest fractures ranges from north northwest-south southeast to north-south, varying regularly with stratigraphic and structural position. Finch (1994) reported similar north northwest fracture orientations and photo-lineaments in lower Tertiary strata exposed in the Animas River valley south of Durango.

Our field data at the northern rim of the San Juan Basin generally concur with these earlier observations: i.e., we have measured from north-south to north northeast-south southwest strikes of bed-normal, extension fractures in both the Mesaverde and Dakota sandstones in this area. However, in addition to the extension fractures, two pairs of conjugate shear planes are also present in Dakota sandstones. The Dakota conjugate-fracture pairs have two consistent orientations: 1) bed-normal, with a bed-parallel acute-angle bisector (i.e., strike-slip offset), and 2) oblique to bedding and dipping at shallow angles,

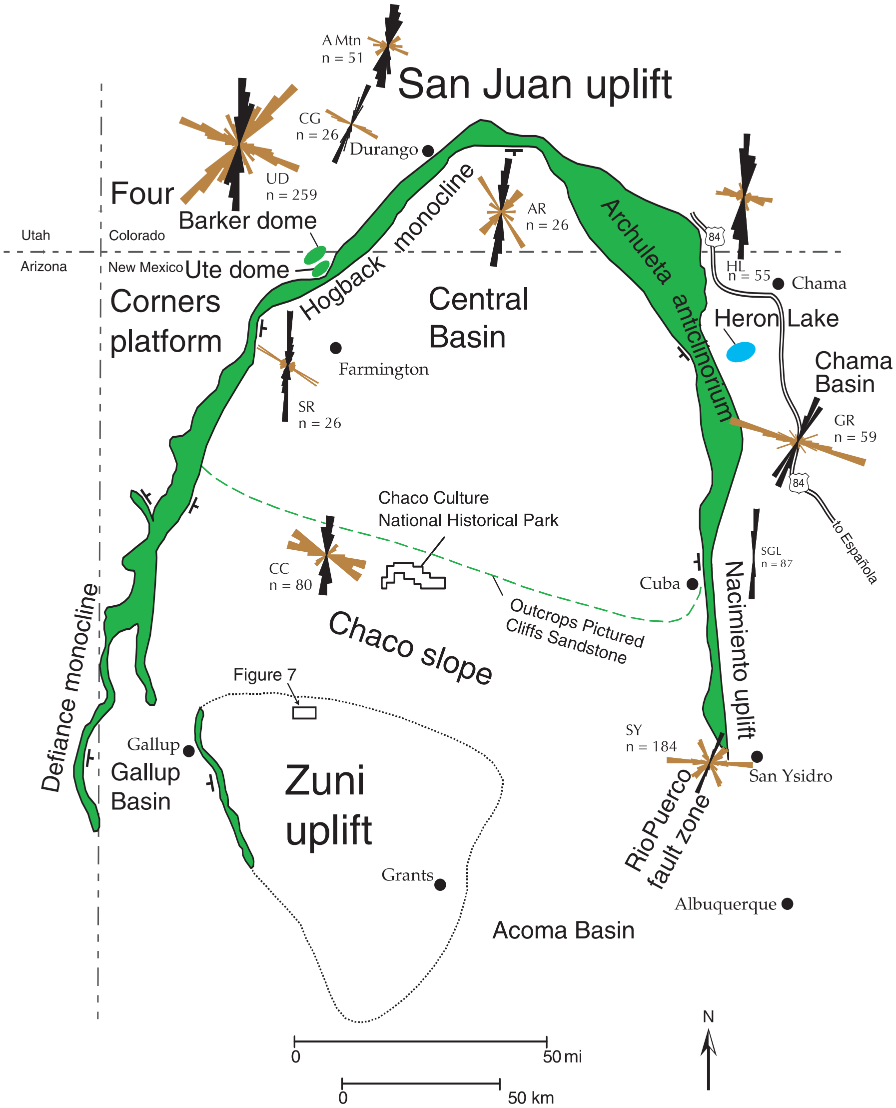

FIGURE 6—Rose diagrams of shear and extension fracture orientations in outcrop. The north to north-northeast oriented extension fractures are shown in black. Diagrams are overlain on an index map illustrating the structural features of the San Juan Basin. Areas of steep dip are shown in green; **CC** = Chaco Canyon, **SR** = Shiprock, **UD** = Ute dome, **CG** = Campground, **A Mtn** = Animas Mountain, **AR** = Animas River, **HL** = Heron Lake, **GR** = Ghost Ranch, **SGL** = San Gregorio Lake, **SY** = San Ysidro (base map modified after Fassett, 1989).

with a bed-parallel, acute-angle bisector (reverse dip-slip/thrust offset). The acute-angle bisectors of both sets strike either northeast-southwest or north-south when bedding is rotated back to horizontal. The relative age relationship between the conjugate fractures and the north-south extension fractures is obscure.

Fractures at the eastern and western basin margins

Multiple sets of fractures are present in Mesaverde strata north and northwest of Farmington. Again, the oldest fracture set along the Hogback and in the adjacent, less-deformed strata is a set of bed-normal extension fractures that strikes north northeast-south southwest. Condon (1988) reports a similar average strike of 15° for these fractures between the Colorado–New Mexico border and Durango. In some areas these are the dominant fractures, whereas in other areas (Fig. 8) they are poorly developed and their presence is obscured by younger fractures.

Cretaceous strata adjacent to the Precambrian-cored Nacimiento block, across the basin on its southeastern side, have been caught up in the steeply dipping cuestas that front the western face of this uplift. These strata contain high-strain deformation structures such as folds and faults, as well as fractures created by the local bulldozing effects of the overthrust uplift. However, Baltz (1967, pp. 62–63) reports that the most conspicuous fractures strike 008–025° in this area, and that these fractures imprint a north northeast-south southwest trending grain onto the topography. Low-altitude, oblique aerial photos show that this generally north northeast-south southwest pattern is also pervasive in the less steeply dipping Mesaverde and Tertiary strata approximately 10 km (6 mi) west of the uplift (Fig. 5), suggesting that this fracturing was not a product of flexure. Moreover, there is a pervasive fabric of closely spaced vertical extension fractures (as dense as 22 fractures/m) striking consistently north-south, parallel to the mountain front, in the granite core of the Nacimiento uplift itself (well exposed near San Gregorio Lake: see Fig. 6).

Outcrops of Dakota sandstones along NM–84 and at Heron Lake, within the Archuleta anticlinorium on the northeastern corner of the basin, show that the north-south to north northeast-south southwest theme of regional vertical extension fractures extends to these areas as well. However, conjugate shear fractures indicating northeast-southwest compression are also present in the outcrops at the latter site.

Discussion

The distinctive, thrust-oriented conjugate fractures at Heron Lake and east of Durango are a significant deviation from the more common north-south extension-fracture fabric. This northeast-southwest directed thrust geometry may fit with the late-stage changes in Laramide motion vectors for the Colorado Plateau area suggested by Bird (1998) among others, or they may represent local variations in stress orientation related to nearby westward- and southwestward-directed thrusting during transpressive wrench faulting.

A northeasterly trending maximum horizontal compression is also suggested by three pairs of conjugate deformation bands found in Jurassic sandstones at the northern end of the Rio Puerco fault zone, southwest of the town of San Ysidro. These three conjugate deformation-band sets are probably related to a late Laramide, local stress array created in the southeastern corner of the basin between the Zuni uplift and the Nacimiento uplift as described above. They document a three-stage increase in the magnitude of the northeast-southwest oriented horizontal compressive stress, as it increased to become the intermediate compressive stress and finally the maximum compressive stress, with no rotation in orientation (Olsson et al., in press).

Sandstones of the overlying Cretaceous Dakota interval at the same San Ysidro location contain a significantly different pattern of fractures, consisting of an apparent conjugate shear fracture pair with strikes of 10–20° and 60–70°. Intersection relationships, however, suggest that the fractures striking 10–20° are an older set, imposed on the rock as extension fractures under the same conditions of north northeast-south southwest maximum horizontal stress seen widely elsewhere in the basin. This set was present as a background fabric, and was reactivated in shear during

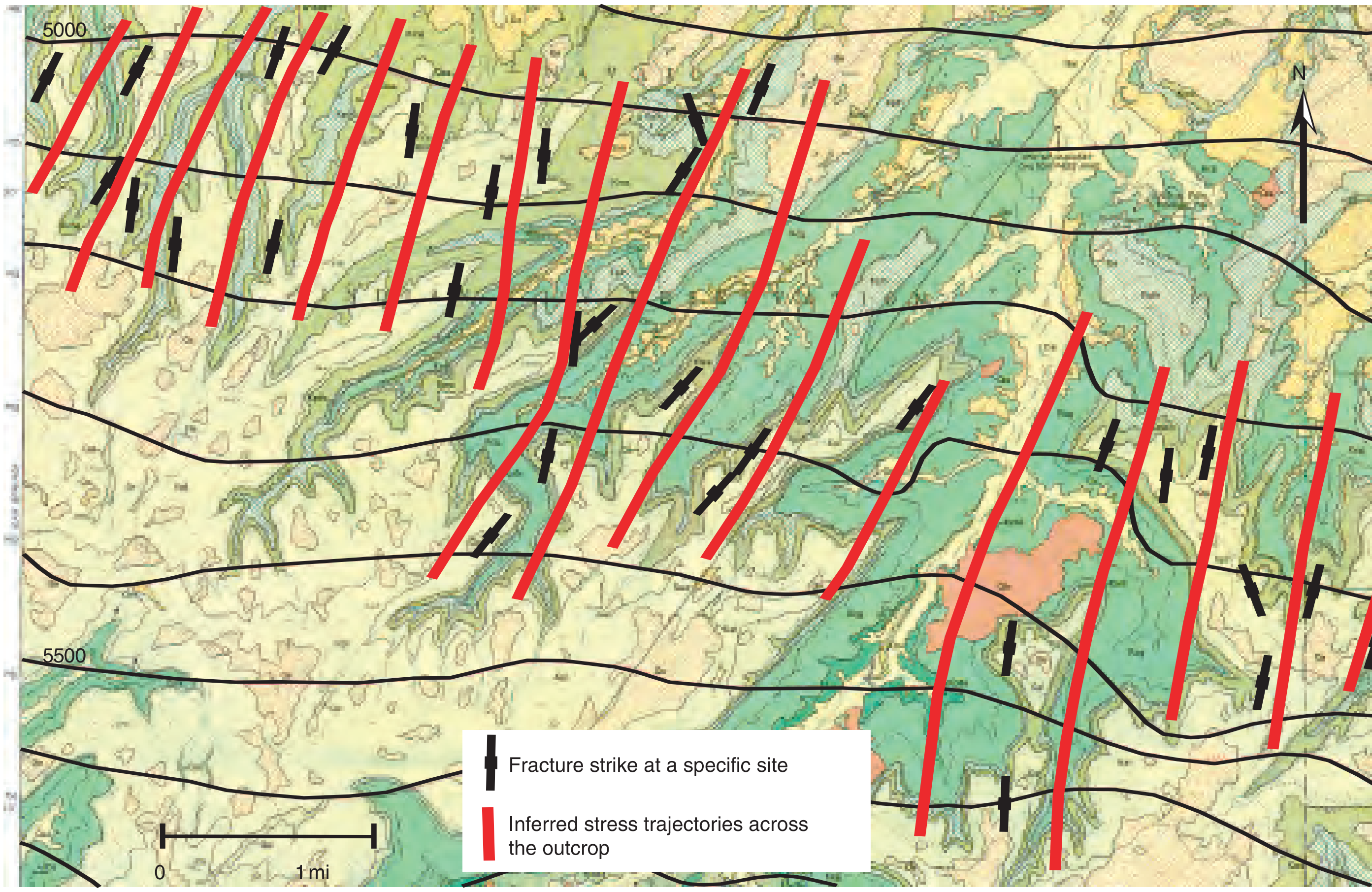

FIGURE 7—Pervasive north northeast to northeast striking natural fractures within the Cretaceous Point Lookout Sandstone of the Mesaverde Group illustrated on the geologic map of the Dalton Pass quadrangle, McKinley County, New Mexico. Structure contours are drawn on the base of the Dakota Sandstone; contour interval is 100 ft (modified from Kirk and Sullivan, 1987). See Figures 4 and 6 for location in the basin.

formation of the younger, 60–70° shear fractures, as it had the optimum strike with respect to the re-oriented stresses to become one set of the conjugate pair. The complementary shear-fracture set of the pair formed ab initio.

Fractures in core

Cores from 19 wells drilled into Mesaverde and Dakota strata and stored at the New Mexico Library of Subsurface Data in Socorro were studied for this project.

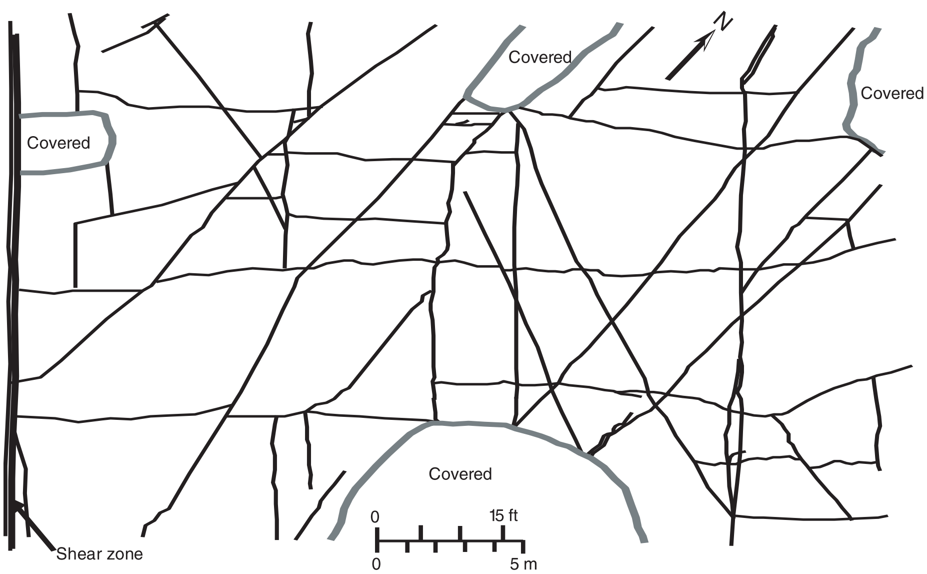

FIGURE 8—Plan-view fracture map on the Hogback monocline east of the town of Shiprock, New Mexico. Note the through-going, oldest, north-south striking fracture set.

These cores were examined in order to document the subsurface fracture characteristics, to compare them with outcrop fracture characteristics, and to provide insights into the viability of extrapolating outcrop fracture data into the subsurface. None of the cores examined for this study were oriented.

Natural fractures in the Mesaverde sandstones are primarily vertical extension fractures filled or partially filled with calcite and/or quartz. Quartz may in fact be an early mineralization phase that is obscured under later calcite layers in most fractures. Most of the cored fractures are less than 1 mm in total width, and the narrower fractures are typically completely occluded by mineralization. Striated bedding-parallel shear fractures are also present locally in Mesaverde sandstones.

Similar but more common vertical extension fractures occur in cores of the underlying Dakota sandstones, although vertical, intersecting conjugate fractures may also be present in this layer (Lorenz et al., 1999). Dakota fractures are filled or partially filled with quartz, calcite, and locally with kaolinite in successive layers or patches. Horizontal stylolites are common in the cleaner Dakota sandstones, and short, wide fractures having variable ori-

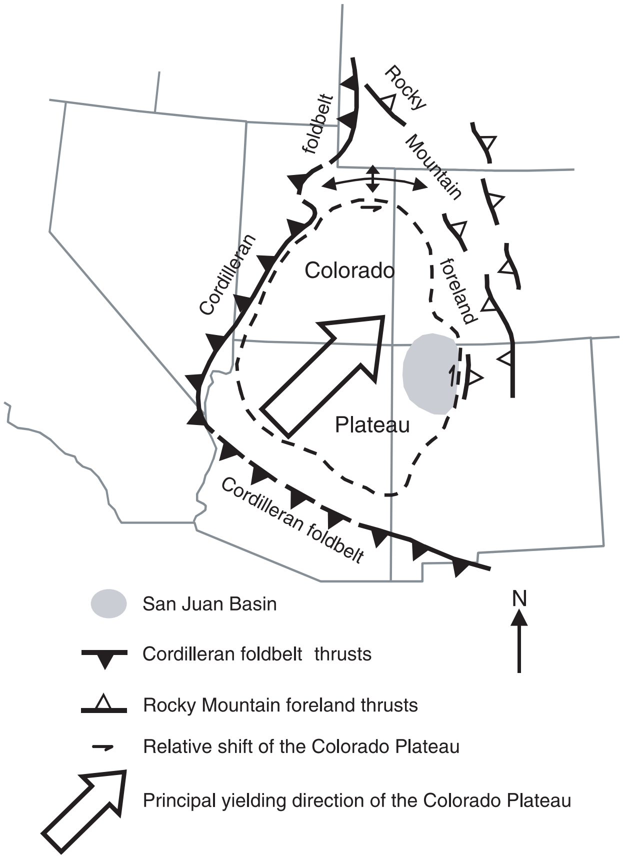

FIGURE 9—Map illustrating the northeastward yielding of the Colorado Plateau relative to the Cordilleran foldbelt, the Rocky Mountain foreland, and the San Juan Basin (modified after Woodward and Callender, 1977).

entations and filled with kaolinite may extend a few tens of centimeters vertically from the larger teeth of the stylolites.

The core data suggest that there is a set of sub-parallel fractures, striking parallel to the maximum in situ horizontal compressive stress (as indicated by associated petal fractures: Lorenz et al., 1990) in the Mesaverde and Dakota subsurface strata. The orientation of this fracture set is not restricted by the data presented here, but published fracture orientations for subsurface core (Ortega and Marrett, 2000; TerBest, 1997; Lorenz et al., 1999) suggest that the same north northeast-south southwest fracture fabric seen in outcrop is also dominant in the subsurface. The east-west fracture indications reported by Ortega and Marrett (2000) for the Sunray H Comp #6 well may be the product of an anomalous stress orientation near the north-south striking Bonito dike (Fig. 1).

This north northeast-south southwest fracture orientation is consistent with production engineering data that show a horizontal permeability anisotropy, on the order of 10:1, elongated in the north-south to north northeast-south southwest direction in Mesaverde reservoirs in many parts of the basin (e.g., Harstad et al., 1998; New Mexico Institute of Mining and Technology, 2000). Such anisotropy should be less pronounced in Dakota reservoirs because of a higher degree of fracturing, but tests measuring the anisotropy for this unit have not been reported.

Tectonic model

The Laramide orogeny, extending from latest Cretaceous through Eocene time, was the first tectonic event to influence the San Juan Basin following deposition of the Dakota and Mesaverde strata under study. Reconstructions suggest that the Colorado Plateau, which encompasses the San Juan Basin within its southeastern corner, was translated northeastward with respect to the Rocky Mountain foreland during the Laramide orogeny (Fig. 9; Kelley, 1957; Woodward and Callender, 1977; Chapin and Cather, 1981; Woodward et al., 1992). In the process, the Colorado Plateau may have been rotated several degrees clockwise about a pole in northern Texas (Hamilton, 1981, 1988). Many northeast-facing Laramide folds within the Cordilleran foldbelt of southwestern New Mexico (Corbitt and Woodward, 1973) document related northeastward yielding.

The descriptions of the individual structural features and their kinematics presented earlier (pages 5–6) can be synthesized into a conceptual model of the tectonic dynamics of the San Juan Basin within its Laramide orogenic setting. The model can be used iteratively to estimate Laramide stress orientations across the basin, to predict the probable orientations of natural fractures that formed under such conditions, and to understand observed fracture patterns in outcrops and the subsurface.

We suggest that most of the strain recorded by the pervasive fracturing of Cretaceous strata in the San Juan Basin was caused by the displacement of the San Juan and Zuni uplifts toward each other, with the San Juan Basin caught between them. The kinematics were ultimately driven by continental-scale, base-of-the-crust crustal subduction, which jostled the basement blocks in the crust below the San Juan Basin against each another along ancient faults. Jostling raised some blocks, such as the San Juan and Zuni uplifts, which were then thrust laterally into the adjacent basin, affecting stresses and creating fractures in the shallower strata. The stress orientations within the sedimentary units filling the basin were the result of the frontal configuration and indentation vectors of these uplifts, and were not directly related to the more regional plate motions and geometries. Orientations of the preexisting faults, more than the orientation of the deep crustal stresses or directions of subduction, dictated the geometry of the resulting structures. In general the resultant stress trajectory was north-south to north northeast-south southwest within the San Juan Basin, as recorded by the fracture sets within the Dakota Sandstone and Mesaverde Group.

Concurrent with indentation from the north and south, basement blocks on either side of the Hogback monocline and Nacimiento uplift were transpressively wrench faulted against each other with a right-lateral sense of motion. Deep-seated Laramide strain was accommodated by basement thrusting at the northern and southern basin margins, and by basement wrenching at the eastern and western margins.

Discussion

Although right-lateral shear was concentrated at the basin margins, small amounts of similar offset probably occurred along the northeast-southwest and northwest-southeast trending basement faults within the basin at this time as well, enhancing fracturing in the immediately overlying strata. Evidence for additional, more pervasive shear within the Cretaceous strata is suggested by conjugate shear fractures found in Dakota cores (Lorenz et al., 1999). Asymmetry between the northern and southern indenters may have contributed to this shear, as the positions of these structures and their directions of thrusting are not directly opposed to each other (Fig. 10). Differential motion of the Colorado Plateau (i.e., faster northeastward movement at the western edge of the basin than at the eastern side: see diagrams of Bird, 1998) also might have contributed to pervasive right-lateral shear.

As described above, the resulting compressional and shear strains in the strata of the basin are recorded by north-south to north northeast-south southwest striking vertical extension fractures within the Mesaverde Group and Dakota Sandstone along with conjugate fractures in the Dakota. High horizontal stresses, coupled with overpressuring in Eocene to Oligocene time (Bond, 1984), would have produced stress conditions and mechanical properties favorable to fracturing.

Most of the observed fracture characteristics and orientations are compatible with this north-south to north northeast-south southwest shortening within the San Juan Basin. In fact, the two pairs of conjugate shear fractures in Dakota strata at the northern edge of the basin (described earlier, page 8) suggest exceptionally strong north-south compression. One conjugate pair has a bed-parallel axis of intersection, and the other has a bed-normal axis of intersection, but both have bed-parallel, acute-angle bisectors that strike approximately north-south. These conjugate, strike-slip, and thrust-oriented fracture pairs are consistent with a southward-directed horizontal compressive force, one that exceeded the magnitude of the overburden stress for a time at these locations.

It is commonly assumed (although not published) that the north-south striking extension fractures in the San Juan Basin formed under conditions of east-west Rio Grande extension. However, extension does not produce strike-slip or reverse-dip-slip conjugate patterns. Only significant compression forms such conjugate geometries, and only the Laramide orogeny produced compression of any sort in the region of the San Juan Basin during post-Jurassic time. Moreover, it is unlikely that the strata hosting north-south extension fractures would have remained unfractured during the high-stress, north-south Laramide compressive conditions that formed the observed conjugate fracture systems. It is plausible, and more likely, that the extension and conjugate fracture systems are genetically related to the same Laramide north-south thrust events, a correlation that is strongly supported by the common symmetry axes of the two fracture systems.

Other conjugate shear fractures (described earlier, page 8) suggest that locally, as at Heron Lake in the northeast corner of the basin and near San Ysidro in the southeastern corner of the basin, the maximum horizontal compressive stress was oriented northeast-southwest. These shear fractures may be related to a late Laramide stress superimposed locally onto strata in the corners of the basin. Possible sources of northeast-southwest compression in parts of the basin include a change from wrench faulting to overthrusting along the Nacimiento front (Woodward et al., 1972), resulting in compression of the strata between that front and northeastward indentation of the Zuni uplift.

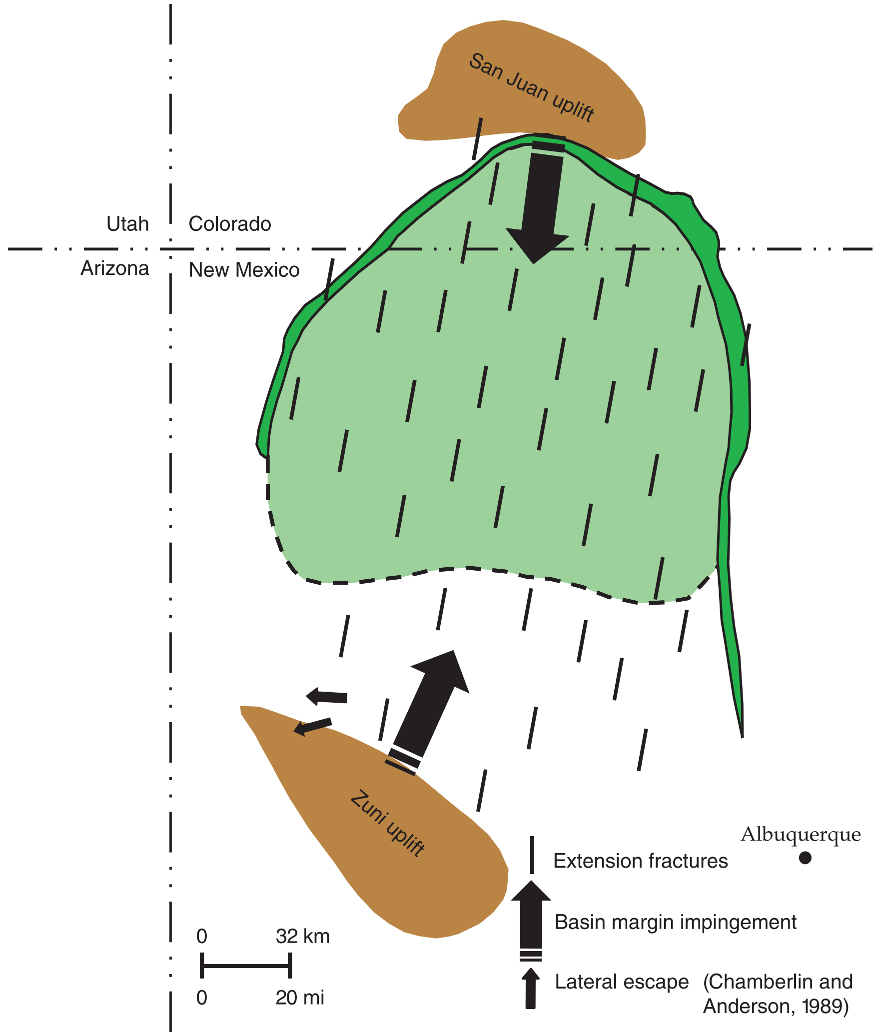

FIGURE 10—Tectonic fracture model of the San Juan Basin. A dominant oldest set of vertical extension fractures striking primarily north northeast-south southwest is observed across the basin. These features are primarily the result of southward and northward indentation of the San Juan and Zuni uplifts, respectively (base map after Kelley, 1957).

Laramide shortening was replaced by incipient Basin and Range extension in west-central New Mexico approximately 36 million years ago (Cather, 1989), and extensional structures related to the Rio Grande rift have overprinted parts of the San Juan Basin. The east-west Basin and Range extensional tectonic system has axes of symmetry that are, coincidentally, nearly parallel to the shallow Laramide stress axes. However, whereas Laramide tectonics were derived from an increase in the north-south horizontal compressive stress, the later extensile regime involved a decrease in the east-west horizontal compressive stress. Some large-scale paleostress indicators, such as the post-Laramide (Miocene), north-south trending Archuleta dike swarm in the northeastern corner of the basin (Fig. 1), represent a response to Rio Grande rift extension.

Post-Laramide extension fractures with north-south strikes could conceivably have formed in the Cretaceous strata in this extensional setting. However, earlier fracturing is the preferred interpretation because extension can not account for the conjugate fracture pairs, many examples of shear, or for the north-south thrusting seen in the outcrop and subsurface at several scales. Moreover, extensional faulting of the crust would concentrate fractures over the normal faults rather than producing the pervasive, dilational fracture texture observed. Baltz (1967, 1978) in fact suggested that there is little or no evidence for late Tertiary east-west extension across northern New Mexico, other than the normal faults that accommodate the rift itself and the north-south striking igneous dikes.

It is not the intent of this paper to contribute to the discussion of the different models currently under consideration for Laramide kinematics in the southern Rocky Mountain region (e.g., Cather, 1999; Erslev, 2001; Bird, 1998; Yin and Ingersol, 1997). Rather, our intent is to integrate the aspects of those different models that are compatible with fracturing in the San Juan Basin, recognizing that the fractures that record Laramide stresses in the shallow reservoir rocks do not necessarily reflect the contemporaneous basement-level stresses and kinematics. At the simplest level, our fracture data support dilation and fracturing of the Cretaceous strata from compression along a north-south to north northeast-south southwest axis, with evidence for compression along a northeast-southwest axis at certain localities.

Subsurface stresses

Stress is important in that 1) it creates and orients natural fractures, 2) it dictates, along with mechanical properties, the behavior of fractures during hydrocarbon production (Lorenz, 1999), and 3) it dictates the orientation and behavior of hydraulic stimulation fractures. However, few measurements documenting the in situ stress orientations within the shallow reservoirs of the San Juan Basin have been made, and fewer published. The large, north-south striking Tertiary dikes of the Archuleta dike swarm (Fig. 1), clustered in the northeastern part of the basin and scattered sparsely elsewhere, suggest that the maximum in situ horizontal stress was oriented north-south during the time of intrusion (Miocene). This does not constrain either the stress orientations at the significantly earlier time of fracturing, or the current stress conditions.

Present-day subsurface stress-orientation indicators include coring-induced petal fractures in oriented core, and wellbore breakouts seen in oriented caliper or wellbore-image logs. Lorenz et al. (1999), and unpublished company reports, suggest that these indicators in the San Juan Basin show a maximum horizontal compressive stress striking consistently from north-south to north northeast-south southwest across most of the interior basin, consistent with the engineering permeability-anisotropy data. A wellbore-image log run recently by Marathon near the Hogback northwest of Farmington recorded a 035° maximum horizontal stress orientation (J. Bucci, pers. comm. 2000).

Yale et al. (1993) reported a nearly northeast-southwest (41°) trend for the maximum horizontal compressive stress in four wells in an unspecified field in the southeastern corner of the basin. This probably reflects a late Laramide influence of the nearby Nacimiento uplift. The northeast-southwest trending maximum horizontal compressive stress does not appear to be widespread within the basin.

These subsurface fracture and stress patterns control a significant horizontal permeability anisotropy in the Cretaceous reservoirs of the San Juan Basin, and support the tectonic model presented earlier. The orientation of this stress anisotropy has not been significantly modified by the younger east-west extensional tectonics associated with Rio Grande rifting.

Summary

The conceptual model constructed here for the tectonic setting in which Cretaceous reservoirs in the San Juan Basin fractured suggests that an approximately north-south directed compressive stress created fractures in the shallow reservoir strata during the Laramide orogeny. This stress system resulted indirectly from northeastward translation of the San Juan Basin as part of the Colorado Plateau, during which the basin was caught between southward indentation of the San Juan uplift and north- to northeastward indentation of the Zuni uplift. Contemporaneous, right-lateral wrench motion was concentrated along the Nacimiento uplift and Hogback monocline, defining the margins of the inner basin. These shallow, basin-scale stresses were controlled by local basement-seated structures and thus were the indirect product of, but not co-linear with, continental-scale, Laramide crustal dynamics.

Within this framework, a set of vertical extension fractures, striking generally from north-south to north northeast-south southwest (but with local variations), was formed in both Mesaverde and Dakota sandstones. Additional sets of conjugate shear fractures were created in some of the Dakota strata. Fractures in the immature Mesaverde sandstones typically formed as relatively long, irregular extension fractures, whereas the quartzitic Dakota sandstones contain short, sub-parallel, closely spaced extension fractures. These fractures are a primary control on hydrocarbon production within the Cretaceous-age tight-gas sandstone reservoirs of the San Juan Basin.

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Gallery of Geology
Tierra Amarilla anticline

This photo, looking north, shows the Tierra Amarilla anticline, located 4 mi southwest of the village of San Ysidro, New Mexico. The feature is surely a fine example of an anticline and probably the most accessible anticline in New Mexico.

The sharp flanks of this Laramide-age structure are held up by the light-colored Todilto Formation overlying the Entrada Sandstone, both of Middle Jurassic age. The soft underlying slopes are made up of the Upper Triassic Petrified Forest Formation of the Chinle Group.

The raised core of the structure in the valley is underlain by a welt of highly contorted Petrified Forest mudstones and channel sandstones. The core is capped by a carapace of Pleistocene and Holocene travertine. The older travertine reaches a maximum thickness of about 10 m (33 ft). This competent material slopes away from the linear crest, has rifted along an axial fault system, and is gliding and breaking up downslope over the incompetent Petrified Forest mudstones. Some springs are still active and deposit cascading tongues of light-colored travertine along the north (not seen in this photo) and west sides of the core. The light-colored horizontal strip in the upper right of the photo is the stream bed of the Rio Salado, and just beyond it (but not visible) is US–550 and the southern tip of the Nacimiento uplift.

The southern two-thirds or so of the anticline is on U.S. Bureau of Land Management (BLM) land (secs. 21 and 28 T15N R1E). The northern one-third is on New Mexico state land (sec. 16 T15N R1E). Access to the BLM part is from a parking spot along Cabezon Road on the south. Access to the northern part is either from the same southerly route with a longer walk or from the north over a tricky four-wheel-drive road that crosses a parcel of land recently acquired by Zia Pueblo. One needs to purchase a permit to set boot on the state-owned land.

—Dirk Van Hart
Photo taken on May 25, 2001