Steve Finch's research specialties include the hydrogeologic evaluation of soil and groundwater contamination, the quality-assurance evaluation of chemical data, and the design, calibration and validation of groundwater flow models. He has studied the hydrologic and geochemical effects of reinjection of produced waters from oil and gas operations in the San Juan Basin. Steve received a B.S. in geology from Sul Ross State University and an M.S. in geology from Northern Arizona University.

GROUNDWATER ISSUES RELATED TO COAL-BED METHANE PRODUCTION NORTHERN SAN JUAN BASIN, NEW MEXICO AND COLORADO

Steven T. Finch, Jr.
John Shomaker & Associates, Inc.
2703 Broadbent Parkway NE, Suite D
Albuquerque, NM 87107

INTRODUCTION

The Northern San Juan Basin, particularly the Durango area, has been undergoing a population explosion accompanied by new housing developments in rural areas. Many of the developments are dependent on wells for their water supply. Recently, an increase in coal-bed methane wells has raised community concern regarding the contamination of water-supply wells by possible migration of Fruitland coal gas resulting from coal-bed methane development. In the past 10 years, observed gas seeps in the Animas River Valley, Pine River Valley, and along the Fruitland Formation outcrop, and elevated methane concentrations in groundwater, have heightened public awareness of methane-contamination hazards.

The area pertaining to this study includes the Northern San Juan Basin between the outcrop of the Fruitland Formation in the northern limit of the study area, and the San Juan River (Figure 1). This is where most of the coal-bed methane is produced from the Fruitland Formation, and where the groundwater quality has been affected by elevated dissolved-methane concentrations. Groundwater quality effects are primarily aesthetic; however, the most troublesome effect is the potential for explosion hazard resulting from the concentration of methane gas under homes and in confined spaces.

Most information included in this study is from previous work performed by the U.S. Geological Survey (USGS) (Chafin et al. 1993; Chafin 1994), Bureau of Land Management (1994), records and unpublished data from New Mexico Oil Conservation Division, La Plata County (Finch et al. 1994b), New Mexico Geological Society Guidebooks, Four Corners Geological Society publications (in particular, Fassett 1978), Rocky Mountain Association of Geologist's publication, Gas Research Institute (GRI)

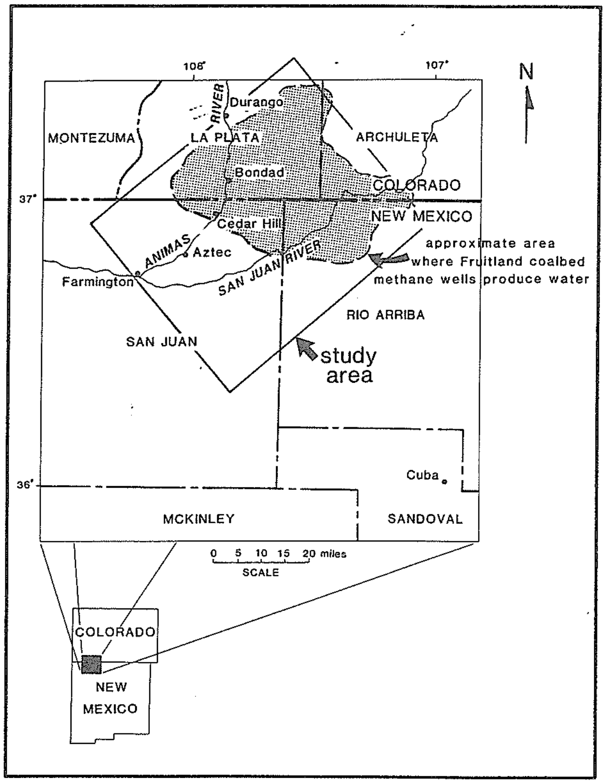

Figure 1. Map of the San Juan Basin with approximate location of study area and area where Fruitland coal-bed wells produce water as a result of formation overpressure.

(Kaiser et al. 1991; Finch 1994; Finch et al. 1994a), Southern Ute Tribe, and information from newspaper articles and unpublished data. The reader is encouraged to review references listed at the end of this paper for more detailed discussion of the topics presented.

In the past several years while I was involved with projects for GRI and La Plata County, Colorado, I noticed an overwhelming amount of data on methane contamination of shallow groundwater with various interpretations on its origin and source. As methane-related problems were identified and lawsuits filed, the community quickly divided into two groups: concerned citizens and the coal-bed methane industry. Much of the research was devoted to identify a source and responsible party, but little of it was used to develop a remedy for reducing methane-related problems. Part of my objective is to provide a comprehensive list of references on these matters, and to present some of my ideas as to remedies for alleviating methane problems in the shallow groundwater, that are not reflective of one particular interest or party. I have concluded that identifying a specific source and responsible party for each methane contamination case is impossible due to the complexity of the hydrogeologic setting, and land-use and development patterns within the study area.

HISTORICAL SIGNIFICANCE

A long history of recorded methane-seep observations exists that dates back to the 1880s, when settlers arrived in the area and continues to current times. A time line is provided as Figure 2. Observed natural gas and oil seeps along the San Juan and Animas River valleys were frequently described in USGS field investigation reports from 1880 to 1900.

Exploration and development started in the San Juan Basin as early as 1900. The Northern San Juan Basin was not considered a potential area for oil and gas exploration about the turn of the century due to the apparent lack of surface expression that would indicate structural traps. Drilling of water supply wells for irrigation along the Animas and San Juan River valleys resulted in discoveries of shallow gas throughout the region. An important gas discovery occurred when the Aztec #1 well was drilled north of the town of Aztec, New Mexico along the Animas River in 1923 (Barnes 1950). Great enough quantities were produced from Aztec #1, that a pipeline was constructed so the produced gas could be used by the residents of Aztec for heating.

Development of Conventional-Gas Deposits

From 1923 to 1980 most gas-production wells were completed as conventional-gas wells. High water production from the Fruitland coal beds was a nuisance, and the coal-bed methane reservoirs subjected to hydrostatic pressure were ignored. Sandstone formations above and below the Fruitland coal beds were targeted for conventional development of sandstone oil and gas bearing reservoirs; for that reason wells were termed conventional-gas wells. Gas exploration and development in the Northern San Juan Basin really did not take off until the construction of a gas pipeline around 1950 from Farmington, New Mexico to California. This pipeline made it economical to develop, produce, and transport natural gas from the San Juan Basin.

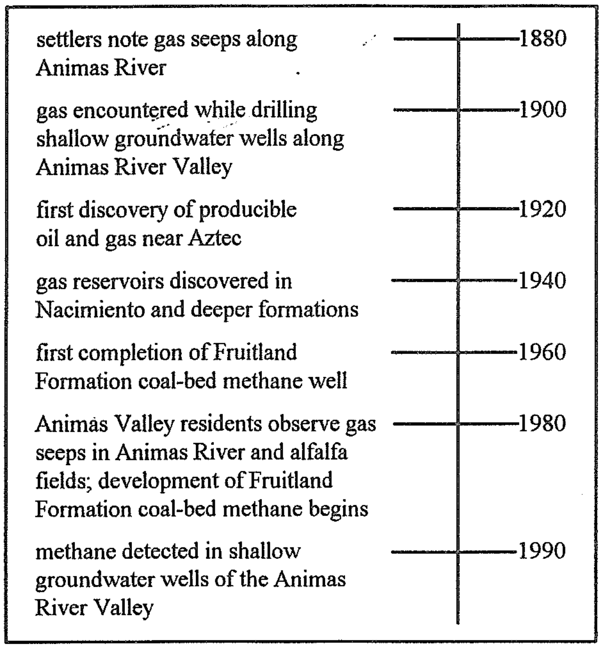

Figure 2. A time line illustration showing historical reports of gas seeps, development of coal-bed methane, and accounts of shallow groundwater contamination in the Animas River Valley area of the San Juan Basin (after Finch 1994).

Conventional-gas wells were constructed to the standards at the time, but now are considered problematic due to leaky casing and improper surface seals. In general, a conventional-gas well is drilled to the target depth, perforated across the producing zone, and an annular seal is spotted above the perforated interval. Many of the older conventional-gas wells were completed with an open annulus or bradenhead from the surface casing to the seal above the production zone (Figure 3). A bradenhead is basically a seal between the production zone tubing and surface casing at the top of the casing. In the past five to ten years, the New Mexico Oil Conservation Division and the Colorado Oil and Gas Conservation Commission have implemented programs for plugging and abandonment of out-of-service gas wells and for bradenhead repair.

Coal-Bed Methane Development

About 1956 the first successful coal-bed methane well (as contrasted with unconventional-gas wells) was constructed. Due to the initial high water production, coal-bed methane wells were not feasible and therefore not popular. Not until 1980 was coal-bed methane development feasible. The 1980 Fuel Tax Credit was available to the industry for development of unconventional fuels, and coal-bed methane fit into this category. The Unconventional Fuel Tax Credit expired in 1993; this short-term financial credit sparked a development frenzy for coal-bed methane within a 13-year period. In 1986 there were approximately 100 coal-bed methane wells; today there are close to 5,000 coal-bed methane wells in the Northern San Juan Basin area. Figure 4 provides a bar graph showing the effect of the tax credit deadline on coal-bed methane development.

Coal-bed methane wells are constructed with annular seals from surface to the production zone, as are artesian water-supply wells (Figure 3). The potential for methane escaping a properly completed coal-bed methane well is minimal.

Onset of Environmental Problems Associated with Coal-Bed Methane Development

The economy and population growth increased with the coal-bed methane industry from 1980 to current time. At the same time, a tourism-based economy was developed in southern Colorado, in which second homes in the rural Northern San Juan Basin area became very popular. Allowable density of gas-production wells was set at one well per 160-acre parcel. Housing development in the rural areas of the study area was virtually unlimited (depending on the county's subdivision regulations), and subdivision of rural communities occurred almost overnight with little community planning. Nearly 90 percent of the rural residents in the Animas River Valley rely on domestic water supplies. Driving from Aztec to Durango, one can see places where gas-production wells and domestic water supply wells are virtually in the same back yard.

Animas River Valley residents observed gas seeps in the Animas River and in alfalfa fields about the same time coal-bed methane was being developed in the early 1980s. Methane was detected in groundwater produced from domestic wells as a result of several water fairs conducted by New Mexico Oil Conservation Division. Prior to learning of results from the water sampling fairs and other early investigations on methane-source identification, much of the affected community became impatient with the methane-related problems and decided to request the

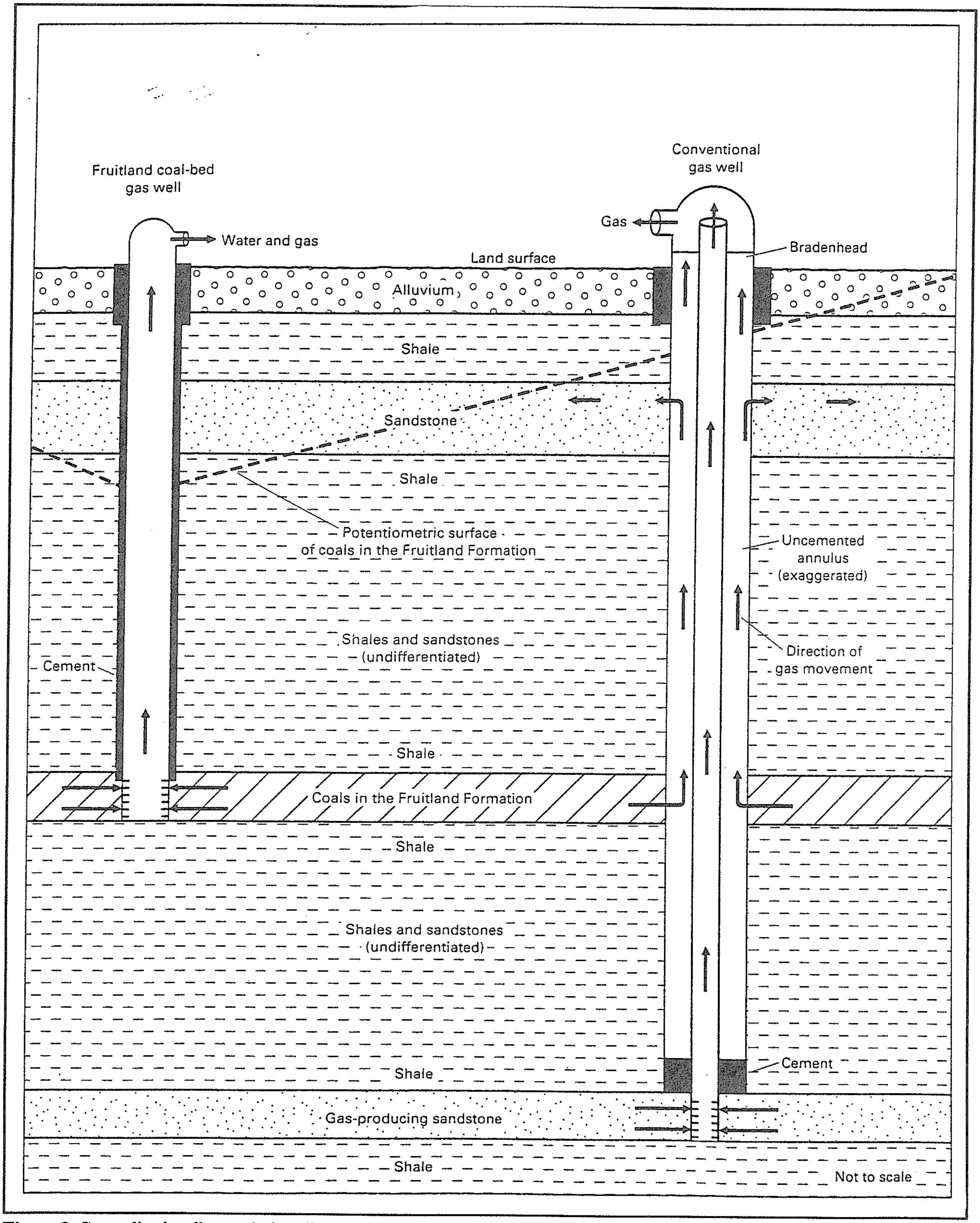

Figure 3. Generalized well-completion diagram for conventional-gas and coal-bed methane wells, with idealized stratigraphy of the Northern San Juan Basin (from Chafin 1994).

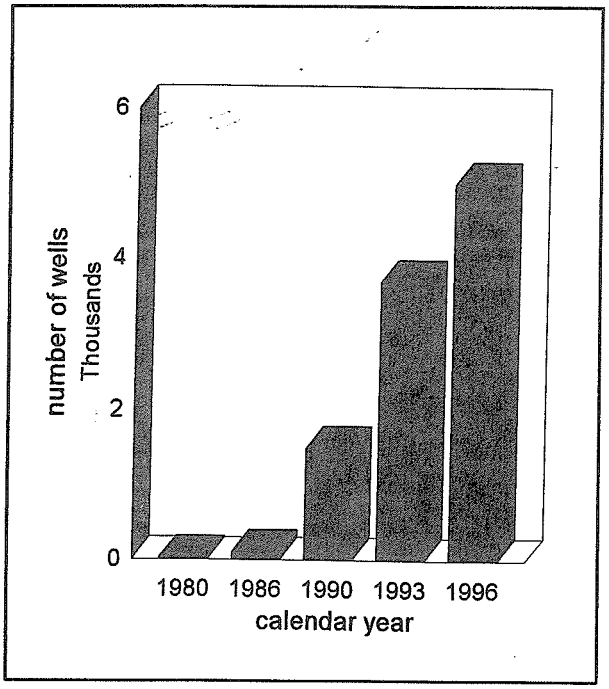

Figure 4. The cumulative number of coal-bed methane wells completed in the Northern San Juan Basin area from 1980 to July 1996.

gas industry to take responsibility and provide solutions to the problems.

By the early 1990s, lawsuits filed by resident groups against the gas industry quickly developed, which led to several investigations. One of the first investigations by AMOCO, Inc. concluded that the gas seeps and coal-bed methane wells are not connected, and the methane was from several sources; the findings discouraged residents (Durango *Herald*, August 17, 1994). By this time several communities had methane seeps that were considered environmental problems, including Bondad Hill, Pine River Ranch Subdivision, Colorado, and Cedar Hill, New Mexico.

The Bureau of Land Management performed a water-well testing program for La Plata County. Samples were taken from 193 water wells, 60 having undergone prior testing as a part of other studies. Bradenhead tests of gas wells also have indicated possible leakage problems in the casing and annulus. The Bureau has observed no correlation between water with measurable methane levels, and wells with significant bradenhead pressures (Bureau of Land Management 1994).

The USGS conducted a study to investigate the sources and migration pathways for natural gas beneath the Animas River Valley (Chafin 1994). The researcher concluded that "manmade migration pathways probably introduce most near-surface gas to the study area." This report was highly scrutinized due to some speculative conclusions without technical basis. The outcome confused the community; those who did not understand the reason for the scrutiny felt that the coal-bed methane industry was working against the best interests of the health and safety of the citizens affected.

The Pine River Ranch Subdivision community in Pine River Valley along the Hogback Monocline north of Bayfield, Colorado started to experience some serious methane seep problems in August 1993. Wells were showing methane contamination, seeps killed vegetation, and explosion hazards were of concern. A study of the Pine River Valley community was performed by the Pine River Investigative Team (1995). The outcome of the study was that dewatering the Fruitland Formation lowered the groundwater head near the Hogback Monocline, and the loss in hydrostatic pressure resulted in release of methane from Fruitland coal beds to the surface. Remedial options, such as replenishing the hydrostatic head, currently are being evaluated.

Other investigations along the hogback were initiated as methane-related problems came about. La Plata County currently is investigating the potential methane hazards along the Hogback Monocline (StoneBrooke Resources, Inc. 1996), to determine if conditions for development and land use need to be considered.

HYDROGEOLOGIC SETTING

Many references describe the geologic setting of coal-bed methane in the Northern San Juan Basin. In this paper I only will provide an overview of the hydrogeologic setting and explain some of the potential pathways for methane migration. I encourage the reader to review literature listed in the reference section for details on the stratigraphy and overall geology.

Most of the gas-producing zones in the Animas River Valley area are in the late-Cretaceous-age Fruitland Formation, Picture Cliffs Sandstone, and

Mesaverde Group. Substantial natural gas deposits have also been found in the Tertiary-age Nacimiento Formation (Fassett 1978). Figure 5 illustrates a cross-section of the San Juan Basin showing the time-stratigraphic framework and nomenclature (Triassic through Tertiary age). Within the Animas River Valley, these geologic units occur from zero to approximately 8,000 ft below land surface. Coal-bed methane developments are exclusively located in the Fruitland Formation, which occurs at the land surface along the Hogback Monocline near Durango, Colorado, to a depth of 3,500 ft below the San Juan River.

The San Juan Basin is a regional structural feature of the Colorado Plateau that was formed during the Laramide Orogeny. Structural features associated with the Laramide Orogeny include folds and fracture trends resulting from widespread tectonic stresses, which are associated with periods of uplift and erosion. Zoback (1988) noted that the present stress regime of the Colorado Plateau is extensional, "pulling apart." Extensional faulting and fracturing were due to uplift, possibly as a result of pushing by mantle bulge beneath the Rio Grande Rift and Colorado Plateau (Woodward and Callender 1977). This extensional faulting and fracturing may explain the natural migration and widespread natural gas deposits in the rocks below the study area.

Within the study area, four geologic units occur at the surface and include Quaternary-age valley fill and terrace deposits, and the Tertiary-age San Jose and Nacimiento formations (Stone et al. 1983).

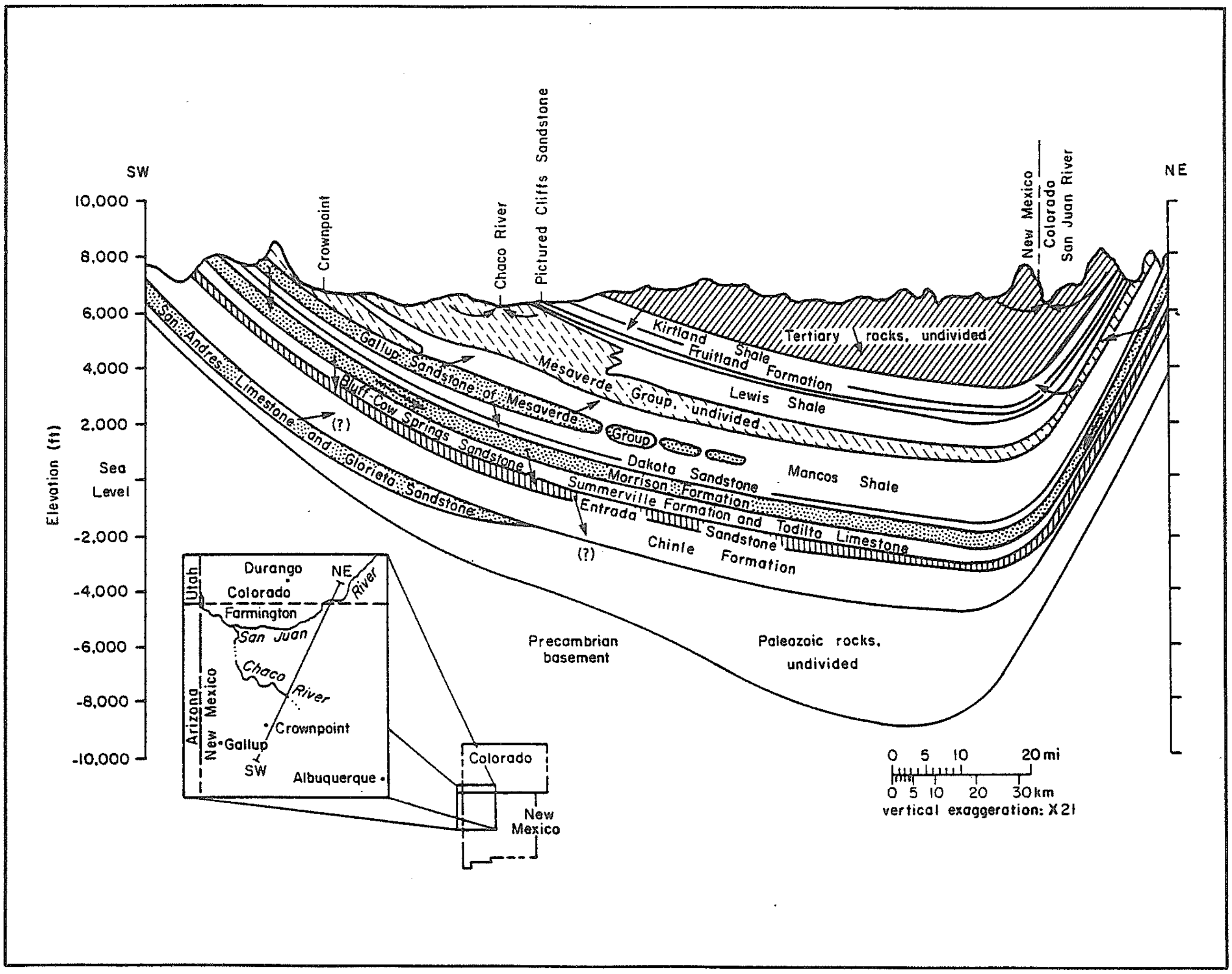

Figure 5. Generalized hydrogeologic cross-section of San Juan Basin, showing major aquifers (stippled), confining beds (blank), and direction of groundwater flow (arrows) (after Stone et al. 1983).

Groundwater in the Animas River Valley is most commonly obtained from the valley fill and terrace deposits, where groundwater recharge readily occurs from the Animas River system. These deposits are poorly sorted gravel, sand, silt, with minor clay, and range in saturated thickness from 0 to 50 ft (Robson and Wright 1995). Well yields from these deposits are relatively high, and transmissivity of the valley fill ranges from 1,000 ft^2/day to 40,000 ft^2/day (Stone et al. 1983; Finch et al. 1994b). The water quality in the valley-fill deposits generally resembles that of the Animas River, but may vary where influenced by irrigation returns or contributions from the underlying Tertiary-age rocks (San Jose and Nacimiento formations).

The presence of total dissolved solids (TDS) and methane concentrations in shallow-groundwater wells in the Animas River Valley were noted to be seasonal occurrences (personal communication with well owners 1990). This is thought to be hydrogeologically controlled and results from the predominance of different sources of recharge during the year. From March to November, irrigation ditches recharge the Animas River Valley, as a result of their topographic position along the valley fringe. Irrigation ditches are shut off from November to March when the Animas River flow is at a minimum, so that there is little recharge from the surface to groundwater. This change in water-table elevation can have a profound effect on the hydraulic head imposed on the underlying Tertiary-age consolidated-rock aquifers, and may have some control on methane migration from these rocks to the valley-fill aquifer.

Below the study area, groundwater in the Fruitland Formation is under artesian conditions (Kaiser et al. 1991). The pressure gradient defined by Kaiser et al. (1991) indicates a potential for groundwater to move upward from the Fruitland Formation to the land surface. Groundwater leakage and dissolved gases from the Fruitland Formation are controlled by the overlying low permeability rocks of the Kirtland Shale and younger strata. Other controls on leakage from the Fruitland Formation include areas with a higher degree of fracturing and changes in horizontal permeability in the overlying rocks. This overpressure zone is indicative of high hydraulic conductivity and high gas concentration.

A north-south hydrostratigraphic cross section of the study is provided as Figure 6. The Fruitland coal and sandstone receive recharge along Hogback and discharge to the Animas and San Juan rivers. Hydraulic gradient is the driving force for upward movement through preferential pathways.

PREFERENTIAL PATHWAYS AND MECHANISMS FOR METHANE MIGRATION

Research in oil and gas exploration has indicated that migration of oil and gas through fractures and zones of higher permeability from the source to a physical boundary or structural trap that forms a reservoir is a common occurrence. Furthermore, natural subsurface oil and gas reservoirs can slowly dissipate upward through fracture systems and faults to another structural trap or land surface (Finch 1994).

Studies such as Jenden et al. (1993) have documented vertical migration of natural gases from interbedded organic-rich shales along pervasive rock fractures and faults into overlying rocks. The potential for deep coal-bed methane to migrate along fractures to shallow groundwater is difficult to discount, given the number of studies documenting vertical migration of oil and natural gas from deep formations.

The structures present in the rock strata provide preferential pathways through fractures. Subsurface structures and fracture patterns from regional stresses have provided the fracture network for preferential pathways. Two types of fractures exist: one can be considered as a shear fracture with little aperture or opening resulting in low hydraulic conductivity; and the other is an extensional fracture with relatively larger openings and high hydraulic conductivity (Figure 7).

A study by Finch (1994) investigated the possibility of fractures as pathways for methane migration from Fruitland coal beds to water-supply wells completed in shallow alluvium along the Animas River Valley. The major findings on preferential pathways included the following:

1. Fracture flow from gas-producing zones of the Fruitland Formation to the Animas River Valley fill is a probable cause for methane in shallow groundwater.

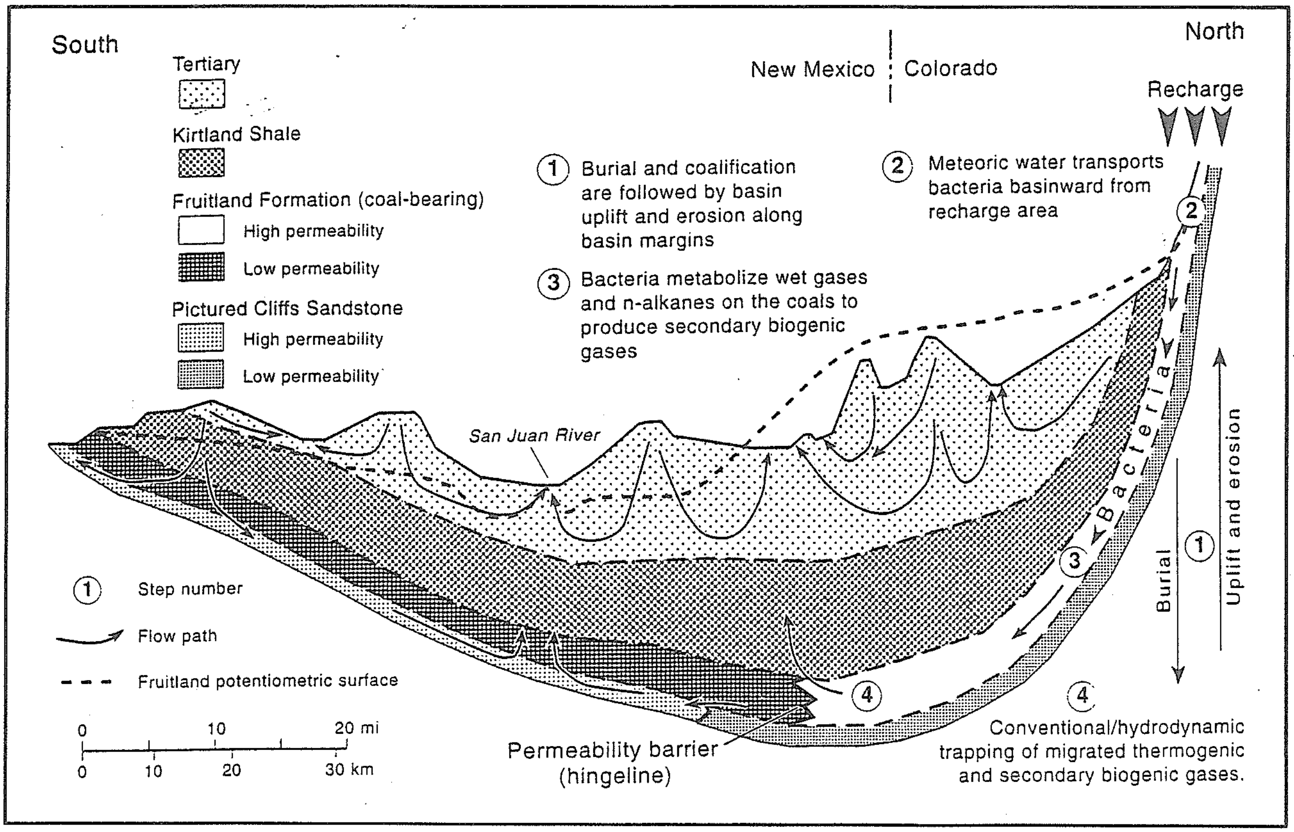

Figure 6. North to south cross-section showing groundwater flow in the San Juan Basin, the hydrodynamics of the Fruitland Formation, and methane generation along flow paths (after Scott et al. 1994).

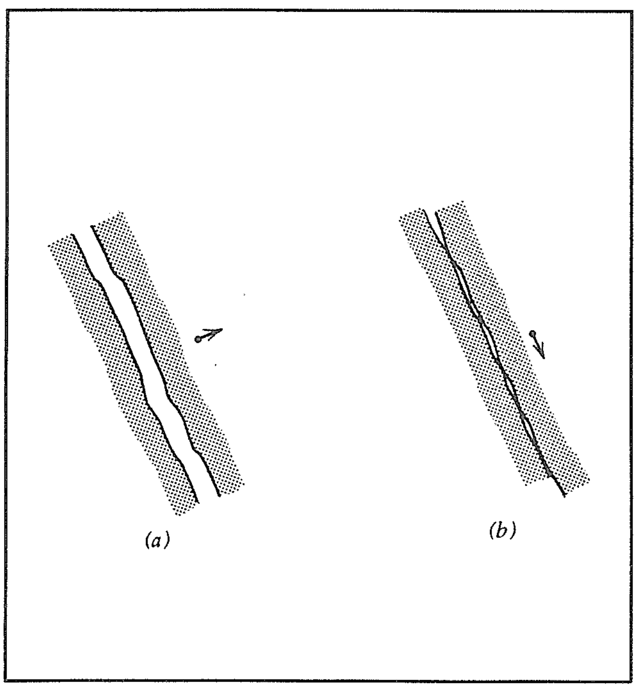

Figure 7. Illustrations of two types of fractures: (a) extension fractures and (b) shear fractures, with relative displacement (from Hobbs et al. 1976).

2. The hydrologic and geologic conditions below the Animas River Valley are favorable for a mechanism by which methane occurs naturally in shallow formations and groundwater, and as seeps at the surface.
3. Fracture flow may explain the repeated occurrence of methane, observed over the past 100 years, in shallow groundwater and at the surface.

Dewatering the Fruitland coals for coal-bed methane production may alter the migration of gas locally around the wells and on a regional scale. Depressurization of the coal-beds cause adsorbed methane to escape. Regional depressurization may increase the rate of gas escaping to the surface through preferential pathways. As previously discussed, coal-bed methane wells must pump off a substantial amount of water before methane production is viable. Typical water production for a coal-bed methane well is about 8,000 gallons per day for the first year, and then tapers off to about 1,000 gallons per day after several years of production. Dewatering the coal-bed has been lowering the hydrostatic head throughout the Fruitland Formation, and most likely affecting the area near the outcrop. Even though the number of coal-bed methane well completions is tapering off and water production is decreasing for the existing wells, calculation of the potential water in storage, the amount removed, and the amount replenished by recharge would help understand the potential for hydrostatic head fluctuations on release of methane from coal beds.

In summary, potential methane migration pathways include the following:

- along outcrop where hydrostatic head is decreasing and methane is released from coal beds
- through fractures with hydraulic gradient
- leaky well annuli

REMEDIES FOR METHANE HAZARDS

The usual scientific method for remediation of a contaminant involves identifying a source and treating the source. The problem with methane contamination in the Northern San Juan Basin is the occurrence of a regional source that is dispersed through thousands of feet of geologic material. Feasibility and success of treatment would depend on the degree of localization of the contaminant, the ability to identify the source, and the pathway in which it is transported. This raises the question, "Are the occurrences of methane in the shallow groundwater artificial and localized or natural and regional?" There is no correct answer to that question, but the following may be considered:

- case by case situation for each occurrence of methane contamination
- may need to observe long-term trends to assign remedial option
- too much activity and development to determine a remedial option
- most likely varies according to locale of the contaminant receptor
- each occurrence of methane contamination can be from several sources transported through several pathways

Methane contamination problems in the Cedar Hill, New Mexico area have improved over the last several years as a result of plugging and abandonment of old out-of-service gas wells, and bradenhead repair program of conventional gas-production wells still in service (personal communication, Ernie Bush, New Mexico Oil Conservation Division, September 1996). The area currently experiencing an increase in occurrences of potential methane contamination problems is along the Fruitland Formation outcrop, between Durango and Bayfield, Colorado. For such a large area, it appears that the best possible remedy is to implement building codes for mitigating build up of methane gas, and develop land-use planning for gas production and housing development. Existing structures easily could be retrofitted for venting methane gas.

SUMMARY AND CONCLUSIONS

If steps are not taken to vent methane from building structures and wells, explosive and asphyxiation hazards are likely to develop regardless of the oil and gas industry activities. These hazards may be more acute with increase in occupancy density of the Northern San Juan Basin area.

In summary, findings from this study and other researchers, include the following:

- methane and other natural gas seeps have been documented for the last 100 years
- there are regional and localized occurrences of methane in groundwater and as seeps at the land surface
- land use may affect recharge and methane migration in the valley-fill deposits and along the Fruitland Formation outcrop
- coal-bed dewatering has some effect on release of methane to the land surface
- hydrogeologic concepts and potential pathways for methane migration are very complex and lend no simple identification of source remediation
- land-use planning issues related to groundwater and coal-bed methane seeps are truly the only remedy for reducing methane-related hazards

It is the author's opinion that the time and money spent on lawsuits between citizen groups and the industry is a waste, and it is time to consider some simple remedies for potential methane-contamination hazards. Simple remedies include county adopted land-use planning for gas industry and housing development, centralized water supply (which is eminent in the future as population density increases), and building codes to address methane hazards. Some of these remedies have already been initiated, but the Northern San Juan Basin community still has many obstacles with water right issues, financial responsibility, and adopting land-use plans.

REFERENCES

Barnes, F.C. 1950. History of development and production of oil and gas in the San Juan Basin: New Mexico Geological Society, Guidebook of the San Juan Basin, First Field Conference, p. 144-148.

Beckstrom, J.A. and D.G. Boyer. 1991. Aquifer protection considerations of coalbed methane development in the San Juan Basin: Society of Petroleum Engineers, Rocky Mountain Regional Meeting and Low-Permeability Reservoirs Symposium, Denver, Colorado, April 15-17, p. 371-386.

Billings, M.P. 1960. Structural Geology 2nd ed.: Prentice-Hall, Inc., 514 p.

Bland, D.M. 1992. Coalbed methane from the Fruitland Formation, San Juan Basin, New Mexico: New Mexico Geological Society Guidebook, 43rd Field Conference, San Juan Basin IV, pp. 373-383.

Brown, D.R. and W.J. Stone. 1979. Hydrogeology of Aztec quadrangle, San Juan County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Hydrogeologic Sheet 1.

Boyer, D.G. 1990. Unpublished map showing gas well locations and completion status: New Mexico Oil Conservation Division.

Bureau of Land Management. 1994. Dissolved methane concentrations in ground water La Plata and Archuleta Counties, Colorado: HD Mountains EIS study area and selected lands peripheral to federal jurisdictional lands, U.S. Department of Interior, Bureau of Land Management, San Juan Resource Area, February 28, 1994, 54 p.

Chafin, D.T. 1994. Sources and migration pathways of natural gas in near-surface ground water beneath the Animas River Valley, Colorado and New Mexico: U.S. Geological Survey, Water-Resource Investigations Report 94-4006, 56 p.

Chafin, D.T., D.M. Swanson, and D.W. Grey. 1993. Methane-concentration and methane-isotope data for ground water and soil in the Animas River Valley, Colorado and New Mexico, 1990-91: Interim Report, U.S. Geological Survey, Water-Resources Investigation Report 93-4007, 86 p.

Chapin, C.E. and S.M. Cather. 1981. Eocene tectonics and sedimentation in the Colorado Plateau - Rocky Mountain area: *in* Relations of tectonics to ore deposits in the Southern Cordillera, W.R. Dickinson and W.D. Payne, eds., Arizona Geological Society Digest, Vol. XIV, Tucson, AZ, p. 173-199.

Condon, S.M. 1988. Joint patterns on the northwest side of the San Juan Basin (Southern Ute Indian Reservation), southwestern Colorado: *in* Geology and coal-bed methane resources of the northern San Juan Basin, Colorado and New Mexico, J.E. Fassett, ed., Rocky Mountain Association of Geologists, Denver, CO, p. 61-68.

Davis, J.C. 1986. Statistics and data analysis in geology: John Wiley & Sons, New York, 2nd edition, p. 34-45.

Decker, A.D., J. Close, and R.A. McBane. 1989. The use of remote sensing, curvature analysis, and coal petrology as indicators of higher coal reservoir permeability: *in* Proceedings of the 1989 Coalbed Methane Symposium, The University of Alabama, Tuscaloosa, April 17-20, 1989, p. 325-340.

Decker, A.D., S.J. Jeu, J.D. Cooper, and D.E. Wicks. 1988. Geology, geochemistry, reservoir engineering, and completion methods at the Cedar Hill Field, San Juan County, New Mexico: A field study of classic coal-degassification behavior: *in* Geology and coal-bed methane resources of the northern San Juan Basin, CO and New Mexico, J.E. Fassett, ed., Rocky Mountain Association of Geologists, Denver, Colorado, p. 221-236.

Dugan, T.A. and B.L. Williams. 1988. History of gas produced from coal seams in the San Juan Basin: *in* Geology and coal-bed methane resources of the northern San Juan Basin, Colorado and New Mexico, J. E. Fassett, ed., Rocky Mountain Association of Geologists, Denver, CO, p. 1-10.

Fassett, J.E. (ed.) 1978. Oil and gas fields of the Four Corners area, Volume 1: Four Corners Geological Society, 368 p.

Finch, S.T., Jr. 1994. Fracture and methane contamination study of the Animas River Valley from Bondad Hill, Colorado to Cedar Hill, New Mexico: Gas Research Institute Topical Report, GRI-93-0303, ENSR Sub-Contract No. 89088, 45 p.

Finch, S.T., Jr., R.W. Newcomer, M.E. Fetsko, P.J. Barth, and J.P. Fillo. 1994a. Hydrogeological and hydrogeochemical effects of deep well injection, North-Central San Juan Basin: Gas Research Institute, GRI Contract No. 5091-253-2160, ENSR Sub-Contract No. 89088, 16 p.

Finch, S.T., Jr., R.W. Newcomer, Jr., C. Matthews, and S. Matthews. 1994b. Impacts of ground water use from proposed Artesian Valley Ranch subdivision, La Plata County, CO: Consultant's report to La Plata County, 39 p.

Hobbs, B.E., W.D. Means, and P.F. Williams. 1976. An outline of structural geology: John Wiley & Sons, Inc., p. 571.

Geohydrology Associates, Inc. 1985. Assessment of potential for ground-water development near Mora, Bloomfield, and Aztec, New Mexico: State of New Mexico, Department of Game and Fish, Santa Fe, NM, Contract no. 516-73-24, p. 48-52.

Jenden, P.D., D.J. Drazan, and I.R. Kaplan. 1993. Mixing of thermogenic natural gases in Northern Appalachian Basin: The American Association of Petroleum Geologists Bulletin, 77:6:980-998.

Johnson, V.G., D.L. Graham, and S.P. Reidel. 1993. Methane in Columbia River Basalt Aquifers: Isotopic and geohydrologic evidence for a deep coal-bed gas source in the Columbia Basin, Washington: The American Association of Petroleum Geologists Bulletin, 77:7:1192-1207.

Kaiser, W.R., T.E. Swartz, and G.J. Hawkins. 1991. Hydrogeology of the Fruitland Formation, San Juan Basin: *in* Geologic and hydrologic controls on the occurrence and producibility of coalbed methane, Fruitland Formation, San Juan Basin: Gas Research Institute Topical Report, Contract No. 5087-214-1544, p. 195-235.

Kelley, V.C. and N.J. Clinton. 1960. Fracture systems and tectonic elements of the Colorado Plateau: University of New Mexico Publications in Geology, Number 6, University of New Mexico Press, Albuquerque, 104 p.

Manydeeds, M.T. 1988. Southern Ute Indian Reservation, Colorado Landsat lineament study: Systems and Applied Sciences Corporation, Administrative Report for the Bureau of Indian Affairs, Division of Energy and Mineral Resources, 10 p.

Matheny, M.L. 1978. A history of the petroleum industry in the Four Corners area: *in* Oil and gas fields of the Four Corners Area, Vol. 1, edited by J.E. Fassett, Four Corners Geological Society, p. 17-24.

Matheny, M.L. 1964. A history of the petroleum industry in the Four Corners area: Four Corners Geological Society, Durango-Silverton Guidebook

Oldaker, P. 1990. (Draft) Preliminary draft of history section of Animas Valley hydrogeologic report: prepared for San Juan Basin Industry Action Team.

Pine River Investigative Team Report, February 21 1995, 11 p.

Quinn, J.C. and S.A. Marinello. 1994. Desorption of methane from coal stringers in shallow aquifer regimes: unpublished paper, Petroleum Engineering Department, Colorado School of Mines.

Robson, S.G. and W.G. Wright. 1995. Ground-water resources of the Florida Mesa area, La Plata County, Colorado: U.S. Geological Survey, Water-Resources Investigations Report 95-4190, 30 p.

Scott, A.R., W.R. Kaiser, and W.B. Ayers. 1994. Thermogenic and secondary biogenic gases, San Juan Basin Colorado and New Mexico - Implications for coalbed gas producibility: American Association of Petroleum Geologists Bulletin, 78:8:1186-1209.

Shuey, C. 1990a. Selected Animas Valley water quality results, 1985-1990: unpublished data from New Mexico Oil Conservation Division, compiled by Chris Shuey, Southwest Research and Information Center, Albuquerque, NM, 17 p.

Shuey, C. 1990b. Bald alfalfa fields and gassy water: Coal-bed methane premiers in Cedar Hill and Bondad: *in* The Workbook, Southwest Research and Information Center, 15:2:53-61.

Stevens, T.A., P.W. Lipman, W.J. Hail, Jr., F. Barker, and R.G. Luedke..1974. Geologic map of the Durango Quadrangle, southwestern Colorado: U.S. Geological Survey, map I-764.

Stone, W.J., F.P. Lyford, P.F. Frenzel, N.H. Mizell, and E.T. Padgett. 1983. Hydrogeology and water resources of San Juan Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Hydrologic Report 6, 70 p.

StoneBrooke Resources, Inc. 1996. Fruitland Formation outcrop gas seep study, La Plata County, Colorado: consultant's report to La Plata County.

Tremain, C. M., S.E. Laubach, and N.H. Whitehead, III. 1991. Coal fracture (cleat) patterns in upper Cretaceous Fruitland Formation, San Juan Basin, Colorado and New Mexico: Implications for coalbed methane exploration and development: *in* Geologic and hydrologic controls on the occurrence and producibility of coalbed methane, Fruitland Formation, San Juan Basin, Gas Research Institute, Topical Report, Contract No. 5087-214-1544, p. 97-117.

Tremain, C. M. and N.H. Whitehead. 1990. Natural fracture (cleat and joint) characteristics and patterns in upper Cretaceous and Tertiary rocks of the San Juan Basin, New Mexico and Colorado: Gas Research Institute, Topical Report, Contract No. 5087-214-1544, p. 73-95.

Wandrey, C.J. 1989. Lineament map of part of the Southern Ute Reservation, San Juan Basin, Southwestern Colorado: U.S. Bureau of Indian Affairs, Administrative Report BIA-19-II-N.

Whitehead, N.H. 1991. Coalbed methane in New Mexico: New Mexico Geology, 13:4:82-88.

Woodward, L.E. and J.F. Callender. 1977. Tectonic framework of the San Juan Basin: New Mexico Geological Society, 28th Field Conference, San Juan Basin III, p. 209-212.

Zoback, M.L. 1988. State of stress in the Rocky Mountain region (abs): Geological Society of America, Abstracts with Programs, v. 20, A12 p.