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STRUCTURE, STRATIGRAPHY AND PETROLEUM POTENTIAL OF THE EL VADO AREA, RIO ARRIBA COUNTY, NEW MEXICO

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Abstract—The El Vado area is located in eastern Rio Arriba County, New Mexico, on the eastern margin of the San Juan Basin. Observed structures and interpretation of existing well logs within and in close proximity to the study area indicate that the area underwent structural deformation during ancestral Rocky Mountain, Laramide, and Rio Grande rift deformational events. Well log interpretation indicates that surface exposures of Cretaceous rocks are underlain by Mesozoic (Jurassic and Triassic) and late Paleozoic (Permian and Pennsylvanian) strata. Abrupt thickening of both Permian and Pennsylvanian strata from east to west indicates that this area overlies a significant late Paleozoic structural boundary that either marks or was proximal to the late Paleozoic Uncompahgre uplift. Observed structures in the study area include an anticlinal/synclinal fold pair and normal faults, thrust faults, and strike-slip faults. North-northwest-striking thrust faults and strike-slip faults of varied strike direction are comparatively small-scale structures that are interpreted to have originated during Laramide deformation. In contrast, north-striking normal faults are comparatively large-scale, mappable structures that strike parallel to both the axial trend of the anticlinal/synclinal fold pair and the mid-Tertiary Dulce dike swarm. Accordingly, the normal faults and the fold pair are interpreted as structures that developed during Rio Grande rift tectonism. The development of anticlinal and synclinal flexures in an otherwise extensional setting, combined with subsurface stratigraphic data from well logs, indicates that the flexures overlie and mimic an underlying horst/graben topography of late Paleozoic origin. Historic oil and gas production in the area has occurred from shallow, fractured Cretaceous reservoirs; other potential may exist in Pennsylvanian and Jurassic reservoirs.

INTRODUCTION

The study area occupies approximately 12.6 mi^2 on the eastern edge of the San Juan Basin in the vicinity of Heron Lake and El Vado Reservoir, eastern Rio Arriba County, New Mexico (Figs. 1, 2). The area has undergone deformation during Proterozoic, late Paleozoic (ancestral Rocky Mountain), late Mesozoic to early Tertiary (Laramide), and mid- to late-Tertiary (Rio Grande rift) tectonic events. Regional tectonic elements (Fig. 1) in and around the study area include the Laramide Archuleta anticlinorium (Dunn, 1964; Brister and Chapin, 1994), a positive structural element that separates the San Juan Basin (Kelley, 1950) to the west and the Chama Basin (Dunn, 1964) to the east; the Nacimiento uplift, a positive structural element known to have been active during several Phanerozoic tectonic events (Baltz, 1967; Baars, 1982; Chapin, 1983) and thought to be the southern extension of the Archuleta anticlinorium; and the Dulce dike swarm, a series of generally north-trending, mid-Tertiary lamprophyre dikes (Bingler, 1968). Additional tectonic elements of late Paleozoic origin include the late Paleozoic Uncompahgre

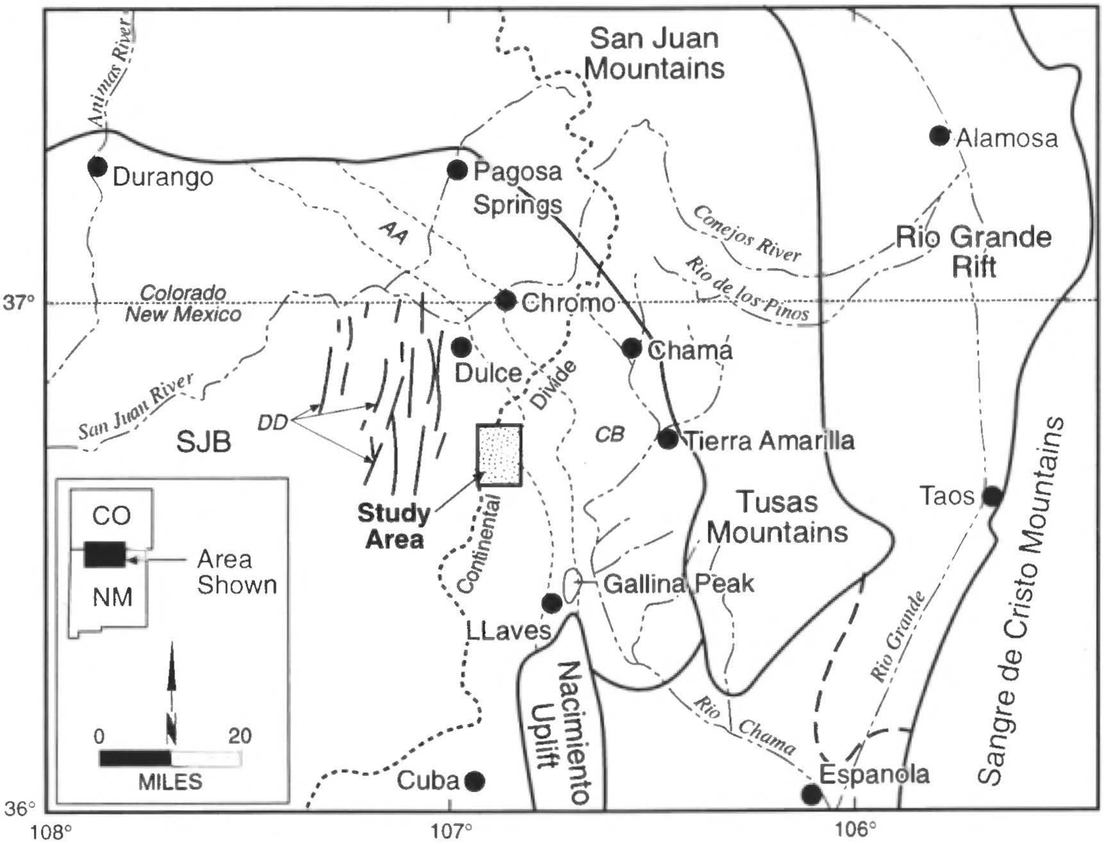

FIGURE 1. Tectonic element map showing regional features and location of the study area, including the Dulce dike swarm (DD); Archuleta anticlinorium (AA); San Juan Basin (SJB); and Chama Basin (CB). Modified from Doney (1968).

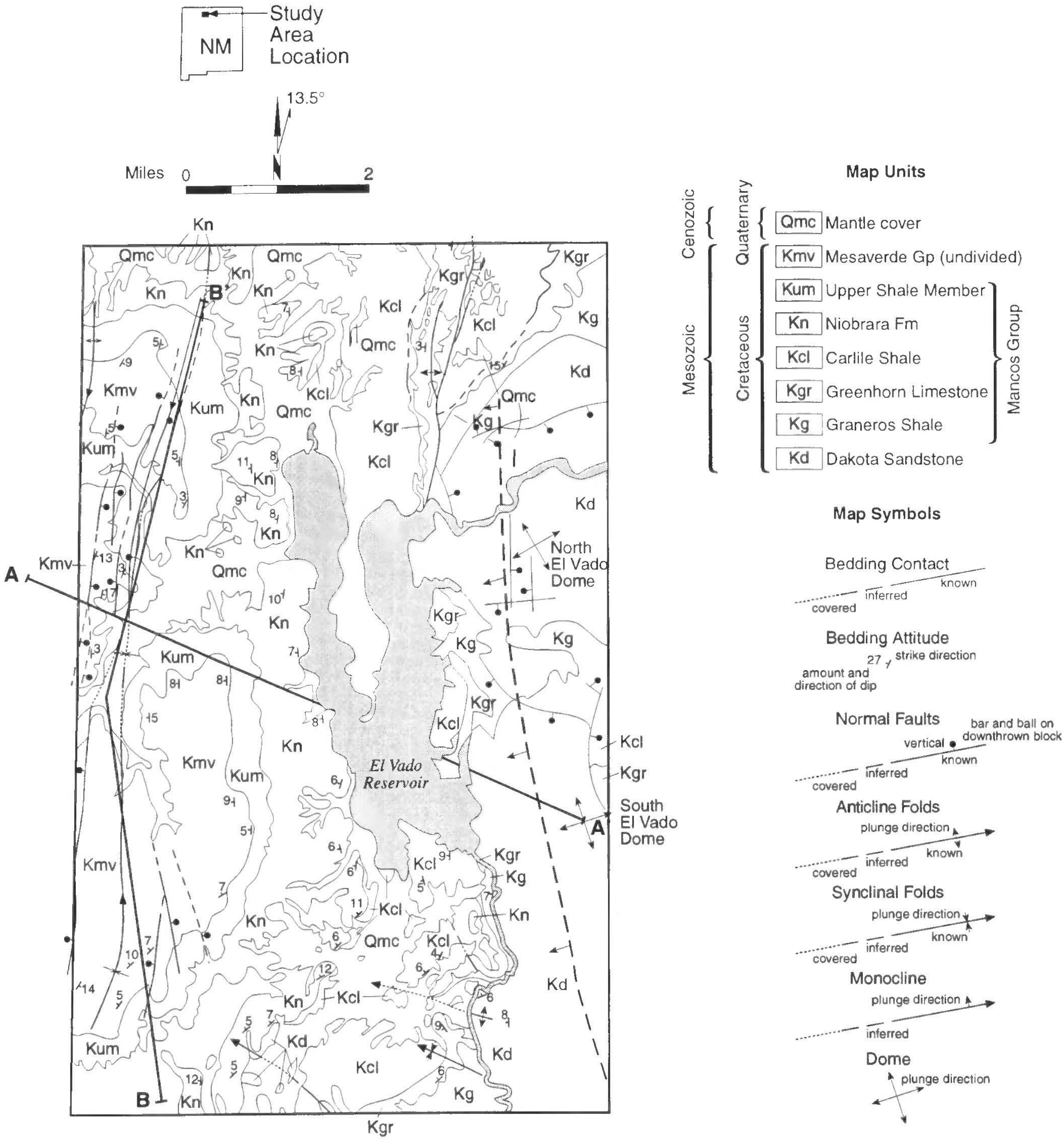

FIGURE 2. Geologic map of the El Vado area and location of section lines A-A' and B-B'.

uplift (Stevenson and Baars, 1977; Peterson, 1980; Huffman and Condon, 1993), adjacent Cabezon sag (Kottlowski, 1960), and/or the San Juan trough (Huffman and Condon, 1993).

Although minor portions of the study area overlie the Archuleta anticlinorium, the majority lies immediately west of the monoclinal flexure that marks the boundary between the San Juan Basin and the Archuleta anticlinorium (Fig. 2). Exposures of Cretaceous bedrock typically dip gently (5°-10°) westward, with broad, open anticlinal and synclinal folds superimposed upon this regional inclination. In addition, several normal faults offset the general incline and are of sufficient magnitude to be mappable structures. Although the majority of wells (> 85%) drilled in the area have penetrated only the Cretaceous section (Table 1; Fig. 3), those that have drilled to Precambrian basement indicate that as much as 3700+ ft of Jurassic (930-1000 ft), Triassic (250-420 ft), Permian (320-1660 ft), and Pennsylvanian (0-700 ft) strata underlie the surficial exposures of Cretaceous strata.

Because several fields in this part of the San Juan Basin have been interpreted as fractured reservoirs (e.g., the Puerto-Chiquito-Mancos [Greer, 1978] and Boulder [Needham, 1978] fields), field investigations were undertaken to provide stratigraphic and structural data that could be used to gain an understanding of the local and/or regional structural trends and fracture orientations and aid further exploration for potential unproven reserves.

The purpose of this paper is to present structural data from surface observation and subsurface stratigraphic data from well log interpretation.

TABLE 1. Summary of well log and scout ticket information. Total depth (TD) in feet; datum of formation tops is mean sea level; temporarily abandoned (TA); plugged and abandoned (PA). Log column indicates source and availability of well information, either Y (yes) or N (no) or SC (scout ticket information only). Cretaceous Greenhorn Limestone (Kgr), Graneros Shale (Kg), Dakota Sandstone (Kd); Jurassic Morrison Formation (Jm), Todilto Formation (Jt), Entrada Sandstone (Je); Triassic undifferentiated (Tr); Permian undifferentiated (Perm); Pennsylvanian undifferentiated (Penn); and Precambrian undifferentiated (Precam).

				UTM coord.		Formation Tops												producing			
OPER	Well Name and #	GL	TD	X	Y	Kgr	Kg	Kd	Jm	Jt	Je	Tr	Perm	Penn	Precam	status	year	interval	BOPD	BWPD	Log
Alana	Samantha #1	7252	1730	338809	4052547	5610	5563	5412								TA		Kgr	14		SC
Alana	Samantha #2	7282	1788	339238	4052667	5581										TA		Kgr	12		SC
Alana	Samantha #3	7313	1778	339333	4052333	5614										TA		Kgr	10		SC
Suntex	#1 Suntex	7195	2000	338548	4053405	5532	5494	5332								TA		Kgr			SC
Suntex	#2 Suntex	7170	1974	338452	4054095	5427	5388	5224								TA		Kd			SC
Suntex	#3 Suntex	7194	1660	339119	4056357	5633	5585									TA		Kgr			SC
Suntex	#4 Suntex	7127	1769	338712	4054714	5572	5532	5382								TA		Kgr			Y
Texas Rose	#1 El Poso	7076	1630	339595	4055905	5786	5743									TA		Kgr	37	10	Y
Texas Rose	#2 El Poso	7095	1710	339452	4055595	5671	5625									TA		Kgr	37	4	Y
Texas Rose	#3 El Poso	7248	1710	339238	4057219	5756	5712									TA		Kgr	14	10	Y
Texas Rose	7 El Poso Ranch	7078	1464	339220	4055489	5788										TA		Kgr	7		N
Alana	#1 Alana	7108	1335	339333	4047476											PA	87				Y
BMG	El Poso 1-H	7251	1186	341571	4049762	6115										PA	62			in Kgr	N
BMG	#3-I El Poso	8086	1956	338167	4049476											PA	62				N
BMG	#35 El Poso	7142	1226	340167	4060690	6183	6143	6000								PA	62				Y
C&J Drlg	#1 El Poso	7282	2006	338786	4052452	5614	5563	5412								PA					Y
Dawsey	#1 El Vado	7132	1579	339214	4047523											PA	86				N
Dawsey	#2 El Vado	7157	1340	339667	4047714											PA	86				N
Suntex	6 Maddox WA	7125	82	338831	4054416											PA	83				SC
Tamanaco	26 Pound Ranch D	7162	2008	338738	4053547	5502	5452	5302								PA	60				SC
Tamanaco	#11-N El Poso	7230	1451	339143	4057047											PA	78	Kgr	10		SC
Tamanaco	#14-C Pound Ranch	7177	1788	339143	4056714	5679	5633	5499								PA	63				Y
Tamanaco	27 Pound Ranch B	7102	1928	338166	4053738	5446	5392	5237								PA					Y
Belco	#1-32	7338	1535	334381	4050833											PA	64				N
Derby Drlg	#1 Jic. Apache	7335	5853	336643	4051690	5759	5715	5410	5257	4605	4510	4265		2185	1487	PA					Y
EPROC	#1 Jic. Tribal	7151	1572	337143	4052405	5869	5821	5670								PA	61				Y
EPROC	#1 Puerta Grande	7151	1550	337143	4053595	5868	5830	5670								PA					Y
J.L. Foutz	#1 Rayos	7108	2270	335048	4053357	5216	5155	5009								PA	63				Y
Phillips	#1 El Vado	7621	2009	348309	4051881					6651		6396			5806	PA	43				Y
SW Expl	Penn Bldg #1	7559	2460	347167	4057500				7169	6509	6406				5100	PA					N

Collection of surface structural data (determination of bedding, fold-axis, joint and fault orientations) was combined with geologic mapping. Subsurface stratigraphic and structural relationships have been interpreted from well logs (resistivity, gamma ray, spontaneous potential, and neutron) located within and in close proximity to the study area. Both structural data and well log data have been combined to produce geologic cross sections, to identify different hydrocarbon generating and entrapment systems, and insofar as possible, to interpret the geologic history of the El Vado area.

STRATIGRAPHY AND DEPOSITIONAL HISTORY

Bedrock exposures in the El Vado area are exclusively Cretaceous. Exploration wells drilled just to the west (Derby Drilling, #1 Jicarilla-Apache) and in the east (Phillips Petroleum, #1 El Vado; Southwestern Exploration, Penn Bldg. #1) of the area show Precambrian basement is overlain by Pennsylvanian, Permian, Triassic, and Jurassic rocks (Table 1; Fig. 4). The thickness of this unexposed package ranges from ~800 ft (east) to more than 4,000 ft (west). However, due to the paucity of deep well data, the subsurface distribution of these units within the study area is inferred.

Precambrian granite and metamorphosed supracrustal rocks (e.g., quartzites and schists) constitute basement lithologies in the study area and in most of the San Juan Basin (Woodward et al., 1977). Cambrian-Early Devonian sediments were probably deposited and subsequently eroded in the vicinity, as this area was a highland and a source of sediments deposited to the north and west during the Late Devonian (Stevenson and Baars, 1977).

Pennsylvanian arkosic sandstone and arkosic limestone were deposited nonconformably on Precambrian rocks (Bingler, 1968). Outcrop of these strata at Gallina Mountain show the arkosic sandstone is semiporous with a calcite cement. The uppermost arkosic limestone is a medium-grained recrystallized carbonate and is not fetid. Fossil content and lithologic properties are similar to the Arkosic Member of the Madera Formation as described by DuChene (1974).

Permian strata are composed entirely of reddish-brown arkosic clastics of the Cutler Formation derived from the Uncompahgre uplift (Baars and Stevenson, 1977). This formation thins to the southwest but is locally thick in the El Vado area (Fig. 4) due to its apparent proximity to the Uncompahgre highlands, which were the source of Cutler sediments.

Triassic strata were deposited in various desert environments similar to those recognized in southern New Mexico today (dune fields, playas, saline lakes, and wet alluvial aprons; O'Sullivan, 1977). In the study area Triassic rocks are only present in the subsurface and thicken from east to west by 170 ft (Fig. 4).

Jurassic rocks consist of interbedded redbeds with cross-bedded sandstone and lesser amounts of claystone, limestone, and gypsum, which make up the Entrada Sandstone, Todilto Formation, Summerville Formation and Morrison Formation. The Entrada is composed exclusively of reddish-orange, fine- to medium-grained, well-sorted quartzose sandstone of eolian origin and relatively thinner, interbedded, dark reddish-brown siltstone beds of inland sabkha and interdune origin. The Todilto is composed of a lower limestone facies present throughout the Four Corners area and an upper gypsum-anhydrite facies, which is restricted to the deeper part of the lacustrine basin centered along the eastern boundary of the present San Juan Basin. This limestone is thin bedded, arenaceous, and gives off a fetid odor when broken. The Morrison Formation consists of mudstone, sandstone and conglomeratic sandstone deposited in an alluvial/fluvial system. The upper contact of the Morrison Formation with the overlying Cretaceous strata is generally an unconformable scour surface (Stokes, 1952).

The Cretaceous Burro Canyon Formation, with clasts of quartz, quartzite, and chert, consists primarily of conglomeratic sandstones. Depositional environments changed from alluvial/fluvial (Burro Canyon) to marine during Dakota time. The lowermost Dakota Sandstone consists of alternating tan- to brown-weathering sandstone and dark-gray carbon-

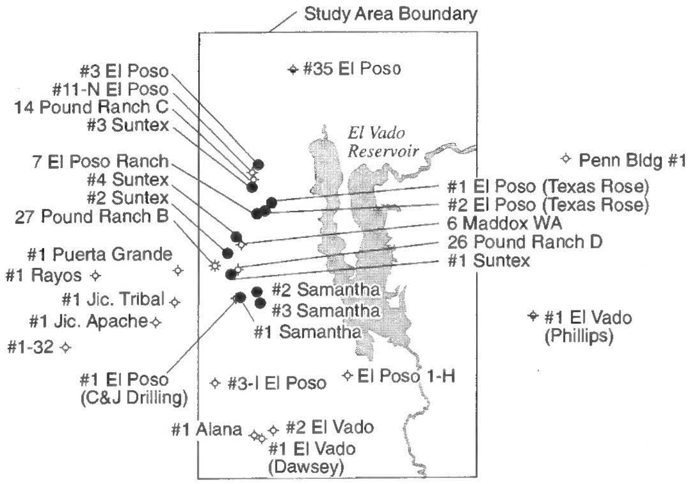

FIGURE 3. Location map of wells within and in proximity to the study area.

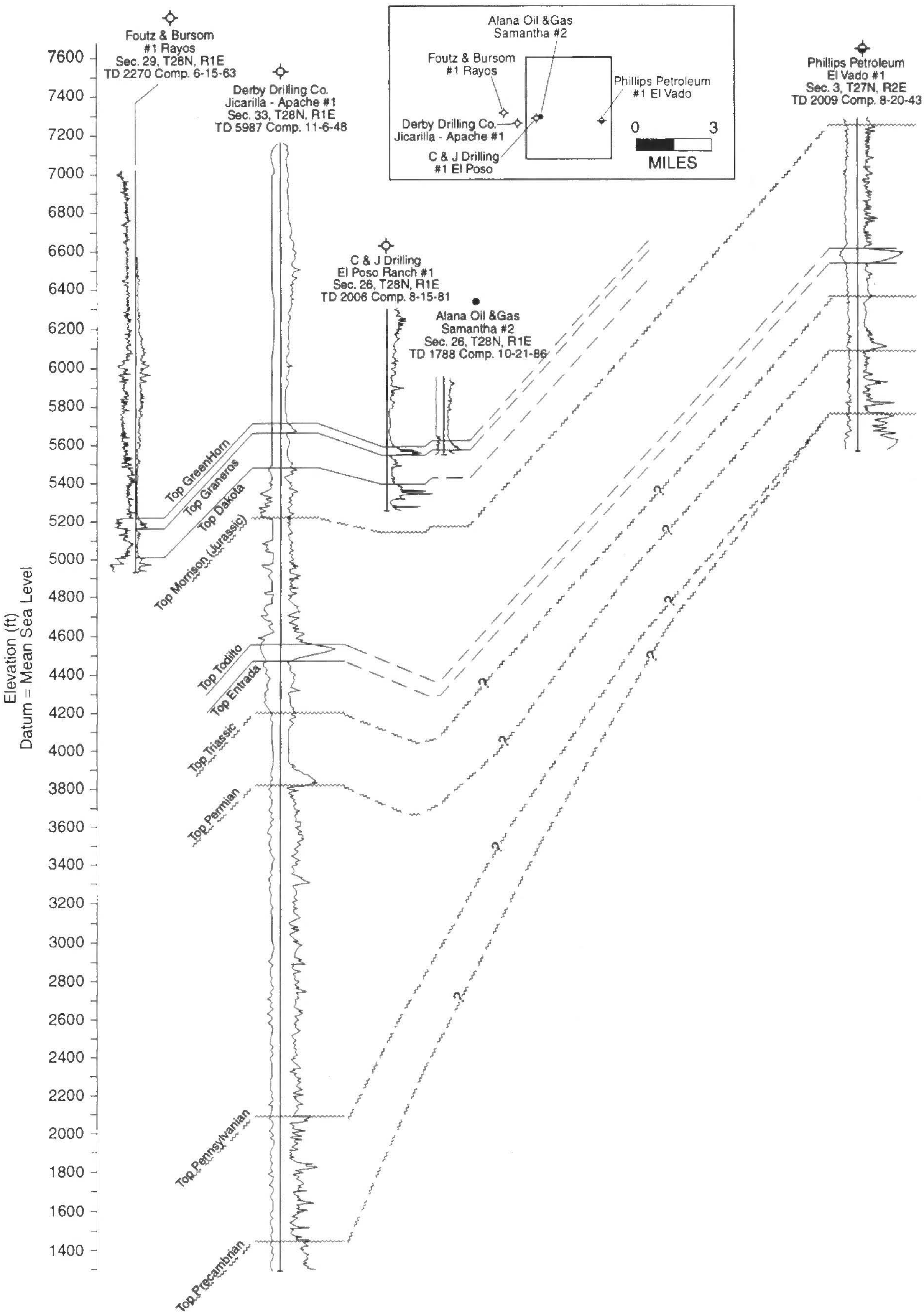

FIGURE 4. West-east well log section across the study area.

aceous shale and siltstone. Sandstones are thin to thick bedded, massive and locally cross bedded. Ripples may also be present with abundant burrows. During Late Cretaceous time the shoreline shifted back and forth across the area and deposited alternating marine deposits and nonmarine coastal deposits of the Mancos and Mesaverde Groups.

The Mancos Group in the area contains lithologic equivalents of parts of the Graneros Shale (bottom), Greenhorn Limestone, Carlile Shale, Niobrara, and upper shale member (top). These formations were probably deposited as limy, muddy oozes in a shallow Cretaceous sea. Mesaverde Group rocks are a collection of thick marine and nonmarine sediments divided into three formations in ascending order, Point Lookout Sandstone, Menefee Formation and Cliff House Sandstone.

By early Tertiary time, the sea had retreated from the area and subsidence of the Laramide San Juan Basin accelerated. Tectonic uplift (Laramide orogeny), initiated during the Late Cretaceous, continued through the Eocene affecting marginal-basin regions (e.g., El Vado to Llaves), as suggested by an angular unconformity between the Nacimiento Formation (Paleocene) and overlying San Jose Formation (Eocene) near Llaves (Bingler, 1968) and on the Nacimiento uplift north of Cuba (Baltz, 1967). Late Eocene time was marked by extensive erosion in many areas of the southern Rocky Mountains (Epis and Chapin, 1975; Scott, 1975). Strata of Oligocene, Miocene, and Pliocene age are also absent in the area. Quaternary deposition includes the formation of outwash terraces, sand dunes on higher plateaus, and the cutting and filling of alluvial channels in selected areas as a result of the formation of the current Rio Chama drainage system.

Stratigraphic interpretation

Logs and scout tickets from 30 wells were interpreted with tops of diagnostic stratigraphic intervals picked and correlated (Table 1; Fig. 4). This correlation shows at least 4300 ft of relative structural relief between the Archuleta anticlinorium and the adjacent San Juan Basin. This indicates significant relative movement along the north-trending anticlinorium, which is interpreted here to be the cumulative effect of ancestral Rocky Mountain, Laramide and Rio Grande rift tectonism.

Almost 700 ft of Pennsylvanian stratigraphic thinning across a 5 mi west-east section (Fig. 4; compare Jicarilla-Apache #1 and El Vado #1) indicates that the structure currently identified as the Archuleta anticlinorium was a paleogeographic high during Pennsylvanian deposition. We infer that the western margin of the anticlinorium was a bounding fault and structurally active during the Pennsylvanian although no wells penetrate this structure. Permian stratigraphic thinning is even greater, with a decrease of about 1400 ft of Cutler Formation conglomerate, sandstone, siltstone, and mudstone across the same west-east 5 mi section (Fig. 4). Stratigraphic thinning to a lesser degree (170 ft) is also observed in the Triassic section. Well log correlation of Jurassic and Cretaceous strata across the study area shows only minor scale fluctuation in total stratigraphic thickness, indicating that during this time the bounding fault was relatively inactive, and that paleotopographic relief was minimal across the area.

STRUCTURAL DATA

Exposures of Cretaceous bedrock within the El Vado area host several structural features, including joints, faults (normal, reverse and strike-slip) and both anticlinal and synclinal folds. Fieldwork and subsequent structural analyses identified and resolved these structures in an attempt to understand the structural development within the area and to aid continued hydrocarbon exploration. Fieldwork included geologic mapping and measuring the orientations of observed structures (bedding inclination, joint and fault attitudes) at over 250 locations. These orientations were then evaluated by computerized analysis and plotted in stereographic projections (Fig. 5), and used to determine preferred structural orientations. Both map relationships (Fig. 2) and structural orientations, as determined in stereographic projection, were used to construct geologic cross sections and to infer subsurface relationships (Fig. 6).

Evaluation and interpretation of fracture orientations follow the analytical procedures proposed by Beck (1993), in which (1) fractures are evaluated in their current orientations (field-recorded orientations), and (2) fractures are evaluated as structures that may predate appreciable rotation of strata during a deformational event (restored orientations). This simply means that fracture orientations have been evaluated in both their current orientations, and the orientations they would have had if they developed prior to appreciable folding of strata. In the interest of simplicity and minimizing the number of plots presented herein, most fracture data is presented as restored orientations.

Bedding orientations and fold trends

Cretaceous strata typically strike northward and dip gently (5°-10°) to the west. A stereographic plot of all field-recorded bedding orientations (Fig. 5A) indicates that the average bedding attitude (regional bedding) forms a strong concentration at roughly N13°E/05°NW. This general orientation is most common in the central portions of the area (Fig. 2), and represents the general westward dip off the Archuleta anticlinorium into the San Juan Basin.

Several folds of both north and northwest trend have been superimposed on this regional inclination. Comparatively small-scale, northwest-trending folds have been observed in the southern portion of the area. These folds are of limited areal extent and are probably of little consequence. In contrast, north-trending folds form a continuous, areally extensive anticlinal/ synclinal fold pair along the westernmost portion of the area (Figs. 2, 6). These folds are characterized as broad, open flexures in which both east- and west-dipping limbs are inclined an average of 7°. Stereographic analysis of these folds (Fig. 5B) indicates that fold axes trend N13°E/S13°W, parallel to the strike of regional bedding. Fold axes in the northern part of the area plunge southward (approximately 3°), and fold axes in the southern part of the area plunge northward (approximately 3°), forming a shallow structural sag roughly midway along the fold trend (Figs. 2, 6).

Fracture orientations

Fractures are the most commonly observed structural features in the rocks of the El Vado area. These include both joints and faults, with joints being far more common than faults. Although both mineralized and nonmineralized joints have been observed, nonmineralized joints are much more numerous than mineralized joints.

Normal, reverse (thrust), and strike-slip faults have been observed. Of these, normal faults appear to be the most important, in that they commonly display 20-60 ft of offset in surface exposures and are of sufficient magnitude and areal extent to be mappable structures. In contrast, thrust faults and strike-slip faults are of limited areal extent and commonly exhibit comparatively limited ($<$ 1 ft) displacements.

A stereographic plot of 565 field-recorded fracture orientations (Fig. 5C) indicates that observed fractures demonstrate a wide variety of orientations. This is most likely due to the combined effects of both Laramide and Rio Grande rift deformation. Although the orientations are diverse, a preferred strike direction of approximately N10°E is evident. Of these north-striking fractures, most are high-angle structures, inclined between 60° and 90° to the horizontal. A lesser concentration of subvertical fracture orientations strikes west-northwest.

A stereographic projection of restored normal fault orientations (Fig. 5D) defines two preferred shear orientations. Most normal faults plot as a conjugate pair of faults that strike N5°-10°E (referred to herein as northward), dipping approximately 60° to the east or west. The limited number of fault striae observed on these faults indicate dip-slip displacements. When considered as a fault system, the normal faults are indicative of horizontal extension, oriented along an approximate bearing of N80°W/S80°E.

Restored thrust faults (Fig. 5E) also define a conjugate pair of shear orientations. Individual thrust fault planes strike to roughly N20°W and dip roughly 25° to the west-southwest or east-northeast. Comparably restored fault striae indicate dip-slip displacements. When considered as a fault system, the thrust faults indicate horizontal compression, directed along an approximate bearing of N70°E/S70°W.

Restored strike-slip faults (Fig. 5F) plot as subvertical fault planes of diverse strike direction. Although comparably restored fault striae indicate subhorizontal displacements, the sense of displacement (dextral or sinistral) was seldom accomplished in the field. As a result of both the diversity of strike direction in observed strike-slip faults and the absence of sense of

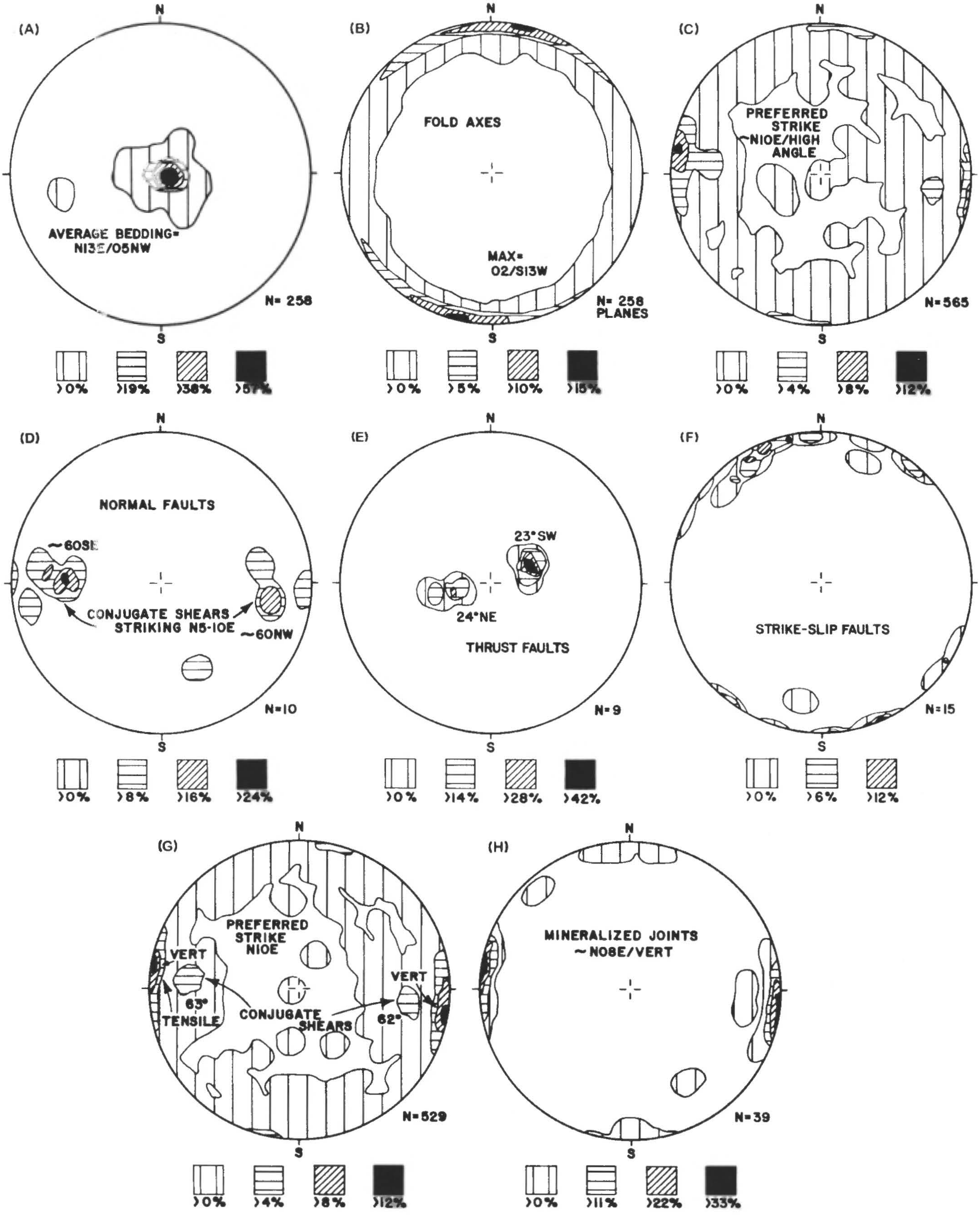

FIGURE 5. Stereographic projections of structural data recorded in the study area. A, bedding orientations; B, mean fold axes; C, field-recorded fracture orientations (joints and faults); D, restored normal faults; E, restored thrust faults; F, restored strike-slip faults; G, restored joint orientations; and H, restored mineralized joints (calcium carbonate or iron stain). Poles to planes (A, C, D, E, F, G and H) and beta diagram (B) contoured at specified intervals per 1% area.

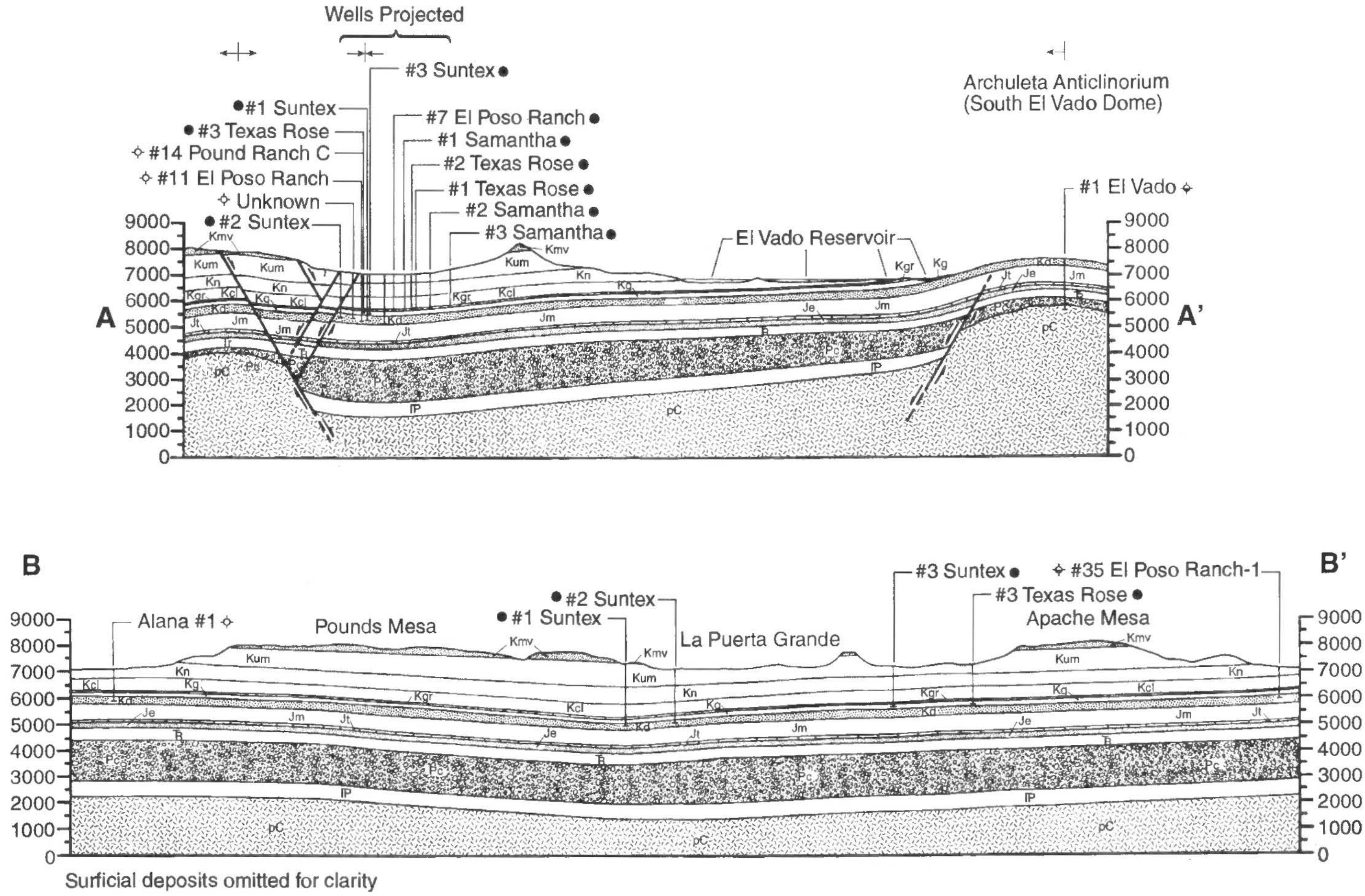

FIGURE 6. Structural cross sections A-A' and B-B'. Cretaceous Mesaverde (Kmv), upper Mancos (Kum), Niobrara (Kn), Carlile Shale (Kcl), Greenhorn Limestone (Kgr), Graneros Shale (Kg), Dakota Sandstone (Kd); Jurassic Morrison (Jm), Todilto (Jt), Entrada (Je); Triassic undifferentiated (T); Permian Cutler (Pc); Pennsylvanian undifferentiated (P); and Precambrian undifferentiated (pC).

displacement determination, little to no inference has been drawn from these data.

A stereographic plot of all restored joint orientations (Fig. 5G) also displays four preferred fracture orientations. Three of these concentrations strike approximately N10°E and are inclined at roughly 60° and 90° to horizontal. Those that plot at 90° are commonly mineralized (Fig. 5H; a subset of Fig. 5G), indicating that the north-striking, subvertical joints originated as tensile structures. Those inclined at 60° are symmetrically disposed about the preferred orientation of mineralized joints and also parallel to known shear orientations as defined by normal faults (Fig. 5D), and correspondingly these joints are considered to be shear joints (Fig. 7). The fourth concentration of joint orientations, oriented west-northwest and subvertical (orthogonal to the mineralized joints; Fig. 5H), is comparatively uncommon and poorly understood.

Structural interpretation

Deformation associated with three orogenic events (ancestral Rocky Mountain, Laramide, and Rio Grande rift) can be recognized within the surface and subsurface stratigraphy of the study area. Ancestral Rocky Mountain (late Paleozoic) deformation can be recognized only in the subsurface through interpretation of well logs (Table 1; Fig. 4). The westward increase in thickness of Pennsylvanian strata from 0 to 700 ft and Permian strata from 320 to 1660 ft indicates that the area overlies a significant late Paleozoic structural boundary. This boundary delineates or is part of the western margin of the late Paleozoic Uncompahgre highland (Kottlowski, 1960; Peterson, 1980). The relative thinning and/or absence of Permian and Pennsylvanian strata (e.g., Phillips Petroleum #1 El Vado, Southwestern Exploration Penn Bldg. #1) to the east of this boundary indicate that the Uncompahgre highland was uplifted during late Paleozoic deformation and sedimentation (compare with Baars, 1982, fig. 3; Beck and Johnson, 1982; and Beck and Chapin, 1994). Although both the location and orientation of this subsurface structure is uncertain, it is interpreted to strike northward and to directly underlie the monoclinal flexure that marks the boundary between the modern Archuleta anticlinorium and the San Juan Basin. The subsurface structure is further interpreted as a west-dipping normal fault, although the specific inclination is also uncertain (depicted at 60° in Fig. 6). These interpretations are based on seemingly comparable styles of late Paleozoic deformation in New Mexico as identified by Pray (1961), Baars (1982), and Beck and Chapin (1991, 1994). The net effect of this deformation is that thick accumulations of Pennsylvanian and Permian strata should exist to the west of this fault. Acquisition of seismic lines across this structure would greatly enhance the definition of both the location and orientation of the structure and the subsurface distribution of late Paleozoic strata.

Additional interpretation of well logs (Table 1; Fig. 4) indicate that Triassic strata also thicken (250-420 ft) from east to west across this subsurface structure. Although the implications of this observation are not clear, the apparent thickening of Triassic strata may indicate that either deformation that originated during the late Paleozoic continued into Triassic time, or that the Uncompahgre uplift persisted as a subdued topographic high into the Triassic.

In that the Laramide orogeny has been interpreted as a compressive deformational event involving both strike-slip faulting and thrust faulting (e.g., Baltz, 1967; Chapin and Cather, 1981; Chapin, 1983; Beck and Chapin, 1994), observed thrust faults and strike-slip faults are assumed to have originated during Laramide tectonism. Thrust faults (Fig. 5E) strike to the north-northwest and dip at a shallow angle (approximately 25°) to either the east-northeast or west-southwest. When considered as a fault system, the thrust faults indicate horizontal compression directed approximately N70°E/S70°W. Although the implications of compression along this bearing are not

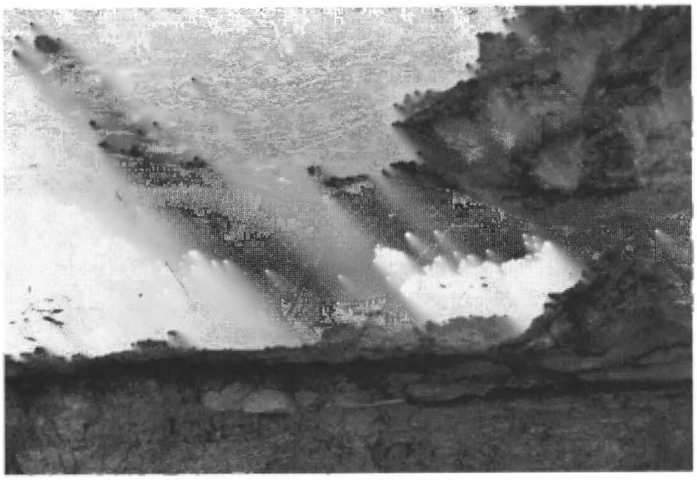

FIGURE 7:.Conjugate shear joints observed in Point Lookout Sandstone. Ledge-forming sandstone unit is approximately 1ft thick.

clear, we infer that these thrust faults are related to the same compressive forces that produced the northwest to north-northwest-trending fold axes that exist along the Nacimiento fault (e.g., Woodward et al., 1992).

Restored strike-slip faults (Fig. 5F) plot as subvertical planes of diverse strike direction. Although commonly marked by subhorizontal fault striae, the sense of displacement (dextral or sinistral) was typically indeterminate. Due to the absence of reliable sense of shear determinations and the diversity in strike direction, little inference is drawn from these data beyond their origin during the Laramide orogeny. Moreover, in that observed strike-slip faults and thrust faults exhibit limited displacements and/or appear to be of limited areal extent, these structures are considered to be fairly inconsequential with respect to the overall development of the map-scale structures observed within the study area.

In contrast, restored normal faults (Fig. 5D) are mappable structures that strike northward and dip at roughly 60° to either east or west. These fault orientations parallel two of the preferred orientations of nonmineralized joints (Fig. 5G), and accordingly joints of these orientations are interpreted as shear joints. Further, the acute angle formed by the preferred normal fault orientations is bisected by the preferred orientations of mineralized joints (Fig. 5H). When considered as a fracture system, the combination of normal faults, shear joints, and mineralized joints form a fracture pattern compatible with lateral extension directed along an approximate bearing of N80°W/S80°E. Extension along this general bearing is compatible with the general strike direction of the mid-Tertiary Dulce dike swarm (Fig. 1; Bingler, 1968; probably late Oligocene to early Miocene, C.E. Chapin, personal commun., 1993), and on this basis, the extensional deformation in the area is interpreted to have originated during Rio Grande rifting.

The compatibility between the north-striking extensional fracture system and the north-trending anticlines and synclines indicates that the development of these respective structures is intrinsically related. The development of the anticline and syncline (to the west, Figs. 2, 6) as well as the subparallel monocline (to the east, Figs. 2, 6) in an extensional setting suggests that these folds resulted from drape folding (Davis, 1984; Suppe, 1985) and flexure of strata above subsurface structures. Based on apparently similar styles of ancestral Rocky Mountain deformation as documented by Pray (1961), Baars (1982), and Beck and Chapin (1991, 1994), the subsurface structures are interpreted as normal faults and a resultant horst/graben topography. In this scenario, renewed extension during Rio Grande rifting reactivated an existing (subsurface) extensional deformational system in place since at least the late Paleozoic. Renewed extension resulted in renewed uplift of horst blocks (anticline, Archuleta anticlinorium, monocline), renewed subsidence of grabens (syncline), and renewed normal fault displacements on existing faults as depicted in Figure 6.

OIL AND GAS POTENTIAL

Nearby fields produce oil from Mancos Shale and Dakota Sandstone. The Chromo field, northwest of Chama, had produced over 150,000 BO by 1977 from fractured Carlile, Tocito, and Greenhorn formations along the flanks of an anticline (Osterhoudt, 1978). The Gramps field, with a cumulative production of more than 5,800,000 BO as of 1977, produces from Dakota Sandstone in a faulted anticlinal structure (Donovan, 1978). The Boulder and Puerto Chiquito fields produce from fractured Mancos Shale. Cumulative production was more than 1,859,586 BO for the Boulder field and over 16,926,157 BO for the Puerto Chiquito fields as of 1993. Total Mancos oil production in the San Juan Basin is nearly 30 million BO with approximately 75% of the total coming from the above fields.

Petroleum is produced from both Paleozoic and Mesozoic rocks in the San Juan Basin. Multiple episodes of uplift around the basin margins have resulted in complexly folded and faulted margins, creating both structural traps and structural/stratigraphic traps along reactivated basement fault zones. Of the thirty wells in and adjacent to the study area, eleven are temporarily abandoned and the remaining are plugged and abandoned (Table 1). The eleven wells that have shown minimal historic production (approximately 130 BO) are all located along the north-south-trending syncline (Figs. 3, 6). Three potential hydrocarbon reservoirs are discussed—Pennsylvanian, Jurassic and Cretaceous.

Pennsylvanian strata in the study area are assumed to be similar to those of Gallina Mountain and may include arkosic sandstones and arkosic, fossiliferous limestones. Reservoirs may occur, but it is unknown if these strata were hydrocarbon source rocks. Well logs from the Derby Drilling #1 Jicarilla-Apache and Phillips Petroleum #1 El Vado indicate at least 2000 ft of stratigraphic and/or structural thinning against the Archuleta anticlinorium within the Pennsylvanian-Permian section. Stratigraphic (pinchout) traps are likely against the flank of the anticlinorium. However, traps may have been disrupted during Laramide and later Rio Grande rift reactivation of the bounding fault.

Lacustrine source rocks in the Todilto Formation (Jurassic) are characterized by kerogen-rich laminae within limestone and anhydrite beds (Vincelette and Chittum, 1981). The Todilto Formation, together with the underlying Entrada Sandstone constitute an ideal source/trap combination. Todilto source rocks are mature in the deep northern part of the San Juan Basin (Vincelette and Chittum, 1981) and have expelled oil into the underlying Entrada. One of the principal migration paths within the Entrada and beneath the Todilto, which also serves as a top seal migration barrier in addition to being a hydrocarbon source, was updip on the gentle south flank of the San Juan Basin; a similar eastward updip migration path may exist in this area. In the southern part of the San Juan Basin oil migrated updip and accumulated in stratigraphic traps formed by the preserved configuration of Entrada sand dune reservoirs (Meissner et al., 1984). Dead oil shows have been reported in Entrada Sandstone on south El Vado dome. However, no commercial hydrocarbon accumulations have been discovered. Most of the Entrada pools (e.g., Media, Papers Wash, Snake Eyes, Ojo Encino) have been discovered since the early 1970s through reflection seismic techniques. However, because of the unique location of the area (near basin margin) and the tendency for synclinal traps, the Entrada is a moderate risk with moderate potential.

Fields near the study area produce oil from fractured shale reservoirs (e.g., Boulder, Puerto Chiquito) which are a common reservoir type in the northeastern corner of the San Juan Basin. Typical fractured reservoirs are composed of individual fracture blocks of low permeability but the key to any fractured shale reservoir is to find an interconnected, high-capacity fracture system. In any fractured reservoir development program, it is important to integrate fracture data with fold axis trends, particularly synclines, and possibly take advantage of gravity drainage.

Cretaceous source rocks containing Type II kerogen (oil prone) occur near the base of the Greenhorn Limestone (Upper Cretaceous) and appear to be associated with minor cycles of transgression or basin deepening which produced anoxic conditions. Bedding thickness influences competence and it is believed that density of joints is greater in thin beds (Gorham et al., 1977). The Greenhorn Limestone or any brittle zones in the ductile Mancos Shale are good candidates for high fracture density. Interbedded ductile shales may act as seals to the fracture systems. Reservoirs are likely to be of the fractured permeability variety (i.e., Greenhorn) or porous Dakota Sandstone. Potential for Cretaceous targets is moderate with risk being low since the Greenhorn is less than 2000 ft deep and the Dakota is less than 2150 ft deep.

Eleven wells within the area have shown historic production from Cretaceous reservoirs (Table 1) but all are currently temporarily abandoned. Future Cretaceous hydrocarbon exploration in this area might consider taking advantage of the fold trend and deviated and/or horizontal drilling. Pennsylvanian and Jurassic strata along the same fold trend may be productive but have not yet been drilled.

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