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PREDICTION OF PERMEABILITY TRENDS AND ORIGINS IN COAL-BED METHANE RESERVOIRS OF THE RATON BASIN, NEW MEXICO AND COLORADO

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Abstract—The purpose of this paper is to propose methods for identifying trends and origins of inferred fracture permeability in potential Cretaceous-Tertiary coal-bed methane reservoirs of the Raton basin, northeastern New Mexico and southeastern Colorado. Permeability is a crucial reservoir characteristic that strongly influences the producibility of natural gas from coal seams. The regional trends of inferred primary and secondary permeability in potential coal-bed methane reservoirs of the central and southern Raton basin are approximately east and north, respectively. Published emplacement models for middle Tertiary syenite and syenodiorite dikes of West Spanish Peak in the northwestern Raton basin show that the trend of maximum principal horizontal regional stress during magmatic invasion was approximately N80°E (roughly perpendicular to the trend of the Sangre de Cristo Mountains thrust front along the western basin flank). Field evidence indicates that dike magmas south of the Spanish Peaks intruded pre-existing fractures, which are thus interpreted to have formed in the same stress regime as that calculated for the dikes. Therefore, primary extensional and secondary compressional release fractures and the corresponding inferred permeability freeways in potential central and southern Raton basin coal-bed methane reservoirs formed parallel and perpendicular, respectively, to east-directed Laramide compressional forces.

INTRODUCTION

The purpose of this paper is to propose methods for identifying trends and origins of inferred fracture permeability in potential coal-bed methane reservoirs of the Raton basin, northeastern New Mexico and southeastern Colorado. Permeability is a crucial reservoir characteristic that strongly influences the producibility of natural gas from coal seams. Given the nearly impermeable nature of most coal matrices, sufficient interconnected fracture permeability must be present to allow reservoir depressurization and subsequent gas movement to the wellbore. Optimal fracture characteristics for coal beds are based upon three phenomena unique to coal. Natural gas is released from adsorption in coal matrices by pressure decrease. Following this process, termed desorption, the gas must travel through natural fracture systems to the wellbore. Low reservoir pressure is necessary for release of significant quantities of adsorbed gas, which requires the presence of extensive interconnected natural fractures with permeability. Because natural fracture systems in coal-bed methane reservoirs are commonly water saturated, two-phase flow of gas and water, in combination with high capillary pressures at high water saturations, results in an initially low permeability relative to gas. Consequently coal-bed methane reservoirs require more extensive fracture systems than do sandstones with comparable effective permeability.

Interest concerning delineation and potential development of coal-bed methane in the Raton basin is on the strong upturn, as evidenced by recent acquisitions of prospective properties by several operators during 1989. Qualitative inferences concerning potential permeability trends and magnitude in Raton basin coal-bed methane reservoirs can be useful, along with supporting geological and reservoir engineering data, for optimizing production-well locations.

Quantitative permeability data for Lower Pennsylvanian coals at the Gas Research Institute Rock Creek Site in the Black Warrior basin near Birmingham, Alabama, for example, indicate that maximum permeability development in these reservoirs, with respect to the present-day stress field orientation, is parallel to the major fracture system (Horner, 1986, 1987; Schraufnagel and Schwerer, 1986; Schraufnagel, 1987; Way, 1987). The same relationship between maximum permeability development, present-day stress field regime and the major coal fracture system has also been documented at the Gas Research Institute Red Mountain Unit in the Piceance basin near Grand Junction, western Colorado (see references cited in previous sentence).

Fracture permeability is a key reservoir property. Permeability has a direct influence on productivity, and therefore is an important factor in the economic success or failure of coal-bed methane exploration and development programs, given adequate in-place coal-bed gas resources.

CONCLUSIONS

The conclusions of this study concerning the proposal of methods that may be used to identify trends and origins of inferred fracture permeability in potential Cretaceous-Tertiary coal-bed methane reservoirs in the central and southern Raton basin are presented here:

1. Field mapping indicates that the regional trends of primary and secondary systematic fractures in sedimentary rocks of the central and southern Raton basin south of the Spanish Peaks are east and north, respectively. Therefore, the regional trends of inferred primary and secondary fracture permeability in these areas with potential Cretaceous-Tertiary coal-bed methane reservoirs are east and north, respectively.

2. Published emplacement models for middle Tertiary syenite and syenodiorite dikes of West Spanish Peak in the northwestern Raton basin show that the regional orientation of maximum principal horizontal stress during magmatic invasion was approximately N80°E. This trend is essentially perpendicular to the trend of the Sangre de Cristo Mountains thrust fault system along the western margin of the Raton basin.

3. Field evidence indicates that dike magmas in the central and southern Raton basin south of the Spanish Peaks intruded pre-existing fractures. Thus, primary extensional and secondary compressional release fractures, and corresponding inferred primary and secondary permeability freeways, formed parallel and perpendicular, respectively, to east-directed Laramide Sangre de Cristo thrust forces.

4. Published emplacement models for post-syenite/syenodiorite dikes of West Spanish Peak indicate that the polarity of the stress field in the Raton basin rotated 90° in the late Oligocene due to the inception of active Rio Grande rift extension just west of the Raton basin. North-trending secondary Laramide compressional release fractures and corresponding inferred secondary fracture permeability freeways may have been further enhanced by Oligocene-Recent extensional forces, in combination with stress release resulting from late Neogene denudation of at least 1000 m of strata. It is likely that the dominance of inferred primary east-trending permeability has not been changed by west-directed Rio Grande rift extensional forces.

5. The chemistry of waters produced from central Raton basin coal beds indicates a hydrologic system with moderate permeability. Brackish sodium bicarbonate waters suggest relatively slow movement of meteoric waters into coal beds so that sulfate has been removed under anaerobic reducing conditions. Both sodium and bicarbonate have been concentrated during residence time in the coal beds. Low salinity may allow approval of surface disposal of produced coal-bed water.

6. It is suggested that, if the geological and engineering characteristics of the potential coal-bed methane reservoirs allow, primary pro-

duction wells be aligned east and west of a central producing well, and secondary production wells be located north and south of the central producing well. This may enable efficient reservoir depressurization, dewatering and methane drainage. Exact well spacings for optimum interference will be dependent upon several factors, including economics, individual and net coal thicknesses, coal reservoir continuity, permeability magnitudes and reservoir pressure.

RATIONALE

Knowledge concerning fracture permeability will strongly influence further delineation and development of coal-bed methane resources in the Raton basin. Potential Raton basin coal-bed methane reservoirs at depths from 210 to 760 m may contain between 0.17 to 1.1 BCM (billion cubic meters; 6 to 40 BCF [billion cubic feet]) of gas per 2.6 km^2, based upon gas content data from Danilchik et al. (1979), Tremain and Toomey (1983) and Tremain (1984), and subsurface coal mapping. Because the Raton basin contains significant coal-bed natural gas resources, and coal-bed reservoir gas and water flow in fractures is governed by Darcy's Law, the magnitude of fracture permeability, along with reservoir pressures, gas desorption (diffusion) characteristics and degree of formation damage (skin factor), will impact Raton basin coal-bed natural gas and water production. It is the possible productivity of these reservoirs that will in turn dictate, along with gas marketability and water disposal costs, whether or not economics will permit installation of a pipeline infrastructure. The lack of long-term commercial conventional oil and gas and unconventional gas production in the Raton basin has prevented pipeline development into the basin interior. Because coal-bed methane reservoirs may contain the largest and possibly the only commercially significant Raton basin "hydrocarbon" resource, the fate of commercial gas development will be greatly influenced by the nature and magnitude of coal-bed methane reservoir permeability.

METHODS

A set of field data for fractures, structure, stratigraphy and igneous intrusive rocks has been integrated with basin geologic history, gas and water productivity and coal-bed-methane-well-water chemistry in order to infer the presence, trends and origins of fracture permeability in potential Raton basin coal-bed methane reservoirs. Inferences concerning Raton basin coal-bed methane reservoir permeability at present (early 1990) must rely on the above described data set for the folloiwng reasons: (1) photogeologic interpretations of Raton basin fractures are complex and ambiguous; (2) oriented core fracture description and well test permeability data are not publicly available; (3) well control in the Raton basin is not sufficient to allow preparation of detailed curvature (structural trend surface) maps from which fracture trends and frequency may be obtained; (4) production data for Raton basin coal-bed methane reservoirs are too sparse to permit meaningful production mapping; and (5) specialized seismic and openhole geophysical log data required for fracture assessment are not publicly available.

GEOLOGIC OVERVIEW

The Raton basin is the southeasternmost of the Laramide Rocky Mountain basins that contains a nearly complete Cretaceous and Tertiary stratigraphic succession (Baltz, 1965). The Cretaceous-Tertiary stratigraphy of the basin is presented in Figure 1. The Vermejo and Raton Formations contain potentially commercial coal-bed methane reservoirs. Outcrop observations and interpretation of openhole high resolution density geophysical logs indicates that Vermejo and Raton coals are 0.60 to 3 m thick and are typically distributed throughout a stratigraphic interval of 300 m or more. The Raton basin covers approximately 5700 km^2 in northeastern New Mexico and southeastern Colorado, as shown in Figure 2. The basin extends about 280 km north-south and is a maximum of 105 km wide along the New Mexico-Colorado border. The basin is an asymmetrical synclinorium with a steeply dipping to overturned western limb, a gently sloping eastern limb and a broad central region where the strata are nearly horizontal (Baltz, 1965). Structural elements of the basin were originally formed during the Pennsylvanian and Permian (Baltz, 1965). The western flank of the

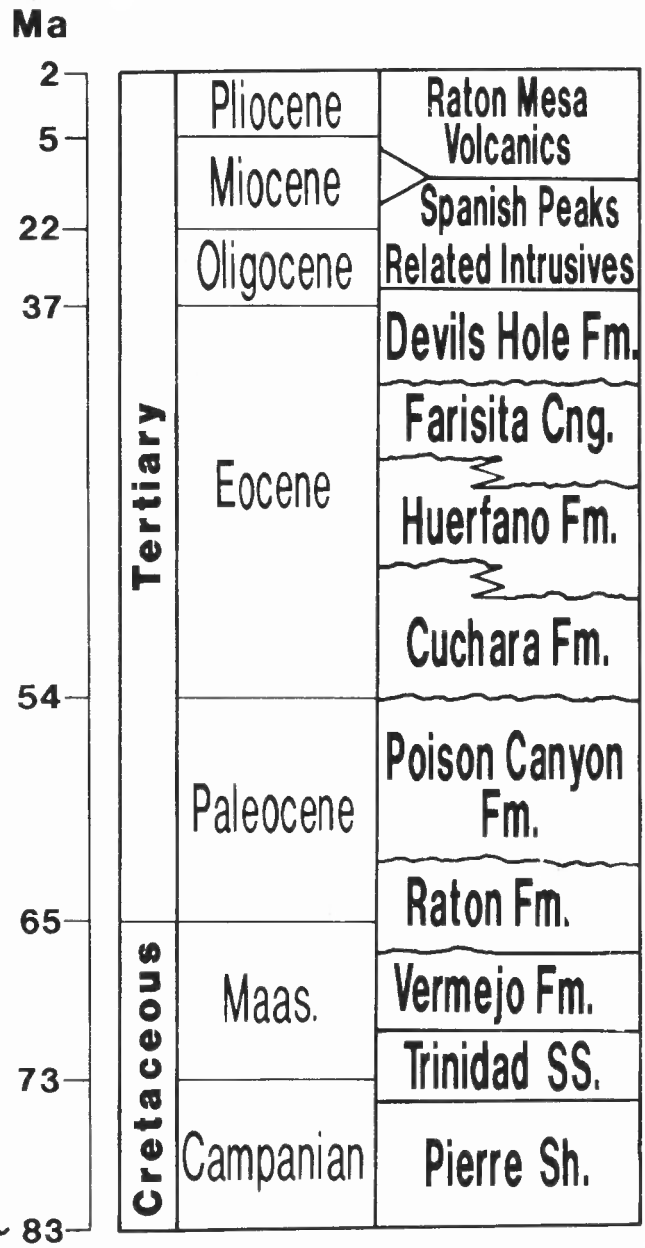


FIGURE 1. Upper Cretaceous and Tertiary stratigraphy of the Raton basin, New Mexico and Colorado (see references in text).

Raton basin is bordered by the Sangre de Cristo Mountains, which were thrust eastward (Applegate and Rose, 1985) during Laramide rejuvenation of Paleozoic structures (Lindsey et al., 1986; Dickinson et al., 1988) in the latest Cretaceous to the late Eocene. These compressional forces formed the La Veta syncline, which marks the axis of the post-Eocene Raton basin, as shown in Figure 2.

Major middle Tertiary intrusive events are recorded by the Spanish Peaks stocks and related dikes in the northwestern Raton basin (see Figure 2). Prominent dikes radiate outward from the Spanish Peaks and are most abundant proximal to the stocks. The Spanish Peaks dominate the physiography of the northern Raton basin, as shown in Figure 3.

FRACTURE AND DIKE FIELD RELATIONSHIPS

Introduction

Field evidence collected during study of Raton basin outcrops indicates that magmas composing dikes related to Spanish Peaks intrusives south of West Spanish Peak proper intruded pre-existing systematic

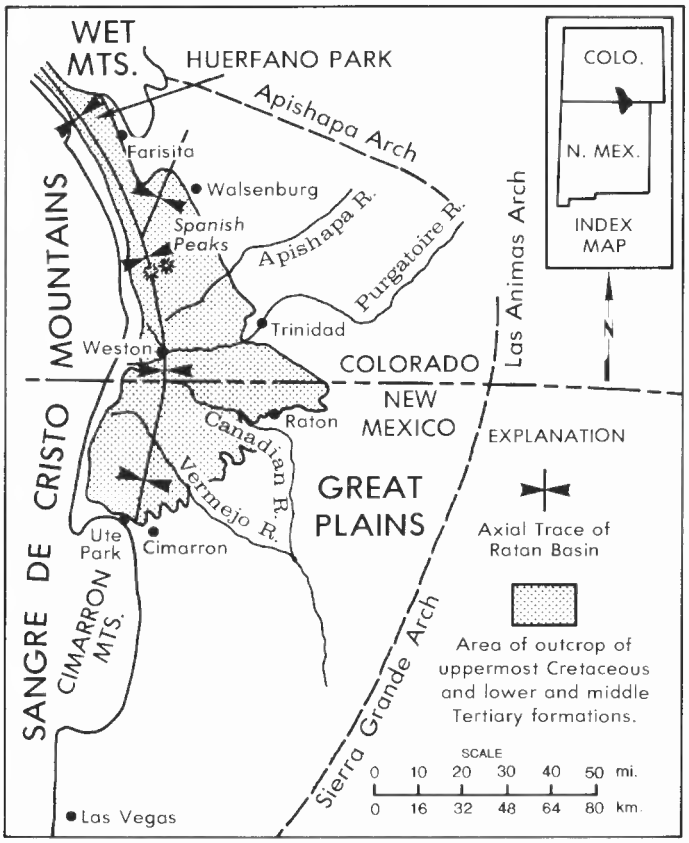


FIGURE 2. Structure and location map of the Raton basin, New Mexico and Colorado (after Johnson and Wood, 1956).

fractures. Another important conclusion is that the coincidence of joint and cleat (joint in coal) orientations in rocks of diverse ages, lithology and structural association throughout the southern two-thirds of the Raton basin south of the Spanish Peaks supports the observation that vertical extrapolation and lateral correlation of systematic fractures, and primary and secondary (face and butt) cleats in particular, is probably warranted.

It should be noted that fracture data along with stratigraphic and structural relationships for the northernmost Raton basin north of the Spanish Peaks suggest a complex set of trends and origins for these fractures, which do not fit the published West Spanish Peak dike paleostress analysis models reviewed in this paper. Thus, the permeability model proposed below is not applicable to the northernmost Raton basin. A review of published thought concerning the relative timing of fracture genesis and magmatic invasion is discussed, and then evidence indicating that dike magmas intruded fractures and that fracture associations are uniform, is presented in this section.

Merry and Larsen (1982) noted that the trends of primary joints, face cleats and dikes in the vicinity of the Spanish Peaks correspond very closely. Examples of Raton basin joints and cleats as they appear in the field are shown in Figures 4 and 5. In general, in the central Raton basin, the face cleats, principal systematic joints and most of the dikes are oriented perpendicular to the axis of the La Veta syncline (Merry and Larsen, 1982). The fractures were probably intruded by dike magmas as first suggested by Knopf (1936). Harbour and Dixon (1959) noted that vertical joints which were probably intruded by the dike-forming magmas are abundant in the Trinidad coal field. They suggested that the joints in the northern Raton basin belong to two systems. System I is a radial joint set that perhaps resulted from radial extension during emplacement of Spanish Peak stocks. System II is an east-trending joint set perpendicular to the Sangre de Cristo Mountains front and La Veta syncline, which Harbour and Dixon (1959) inferred to have resulted from extension parallel to east-directed Laramide compression. Johnson (1961) argued that stresses associated with folding of the La Veta syncline caused the formation of joints, and that selective magmatic invasion into these joints could account for the observed Spanish Peaks dike pattern. Jurich and Adams (1984) indicated that the dikes trend perpendicular to the La Veta syncline, and that magmas comprising the dikes were probably intruded along tensional fractures created by Laramide folding of the Raton basin.

Field evidence

A summary of the evidence which indicates that dike magmas south of the Spanish Peaks intruded pre-existing fractures is presented in this section. Raton basin fracture data were collected from outcrops of



FIGURE 3. S45°W view of the Spanish Peaks from sec. 11, T29S, R69W, Huerfano County, Raton basin, Colorado. Note prominent dike that crops out just north of West Spanish Peak. Jack Close is the field assistant.



FIGURE 4. N15°W view of secondary systematic regional joints in the Trinidad Sandstone in Berwind Canyon at SE¼ NW¼ SE¼ sec. 15, T31S, R65W, Las Animas County, Raton basin, Colorado. Field of view of approximately 5 m wide.

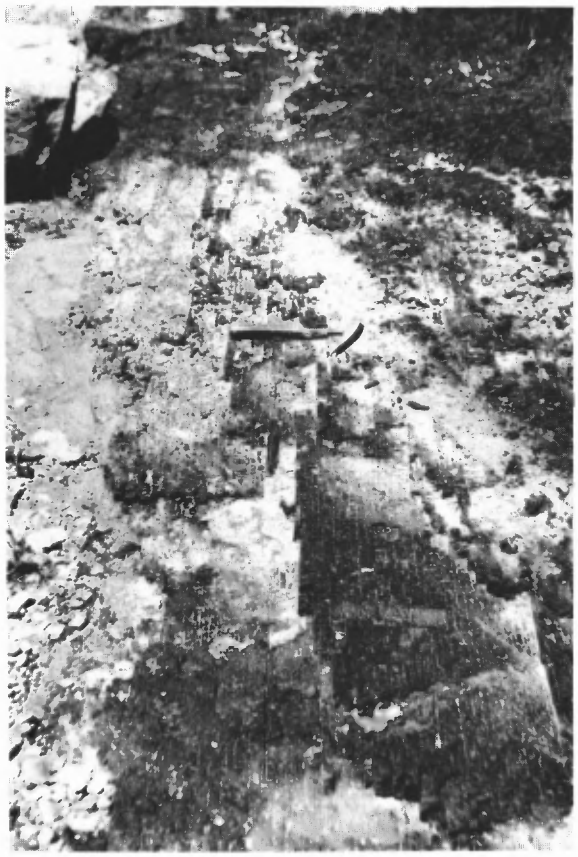


FIGURE 5. N70°W view of face cleats trending N70°W and butt cleats trending N20°E in a Vermejo Formation coal seam at Dawson ghost town, Rail Canyon, 36° 41′ 28″ N latitude, 104° 45′ 29″ W longitude, Colfax County, Raton basin, New Mexico. Note that face cleats are more continuous, and that butt cleats terminate in face cleats.

Pennsylvania through Eocene rocks at 276 stations throughout the basin. (A map of Raton basin field fracture stations visited for this study and the field fracture data are available from the authors.) Sites representing diverse structural and stratigraphic settings were selected using maps and work by Johnson and Wood (1956), Johnson et al. (1958), Wanek (1963), Robinson et al. (1964), Baltz (1965), Johnson (1968, 1969), Pillmore (1969) and Vine (1974) and field observations made for this study during 1986 and 1987 (Close, 1988). It is crucial to note that the "number of fracture measurements" noted on forthcoming fracture rose diagrams refers to the different number of fracture trends documented at the field stations. If the same fracture trend (defined as a trend with a variance of less than or equal to 10°) was noted at a particular station, then that field-data set was classified as only "one measurement," and so on. The actual number of fractures in the same fracture trend set at a given station typically far exceeds one actual fracture. This approach for reporting the fracture data in this paper is unconventional. However, in this way the fracture data are less biased by the number of measurements and serve to more strongly emphasize the actual fracture trends documented in the field.

Delaney et al. (1986) presented criteria to infer relative ages of joints and dikes, and commented on magmatic emplacement processes and paleostress analyses. They defined three types of joints: (1) "adjacent joints," which are present within distances comparable to 1% of the dike-outcrop length; (2) "local joints," which are present within distances comparable to the dike-outcrop length; and (3) "regional joints," which are present over distances that are much greater than dike-outcrop length. Delaney et al. (1986) also stipulated that to further verify the possibility that magmas invaded joints, local and regional joints must be present and must have similar or greater frequency than adjacent joints.

Fracture data collected during field mapping in the Raton basin (Close, 1988) indicate that primary local and regional systematic vertical joints and corresponding face cleats south of the Spanish Peaks have trends between N80°E and N70°W, as shown in Figures 6 and 7. These primary local and regional fractures have similar or greater frequencies than adjacent fractures, and thus meet the criteria set forth by Delaney et al. (1986). Local face cleat trends are perpendicular to the respective local trend of the Sangre de Cristo Mountains thrust front, which is regionally arcuate and slightly convex toward the east. Secondary local and regional systematic vertical joints and corresponding parallel butt cleats are perpendicular to respective local and regional primary joint set trends and corresponding face cleat trends. Thus, these secondary fractures trend approximately north. All of these fracture sets are also present in areas south of the Purgatoire River in Colorado as well as in adjacent areas in New Mexico. These occurrences clearly define the primary and secondary fractures as regional. Additional lines of evidence which collectively serve to indicate that magmas composing dikes south of the Spanish Peaks intruded pre-existing fractures are presented below.

A few dikes bifurcate along primary fractures perpendicular to the axis of the La Veta syncline, or cross to an adjacent parallel east-trending joint along north-trending joints (see Johnson, 1968). This evidence suggests emplacement of dike magmas along pre-existing east- and north-trending fractures. Good examples of these bifurcations can be seen in the vicinity of Gulnare, which is located east of the Spanish Peaks and northwest of Trinidad. No dikes observed during the course of field study are cut by penetrative joints correlative to primary and secondary systematic local and regional joints (Close, 1988). This relationship suggests that the dikes could be younger than the fractures.

Stratigraphic and structural evidence suggests that: (1) a major fold event caused by Sangre de Cristo thrusting occurred after coal-bearing

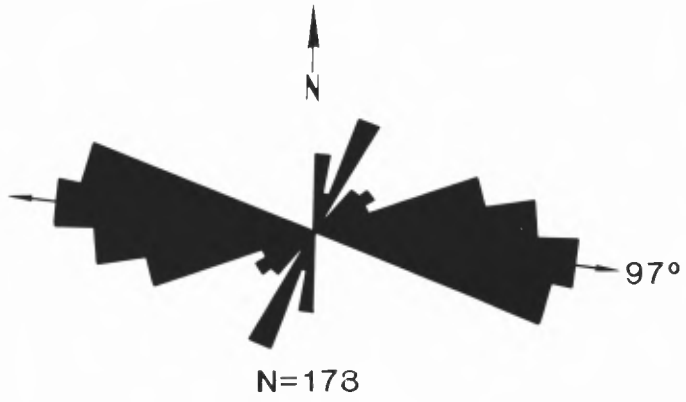


FIGURE 6. Equal area rose diagram of local and regional joint trends at 123 Raton basin fracture stations (178 measurements; see text) south of West Spanish Peak and north of Cimarron, New Mexico.

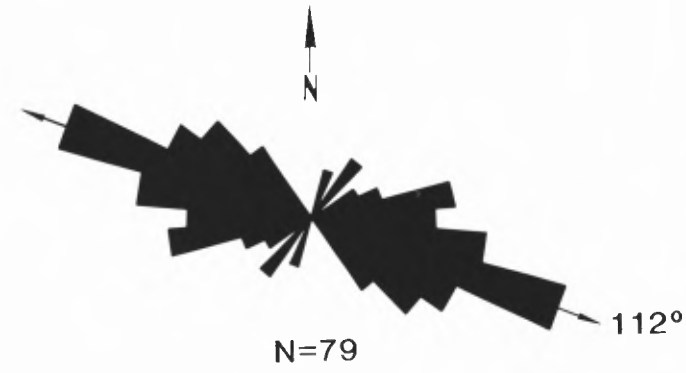


FIGURE 7. Equal area rose diagram of local and regional face cleat trends at 67 Raton basin fracture stations (79 measurements; see text) south of West Spanish Peak and north of Cimarron, New Mexico.

Vermejo and Raton Formation sediment deposition and prior to middle and late Paleocene (Robinson, 1972) Poison Canyon sediment deposition; and (2) thrusting ceased after the Eocene (prior to latest Oligocene-earliest Miocene dike magma emplacement). Reasons for this interpretation are as follows:

1. The base of the Poison Canyon is characterized by a marked angular disconformity at Midnight Mesa (near Cimarron in the southernmost Raton basin; see Robinson et al., 1964) and north of La Veta in the northern Raton basin (cf. Johnson and Stevens, 1954), where rocks as old as the Pierre Shale have been truncated (see stratigraphic chart in Figure 1). Field observations by the authors confirmed the presence of these significant disconformities. These field relationships indicate that a major folding event occurred after Raton Formation, but before Poison Canyon Formation sediment deposition.

2. The Devil's Hole Formation, which overlaps Laramide Sangre de Cristo thrust plates in Huerfano Park (Johnson, 1959), northwesternmost Raton basin, is no younger than earliest Oligocene (see Close, 1988). Therefore, thrusting must have ceased by the latest Eocene, before magma emplacement. These relationships document Middle Paleocene-latest Eocene folding and thrusting.

Drainage on latest Cretaceous-early Paleocene Raton Formation and older rocks is in many places controlled by fractures, which suggests post-early Paleocene fracture development. Recall the field evidence showing that: (1) the Poison Canyon Formation rests disconformably on Raton Formation and older rocks, which indicates a major post-Raton Formation folding episode; and (2) Poison Canyon and younger rocks are not nearly as pervasively fractured as Raton and older rocks (irrespective of lithology, cementation and bed thickness), which suggests that the major fracture genesis event in Raton basin was during the earliest middle Paleocene (Close, 1988). Examples of structural control on drainage can be observed in the central Raton basin west of Trinidad in Sarcillo Canyon in the Weston, Colorado 7.5-minute quadrangle, in Long Canyon and the Purgatoire River in the Valdez, Colorado 7.5-minute quadrangle, and in Lorencito Canyon and the Purgatoire River in the Little Pine Canyon, Colorado 7.5-minute quadrangle. These fluvial systems closely follow east- and north-trending primary and secondary systematic fracture sets on a very local scale. On a more regional scale, the Purgatoire River and large arroyos at least 8 km long on the eastern flank of the basin in Colorado are structurally controlled drainages that follow respective trends of the primary, east-trending fracture set. However, the overall drainage pattern is dendritic, which indicates that the younger, structurally controlled drainages were superimposed on flat lying, relatively weakly fractured younger rocks. In other words, the middle Paleocene Poison Canyon and younger sediments were deposited after the major Laramide folding episode that influenced significant fracture genesis. This late-early to early-middle Paleocene fracture event was well before latest Oligocene-earliest Miocene (cf. Stormer, 1972) dike emplacement.

Further indication that the dikes were emplaced after folding is that undeformed dikes are often present in rocks affected by Laramide folding and thrusting. For example, the Pennsylvanian-Permian Sangre de Cristo Formation along the thrust front at Monument Lake and Cuchara (the west-central Raton basin west of Trinidad) strikes north and is vertical, and is cut by vertical undeformed dikes trending roughly east (Close, 1988).

Composite dikes are present. Intrusion of younger magmas along and into pre-existing dikes or partially cooled magmas is clearly documented for Walsen dike near Walsenburg in the northern Raton basin northeast of the Spanish Peaks (Johnson, 1964). Johnson's observations were confirmed during field work by the authors. This evidence implies repeated magmatic invasion into pre-existing areas of weakness.

Several dikes in places are found discontinuously along the lengths of joints in areas of nearly flat, horizontal land surfaces, which implies that the magmas were not intruded horizontally from below (Johnson, 1968, p. G13). Abrupt thinning or bulging of these dikes is uncommon (Johnson, 1968, p. G13), which further suggests structural control on locations of magmatic emplacement. These field relationships were traced by the authors along dikes northeast and east of the Spanish Peaks southwest of Walsenburg in the northern Raton basin. These observations collectively document that dike magmas which are part of the Spanish Peaks intrusive system, but are south of West Spanish Peak, were intruded into pre-existing fractures formed as a result of Laramide tectonic forces.

WEST SPANISH PEAK DIKE EMPLACEMENT MODELS

The orientation of the paleostress field present during intrusion of magmas composing West Spanish Peak and related dikes has been determined through the use of published emplacement models. The emplacement models can be used to infer that remnant Laramide compressional forces present during intrusion of the volumetrically significant dikes were oriented N80°E. A review of these emplacement models with respect to stress fields and basin structure is presented in this section.

Extensive middle Tertiary (primarily Oligocene) igneous intrusive activity in the Raton basin is represented by the Spanish Peaks stocks (Fig. 3) and associated dikes (Knopf, 1936; Johnson, 1968; Armstrong, 1969; Larsen and Strangway, 1969; Stormer, 1972; Smith, 1973). The striking radial pattern has been noted by many geologists (Knopf, 1936; Johnson, 1968), and several mechanical models have been published to account for the mapped dike pattern shown in Figure 8. Ode (1957) first demonstrated that the dike pattern could be reasonably explained with a two-dimensional elastic model containing a pressurized zone now occupied by West Spanish Peak stock, a rigid north-south boundary (the western flank of the basin), and regional stresses that were superimposed orthogonal to the rigid boundary (remnant east-directed Sangre de Cristo thrust forces). Johnson (1970) reviewed Ode's model. Muller and Pollard (1977) showed that a better geometric fit between the observed and mathematically predicted dike pattern could be obtained if the dikes were divided into groups based upon petrography and age, and if regional stresses were not constrained to be exactly orthogonal to the rigid boundary, as shown schematically in Figure 9. Muller (1986) extended this analysis to different groups of dikes. Muller and Pollard (1977) and Muller (1986) showed that the orientation of the maximum principal regional horizontal stress was between N79°E and N82°E (during intrusion of magmas forming most of the volumetrically significant West Spanish Peaks dikes.

PREDICTION OF PERMEABILITY TRENDS AND ORIGINS

The Spanish Peaks dike emplacement models of Muller and Pollard (1977) and Muller (1986), when considered with the field fracture data, can be used to infer the trends and origins of fracture permeability in potential Vermejo and Raton Formation coal-bed methane reservoirs in the central and southern Raton basin. This is because emplacement of

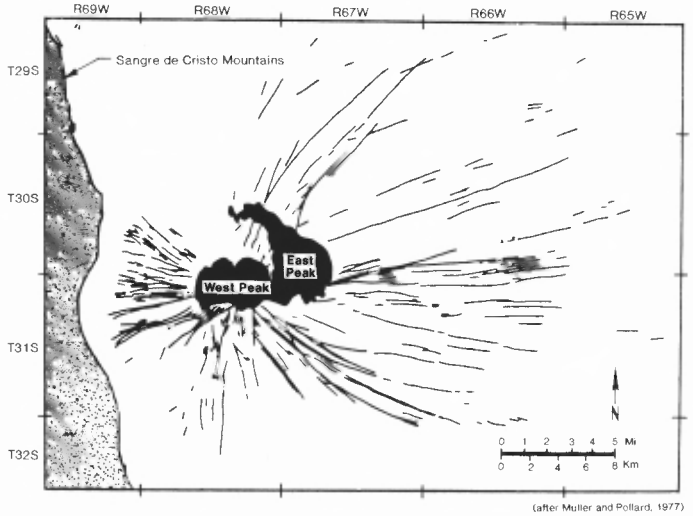


FIGURE 8. Syenite and syenodiorite dike pattern used in paleostress analysis. Map from Johnson (1968).

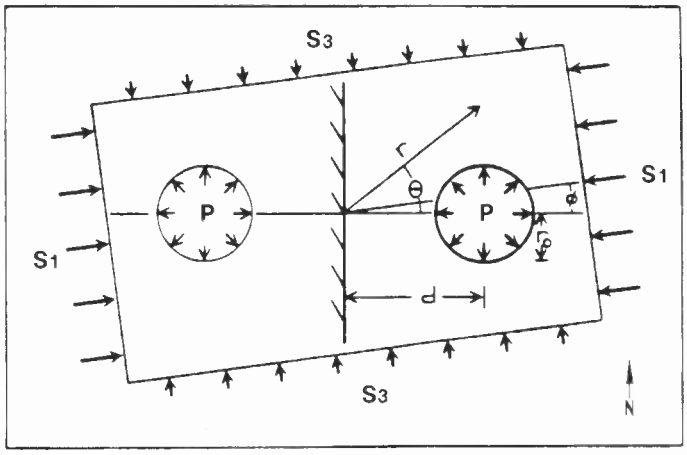


FIGURE 9. Boundary conditions and parameters used in West Spanish Peak dike paleostress analysis. The main and secondary compressive stresses are S1 and S3 respectively, P is pressure exerted by magmas composing West Spanish Peak stock, r and theta are polar coordinates, r(o) is the radius of West Spanish Peak stock, d is the distance from the center of West Spanish Peak stock normal to the local trend of the Sangre de Cristo Mountains thrust front, and the regional stress system S1, S3 is rotated by phi from being exactly perpendicular to the rigid Sangre de Cristo thrust boundary (see Muller and Pollard, 1977).

the volumetrically significant Spanish Peaks intrusive system was controlled by a regional stress field that was consistent with the stress field that gave rise to the primary east-trending joints and cleats. The orientation of face cleats in these areas, and thus the orientation of inferred primary permeability, is perpendicular to the local trend of the Sangre de Cristo thrust front. In other words, primary permeability is inferred to trend N80°E just south of the Spanish Peaks, N90°E in areas just north of and along the Purgatoire River and between N85°W and N70°W in areas south of the Purgatoire River in Colorado and in the southern Raton basin in New Mexico. These east-trending face cleats and corresponding primary permeability avenues formed parallel to east-directed maximum compressive stress that also produced the Laramide Sangre de Cristo thrusting. An important secondary fracture pattern (butt cleats), and corresponding inferred secondary permeability trend, is perpendicular to respective face cleat trends in the central and southern Raton basin. Thus, these secondary inferred permeability trends formed perpendicular to Laramide compressional forces, and are themselves of compressional release origin.

"Five-spot" well production configurations for two central Raton basin coal-bed methane production sites (shown in Figure 10) just south and approximately 10 km north of the Purgatoire River (27 km west of Trinidad) are such that the wells are placed along face and butt cleat trends determined in the field with respect to a central well location. This well placement pattern implies that cleats in Vermejo and Raton Formation coal-bed methane reservoirs in these locations have the same trend as cleats and joints present in outcrops at or near the well sites, and that vertical extrapolation of surface fractures into the subsurface is probably warranted in the central Raton basin. The five-spot well patterns and spacings suggest that fracture permeability orientations were given a priority in planning two major Raton basin coal-bed methane reservoir evaluation programs, and that primary and secondary permeability magnitudes may be the same or similar. Although oriented core fracture description data are not publicly available for these central Raton basin wells, the evidence presented in this paper indicates that vertical extrapolation of systematic fracture trends into the shallow subsurface at Vermejo and Raton Formation coal-bed methane reservoir depths is probably possible. It is emphasized that the orientations of primary and secondary joints as measured in the field (tabulated in Close, 1988), in the absence of supporting subsurface face and butt cleat trend data, may be used to infer primary and secondary permeability orientations in central and southern Raton basin coal-bed methane

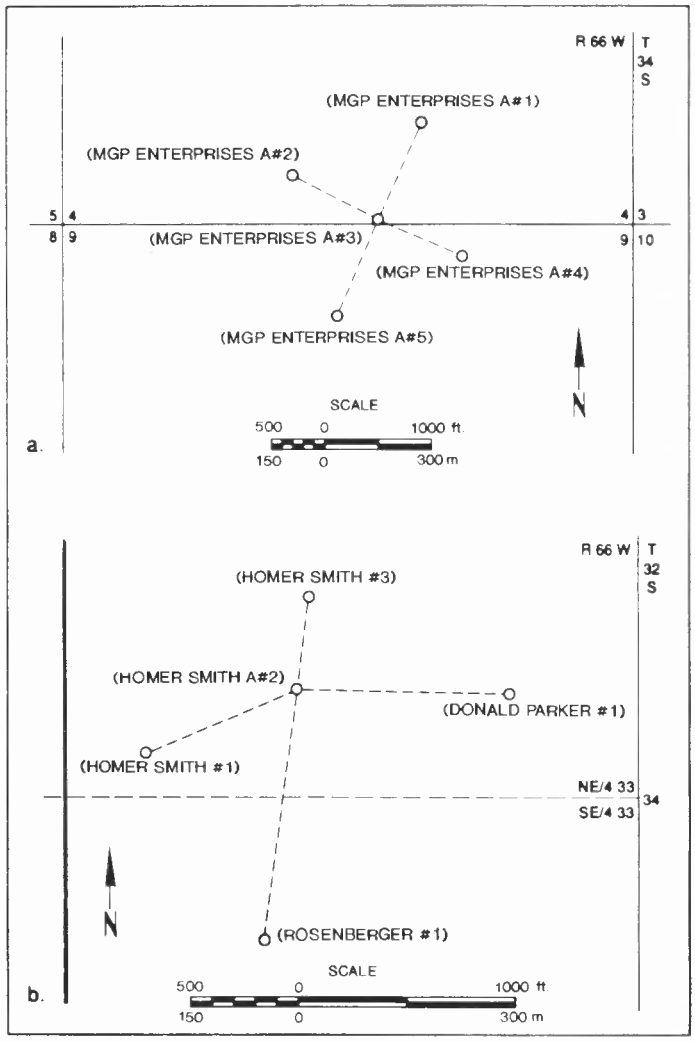


FIGURE 10. Amoco Production Co. coal-bed methane pilot sites, Las Animas County, Raton basin, Colorado, illustrating five-spot dewatering configurations for (a) MGP wells, and (b) Homer Smith and others wells. Adapted from Gas Research Institute (1988).

reservoirs prior to drilling. However, site-specific determination of subsurface cleat trends using oriented cores, from which permeability trends may be inferred, is an essential, relatively low-cost part of formation evaluation in potential coal-bed methane reservoirs.

DISCUSSION

Late stage tectonic enhancement of secondary fractures

Secondary north-trending fractures in the central and southern Raton basin were probably tectonically enhanced during the earliest Miocene to Recent. The significance of this inferred fracture enhancement event is that, as a result of Miocene-Recent extension, the magnitudes of primary east-trending and secondary north-trending permeability may be similar.

Muller (1986) demonstrated that the polarity of the regional principal horizontal stress field proximal to the Spanish Peaks changed at approximately 22 Ma (the earliest Miocene). The orientation of principal regional compressional horizontal stress during emplacement of West Spanish Peak syenite and syenodiorite dike magmas at 22–25 Ma was N80°E (Muller and Pollard, 1977). This N80°E direction then became the azimuth of least compressive regional horizontal stress during later intrusion of a volumetrically much smaller set of granite and granodiorite magmas at 22 Ma (Muller, 1986). The orientation of principal regional horizontal compressional stress during intrusion of these granite

and granodiorite dike magmas was between N and N6°W inclusive (Muller, 1986).

The Rio Grande rift, which is a regionally significant Miocene-Recent extensional terrane in the central and southern Rocky Mountains, borders the western flank of the Sangre de Cristo Mountains in southern Colorado and northern New Mexico (Chapin, 1971). Lindsey et al. (1986) indicated that major post-Laramide Sangre de Cristo uplift occurred at approximately 19 Ma, based upon interpretation of apatite fission-track blocking temperatures with respect to Raton basin structural history. Significant Rio Grande rift activity commenced by 18 Ma as evidenced by middle and late Miocene fossils in basal alluvial sediments and by K-Ar dates on interbedded rift affinity volcanic rocks (Chapin, 1971). Therefore, the stress polarity change fron N80°E to approximately N, which began at about 22 Ma in the Raton basin (Muller, 1986), is attributable to the inception of major Rio Grande rifting (extension) along the western flank of the Sangre de Cristo Mountains west of the Raton basin. North-trending secondary fractures in the basin were then subjected to an extensional strain field during the onset of major Rio Grande rift development. These secondary fractures were probably further developed as influenced by this regionally significant middle Miocene-Recent extensional regime. In effect, these north-trending fractures now probably represent a significant trend of permeability anisotropy in potential Raton basin coal-bed methane reservoirs, along with east-trending inferred primary fracture permeability.

Interpretation of coal-bed well production data

A discussion concerning the significance of coal-bed methane gas production data from several central Raton basin wells is presented here. The major conclusion that arises from this discussion is that a combination of unfavorable reservoir characteristics, completion problems and formation damage have inhibited the production of commercial quantities of gas from these wells.

That permeability in Raton basin coal-bed methane reservoirs even exists is verified by the fact that modest volumes of coal-bed gas and water were produced from several wells. This statement is supported by non-oriented core and outcrop fracture description data, which indicate significant cleat frequency development in clean Vermejo and Raton Formation coal intervals interbedded with discrete non-coal (clastic) materials. Two Raton Formation coal-bed methane wells produced an average of 935 m^3 (22 MCF [thousand cubic ft]) of gas and 48 BW (barrels of water) per day, and eight Vermejo Formation coal-bed methane wells produced an average of 538 m^3 (19 MCFD) and 87 BW per day (Gas Research Institute, 1986, 1987a, 1988).

The gas production rates are low, and the significance of the data can be interpreted in several ways: (1) Raton basin coal-bed methane permeability magnitudes unfortunately may not be great enough to allow significant gas production; (2) reservoirs in the aforementioned coal-bed methane wells may not have been depressured long enough to allow active gas desorption and commensurate gas production. Producing bottomhole pressures may not have been low enough for the time required to initiate significant depressurization (dewatering) and subsequent gas movement. Water encroachment from adjacent sandstones may have further increased the amount of water to be pumped off; (3) significant physical and chemical formation damage during drilling and completion (cased hole hydraulic fracturing) may have greatly lowered near-wellbore permeability magnitudes. Also, it is possible that completions in the thin, multiple Vermejo and Raton Formation coal zones were not effective; (4) average daily production figures may be misleading, as detailed production data including shut-in durations are not available; and (5) reservoir pressures may be low, and thus the amount of producible gas as strongly influenced by the pressure differential between surface and reservoir pressures may be commensurately low.

It is emphasized that initial gas production (IP) rates for many coal-bed methane wells in other basins which have been commercial over the longer term were quite minimal. Some coal-bed methane well production data show an inverse decline curve during early well life, which is the opposite of the production trends of most conventional gas wells. Therefore, low IP gas rates do not necessarily indicate non-commercial coal-bed wells, particularly if the formation evaluation data indicate a potentially commercial reservoir. Many months may be required for reservoir depressurization to initiate significant gas production, which can significantly increase the time to payout. Prediction of the time required for reservoir depressurization prior to potentially commercial gas production (using reservoir simulation models) may not be possible. It may be very difficult to convince management accustomed to conventional gas reservoir decline curves to continue pumping off water from coal-bed wells for an extended period of time. However, the upside is that the life of a coal-bed methane well may be much longer than a conventional gas well with comparable reserves.

Given that the Raton basin contains appreciable coal-bed methane resources and probably has coal-bed methane reservoirs with moderate permeability, it is tempting to speculate that these reservoirs were damaged during completion, multiple thin-zone completions may not have been as effective as planned, and the coal reservoirs may not have been allowed to depressurize to low levels necessary for notable gas production. It is also possible that Raton basin coal-bed methane reservoirs are underpressured (see Dolly and Meissner, 1977) and undersaturated, resulting in low reservoir pressure differentials which limited Darcy flow of gas and water during post-(hydraulic) frac-production testing.

Interpretation of produced water chemistry

Chemistry of water produced from coal beds in the central Raton basin can be used to infer the relative magnitude of permeability. This section demonstrates that brackish sodium bicarbonate water chemistry data from several coal-bed wells in the central Raton basin suggest moderate permeability and lateral continuity in an eastward-flowing hydrodynamic system.

Chemical type and salinity (total dissolved solids [TDS]) are functions of residence time and degree of displacement of connate water which, in turn, are controlled by permeability and distance from a point of meteoric recharge. Shallow ground water, including that in coal beds, commonly evolves from a fresh (<1000 ppm TDS) calcium sulfate chemistry to a fresh, brackish (1000 to 10,000 ppm TDS), or slightly saline (>10,000 ppm TDS) sodium bicarbonate chemistry. Fresh water may extend far into a basin along narrow high-permeability trends, or water may vary across a basin from fresh at the recharge area to brackish or saline at the discharge area, if the size of the recharge area is limited compared to the total strike dimension of the aquifer. For example, see Domenico and Robbins (1985; see also Davis and DeWiest, 1966).

In a gaseous coal bed, anaerobic conditions begin at very shallow depths below which anaerobic bacteria pervasively reduce sulfate to HS^- ion during metabolic oxidation of organic nutrients. Reduced sulfur rapidly reacts with available iron to create pyrite. Sodium, which is highly soluble, becomes the dominant cation as calcium and magnesium are exchanged on clay surfaces or removed by carbonate mineral precipitation. Ubiquitous carbon dioxide, under the usually prevailing slightly alkaline conditions, exists as the bicarbonate ion. In this manner, coal-bed water commonly evolves to a sodium bicarbonate chemical type. In low permeability areas and/or in higher permeability areas far from a limited recharge area, coal-bed waters may become brackish or slightly saline. Chlorine, which is highly soluble and common in trace amounts in coal-bed waters (or in connate waters from adjacent strata), may be retained as a secondary anion.

Coal-bed methane well water chemistry data for nine central Raton basin wells (Gas Research Institute, 1987b) indicate that bicarbonate, chlorine and sodium are the major ionic constituents. The average bicarbonate ionic concentration is 1368 ppm (range 750–2060 ppm), the average sodium ionic concentration is 808 ppm (range 359–1002 ppm), and the average chlorine ionic concentration is 378 ppm (range 95–927 ppm). The average total salinity expressed as TDS for these coal-bed water samples is 2438 ppm (range 1272–3387 ppm), which indicates brackish water quality. In other words, water chemistry demonstrates that the coal beds contain water with significant residence time under anaerobic conditions so that sulfate has been reduced and eliminated from solution. In addition, the coal beds are not being rapidly displaced by meteoric waters because of significant, although moderate, concentration of sodium, bicarbonate and chlorine ions.

Since the northern and central Raton basin is probably underpressured

(Dolly and Meissner, 1977), and regional topographic relief in the Raton Basin area is as much as 2440 m, fresh meteoric waters may generally move from western Raton basin Vermejo and Raton Formation outcrop recharge areas in the Sangre de Cristo Mountains, along east-trending inferred fracture permeability, down into central Raton basin coal-bed methane reservoirs and discharge along the eastern basin flanks. The lack of a reservoir seal for the Vermejo and Raton Formations along the eastern Raton basin margin, along with the strong downdip groundwater pressure flow potential along east-trending permeability freeways, may be a major cause for the probable underpressured regime in central and northern Raton basin. In summary, these essentially fresh coal-bed methane well water chemistry data imply significant lateral communication with the outcrop belt, which, in turn, implies significant lateral Vermejo and Raton Formation coal-bed methane reservoir permeability.

SUMMARY

This paper suggests methods that may be used to identify the presence and origins of inferred primary east-trending and secondary north-trending fracture permeability in potential coal-bed methane reservoirs of the Raton basin, northeastern New Mexico and southeastern Colorado. Fracture permeability is a key ingredient of commercial coal-bed methane reservoirs. It is believed that the development of these inferred fracture permeability freeways is directly related to tectonism during two major deformational events.

It is suggested that, if supporting geologic and reservoir characteristics allow, groups of wells could be placed along east- and north-trending fracture permeability with respect to a central producing well for potentially more efficient reservoir drainage. Outcrop fracture data can be used to infer the trends of primary and secondary coal-bed methane reservoir permeability in central and southern Raton basin prior to drilling.

The Raton basin contains significant coal-bed methane resources, but commercial levels of coal-bed methane production based upon public records have not to date (early 1990) been achieved. The magnitude of permeability in potential Raton basin coal-bed methane reservoirs will, in part, influence potential further delineation and development of coal-bed gas in the basin. Lack of encouraging production rates and lack of a pipeline infrastructure in combination with low gas prices and significant water disposal costs are impeding commercialization of Raton basin coal-bed gas. Nevertheless, increases in gas price combined with a decrease in water disposal costs could result in favorable financial incentives.

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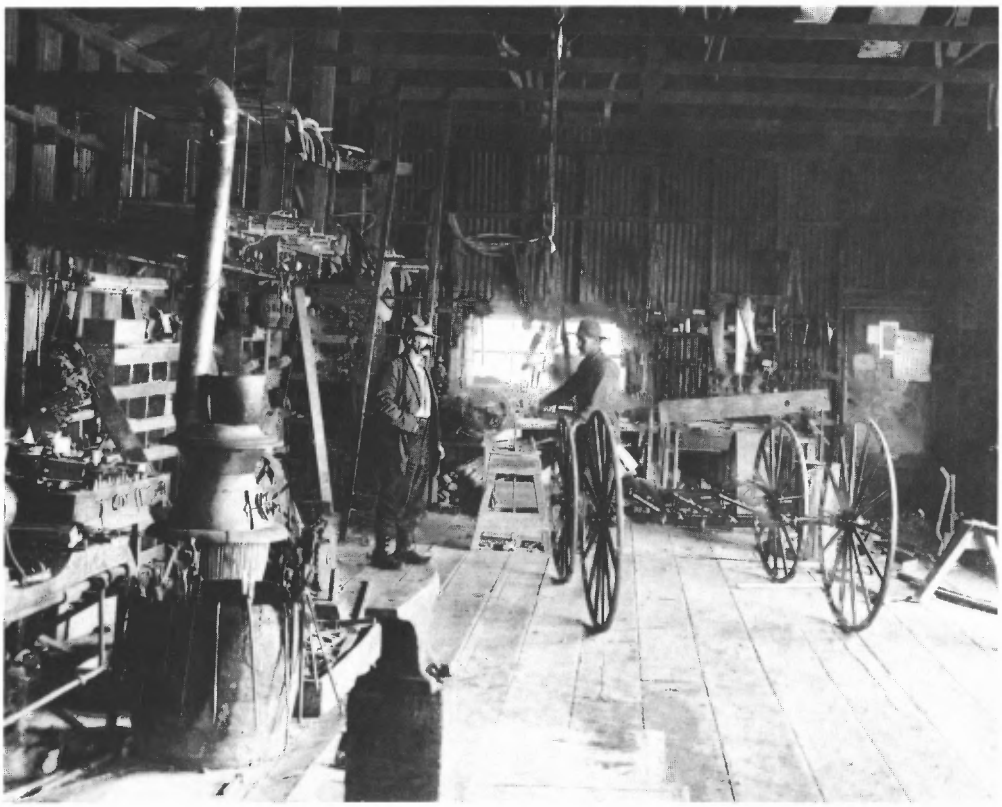
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Interior of Lail and Wilkins blacksmith shop, Cimarron, 1920. Man on left is Jim Lail. Courtesy of Kit Carson Foundation.



Only the most daring of argonauts would venture forth upon New Mexico's primitive, pre-WWI dirt roads (usually either powder dry or knee-deep muddy) in 1910. But these excursionists, stopping to pose for the camera somewhere between Mora and Las Vegas, could at least take comfort in the fact that their brand-new Buick touring car was extremely reliable and not likely to leave them stranded for mechanical reasons. Photo courtesy of Las Quince Letras.