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 N-S to NNE-SSW 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 basin margins of the basin to form the Hogback Monocline and the Nacimiento Uplift at the same time, and small amounts of shear may have been pervasive within the basin as well. Vertical extension fractures, striking N-S to NNE-SSW with local variations (parallel to the Laramide maximum horizontal compressive stress), formed in both Mesaverde and Dakota sandstones under this system, and are found in outcrops and in the subsurface of the San Juan Basin. The immature Mesaverde sandstones typically contain relatively long, irregular, vertical extension fractures, whereas the quartzitic Dakota sandstones contain more numerous, shorter, sub-parallel, closely spaced, extension fractures. Conjugate shear planes in several orientations are also present locally in the Dakota strata.

DISCLAIMER

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INTRODUCTION

Purpose. This report is two-fold: 1) it provides a brief characterization of natural fractures that control the production of natural gas from the sandstone reservoirs in the Mesaverde and Dakota intervals in the San Juan Basin, and 2) it reconstructs a plausible tectonic framework for the genesis of these fractures. Since the tectonic model was not based on the fracture study but was iteratively derived from the fracture data and study of the structure of the basin, we have presented the tectonic model first. This might seem backwards, but in fact the tectonic model was only developed in order to gain an understanding of the natural fracture systems in the basin, as the purpose of the original study was to understand the fracture control on reservoir plumbing in the basin. The tectonic model presented here provides a basis for extrapolations of fracture characteristics from outcrops to subsurface and for predicting 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 from the National Technical Information Service.

Location and General Geology. The San Juan Basin of northwestern New Mexico and southwestern Colorado is asymmetric, with strata dipping gently to the north and northeast toward the off-center synclinal hinge located near the Colorado-New Mexico state line (**Fig. 1**). Regional structure reverses at the basin axis, and dips are steeper, back toward the southwest, in the northern third of the basin.

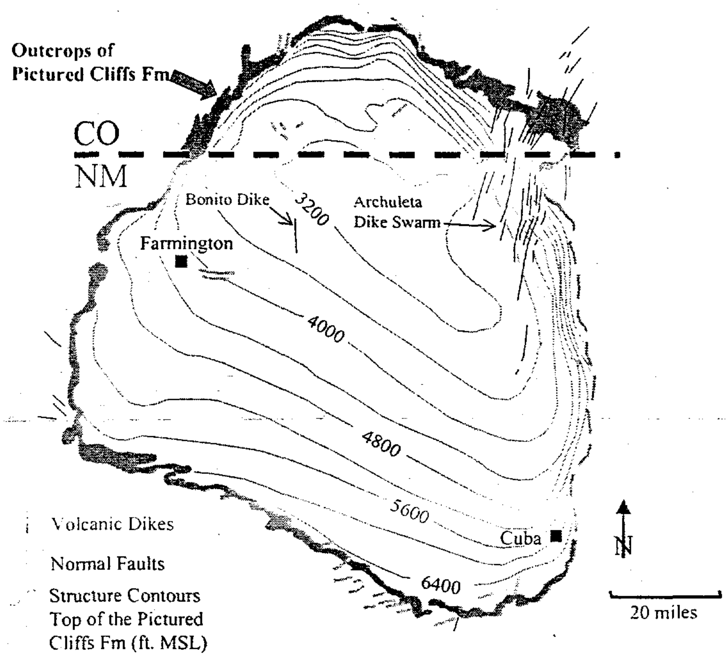

Figure 1: Structure contour map of the inner or central section of the San Juan Basin. Contours are drawn on the top of the Pictured Cliffs Formation. The basin is asymmetric with the northwest striking synclinal hinge nearer the northern edge of the basin.

Most of the hydrocarbon production from the San Juan basin comes from an inner zone, approximately delineated by the outcrop belt of the Pictured Cliffs sandstone and separated from the peripheral areas by a relatively continuous hogback nearly 400 km long, consisting of gently-dipping to near-vertical strata. As described below, however, despite the apparent continuity of this feature, the Hogback does not have a common mechanical origin along its entire length. Cretaceous strata crop out at the margins of the San Juan Basin and extend into the subsurface to depths as great as 2500 m, 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 2500 m 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 the horizontal stylolites that are locally common in Dakota sandstone cores.

Previous work. Published structural studies associated with the San Juan basin have focused on the specific tectonic elements bounding the basin (e.g., the Nacimiento uplift: Woodward, 1987; Baltz, 1967), or have dealt with the basin as a sub-unit within the Colorado Plateau (e.g., Chapin and Cather, 1981; Cather, 1999). Taylor and Huffman (1988; 1998) have published several seismic sections across the monoclines that bound the inner basin, suggesting locally significant thrust indentation and overhang at the basin margins. Erslev (2001) and Cather (1999) have interpreted the structural composition 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 have been primarily descriptive, and have concentrated on outcrops of Mesaverde strata (e.g., Whitehead, 1997; Tremain et al., 1991; Laubach, 1992). These studies have suggested a demarcation in surface fracture domains that is approximately coincident with the New Mexico-Colorado border. This demarcation has not been apparent during the course of this study, perhaps because this study has concentrated on the oldest fractures present in the outcrops, those fractures not related to folding and uplift and that are therefore most likely to be present in the subsurface. Whitehead (1997) has even suggested that many of the fractures in outcrops, particularly on the Chaco Slope area, are due entirely to 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.

Kelley (1957) and Kelley and Clinton (1960) also noted 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 have inferred 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) have published subsurface fracture data for the Mesaverde for three wells in the central part of the basin, and Lorenz et al. (1999) presented a preliminary synthesis of the tectonic framework of the basin based on wellbore-image logs and measured fracture characteristics in 32 Dakota cores. The following interpretations build on the Lorenz et al. (1999) conclusions, expanding them to encompass Mesaverde reservoirs.

TECTONIC SETTING

Introduction. The inner part of the San Juan Basin appears to be relatively structureless despite low-amplitude flexures and gentle, regional dips. However, the basin is underlain by a Proterozoic crystalline basement with numerous ancient and locally re-activated faults trending NE-SW and NW-SE (Taylor and Huffman, 1998). These faults may have been important controls on the fracture patterns in the strata directly overlying basement faults, but we suggest here that the tectonic elements surrounding the basin provided the main controls in forming the pervasive, regional fractures pattern found in the reservoirs.

The principal tectonic elements 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. 2**). 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).

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 dip to the north and northeast, but includes broad folds and significant fault zones. The Zuni Uplift is a deceptively small tectonic unit that played a major role in fracturing the basin strata. There is over 4000 m 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).

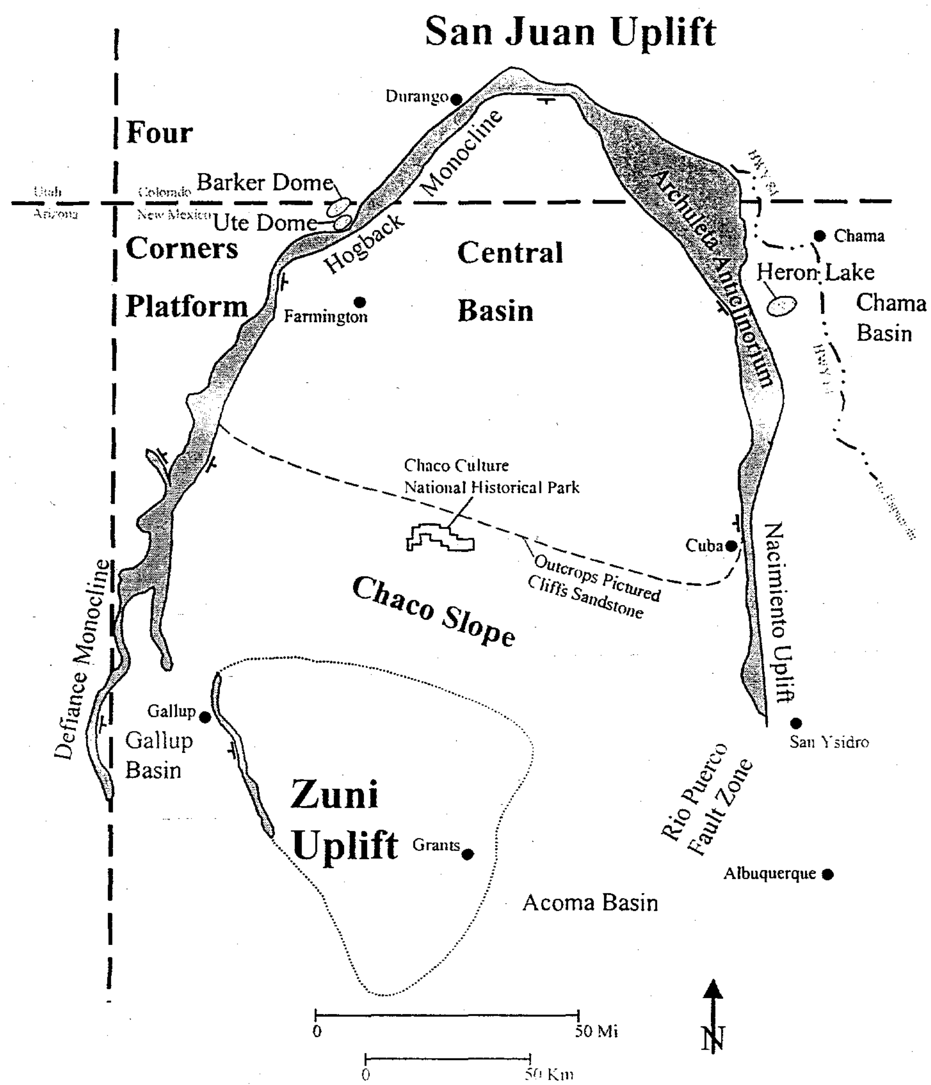

Figure 2: Index map showing the structural elements of the San Juan Basin. Areas of steep dip (monoclines) are shown as patterned areas with the direction of dip indicated by strike and dip tic marks; long dashed line separates the Chaco Slope from the Central Basin and is drawn approximately where the Pictured Cliffs Sandstone is subaerially exposed (modified from Fassett, 1989).

The Zuni Uplift has had a compound tectonic history, going back as far as late Paleozoic time (Jentgen, 1977), but Chamberlin and Anderson (1989) have suggested 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 north- 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. 3**). As much as five km of left-lateral slip has been 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 in diameter, lies immediately north of the Hogback Monocline. It has been partially obscured by the superimposed, Tertiary, San Juan volcanic complex. Kelley noted that the floor of the San Juan Basin "is tilted northward and its deepest part generally adjoins the greater uplift of the San Juan Uplift as though they were counterparts of a single mechanism at depth" as far back as 1957. Over time this concept has been forgotten, and the San Juan Uplift has been referred to only briefly as a Laramide structure (Steven, 1975), or else largely dismissed as a relatively passive dome that was magically elevated, and essentially disconnected from the San Juan Basin.

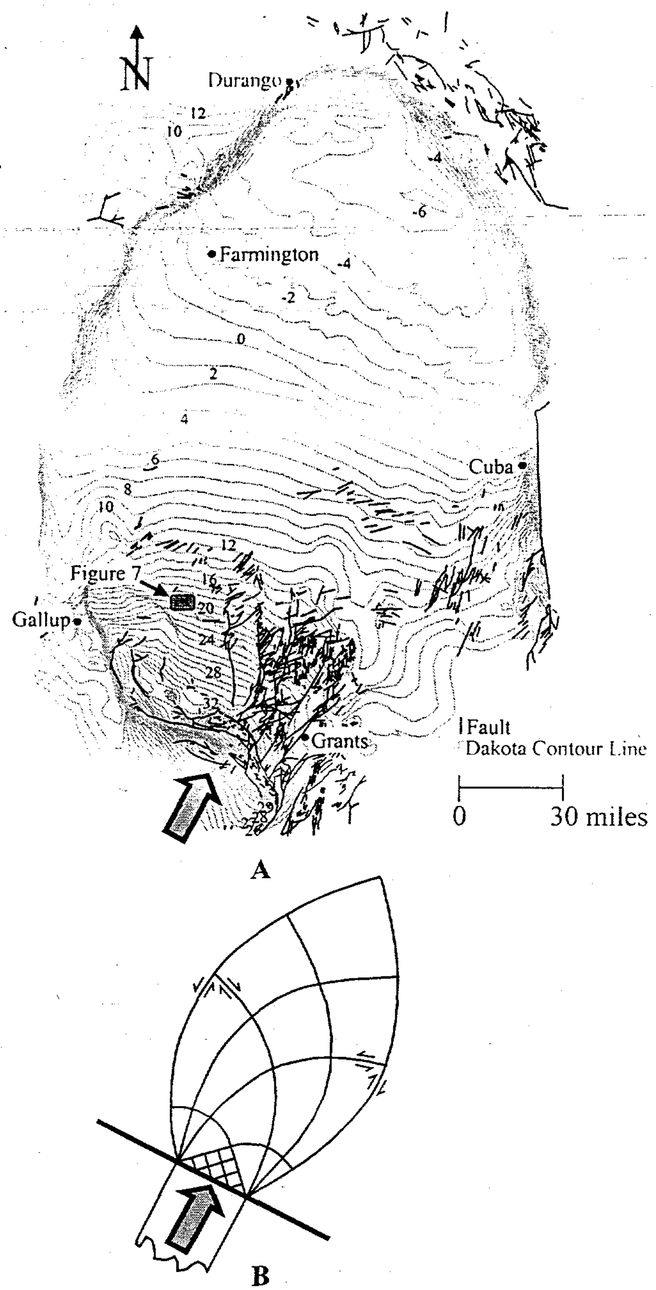

Figure 3: A) Structure map of the San Juan basin, contours drawn on the base of the Dakota Sandstone with intervals of meters x 100 relative to mean sea level. (Modified after Thaden and Zech, 1986). Faults (shown in black) along the southern margin of the basin are oriented in an array which resembles 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).

However, Precambrian rocks within this structure are now positioned at least 4300 m above sea level, and approximately 6100 m of structural relief separate the top of the uplift from the deepest portions of the adjacent basin. Much of the difference (3500 m) is taken up across the short distance spanned by the Hogback Monocline that 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.

Our field studies have found southward-directed slips along shaley bedding-planes documenting similar, though smaller-scale, southward-directed motion. North-south striking extension fractures found in the strata forming the adjacent Hogback also record a north-south trending maximum horizontal compressive stress along this margin of the basin.

The structural relief forming the San Juan Uplift, and the geometry of the adjacent asymmetric basin, are similar in form and magnitude to those of the thrust-bounded Uinta Uplift and adjacent Uinta basin. We suggest that the San Juan Uplift was thrust southward toward the San Juan Basin during Laramide time, forming the east-west trending section of the Hogback Monocline. Thrusting of the San Juan Uplift and the Zuni Uplift was the major source for an approximately N-S directed, horizontal compressive stress that created N-S striking extension fractures within the 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 about 13 km 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. This structure has a compound 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 1200 m 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.

The Hogback 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).

To the east, Huffman and Taylor (1999) have presented 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 3000 m of total structural relief separate the uplift from the adjacent basin.

The Laramide history of the Nacimiento uplift has been interpreted in different ways. Early interpretations (Renick, 1931) indicated that it was a westward overthrust, but further mapping suggested that an early phase of right-lateral offset of 3-5 km formed the NNW-SSE striking en echelon folds along the western margin of the uplift (Baltz, 1967; Woodward et al., 1972; Woodward et al., 1992). Right lateral offset along the western margin has been interpreted to be up to 33 km (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) have 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).

The southern end of the Nacimiento Uplift transitions southward into northeast-striking normal faults of the Rio Puerco Fault Zone. Slack and Campbell (1976), and Slack (1973) suggested this zone was the result of right lateral wrench movement with an offset of less than 2.5 km. The fault zone has been related to right-lateral Laramide deformation induced by north-northeast directed, regional horizontal compression (Slack and Campbell, 1976).

Tectonic Element 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 is 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 Juan uplift area at the northern margin of the basin. The Zuni Uplift has less dramatic expression, but was equally important. The alignment and connection of these structures into a single curvilinear feature, outlining the more stable basement underlying the central basin, was in effect coincidental.

TECTONIC MODEL

Introduction. 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. Regional, base-of-the-crust traction probably provided a mechanism for the formation of the local basement-block uplifts (e.g., Bird, 1998). 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. 4**). In the process, it may have been rotated several degrees clockwise about a pole in northern Texas (Kelley, 1957; Woodward and Callender, 1977; Chapin and Cather, 1981; Woodward et al., 1992; Bird, 1998). Numerous northeast-facing Laramide folds within the Cordilleran Foldbelt of southwestern New Mexico (Corbitt and Woodward, 1973) document related northeastward yielding.

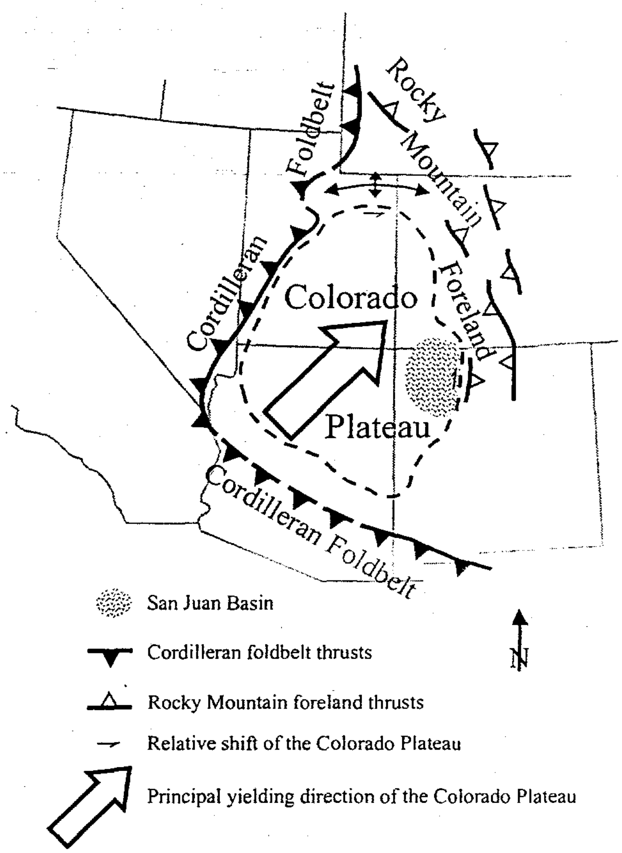

Figure 4: Map illustrating the northeastward yielding of the Colorado Plateau relative to the Cordilleran foldbelt, the Rocky Mountain foreland and the San Juan Basin (modified after Woodward et al., 1992).

The descriptions of the individual structural elements and their kinematics presented above can be synthesized into a conceptual model of the tectonic dynamics of the San Juan Basin within its Laramide orogenic setting. This model can then be used to iteratively 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.

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, into block-faulted units which were then thrust laterally into the adjacent basin, affecting stresses and fracturing 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 pre-existing 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 N-S to NNE-SSW within the San Juan Basin, as recorded by the fracture sets within the Dakota Sandstone and Mesaverde Group.

Concurrently 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. Laramide deep-seated 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 NE-SW and NW-SE 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. 5**). 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) might also have contributed to pervasive right-lateral shear.

As described below, the resulting compressional and shear strains in the strata of the basin are recorded by N-S to NNE-SSW 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 N-S to NNE-SSW shortening within the San Juan Basin. In fact, two pairs of conjugate shear fractures present locally in Dakota strata at the northern edge of the basin suggest exceptionally strong N-S 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 N-S. 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 at some point.

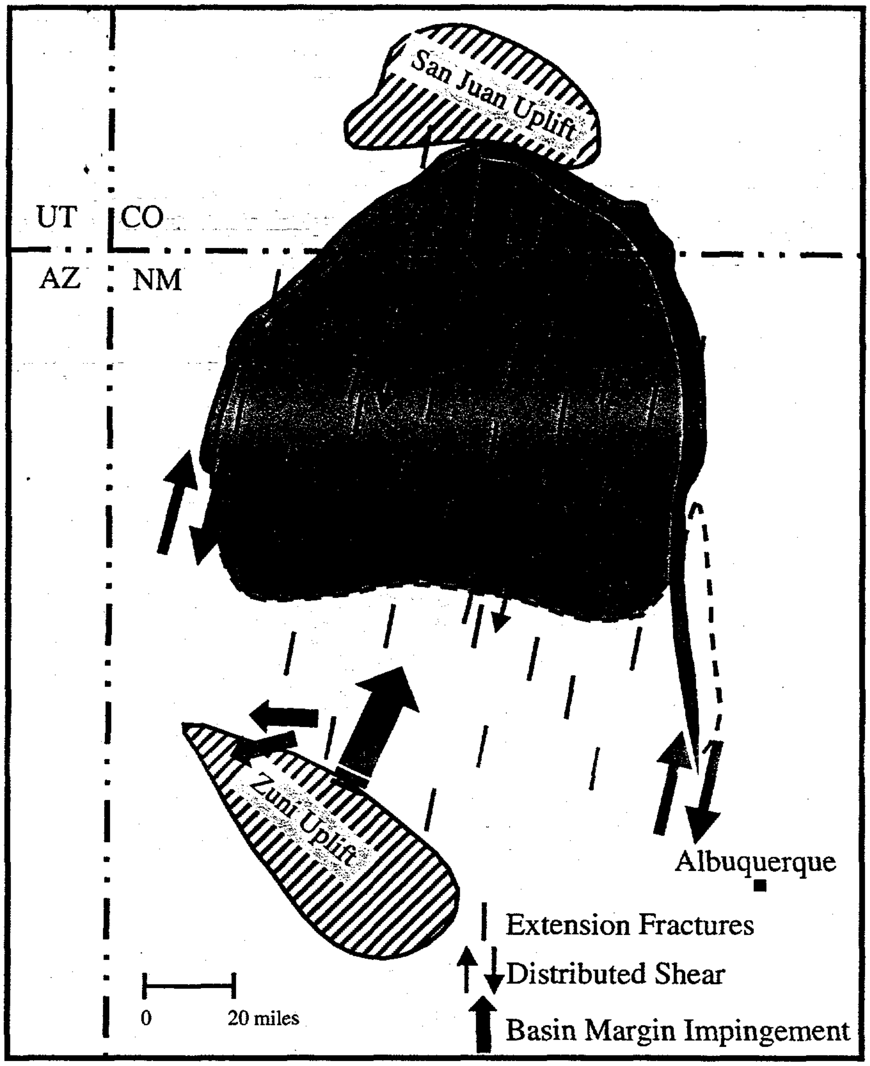

Figure 5: Tectonic fracture model of the San Juan basin. A dominant oldest set of vertical extension fractures striking primarily NNE-SSW is observed across the basin. Pervasive right lateral shear is also observed across the basin. These features are primarily the result of southward and northward indentation of the San Juan and Zuni uplifts respectively (base map after Kelley, 1957).

Other conjugate shear fractures (described below) 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 NE-SW. These may be related to a late-Laramide stress superimposed locally onto strata in the corners of the basin. Possible sources of NE-SW compression in parts of the basin include a change from wrench faulting to overthrusting along the Nacimiento front, resulting in compression of the strata between that front and northeastward indentation of the Zuni Uplift.

Laramide shortening was replaced by 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 E-W, Basin and Range extensional tectonic system has axes of symmetry that are, coincidently, nearly parallel to the shallow Laramide tectonic/stress axes. However, whereas Laramide tectonics were derived from an increase in the N-S horizontal compressive stress, the later, extensile regime involved a decrease in the E-W horizontal compressive stress. Some large-scale paleostress indicators, such as the Post-Laramide (Miocene), N-S trending, Archuleta dike swarm in the northeastern corner of the basin, represent a response to Rio Grande rift extension.

Post-Laramide extension fractures with N-S strikes could conceivably have formed in the Cretaceous strata in this extensional setting. However, the Cretaceous reservoirs had probably already fractured by this time and were not noticeably affected by E-W extension. Earlier fracturing is preferred because extension would not account for the numerous examples of shear and 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 E-W extension across northern New Mexico, other than the normal faults which accommodate the rift itself and the N-S striking igneous dikes.

It is not the intent of this paper to contribute to 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, summarized below, support dilation and fracturing of the Cretaceous strata due to compression along a N-S to NNE-SSW axis, with compelling evidence for localized but strong compression along a NE-SW axis.

OUTCROP FRACTURE DESCRIPTIONS

Introduction. The outcrop fracture descriptions given here are abbreviated due to space constraints: more complete descriptions are given in Lorenz and Cooper (2001). The earliest fractures seen in outcrops around the basin typically strike N-S to NNE-SSW. 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. However, the secondary fracture sets can typically be related to the local structure, whereas there is a pervasive theme of early-formed, generally N-S to NNE-SSW striking regional fractures of Laramide age around the basin (**Fig 6**).

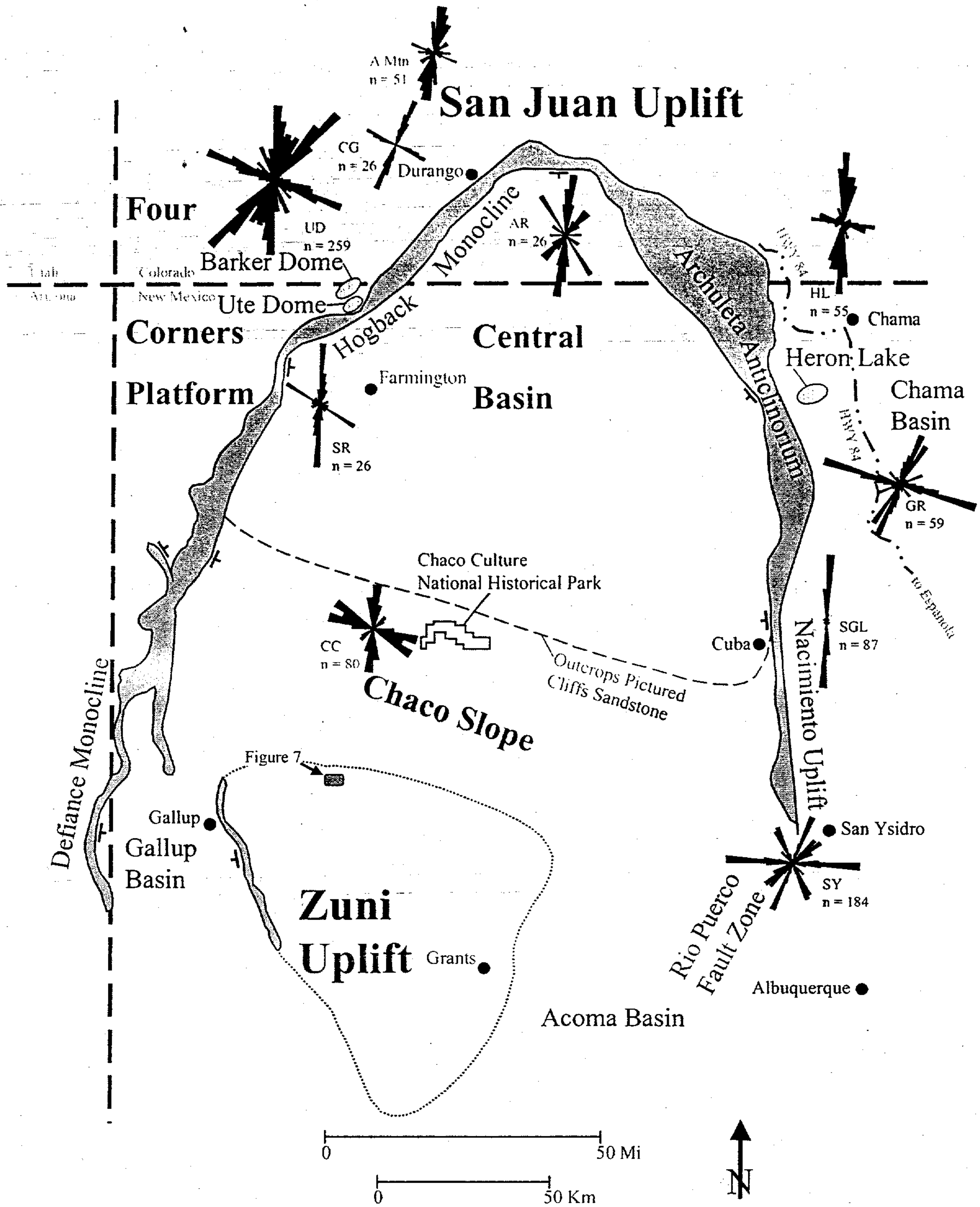

Figure 6: Rose diagrams of fracture orientations in outcrop. Diagrams are overlain on an index map illustrating the structural elements of the San Juan Basin. Areas of steep dip are shown in gray; CC = Chaco Canyon, SR = Shiprock, UD = Ute Dome, CG = Campground, A Mtn = Animas Mountain, AR = Animas River, HL = Heron Lake, GR = Ghost Ranch, SGL = San Gregorio Lake, SY = San Ysidro (base map modified after Fassett, 1989).

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 typically mature to quartzitic. The Dakota sandstones are well cemented with siliceous cement except where bioturbation has mixed clays into the sandstones. 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.

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 NNE-SSW strikes that are consistent over tens of square miles (Gilkey, 1953; Gilkey and Duschatko, 1953; Hallett et al, 1999; USGS Geologic Quadrangle maps; **Fig. 7**). Fractures farther to the northwest of the Zuni Uplift have a more north-northwesterly strike. To the north, Point Lookout sandstones 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 N-S fracture pattern is still present in the background.

A similar suite of approximately north-south striking, bed-normal extension fractures is present in 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; personal communication 1999) mapped fracture strikes around this northern edge of the basin, reporting that the average strike of the earliest fractures ranges from NNW-SSE to N-S, varying regularly with stratigraphic and structural position. Finch (1994) reported similar NNW fracture orientations and photo-lineaments in lower Tertiary strata exposed in the Animas river valley south of Durango.

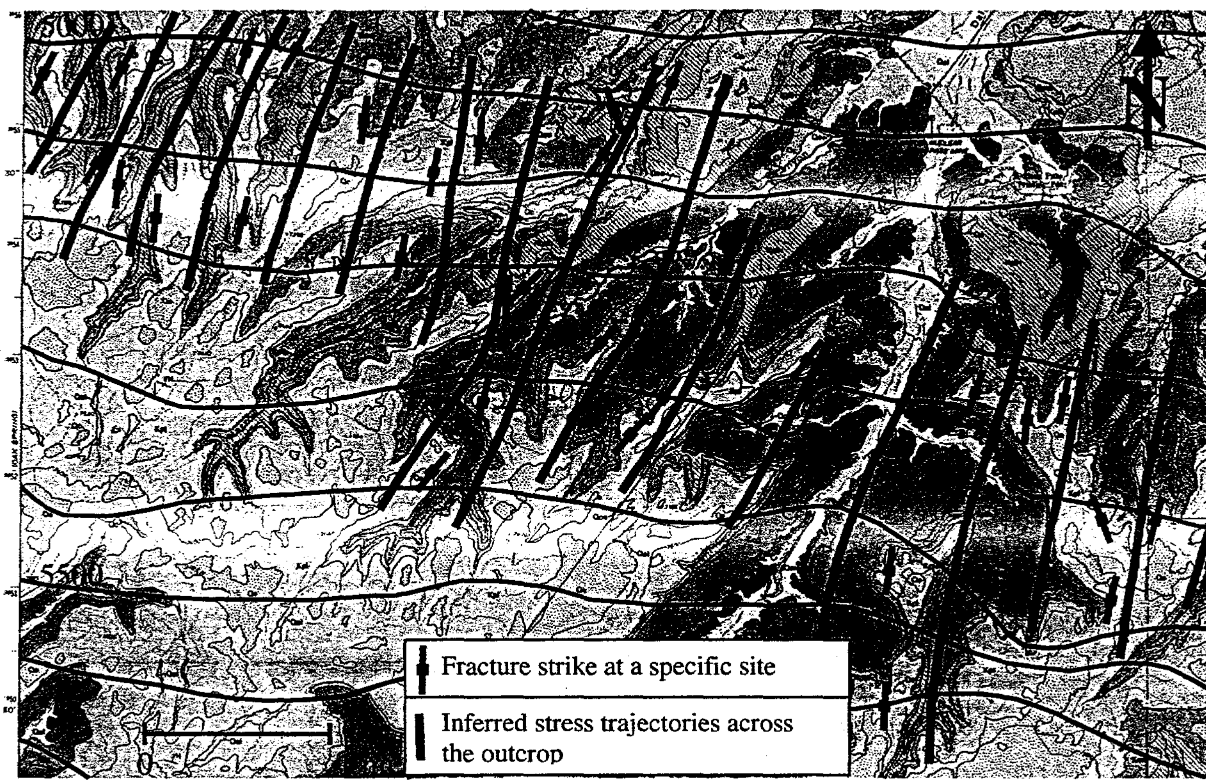

Figure 7: Pervasive NNE to NE striking natural fractures within the Cretaceous Point Lookout sandstone member of the Mesaverde Group illustrated on the geologic map of the Dalton Pass quadrangle, McKinley County, New Mexico. Structure contours are drawn on the base of the Dakota Sandstone; contour interval is 100 ft (modified from Kirk and Sullivan, 1987). See Figures 3 and 6 for location in the basin.

Our field data at the northern rim of the San Juan basin generally concur with these earlier observations: i.e., we have measured N-S to NNE-SSW 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 are consistently oriented 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, with a bed-parallel, acute-angle bisector (reverse dip-slip/thrust offset). The acute-angle bisectors of both sets strike either NE-SW or N-S when bedding is rotated back to horizontal. The relative age relationship between the conjugate fractures and the N-S 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 NNE-SSW (**Fig. 8**). Condon (1988) reports a similar average strike of 15° for these fractures between the Colorado-New Mexico line and Durango. In some areas these are the dominant fractures, in other areas 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, p. 62-63) reports that the most conspicuous fractures strike 8-25° in this area, and that these fractures imprint a NNE-

SSW trending grain onto the topography. Low-altitude, oblique aerial photos show that this generally NNE-SSW pattern is also present in the less steeply dipping Mesaverde strata about 10 km west of the uplift, suggesting that this fracturing was not a product of flexure. Moreover, there is a pervasive fabric of closely spaced vertical-extension fractures (up to 22 fractures/m) striking consistently N-S, parallel to the mountain front, in the granite core of the Nacimiento uplift itself (well exposed near San Gregorio Lake: see Figure 6).

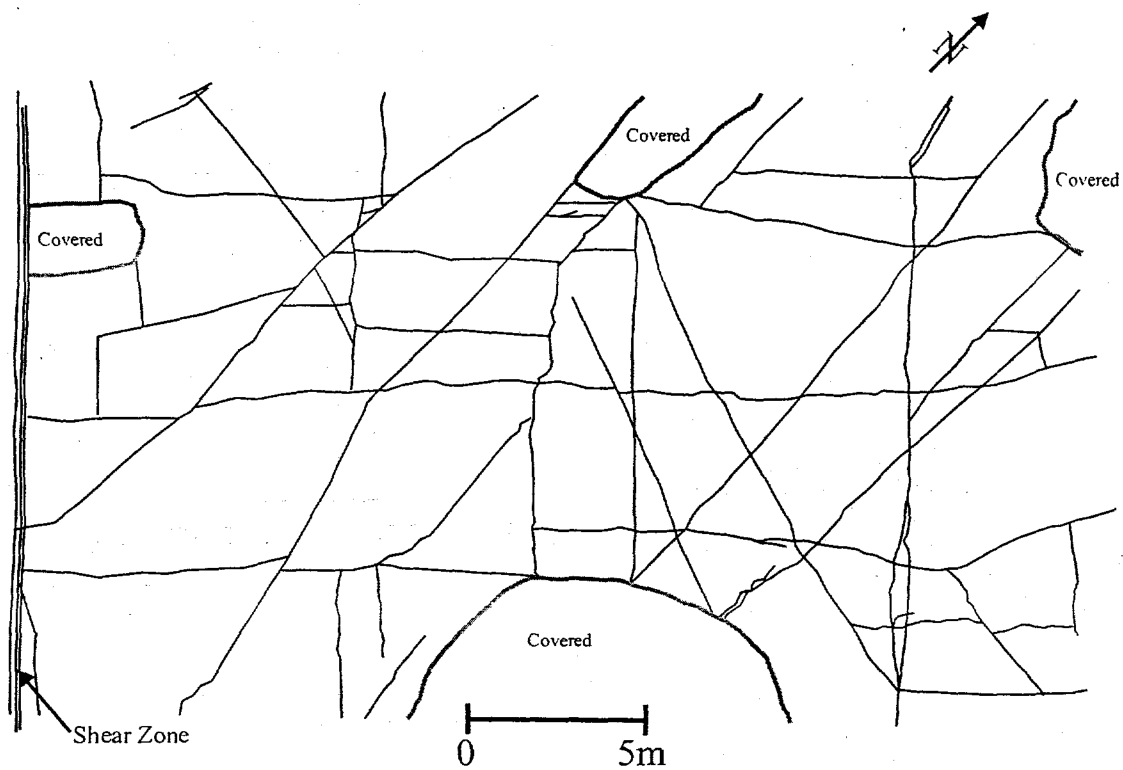

Figure 8: Plan-view fracture map on the Hogback monocline east of Shiprock, New Mexico. Note the through-going oldest, north-south striking fracture set.

Outcrops of Dakota sandstones along NM route 84 and at Heron Lake, within in the Archuleta Anticlinorium on the northeastern corner of the basin, show that the N-S to NNE-SSW theme of regional vertical-extension fractures extends to these areas as well.

However, conjugate fractures indicating NE-SW 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 comprise a significant deviation from the more common N-S 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 NE-SW oriented horizontal compressive stress, from the intermediate compressive stress to the maximum compressive stress with no rotation in orientation (Olsson et al., 2001; in preparation).

Sandstones of the overlying Dakota interval at the same San Ysidro location contain a significantly different pattern of fractures, consisting of an apparent conjugate fracture pair with strikes of 10-20° and 60-70°. Intersection relationships, however, suggest that the fractures striking 10-20° comprise an older set, imposed on the rock as extension fractures under the same conditions of NNE-SSW maximum horizontal stress seen widely elsewhere in the basin. This set was present as a background fabric, and was reactivated in shear during formation of the younger, 60-70° shear fractures since it had the optimum strike with respect to the re-oriented stresses to become one set of the conjugate pair. The other complementary shear fracture set of the pair formed ab initio.

FRACTURES IN CORE

Introduction. Cores from 19 wells drilled into Mesaverde and Dakota strata and stored at the New Mexico Library of Subsurface Data in Socorro, NM, were studied for this project. 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. Fractures are not sufficiently numerous in any one core to support a quantitative, tabular database, and space does not permit full fracture descriptions here. None of the cores examined for the present study were oriented.

Fracture Characteristics. Natural fractures in the Mesaverde sandstones are primarily vertical, extension fractures, filled to partially filled with calcite and/or quartz. Quartz may in fact be an early mineralization phase that is present but obscured under later calcite layers in most fractures. The majority 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 frequent vertical-extension fractures are present in cores of the 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 with variable orientations and filled with kaolinite may extend a few tens of centimeters vertically from the larger teeth of the stylolites.

Fracture Orientations. 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), in the Mesaverde and Dakota subsurface strata. The orientation of that fracture set is unconstrained 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 NNE-SSW fracture fabric seen in outcrop also dominates the subsurface fracture fabric. (The E-W 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 N-S striking igneous Bonito dike.)

This NNE-SSW fracture orientation is consistent with production engineering data that show a horizontal permeability anisotropy on the order of 10:1, elongated in the N-S to NNE-SSW 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 due to a higher degree of fracturing, but tests measuring the anisotropy have not been reported for this unit.

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, N-S striking Tertiary dikes clustered in the northeastern part of the basin and that are scattered sparsely elsewhere suggest that the maximum in situ horizontal stress was oriented N-S 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 N-S to NNE-SSW 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 35° stress orientation (J. Bucci, personal communication, 2000).

Yale et al. (1993) reported a nearly NE-SW (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 NE-SW trending maximum horizontal compressive stress does not appear to be widespread within the basin.

These subsurface fracture and stress patterns control a significant drainage 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 E-W 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, but may also have been more widely distributed within the 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 N-S to NNE-SSW (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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