Identifying and Remediating High Water Production Problems in Basin-Centered Formations

Final Report

Reporting period: April 1, 2002 to September 30, 2005

Prepared by:

R. L. Billingsley

December 2005

DOE Award No. DE-FC26-02NT41437

Submitting Organization:

Advanced Resources International, Inc.
4501 Fairfax Drive, Suite 910
Arlington, Virginia 22203-1661

Significant Subcontractors

Maria Wood Henry
Henry GeoConsulting Services, Inc.
863 W. Geddes Ave.
Littleton, CO 80120

Keith Jagiello, Ph.D.
Petro Data Integration, LLC
8770 West Eden Drive
Littleton CO 80127

Leta K. Smith, Ph.D.
Consultant
10154 Whiteside Lane
Houston, TX 77043

-

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Abstract

Through geochemical analyses of produced waters, petrophysics, and reservoir simulation we developed concepts and approaches for mitigating unwanted water production in tight gas reservoirs and for increasing recovery of gas resources presently considered noncommercial. Only new completion research (outside the scope of this study) will validate our hypothesis.

The first task was assembling and interpreting a robust regional database of historical produced-water analyses to address the production of excessive water in basin-centered tight gas fields in the Greater Green (GGRB) and Wind River basins (WRB), Wyoming. The database is supplemented with a sampling program in currently active areas. Interpretation of the regional water chemistry data indicates most produced waters reflect their original depositional environments and helps identify local anomalies related to basement faulting.

After the assembly and evaluation phases of this project, we generated a working model of tight formation reservoir development*, based on the regional nature and occurrence of the formation waters.* Through an integrative approach to numerous existing reservoir concepts, we synthesized a generalized development scheme organized around reservoir confining stress cycles. This single overarching scheme accommodates a spectrum of outcomes from the GGRB and Wind River basins.

Burial and tectonic processes destroy much of the depositional intergranular fabric of the reservoir, generate gas, and create a rock volume marked by extremely low permeabilities to gas and fluids. Stress release associated with uplift regenerates reservoir permeability through the development of a penetrative grain bounding natural fracture fabric. Reservoir mineral composition, magnitude of the stress cycle and local tectonics govern the degree, scale and exact mechanism of permeability development.

We applied the reservoir working model to an area of perceived anomalous water production. Detailed water analyses, seismic mapping, petrophysics, and reservoir simulation indicate a lithologic and structural component to excessive in situ water permeability. Higher formation water salinity was found to be a good pay indicator. Thus spontaneous potential (SP) and resistivity ratio approaches combined with accurate formation water resistivity (Rw) information may be underutilized tools. Reservoir simulation indicates significant infill potential in the demonstration area. Macro natural fracture permeability was determined to be a key element affecting both gas and water production.

Using the reservoir characterization results, we generated strategies for avoidance and mitigation of unwanted water production in the field. These strategies include (1) more selective perforation by improved pay determination, (2) using seismic attributes to avoid small-scale fault zones, and (3) utilizing detailed subsurface information to deliberately target optimally located small scale fault zones high in the reservoir gas column. Tapping into the existing natural fracture network represents opportunity for generating dynamic value.

Recognizing the crucial role of stress release in the *natural generation* of permeability within tight reservoirs raises the possibility of *manmade generation* of permeability through local confining stress release. To the extent that relative permeabilities prevent gas and water movement in the deep subsurface a reduction in stress around a wellbore has the potential to increase the relative permeability conditions, allowing gas to flow. For this reason, future research into cavitation completion methods for deep geopressured reservoirs is recommended.

Table of Contents

List of Graphical Materials

Figures

Tables

Acknowledgements

Advanced Resources International, Inc. would like to acknowledge the National Energy Technology Laboratory (NETL), Morgantown, WV, for their role as lead funding agency together with the following companies and other governmental groups who contributed data, sampling opportunities or discussion: BP America, Schlumberger, Bill Barrett Corp., Anadarko Petroleum Corp., Devon, Shell Western E&P, Stone, Ultra Petroleum, USGS, and Wyoming Oil and Gas Commission.

We would also like to thank the following individuals for their interpretive efforts or insightful discussion and comments; Vello Kuuskraa, George Koperna, Maria Fokin, Paul Ozanich, Marty Williams, John Forster, and Tim Schowalter. David Sears provided database coaching and processing support. Diane Suchomel and Dianne Finch-Smith deserve special recognition for their tireless efforts collecting data, sampling, editing and keeping us organized.

INTRODUCTION

Advanced Resources International Inc. (ARI), with support from the U.S. Department of Energy, conducted a research program (DE-FC-02NT41437) to characterize the nature, distribution and flow paths of moveable fluids in the subsurface of the Greater Green River basin (GGRB) and Wind River basin (WRB). The project goals were to improve resource characterization, develop water remediation strategies and enhance gas recoveries in these resource-rich basins.

Specific project objectives include the following tasks:

- Build a digital water chemistry database and construct key maps using the data.
- Compile a digital atlas of maps that increases the usability of the database.
- Conduct an in-depth evaluation of produced water geochemistry that includes interpretation as well as application to the practical aspects of the project objectives
- Develop a working model for movement of water and gas through low permeability basins (based on the geochemical evaluation).
- Conduct a field demonstration for an area with known water production problems (to test the working model).
- Transfer the technology to industry through a demonstrated conceptual model

The results and discussion summarize the project. The bulk of the text, figures and data are included as appendices. This report is organized as follows:

I. Digital Database (Appendix A)

II. Digital Map Atlas (Appendix B)

III. Produced Water Geochemistry Evaluation (Appendix C)

IV. Working Model for Reservoir Development (Appendix D)

V. Wild Rose Field Demonstration (Appendix E: Petrophysics) and (Appendix F: Simulation)

EXECUTIVE SUMMARY

Advanced Resources International Inc. (ARI), with support from the U.S. Department of Energy, conducted a research program (DE-FC-02NT41437) to characterize the nature, distribution and flow paths of moveable fluids in the subsurface of the Greater Green River basin (GGRB) and Wind River basin (WRB). The project goals were to improve resource characterization, develop water remediation strategies and boost gas recoveries in these resource-rich basins.

Specific project objectives included the following tasks:

- Build a digital water chemistry database.
- Compile a digital atlas of maps that increases the usability of the database.
- Conduct an in-depth evaluation of produced water geochemistry that includes interpretation as well as application to the practical aspects of the project objectives.
- Develop a working model for movement of water and gas through low permeability basins (based on the geochemical evaluation).
- Conduct a field demonstration in an area with known water production problems.
- Transfer the technology to industry.

The results of this project provide the produced water chemistry backdrop, together with concepts and tools to reduce unwanted water production in tight gas reservoirs. The concepts and approaches generated also offer potential for the development of completion technologies to enhance permeability within tight reservoirs and achieve commercial production rates.

A large database of historical produced water analyses, supplemented with a targeted sampling program, was assembled and interpreted to address the production of excessive water in basin-centered tight formation gas fields of the Greater Green and Wind River Basins, Wyoming. In excess of 16,000 historical chemical component and isotopic analyses from government, academic and industry sources were winnowed to produce a geographically referenced database of nearly 3,700 discreet formation tests. The analyses were screened for analytical validity and merged with perforation data and other support information (as available) to create a composite georeferenced water chemistry resource to support exploration and production activities across the GGRB and WRB.

A digital atlas showing the distribution of the data and some specific analyses has been constructed using Arc Reader and is contained in Appendix B. The digital atlas has query and limited mapping capability for users without ready access to Geographic Information Systems (GIS) software. GIS techniques were used extensively in the project.

Regional evaluation of chemical and isotopic analyses indicates little mass movement of waters in the subsurface. Depositional environment is the chief influence on the composition of intra formation waters. Localized vertical movement of water along basement fault zones appears as more restricted anomalies in contrast to regional compositional variability. Both regional and local knowledge is required to successfully utilize water chemistry as an exploration or development tool. Public availability of the extensive database constructed as a result of this project will supplement the use of water chemistry at the field scale to increase gas production.

A working model of tight formation reservoir development was synthesized using the results of the assembly and evaluation phases. An integrative approach was used to assemble numerous existing reservoir concepts into a generalized development scheme organized around reservoir confining stress cycles. Within this scheme, burial and tectonic processes destroy much of the depositional intergranular fabric of the reservoir, generate gas and create a rock volume marked by low permeabilities to gas and fluids.

Stress release associated with uplift regenerates reservoir permeability through the development of a penetrative grain bounding natural fracture fabric. Reservoir mineral composition, magnitude of the stress cycle and local tectonics govern the degree, scale and exact mechanism of permeability development. Recognition of the primary role of stress release in generation of naturally occurring reservoir permeability creates the opportunity to replicate the process artificially. Local permeability enhancement induced by some alternative stress reducing completion methodology could change the local gas-water relative permeability conditions and potentially allow gas to flow into the well.

The working reservoir model was demonstrated in an area of anomalous water production. Detailed water analyses, seismic mapping, petrophysics and reservoir simulation indicate a lithologic and structural component to excessive in situ water permeability. Reservoir simulation indicates significant infill potential in the demonstration area. We found higher formation water salinity to be a pay indicator. Spontaneous potential (SP) and resistivity ratio approaches combined with accurate formation water resistivity (Rw) information are tools that can be utilized for improved pay recognition. We found macro natural fracture permeability to be a key element affecting both gas and water production. The results of the field study were used to generate strategies for avoidance or mitigation of excessive water production.

Strategies developed to reduce unwanted water production in the field area include 1) more selective perforation through improved pay determination 2) use of seismic attributes to avoid small-scale fault zones and 3) capture of dynamic value through the use of infill drilling information to deliberately target optimally located small scale faults zones high in the reservoir gas column.

EXPERIMENTAL

Work performed during this project conformed to generally accepted principles of petroleum geology and geochemistry. No laboratories were operated directly by ARI during the performance of this project. Laboratories used as part of this study are documented in Appendix C. The analytical vendors in accordance with applicable local and federal standards destroyed all samples collected during this project.

Specific laboratory or interpretation techniques are referenced in the applicable appendices as follows:

Geochemistry ....Appendix C

Petrophysics ....Appendix E

Reservoir Simulation ....Appendix F

The following specific trademarked commercial software packages were used during the interpretive or documentation phases of this project:

Petra, Petraseis™ (Geoplus Inc.)

ArcCatalog™, ArcMap™, ArcPublisher™, Spatial Analyst™ (ESRI, Inc)

Microsoft Office Suite (Microsoft Corporation)

Surfer 8™, Grapher 5™ (Golden Software, Inc.)

Canvas 8™ and Canvas 9™ (ACD Systems, Inc)

Comet 3™ (Advanced Resources International, Inc.)

The following non-commercial research software programs were used:

NextGen™ (ARI, Inc)

Poly3D™ (1993 Stanford University, Thomas)

FracGen™ (discrete fracture network modeling, NETL)

The majority of the project work was performed at ARI offices in Denver, CO. The reservoir simulation was performed at ARI offices in Arlington, VA.

RESULTS AND DISCUSSION

I. Digital Database

Accurate information regarding the composition of waters trapped in the interstices of petroleum reservoirs is crucial to effective formation evaluation and resource estimation. Eight decades of oil and gas exploration in the Greater Green (GGRB) and Wind River Basins has resulted in a large volume of valuable produced water chemical analyses collected during formation evaluation, workover and water disposal operations. The preponderance of historical water composition data is the result of thousands of non-recurring opportunities and is impossible to recreate.

A primary objective of this project was to make available the abundant resource (spanning decades) of existing analytical data on produced water composition. Thus the first step in this project was to collect data from governmental entities, operators, abandoned files, and previous studies. It was then digitized as necessary and compiled into a digital database.

The result of this collection effort was a comprehensive body of data, but one with considerable overlap and duplication. The next step was to use structured query language (SQL) queries to eliminate duplicate analyses and data with poor quality or otherwise erroneous aspects. Then, the location identification data was screened to

1. Ensure that reported location data and American Petroleum Institute (API) numbers were correct to the fullest extent possible. Some otherwise valid data failed this final screening.
2. Match as much high quality compositional data to valid API and location data as possible. In some cases this required examining the original location surveys.

The final database was spot checked against randomly selected raw input data to ensure the integrity of the compilation process.

The final product is a highly usable digital database of nearly 8,000 water analysis results from over 3,200 wells (fig. I-1). It spans nearly eight decades of exploration and production activity across two states (Wyoming and Colorado) and numerous productive basins including the strategically important Greater Green and Wind River Basin areas. *Compilation of this data into a single database, with removal of duplicate and invalid analyses, opens the data to access by a broad audience of users with interests in resource assessment, formation evaluation, prospect generation and exploitation of tight formation gas.*

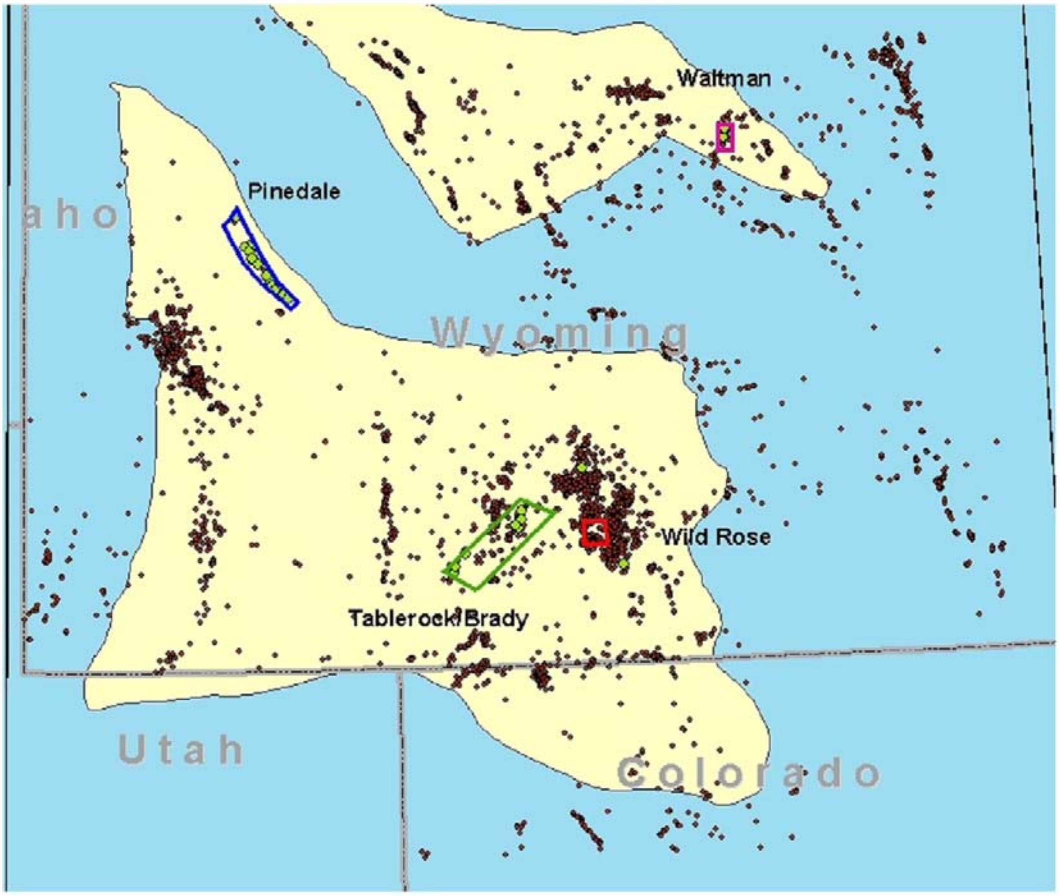


Fig. I-1 Areal distribution of water sample locations contained in the database

The database contains the results of routine chemical analyses performed on fluids produced during all phases of petroleum wellbore operations. The source and sampling method of the individual water samples is included where reported. Fluid sample analyses from drill stem test recoveries, as well as completion, workover, and production operations are represented.

As a result, there is a wide range of applications for the data depending on the specific purposes of the user.

Format and Structure

The digital database format facilitates the effective use of the data by professionals working to increase gas production from these areas. The database is available in native Access™ format as well as spreadsheet, text and Dbase™ formats, making possible immediate utilization in Geographic Information Systems (GIS) or other workstation systems. Details of the data quality screening criteria and final database structure are included in the Read me file located with the database in Appendix A.

The database structure was designed to support use of stable and radiogenic isotope technology in the interpretive process. Produced waters from eighty-eight currently producing wells in four separate areas (Waltman/Cave Gulch fields (WRB), Pinedale, Table Rock and Wild Rose fields (GGRB) were sampled for routine and isotopic characterization as part of this study.

Although the analyses were screened for validity, formation tops and other data were assumed valid as reported by operators. Local lithostratigraphic and formation names were consolidated into broad groupings for mapping purposes. Those group names are included in the 'Revised Formation' database field.

Consolidation of these data into an organized, accessible digital format enables immediate use of an irreplaceable body of knowledge accumulated as a result of literally thousands of non-recurring opportunities. Acquired at enormous expense over decades of exploration and production activity, this information, now accessible, will prove an invaluable resource in meeting the challenge of increasing available domestic energy resources.

II. Digital Map Atlas

Our primary purpose in creating this digital atlas of maps was to increase the usability of the database with a high-level tool for exploring it geographically.

A principal value of a sizeable geographically-controlled digital database is the ability to identify large-scale regional variations in numerical data. This is particularly important for establishing a regional context when interpreting smaller prospect or field scale data sets. A digital atlas of maps displaying data distribution and several attributes potentially of interest to users is presented as Appendix B.

Map layers have been constructed using common queries likely to be of interest to the high level user exploring data distribution. These include layers of data distribution by quality, revised formation, sample and analysis types.

These maps are constructed in Arcmap™ (ESRI) and electronically published in Arcpublisher™ (ESRI). A copy of the current ArcReader™ (Windows version, ESRI) package is included in Appendix. B. The software package is freely available by download from the web link: http://www.esri.com/software/arcgis/arcreader/index.html. Versions for Linux and Solaris operating systems are also available from this site. Refer to the ESRI website for hardware requirements, compatibility, and installation information.

ArcReader™ offers the ability to zoom and pan at the discretion of the user. Crude state and field outlines have been included for general reference. It includes public land survey grids to the section level. Users without direct access to GIS software can still use ArcReader™ with some query and data export limitations.

III. Produced Water Geochemistry Evaluation

Compiling a digital database of existing data and optimizing its accessibility with a digital map atlas laid were pre-cursors to the next phase of this project—conducting an in-depth evaluation of produced water geochemistry. The evaluation included interpretation as well as application to the practical aspects of the project objectives. This section is a high-level discussion of the results of the geochemical evaluation. Appendix C contains a detailed discussion of the analyses and interpretations.

The Process of Geochemical Analyses

First, aggregate produced water composition database were analyzed to establish regional trends and demonstrate potential uses for water chemistry as a tool to identify and remediate production of unwanted water. Geochemical interpretations were based on high-graded regional subsets and local samples collected as part of this project. Fig. I-1 is an index map showing general distribution of the data, which includes historical sample distribution and locations sampled and analyzed.

Then, new samples were collected specifically for the geochemical water evaluation. Data cluster of samples were chosen from areas known for their anomalous character or high-profile development activities. These areas were Table Rock, Waltman/Cave Gulch, Pinedale and Wild Rose Fields (fig. I-1). Appendix B includes a detailed discussion of each area. Fig. III-1 is a generalized stratigraphic column identifying the major units sampled and their geologic ages.

Finally, we performed three types of analyses on the formation water samples:

1. Major and minor elements
2. Stable isotopes (oxygen and hydrogen)
3. Strontium radiogenic isotopes

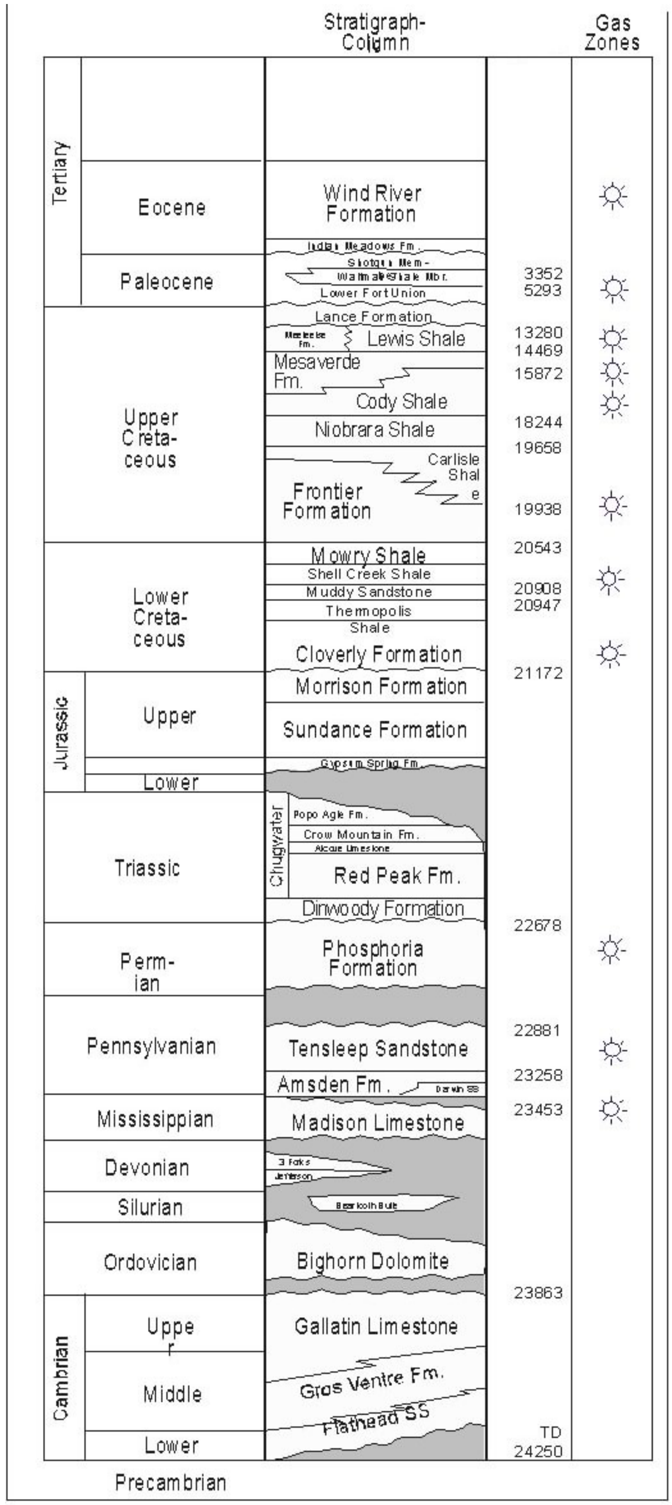


Fig. III-1. Stratigraphic column identifying major units & their ages

Assertions

From our analysis of formation waters produced from wells in the core study areas of Greater Green (GGRB) and Wind River Basin we assert that there is no large-scale fluid movement. Instead there are smaller areas of water moving along faults and other breaks in the vertical continuity of the basin fill, *more specifically*:

Depositional Environment of Host Rock

The main control on formation water chemistry is the original depositional environment of the host rock. The following evidence supports this assertion:

- There is little to no relationship between salinity of produced water and the depth of recovery for the three main producing horizons: Lance, Mesaverde, and Frontier formations (fig. III-2)

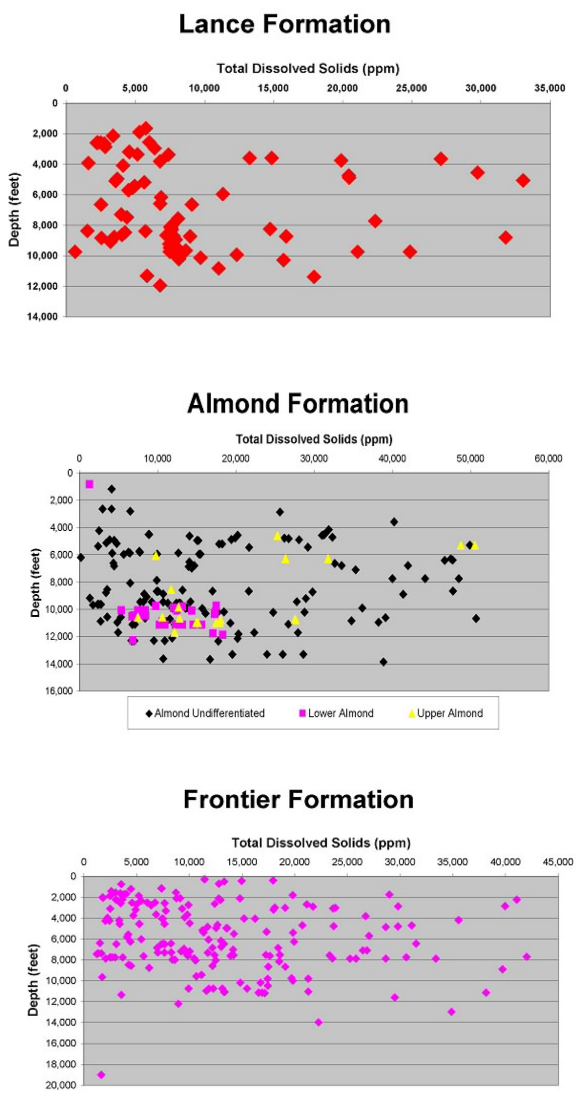


Fig. III-2. Salinity vs., depth for Lance, Almond and Frontier (Enlarged in Appendix C-20)

- The Frontier and Mesaverde formations are generally more saline, i.e., they exhibit wider ranges of salinity than the Lance formation waters. This is consistent with the marine affinities of the Frontier and the Mesaverde formations whereas the Lance is considered non-marine in origin and shows a fresher average salinity with less range (Table III-1).

Table III-1. Range of TDS from water analyses by formation

Formation	Range
Frontier	**1,500 and 42,000 ppm**
Almond	**1,700 and 50,000 ppm**
Lance	**600 and 33,000 ppm**

Both the Frontier and Mesaverde formations, in general, represent retrograde transgressive sequences, and in the study area are overlain with thick sequences of marine shale.

Thus, those formations deposited in marine environments produce water that tends to have higher total dissolved solids (TDS), has chloride as its dominant anion, and whose deuterium isotopes are less negative as compared to formations deposited in non-marine environments. Those deposited in non-marine environments tend to produce water that is fresher, has bicarbonate as the dominant anion, and has deuterium isotopes that are more negative (Table III-1).

The overall lower TDS of the Lance formation, both in the average and the range, is in keeping with its non-marine origin as compared to the marine Frontier formation.

- Where the Almond formation can be divided into upper and lower units, two distinct salinity populations are present. The Upper Almond, of marine origin, shows a wider range of TDS and a higher average TDS than the Lower Almond, which is predominantly of non-marine origin (Table III-2).

Table III-2. Range of TDS by salinity population

Salinity Populations	Range
Upper Almond	**19,000 ppm**
Lower Almond	**13,000 ppm**
Lance	**9,000 ppm**

The overall lower TDS of the Lance formation, both in the average and the range, is in keeping with its non-marine origin as compared to the marine Frontier formation.

Assessing Anomalies Against the Base

Second Assertion: *Local salinities, TDS values or isotope signatures*, at extreme variance to regional formation or facies norms, *represent vertical disruption of the basin fill and fluid or charge transport along permeability conduits associated with basement faulting*.

- Water samples collected along major lineaments or areas of high surface lineament density exhibit anomalous local values of salinity, TDS or isotopes in contrast to regional means for these same values. See Appendix C for a complete discourse on this significant assertion.

- Water samples collected along major lineaments or areas of high surface lineament density exhibit anomalous local values of salinity, TDS or isotopes in contrast to regional means for these same values. This phenomenon is exhibited in fig. V-10, and Appendix C figs. C-32 and C-33 where individual attributes such as Rw, isotopes, and saturation indices exhibit local departures from overall geographic trends established by relatively higher density sampling. See Appendix C for a complete discourse on this significant assertion.

- *Some local and regional geologic problems can best be understood through interpretation of chemical and isotopic compositions of produced formation waters.*

Geochemical attributes afford significant potential for impact on near and long-term exploration and development activities when properly sampled, analyzed, and interpreted. *A geodatabase is a powerful approach as it enables rapid evaluation of local analytical results and identification of anomalies within a regional geologic context.*

IV. Working Model for Reservoir Development

Background

Data from the produced water database, geochemistry, field demonstration phases of this project, as well as public information sources were used to develop a working model for movement of gas and water through low permeability basins within a framework of basin history.

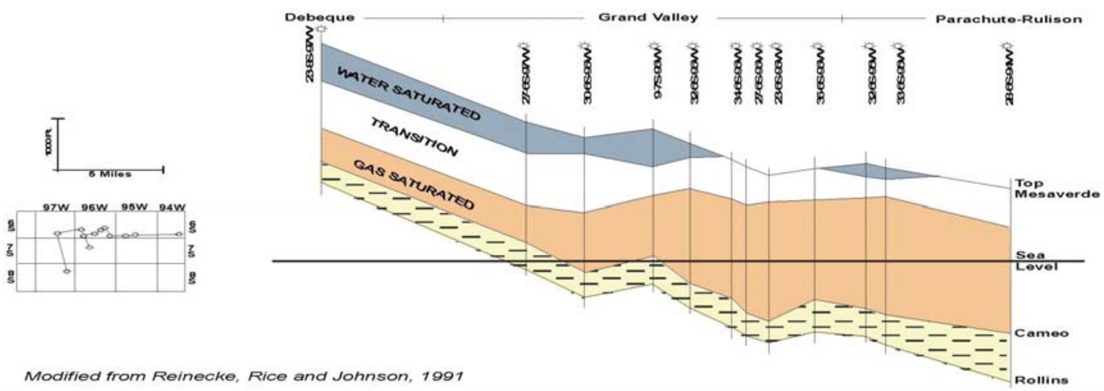
The nature and occurrence of moveable water, geomechanics, stratigraphy, and reservoir engineering guided our conceptualization of tight gas reservoir development. Knowledge of lithology, stratigraphy and basin history (particularly uplift) in the development of these enigmatic reservoirs was referenced extensively.

The results of the compositional study of the produced waters were applied, together with the authors' operating and research experience, to formulate working hypotheses about the origins of the produced waters. These hypotheses laid the foundation of our working model for strategies to avoid and/or remediate unwanted water production. The working model ensured consistency as our hypotheses were tested, refined, and ultimately incorporated into a conceptual model for water in tight gas reservoirs.

Iterations of the working model were presented at the AAPG Hedberg Tight Formation Gas Symposium in Vail, CO (April 2005) and at the 2005 AAPG national convention in Calgary, Alberta (June 2005). The Hedberg poster and the AAPG slides are included in Appendix D, which also includes an in-depth discussion of the reservoir development model.

Basin-Centered Gas Paradigm

The basin-centered gas paradigm postulates the presence of a large volume of gas-charged sediments at near irreducible water saturation. Located in a down dip position relative to an up dip water saturated volume it is depicted in fig. IV-5. Such units generally yield gas shows when drilled but are projected to have very low permeability to water.



Cross-section showing relative position of gas-saturated, transition, and water-saturated zones

Fig. IV-5. Williams Fork fm Southern Piceance basic example

The United States Geological Survey (USGS) considers these to be continuous class hydrocarbon deposits. Since the early phases of basin-centered gas exploitation, it was commonly believed industry-wide that the only significant unknown variable was permeability—that exploitation of these widespread resources could be pursued on a statistical basis.

As development continues, it's become clear that this concept was limited by the data available. Encountering excess (moveable) water is a far more frequent outcome in recent years as tight gas development operations intensify. The rising risk of unwanted water production has prompted efforts (2004, Shanley and others) to re-evaluate the basin-centered paradigm.

Working Concept Premises

A major given for this study was a basin with a mixed fill of coarse and fine-grained clastic sediments with sufficient source, heat and reservoir to provide moderate gas charge, reservoirs and seals. We incorporated the following from our study of subsurface waters, previous work by others, and experience to frame our conceptualization of tight gas reservoir development within such a basin.

1. Produced water compositions generally reflect host rock environments of deposition. (2004 Henry and Billingsley).
2. Areas of faulting and vertical transport may be indicated by anomalous chemical and/or isotopic compositions as measured against background regional trends (2004 Henry and Billingsley).
3. One study of water chemistry suggests gas and water production from coals. (1998 Smith and Surdam).
4. Gravity segregation of some gas accumulations in the Greater Green River basin is well-documented (2004 Shanley, et al).
5. The impact of stress dependency on relative permeability is mathematically corroborated by Ostensen (1983), Byrnes (1997) and Shanley (2004).
6. The significant role of temperature in generation of subsurface stress as established by Warpinski (1989), Engelder (1985), and others.
7. The role of poro-elastic effects during uplift of gas charged sediments as documented by Katahara and Corrigan (2002).
8. Last, but not least we took into account that:
   - The ability of water to flow in the deep subsurface is more restricted than gas; water is more easily characterized chemically than gas.
   - Most significant large-scale tight gas basins have undergone significant uplift after gas generation.

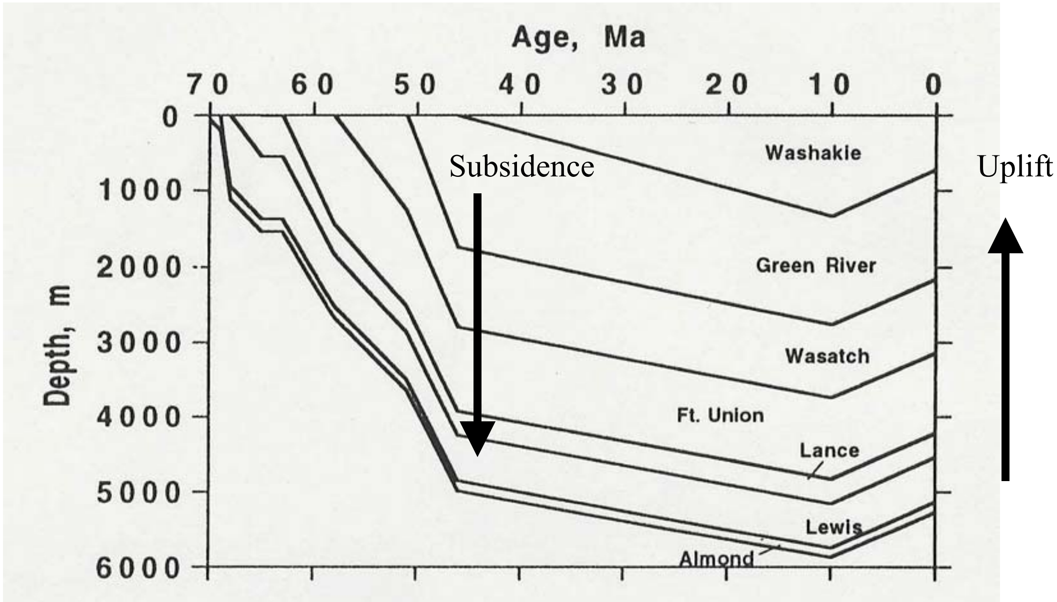
Two-Phase Tight Gas Reservoir Development

Introduction
Bourne (2001) observed that natural fracture development, particularly type, was influenced by whether net mean confining stress was increasing or decreasing when failure occurred. He used a modified Griffith –Coulomb failure criterion to show that shear failure in rocks would most likely occur when net mean stress was increasing, and that extensional failure would most likely occur when the net mean stress was decreasing (commonly during uplift).

Widespread extensional failure during uplift can be predicted using poroelastic (1993 Higgs and Bradley) or viscoelastic (1989 Warpinski) methods. Engelder (1990) also demonstrated the potential for widespread failure during uplift using thermoelastic methods (the fixed-grips Griffith energy balance approach). Regardless of the method used—poroelastic, viscoelastic and thermoelastic—the potential for widespread extensional failure can be shown to occur during periods of falling mean confining stress. The overall direction of our investigation was influenced by the convergence of these methods.

Other factors in tight gas reservoir development parallel the two-stage increase-decrease pattern. It is generally accepted that hydrocarbon generation occurs during increasing burial and slows or ceases during uplift. The progressive mechanical and chemical destruction of original porosity and permeability is often referred to as "burial" diagenesis. The generation of abnormal pressures at depth is envisioned as a consequence of increasing burial. The response of the basin fill to increasing burial (increasing stress) is different than it is to uplift.

A major common theme in the geologic history of the Rocky Mountain tight gas basins is a late stage uplift event. Fig. IV-6 is a representative example from the Washakie basin (1994 MacGowan et al). Cycles of energy input (increasing temperature and confining stress), and release (decreasing temperature and confining stress) control mechanical strains, and chemical diagenesis of sediments through time. This common sequence of events across several basins (not necessarily in severity or timing) prompted us to use frame the burial-uplift cycle and its impact on the basin fill as an organizational framework for our working model.



Although depth of burial, amounts of uplift and timing vary between basins, the Rocky Mountain tight gas basins share a common history of subsidence followed by later uplift. Modified after MacGowan et al, 1994.

Fig. IV-6. Burial history central Washakie basin

Basin Scale Processes

Stages in tight gas reservoir development

Stages in tight gas reservoir development (fig. IV-7) can be organized into two phases, each defined by the direction of net mean stress change over time: Phase I is a time of net mean stress increase and Phase II is a time of net mean stress decrease. Reservoir development is also highly influenced by mechanical properties of the reservoir, mineralogy (provenance), proportions of mineralogies present in different facies and diagenesis

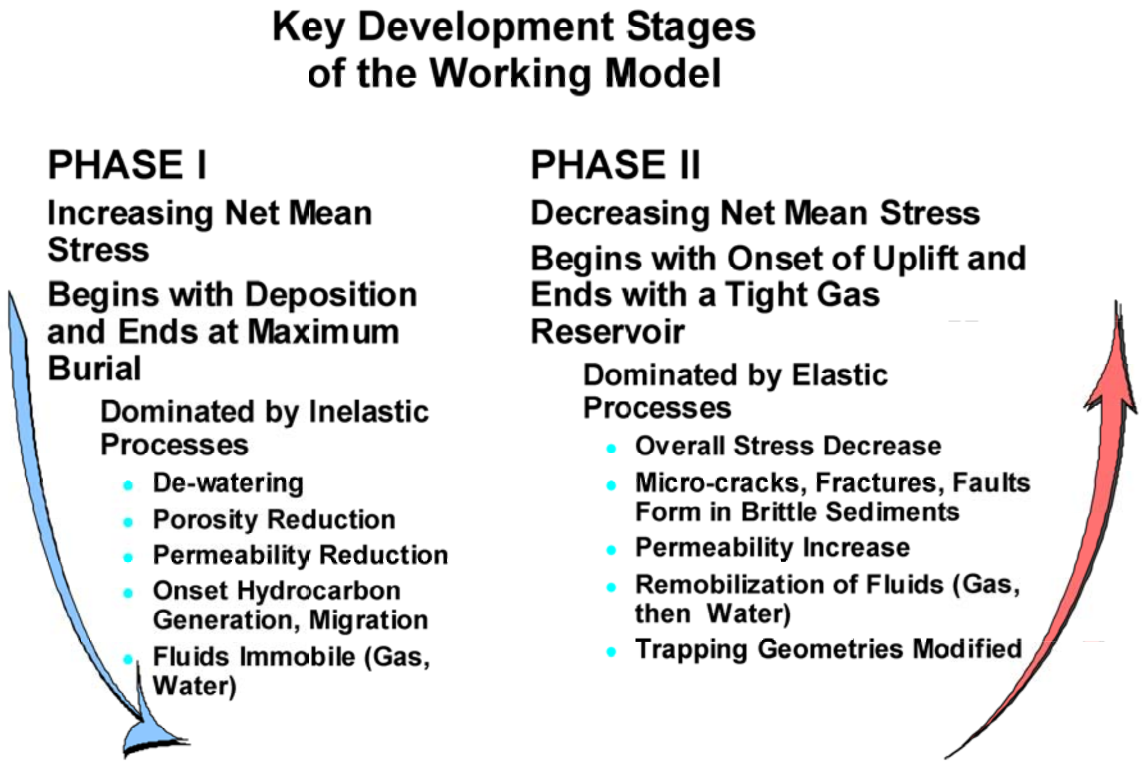


Fig. IV-7. The working model

Phase I (Burial)

Phase 1 of tight gas reservoir development begins with the deposition of the reservoir/ source system and ends with the system at maximum temperature and burial depth. During Phase I the mechanical and chemical diagenetic effects of burial destroy a majority of the reservoir's primary porosity and permeability. Hydrocarbon generation occurs during the later stages of Phase I and peaks near maximum depth of burial.

At the end of Phase I the potential reservoir has reached its minimum porosity and permeability. It may be locked in the "permeability jail," which Byrnes defined as conditions of porosity, permeability and relative saturation in a two-phase system such that neither phase present (gas or water for example) has significant permeability (2004 oral comm, Shanley). Permeability jail is a useful concept to mark the transition between developmental Phases I and II.

Phase II (Basin Uplift)

The onset of basin uplift marks the beginning of Phase II. Rock strength declines with net confining stress. Effective porosity and permeability increase (particularly in quartz rich sediments) as microfractures develop along the margins of shrinking quartz grains (tabular pore throats) and connect previously isolated primary porosity. Fig. IV-8 is a schematic illustration of the grain expansion and contraction process.

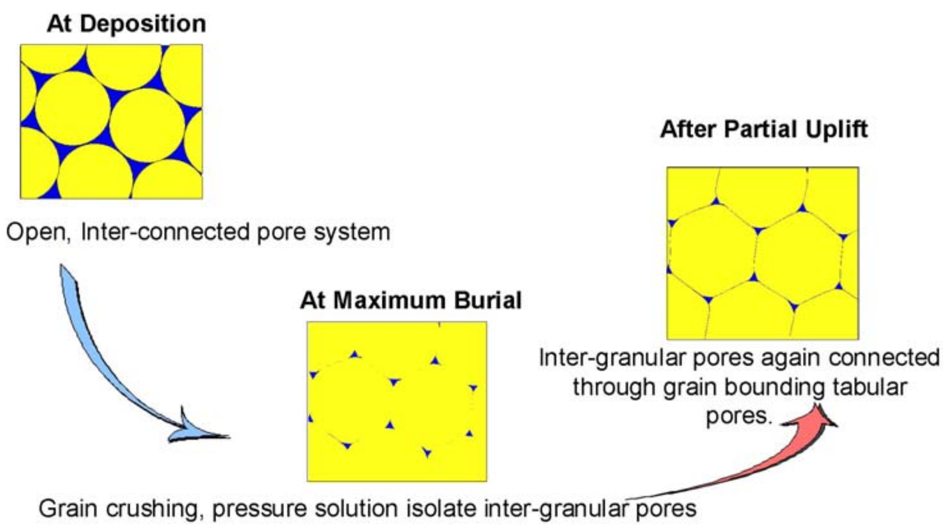


Fig. IV-8. Conceptual grain expansion & contraction

During Phase II of the developmental cycle, net mean stress on the rocks declines and permeability increases. Thermoelastic and lithostatic confining stresses decline while pressures from fluids and gases in pore spaces remain constant. The individual grains of the rock matrix contract, the external confining stresses decrease, and fractures develop along the grain boundaries. Remobilization of fluids (gas, water) begins—with gas expanding to fill developing pore space—and increasing its saturation with respect to water.

This process continues until the strains can no longer be accommodated within the matrix structure and macro fracturing begins. The pore throats expand throughout this process. Gas, both as free gas in pores and sorbed gas in coals and organic shales, expands to fill the voids.

When relative permeability conditions for flow are satisfied the substances previously trapped in the pore spaces begin to migrate. It is likely that gas moves first and most easily (as compressible gas expands to fill any increased porosity) while increasing its saturation at the expense of the water. This initiates gravity segregation, which generally leaves the original waters from deposition in place. As the uplift process continues, shrinkage of matrix grains reduces net confining stress and increases permeability.

Basin uplift cycles are most often driven by tectonic activity. The lateral accommodation required during this process typically involves faulting. Displacements from basement faulting will propagate upwards through the basin fill and disrupt its vertical integrity, allowing some migration of fluids across unit boundaries, leading to localized migration of formation water. Depending on the timing, water composition, temperature, and pressure conditions, mobility of waters across bed boundaries potentially alters the mineral stability fields, potentially enabling development of secondary porosity, as diagrammatically shown in fig. IV-9.

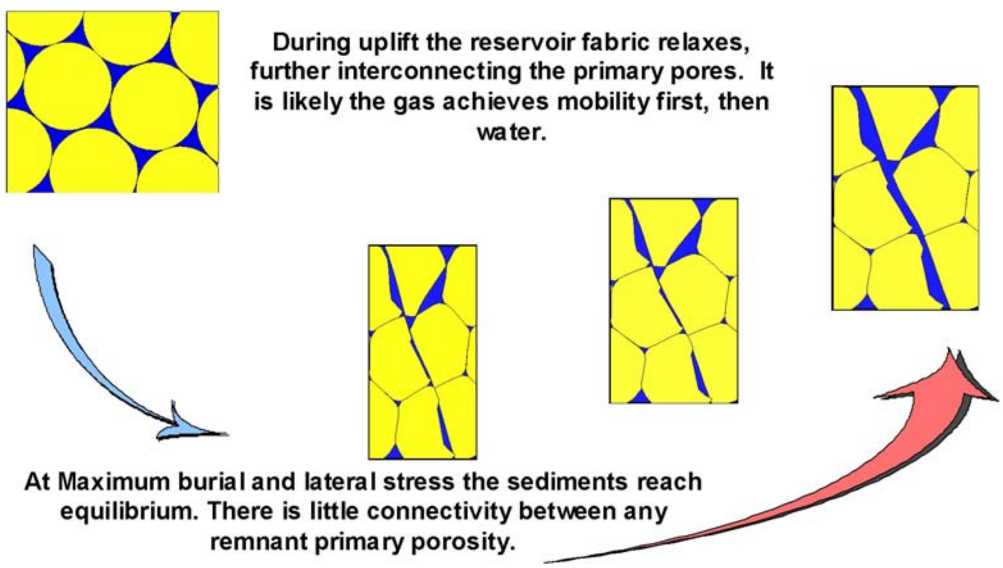


Fig. IV-9. Influence of lateral stress

Application of differential lateral stress during the development process imparts a weak planar fabric on the reservoir sediments perpendicular to the paleo-principal horizontal stress. Following relaxation of the lateral stress the planar surfaces open and support further enhancement of permeability. Extension fractures may develop in high strain zones parallel to axial trends of anticlines. Permeability development may be irregularly distributed according to the reservoir mineralogy, lithology and strain history of the local area.

The macro-stratigraphic architecture of the depositional systems remains intact unless disrupted by faulting. Interbedded or overlying ductile shales remain intact and function as lateral or vertical permeability barriers. Interbedded coals and organic-rich shales may also store hydrocarbons and eventually release gas as reservoir pressures decline. The exact contribution of interbedded organic-rich shales and coals to reservoir storage and flow is poorly understood possibly underestimated. The uplift process; improves permeability for tight gas reservoirs, preserves seals and releases charge.

With sufficient cooling, pore pressure, and lithostatic stress release, lithologically controlled bed scale extensional failure in the reservoir unit is induced, forming macro fractures. With sufficient uplift (and associated strain), the brittle reservoir may develop a large-aperture, saturated, extensional fracture system. The onset of macro fracturing increases total permeability within the reservoir and further facilitates gravity segregation of the gas and water.

Large-scale uplift events are typically associated with faulting of the basement. Late stage basement faulting will propagate upwards through the sedimentary section, disrupting lateral continuity of sediments with varying scales of shear fractures, and further facilitating gravity segregation of gas and water. These fault-related shear fracture systems in reservoirs can create areas of high permeability. If they coincide with high gas saturation, they produce gas at high rates. Likewise, if fractures coincide with areas of high water saturation, they can produce large volumes of water at high rates. Water will move through open natural fractures of any type or size when saturation conditions for flow are met.

Summary

The outcomes of the burial-uplift reservoir development run the gamut of structural, stratigraphic, and relative-permeability controlled, reservoir-trapping configurations. Depending on their stage of reservoir and trap development, these configurations show a variety of characteristics. Many are dual permeability, dual (and sometimes triple) porosity systems with some degree of gravity segregation. Uncovering the full range of potential commercial reservoir settings may require tools and concepts that shift away from conventional and historical analogs.

We envision the development of a tight gas reservoir as a process involving multiple simultaneous process threads. The process threads are inter-related and often involve irreversible changes to the chemical and physical structure of the basin fill. As a consequence, alterations to the basin fill in response to the subsidence process are not simply reversed on uplift. Rather, basin fill develops different features thru different alteration mechanisms.

V. Wild Rose Field Demonstration

Overview

The purpose of the field demonstration was to apply our working conceptual model, for reducing unwanted water production, in a practical setting. The team performed a thorough reservoir characterization and simulation of the field demonstration area to establish a base from which water avoidance or remediation strategies could be developed.

Site Selection

The Wild Rose field matched our profile and was selected for the demonstration because the operator (BP) recognized the need to minimize water production for the field while maximizing the amount of gas produced. Wild Rose Field is located along the Wamsutter arch area of the Washakie basin to the west of the Echo Springs/Standard Draw field complex (fig. V-1). The operator contributed the following data for study: well logs, 3D seismic, production data and water chemistry data. In addition, a number of new water samples were collected.

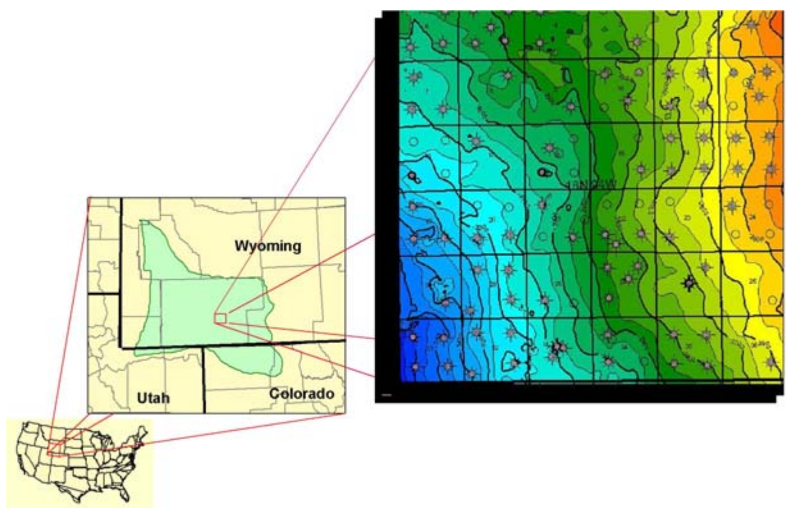


Fig. V-1. Wild Rose Field demonstration location map

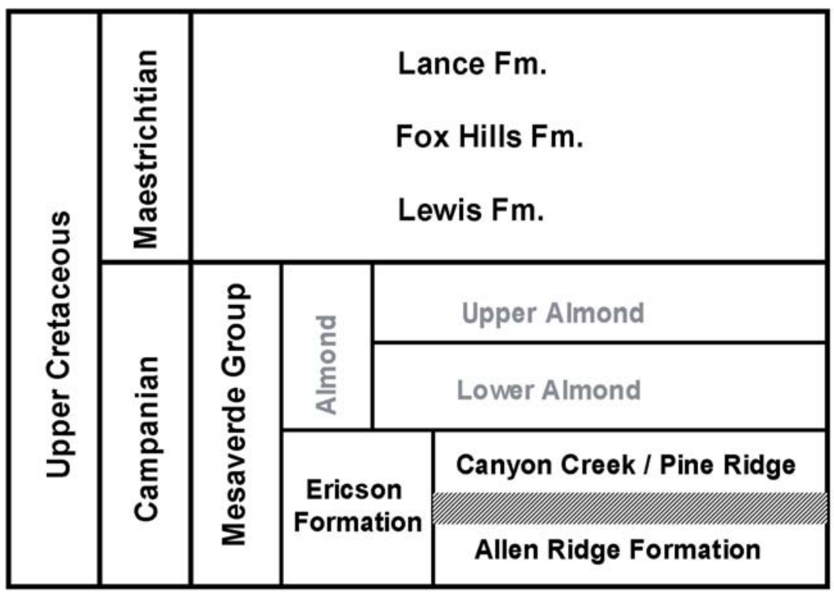
The Geologic Characterization of the Field Demonstration Area

The reservoir characterization followed routine practice for construction of a reservoir model. The reservoir units were mapped using locally correlative electric log (elog) markers. Available core and log data was integrated petrophysically to generate reservoir porosity and saturations.

The 3D seismic data was mapped at the Almond (primary reservoir interval) and at a prominent deep reflector believed to be near the Paleozoic level. Mapping of reservoir units and 3D seismic was completed using the Petra software package.

The Petra project files with data (no seismic) and grids are included in Appendix E. Water samples from wells not previously sampled were collected and analyzed. Completion information and production data for the area was acquired, edited for quality and sequenced in time for the simulation.

Fig. V-2 is a general stratigraphic column for Wyoming.



Modified from Roehler (1990)

Fig. V-2. Stratigraphic column for Upper Cretaceous in Washakie basin, Wyoming

An Almond type log summarizing depositional environments and regional water salinities is shown in fig. V-3.

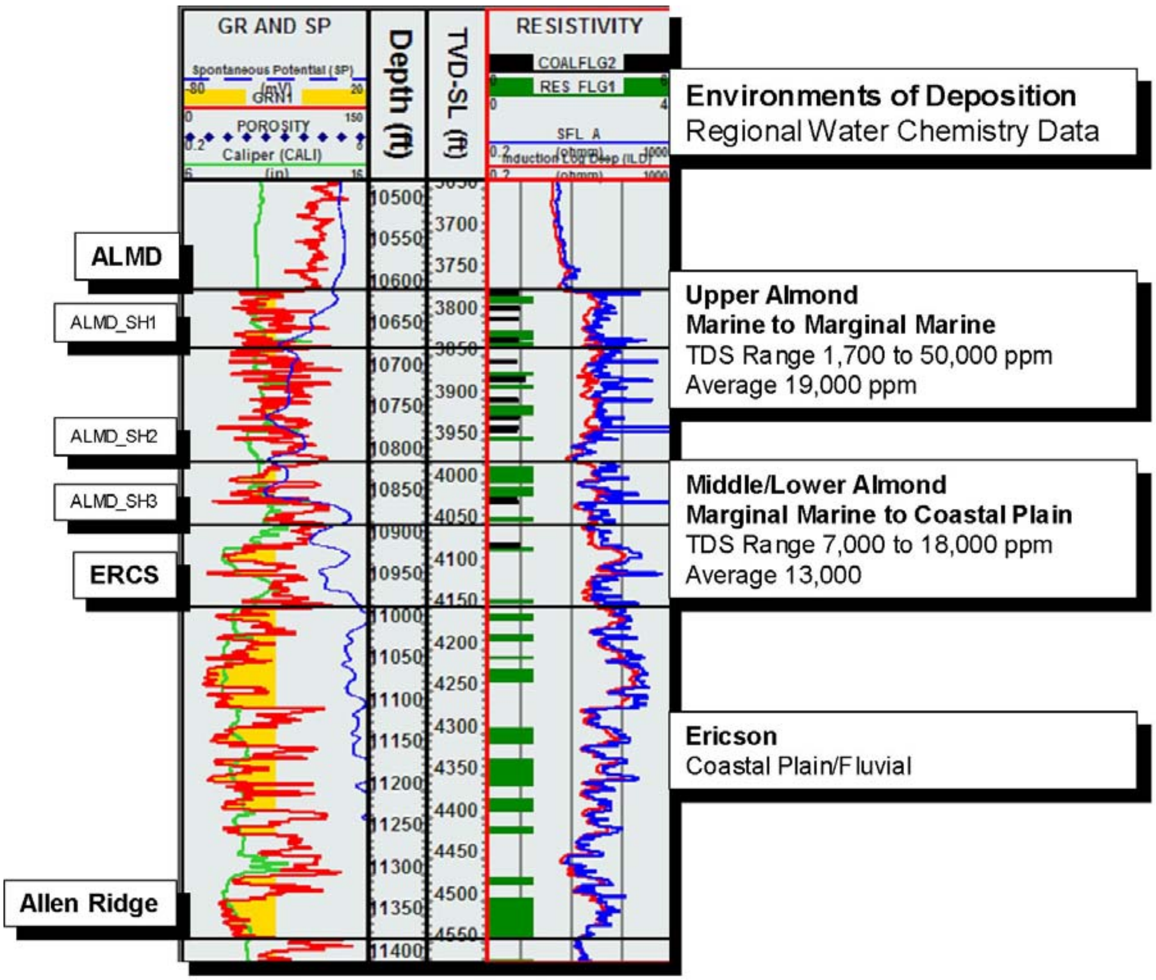


Fig. V-3. Wild Rose type log

The primary reservoir unit is the Almond formation of the Mesaverde Group. It is composed of stacked, laterally discontinuous marine and estuarine sandstones interbedded with coals, siltstones and shales. In general, individual sandstones are thin (1-20 feet), coarsening upward sequences. Local channels do occur, and are cleaner, higher quality reservoirs.

There is a prominent flooding surface within the Almond formation (ALMD_SH2) that spans the study area. Above the Almond is the Lewis formation, a marine shale/siltstone sequence that forms the top seal of the reservoir interval. The upper part of the sequence (L-Marker) is high gamma ray “hot” bentonite shale—a prominent stratigraphic marker and seismic horizon. Below the Almond formation is the Ericson formation. Cleaner, more porous fluvial channel sandstones characterize the Ericson formation.

Regionally, north to south trending Upper Almond retrograde marine barrier island facies produce large volumes of gas in fields such as Echo Springs/Standard Draw. Wild Rose field lies to the west of the Standard Draw barrier island facies, thus the bulk of the field's production is from stacked thin marine, estuarine and channel facies of the Lower and Upper Almond back bar facies (fig. V-4).

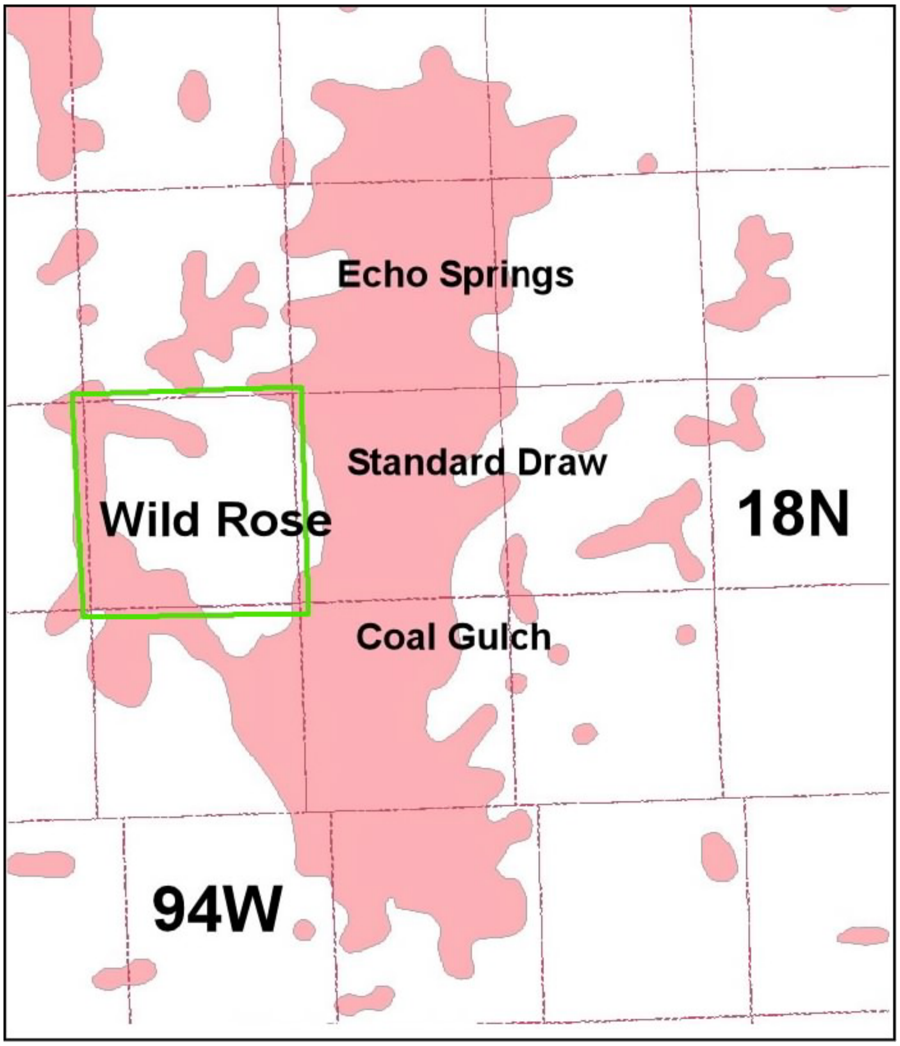
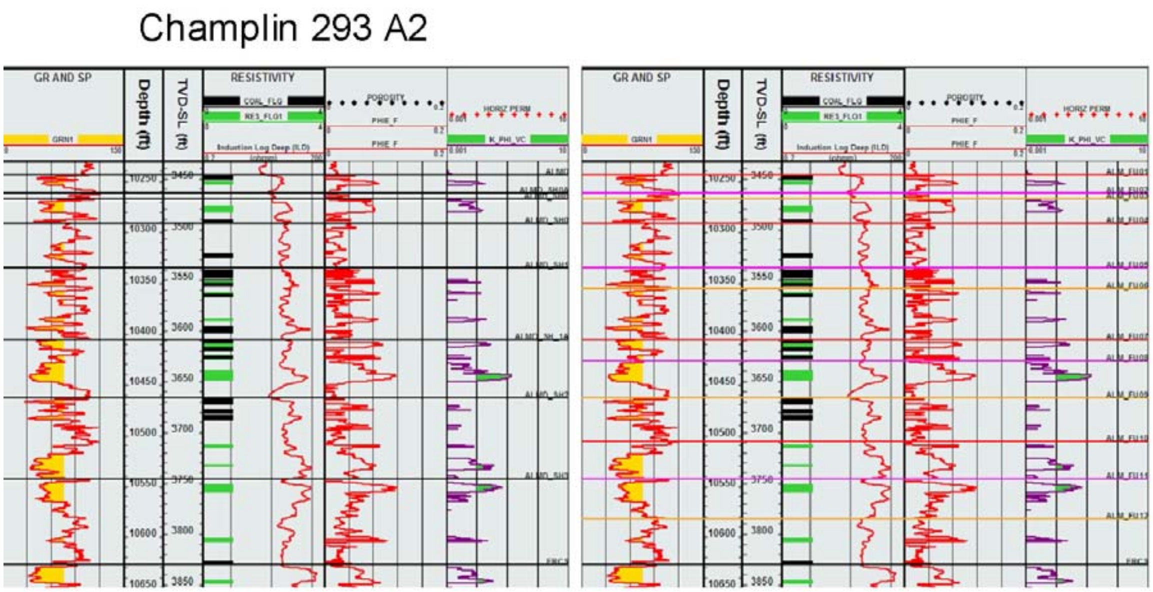


Fig. V-4. Local Wild Rose field index map

The Almond was broken into eight lithostratigraphic units (fig. V-5) based upon local flooding surfaces (shales) and correlative coal beds. The reservoir interval was then subdivided into 23 flow units for petrophysical characterization and simulation.

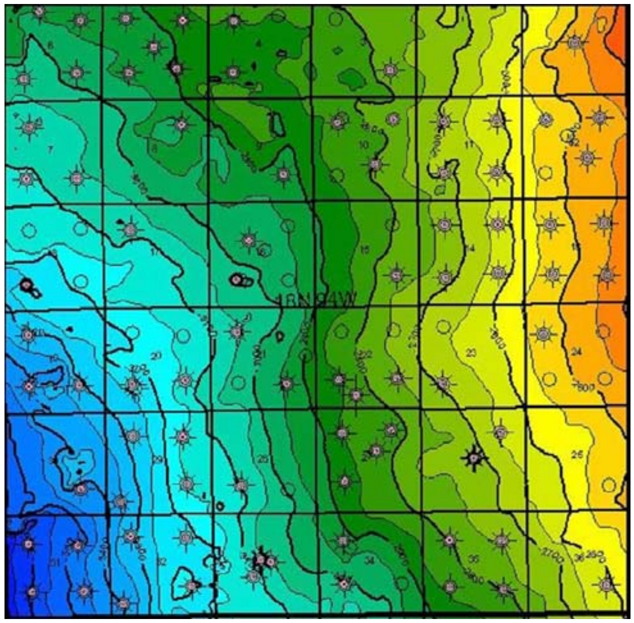


Flow unit picks match ARI stratigraphic picks except where subdivided.

Fig. V-5. Flow unit and stratigraphic pick relationships

These units were further defined as flow units for petrophysical study and put into the reservoir simulation model as displayed in fig. V-4. The ALMD_SH2 is a regional flooding surface and can be correlated with some confidence across the demonstration area. Other markers are less continuous, as are individual sandstones between the marine flooding events.

An upper Almond structure map was constructed using seismic and well control. The Almond strikes northwest to southeast across the study area and dips gently to the southwest (fig. V-6).



Map contour interval is 50 feet. Total depth change across the township is approximately 1,100 feet. Changes in the Almond strike are construed to represent small scale (+/- 50 ft) faulting at the reservoir level.

Fig. V-6. Top Almond subsea structure from 3D seismic and wells

Local strike changes, some abrupt, occur as the result of warping and small scale faulting that trends northeast-southwest across the township. The map constructed at the Paleozoic level from 3D seismic is considerably more complex with a clear northeast-southwest trending fault system bifurcating in the northeast portion of the study area. Breccias, vertical stylolites, extension fractures and other evidence of strain are commonly observed in Almond cores throughout the Wamsutter area.

The small scale faulting and changes in strike observed at the Almond level are interpreted to reflect the displacements across the basement faults. Stratigraphic complexity and low seismic frequency content, however, precluded detailed three dimensional fault interpretations within the Almond itself.

A prominent high-energy reflector, inferred to be near the Paleozoic, is displaced across a complex northeast-southwest trending fault system at around 20,000 feet subsurface (14,000 feet subsea). There are observable strike changes reflecting numerous smaller displacement subparallel faults distributed across the township (fig. V-8).

The prominent deep (possibly Paleozoic) reflector was mapped in detail for the demonstration area (fig. V-7).

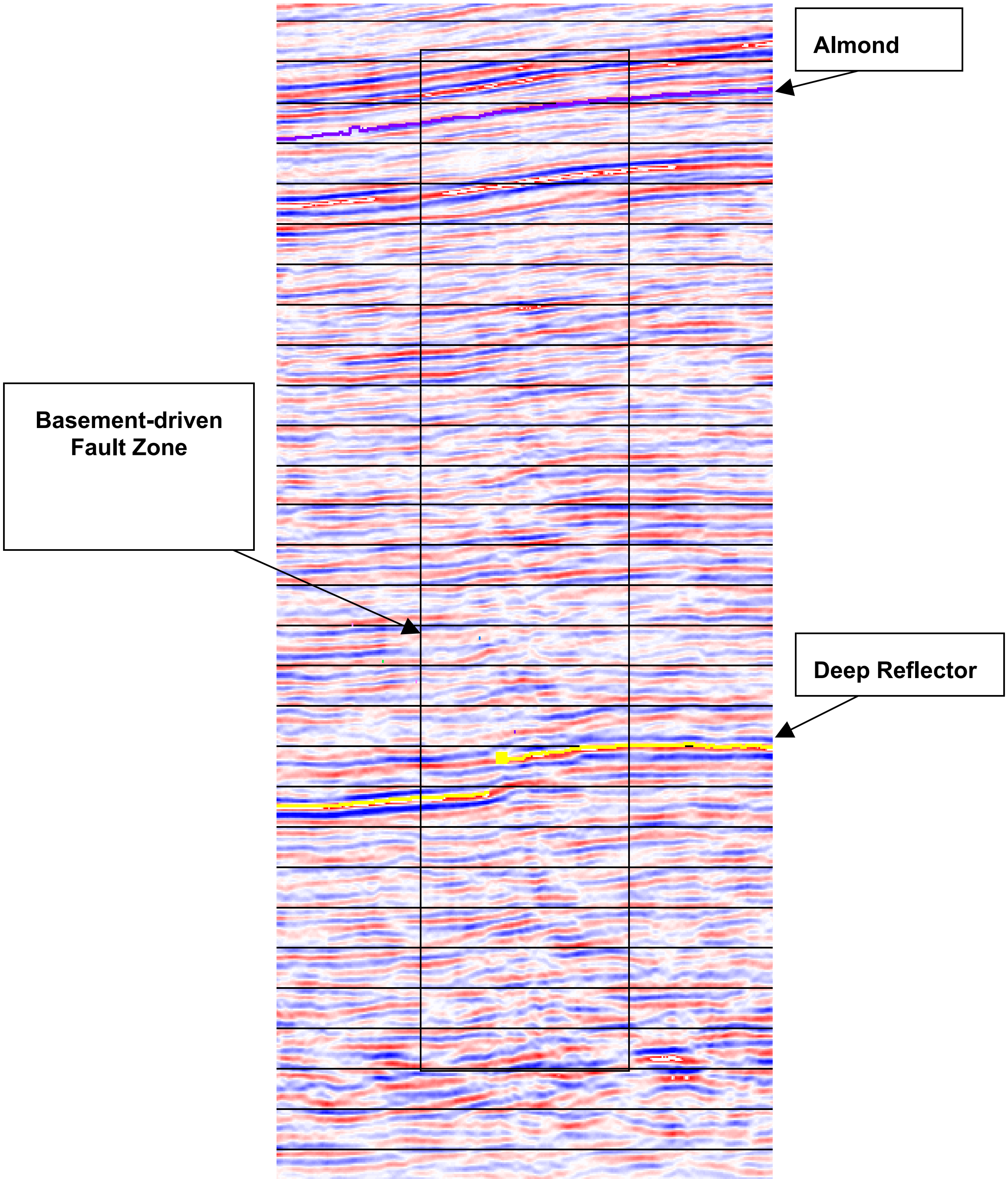


Fig. V-7 Northwest-southeast seismic time section

The Paleozoic structure was selected for mapping because of its potential to affect the distribution of natural fracture permeability within the Almond reservoir. Depth-wise there was sufficient displacement across the faults to determine the three-dimensional geometry of the fault system.

The faults dip predominantly southeast and show reverse displacement. The system bifurcates in the northeast corner of the demonstration area. A subset of faults, located to the southeast of the juncture, show northwest dip and reverse displacement (fig. V-8).

These faults lie immediately beneath the small closed Paleozoic structure in sections 23-24 (fig. V-8), and at the Almond level of the prominent southwest plunging antiform in the same sections. This movement at depth propagates upward, resulting in flexure and small scale faulting at the Almond interval and forms the prominent southwest plunging antiform at this level.

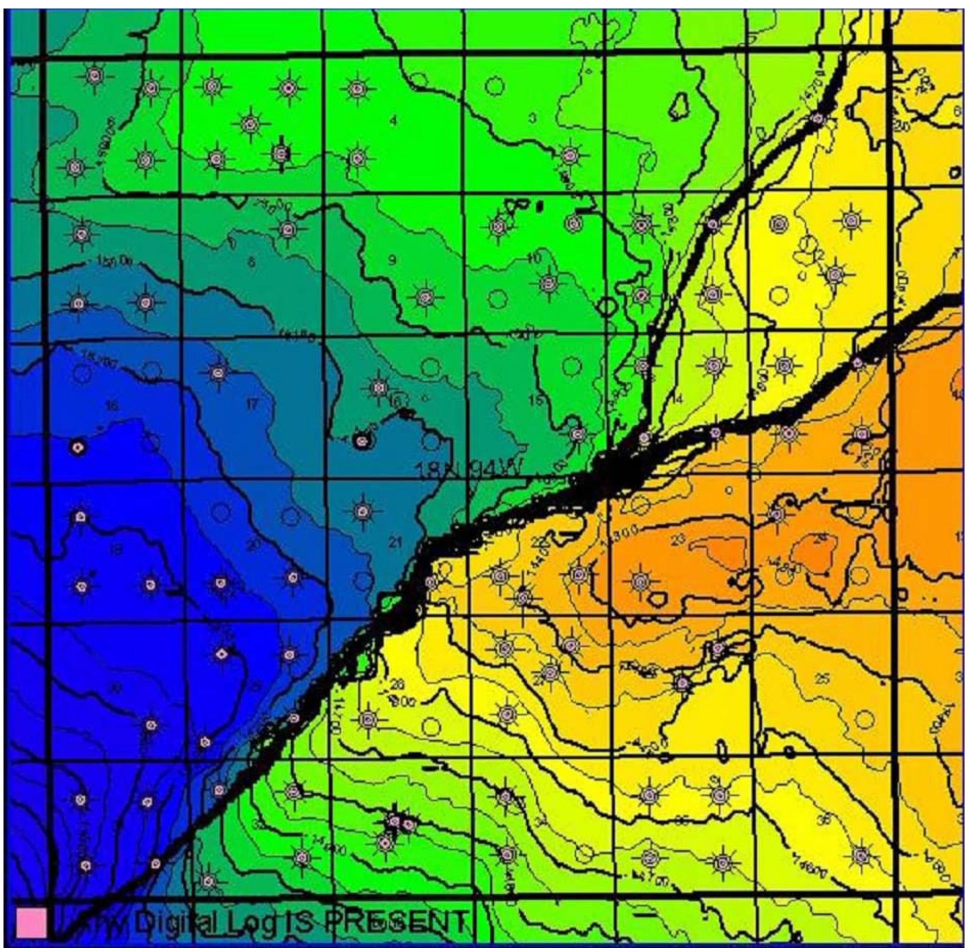
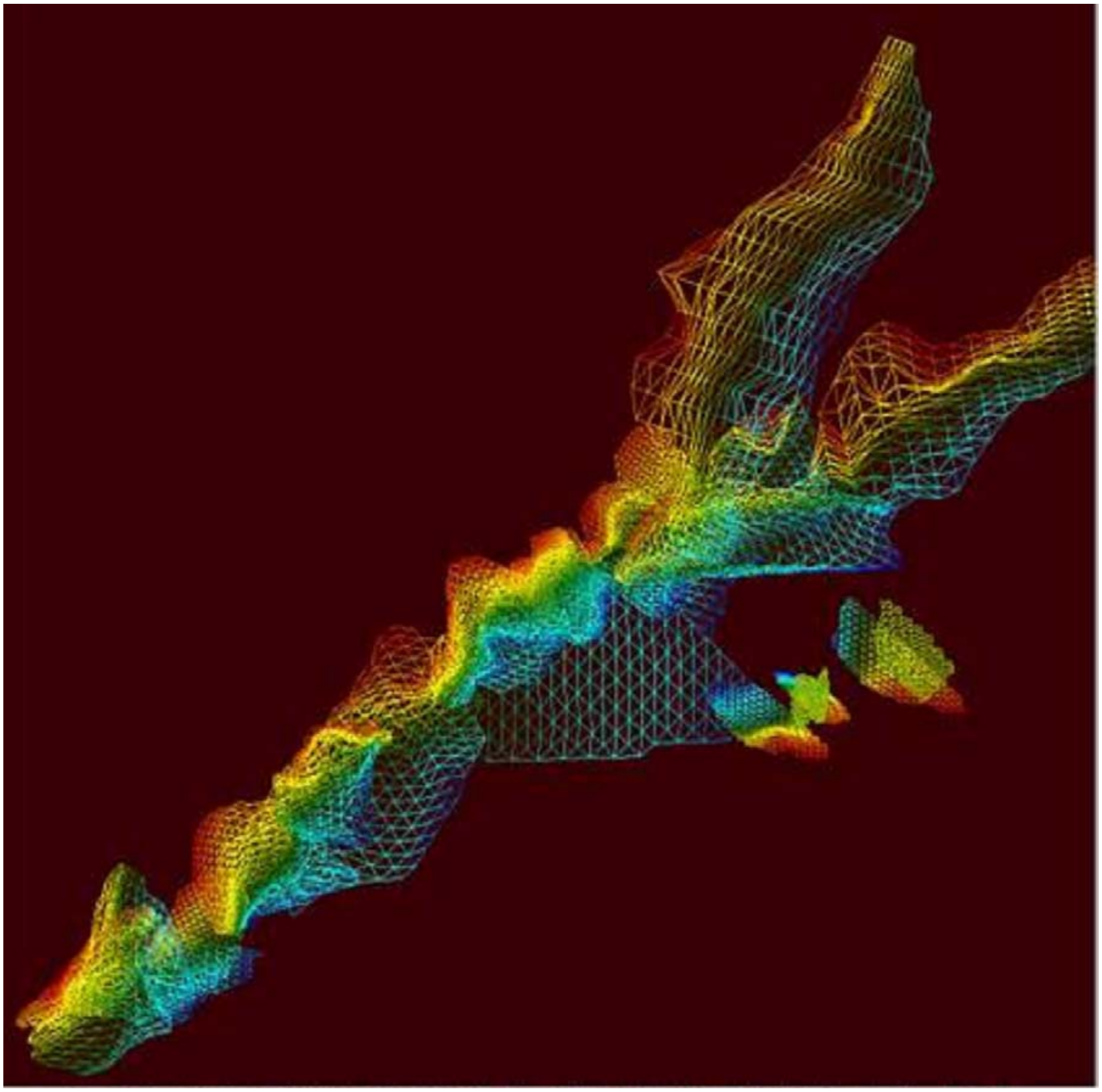


Fig. V-8. Paleozoic Depth Structure from 3D seismic

The deep Paleozoic fault system was exposed as a complex of over twenty anastomosing reverse faults (the wireframe in fig. V-9).



In this wireframe illustration of the deep fault system the wireframe elements reflect their relative depth in the subsurface, blue (deeper) to red (shallower). North is to the top of the screen capture and the area is the same as the depth structure maps of the Almond and Paleozoic horizons previously referenced.

Fig. V-9. Wireframe illustration of deep Paleozoic fault system

Petrophysical Reservoir Characterization

Particular attention and care was paid to the determination of reservoir properties from the well logs and core available, both inside the demonstration area and from the greater Wamsutter area. Our working concept suggested permeability and relative permeability would be key issues in the field demonstration.

A variety of approaches, techniques and calculation methods were scrutinized in order to derive a solid petrophysical model for determining saturation. The petrophysical aspects of the demonstration are summarized here and discussed in detail in Appendix E.

The primary tasks of the petrophysical reservoir characterization were:

- Build a petrophysical model for clay volume, porosity, permeability, and water saturation based on openhole log suites and core data.

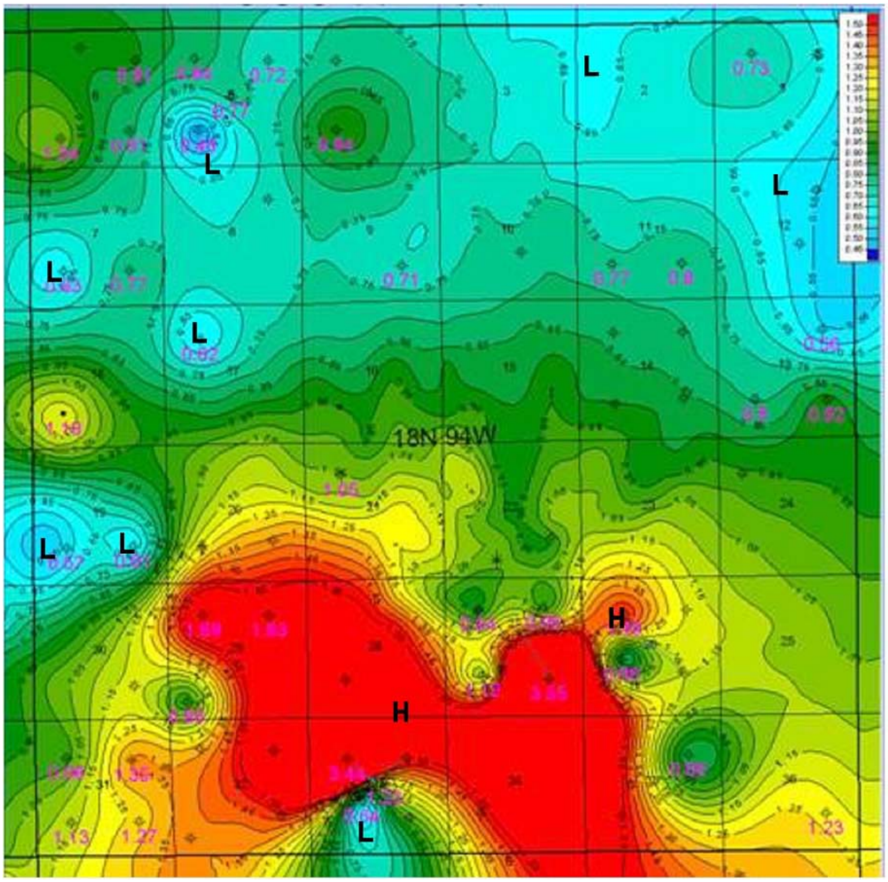
  - Review prior petrophysics and revise/incorporate as appropriate.
- Calibrate cased-hole pulsed neutron log response (TDT) to the petrophysical models developed for the openhole logs.
- Correct core data to in situ reservoir pressure conditions and shift, relative to logs.
- Utilize log suites to distinguish between gas and low salinity formation water.
- Define and distribute flow units based on stratigraphy, facies and petrophysical characteristics.
- Export and incorporate summations into a reservoir simulation model.

A total of 103 wells were loaded and screened for petrophysics. Seventy-one had openhole logs, and thirty-seven had cased hole logs. Of this 108, five had both cased and openhole logs. Eleven of the 103 wells were cored. Of the 103 wells, eighty-five were *fully processed* for petrophysics; the remaining wells had cased hole logs with limited or poor data sets. Production logging information was limited to one well within the demonstration area.

Present wellbore mechanical designs and operating practice precluded acquisition of additional logs during the project.

Rw Calibration

Produced water analyses were used to calibrate the petrophysical interpretation. Accurate in situ Rw values are critical to effective pay determination. Resistivity values from samples collected indicate a prominent high Rw anomaly in the southwest portion of the demonstration area, immediately overlying the trace of the major basement fault (fig. V-10).

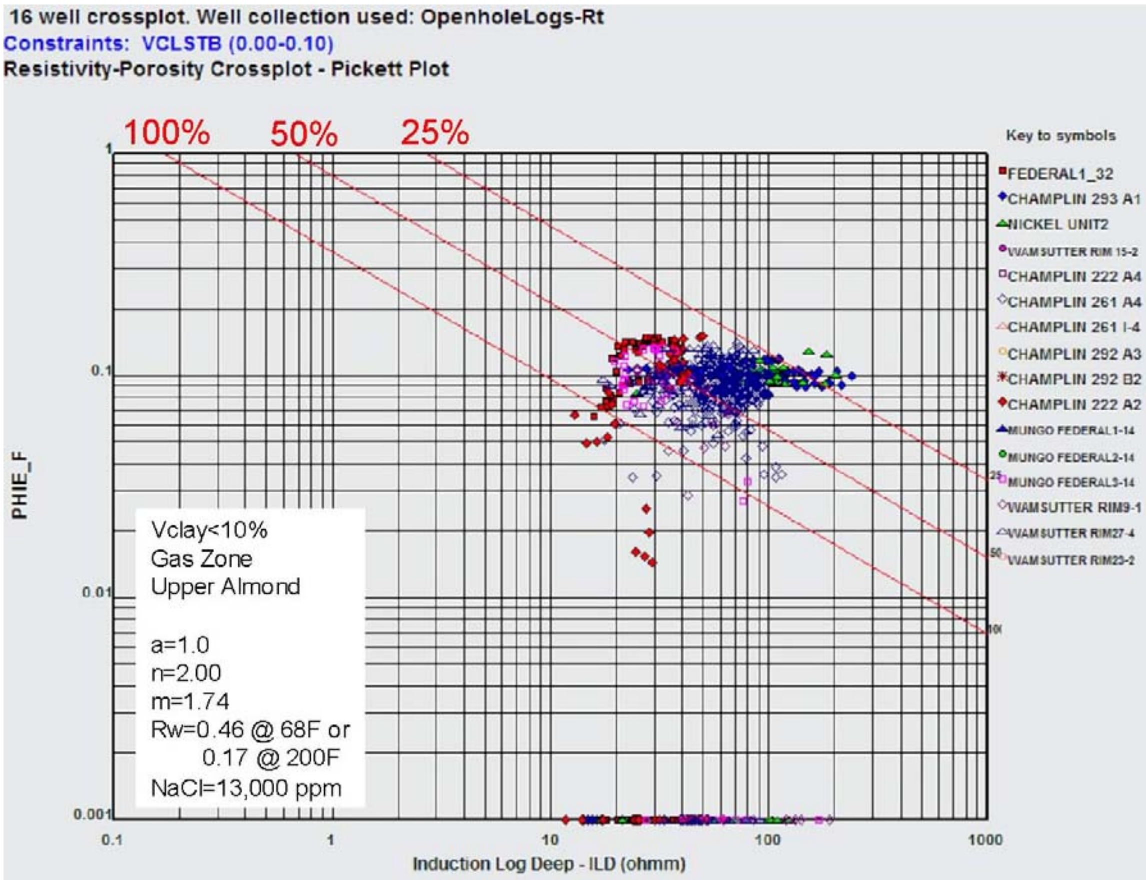


This map shows the average resistivity of the produced water samples (measured at 68 deg F) in the Wild Rose demonstration area. **H** indicates areas of high Rw and **L** indicates areas of lower Rw. There is a conspicuous high resistivity anomaly in sections 28, 29, 32, 33 and 34 that is most likely related to faulting.

Fig. V-10. Produced water Rw map of Wild Rose field demonstration area

Historical analyses were particularly valuable in this effort because they were typically collected from specific intervals within the Almond as opposed to the present-day practice of commingling the entire Almond section.

Spontaneous potential (SP) and resistivity ratio techniques were used to calibrate Rw, which as a reality check were then tested via Pickett plot methods (fig. V-11).

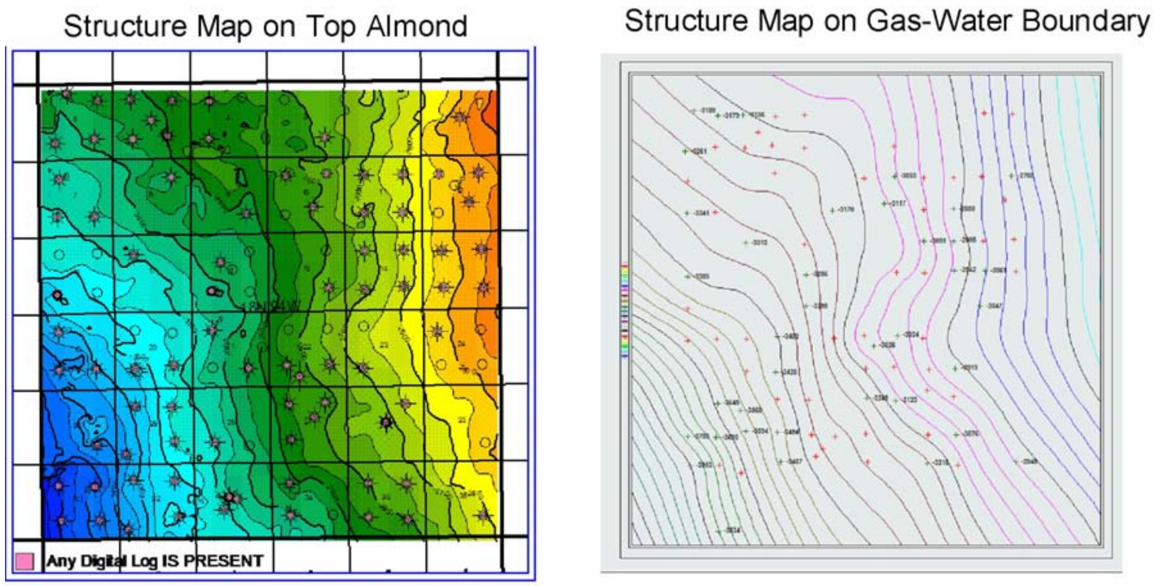


Using Rw=0.46@68F, Pickett plots show the gas-bearing intervals to calculate 25-60% water saturation.

Fig. V-11. Pickett plot gas zone – Rw =0.46 @ 68F

Some limited special core analysis data was available to support the saturation validity. Complete details and examples of this work are in Appendix E.

Vertically and laterally shifting Rw values make pay determination a challenge in this area. Combining the Rw and pay determination techniques led to the identification of an apparent salinity interface that appears to delineate the boundary between discontinuous gas charged sands of the Almond and underlying sands with lower gas saturation (fig. V-12) although it neither follows structure rigorously nor appears to be flat.



Gas-water boundary follows dipping structure, but not rigorously; therefore, is a boundary between discontinuous gas-charged & aquifer sands rather than an actual contact.

Fig. V-12. Inferred SP-GWC structure map

Despite mineralogical and textural complexity, a high-quality petrophysical model (Appendix E) for Vclay, porosity, permeability and water saturation was developed and applied. It works well in most openhole logs and in approximately 60% of the cased hole logs but requires extensive quality control. Permeability was found to be affected by both porosity and Vclay.

The conclusion that SP and resistivity ratios can be used effectively to determine changes in formation water (Rw) is a valuable, immediately applicable outgrowth of this demonstration. Although the theory and techniques themselves are old, they have not been applied of late because of the difficulties in calibration against Rw. Improved understanding of Rw brought about by this project may make the techniques valuable tools in pay determination and water avoidance.

The results of the structural mapping and petrophysical study were broken down into flow units, gridded across the demonstration area and sampled on a regular grid node basis for incorporation into the reservoir simulation input files. Initially, a natural fracture permeability grid was generated using Discrete Fracture Network (DFN) techniques and integrated into the permeability grids for each layer. There was no local fracture data with which to calibrate the network; however, and subsequent permeability adjustments (increases) required to achieve an effective history match across the field were sufficiently extreme as to make the DFN permeability approach irrelevant.

The Reservoir Simulation

Reservoir simulation technology was used to link the petrophysical reservoir characterization with the actual production behavior of the field. This was done to identify relationships between water production and reservoir characterization that could be used to minimize water production during continuing development. Historical gas and water production data, completion intervals, gathering pressures, and other engineering data were compiled into simulator files together with the earth science and petrophysical interpretations.

Matching Procedures

Appendix includes a detailed discussion of the matching procedures as well as input and output simulator files with a Comet™ post processor for displaying them.

To perform this modeling work, the township study area was discretized into a 40- by 40-foor rectangular grid of 800-foot by 800-foot squares. This grid spacing covered the complete 23,000-acre demonstration area. Vertically, the model contained twenty-three layers of alternating gas and water-charged sand and coal layers, with each layer having variable thicknesses, spatially (fig. V-13).

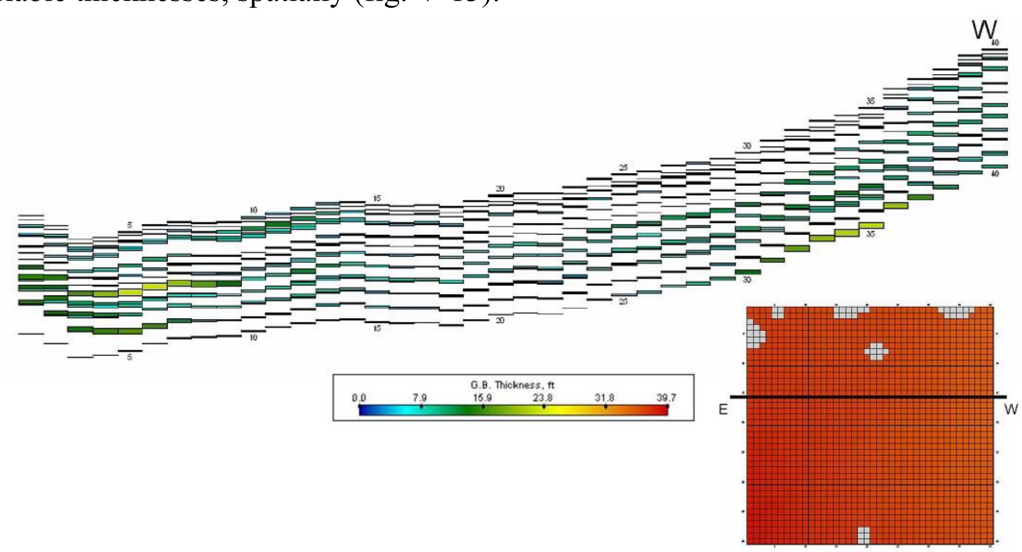


Fig. V-13. Cross-section from east to west along northern portion of model grid

There were twelve sand layers and eleven coal layers, with odd-number layers being sand bodies (from top to bottom in the reservoir column). When constructing these alternating sand/coal layers, only immediate sand/coal pairs were permitted to communicate vertically. This procedure emulated the rather interspersed nature of coal stringers through the Almond formation.

Consistent with field completion practices no coal seams were perforated in the model. Sands were completed in accordance with industry-reported data.

With nearly twenty-eight years of historical production data available for the Wild Rose area, wells were controlled through monthly gas rates. Field-observed backpressures were a secondary operational constraint. Changes in operating practice and regulations over the years contributed uncertainty to the history match. Additional dynamic production data (e.g., detailed wellhead flowing or gathering pressures, additional production logs, etc.) could have strengthened the history match.

A reservoir model representing the Wild Rose demonstration area was built, executed and adjusted until we achieved a reasonable match between reservoir attributes and production. The petrophysically derived reservoir parameters were held constant through the match process. No additional information indicated a need to revisit the petrophysics and the underlying data was considered more reliable than other model inputs.

Permeability was used as the primary attribute for adjustment. Initial coarse areal adjustments were made, progressing to individual wells near the conclusion of the match process. Original gas-in-place volumes, as calculated in the simulator, are shown in Table V-1.

Table V-1. Initial gas & water in place for 23 model layers

	Initial GIP (bcf)			Initial WIP
	Sorbed	Free	Total	(MMbbls)
layer 1	0	57.5	57.5	39,148.4
layer 2	9.2	0	9.2	916.1
layer 3	0	5.3	5.3	3,123.9
layer 4	0.2	0	0.2	19.4
layer 5	0	36.3	36.3	31,842.1
layer 6	37.8	0	37.8	3,780.3
layer 7	0	104.1	104.1	80,521.7
layer 8	46.5	0	46.5	4,641.3
layer 9	0	30.2	30.2	24,686.3
layer 10	86.8	0	86.8	8,661.0
layer 11	0	39.0	39.0	32,213.8
layer 12	37.9	0	37.9	3,782.2
layer 13	0	54.9	54.9	47,278.2
layer 14	98.7	0	98.7	9,853.0
layer 15	0	105.0	105.0	82,417.4
layer 16	2.2	0	2.2	223.0
layer 17	0	99.5	99.5	90,124.4
layer 18	99.9	0	99.9	9,964.2
layer 19	0	50.8	50.8	82,367.7
layer 20	49.1	0	49.1	4,901.3
layer 21	0	68.7	68.7	147,257.4
layer 22	13.8	0	13.8	1,382.0
layer 23	0	33.1	33.1	112,308.1
TOTAL	**482.1**	**684.4**	**1,166.5**	**821,413.4**

Overall, 1.1 tcf of gas and 820-billion barrels of water were estimated to be in-place in the study area (Table V-1). Noting that sand and coal (odd and even layers, respectively) bodies alternate within the model, nearly 60% of the original hydrocarbons in-place were estimated to have been contained in the sands, leaving the remaining 480 bcf in the adsorbed state within the coal seams. Field verification of the employed isotherm should be conducted to confirm the accuracy of the estimated gas in-place in the coal seams.

Field Match Results

While the field match was quite good, individual well matches did vary; however, these variabilities were considered acceptable within the overall field match. Table V-2 shows the by-layer production during the twenty-three year history.

Table V-2. By-layer voidage & cumulative gas recovered in field thru October 2003

	Initial GIP (bcf)	Cumulative Gas Produced (bcf)	Gas Recovery Percent IGIP
layer 1	57.5	3.1	5.3
layer 2	9.2	0.0	0.0
layer 3	5.3	0.2	4.2
layer 4	0.2	0.0	0.0
layer 5	36.3	1.8	4.8
layer 6	37.8	0.0	0.0
layer 7	104.1	3.7	3.5
layer 8	46.5	0.0	0.0
layer 9	30.2	2.2	7.3
layer 10	86.8	0.0	0.0
layer 11	39.0	3.4	8.7
layer 12	37.9	0.0	0.0
layer 13	54.9	2.4	4.3
layer 14	98.7	0.0	0.0
layer 15	105.0	6.9	6.6
layer 16	2.2	0.0	0.0
layer 17	99.5	7.5	7.6
layer 18	99.9	0.0	0.0
layer 19	50.8	2.3	4.6
layer 20	49.1	0.0	0.0
layer 21	68.7	0.8	1.1
layer 22	13.8	0.0	0.0
layer 23	33.1	0.3	0.9
TOTAL	**1,166.5**	**34.5**	**3.0**

	Remaining Gas (bcf)
Sands (odd layers)	649.8
Coals (even layers)	482.1
TOTAL	**1,131.9**

It is noteworthy that the coal seams are negligible contributors to date, while the sands have produced only 5% of their initial volume and 3% of the overall system in-place volume. Depletion in this system, via pressure for sand layer 15, is depicted in fig. V-14.

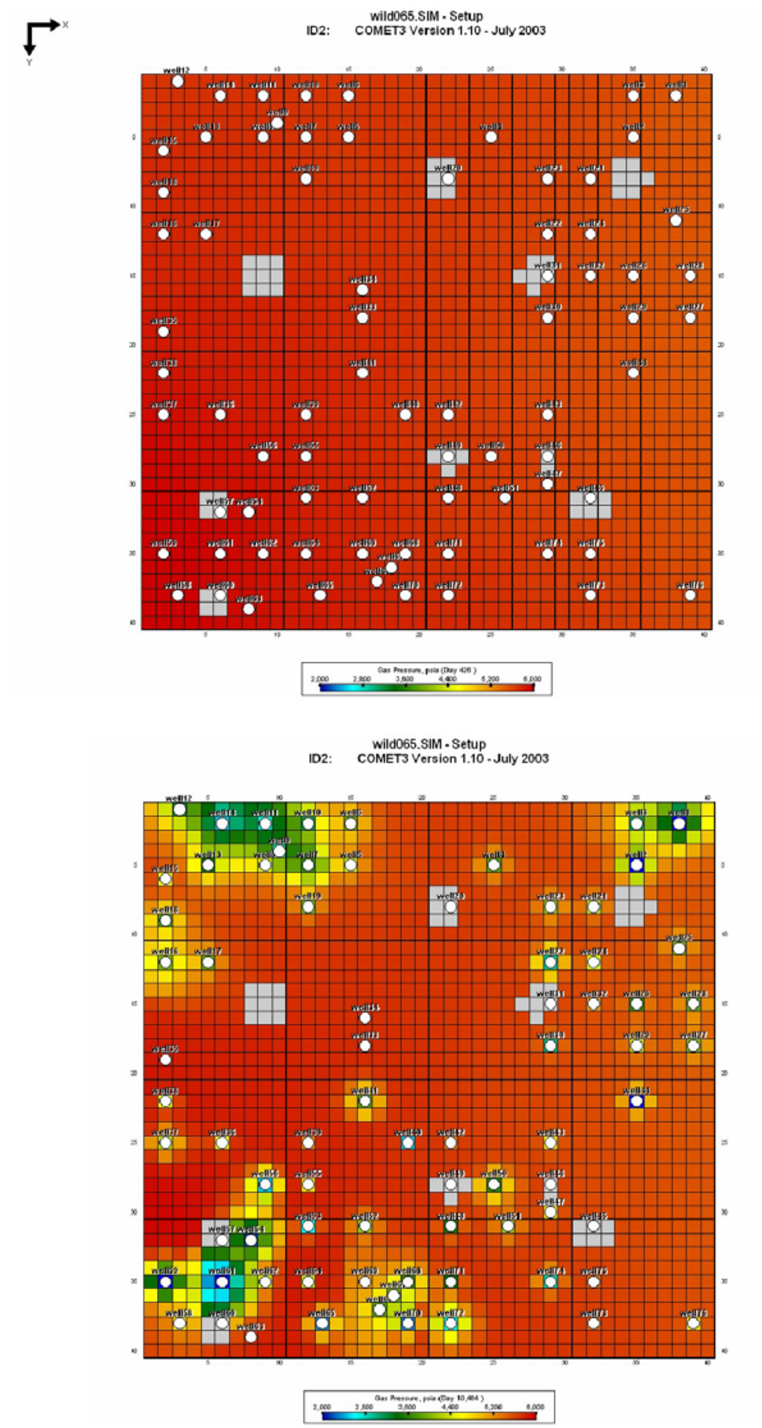


Fig. V-14. Initial to final gas pressure arrays (layer 15) depicting some edge effects & showing relative depletion for inter-grid wells

The Wild Rose area history match results supported the following suppositions.

1. There appears to be infill potential in this area because of the low volumes produced to date. The operators are currently undertaking infill projects. (Eleven of seventy-nine permitted wells had been drilled as of 9/05).
2. Taking away edge effects, average well drainage appears to be eighty acres in the developed areas and interference appears to be minimal (fig. V-15). Therefore, the infill pattern development is justified.
3. The coal seams apparently have not contributed to the overall production. Confirmation of coal initial gas-in-place (IGIP) is necessary to better gauge the future contribution of these seams.

The field-wide cumulative gas and water production matches are shown in fig. V-15.

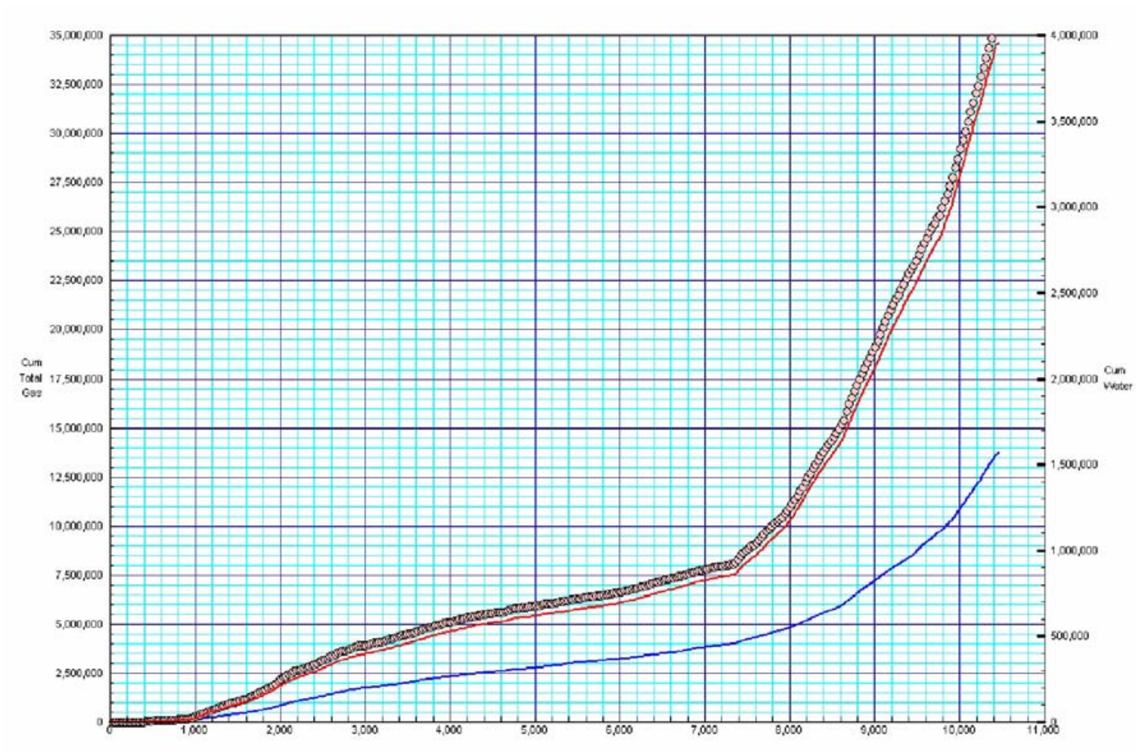


Fig. V-15. Final field-wide cumulative gas & water production

ARI experience during this production simulation is in stark contrast to the assertion of Shanley, et al (2004) that *little* correction was usually required to match bulk production permeabilities to values generated using core and petrophysical methods. It is clear from fig. V-16 that major upward adjustments to permeability were required to match the historical production rates. Only twelve of the well bore cells required less than a two-fold adjustment between original matrix kh and that required to match production. The average adjustment was 7.5-fold and the maximum was 36-fold. For this reason a major reassessment of the permeability model was made in order to generate a more geologically reasonable permeability map across the demonstration area. Fig. V-16 is a comparison between the original and matched arrays for one of the layers.

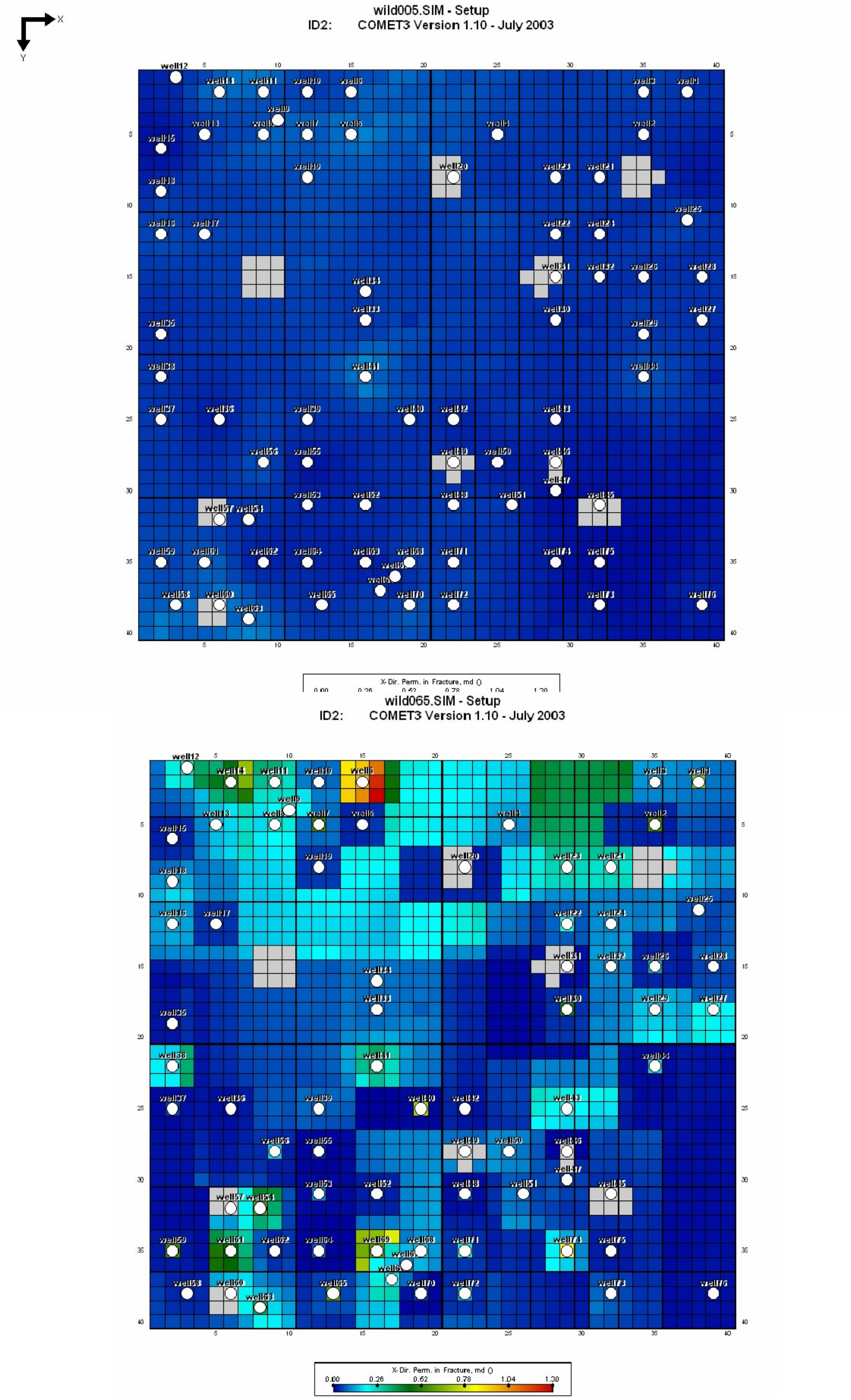


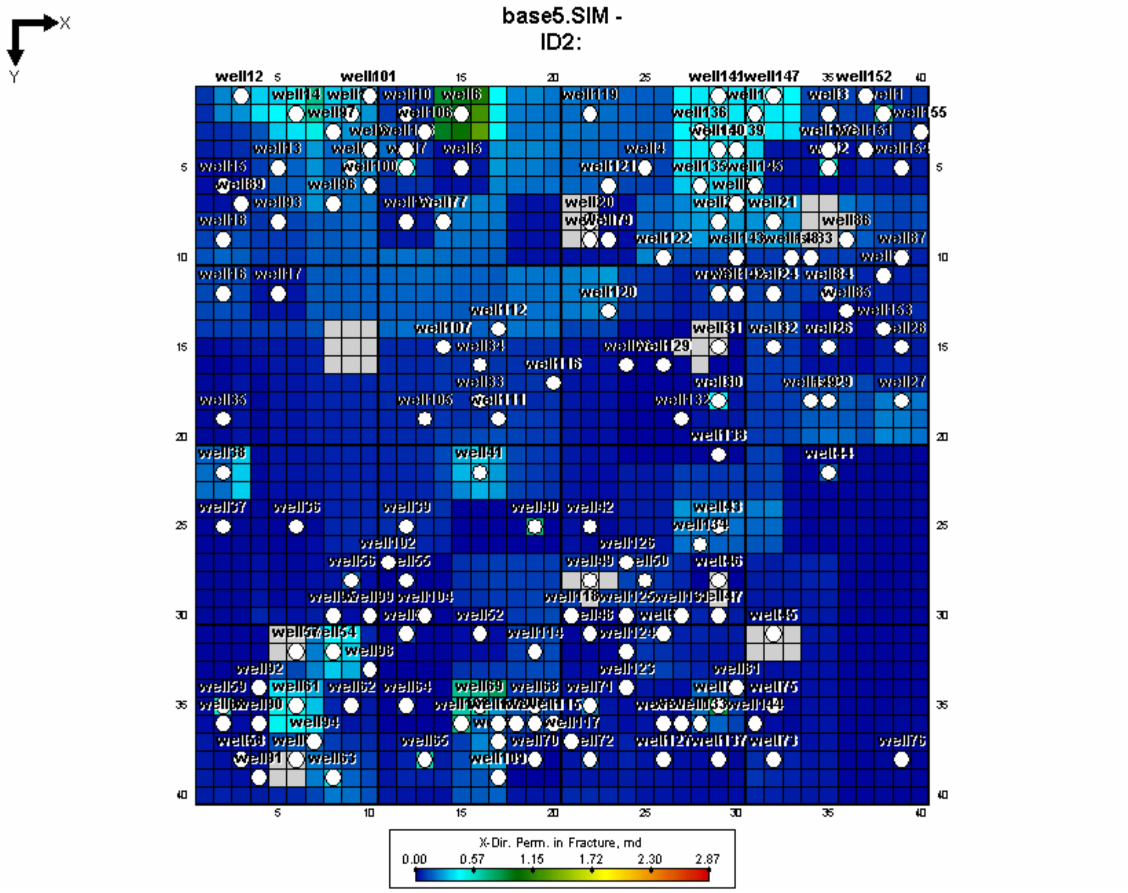
Fig. V-16. Permeability arrays before and after modifications (layer 15)

Forecast Model

The permeability matrix for the forecast model was generated using the original matrix values (petrophysically derived) and conditional simulation methods. The composite, matched permeability array was deconstructed and the matrix permeability values were subtracted. The wellbore cells alone were geostatistically described using variography.

A conditional simulation was run using the wellbore cells and the eight surrounding cells as inputs. The permeability matrix was repopulated using the nine cells around each wellbore as givens and populating the intervening areas from the simulation array. The resulting fracture permeability array was added back to the matrix arrays and re-integrated into the simulation file.

In this way, the local wellbore match values were held constant and the inter-well areas received statistically valid values that reflected the range of the control data set. The final layer 15 permeability array is shown in fig. V-17 as an example.



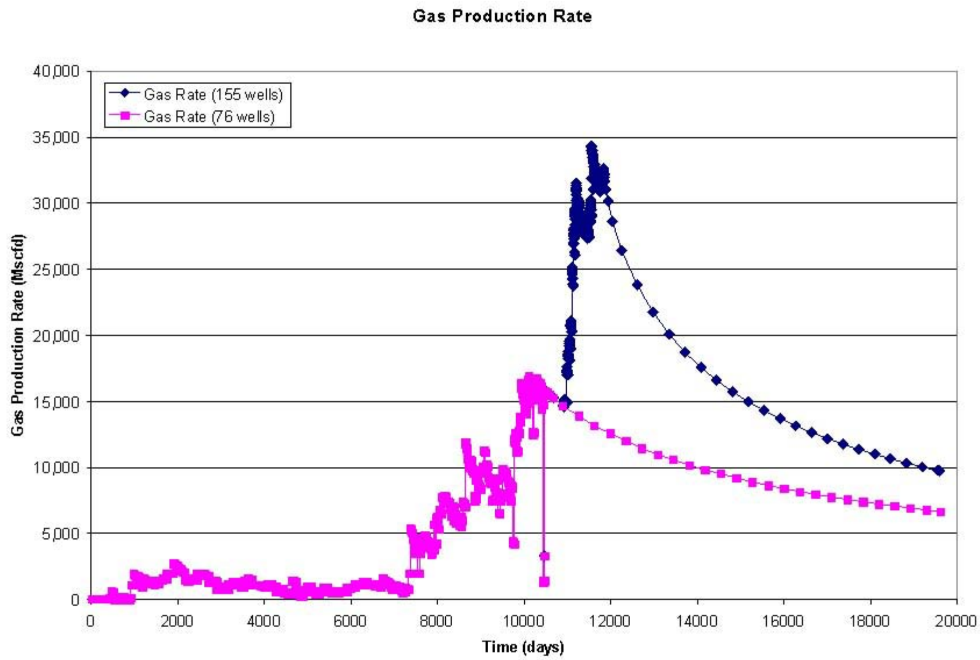
This map is the permeability grid (of layer 15) used for the forecast runs. The variography indicated a significant nugget effect and directional anisotropy in a northeast-southwest trend.

Fig. V-17. Final layer 15 forecast permeability grid

The Wild Rose area production forecast used the existing seventy-six wells as a base. Additionally, the eleven wells drilled and completed during the demonstration were post-appraised against the forecast. Sixty-eight permitted well locations were *projected* to be drilled at a rate of two per month going forward and then added to the forecast.

The forecast run was executed for twenty-five additional years, through 2028. See fig. V-18 for the gas rate and cumulative gas forecasts for the 155 well-run as compared to forecasting only the pre-existing seventy-six wells already matched in the base case. This forecast estimates that peak gas rate will be on the order of 35 MMcfd and further suggests that cumulative gas production from the area will eventually surpass 200 bcf (projected to the year 2035).

The cumulative gas production from the eleven new wells compared favorably to the forecast, suggesting the history match should be adequate to predict aggregate infill potential as well as estimate future production. However, point forward the forecast model should be updated on an ongoing basis to reflect the data gathered (via geophysical logs and production) and minimize the differences between the forecast and actual field performance.



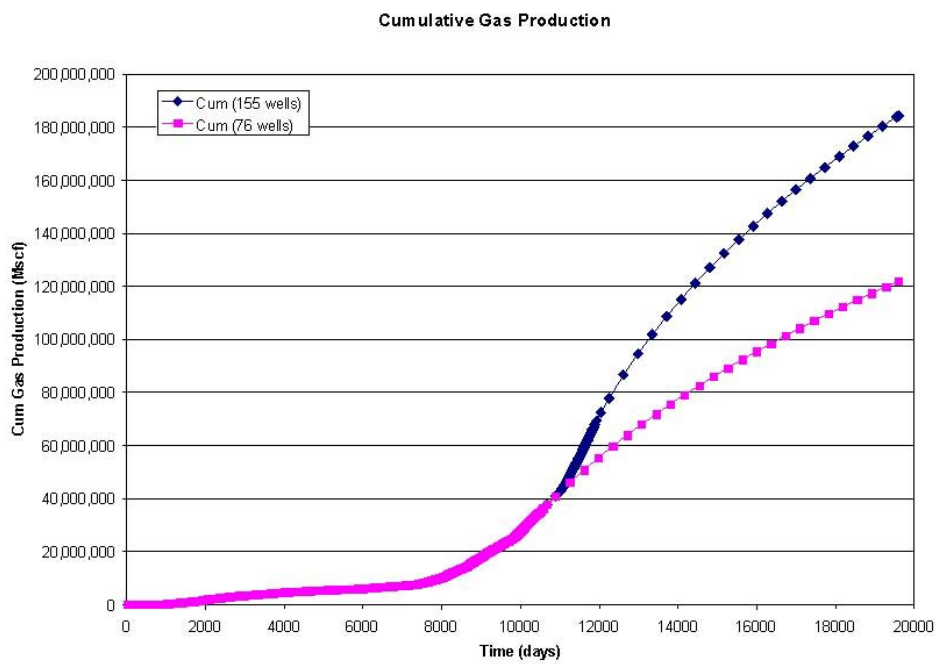


Fig. V-18. Gas rate (A) & cumulative gas (B) forecasts for 155 wells, compared to forecasting pre-existing 76 wells

Analysis

The simulation results were reviewed to identify any observable relationships between bulk permeability and water production. A data set of seventy-five current wells with over 12 months production was selected for reasons of completion and operating consistency. Total matrix permeability-thickness (kh) was subtracted from the simulation (match) kh. This difference is attributed to the permeability contribution of natural fractures.

The wells were ranked 1/low through 75/high in (1) matrix kh, (2) natural fracture kh, (3) first 12 months gas production and (4) water gas ratio. A four-variable bubble plot (fig. V-19) was constructed using the resulting relative rankings.

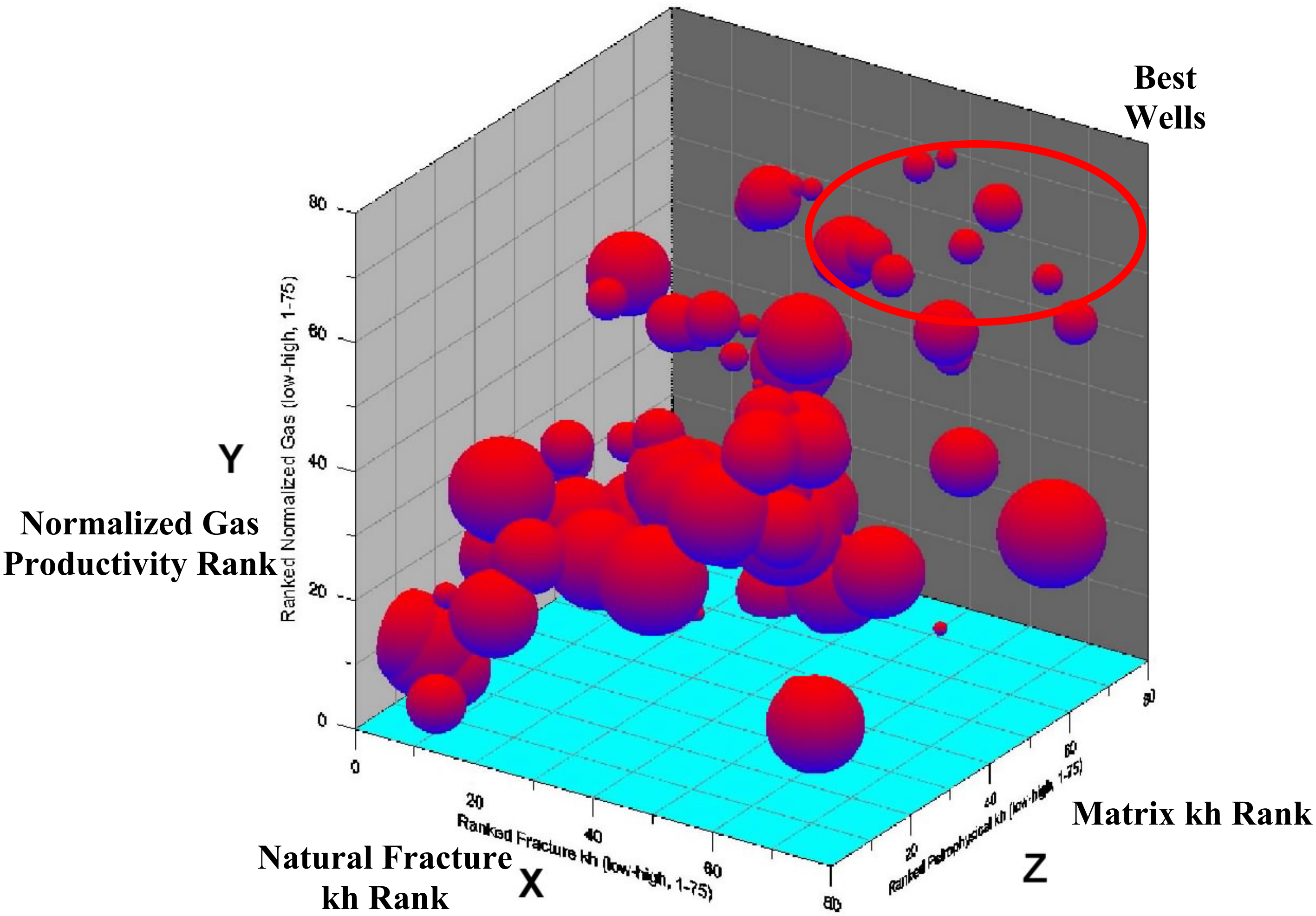


Fig. V-19. Four-variable plot of Wild Rose reservoir attributes

This plot (fig. V-19) shows clearly that the highest productivity gas wells with the smallest water gas ratio are those with the most matrix kh and the most fracture kh (small bubbles (upper right back corner of the cube).

The size of the bubbles represents the water-gas ratio ranking (smaller is better). The matrix kh, fracture kh and normalized gas variables are plotted against the axes (z, x and y respectively). The origin (0,0,0) is located at the lower left front corner of the cube. The upper right back corner of the cube is 80, 80, 80 and represents the highest-ranking wells for each variable within the population. A point located at the lower front corner of the plot would exhibit the worst matrix kh, greatest fracture kh component and worst gas production.

The upper back corner represents the best matrix kh, worst fracture kh component and the best production rank. There are no points in the upper back corner.

The majority of the wells with relatively small fracture permeability components also rank lower in normalized gas production (near the axis between 0,0,0 and 80,0,0), with a mixture of water-gas ratio rankings. There is also a significant number of low productivity, high fracture component wells with high water production (large bubbles, low in the cube, towards the right.

The simulation results from the Wild Rose area demonstrate that the Almond reservoir is a composite system of both matrix and natural fracture permeabilities. Wells optimally located to access significant pore volume and fracture permeability structurally high in a gas column will flow significant gas at low water to gas ratios. Wells with little fracture permeability component tend to be poor producers of gas although they may generate less water as well.

This relationship of gas to water is also observed with high fracture permeability wells, which tend to produce at high water gas ratios. Thus the impact of natural fracture permeability on production quality is neither all good nor all bad. Rather, *the negative or positive impact of natural fracture permeability on production is determined by its relative position within the gas column—high or low.*

Trends and Context

Understanding the nature and occurrence of water in tight gas settings is more a question of understanding trends and context than specific determinative criteria. There are several significant, related trends in the Wild Rose demonstration area.

Salinity Trends

For example, a variation in water salinities (high to low) should be expected between the marine upper Almond, transitional middle Almond, and lower Almond/Ericson. A consistent Rw across these intervals would be anomalous. Successful pay determination in these situations requires rigorous data collection to capture changing salinity trends because individual data points have little value out of context.

Fig. V-8 is a map of produced water resistivity in the demonstration area showing a major Rw anomaly in the southwest portion of the township. Strontium isotopes and calcite saturation indices were anomalous as well (elucidated in Appendix C). Water has moved in this area on the basis of the geochemical signatures.

Basement Structural Trends

Structure mapping at the deep Paleozoic level confirmed a prominent fault trend extending from the southwest corner of the township to the northeast corner (fig. V-7). There is an analogous trend in the Almond structure (fig. V-7).

The inflection of the prominent flexure at the Almond level is subparallel to, and nearly overlies, the deep fault itself. The first-year water production map shows a less prominent but nonetheless visible alignment along the same trend (fig. V-21). The high permeability cells from the reservoir simulation display similar directional trends (fig. V-17).

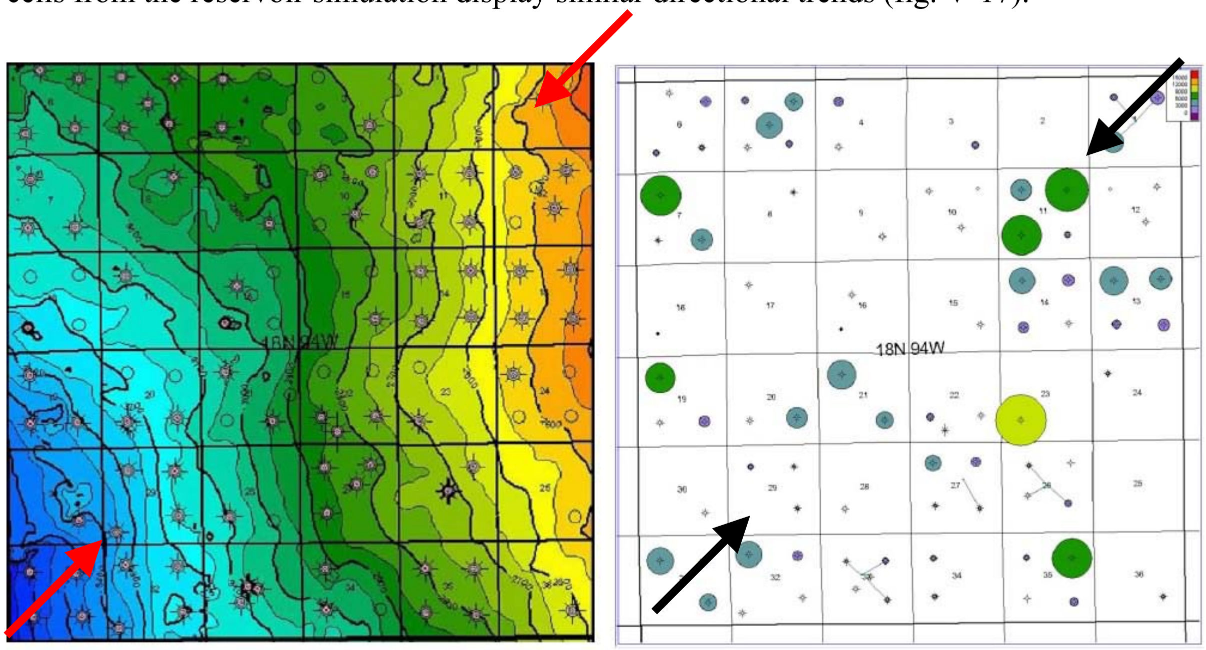
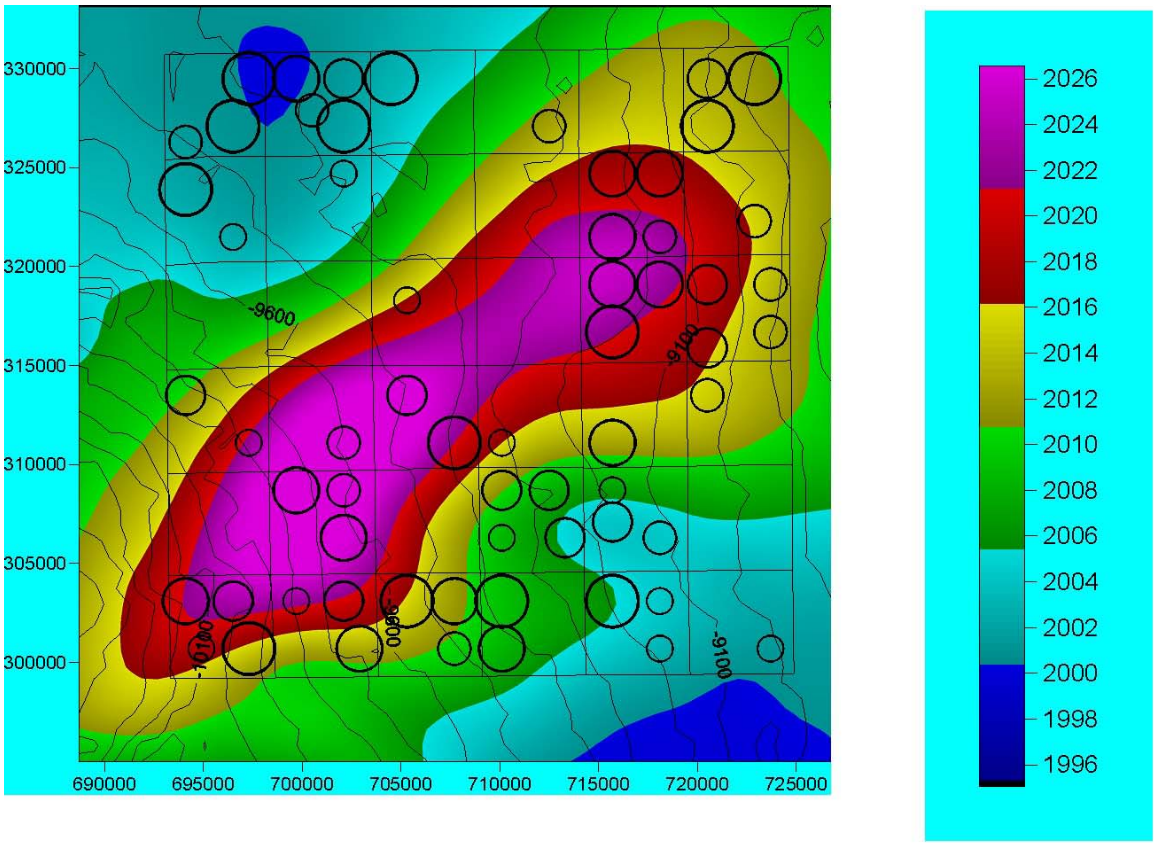


Fig. V-21. Wild Rose field—first year water production

Structural Modeling

To analyze the impact of the deep Laramide displacements on the reservoir horizon we constructed a geomechanical model of the deep basement fault system (fig. V-7). From the model we created a map of estimated shear stress at the Almond level (fig. V-22).



Structure contours at the Almond level are shown superimposed on shear stress, estimated from boundary element modeling of the deep Paleozoic fault system. The open circles represent fracture permeability rank (larger is better). Only the central NE-SW fault system was modeled, resulting in the NW and SE quarters of the township containing no valid stress values. The purple area (dark center area) represents maximum concentration of shear stresses along fault trend at Almond level.

Fig. V-22. Projected Laramide shear stresses at Almond level

Not surprisingly, the distribution of the simulated shear stresses generally follows the northeast southwest corridor delineated by the water production and simulator permeabilities.

Structural geometries, water production, and simulator match permeabilities all support a northeast-southwest structural grain across the demonstration area. Time slices of the confidential seismic data and small deflections of the structure contours indicate the presence of small scale, small displacement shear zones traversing the demonstration area along the general corridor of the simulated shear stress maxima. At least one source of unwanted water production in this area is related to subseismic (resolution) fault systems.

Vertical Mineralogical Trend

Another aspect of the Wild Rose demonstration area is a vertical mineralogical trend. Yin and Surdam (1994) characterized Almond and Ericson sandstones petrographically and mineralogically from cores taken around the GGRB. They found the Almond to be significantly more feldspar rich than the Ericson. Two-direction whole core permeability data (presented in Appendix D) demonstrates the extreme sensitivity of the Ericson core to stress release microfracturing versus other units, including the Almond.

In the Wild Rose area, the sandstone maturity (increasing quartz content) improves downward through the Almond intervals to the Ericson. Permeability is likely to parallel this trend, increasing with depth. Traditionally this was considered a positive but as the saturation calculations from the petrophysics study show, gas saturation decreases with depth, particularly below the more significant coal units. An increasing permeability trend in the face of decreasing gas saturation may not be desirable if the objective is to avoid water production.

Production Validation

The operator ran only one production log for the Wild Rose demonstration area. A simple log montage of this production log, a TDT log, and the mudlog was constructed and is available in Appendix F. Water-gas ratios for the fluid gas influx at each perforation are shown in Table V-3.

Table V-3. Water-gas ratios for fluid gas influx at each of 9 perforation sets

Perforation Set	Depth	Water Rate (Bbls/d)	Gas Rate (Mcfd)	Water-Gas Ratio
1	**9550**	**0**	**12**	**0.000**
2	**9600**	**1.8**	**121**	**0.015**
3	**9640**	**19.8**	**1463**	**0.014**
4	**9690**	**12.8**	**81**	**0.158**
5	**9730**	**2.7**	**20**	**0.135**
6	**9750**	**1.1**	**15**	**0.073**
7	**9790**	**0**	**6**	**0.000**
8	**9830**	**0**	**2**	**0.000**
9	**>9900**	**4.6**	**31.7**	**0.145**

Nine intervals were perforated across approximately 400 feet of the Almond reservoir. Three out of nine perforated intervals in this well flow at a water gas ratio ten-fold higher than the other six. Perforation sets 4, 5,and 9 produce less than 10% of the gas and nearly 50% of the water. Perforation sets 1, 2 and 3 yield 91% of the gas and 50% of the water. Visual examination of the TDT log (log panel in Appendix F) does not suggest major differences in sand quality across the interval yet a single perforation zone makes four times the gas rate as all other zones combined at only a tenth of the water-gas ratio of the lower zones.

Our petrophysical study projected the salinity/gas-water boundary (GWB) interface to be at approximately 9,800-feet MD in this well. Based on that projection, the lower zone at 9,900 feet is most likely a low-gas saturation, quartz-rich, high-permeability lower Almond sand. The low-gas rate, low-water ratio zones 7 and 8 reflect tight, low permeability reservoir rock and zones 4, 5 and 6 are transitional, with permeability to both gas and water. Zone 3 has a conspicuously high flow rate but low water gas ratio. It most likely represents a natural fracture zone. Zones 1 and 2 are low permeability zones high in the gas column, right beneath the Lewis Shale.

Lack of openhole logs precludes solid confirmation of this production scenario. It does display potential interpretations upon which a water avoidance strategy based on selective completion could be built and executed within an operational program. A consistent data collection policy would enable such strategies to be implemented.

Water Remediation Strategies

In the demonstration area simulation unwanted water was produced when higher permeability intervals were encountered and perforated in zones with low gas saturation. We found no pervasive irreducible gas saturation settings within the Wild Rose area that uniformly produce gas at low water-gas ratios. This was indicated by the presence of a generally identifiable salinity boundary that coincides with increased gas saturations in the upper few hundred feet of the Almond formation.

This salinity boundary does not correspond directly to structure. On openhole electric logs this boundary presented as a saline SP log deflection. (For other indicators see Appendix E, Petrophysical section.) With additional calibration, the boundary may be identifiable on TDT logs. Thus, in new wells the boundaries should be identified and completion operations planned accordingly.

To understand the salinity boundary with respect to stratigraphy, formation waters will be routinely sampled during completion operations. Periodic flow tests prior to hydraulic fracture completion operations may yield fluids for Rw analysis. This will improve petrophysical pay determinations and reduce completion of highly permeable, low gas saturation zones.

Quartz and calcite rich reservoir intervals are particularly susceptible to developing permeability to water. The large thermal expansion coefficients of quartz and calcite contribute to the development of large aperture grain-bounding microfractures during uplift. Large pore throats create low capillary entry pressures and increase mobility of fluids.

Quartz content of Mesaverde sediments peaks in the delta plain fluvial facies (lower Almond channels and Ericson formation). These units are also more likely to contain relatively fresh formation water, complicating gas saturation determinations. Based on the results presented here, these units are at high-risk of low-gas saturation coupled with high permeability to water.

To avoid completion of high permeability, low gas saturation zones in these intervals, we recommend perforation followed by flow testing. While not specifically investigated here, we hypothesize that these units also have lower internal stresses that could cause hydraulic fractures to propagate towards them. Even a modest program of stress determination and hydraulic fracture mapping, early in a development program, could avoid or ameliorate such issues.

Unwanted water production from natural fracture zones occurring low in a low-saturation gas zone is another significant menace identified during this study. These zones are identifiable by their extremely high permeabilities. We advocate two strategies for managing this setting: (1) avoidance or (2) capture.

Avoidance Strategy for Small Scale Faulting

Our proposed strategy for avoiding small scale faulting is to identify and avoid them prior to drilling. Throughout the Wild Rose demonstration area there are small-scale fault zones at or below the effective resolution of seismic. We believe the primary producing perforation in the Wamsutter Rim 15-2 (discussed earlier) is such a zone. Typically these fault zones are highly permeable, and when optimally located within the gas column, very prolific gas producers. However, when located in a transitional or low gas saturation zone they can be a significant economic drag on the well.

An attempt was made during this project to construct detailed fault maps within the Almond reservoir interval. Stratigraphic complexity and low seismic frequency content were major barriers to successfully completing this effort. The Colorado School of Mines Reservoir Characterization Project (RCP) has demonstrated the use of an automated fault-picking software package (Ant Tracker Algorithm™, Schlumberger) for interpreting small-scale faults within reservoir volumes (supplemented with human editing). In the future such a semi-automated process might be an effective tool in finding and avoiding small-scale fault zones. Seismic resolution will likely remain a challenge because velocity or other issues may preclude the level of accuracy required to intersect or avoid a 50-foot discontinuity at 10,000 feet subsurface.

Capture Strategy for Small Scale Faulting

A second strategy to address the issue is to capture the permeability fabric of the unanticipated small scale fault. Most natural small-scale faults contact significantly more reservoir than man-made hydraulic fractures. If this were not the case hydraulic fractures would consistently perform much better, and more consistently.

Significant downspacing of an area substantially increases the subsurface sampling. Thus downspacing offers the opportunity to perform detailed subsurface mapping if appropriate information and logs are obtained and analyzed. While there were no image logs available for this study, our experience suggests consistent image log collection during the downspacing program offers the opportunity to map fracture zones directly, developing detailed maps of their geometry.

Highly detailed fault maps would enable the deliberate intersection of these extremely permeable zones at the optimal point in the reservoir. While is it projected that the rate of return could increase, an economic analysis of each location would substantiate the value.

CONCLUSION

Oil and gas exploration and development are progressive processes that are hugely dependent on historical data and experience for successful results. Data pertaining to the chemical and electrical properties of intra-formational waters is also crucial but has been difficult to effectively access. This is no longer the case as a primary output of this project is a robust database amassing thousands of formation water analyses.

Digital Database and Atlas

The *digital database* provides data with dynamic value for operators to increase gas production from key Rocky Mountain basins, without significant additional overhead. Along with electric logs, core, and seismic, the database becomes yet another valuable tool for maximizing production.

A *digital atlas* showing the distribution of the data and some specific analyses has been constructed using ArcReader to increase the usability of the database. The digital atlas has query and limited mapping capability for users without ready access to Geographic Information Systems (GIS) software.

Applications

Beyond the database however, this project has demonstrated techniques of interpretation and applications of the formation water data to identify and solve common exploration and production (E&P) issues. The tools, techniques and strategies presented here have potential for impacting secondary porosity prediction, formation evaluation, and development strategies.

1. Secondary Porosity Prediction

Formation water geochemistry is an indicator of the in situ diagenetic system. The chemical compositions of subsurface waters can be interpreted within the context of their host sediments to reveal anomalies of potential significance. For example, local variations in ion saturation indices can reflect inter-formational water movement with significant implications for secondary porosity development.

2. Formation Evaluation

Vertical and lateral formation water resistivity changes are common. Collecting water samples for Rw and using the information in log interpretation will improve pay determination and completion decisions.

Bulk system permeabilities are often underestimated. Bulk reservoir permeabilities determined through reservoir simulation can be many times greater than those initially estimated through petrophysical studies alone. (Bottom hole build up pressure tests also show bulk reservoir permeabilities, but were not within the scope of this project.)

3. Development Strategies

Perforation Strategy

Avoid completion of high permeability low gas saturation zones. In higher risk intervals, we recommend perforation followed by flow testing. While not specifically investigated here, we hypothesize that these units also have lower internal stresses that could cause hydraulic fractures to propagate toward the high-permeability unit. Even a modest program of stress determination and hydraulic fracture mapping, early in a development program, could avoid or mitigate such issues.

Avoidance Strategy for Small Scale Faulting

Identify and avoid small-scale faults prior to drilling. Throughout most tight gas reservoirs there are small-scale fault zones at or below the effective resolution of seismic. We believe the primary producing perforation in the Wamsutter Rim 15-2 (discussed earlier) is such a zone. Typically these fault zones are highly permeable, and when optimally located within the gas column, very prolific gas producers. However, when located in a transitional or low gas saturation zone they can be a significant economic drag on the well. In the future semi-automated fault-picking processes might be an effective tool in finding and avoiding small-scale fault zones.

Capture Strategy for Small-Scale Faulting

Capture the dynamic value of the drilling program. Most natural small-scale faults contact considerably more reservoir than man-made hydraulic fractures. Significant downspacing of an area substantially increases the subsurface sampling. Thus downspacing offers the opportunity to perform detailed subsurface mapping. Consistent image log collection during the downspacing program allows for identifying fracture zones directly, and developing detailed maps of their geometry. This would enable the deliberate intersection of these extremely permeable zones at the optimal point in the reservoir.

Future Research

A key result of this project is an integrative conceptual gas reservoir development model. This model encompasses diverse views within a single developmental continuum. Effective tight gas reservoir development is the result of a dynamic process with multiple essential ingredients:

- The original sedimentary provenance
- The proper mix of depositional systems and facies
- A strong history of *burial* and *uplift*

It follows from the conceptual model that:

Generation of increasing reservoir permeability is a natural by-product of stress release during uplift. Gas sweet spots form in traps delineated by strain fields or ductility contrasts. Understanding the natural process of sweet spot development—by stress release and concentration of gas in traps formed by strain fields and/or ductility contrasts—offers options for manmade replication through engineering technologies.

A prime example is cavitation, used commonly in coalbed methane plays and less commonly in conventional reservoirs to increase permeability around a wellbore (1999 Palmer). During cavitation completions, a large volume of rock material is removed from the reservoir creating a cavity or void space. The cavity accentuates the normal disturbance of the local in situ stress field created by the wellbore. Under favorable conditions shear failure occurs in the rocks surrounding the cavity and fractures propagate away from the wellbore into the reservoir. The shear fractures improve production by creating permeability conduits and increasing the effective wellbore radius.

By creating room for expansion of the rocks themselves, the cavitation technique might also initiate stress release and associated permeability increases in the rocks surrounding the well. Speculation suggests development of the cavity should parallel the natural process of permeability enhancement during uplift and allow the gas and water to self-segregate. Developing the practical methods of deliberately inducing such events in tight gas sands will require additional research.

The uplifted gas basins of the Rocky Mountains have large volumes of gas trapped in low-saturation, low-permeability settings, outside established field areas. Where hydraulic fracturing techniques improve connection to a reservoir, effective application of cavitation (or similar) techniques may not only improve connectivity *they may actually increase local permeability in the reservoir and release trapped gas*.

Developing the technology to proactively create the conditions for increased permeability of these reservoirs and allowing the gas to segregate itself in situ and flow into the wellbore for recovery would capture the full dynamic value of the large resource base and should be considered a long term research goal.

REFERENCES

Advanced Resources International, Inc. 1993. Well equipment design plans for the Shenyang General Gas Corporation. *Shenbei Pilot Well* no. 3: 21 and appendices.

Aguilera, Roberto and M.S. Aguilera. 2002. The integration of capillary pressures and Pickett plots for determination of flow units and reservoir containers. *SPE Reservoir Evaluation & Engineering* 5-6: 465-471.

Aguilera, Roberto, and Luis A. Acevedo. 1981. Computerized process for interpretation of well logs in naturally fractured reservoirs. *AAPG Bulletin* 65: 1495.

Aguilera, Roberto. 1981. Exploring for naturally fractured reservoirs-a petroleum engineer's point of view. *AAPG Bulletin* 66: 242.

Aguilera, Roberto. 1988. Determination of subsurface distance between vertical parallel natural fractures based on core data. *AAPG Bulletin.*72-7: 845-851.

Aguilera, Roberto. 2002. Incorporating capillary pressure, pore throat aperture radii, height above free-water table, and Winland R (sub 35) values on Pickett plots 86-4: 605-624.

Aguilera, Roberto. 2003. Geologic and engineering aspects of naturally fractured reservoirs. *Canadian SEG Recorder (Feb):* 44-19.

Ali, Maqsood et al. 1998. Extracting maximum petrophysical and geological information from a limited reservoir database. In Reservoir characterization-recent advances, ed. R. Schatzinger and J. Jordan. *AAPG Memoir*. no. 71:191–208.

Ammer, James R. et al. 2000. Technology for increased production from low-permeability gas reservoirs: An overview of U.S. DOE's gas program-successes and future plans. Paper presented at 2000 SPE Rocky Mountain Regional/Low Permeability Reservoirs Symposium and Exposition. 12-15 March, at Denver, CO. *SPE* no. 60310: 1-15.

Anderson, E.M. 1951. *The Dynamics of Faulting and Dyke Formation with Applications to Britain*. 2nd edn., Edinburgh, Oliver and Boyd.

Antonelli, Marco and Atilla Aydin. 1995. Effect of faulting on fluid flow in porous sandstone: geometry and spatial distribution. *AAPG Bulletin* 79-5: 642-671.

Apel, R. , K. Fuchs and Mark D. Zoback. 1993. Drilling-induced tensile fractures in the KTB pilot hole. *SPWLA Log Analyst (March-April)* 34-2: 48-49.

Aplin, A. C., E. A. Warren, S. M. Grant and A. G. Robinson. 1993. Mechanisms of quartz cementation in North Sea reservoir sands: constraints from fluid compositions. In Diagenesis and basin development, ed. A.S. Horbury and A. G. Robinson. *AAPG Studies Geology* no. 36:7-23.

Baltz, Elmer H. 1967. Stratigraphy and regional tectonic implications of part of upper cretaceous and tertiary rocks, east-Central San Juan basin, New Mexico. *U.S. Geological Survey Professional*. no. 552:1-101.

Barker, Charles E. 1990. Rock-evaluation analysis of sediments and ultimate analysis of coal, Mesaverde group multiwell experiment site, Piceance basin, Colorado. In Geology of tight gas reservoirs in the Pinedale Anticline area, Wyoming and at the multiwell experiment site, Colorado, ed. B.E. Law and C.W. Spencer. *USGS Bulletin* no.1886: N1-N11.

Barker, Collin and Brian Horsfield. 1982. Mechanical versus thermal cause of abnormally high pore pressures in shales. *AAPG Bulletin* 66-1: 99-100.

Barton, Colleen A. and Daniel Moos. 1988. Analysis of macroscopic fractures in the Cajon Pass scientific drillhole: over the interval 1829-2115 meters. *American Geophysical Union (AGU) Geophysical Research Letters (August supplement)* 15-9: 1013-1016.

Barton, Colleen A. and M.D. Zoback. 1990. Self-similar distribution of macroscopic fractures at depth in crystalline rock joints. In *Proceedings of the International Symposium on Rock Joints, 4-6 June at Loen, Norway*, ed. N. Barton and O. Stephansson, pub. A.A. Balkema: 163-170.

Barton, Colleen A. and Mark D. Zoback. 1992. Self-similar distribution and properties of macroscopic fractures at depth in crystalline rock in Cajon Pass scientific drill hole. *American Geophysical Union (AGU) Journal of Geophysical Research (10 April)* 97-B4: 5181-5200.

Barton, Colleen A. and Mark D. Zoback. 1994. Stress perturbations associated with active faults penetrated by boreholes: possible evidence for near-complete stress drop and a new technique for stress magnitude measurement. *American Geophysical Union (AGU) Journal of Research (10 May)* 99-B5: 9373-9390.

Barton, Colleen A. and Mark D. Zoback. 2002. Discrimination of natural fractures from drilling-induced wellbore failures in wellbore image data-implications for reservoir permeability. *SPE Reservoir Evaluation & Engineering (June)* no. 78599: 249-254.

Barton, Colleen A., Mark D. Zoback and Daniel Moos. 1995. Fluid flow along potentially active faults in crystalline rock. *Geology (Aug)* 23-8: 683-686.

Baumgartner, J. and M.D. Zoback. 1989. Interpretation of hydraulic fracturing pressure-time records using interactive analysis methods. *International Journal of Rock Mechanics & Mining Sciences & Geomechanics Abstracts* 26-6: 461-469.

Billingsley, Randal L. 2001. Evolution of gas exploitation in the eastern Green River basin, Carbon and Sweetwater Counties, Wyoming, 1990-1998. In Wyoming Gas and Resources Technology, ed. Dean Stilwell. *WGA 52nd Field Conference Guidebook*: 131-147.

Billingsley, Randal L. and L. W. Evans. 1995. Old wells, new concepts and a fractured reservoir: the Amoco, Champlin 242d #1, Echo Springs Area, GGRB, Wyoming. Paper presented at AAPG Rocky Mountain Section Meeting, April, at Reno, NV: vol. 79, no. 6:915.

Billingsley, Randal L. and L.K. Smith. 2003. Identifying and remediating high water production in basin centered formations. Poster presentation at AAPG Annual Meeting, May, at Salt Lake City.

Bird, P. 1988. Kinematic history of the Laramide orogeny in latitudes 35 degrees-49 degrees N, western United States. *Tectonics* 177: 780-801.

Blackstone, D. L. Jr. 1993. The Wind River Range, Wyoming: an overview. *Wyoming Geological Association Jubilee 50th Anniversary Field Conference Guidebook*, ed. Betty Stroock and Sam Andrew: 121-140.

Bloch, S. 1993. Empirical prediction of porosity and permeability in sandstone. *AAPG Bulletin* 75-7: 1145-1160.

Bloch, S. and K.P. Helmold. 1995. Approaches to predicting reservoir quality in sandstones. *AAPG Bulletin* 79-1: 97-115.

Bolas, Nordgard, Hege Marit and Christian Hermanrud. 2002. Rock stress in sedimentary basins-implications for trap integrity, hydrocarbon seal quantification. Paper presented at Norwegian Petroleum Society (NPS) Conference. 16-18 October 2000. *NPS Special Publication* No. 11: 17-35.

Boult, J., N. Theologou and J. Foden. 1997. Capillary seals within the Eromanga basin, Australia: Implications for exploration and production. In Seals, traps and the petroleum system, ed. R.C. Surdam. *AAPG Memoir* no. 67: 143-167.

Bourne, Stephen J. and E. J.M. Willemse. 2001. Elastic stress control on the pattern of tensile fracturing around a small fault network at Nash Point, UK. *Journal of Structural Geology* 23:1753-1770.

Bourne, Stephen J. and E. J.M. Willemse. 2001. Elastic stress control on the pattern of tensile fracturing around a small fault network at Nash Point, UK. *Journal of Structural Geology* 23: 1753-770.

Bourne, Stephen J. et al. 2000. Predictive modeling of naturally fractured reservoirs using geomechanics and flow simulation. *9th ADIPEC* paper no. 0911: 1-10.

Boyd, Harold A. 1995. The Laramide orogeny and associated lithostratigraphic units, southwestern Wyoming. *WGA 1995 Field Conference Guidebook*: 313-341.

Brace, W.F. 1965. Some new measurements of linear compressibility of rocks. *American Geophysical Union (AGU) Journal of Geophysical Research* 70-2: 391-398.

Bradley, John S. 1975. Abnormal formation pressure. *AAPG Bulletin* 59-6: 957-973.

Bradley, John S. 1976. Abnormal formation pressure: reply. *AAPG Bulletin* 60-7: 1127-1128.

Branagan, P.T. et al. 1993. Horizontal gas well completion technology in the Mancos B-analysis of the Chandler & Associates Southwest Rangely Federal 8H-1-2, Rio Blanco County, Colorado. In Topical report -enhanced production from conventional resources project area, contract nos. 5091-212-2242 and 5091-212-2249. *GRI* no. 93-0037: 1-48 and appendix.

Braun, E.M. and R.F. Holland. 1995. Relative permeability hysteresis: laboratory measurements and a conceptual model. *SPE Reservoir Engineering* 10-3: 222-228.

Breckels, I.M. and H.A.M. van Eekelen. 1982. Relationship between horizontal stress and depth in sedimentary basin. *Journal of Petroleum Technology* (JPT) 34-9: 219-2199.

Bryant, Steven , Christopher Cade and David Mellow. 1993. Permeability prediction from geologic models. *AAPG Bulletin* 77-8: 1338-1350.

Bugden, Miriam H. 1990. A little information on Bridger Lake field. In Geologic resources of Summit County, Utah. *Utah Geological and Mineral Survey Public Information:* Series 7.

Burch, Donald N. and Robert M. Cluff. 1997. A volumetric analysis of Almond formation (cretaceous Mesaverde group) gas production in the Coal Gulch-Echo Springs-Standard Draw field complex, Washakie basin, southwest Wyoming. Paper presented at SPE Rocky Mountain Regional Meeting, 18-21 May, at Casper, Wyoming. *SPE* no. 38368*:* 203-215.

Burke, W. H. et al. 1982. Variation of seawater $^{87}Sr/^{86}Sr$ throughout Phanerozoic time. *Geology* 10:516-519.

Byerlee, J. D. 1971. An exact effective stress law for elastic deformation of rock with fluids. *American Geophysical Union (AGU) Journal of Geophysical Research* 76-26: 6414-6419.

Byrnes, Alan P and James W. Castle. 2000. Comparison of core petrophysical properties between low-permeability sandstone reservoirs: Eastern U.S. Medina group and Western U.S. Mesaverde group and Frontier formation. Paper presented at SPE Rocky Mountain Regional Low-Permeability Reservoirs Symposium and Exhibition. 12-15 March, at Denver, CO. *SPE*: 1-10.

Byrnes, Alan P. 1994. Measurement of dependent variables-petrophysical variables, In SEPM short Course 30: *Reservoir Quality Assessment and Prediction in Clastic Rocks*, ed. Michael D. Wilson: 231-246.

Byrnes, Alan P. 1997. Reservoir characteristics of low permeability sandstones in the Rocky Mountains. *RMAG Mountain Geologist* 34-1: 37-48.

Byrnes, Alan P. 2003. Aspects of permeability, capillary pressure, and relative permeability properties and distribution in low permeability rocks important to evaluation, damage, and stimulation. Paper presented at 2003 RMAG/PTTC Fall Symposium. In Low-Petroleum Core Petrophysics & Reservoir Assessment. *DWLS Short Course 107* (2004).

Byrnes, Alan P. and Michael D. Wilson. 1994. Measurement of independent variables-pressure, time, temperature. In SEPM Short Course 30: *Reservoir Quality Assessment and Prediction in Clastic Rocks*, ed. Michael D. Wilson: 293-309.

Byrnes, Alan P., K. Sampath and L. Randolph. 1979. Effect of pressure and water saturation on permeability of western tight sandstones. Paper presented at Fifth Annual DOE Symposium on Enhanced Oil and Gas Recovery and Improved Drilling Technology. 22-24 August, at Tulsa, OK.

Cacas, M.C., S. Sarda, B. Bourbiaux and J.C. Sabathier. 1981. How to turn the geological image of a fractured reservoir into a dual-porosity model. *AAPG Bulletin* 81-8: 1365.

Cai Dongsheng et al.2000. Structures of the Bohai petroliferous area, Bohai Bay basin. *ACTA Geologica Sinica, Geological Society of China, Special Issue* II74-3: 641-649.

Campagna, David J., John Amos and Vello Kuuskraa. 1998. The Midas touch in macro exploration. *Hart's Oil and Gas World (Feb):* 35-38.

Cannon, Jan. 2001. Gravity-tide tectonics and sedimentary basins. Paper presented at 2000 Symposium on petroleum systems of sedimentary basins in the southern midcontinent, ed. K.S. Johnson and D.F. Merriam. *Oklahoma Geological Survey Circular* 106:15-18.

Carothers, William W. and Yousif K. Kharaka. 1978. Aliphatic acid anions in oil-field waters-implications for origin of natural gas. *AAPG Bulletin* 62-12: 2441-2453.

Carpenter, A.B. and M. L. Trout. 1979. Interim report on lead and zinc in oil-field brines in the central Gulf Coast and in southern Michigan. *Am. Inst. Metall. Petroleum Engineers Preprint* 79-95:15

Castle, James W. 1998. Regional sedimentology and stratal surfaces of a lower Silurian clastic wedge in the Appalachian foreland basin. *SEPM Journal of Sedimentary Research (Nov)* 68-6: 1201-1211.

Chang, Carl , Daniel Moss and Mark D. Zoback. 1996. Anelasticity and dispersion in unconsolidated sands. *Proceedings of the EOS 1996 Fall Meeting Supplement* 77-46: F745-746.

Chapman, D.S., S.D. Willett, C. Clauser and C.B. Forster. 1998. Using thermal fields to constrain system permeability at the kilometer scale in continental crust. *American Geophysical Union (AGU) EOS Transactions* 69-44: 1187.

Chapman, Richard E. 1980. Mechanical versus thermal cause of abnormally high pore pressures in shales. *AAPG Bulletin* 64-12: 2179-2183.

Chapman, Richard E. 1982. Mechanical versus thermal cause of abnormally high pore pressures in shales: reply. *AAPG Bulletin* 66-1: 101-102.

Chapman, Richard E. 1982. Mechanical versus thermal cause of abnormally high pore pressures in shales: discussion. *AAPG Bulletin* 66-1: 101-102.

Charpentier, Ronald R., B.E. Law and S.E. Prensky. 1986. Quantitative model of overpressured gas resources of Pinedale anticline, Wyoming. *AAPG Bulletin* 70-8: 1034-1035.

Charpentier, Ronald R., B.E. Law and S.E. Prensky. 1990. Quantitative model for overpressured gas resources of the Pinedale Anticline, Wyoming . In Chapter 1: Geology of tight gas reservoirs in the Pinedale Anticline area, Wyoming and at the multiwell experiment site, Colorado, ed. B.E. Law and C.W. Spencer. *USGS Bulletin* no. 1886: I1-I13. First published in *SPE/DOE* no. 16404: 153-164.

Chawathe, Adwait A. and A. Ouenes. 1998. Interwell property mapping with Crosswell seismic attributes. *Journal of Petroleum Technology (JPT) (January)* SPE no. 3874750-1: 48-49.

Chawathe, Adwait A., A. Ouenes and W.W. Weiss. 1997. Interwell property mapping using Crosswell seismic attributes. Paper presented to SPE Annual Technical Conference and Exhibition on Formation Evaluation and Reservoir Geology. 5-8 October at Dallas, TX. *SPE* Part 2, no. 38747: 467-474.

Chawathe, Adwait A., T. Ertekin and A. Grader. 1996. Understanding multimechanistic gas-water flow in fractured reservoirs: mapping of the multimechanistic flow domain. Paper presented at SPE Annual Technical Conference and Exhibition. 6-9 October, at Denver. CO. *SPE* no. 36738: 565-577.

Chen, Quan and U.Q. Song. 2002. What is the shape of pores in natural rocks? *American Institute of Physics Journal of Chemical Physics (15 May)* 116-19: 8247 -8250.

Chidsey, Thomas C. Jr. 1999. Petroleum plays in Summit County, Utah. In Geology of northern Utah and vicinity, ed. Lawrence E. Spangler and Constance J. Allen. *Utah Geological Association Publication* no. 27: 233-256.

Cipolla, C.L., D.N. Meehan and L. Stevens. 1993. Hydraulic fracture performance in the Moxa Arch Frontier formation. Paper presented at SPE Rocky Mountain regional/Low Permeability Reservoirs Symposium. 12-14 April, at Denver, CO. *SPE* no. 25918: 1-13.

Cluff, Robert M. 2002. The origin of Jonah field: evidence for pressure leakage from sonic and resistivity log anomalies in the northern Green River basin, Wyoming. *RMAG Newsletter* 51-6: 4.

Cluff, Robert M. and Catherine M. Murphy. 1997. Upper Almond (Mesaverde group) paleoshoreline trends, eastern Green River basin, Wyoming. *American Association of Petroleum Geologists Bulletin* 81-7: 1221

Cluff, Robert M. and Suzanne G. Cluff. 1997. Log analysis of Mesaverde sandstone gas reservoirs, Piceance basin, Colorado. *AAPG Bulletin* 81-7: 1221.

Colburn, James A. 1979. Table Rock and Table Rock. Paper presented at Wyoming Oil and Gas Fields Symposium. Ed. W.A. Bradley, S.C. Champlin, J. Kennedy, O.P Miles, Jr., M.E. Smithwick and R.E. Walker. *WGA Greater Green River Basin* II: 379-383.

Collins, A.G. 1975. *Geochemistry of Oilfield Waters*. Amsterdam: Elsevier Scientific Publishing Company: 496

Comer, John B. et al.2000. Fracture prediction with a 3-D finite element diagenetic, hydrologic, mechanical model. *AAPG Bulletin* 84.

Comer, John B. et al.2001. Predicting fractured gas reservoirs using a 3-D finite element diagenetic, hydrologic, rock mechanics model, Rulison field, Piceance basin, Colorado. *AAPG Bulletin* 85.

Conner, Carol Waite. 1992. Chapter 1: The Lance formation-petrography and stratigraphy. Powder River basin and nearby basins, Wyoming and Montana. In Evolution of sedimentary basins-Powder River basin. *U.S. Geological Survey Bulletin* no. 1917: I1-I17.

Cook, Robert A. 1978. A relationship between strike-slip faults and the process of drape folding of layered rocks. In Laramide folding associated with basement block faulting in the western United States, ed. Vincent Matthews III. *GSA Memoir* no. 151: 197-214.

Corapcioglu, M. Yavuz et al. 1994. Analytical expressions to estimate the free product recovery in oil-contaminated aquifers. *American Geophysical Union (AGU) Water Resources Research (Dec)* 30-12: 3301-3311.

Corapcioglu, M. Yavuz, Kagan Tuncay, and B. Kagan Ceylan. 1996. Oil mound spreading and migration with ambient groundwater flow in coarse porous media. *American Geophysical Union (AGU) Water Resources Research (May)* 32-5: 1299-1308.

Corcoran, D.V. and A. G. Dore. 2000. Top seal assessment in exhumed basin settings—some insights from Atlantic margin and borderland basins. Paper presented at Norwegian Petroleum Society (NPS) Conference on Hydrocarbon Seal Quantification. 16-18 October. *NPS Special Publication* no. 1189: 107.

Core Laboratories. 1988. Applications of the automated core measurement system (CMS300). Pub. *Technology Applications Group*: 1-41.

Cox, D.O., V.A. Kuuskraa and J.T. Hansen. 1996. Advanced type curve analysis for low permeability gas reservoirs. Paper presented at SPE Gas Technology Conference. 28 April-1 May, at Calgary, Alberta, Canada. *SPE* no. 35595: 1-14.

Coyle, Brian J. and Mark D. Zoback. 1988. In situ permeability and fluid pressure measurements at ~2 km depth in the Cajon Pass research well. *American Geophysical Union (AGU) Geophysical Research Letters (August supplement)* 15-9: 1029-1032.

Craig, Jeff. (2003) Core Labs—pers. comm. To K. Jagiello.

Cross, T.A. 2000. Stratigraphic controls on reservoir attributes in continental strata. *Earth Science Frontiers* 7: 322-350.

Dart, Richard L. and Mary Lou Zoback. 1989. Wellbore breakout stress analysis within the central and eastern continental United States. *SPWLA Log Analyst (Jan-Feb)* 30-1: 12-25.

Dawson, William, C. and William R. Almon. 1999. Seal character and sequence stratigraphy of marine shales in Gulf-coast style basins. *AAPG Bulletin* 83-8: 1351-1352.

de Hemptinne, J-C. et al.1997. Influence of water on estimation of gas in place. *SPE Reservoir Engineering (Aug)* 12-3: 207-210.

Deimbacher, F.X., M.J. Economides and O.K. Jensen. 1993. Generalized performance of hydraulic fractures with complex geometry intersecting horizontal wells. Paper presented at SPE Production Operations Symposium. 21-23 March, at Oklahoma City, OK. *SPE* no. 25505: 19-30.

Desouky, S.E.D.M. 2003. A new method for normalization of capillary pressure curves. *Oil & Gas Science and Technology-Review* IFP 58-5: 551-556.

Devlin, W.J. et al. 1993. The effect of tectonic and eustatic cycles on accommodation and sequence-stratigraphic framework in the upper cretaceous foreland basin of southwestern Wyoming. In Sequence stratigraphy and facies, ed. G. Allen. *International Association of Sedimentologists Special Publication* no. 18: 501-520.

Dickey, Parke A. 1976. Abnormal formation pressure: discussion. *AAPG Bulletin* 60-7: 1124-1127.

Dickinson, Roger G. 1992. Table Rock field-Frontier formation an overpressured reservoir. In Rediscover the Rockies, ed. Christopher E. Mullen. *Wyoming Geological Association 43rd Field Conference Guidebook*: 139-144.

Dickinson, Warren W. 1984. Isotope geochemistry of carbonate minerals in upper cretaceous and tertiary sandstones from the Pinedale Anticline, Wyoming. In Geological characteristics of low-permeability upper cretaceous and lower tertiary rocks in the Pinedale Anticline area, Sublete County, Wyoming, ed. Ben E. Law, *USGS Open File Report* no. 84:753and no. 95: 107.

Dickinson, Warren W. 1990. Chapter F: Analysis of vitrinite maturation and tertiary burial history, northern Green River basin, Wyoming. In Geology of tight gas reservoirs in the Pinedale Anticline area, Wyoming and at the multiwell experiment site, Colorado, ed. B.E. Law and C.W. Spencer, *USGS Bulletin* no. 1886: F1-F17.

Dickinson, William R. et al. 1988. Palegeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky mountain region. *GSA Bulletin (July):* 1023-1039.

Dinwiddie, George A. 1973. hydraulic testing and sampling of water well number 2. In project wagon wheel, Sublette County. Wyoming. USGS report 474-142.

Dolenc, Max R. 1973. the ecological considerations of project wagon wheel. Paper presented at Wyoming Geological Association (WGA) 25th Annual Symposium and core Seminar on the geology and mineral resources of the Greater Green River basin, ed. Elmer. M. Schell et al, *WGA 25th Field Conference Guidebook*: 215-223.

Dott, Dr. R.J. Jr. and G. Nadon, eds. and comps. 1992. Modeling of pressure compartments in the St. Peter sandstone gas reservoir in the Michigan basin. *Gas Research Institute 93/0015*, contract no. 5089-260-1810: 1-59.

Doveton, John H. 2001. Modeling vertical changes in reservoir pore-throat microarchitecture from petrophysical logs: Implications for petroleum geology and hydraulic, geological modeling and simulation: Sedimentary systems, ed. D.F. Merriam and J.C. Davis, pub. Kluwer Academic/Plenum: 229-246

DuBois, Dean P. et al. 2003. Jonah field-new drilling, new perspectives. In SPE abstract. *WGA Contact Newsletter (Oct) L*-10: 8.

Dunn, Thomas L. et al. 1995. Cements and in situ widths of natural fractures, Almond formation. Green River basin, Wyoming: *Wyoming Geological Association 52nd Annual Field Conference Guidebook*: 255-270.

Dutton, Shirley et al. 1993. Major low-permeability-sandstone gas reservoirs in the continental United States, Texas Bureau of Economic Geology Report of Investigations, *Texas Bureau of Economic Geology*, no. 211: 221

Dyman, Thaddeas S. and James W. Schmoker. 1997. Comparison of natural gas assessments. *U.S. Geological Survey Open File Report* no. 97-445: 1-30.

Dyman. Thaddeus S., James W. Schmoker and David H. Root. 1996. Assessment of deep conventional and continuous-type (unconventional) natural gas plays in the United States. U.S. Geological Survey Open File Report no. 96-529: 1-30.

Eaton, B.A. 1969. Fracture gradient prediction and its application in oilfield operations. *Journal of Petroleum Technology (JPT)* 21-10: 1353-1360.

Eberhart-Phillips, Donna, De-Hua Han, Mark D. Zoback. 1987. Empirical relationships between seismic velocity, effective pressure, porosity and clay content in sandstone. *EOS (3 Nov)* 68-44: 1481.

Edman, Janell and Ronald C. Surdam. 1986. Organic-inorganic interactions as a mechanism for porosity enhancement in the upper cretaceous Ericson sandstone, Green River basin, Wyoming. In SEPM Special Publication: 38 roles of organic matter in sediment diagenesis, ed. Donald L. Gautier, *SEPM Special Publication* no.38: 85-109.

Edwards, Kimberly K. 1998. Evaluating the sealing capacity of two cretaceous marine shales, Denver basin, co. *AAPG Bulletin* 82-11: 2162.

Edwards, Kimberly K. et al. 1999. Seal capacity in lower and upper cretaceous shales, Denver basin, Colorado. *AAPG Bulletin* 83-7: 1182.

Edwards, Kimberly K., William R. Almon and W.C. Dawson. 1999. Evaluating the sealing capacity of the cretaceous Skull creek and graneros shales within a sequence stratigraphic framework, Denver basin, CO. *AAPG Annual Meeting Abstracts:* A37.

Ehrlich, Robert and William E. Full. (1986). Chapter 3: Sorting out geology-unmixing mixtures. In Statistical methods in earth sciences. *Mathematical Geology*: 33-46.

Eilerts, C.K., E.F. Sumner and N.L. Potts. 1965. Integration of partial differential equation for transient radial flow of gas-condensate fluids in porous structures. *SPE Journal (June):* 141-152.

El Paso Natural Gas Company. 1971. Technical studies report PNE-WW-1: Project Wagon Wheel, pub. El Paso Natural Gas Company: 1-248.

Engelder, T. 1985. Loading paths to joint propagation during a tectonic cycle: an example from the Appalachian plateau, U.S.A. *Journal of Structural Geology* 7-3 & 4: 459-476.

Engelder, T. 1990. Natural hydraulic fracturing. In *Proceedings of the International Symposium on Rock Joints, 4-6 June at Loen, Norway*, ed. N. Barton and O. Stephansson, pub. A.A. Balkema: 35-43

Engelder, T. and Mark P. Fisher. 1996. Loading configurations and driving mechanisms for joints based on the Griffith energy-balance concept. *Tectonophysics* 256:253-277.

Erlich, Robert et al. 1991. Petrography and reservoir physics I: objective classification of reservoir porosity. *AAPG Bulletin* 75-10: 1547-1562.

Evans, C.E. and E.T. Guerrero. 1979. Theory and application of capillary pressure. Paper presented at SPWLA Twentieth Annual Logging Symposium. 3-6 June. *Transactions of the SPWLA Twentieth Annual Logging Symposium* II: MM1-MM20.

Evans, J.C. and R. Ehrlich. 1992. A comparison between polytopic vector analysis and empirical orthogonal function analysis for analyzing quasi-geostrophic potential vorticity. *American Geophysical Union (AGU) Journal of Geophysical Research* 97-C2: 2365-2378.

Evans, Lesley and Leif Colson. Pers. comm to Schlumbeger

Fagan, Joseph P., Jr. 1996. Reinterpreting the Pinedale anticline in the Green River basin: implications for future hydrocarbon exploration. *AAPG Bulletin* 80-6: 969.

Fatt, I. 1956. Technical paper 4272: the network model of porous media. In Part. I: Capillary pressure characteristics. *Petroleum Transactions of AIME* 207: 144-159.

Fatt, I. 1956. Technical paper 4272: the network model of porous media. In Part. II: Capillary pressure characteristics. *Petroleum Transactions of AIME* 207: 160-163.

Fatt, I. 1956. Technical paper 4272: the network model of porous media. In Part. III: Capillary pressure characteristics. *Petroleum Transactions of AIME* 207: 164-177.

Finch, R.W., W.W. Aud and J.W. Robinson. 1997. Evolution of completion and fracture-stimulation practices in Jonah field, Sublette County, Wyoming. In Innovative applications of petroleum technology in the Rocky Mountain area, ed. Edward B. Coalson, John C. Osmond and Eugene T. Williams. *RMAG*: 13-24.

Finkbeiner, Thomas R. and Mark D. Zoback. 1997. Characterization of stress orientation and magnitude in the south Eugene island field, Gulf of Mexico. *Proceedings of EOS 1997 Fall Meeting Supplement* 78-46: F704.

Finkbeiner, Thomas R. et al. 1996. Least principal stress, pore pressure and overburden in plio-pleistocene strata of the south Eugene island 330 field, Gulf of Mexico. *Proceedings of EOS 1996 Fall Meeting Supplement* 77-46: F642.

Finkbeiner, Thomas R. et al. 2001. Stress, pore pressure, and dynamically constrained hydrocarbon columns in the south Eugene Island 330 field, northern Gulf of Mexico 85-6: 1007-1031.

Finkbeiner, Thomas R., Coleen A. Barton and Mark D. Zoback. 1997. Relationships among in situ stress, fractures and faults, and fluid flow: Monterey formation, Santa Maria basin, California. *AAPG Bulletin (Dec)* 81-12: 1975-1999.

Finkbeiner, Thomas R., Colleen A. Barton and Mark D. Zoback. 1996. Relationship between in situ stress and fractures and faults in the Monterey formation, Santa Maria basin, California. AAPG 1996 Annual Meeting Abstracts: A45.

Finley, Robert J. 1984. Geology and engineering characteristics of selected low-permeability gas sandstone: A National Survey. *Texas Bureau of Economic Geology Report of Investigations* no. 138.

Finneran, Joseph M. and Y. Keith Bally. 1999. Petrophysical characteristics of an emerging giant gas province: the Columbus basin southeast Coast of Trinidad. *AAPG Bulletin* 83-8: 1312.

Firoozabadi, Abbas and Jan Hauge. 1990. Capillary pressure in fractured porous media*. Journal of Petroleum Technology (JPT)* 42-6: 784-791.

Flemings, Peter B., Mark D. Zoback and Roger N. Anderson. 1996. State of stress in a plio-pleistocene Gulf Coast growth fault: implications for fracture driven fluid flow. *AAPG Annual Meeting Abstracts:* A46-A47.

Flemings, Peter, B. et al. 2002. Flow focusing in overpressured sandstones: theory, observations, and applications. *American Journal of Science (Dec)* 302-10: 827-855.

Flores, Romeo M. and C.W. Keighin. 1993. Reservoir anisotropy and facies stratigraphic framework in the Paleocene Fort Union formation, Western Wind River basin, Wyoming. Paper presented at Special Symposium on Oil and Gas and Other Resources of the Wind River Basin, Wyoming, 14-17 August at Casper, WY. William R. Keefer. William J. Metzger and Larry H. Godwin, ed. *Wyoming Geological Association Guidebook*: 121 –141.

Flores, Romeo M., C.W. Keighin and S.B. Roberts. 1994. Road log and general geology of the Wind River basin. In Wyoming in organics and the Rockies field guide, ed. R.M. Flores, K.T. Mehring, R.W. Jones and T.L. Beck. *Wyoming State Geological Survey Public Information Circular* No. 33: 39-52.

Flores, Romeo M., C.W. Keighin and William R. Keefer. 1991. Basin-wide architecture of sandstone reservoirs in the fort union formation, Wind River basin, Wyoming. *AAPG Bulletin* 75-6: 1126.

Flores, Romeo M., C.W. Keighin, and W.R. Keefer. 1992. Paleodepositional dip perspective of fort union sandstone reservoir architecture, Wind River basin, Wyoming. *AAPG Bulletin* 76-8: 1258-1259.

Gas Research Institute (GRI) 2001. Natural Gas Supply-Project Advisor Group Meeting. *Coalbed methane project area*. 16-18 September, at Colorado Springs. CO.

Gas Research Institute (GRI). 1989. Coalbed methane development in AL: Biomonitoring of produced water discharge from the Cedar Cove degasification field, AL. *Final Report (June 1989), GRI-89/0073*: 195

Gas Research Institute (GRI). 1990. Minutes of Devonian Gas Shales Project Advisors Group, 29-30 November, at Chicago. IL.

Gas Research Institute (GRI). 1991. Coalbed methane potential of the Greater Green River, Piceance, Powder River and Raton basins: geologic and hydrologic overview. Paper presented at GRI Session, 4 September, at Austin. TX.

Gas Research Institute (GRI). 1991. Distribution of natural gas and reservoir properties in the continental crust of the U.S. Paper presented at GRI Coalbed Methane Workshop. October 1991, at Pittsburgh, PA. *Final Report June 15. 1988-June 15. 1989*.

Gas Research Institute (GRI). 1991. SPE Rocky Mountain Regional/Low Permeability Reservoir Symposium, 14-April.

Gas Research Institute (GRI). 1993. Coalbed methane open-hole cavity completion. Paper presented at GRI Coalbed Methane Workshop. 25 April at Denver, CO.

Gas Research Institute (GRI). 2000. Multi-disciplinary analysis of tight gas sandstone reservoirs, Almond formation, Siberia Ridge, Wyoming. Contract #5094-210-3021.

Geoquest - Core Petrophysics, Inc. 1998. Siberia Ridge no. 5-2. *Special core analysis study*: file no. 8-980731-1.

Goolsby, Steven M., Edward B. Coalson and Mark H. Franklin. 1994. Petrophysical constraints in the evaluation of hydrodynamic and capillary pore-throat traps. *AAPG Annual Meeting Abstracts:* 157.

Gosnold, William D. Jr. 1991. Subsurface temperatures in the northern Great Plains, In Chapter 27: Neotectonics of North America, Eds. D. Burton Slemmons, E.R. Engdahl, Mark D. Zoback and David D. Blackwell *Geological Society of America*: 467-472.

Graue, Arne. 2001. Impacts of wettability on oil recovery in fractured reservoirs. Presentation made to Rice University SPE Student Chapter on Jan. 30, 2001. Available from http://www.ruf.rice.edu/~spe/Files/Newsletter00_01.pdf: INTERNET.

Grauls, Dominique, Frederic Pascaud and Thierry Rives. 2002. Quantitative fault seal assessment in hydrocarbon-compartmentalised structures using fluid pressure data. hydrocarbon seal quantification. Paper presented at Norwegian Petroleum Society (NPS) Conference16-18 October, *NPS Special Publication* no. 11141:156.

Gray, David et al. 2003. Fractured reservoir characterization using avaz on the Pinedale anticline, Wyoming. *Canadian Society of Exploration Geophysicists (CSEG) Recorder (June):* 40-47.

Gray, Donald H., Irving Fatt and Gabriella Bergamini. 1963. The effect of stress on the permeability of sandstone cores. *SPE Journal (June):* 95-100.

Greenfield, Harvey et al. 1981. Resource evaluation and production research on tight sands in the Pinedale unit, Sublette County, Wyoming. *GRI Contract No. 5080-321-0328 Final Report* no. 81-0049: appendices, core descriptions and well data on Mesa unit #1 (sec 7 32N 109W) & Mesa unit #2 (sec16 32N 109W).

Gretener, Peter E. 1991. The fractured reservoir—a new definition. Paper presented at the 1st Archie Conference on the Integration of Geology, Geophysics and Petroleum Engineering in Reservoir Delineation, Description and Management. 22-25 October 1990 at Houston. TX. Comps. Robert M. Sneider; Wulf Massell; Rob Mathis; Dennis Loren and Paul Wichmann. *AAPG Expanded Abstract*: 197-201.

Grollimund, Balz et al. 2001. Stress orientation, pore pressure and least principal stress in the Norwegian sector of the North Sea. *Petroleum Geoscience* 7-2: 173-180.

Grout, Marilyn A. and Earl R. Verbeek. 1992. Joint-history summary and orientation data for upper cretaceous sandstones. Rawlins and Rock Springs uplifts, Washakie basin, southern. Wyoming. *U.S. Geological Survey Open File Report* no. 92-388: 1-30.

Guidish, T.M. et al. 1985. Basin evaluation using burial history calculations: an overview. *AAPG Bulletin* 69-1: 92-105.

Gutierrez, M. L.E. Oino and R. Nygard. 2000. Stress-dependent permeability of a de-mineralised fracture in shale. *Marine and Petroleum Geology* 17-8: 895-907.

Guyatt, R.C.P. and J.P. Allen. 1996. Application of horizontal wells to a tight-gas sandstone reservoir: a case history. *SPE Reservoir Engineering (Aug)* 11-3: 203-209.

Gwilliam, William J. and Betty Felber, comps. 1999. Technology options for producer survival. *1999 Oil and Gas Conference Proceedings* (28-30 June, at Dallas, TX): agenda and abstracts.

Gwynn, J. Wallace. 1995. Resistivities and chemical analyses of selected oil and gas field. water well. and spring waters, Utah. In Dakota water analyses in Bridger Lake field. *Utah Geological Survey Circular*: 87.6.

Hammond, D.E., B.W. Leslie and T.-L. Ku. 1988. 222RN concentrations in deep formation waters and the geohydrology of the Cajon Pass borehole. *American Geophysical Union (AGU) Research Letters (August supplement)* 15-9: 1045-1048.

Hanor, J.S. 1987. The origin and migration of subsurface sedimentary brines. *SEPM Short Course Notes*, no. 21:247.

Harstad, Hugo, Lawrence W. Teufel and John C. Lorenz. 1995. Characterization and simulation of naturally fractured tight gas sandstone reservoirs. *SPE* no. 30573: 437-446.

Hart, C.M. et al. 1987. Fracture diagnostics results for the first multiwell experiment's Paludal zone stimulation. *SPE Formation Evaluation* 2-3: 320-325.

Hartmann, Dan J. and Logan MacMillan 1992. Petrophysics of the Wasatch formation and Mesaverde group. natural Buttes producing area, Uinta basin, Utah. : hydrocarbon and mineral resources of the Uinta basin, Utah and Colorado. Eds T.D. Fouch, V.F. Nuccio and T.C. Chidsey, Jr. *Utah Geological Association Guidebook* no. 20:175-188.

Heasler, Henry and Ronald C. Surdam. 1992. Pressure compartments in the Mesaverde formation of the Green River and Washakie basins, as determined from Drill Stem test data in Rediscover the Rockies. Christopher E. Mullen, ed. *Wyoming Geological Association 43rd Field Conference Guidebook*: 207-220.

Held, Rudolf J., and Michael A. Celia. 2001. Modeling support of functional relationships between capillary pressure, saturation, interfacial area and common lines. *Advances in Water Resources (Feb-Mar)* 24-3 & 4: 325-343.

Helset, Hans Martin et al. 2002. The role of diagenesis in the formation of fluid overpressures in clastic rocks, hydrocarbon seal quantification. Papers presented at Norwegian Petroleum Society (NPS) Conference. 16-18 October 2000. *NPS Special Publication* no. 11: 37-50.

Hendricks, Michael L. 1994. Ravinement surface control on hydrocarbon accumulation in transgressive systems tracts: Almond formation, Green River basin. In Wyoming uniformity-related hydrocarbons in sedimentary sequences. Eds. John C. Dolson, Michael L. Hendricks and William A. Wescott. *RMAG Guidebook for Petroleum Exploration and Exploitation in Clastic and Carbonate Sediments*: 209-218.

Hendricks, Michael L. 1995. A review of the components and controls on basin-centered gas in the Greater Green River Basin, southwestern Wyoming. In Resources of southwestern Wyoming, Richard W. Jones, ed. *WGA 1995 Field Conference Guidebook*: 203-215.

Henry Maria W., et al. 2005. Practical utilization of a regional water chemistry database to improve resource assessment and formation evaluation in low permeability reservoirs of Southwestern Wyoming. Paper presented at AAPG Hedberg Conference: Understanding, Exploring and Developing Tight Gas Sands, April, at Vail, CO.

Higgs, Nigel G and John S. Bradley (1993) pers. comm to R. Billingsley

Hilchie, Douglas W. 1982. Chapter 2: Solutions to problems. *Resistivity, Applied Openhole Log Interpretations (for geologists and engineers):* 2-1-2-14.

Hill, Bradley G. and S. Robert Bereskin, eds. 1993. Oil and gas fields of Utah, In Information on some GGRB fields (Lucky Ditch, Lodgepole, Elkhorn) in Utah. *Utah Geological Association Publication* no. 22.

Hinckley, Bern S. and Henry Heasler. 1987. Geothermal resources of the Wind River basin. *Wyoming Geological Association Report of Investigations*: no. 38

Hitchon, B. and I. Friedman. 1969. Geochemistry and origin of formation waters in the western Canada sedimentary basin – I. stable isotopes of hydrogen and oxygen. *Geochimica et Cosmochemica Acta* 33:1321-1350.

Hitchon, B. and M. Brulotte. 1994. Culling criteria for “standard” formation water analyses. *Applied Geochemistry* 9:637-645.

Hoak, T.E. and A.L. Klawitter. 1995. Delineation of Piceance basin basement structure using multiple source data: implications for fractured reservoir exploration. Paper presented at INTERGAS '95 Conference. 15-19 May, at University of AL, Tuscaloosa, AL: paper no. 9515: 53-95.

Holt, R.M. 1999. Reservoir stress path: evaluation of core and field data. In Proceedings of the 37th U.S. Rock Mechanics Symposium, 6-9 June 6-9 at Vail, CO. Eds. Bernard Amadei, Robert L. Kranz, Gregg A. Scott and Peter H Smeallie. *Rock Mechanics for Industry* 2: 1195-1202.

Holzhausen, G., P. Branagan, H. Egan and R. Wilmer. 1989. Fracture closure pressures from free-oscillation measurements during stress testing in complex reservoirs. *International Journal Rock Mechanical Mineral Science & Geomechanical* Abstract 26-6: 533-540.

Horn, B.W. et al. 2001. Stratigraphic controls on reservoir strata: a comparison of fluvial and tidal reservoirs in the Almond formation, Coal Gulch, Wamsutter, Echo Springs and Table Rock fields, Washakie basin, Wyoming, ed. Dean Stilwell. *Wyoming Gas and Resources Technology (WGA) 52nd Field Conference Guidebook*: 149-161.

Huang, Yaduo, P.S. Ringrose and K.S. Sorbie. 1995. Capillary trapping mechanisms in water-wet laminated rocks. *SPE Reservoir Engineering* 10-4: 287 -292.

Hurley, N.F. and R. Budros 1990. Albion-Scipio and Stoney Point fields, U.S.A, Michigan Basin. In American Association of Petroleum Geologists Treatise of Petroleum Geology Atlas of Oil and Gas Fields. *Stratigraphic Traps* I: 1-29.

Ito, Takatoshi and Mark D. Zoback. 2000. Fracture permeability and in situ stress to 7 km depth in the KTB scientific drillhole. *American Geophysical Union (AGU) Research Letters* (1 April) 27-7: 1045-1048.

Iverson, W. P. and R. C. Surdam. 1995. Tight gas sand production from the Almond Formation, Washakie Basin, Wyoming. Paper presented at SPE symposium, Rocky Mountain Regional/Low-Permeability Reservoir at Denver, CO. 20-22 March: SPE paper 29559:163-176.

Iverson, William, Thomas L. Dunn and Ronald Surdam. 1995. Improvements to formation evaluation, Almond formation, Green River basin, Wyoming. *1995 Wyoming Geological Association Field Conference Guidebook*: 271-279.

Jacques, A.G. 1997. Petrophysical input to simulation: derive rock type maps from log water saturations and capillary pressure data. *SPWLA 38th Annual Logging Symposium, 15-18 June*: U1-U14.

Jaworoski, Cheryl and Robert Simon. 1995. Relating fractures in the eastern Greater Green River basin to oil and gas fields: integrating field measurements, linear features, and digital geologic data. *Wyoming Geological Association (WGA) 1995 Field Conference Guidebook*: 61-75.

Jelmert, T.A. and H. Selseng. 1998. Horner plot aids analysis in stress-sensitive reservoirs. *Oil & Gas Journal* (29 June) 96-26: 67-68, 77.

Jelmert, T.A. and H. Selseng. 2000. Technique characterizes permeability of stress-sensitive reservoirs. *Oil & Gas Journal (12 June)* 98-24: 52, 54, 56, 60, 62.

Jenkins, Carl E. 1955. Pinedale Anticline, Sublette County, Wyoming. In Green River basin. *Wyoming Geological Association (WGA) 10th Annual Field Conference Guidebook*: 155.

Jennings, James B., Herbert B. Carroll and Clarence J. Raible. 1981. The relationship of permeability to confining pressure in low permeability rock. Paper presented at 1981 SPE/DOE Symposium on Low Permeability Gas Reservoirs. 27-29 May, at Denver, CO. *SPE/DOE Proceedings* paper no. 9870: 391-398.

Jiao, Zun Sheng and Ronald C. Surdam. 1993. Low-permeability rocks, capillary seals, and pressure compartment boundaries in the cretaceous section of the Powder River basin. Eds. Betty Stroock and Sam Andrew Wyoming. *Geological Association (WGA) Jubilee 50th Anniversary Field Conference Guidebook*: 297-310.

Johnson, A. 1987. Permeability averaged capillary data: a supplement to log analysis in field studies. In Transactions of the SPWLA Twenty-Eighth Annual Logging Symposium (June 29-July 2. 1987): paper no. EE 1-EE 20.

Johnson, Ronald C. and Dudley D. Rice. 1992. Chemical and isotopic compositions of natural gases in the Wind River basin, Wyoming. *AAPG Bulletin* 76-7: 1261.

Johnson, Ronald C. et al. 1994. A preliminary study of coal-forming environments during deposition of the Paleocene Fort Union formation, Wind River basin, Wyoming. In Organics and the Rockies field guide. Eds. R.M. Flores, K.T. Mehring, R.W. Jones and T.L. Beck. *Wyoming State Geological Survey Public Information Circular* no. 33: 69-81.

Johnson, Ronald C. et al. 1997. Deposition of the upper cretaceous lance formation in central Wyoming. *AAPG Bulletin* 81-7: 1226.

Johnson, Ronald C. et al. 1998. Detailed outcrop studies of the upper part of the upper cretaceous Cody shale and the upper cretaceous Mesaverde, Meeteetse, and Lance formations, Bighorn basin. Wyoming. In Cretaceous and lower tertiary rocks of the Bighorn basin, Wyoming and Montana, William R. Keefer and Jimmy E. Goolsby, eds. *Wyoming Geological Association. (WGA) 49th Guidebook*: 59-78.

Johnson, Ronald C. et al. 1999. An assessment of in-place gas resources in the low-permeability basin-centered gas accumulation of the Big Horn basin, Wyoming and Montana. *U.S. Geological Survey Open File Report* no. 99-315A: 1-46.

Jones, Frank O. 1975. A laboratory study of the effects of confining pressure on fracture flow and storage capacity in carbonate rocks. *Journal of Petroleum Technology (JPT) (Jan):* 21-27.

Jones, Frank O. and W.W. Owens. 1980. A laboratory study of low-permeability gas sands. *Journal of Petroleum Technology (JPT)* (Sept): 1631-1640.

Katahara, K. W. and J. D. Corrigan. 2002. Chapter 7: Effect of gas on poroelastic response to burial or erosion. In Pressure regimes in sedimentary basins and the prediction, A.R. Juffman and G.L. Bowers, ed. *AAPG Memoir* no. 76: 73-78.

Keighin C. William and R.M. Flores. 1994. Late cretaceous to Paleocene clastic reservoir rocks, Wind River basin, Wyoming. *GSA 46th Annual Meeting Abstracts with Programs* 26-6: 22.

Keighin C. William, R.M. Flores and W.J. Perry, Jr. 1991. Provenance tectonism and petrofacies in Paleocene sediments, northern Rocky mountains. *GSA 1991 Annual Meeting Abstracts with Programs* 23-5: A68.

Keighin, C. William and R.M. Flores. 1990. Heterogeneity of sandstone reservoirs in the fort union formation, fuller reservoir field, Wind River basin, Wyoming. *AAPG Bulletin* 74-8: 1331.

Keighin, C. William and R.M. Flores. 1994. Characteristics of oil-saturated fluvial channel sandstone reservoirs, Paleocene upper Fort Union formation southcentral Wind River basin, Wyoming. In Organics and the Rockies field guide, ed. R.M. Flores, K.T. Mehring, R.W. Jones and T.L. Beck. *U.S. Geological Survey Bulletin* no. 1917: 99-108.

Keighin, C. William, B. E. Law and R. M. Pollastro. 1989. Petrology and reservoir characteristics of the Almond Formation, Greater Green River Basin, Wyoming. ed. Edward B. Coalson et al, pub. *The Rocky Mountain Association of Geologists* in *Petrogenesis and Petrophysics of Selected Sandstone Reservoirs of the Rocky Mountain Region*: 281-298 and 344-347.

Keighin, C. William, R. M. Flores and D. J. Nichols. 1992. Comparison of fort union formation reservoir types in outcrop and in nearby abandoned oil fields, southern Wind River basin, Wyoming. *AAPG Bulletin* 76-8: 1261.

Keighin, C. William. 1984. Petrographic and selected reservoir characteristics of some tertiary and cretaceous sandstones, Pinedale Anticline, Sublette County, Wyoming. In geological characteristics of low-permeability upper cretaceous and lower tertiary rocks in the Pinedale Anticline area, Sublette County, Wyoming, Ben E. Law, ed. U.S. *Geological Survey Open File Report no*. 84-753: 16-21.

Keighin, C. William. 1992. Appendix 2: Pore throats. capillary pressures, porosity, and permeability. In Geologic controls and resource potential of natural gas in deep sedimentary basins in the United States, T.S. Dyman, ed. *U.S. Geological Survey Open File Report* no. 92-524: 76-85.

Keighin, C. William. 1993. Petrography of some upper cretaceous Mesaverde formation sandstones, Wind River basin, Wyoming . Paper presented at Wyoming Geological Association (WGA) Special Symposium on Oil and Gas and Other Resources of the Wind River Basin, Wyoming. 14-17 August, at Casper, WY. Ed. William R. Keefer, William J. Metzger and Larry H. Godwin. *WGA Guidebook*:111-119.

Keighin, C. William. 1998. Petrography of selected upper cretaceous sandstones, Bighorn basin, Wyoming. In Cretaceous and lower tertiary rocks of the Bighorn basin, Wyoming and Montana, ed. William R. Keefer and Jimmy E. Goolsby. *Wyoming Geological Association (WGA) 49th Guidebook*: 79-90.

Kharaka, Yousif K. et al. 1988. Origin of subsurface water at Cajon Pass, California. *American Geophysical Union (AGU) Research Letters (August supplement)* 15-9: 1049-1052.

Kharaka, Yousif K. et al. 1988. SOLMINEQ.88: a computer program code for geochemical modeling of water-rock interactions. *U.S. Geological Survey Water Investigations Report* 88-4227.

Kharaka, Yousif K., Robert W. Hill and William W. Carothers. 1985. Water-rock interactions in sedimentary basins. In Chapter 2: Relationship of organic matter and mineral diagenesis. *SEPM Short Course No. 17 Lecture Notes*: 79-176.

Kilmer, N.H., N.R. Morrow and J. K. Pitman. 1987. Pressure sensitivity of low permeability sandstones. *Journal of Petrol. Science and Engineering* 1: 65-81.

Klawitter, A.L., T.E. Hoak and A.D. Decker. 1995. Integrated exploration strategy for locating areas capable of high gas rate cavity completion in coalbed methane reservoirs. Paper presented at INTERGAS '95 Conference. 15-19 May, at University of AL, Tuscaloosa, AL: paper no. 9517: 97-114.

Knackstedt, Mark A., Adrian P. Sheppard and Muhammad Sahimi. 2001. Pore network modeling of two-phase flow in porous rock: the effect of correlated heterogeneity. *Advances in Water Resources (Feb-Mar)* 24-3 & 4: 257-277.

Knudsen, F.P. 1962. Effect of porosity on Young's Modulus of Alumina. *Journal of the American Ceramic Society* (1 Feb) 45-2: 94-95.

Kopaska-Merkel, David C. 1994. Pore-throat morphology in the upper Jurassic Smackover formation of Alabama. *SEPM Journal of Sedimentary Research* A64-3: 524-534.

Kordziel, Walter R. et al. 1996. A case study of integrating well-logs and a pseudo 3D multi-layer frac model to optimize exploitation of tight lenticular gas sands. Paper presented at SPE European Petroleum Conference. 22-24 October, at Milan, Italy. *SPE* no. 36886: 129-141.

Krushin, Jim. 1994. Entry pore-throat size of nonsmectite shales. *AAPG Annual Meeting Abstracts:* 190

Kubik, West and Patrick Lowry. 1993. Fracture identification and characterization using cores, FMS, CAST, and borehole camera: Devonian shale, Pike County, Kentucky. Paper presented at SPE Rocky Mountain Regional/Low Permeability Reservoirs Symposium. 12-14 April, at Denver, CO. *SPE* no. 25897: 543-554.

Kukal, G.C. et al. 1983. Critical problems hindering accurate log interpretation of tight gas sand reservoirs. Paper presented of the SPE AIME/U.S. DOE Symposium on Low Permeability Reservoirs. 14-16 March, at Denver, CO. *SPE/DOE 11620*: 181-190.

Kuuskraa, Vello A., Andrew L. Prestridge and John T. Hansen. 1995. Advanced technologies for producing massively stacked lenticular sands. Paper presented at SPE Gas Technology Conference. 28 April-1 May, at Calgary, Alberta, Canada. *SPE* no. 35630: 1-10.

Lachenbruch, Arthur H. and John H. Sass. 1988. The stress heat-flow paradox and thermal results from Cajon Pass. *American Geophysical Union (AGU) Research Letters (August supplement)* 15-9: 981-984.

Lajtai, E.Z. and J.R. Alison. 1979. A study of residual stress effects in sandstone. *Canadian Journal of Earth Science* 16:1547-1557

Lamarre, Robert A. and Timothy J. Pratt. 2002. Reservoir characterization study: calculation of gas-in-place in ferron coals at Drunkard's Wash unit, Carbon and Emery Counties, Utah. *RMAG Mountain Geologist* 39-2: 41-51.

Land, Lynton S. and Dennis R. Prezbindowski. 1981. The origin and evolution of saline formation water, lower cretaceous carbonates, south-central Texas, U.S.A. *Journal of Hydrology* 54: 51-74.

LaPointe, Paul et al. 1997. The application of discrete fracture network models to fractured reservoir engineering: analytical approach, data sets and early results, Yates field, West Texas. In Fractured reservoirs: characterization and modeling, ed Thomas E. Hoak, Alan L. Klawitter and Peter K. Blomquist, et al. *Rocky Mountain Association of Geologists 1997 Guidebook*: 225-256.

Laubach, Stephen E. and J.C. Lorenz. 1992. Preliminary assessment of natural fracture patterns in Frontier formation sandstones, southwestern Wyoming. In Rediscover the Rockies, Christopher E. Mullen, ed. *Wyoming Geological Association (WGA) 43rd Field Conference Guidebook*: 87-96.

Laubach, Stephen E. et al. 1992. Preliminary map of fracture patterns in coal in the western United States. In Rediscover the Rockies, Christopher E. Mullen, ed. *Wyoming Geological Association (WGA) 43rd Field Conference Guidebook*: 253-267.

Laubach, Stephen E. et al. 1992. Stress directions in Cretaceous Frontier formation, Green River Basin, Wyoming. *Wyoming Geological Association Forty-Third Field Conference Guidebook.* Ed. Christopher E. Mullen: 75-86.

Laubach, Stephen E. et al. 1992. Stress directions in cretaceous Frontier formation, Green River basin, Wyoming. In Rediscover the Rockies, Christopher E. Mullen, ed. *Wyoming Geological Association (WGA) 43rd Field Conference Guidebook*: 75-86.

Law, Ben E. 1979. Section B-B'; subsurface and surface correlations of some upper cretaceous and tertiary rocks, northern Green River basin, Wyoming. *USGS Open File Report* no. 79-1689: plate 1 & 2.

Law, Ben E. 1984. Relationships of source-rock, thermal maturity, and overpressuring to gas generation and occurrence in low-permeability upper Cretaceous and lower Tertiary rocks, Great Green River Basin, Wyoming, Colorado, and Utah. In *Hydrocarbon source rocks of the greater Rocky Mountain region*, eds J. Woodward, F. F. Meissner and J. L. Clayton. Rocky Mountain Association of Geologists: 469-490.

Law, Ben E. 1984. Source-rock evaluation of upper cretaceous and lower tertiary rocks in the Pinedale Anticline area, Sublette County, Wyoming. In Geological characteristics of low-permeability upper cretaceous and lower tertiary rocks in the Pinedale Anticline area, Sublete County, Wyoming. *USGS Open File Report* no. 84-753: 36-50.

Law, Ben E. 1984. Structure and stratigraphy of the Pinedale Anticline, Wyoming. In Geological characteristics of low-permeability upper cretaceous and lower tertiary rocks in the Pinedale Anticline area, Sublete County, Wyoming. *USGS Open File Report* no. 84-753: 6 -15.

Law, Ben E. 2002. Basin-centered gas systems. *AAPG Bulletin (Nov)* 86-11: 1891-1919.

Law, Ben E. and C.W. Spencer. 1989. Chapter A :Introduction. In Geology of tight gas reservoirs in the Pinedale Anticline area, Wyoming, and at the multiwell experiment site, Colorado. *U.S. Geological Survey Bulletin* no. 1886. A1-A7.

Law, Ben E. and J. B. Curtis. 2002. Introduction to unconventional petroleum systems. *AAPG Bulletin (Nov)* 86-11: 1851-1852.

Law, Ben E. and R.C. Johnson. 1990. Chapter B: Structural and stratigraphic framework of the Pinedale Anticline, Wyoming, and the multiwell experiment site, Colorado. In Geology of tight gas reservoirs in the Pinedale Anticline area, Wyoming. and at the multiwell experiment site, Colorado, ed. B.E. Law and C.W. Spencer. *USGS Bulletin* no. 1886: B1-B11.

Law, Ben E. and W.W. Dickinson. 1985. Conceptual model for origin of abnormally pressured gas accumulations in low-permeability reservoirs. *AAPG Bulletin* 69-8: 1295-1304.

Law, Ben E. et al. 1989. Estimates of gas resources in overpressured low-permeability Cretaceous and tertiary sandstone reservoirs, Greater Green River Basin, Wyoming, Colorado, and Utah. *Wyoming Geological Association Fortieth Field Conference Guidebook* 39-61.

Law, Ben E., Charles W. Spencer and Neely H. Bostick. 1980. Evaluation of organic matter, subsurface temperature and pressure with regard to gas generation in low-permeability upper cretaceous and lower tertiary sandstones in Pacific Creek area, Sublette and Sweetwater Counties, Wyoming. *RMAG Mountain Geologist* 17-2: 23-35.

Law, Ben E., Richard M. Pollastro and C.W. Keighin. 1986. Geologic characterization of low-permeability gas reservoirs in selected wells, Greater Green River basin, Wyoming, Colorado, and Utah. In Geology of tight gas reservoirs, ed. Charles W. Spencer and Richard F. Mast. *AAPG Studies in Geology* no.24: 253-269.

Law, Ben E., V.F. Nuccio and C.E. Barker. 1989. Kinky vitrinite reflectance well profiles: evidence of paleopore pressure in low-permeability, gas-bearing sequences in Rocky mountain foreland basins: reply. *AAPG Bulletin* 73-8: 999-1010.

Law, Ben E., V.F. Nuccio and C.E. Barker. 1990. Kinky vitrinite reflectance well profiles: evidence of paleopore pressure in low-permeability, gas-bearing sequences in Rocky mountain foreland basins: discussion*.* *AAPG Bulletin* 71-6: 948-949.

Leary, P.C., T.L. Henyey and Y-G. Li. 1988. Fracture related reflectors in basement rock from vertical seismic profiling at Cajon Pass. *American Geophysical Union (AGU) Research Letters (August supplement)* 15-9: 1057-1060.

Leder, Frederice and Won C. Park. 1986. *Porosity reduction in sandstone by quartz overgrowth. AAPG Bulletin* 70-11: 1713-1728.

Lehman, Donald D. 1979. Greater Green River basin. Paper presented at Wyoming Oil and Gas Fields Symposium. Ed. W.A. Bradley, S.C. Champlin, J. Kennedy, O.P Miles, Jr., M.E. Smithwick and R.E. Walker. *WGA Greater Green River Basin* II: 306- 307.

Lewis, Helen, Peter Olden and Gary D. Couples. 2002. Geomechanical simulations of top seal, hydrocarbon seal quantification. Paper presented at Norwegian Petroleum Society (NPS). Conference. 16-18 October 2000. *NPS Special Publication* no. 11: 75-87.

Lichtenberger, G.J. 1993. Practical aspects of data acquisition and interpretation of horizontal well pressure data. Paper presented at SPE Rocky Mountain Regional/Low Permeability Reservoirs Symposium. 12-14 April, at Denver, CO. *SPE* no. 25922: 741-753.

Lickus, M.R. et al. 1984. Thermal maturity map, northern Green River basin, Wyoming. In Geological characteristics of low-permeability upper cretaceous and lower tertiary rocks in the Pinedale Anticline area, Sublete County, Wyoming. *USGS Open File Report* 84-753: 60-65.

Lickus, M.R. et al. 1990. Chapter G: Thermal maturity patterns in the northern Green River basin. Wyoming. In Geology of tight gas reservoirs in the Pinedale Anticline area, Wyoming, and at the multiwell experiment site, Colorado, ed. B.E. Law and C.W. Spencer. *USGS Bulletin* no. 1886: G1-G5.

Lorenz, John C. and Scott Cooper. 2001. Tectonic setting and characteristics of natural fractures in Mesaverde and Dakota reservoirs of the San Joan basin, New Mexico and Colorado. *Sandia National Laboratories Report* no. SAND2001-0054: 1-77.

Lorenz, John C. and Sharon J. Finley. 1991. Regional fracture ii: fracturing of Mesaverde reservoirs in the Piceance basin, Colorado. *AAPG Bulletin* 75-11: 1738-1757.

Lorenz, John C. et al. 1988. Results of the multiwell experiment: in situ stresses, natural fractures and other geological controls on reservoirs. *EOS* 69-35: 817, 825-826.

Lorenz, John C., A.R. Sattler and C.L. Stein. 1989. The effects of depositional environment on petrophysical properties of Mesaverde reservoirs, northwestern Colorado. *Transactions of SPE 64th Annual Technical Conference* paper no. 19583: 119-132.

Lorenz, John C., Lawrence W. Teufel and Norman R. Warpinski. 1991. Regional fractures I: a mechanism for the formation of regional fractures at depth in flat-lying reservoirs. *AAPG Bulletin* 75-11: 1714-1737.

Lough, Michael F., Seong H. Lee and Jairam Kamath. 1997. A new method to calculate effective permeability of gridblocks used in the simulation of naturally fractured reservoirs. *SPE Reservoir Engineering (Aug)* 12-3: 219-224.

Luo, Xiaorong and Guy Vasseur. 1992. Contributions of compaction and aquathermal pressuring to geopressure and the influence of environmental conditions. *AAPG Bulletin* 76-10: 1550-1559.

Luo, Xiaorong and Guy Vasseur. 1993. Contributions of compaction and aquathermal pressuring to geopressure and the influence of environmental conditions: reply. *AAPG Bulletin* 77-11: 2010-2014.

Lynch, F. Leo and Lynton S. Land. 1996. Diagenesis of calcite cement in Frio formation sandstones and its relationship to formation water chemistry. *Journal of Sedimentary Research* 66-3: 439-446.

MacGowan, Donald, B. et al. 1994. Timing of hydrocarbon generation, organic-inorganic diagenesis, and the formation of abnormally pressured gas compartments in the cretaceous of the Greater Green River basin: a geochemical model. In Chapter 7: *GRI Annual Report of Natural Gas Resource Characterization Study of the Mesaverde Group in the Greater Green River Basin, Wyoming: A Strategic Plan for the Exploitation of Tight Gas Sands*: 271-321

MacGowan, Donald B. et al. 1992. Organic geochemistry and maturation trends of shales and coals, Almond formation, Mesaverde group, Greater Green River basin, Wyoming: a comparison with laboratory maturation of Almond coals by hydrous pyrolosis. In Rediscover the Rockies, ed. Christopher E. Mullen. *Wyoming Geological Association (WGA) 43rd Field Conference Guidebook*: 221-236.

MacGowan, Donald B. et al. 1994. Chapter 21: Formation water chemistry of the Muddy Sandstone and organic geochemistry of the Mowry Shale, Powder River Basin, Wyoming: Evidence for mechanism of pressure compartment formation. In Basin compartments and seals, ed P.J. Ortoleva. *AAPG Memoir* no. 61: 321-331.

MacPherson, G. L. and L. S. Land. 1989. Bromide in Gulf basin formation waters: organics as an additional source. Paper presented at meeting, Geological Society of America: 1989 Annual Meeting Abstracts with Programs: A316.

Maer, N.K., Jr. 1976. Type curves for analysis of afterflow-dominated gas-well buildup data. *Journal of Petroleum Technology (JPT)* (Aug)28-8: 915-924.

Magara, Kinji. 1975. Importance of aquathermal pressuring effect in Gulf Coast. *AAPG Bulletin* 59-10: 2037-2045.

Maglio-Johnson, Tina. 2000. Petrophysical definition of flow units in a deep-water sandstone, Lewis Shale Wyoming. *AAPG Bulletin* 84-11: 1867.

Maglio-Johnson, Tina. 2001. Flow unit definition using petrophysics in a deep water turbidite deposit, Lewis Shale, Carbon County Wyoming. Master's thesis, Colorado School of Mines available from http://www.mines.edu/index_js.shtml: INTERNET

Man, H.N. and X.D. Jing. 2001. Network modeling of strong and intermediate wettability on electrical resistivity and capillary pressure. *Advances in Water Resources Special Issue on Pore-Scale Modeling (Feb-March)* 24-3 & 4: 345-363.

Mann, Gary, M. and Charles E. Meyer. 1993. Late Cenozoic structure and correlations to seismicity along the Olympic Wallowa lineament, northwest United States. *GSA Bulletin* 105: 853-871.

Marin, B.A. et al. 1993. Natural fractures in Sonora Canyon sandstones, Sonora and Sawyer fields, Sutton County, Texas. Paper presented at SPE Rocky Mountain Regional/Low Permeability Reservoirs Symposium. 12-14 April, at Denver, CO. *SPE* no. 25895: 523-531.

Marrett, Randall 1997. Permeability, porosity, and shear-wave anisotropy from scaling of open fracture populations. *Rocky Mountain Association of Geologists Fractured Reservoirs: Characterization and Modeling*: 217-226.

Marrs, Ronald W. and Earnest D. Paylor, II. 1987. Society of Exploration Geophysicists Investigation of a surface spectral anomaly at Table Rock gas field, Wyoming. *Geophysics* 52-7: 841-857.

Marshall, James S. and Raymond C. Pilcher. 1989. Altamont field-a fractured reservoir? *AAPG Bulletin* 73-9: 1166.

Martin, W.B. and Jack Shaughnessy. 1969. Project Wagon Wheel. Paper presented at Symposium on Tertiary Rock of Wyoming. Ed. James A. Barlow, Robert H. Steed, Thomas C. Woodward, E.J. Perry, William H. Laraway, Donald F. Cardinal and Clark A. Mueller. *Wyoming Geological Association (WGA) 21st Annual Field Conference Guidebook*: 145-152.

Martinsen, Randi S. and G. Christensen. 1992. A stratigraphic and environmental study of the Almond formation, Mesaverde group, Greeter Green River basin, Wyoming. In Rediscover the Rockies ed. Christopher E. Mullen. Wyoming Geological Association (WGA) 43rd Field Conference Guidebook: 171-190.

Martinsen, Randi. S., et al. 1995. Stratigraphy and lithofacies of the Almond formation, Washakie and Great Divide basins, Wyoming. Wyoming Geological Association (WGA) 1995 Field Conference Guidebook: 297-309.

Mason, Edward W. and Robert Ehrlich. 1995. Automated quantitative assessment of basin history from a multiwell analysis. *AAPG Bulletin* 79-5: 711-724.

Mason, Geoffrey. 1991. Discussion of pore-scale heterogeneity from mercury porosimetry data: reply to H.H. Yuan's paper. *SPE Formation Evaluation* 6-2: 241 .

Masters, John A. 1979. Deep basin gas trap, western Canada. *AAPG Bulletin (Feb)* 63-2: 152-181.

Matheny, Marvin L. 1979. Pinedale Anticline. Paper presented at Wyoming Oil and Gas Fields Symposium. Ed. W.A. Bradley, S.C. Champlin, J. Kennedy, O.P Miles, Jr., M.E. Smithwick and R.E. Walker. *WGA Greater Green River Basin* II: 282-283.

May, Michael T. 1992. Intra- and extra-basinal tectonism, climate and intrinsic threshold cycles as possible controls on early cretaceous fluvial, Wind River basin, Wyoming. In Rediscover the Rockies, Ed. Christopher E. Mullen. *Wyoming Geological Association (WGA) 43rd Field Conference Guidebook*: 61-74.

Mayer, James R. and John M. Sharp, Jr. 1998. Fracture control of regional ground-water flow in a carbonate aquifer in a semi-arid region. *GSA Bulletin* 110-2: 269-331.

McKetta, J. J. and A.H. Wehe. 1958. Chart for the water content of natural gases. *Petroleum Refiner.* Vol. 37, no. 8:153-154.

McKinley, R.M. and T.D. Streltsova. 1971. Wellbore transmissibility from afterflow-dominated pressure buildup data. *Journal of Petroleum Technology (JPT) (July):* 863-872.

McKinley, R.M. and T.D. Streltsova. 1974. Estimating flow efficiency from afterflow-distorted pressure buildup data. *Journal of Petroleum Technology (JPT) (June)* 26: 696-697.

McKinley, R.M. and T.D. Streltsova. 1984. Early-time pressure buildup analysis for Prudhoe Bay wells. *Journal of Petroleum Technology (JPT) (Feb)* 36-2: 311-318.

McLatchie, A.S., R.A. Hemstock, and J.W. Young. 1958. The effective compressibility of reservoir rock and its effects on permeability. *Journal of Petroleum Technology (JPT) (June):* 49-51.

McMillen, Kenneth J. and Robert D. Winn, Jr. 1991. Seismic stratigraphy of Lewis Shale deltaic and deep-water clastics, Red Desert-Washakie basins, Wyoming. In P. Weimer, and L.H. Linds, eds, *Seismic facies and sedimentary processes of submarine fans and turbidite systems:* 273-287.

McPeek, L.A. 1981. Eastern Green River basin: a developing giant gas supply from deep, overpressured upper cretaceous sandstones. *AAPG Bulletin* 65-6: 1078-1098.

McPherson, Brian J.O.L. and John D. Bredehoeft. 2001. Overpressures in the Uinta basin, Utah: analysis using a three-dimensional basin evolution model. *Water Resources Research* 37-4: 857-871.

Means, J.L. and N. Hubbard. 1987. Short-chain aliphatic anions in deep subsurface brines: a review of their origin, occurrence, properties, and importance and new data on their distribution and geochemical implications in the Palo Duro Basin, Texas. *Organic Geochemistry* 11:177-191.

Meissner, Fred F. 2001. Causes of anomalous deep basin fluid pressures in Rocky mountain basins and their relation to regional gas accumulation. *Four Corner Geological Society Newsletter (March)*

Meshri, Indu D. 1981. Deposition and diagenesis of glauconite sandstone, Berrymore-Lobstick-Bigoray area, south central Alberta: A study of physical chemistry of cementation. Ph.D. diss., University of Tulsa.

Meshri, Indu D. and Jana M. Walker. 1990. A study of rock-water Interaction and simulation of diagenesis in the upper Almond sandstones of the Red Desert and Washakie basins, Wyoming. In Prediction of reservoir quality through chemical modeling, ed. Indu D. Meshri and Peter J. Ortoleva. *AAPG Memoir* 49: 55.

Meybeck, M. 1979. Concentrations des eaux fluviales en éléments majeurs et apports en solution auz océans. *Rev. Géol. Dyn. Géogr. Phys*. Vol. 21, no. 3:215-246.

Middlebrook, M.L. et al. 1993. Reservoir evaluation and completion results from a horizontal well in the Mancos B. Douglas Creek Arch, northwest Colorado. Paper presented at SPE Rocky Mountain Regional/Low Permeability Reservoirs Symposium. 12-14 April, at Denver Colorado. *SPE* no. 25924: 767-780.

Miller, T.W. and C.H. LUK. 1993. Contributions of compaction and aquathermal pressuring to geopressure and the influence of environmental conditions: discussion. *AAPG Bulletin* 77-11: 2006-2010.

Miskimins, Jennifer L. and Constance Dodge Knight. 2003. Analysis of hydrocarbon production in a critically-stressed reservoir. Paper presented at SPE Annual Technical Conference and Exhibition. 5-8 October, at Denver CO. *SPE* no. 84457

Moldovanyi, E. E. and L. M. Walter. 1992. Regional trends in water chemistry, Smackover Formation, Southwest Arkansas: geological and physical controls. *AAPG Bulletin* 76:864-894.

Montgomery, Scott L. and John W. Robinson. 1997. Jonah field, Sublette County, Wyoming: gas production from overpressured upper cretaceous lance sandstones of the Green River basin. *AAPG Bulletin* 81-7: 1049 -1062.

Montgomery, Scott L. et al.2001. Cave Gulch field, Natrona County, Wyoming: large gas discovery in the Rocky Mountain foreland, Wind River basin. *AAPG Bulletin* 85-9: 1543-1564.

Morrow, C.A. and J.D. Byerlee. 1992. Permeability of core samples from Cajon Pass scientific drill hole: results from 2100 to 2500 m depth. *American Geophysical Union (AGU) Journal of Research (10 April)* 97-B4: 5145-5151.

Muller, Margaret M. and Edward B. Coalson 1989. Diagenetic and petrophysical variations of the Dakota sandstone, Henry field, Green River basin, Wyoming. Ed. Edward B. Coalson. *Rocky Mountain Association of Geologists Petrogenesis and Petrophysics of Selected Sandstone Reservoirs of the Rocky Mountain Region*: 149-158 and 326-329 .

Naeser, Nancy D. 1984. Fission-track ages from the Wagon Wheel No. 1 well, northern Green River basin, Wyoming: evidence for recent cooling. In geological characteristics of low-permeability upper cretaceous and lower tertiary rocks in the Pinedale Anticline area, Sublete County, Wyoming, ed. Ben E. Law. *USGS Open File Report* no. 84-753: 66-77.

Naeser, Nancy D. 1986. Neogene thermal history of the northern Green River basin, Wyoming In Roles of organic matter in sediment diagenesis, ed. Donald L. Gautier. *SEPM Special Publication* no. 38: 65-72.

Naeser, Nancy D. 1990. Chapter E: Thermal history and provenance of rocks in the Wagon Wheel No. 1 well, Pinedale Anticline, northern Green River basin-evidence from fission-track dating . In Geology of tight gas reservoirs in the Pinedale Anticline area, Wyoming, and at the multiwell experiment site, Colorado, ed. B.E. Law and C.W. Spencer. *USGS Bulletin* no. 1886: E1-E13.

Nakayama, Kazuo and Daichi Sato. 2002. Prediction of sealing capacity by the equivalent grain size method. hydrocarbon seal quantification. Papers presented at Norwegian Petroleum Society (NPS) Conference. 16-18 October 2000. *NPS Special Publication* no. 11: 51-60.

Narr, W. and J.B. Currie. 1982. Origin of fracture porosity- example from Altamont field, Utah. *AAPG Bulletin* 66-9: 1231-1247.

Natali, Steve, Roy Roux, Peter Dea and Fred Barrett. 2000. Cave Gulch 3-D survey, Wind River basin, Wyoming. *RMAG Mountain Geologist* 37-1: 3-13.

Nelson, Philip H. 2002. A review of the multiwell experiment in tight gas sandstones of the Mesaverde group, Piceance basin, Colorado. *RMAG Mountain Geologist* 39-3: 53-71.

Nelson, Ronald A. et al.1996. Structurally controlled porosity evolution and production, La Paz field, Maraca Ibo basin, Venezuela. *AAPG Bulletin* 80-8: 1318.

Neuzil, C.E. 1986. Groundwater flow in low-permeability environments. *Water Resources Research* 22-8: 1163-1195.

Nicolaysen, Jerry. 1979. Brady deep unit south, Jackknife Springs. Paper presented at Wyoming Oil and Gas Fields Symposium. Ed. W.A. Bradley, S.C. Champlin, J. Kennedy, O.P Miles, Jr., M.E. Smithwick and R.E. Walker. *WGA Greater Green River Basin* I: 67-70.

Ning, Xiuxu et al. 1993. The measurement of matrix and fracture properties in naturally fractured cores. Paper presented at SPE Rocky Mountain Regional/Low Permeability Reservoirs Symposium. 12-14 April, at Denver CO. *SPE* no. 25898: 555-569.

Nuccio, Vito F. and Ronald C. Johnson 1990. Chapter L: Thermal history of selected coal beds in the upper cretaceous Mesaverde group and tertiary Wasatch formation, multiwell experiment site, Colorado in relation to hydrocarbon generation. In Geology of tight gas reservoirs in the Pinedale Anticline area, Wyoming, and at the multiwell experiment site, Colorado, ed. B.E. Law and C.W. Spencer. *USGS Bulletin* no. 1886. L1-L8.

Nuccio, Vito F. and T.M. Finn. 1994. Structural and thermal history of the Paleocene Fort Union formation. Central and eastern Wind River basin, with emphasis on petroleum potential of the Waltman shale member. In organics and the Rockies field guide, ed. R.M. Flores, K.T. Mehring, R.W. Jones and T.L. Beck. *Wyoming State Geological Survey Public Information Circular* no. 33: 53-67.

Nunn, Jeffrey A. 1996. Buoyancy-driven propagation of isolated fluid-filled fractures: implications for fluid transport in Gulf of Mexico geopressured sediments. *American Geophysical Union (AGU) Journal of Research (10 Feb)* 101-B2: 2963-2970.

Nunn, Jeffrey A. and G. Lin. 2002. Insulating effect of coals and organic rich shales: implications for topography-driven fluid flow, heat transport, and genesis of ore deposits in the Arkoma basin and Ozark plateau. *Basin Research* 14-2: 129-145.

Nunn, Jeffrey A. and Peter Meulbroek. 2001. Flexure, bending stresses, and fluid migration in foreland basins. *AAPG Bulletin* 85.

Nunn, Jeffrey A. and Peter Meulbroek. 2002. Kilometer-scale upward migration of hydrocarbons in geopressured sediments by buoyancy-driven propagation of methane-filled fractures. *AAPG Bulletin* 86-5: 907-918.

Oldham, David W. 1997. Exploration for shallow compaction-induced gas accumulations in sandstones of the fort union formation, Powder River basin, Wyoming. *RMAG Mountain Geologist* 34-1: 25-36.

Ormond, Anne and Peter Ortoleva. 2000. Numerical modeling of reaction-induced cavities in a porous rock. *American Geophysical Union (AGU) Journal of Research (10 July)* 105-B7: 16,737-16,747.

Ortoleva, Peter J. et al.2001. Enhanced remote fractured reservoir detection and characterization through basin model / seismic image interpretation integration. *AAPG Bulletin* 85.

Ostensen, R.W. 1983. Microcrack permeability in tight gas sandstone. *SPE Journal (Dec)* 23-6: 919-927.

Paillet, Frederick L. 1985. Problems in fractured-reservoir evaluation and possible routes to their solution. *SPWLA Log Analyst* 26-6: 26-34, 39-41.

Palacas, J.G. et al. 1994. Origin of oil in oil-saturated sandstones in the upper part of the Fort Union formation (Paleocene), Castle Gardens and Signor Ridge areas, Wind River basin, Wyoming. In Organics and the Rockies field guide, ed. R.M. Flores, K.T. Mehring, R.W. Jones and T.L. Beck. *Wyoming State Geological Survey Public Information Circular* no. 33: 83-97.

Palacas, J.G. et al.1992. Characterization and source of oil impregnating a sandstone in the fort union formation, castle garden area, Wind River basin, Wyoming. *AAPG Bulletin* 76-8: 1267.

Pallatt, Nadia and Tony Palmer. 1991. The role of pore geometry in the interpretation of shaly sands. Paper presented at the Society of Core Analysts European 2nd Core Analysis Symposium. 20-22 May, at Sunbury-on-Thames, London, UK. Ed. Paul F. Worthington and Daniel Longeron, BP Research Centre: *Advances in Core Evaluation II, Reservoir Appraisal*: 331-347.

Palmer, Ian D. J.D. McLennan and H.H. Vaziri. 1999. Cavity-like completions in weak sands. Paper presented at the International Symposium on Formation Damage Control. 23-24 February, at Lafayette, LA. *SPE* no. 58719

Park, Anthony J. et al.2001. Comparing observed overpressuring and fracturing characteristics of siliciclastic and carbonate sediments and basin RTM 3-D simulation predictions. *AAPG Bulletin* 85.

Park, Anthony J., Gonca Ozkan and Peter J. Ortoleva. 2000. Computer simulations of grain coating and particle nucleation under closed- and open -system conditions. *AAPG Bulletin* 84.

Park, Yung. 2001. Diffusion of a passive impurity through a porous media: fractal model. *Fractals (Dec)* 9-4: 375-378.

Parker, John M. and Louis C. Bortz. 2001. West side Canal gas field, Carbon County, Wyoming, & Moffat County, Colorado. *RMAG Mountain Geologist* 38-4: 211-224.

Parra, Jorge O. et al. 2000. A methodology to Integrate resonance and acoustic measurements for reservoir characterization. Pub Southwest Research Institute, San Antonio, TX. *Annual Report (April 1999-April 2000) DOE/BC* no. 15203-1.

Patton, Thomas L. and Raymond C. Fletcher. 1995. Mathematical block-motion model for deformation of a layer above a buried fault of arbitrary dip and sense of slip. *Journal of Structural Geology (Oct)* 17-101455-1472

Pawlewicz, Mark J. and Thomas M. Finn 2002. Vitrinite reflectance data for the Greater Green River basin, southwestern Wyoming, northwestern Colorado, and northeastern Utah. *USGS Open File Report* no. 02-339: 1-15.

Payne, David A. 1996. Material-balance calculations in tight-gas reservoirs: the pitfalls of P/Z plots and a more accurate technique. *SPE Reservoir Engineering* 11-4: 260-267.

Payne, Dorothy F. et al.2000. A reaction-transport-mechanical approach to modeling the interrelationships among gas generation, overpressuring, and fracturing: implications for the upper cretaceous natural gas reservoirs of the Piceance basin, Colorado. *AAPG Bulletin* 84-4: 545-565.

Pedersen, P.K. and R. Steel. 1999. Sequence stratigraphy and alluvial architecture of the upper cretaceous Ericson sandstone, glades-clay basin area, Wyoming/Utah border. *RMAG Mountain Geologist (April)* 36-2: 71-84.

Peigui, Yin and Ronald C. Surdam. 1995. Defects of diagenesis on petrophysical properties of reservoir rocks, Washakie basin. In Resources of southwestern Wyoming, ed. Richard W. Jones. *WGA 1995 Field Conference Guidebook*: 247-254.

Peska, Pavel and Mark D. Zoback. 1995. Compressive and tensile failure of inclined well bores and determination of in situ stress and rock strength. *American Geophysical Union (AGU) Journal of Research (10 July)* 100-B7: 12791-12811.

Petroleum Technology Transfer Council (PTTC). 2001. Seals-a critical element to successful exploration and production. Based on PTTC Eastern Region's workshop on 29 March 2000 at Jackson, MS. Available from http://egrpttc.geo.ua.edu/solns/seals.pdf: INTERNET.

Pezard, Philippe A. and Stefan M. Luthi. 1988. Borehole electrical images in the basement of the Cajon Pass scientific drillhole, California; fracture identification and tectonic implications. *American Geophysical Union (AGU) Research Letters (August supplement)* 15-9: 1017-1020.

Pezard, Philippe A. et al.1988. Fracture distribution and basement structure from measurements of electrical resistivity in the basement of the Cajon Pass scientific drillhole, California. *American Geophysical Union (AGU) Research Letters (August supplement)* 15-9: 1021-1024.

Pirson, S.J. 1967. How to ma: fracture development from logs. *World Oil (March):* 106, 108, 113-114.

Pitman, Janet K. and Warren W. Dickinson. 1989. Petrology and isotope geochemistry of mineralized fractures in cretaceous rocks-evidence for cementation in a closed hydrologic system. *USGS Bulletin* no. 1886. J1J15.

Pittman, Edward D. 1992. relationship of porosity and permeability to various parameters derived from mercury injection-capillary pressure curves for sandstones. *AAPG Bulletin* 76-2: 191-198.

Pollastro, Richard M. and Charles E. Barker. 1984. Geothermometry from clay minerals, vitrinite reflectance, and fluid inclusions—applications to the thermal and burial history Green River basin, Wyoming. In Geological characteristics of low-permeability upper cretaceous and lower tertiary rocks in the Pinedale Anticline area, Sublete County, Wyoming, ed. Ben E. Law. *USGS Open File Report* no. 84-753: 78-94.

Pollastro, Richard M. and Charles E. Barker. 1986. Application of clay-mineral, vitrinite reflectance, and fluid inclusion studies to the thermal and burial history of the Pinedale Anticline, Green River basin, Wyoming. In roles of organic matter in Sediment diagenesis, ed. Donald L. Gautier. *SEPM Special Publication* no. 38: 73-83.

Porras, Juan Carlos. 1998. Determination of rock types from pore throat radius and bulk volume water, and their relations to lithofacies, Carito Norte field, eastern Venezuela basin. *Transactions of the SPWLA 39th Annual Logging Symposium*: O1-O-13.

Potocki, D. J. 1989. The Influence of deep meteoric invasion on the reservoir quality of cretaceous sandstones in the Mackenzie Delta, Canada. Ed. Douglas L. Miles. *Proceedings of the 6th International Symposium on Water-Rock Interactions WRI-6 (3-8 August 1989).*

Poulson, S. R., H. Homoto and T. P. Ross. 1996. Stable isotope geochemistry of waters and gases (CO_2, CH_4) from the overpressured Morganza and Moore-Sams fields, Louisiana Gulf Coast. *Applied Geochemistry* 10:407-417.

Pranter, Matthew J. 1999. Use of a petrophysical-based reservoir zonation and multicomponent (3-D, 3-c) seismic attributes for improved geologic modeling. *AAPG Bulletin* 83-11: 1894.

Prats, M. 1981. Effect of burial history on the subsurface horizontal stresses of formations having different material properties. *SPE Journal* 21-6: 658-662.

Pride, Steven R. and James G. Berryman. 2003. Linear dynamics of double-porosity dual-permeability materials. In II: Fluid transport equations. E-68. Available from http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=PLEEE8000068000003036604000001&idtype=cvips&gifs=yes: INTERNET

Pritchett, Ron W., comp. 2001. 3D seismic reflects value. Proceeds of Rocky Mountain Association of Geologists/Denver Geophysical Society 7th Annual 3D Seismic Symposium. 2 March, at Denver, CO. *RMAG Abstract.*

Ptasynski, Harry 1989. Waltman, Bullfrog unit. Paper presented at Wyoming Oil and Gas Fields Symposium on Bighorn and Wind River Basins. *Wyoming Geological Association (WGA) 40th Field Conference Guidebook* 522-526.

Qingshan, Zhai, J.E. Springer and M.D. Zoback. 1990. Analysis of fractures from borehole televiewer logs in a 500m deep hole at Xiaguan, Yunnan Province, southwest China. Paper presented at The International Symposium on Tectonophysics. 10-13 May 1988, at Beijing, People's Republic of China. *Physical Chem. Earth.* 17-1: 199-206

Raymer, L.L. and M. Freeman. 1984. In situ determination of capillary pressure, pore throat size and distribution, and permeability from wireline data. Transactions of the SPWLA Twenty-Fifth Annual Logging Symposium (10-13 June 10 1984) II: CCC1-CCC12.

Reed, Christy L. and Andrew Hajash, Jr. 1992. Dissolution of granitic sand by ph-buffered carboxylic acids: a flow-through experimental study at 100 degrees c and 345 bars. *AAPG Bulletin* 76-9: 1402-1416.

Reeves, Scott. 1994. Design, supervision and analysis of coalbed methane well tests in the People's Republic of China. In exploration for deep coalbed methane. *United Nations U.N.D. project CPR191/214/A/01/99*.

Reisser, K.D. and Steve J. Blanke. 1989. Paleostructural control of Dakota hydrocarbon accumulations on the southern Moxa Arch, southwest Wyoming and northeast Utah. Ed. Edward B. Coalson. *Rocky Mountain Association of Geologists Petrogenesis and Petrophysics of Selected Sandstone Reservoirs of the Rocky Mountain Region*: 135-148 and 322-325.

Renard, Francois, Peter Ortoleva and Jean Pierre Gratier. 1997. Pressure solution in sandstones: influence of clays and dependence on temperature and stress. *Tectonophysics* 280-3 & 4: 257-266.

Richter, Henry R. Jr. 1981. Occurrence and characteristics of ground water in the Wind River basin, Wyoming. *Western Resources Research Institute (University of Wyoming)* IV: Appendix A, B & C.

RMAG, GRI and PTTC. 1998. *The Second Annual Innovative Applications of Petroleum Technology and Compartmentalized Reservoirs*.

Roberts, Laura N. R., Michael D. Lewan, and Thomas M. Finn. 2004. Timing of oil and gas generation of petroleum systems in the southwestern Wyoming province. *RMAG Mountain Geologist (July)* 41-3: 87-118.

Robinson, John W. 2000. Discovery of Jonah field, Sublette County, Wyoming. *RMAG Mountain Geologist* 37-3: 135-143.

Robinson, John W. 2001. Corrections to discovery of Jonah field, Sublette County, WY. *RMAG Mountain Geologist* (Jan)38-1: 52.

Robinson, Lee. 1993. Table Rock-Delaney Rim field Lewis production-base of slope turbidite reservoirs. Ed. Betty Stroock and Sam Andrew. *WGA 50th Anniversary Field Conference: Guidebook*: 201- 214.

Ross, Malcolm I. and Christopher R. Scotese. 1987. Hierarchical tectonic analysis of the Gulf of Mexico and Caribbean region in Tectonophysics. *Geodynamics Conference Special. Report.*

Ruijtenberg, Piet A., Ray Buchanan and Paul Marke. 1990. Three-dimensional data improve reservoir mapping. *Journal of Petroleum Technology (JPT) (Jan):* 22-25, 59-61.

Ryder, Robert T. et al.1989. Seismic profile through Patrick Daw-Table Rock area, east flank Rock Springs uplift, Wyoming. In Gas resources of Wyoming, ed. Janet L. Eisert. *WGA 40th Field Conference Guidebook*: 209-229.

Ryder, Robert T. et al.1996. Continuous-type (basin-centered) gas accumulation in the lower Silurian Clinton Sands, Medina group, and Tuscarora sandstone in the Appalachian basin. *AAPG Bulletin* 80-9: 1531.

Sampath, Krishnaswamy and C. William Keighin. 1981. SPE/DOE Factors affecting gas slippage in tight sandstones. Paper presented at 1981 SPE/DOE Symposium on Low Permeability Gas reservoirs. 27-29 May 27-29, at Denver, CO. *SPE/DOE* paper no. 9872: 409-415.

Sampath, Krishnaswamy. 1982. A new method to measure pore volume compressibility of sandstones. Journal of Petroleum Technology (JPT)34-6: 1360-1362.

Sanders, Lee and Jim Bray. Date. The fracture Intensity log—a proven technique for evaluating fracturing in low permeability reservoirs. *SPE* no. 25894: 1-9.

Sanyal, S.K., H.J. Ramey, Jr. and S.S. Marsden. Jr. 1973. The effect of temperature on capillary pressure properties of rocks. *Transactions of the SPWLA Fourteenth Annual Logging Symposium. (6-9 May 1973):* paper N1-N16.

Saucier, Francois, Eugene Humphreys and Ray Weldon II. 1992. Stress near geometrically complex strike-slip faults: application to the San Andreas fault at Cajon Pass, southern California. American Geophysical Union (AGU) Journal of Geophysical Research (10 April)97-B4: 5081-5094.

Schechter, David S. and Ashish K. Banik. 1997. Integration of petrophysical and geological data with open-hole logs for identification of the naturally fractured Spraberry pay zones. Paper presented at the 1997 SPE Annual Technical Conference and Exhibition. 5-8 October, at San Antonio. TX. *SPE*: 715-724.

Schlumberger. 1972. *Log Interpretation Volume 1-Principles*. New York: Schlumberger Limited: 113.

Schmitt, D.R. and M.D. Zoback. 1989. Poroelastic effects in the determination of the maximum horizontal principal stress in hydraulic fracturing tests-a proposed breakdown equation employing a modified effective stress relation for tensile failure. *International Journal of Rock Mechanics & Mining Sciences & Geomechanics Abstracts* 26-6: 499-506.

Schmoker, James et al .1995. Gas plays of the U.S. Geological Survey 1995 national assessment that underlie regionally extensive surface volcanics. *U.S. Geological Survey Open File Report* no. 96-099: 1-13.

Schmoker, James. W. and Thaddeus S. Dyman. 1996. New, unconventional, technically recoverable United States gas resources for the short to intermediate term. *U.S. Geological Survey Open File Report* no. 96-066: 1-8.

Schowalter, Tim T. 1979. Mechanics of secondary hydrocarbon migration and entrapment. *AAPG Bulletin (May)* 63-5: 723-760.

Schubarth, S. M. Mullen and C. Kessler. 1998. Successful prediction of well productivity from openhole logs improves profitability in several Rocky Mountain formation: case histories. Paper presented at the SPWLA 39th Annual Logging Symposium. 26-29 May 26 –29. *SPWLA Transactions*: AA 1-AA12.

Schumacher, Ann L. 1979. Antelope, Greater Green River basin. Paper presented at Wyoming Oil and Gas Fields Symposium. Ed. W.A. Bradley, S.C. Champlin, J. Kennedy, O.P Miles. Jr., M.E. Smithwick and R.E. Walker. *WGA* I: 18-19.

Seeburger, Donald A. and Mark D. Zoback. 1992. The distribution of natural fractures and joints at depth in crystalline rock. *American Geophysical Union (AGU) Journal of Research (10 April)* 97-B4: 5517-5534.

Senseny, E. and T.W. Pfeifle. 1984. Chapter 41: Fracture toughness of sandstones and shales. In rock mechanics in productivity and production. Paper presented at the 25th Symposium on Rock Mechanics. 25-27 June 25-27. Ed. Charles H Dowding and Madan M. Singh, Society of Mining Engineers. *Piceance Basin Well Info*: 390-397

Shamir, Gadi, M.D. Zoback and F.J. Cornet. 1990. Fracture-induced stress: examples from the Cajon Pass scientific drillhole near the San Andreas fault, California. In *Proceedings of the International Symposium on Rock Joints, 4-6 June at Loen, Norway*, ed. N. Barton and O. Stephansson, pub. A.A. Balkema: 719-724,publ.

Shamir, Gadi. 1992. Stress orientation profile to 3.5 km depth near the San Andreas fault at Cajon Pass, California. *American Geophysical Union (AGU) Journal of Research (10 April)* 97-B4: 5059-5080.

Shanley, Keith W., R. M. Cluff and J. W. Robinson. 2004. Factors controlling prolific gas production from low-permeability Sandstone reservoirs: implications for resource assessment, prospect development, and risk analysis. *AAPG Bulletin (Aug)* 88:8:1083-1121.

Sharp, John M. , Jr. 1983. Permeability controls on aquathermal pressuring. *AAPG Bulletin* 67-11: 2057-2061.

Shaughnessy, Jack and R.H. Butcher. 1974. Geology of wagon wheel nuclear stimulation project, Pinedale field, Wyoming. *AAPG Bulletin* 58-11: 2250-2259.

Shaver, Michael A. and Brian F. Towler. 1997. Reservoir engineering for the Almond formation in the Standard Draw gas field in southern Wyoming. Paper presented at the 1997 SPE Rocky Mountain Regional Meeting. 18-21 May, at Casper, WY. *SPE* no. 38367: 195-202.

Shi, Yaolin and Chi-Yuen Wang. 1986. Pore pressure generation in sedimentary basins: overloading versus aquathermal. *American Geophysical Union (AGU) Journal of Research* 91-B2: 2153-2162.

Shuster, Mark W. and James R. Steidtmann. 1987. Fluvial-sandstone architecture and thrust-induced subsidence, northern Green River basin, Wyoming. In Recent developments in fluvial sedimentology, ed. Frank G. Ethridge, Romeo M. Flores, Michael D. Harvey, Jean N.. Weaver and Barbara H Lidz. *SEPM Special Publication* no.39: 279-285.

Shuster, Mark W. and James R. Steidtmann. 1988. Tectonic and sedimentary evolution of the northern Green River basin, Western Wyoming. In Geological Society of America interaction of the Rocky Mountain foreland and the Cordilleran thrust belt, ed. Christopher J. Schmidt and William J. Perry. Jr. *GSA Memoir* no. 171: 515-529.

Smith, Dan. 1990. Predicting a down dip water level using capillary pressure relationships. Paper presented to the SPWLA 31st Annual Logging Symposium. 24-27 June. *SPWLA Transactions* I: Z1-Z11.

Smith, Leta K. 1998. Formation water chemistry as a tool for studying compartmentalization: example from the Almond Formation. In Petrogenesis and Petrophysics of Selected Sandstone Reservoirs of the Rocky Mountain Region, ed. Roger M. Slatt. *Proceedings of 1998 RMAG Symposium*: 185-204

Smith, Leta K. and R.C. Surdam. 1998. Reservoir connectivity determined from produced water chemistry Standard Draw-Echo Springs gas field, Wyoming, U.S.A. Paper presented at 9th International Symposium on Water-Rock Interaction. 29 March-13 April, at Taupo, New Zealand. Ed. G.B. Arehart and J.R. Hulston. Paper no. 119:1-4.

Smith, Leta K., D.B. MacGowan and R.C. Surdam. 1991. Scale prediction during CO2 huff 'n' puff enhanced recovery, Crooks Gap field, Wyoming . Paper presented at SPE Rocky Mountain Regional Meeting and Low-Permeability Reservoir Symposium. 15-17 April, at Denver, CO. *SPE* no. 21838: 337-344.

Smith, Leta K., Thomas L. Dunn and Ronald C. Surdam. 1996. Cation geothermometry and the effect of organic-inorganic diagenetic reactions. In Siliciclastic diagenesis and fluid: concepts and applications. *SEPM Special Publication* no. 55: 49-58.

Sonnenberg, Stephen A. and Robert J. Weimer. 1993. Oil production from Niobrara formation, Silo field, Wyoming: Fracturing associated with a possible wrench fault system. *RMAG Mountain Geologist* 30-2: 39-53.

Spears, Russell W., and Jeffrey A. Nunn. 2000. Relationship between overpressured compartments and spatial variations in pore fluid salinity in sediments in South Marsh Island OCS 310, offshore Louisiana. *AAPG Bulletin* 84

Spencer, Charles W. 1984. Overpressured tight gas reservoirs in the Pinedale Anticline area, Sublette County, Wyoming. In Geological characteristics of low-permeability upper cretaceous and lower tertiary rocks in the Pinedale Anticline area, Sublete County, Wyoming, ed. Ben E. Law. *USGS Open File Report* no. 84-753: 51-59.

Stanton, Peter T. and Alan Byrnes 1994. Chapter 16: Measurement of independent variables-open-closed system variables. In Reservoir quality assessment and prediction in clastic rocks, ed. Michael D. Wilson. *SEPT Short Course* no. 30: 311-319.

Stone, Donald S. 1987. Northeast-southwest structural transect: Rocky Mountain foreland, Wyoming. *AAPG Bulletin* 71-8: 1015.

Street, Bill A. 1979. Patrick Draw (Arch unit). Paper presented at Wyoming Oil and Gas Fields Symposium. Ed. W.A. Bradley, S.C. Champlin, J. Kennedy, O.P Miles, Jr., M.E. Smithwick and R.E. Walker. *WGA Greater Green River Basin* II: 273 & 275.

Street, Bill A. 1979. Patrick Draw (Monell unit). Paper presented at Wyoming Oil and Gas Fields Symposium. Ed. W.A. Bradley, S.C. Champlin, J. Kennedy, O.P Miles, Jr., M.E. Smithwick and R.E. Walker. *WGA Greater Green River Basin* II: 274 & 276.

Street, Bill A. 1979. Patrick Draw (north). Paper presented at Wyoming Oil and Gas Fields Symposium. Ed. W.A. Bradley, S.C. Champlin, J. Kennedy, O.P Miles, Jr., M.E. Smithwick and R.E. Walker. *WGA Greater Green River Basin* II: 274 & 277.

Stright, D.H., Jr. and R.D. Robertson. 1993. An integrated approach to evaluation of horizontal well prospects in the Niobrara shale. SPE Rocky Mountain Regional/Low Permeability Reservoirs Symposium. 12-14 April, at Denver, CO. *SPE* no. 25923: 755-766.

Stueber, Alan M., Arthur H. Saller and Hisashi Ishida. 1998. Origin, migration, and mixing of brines in the Permian basin: geochemical evidence from the eastern central basin platform, Texas. *AAPG Bulletin* 82-9: 1652-1672.

Sturm, Stephen D. et al. 2001. Almond formation reservoir characterization and sweet spot analysis in Siberia Ridge field, Wyoming. In gas in the Rockies, ed. D.S. Anderson, John W. Robinson, Jane E Estes-Jackson and Edward B. Coalson. *RMAG*: 145-169.

Suchecki, R. K. and L. S. Land.1983. Isotopic geochemistry of burial-metamorphosed volcanogenic sediments, Great Valley sequence, No. Calif. *Geochim. Cosmochim. Acta* 47:1487-1499.

Sung, W. and T. Ertekin. 1987. Performance comparison of vertical and horizontal hydraulic fractures and horizontal boreholes in low permeability reservoirs: a numerical study. Paper presented at SPE/DOE Low Permeability Reservoirs Symposium. 18-19 May, at Denver. CO. *SPE/DOE* no. 16407: 185-193.

Surdam, Ronald C. 1992. Sandstone geometries, petrophysical characteristics, and pressure regimes, Mesaverde group, Green River basin, Wyoming. In Rediscover the Rockies, ed. Christopher E. Mullen. *Wyoming Geological Association (WGA) 43rd Field Conference Guidebook*: 167-169

Surdam, Ronald C. 1997. A new paradigm for gas exploration in anomalously pressured tight gas sands in the Rocky Mountain Laramide basins. Chapter 17: Seal, traps, and the petroleum system. *AAPG Memoir* no. 67 283-298.

Surdam, Ronald C. et al. 1989. Conceptual models for the prediction of porosity evolution with an example from the Frontier sandstone, Bighorn basin, Wyoming. In Petrogenesis and Petrophysics of Selected Sandstone Reservoirs of the Rocky Mountain Region, ed. Edward B. Coalson. *RMAG* no. 7-28: 300-303.

Surdam, Ronald C. et al. 2001. Chapter 13: Delineation of Jonah field using seismic and sonic velocity interpretations. In Gas in the Rockies, ed. D.S. Anderson, John W. Robinson, Jane E Estes-Jackson and Edward B. Coalson. *RMAG*: 189 -208.

Surdam, Ronald C., Steven W. Boese and Laura J. Crossey. 1984. The chemistry of secondary porosity. In Clastic diagenesis, ed. D. McDonald and R.C. Surdam. *AAPG Memoir* no. 37: 127-149.

Surdam, Ronald C., Zung S. Jiao and Jie Liu. 1995. Pressure regime in the upper cretaceous shales and sandstones in the Washakie basin, Wyoming. In Resources of southwestern Wyoming, ed. Richard W. Jones. *WGA 1995 Field Conference Guidebook*: 205-223.

Surdam, Ronald C., Zunsheng Jiao and Yuri Ganshin. 2004. Reducing the risk of exploring for anomalously pressured gas assets. GasTIPS10-1: 4-8.

Swanson, B.F. 1981. A simple correlation between permeabilities and mercury capillary pressures. *Journal of Petroleum Technology (JPT) (Dec):* 2498-2504.

Tannich, J.D. 1975. Liquid removal from hydraulically fractured gas wells. *Journal of Petroleum Technology (JPT) (Nov)*: 1309-1317.

Terrasciences. 2004. *TerraStation™ Online Help Manual*. Available from http://www.terrasciences.com/faqs.htm: INTERNET.

Teufel, Lawrence W. 1991. Permeability of naturally fractured reservoirs. *AAPG Bulletin* 75-3: 680.

Thomas, A.L. 1993. Poly3D: a three-dimensional, polygonal element, displacement discontinuity boundary element computer program with applications to fractures, faults, and cavities in the Earth's crust. Master's thesis, Stanford University, Stanford, CA.

Thomas, Rex D. and Don C. Ward. 1972. Effect of overburden pressure and water saturation on gas permeability of tight sandstone cores. *Journal of Petroleum Technology (JPT) (Feb):* 120-124.

Thomasen, J.B., E.J.M. Willemse and C. Sonderskov. 1997. Improved quantification of matrix block shape and size for simulation of naturally fractured reservoirs. *AAPG Bulletin* 81-8: 1416.

Thomeer, J.H.M. 1960. Introduction of a pore geometrical factor defined by the capillary pressure curve. *Petroleum Transactions of AIME (American Institute of Mining, Metallurgical ad Petroleum Engineers)* 219: 354-358.

Thomeer, J.H.M. 1983. Air permeability as a function of three pore-network parameters. *Journal of Petroleum Technology (JPT) (April):* 809-814.

Thompson, Hugh A., ed. 1992. Proceedings of 1992 Gas Research Institute (GRI) International Gas Research Conference. 16-19 November, at Orlando, FL. I: 1-1330.

Thompson, Hugh A., ed. 1992. Proceedings of 1992 Gas Research Institute (GRI) International Gas Research Conference. 16-19 November, at Orlando, FL. II: 1-1331-2592.

Thorez, J., D. Bossiroy, R.M. Flores and C.W. Keighin. 1992. Clay paragenesis and petrology of sandstone reservoirs, Fuller Reservoir field, Wind River basin, Wyoming. *AAPG Bulletin* 76-8: 1269.

Topper, Ralf et al. 2003. Chapter 6.2: Piceance basin. In Ground water atlas of Colorado. *Colorado Geological Survey Special Publication* no. 53: 97-108.

Topper, Ralf et al. 2003. Chapter 6.4: Sand Wash basin. In Ground water atlas of Colorado. *Colorado Geological Survey Special Publication* no. 53: 115-122.

Torgersen, Thomas and W. B. Clarke. 1992. Geochemical constraints on formation fluid ages, hydrothermal heat flux, and crustal mass transport mechanisms at Cajon Pass. *American Geophysical Union (AGU) Journal of Research (10 April)* 97-B4: 5031-5038.

Tuncay, Kagan and M. Yavuz Corapcioglu. 1995. Effective stress principle for saturated fractured porous media. *American Geophysical Union (AGU) Water Resources Research (Dec)* 31-12: 3103-3106.

Tuncay, Kagan et al.2000. The salt-fault-fracture connection. AAPG Bulletin84

Tuncay, Kagan et al.2002. Pits, outgrowths, and inclusions as coated grain kinetic instabilities. *The Geochemical Society and the Meteoritical Society Geochimica et Cosmochemica Acta* 66-22: 3901-3912.

Tuncay, Kagan, A. Park and P. Ortoleva. 2000. A forward model of three-dimensional fracture orientation and characteristics. *American Geophysical Union (AGU) Journal of Research* 105-B7: 16,719-16,735.

Tuncay, Kagan., A. Park and P. Ortoleva. 2000. Sedimentary basin deformation: an incremental stress approach. *Tectonophysics* 323- 1 & 2: 77-104.

Twiss, Robert J and Eldridge M. Moores. 1992. Griffith fracture criteria. In 9.7: Mechanics of fracturing and faulting. *Structural Geology*: 181-185

Tyler, Roger et al. 1995. Coalbed gas potential of the Greater Green River basin, southwest Wyoming and northwest Colorado. Paper presented at INTERGAS '95 Conference. 15-19 May, at University of AL, Tuscaloosa, AL. Paper no. 9502: 23-38.

Tyler, Roger et al.1997. The potential for coalbed gas exploration and production in the greater Green River basin, southwest Wyoming and northwest Colorado. *RMAG Mountain Geologist* 34-1: 7-24.

Vairogs, Juris et al.1971. Effect of rock stress on gas production from low-permeability reservoirs. *Journal of Petroleum Technology (JPT) (Sept):* 1161-1167.

Vavra, Charles L., John G. Kaldi and Robert M Sneider. 1992. Geological applications of capillary pressure: a review. *AAPG Bulletin* 76-6: 840-850.

Vernik, Lev and Amos Nur. 1992. Petrophysical analysis of the Cajon Pass scientific well: implications for fluid flow and seismic studies in the continental crust. *American Geophysical Union (AGU) Journal of Research (10 April)* 97-B4: 5121-5134.

Vernik, Lev and M.D. Zoback. 1990. Strength anisotropy in crystalline rock: implications for assessment of in situ stresses from wellbore breakouts, rock mechanics contributions and challenges. Eds. W.A. Hustrulid and G.A. Johnson. *Proceedings of the 31st U.S. Symposium, Golden, Colorado. (18-20 June)*, Pub. A.A. Balkema: 841-848.

Vernik, Lev and Mark D. Zoback. 1992. Estimation of maximum horizontal principal stress magnitude from stress-induced well bore breakouts in the Cajon Pass scientific research borehole. *American Geophysical Union (AGU) Journal of Research (10 April)* 97-B4: 5109-119.

Verrecchia, Eric P. 1995. On the relationship between the pore-throat morphology index (a) and fractal dimension (df) of pore networks in carbonate rocks-discussion with David C. Kopaska-Merkel. *SEPM Journal of Sedimentary Research* A65-4: 701-702.

Vincelette, Richard R. and Norman H. Foster. 1992. Fractured Niobrara of northwestern Colorado. Eds. J.W. Schmoker, E.B. Coalson and C.A. Brown. *Rocky Mountain Association of Geologists Geological Studies Relevant to Horizontal Drilling—Examples from Western North America*: 227-242.

Voegeli, Paul T., Sr. 1971. Hydraulic testing and sampling of water well Number 1, project Wagon Wheel, Sublette County, Wyoming. *USGS Open File Report 71-311* (Prev. called USGS 474-87).

Voneiff, G.W. and Craig Cipolla. 1996. A new approach to large-scale infill evaluations applied to the OZONA (Canyon) gas sands. *SPE* no. 35203: 9-24.

Walls, Joel D. 1981. Tight gas sands: permeability, pore structure and clay. Paper presented at 1981 SPE/DOE Symposium on Low Permeability Gas Reservoirs. 27-29 May, at Denver, CO. *SPE/DOE Proceedings* paper no. 9871: 399-407.

Walls, Joel D., Amos M. Nur and Thierry Bourbie. 1982. Effects of pressure and partial water saturation on gas permeability in tight sands: experimental results. *Journal of Petroleum Technology (JPT) (April):* 930-936.

Walsh, J. B. 1963. The effect of cracks on the compressibility of rock. *American Geophysical Union (AGU) Journal of Research (15 Jan)* 70-2: 381-389.

Walsh, J. B. 1963. The effect of cracks on the uniaxial compression of rocks. *American Geophysical Union (AGU) Journal of Research (15 Jan)* 70-2: 399-411.

Wangen, Magnus. 2002. Effective permeability of hydrofractured sedimentary rocks, hydrocarbon seal quantification. Paper presented at Norwegian Petroleum Society (NPS) Conference. 16-18 October 2000. *NPS Special Publication* no. 11: 61-74.

Wanty, Richard B., Peter F. Folger and Paul H. Briggs. 1993. Ground-water chemistry of the coal-bearing upper cretaceous Mesaverde formation, Wind River Reservation, Wyoming. Paper presented at 1993 WGA Special Symposium on Oil and Gas and Other Resources of the Wind River Basin, Wyoming, ed. Wm R. Keefer, William J. Metzger and Larry H. Godwin. *Wyoming Geological Association (WGA) Guidebook*: 271-279.

Waples, Douglas W. 2002. Evolution of sandstone porosity through time. the modified Scherer model: a calculation method applicable to 1-D maturity modeling and perhaps to reservoir prediction. *International Association for Mathematical Geology Natural Resources Research (Dec)* 11-4: 257-272.

Ward, Jill S. and Norman R. Morrow. 1987. Capillary pressures and gas relative permeabilities of low-permeability sandstone. *SPE Formation Evaluation (Sept):* 345-356.

Wardlaw, N.C. 1982. The effects of geometry, wettability, viscosity and interfacial tension on trapping in single pore-throat pairs. *Journal of Canadian Petroleum Technology (May-June)* 21-3: 21-27.

Warner, Edward M. 1997. A structural model for shallower emplacement of gas in overpressured basin centers: Jonah field as a previously undetected abnormally pressured structural trap. *AAPG Bulletin* 81-7: 1236.

Warner, Edward M. 2000. Structural geology and pressure compartmentalization of Jonah field based on 3-D seismic data and subsurface geology, Sublette County, Wyoming. *RMAG Mountain Geologist (Jan)* 37-1: 15-30.

Warpinski, Norman R. 1989. Elastic and viscoelastic calculations of stresses in sedimentary basins. *SPE Formation Evaluation* 4:522-530.

Warpinski, Norman R. 1993. Chapter 34: Case study of hydraulic fracture experiments at the multiwell experiment site, Piceance basin, Colorado, USA. In Rock testing and site characterization, ed. John A. Hudson (Pergamon Press). *Comprehensive Rock Engineering—Principles, Practice & Project* 3: 811-837.

Warpinski, Norman R. and L.W. Teufel. 1987. In situ stresses in low-permeability, nonmarine rocks. *SPE/DOE* no. 16402: 125-138.

Warpinski, Norman R. et al. 1985. Fracturing and testing case study of Paludal. In Tight, lenticular gas sands in low permeability gas reservoirs. *SPE/DOE Symposium Proceedings* no. 13876: 267-278.

Warpinski, Norman R. et al.1987. Fracturing and testing case study of Paludal, tight, lenticular gas sands. *SPE Formation Evaluation* 2-4: 535-545.

Warpinski, Norman R., Paul Branagan, Roy Wilmer. 1985. In situ stress measurements at U.S. DOE's multiwell experiment site, Mesaverde group, Rifle, Colorado. *Journal of Petroleum Technology (JPT)* 37-3: 527-536.

Webb, et al. 2004. Petrology and petrophysics of the Lance formation (upper Cretaceous), American Hunter, Old Road Unit 1, Sublette County, Wyoming. In *Johan Field: Case Study of a Tight-Gas Fluvial Reservoir*. Ed. J. W. Robinson and K. W. Shanley. Rocky Mountain Association of Geologists: no. 52:183-213.

Weimer, Robert J. 1995. Stratigraphic plays of the 1950s on the Wamsutter Arch: discovery of Desert Springs, Patrick Draw and West Desert Springs fields. *WGA 1995 Field Conference Guidebook*: 1-11.

Wel, K.K., N.R. Morrow and K.R. Brower. 1986. Effect of fluid, confining pressure, and temperature on absolute permeabilities of low-permeability sandstones. *SPE Formation Evaluation (Aug):* 413-423.

Wesson, Robert L. 1988. Predicted variation of stress orientation with depth near an active fault: application to the Cajon Pass scientific drillhole, southern California. *American Geophysical Union (AGU) Research Letters (August supplement)* 15-9: 1009-1012.

Westbrook, L. Paul and W. John Lee. 1971. Average water saturation from capillary pressure data. *Transactions of the SPWLA Twelfth Annual logging Symposium (2-5 May 2-5):* F 1-F 12.

Williams, Peggy. 2001. The Pinedale anticline. *Oil and Gas Investor (Dec*): 2-5.

Wilson, Michael D. 1994. Chapter 17: Measurement of independent variables—hydrocarbon emplacement, clay content, textural measurements. In Reservoir quality assessment and prediction in clastic rocks, ed. Michael D. Wilson. *Short Course 30*: 321-327.

Wilson, Michael S. et al. 1998. Abnormal pressures encountered in a deep wildcat well, south Piceance basin, Colorado. Chapter 12: Abnormal pressures in hydrocarbon environments, ed. B.E. Law, G.F. Ulmishek and V.I. Slavin. *AAPG Memoir* no. 70: 195-214.

Wyoming Oil and Gas Conservation Commission (WOOCC) website. Available at www.wogcc.state.wy.us): INTERNET

Yassir, Najwa and M. Anthony Addis 2002. Chapter 8: Relationships between pore pressure and stress in different tectonic settings, pressure regimes in sedimentary basins and their prediction, ed. Alan R. Huddman and Glenn L. Bowers. *AAPG Memoir* no. 76: 79-88.

Yin, Peigui, Jie Liu and Ronald C. Surdam. 1992. Petrographic and petrophysical properties of the Almond sandstone in the Washakie basin. In Rediscover the Rockies, ed. Christopher E. Mullen. *Wyoming Geological Association (WGA) 43rd Field Conference Guidebook*: 191-205.

Young, Genevieve B.C. and G.W. Paul. 1992. Reservoir characterization of Mary Lee and Black Creek coals at the Rock Creek field laboratory, Black Warrior basin. *ARI Topical Report for Contract 5091-214-2316*.

Young, Genevieve B.C., G. W. Paul and V.A. Kuuskraa. 1995. In National Assessment of United States Oil and Gas Resources. *ARI Technical Report:--Reservoir Simulation Study of U.S. Coalbed Methane*.

Yu, Zhihuai, Ian Lerche and Allen Lowrie. 1991. Modeling fracturing and faulting within sediments around rapidly moving lateral salt sheets. *AAPG Bulletin* 75-11: 1772-1778.

Yuan, H.H. 1991. Pore-scale heterogeneity from mercury porosimetry data: discussion. *SPE Formation Evaluation* 6-2: 233-240.

Yuan, H.H. 1991. Pore-scale heterogeneity from mercury porosimetry data: reply. *SPE Formation Evaluation* 6-2: 242.

Zoback, Mark D and J.D. Byerlee. 1973. The effect of confining pressure and pore pressure on the permeability of Berea sandstone. *EOS* 54-11: 1209.

Zoback, Mark D and J.D. Byerlee. 1975. Permeability and effective stress. *AAPG Bulletin* 59-1: 154-159.

Zoback, Mark D and R.S. Wesson. 1983. Modeling of coseismic stress changes associated with the 1975 Oroville earthquake. *EOS (8 Nov)* 78-46: 834.

Zoback, Mark D. 1991. State of stress and crustal deformation along weak transform faults. *Philosophical Transactions of the Royal Society of London* 337-1645: 141-150.

Zoback, Mark D. 1996. Critically-stressed faults, in situ stress and fluid flow-contrasting the Gulf of Mexico with other regions of active faulting. *AAPG 1996 Annual Meeting Abstracts* Appendix: 159.

Zoback, Mark D. and A. H. Lachenbruch. 1992. Introduction to special section on the Cajon Pass scientific drilling project. *American Geophysical Union (AGU) Journal of Research (10 April)* 97-B4: 4991-4994.

Zoback, Mark D. and J.D. Byerlee. 1975. Dilatancy in westerly granite under cyclic differential stress. *EOS* 55-12: 1195.

Zoback, Mark D. and J.D. Byerlee. 1975. The effect of cyclic differential stress on dilantancy in westerly granite under uniaxial and triaxial conditions. *American Geophysical Union (AGU) Journal of Research (10 April)* 80-11: 1526-1530.

Zoback, Mark D. and J.D. Byerlee. 1975. The effect of microcrack dilantancy on the permeability of westerly granite. *American Geophysical Union (AGU) Journal of Research* 80-5: 752-755.

Zoback, Mark D. and J.D. Byerlee. 1975. The effect of stress on the permeability of the westerly granite. *EOS* 55-4: 431.

Zoback, Mark D. and J.D. Byerlee. 1976. A note on the deformational behavior and permeability of crushed granite. *International Journal of Rock Mechanics & Mining Sciences & Geomechanics Abstracts* 13-10: 291-294.

Zoback, Mark D. and John H. Healy. 1992. In situ stress measurements to 3.5 km depth in the Cajon Pass scientific research borehole: implications for the mechanics of crustal faulting. *American Geophysical Union (AGU) Journal of Research (10 April)* 97-B4: 5039-5057.

Zoback, Mark D., D. Moos and D.E. Stephenson. 1989. State of stress and the relation to tectonics in the Central Savannah River area of south Carolina. In Rock mechanics as a guide for efficient utilization of natural resource, ed. A. Wahab Khair. *Proceedings of the 30th U.S. Symposium. Morgantown, West Virginia (11-19 June 1989)*, pub. A.A. Balkema: 553-559.

Zoback, Mark D., Daniel Moos and Larry Mastin. 1985. Well bore breakouts and in situ stress. *American Geophysical Union (AGU) Journal of Research (10 June)* 90-B7: 5523-5530.

Zoback, Mark D., Hiroaki Tsukahara and Stephen Hickman. 1980. Stress measurements at depth in the vicinity of the San Andreas fault: implications for the magnitude of shear stress at depth. *American Geophysical Union (AGU) Journal of Research (11 Nov)* 85-B11: 6157-6173.

Zoback, Mark D., S. Hickman and D. Moos. 1980. In situ measurements in a ~1 km deep well near the San Andreas fault in the western Mohave Desert. *EOS (11 Nov)* 61-46: 1032.

Zoback, Mark, D. and Pavel Peska. 1995. In situ stress and rock strength in the GBRN/DOE pathfinder well, South Eugene Island, Gulf of Mexico. In SPE 29233 revised*. Journal of Petroleum Technology (JPT) (July,* 47-7: 582-585.

Zoback, Mark. D., A.W. Chan and J.C. Zinke. 2001. Production-induced normal faulting. In Rock mechanics in the national interest, ed. Derek Elsworth, John Tnucci and Keith A. Heasle. *Proceedings of the 38th U.S. Rock Mechanics Symposium* (7-10 July 2001) I: 157-163.

Zoback, Mary Lou and Mark D. Zoback. 1985. Uniform one to one maximum horizontal compressive stress throughout mid-plate North America. *EOS* 66-46: 1056.

Zoback, Mary Lou and Mark D. Zoback. 1989. Tectonic stress field of the continental United States. Chapter 24: Geophysical framework of the continental United States, ed. L. C. Pakiser and Walter D. Mooney. *GSA Memoir* no. 172:523-539.

Zoback, Mary Lou. 1989. State of stress and modern deformation of the northern basin and range province. *American Geophysical Union (AGU) Journal of Research (10 June)* 94-B6: 7105-7128.

ACRONYMS AND ABBREVIATIONS

ACRONYMS AND ABBREVIATIONS

ALMD_SH2 ... Almond formation

API .... American Petroleum Institute

ARI .... Advanced Resources Inc.

Bbl .... barrel

bcf .... billion cubic feet

BHPBU .... bulk wellbore scale production permeabilities

BVW_F .... bulk volume water = SWT_F * PHIE_F

bwpd .... barrels of water per day

CAL_BS .... caliper-bit size difference

CEC .... cation exchange capacity

CEC1 .... CEC calculation from porosity

COAL_FLG ... coal flag

COALFLGT ... TDT coal flag

CTE .... coefficient of thermal expansion

DFN .... discrete fracture network

DST .... drill stem test

elog .... electric log

EHS .... effective horizontal stress

EVS .... effective vertical stress

E&P .... exploration and production

fm .... formation

GGRB .... Greater Green River Basin

GIP .... gas-in-place

GIS .... Geographic Information Systems

GRL............... gamma ray linear

GRN1 .... normalized gamma ray

GWB............. gas-water boundary

IGIP............... initial gas-in-place

k .... permeability

kh .... permeability-feet

K_PHI_HI ...... high core porosity-permeability trend

K_PHI_LO..... low core porosity-permeability trend

K_PHI_MD .... medium core porosity-permeability trend

K_PHI_VC..... permeability from modified Timur-Coates equation (PHI & Vclay)

MD................ measured depth

md .... millidarcies

md/pu .... millidarcies/porosity unit

MMcfd .... millions of cubic feet per day

MWX .... multi-well experiment

nms .... net mean stress

NPHILS .... NPHI in limestone units

NPHISS......... NPHI in sandstone units

OGIP .... original gas in place

ohm-m........... ohm meters

phi .... porosity

PHIE.............. effective density porosity

PHIE_D1 .... PHIT_D1 * (1-Vclay)

PHIE_DF....... final effective density porosity (edited for clay, coal & washouts)

PHIE_DG1 .... PHIT_DG1 * (1-Vclay)

PHIE_F.......... final effective porosity

PHIE_ND1..... PHIT_ND1 * (1-Vclay)

PHIE_NDF .... final effective density porosity (edited for clay, coal & washouts)

PHIE_PN3..... final corrected TDT porosity

PHIT_AVG .... average of PHIT_MX and PHIT_VSH

PHIT_D1 .... total density porosity, grain density = 2.68g/cc

PHIT_DG1..... total density porosity with variable grain density and SXO gas correction

PHIT_MX....... maximum porosity based on Vshale-Porosity trend

PHIT_ND1..... total neutron-density crossplot porosity

PHIT_ND2..... total porosity form sum of squares of NPHI and DPHI

PHIT_VSH..... porosity derived from Vshale-porosity trend

ppm .... parts per million

PRES1 .... pressure curve

psi.................. pounds per square inch

QC................. quality control

Qv.................. cation exchange concentration

QV1............... Qv calculation from CEC & porosity

RCP............... Reservoir Characterization Project

RES_FLG1.... reservoir flag

RHOBS .... environmentally corrected & shifted density

RHOMAT....... density of matrix by stratigraphic interval

Ro.................. vitrinite reflectance in oil

RTratDS .... ratio of deep/shallow resistivity

RTratSD .... ratio of shallow/deep resistivity

Rw................. formation water resistivity

RW_Rmf1...... resistivity of mud filtrate

SEM .... scanning electronic microscope

SP .... spontaneous potential (log)

SPE.............. Society of Petroleum Engineers

SQL.............. structured query language

Sw................ water saturation

SW_ARC1..... Archie water saturation in Almond gas zone (1.0, 1.74, 2.00, 0.46 @ 68F)

SW_ARC2..... Archie water saturation in Almond Aquifer (1.0, 1.74, 2.00, 1.74 @ 68F)

SW_ARC3..... Archie water saturation in Erickson (1.0, 2.00, 2.00, 1.74 @ 68F)

SW_DWT1 .... water saturation from dual water equation

SW_SIM1...... water saturation from Simandoux equation

SW_WS2....... water saturation from Waxman-Smits equation

SWT_F.......... final merged water saturation

Sxo............... water zone saturation

SXO_ARC1... Archie water saturation for using RW_Rmf & shallow resistivity

tcf................. trillion cubic feet

TD .... total depth

TDS.............. total dissolved solids

TDT.............. thermal decay time

TDT_RT .... TDT resistivity derived from the sigma curve

TDTratFN...... ratio of TDT far/near counts

TDTratNF ...... ratio of TDT near/far counts

TEMP1 .... temperature Curve

TGRN............ TDT normalized gamma ray

TPHI............. cased hole pulsed neutron porosity

TSW_WS1 .... TDT water saturation from Waxman-Smits equation

TVD.............. true vertical depth

USGS............ United States Geological Survey

VCLSTB........ volume clay by Steiber method

Vr................... vitrinite reflectance

VSH............... volume shale

VSHGRL .... volume shale by gamma ray linear method

WRB.............. Wind River Basin

APPENDICES

A. Database

- Database_Readme
- Database_Access
- Database_CSV
- Database_DBF
- Database_XLS

B. Atlas of Maps

- ArcReader Install
- Digital Atlas

C. Produced Water Geochemistry

D. Working Model for Reservoir Development

E. Wild Rose Field Petrophysics

F. Wild Rose Reservoir Simulation