

Naturally Fractured Tight Gas Reservoir Detection Optimization

Quarterly Report

October 1 - December 31, 1994

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For
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**U.S. DEPARTMENT OF ENERGY
MORGANTOWN ENERGY TECHNOLOGY CENTER
QUARTERLY STATUS REPORT
FOR THE PERIOD
September 1, 1994- December 31, 1994
DATE OF SUBMISSION: 1/30/95**

CONTRACT NO.:
DE-AC21-93MC30086

CONTRACTOR:
Advanced Resources International, Inc.

CONTRACT NAME:
Naturally fractured tight gas
reservoir detection optimization

CONTRACT PERIOD:
September 30, 1993-March 31, 1997

CONTRACT OBJECTIVE: No Change

TECHNICAL APPROACH CHANGES: No Change

TASK NO. 1:

A. SUBCONTRACTS

Indiana University-Laboratory for Computational Geochemistry:

1. Three-Dimensional Basin Simulator:

A fracturing module has been successfully implemented that allows subcritical fracture nucleation and growth initiation when fluid pressure exceeds the magnitude of the least principal stress. System permeability and porosity correspondingly increase upon fracturing. The fracturing module of the pressure solver is completed and tested, and will be calibrated using Piceance Basin data. A new algorithm that solves directly for pressure, instead of indirectly for overpressure, has been implemented and verified with analytical tests. A source of computational

inaccuracy in the temperature equation, which was causing the code to fail during simulation, was found and corrected. A new solver, using the partial pivoting method, was developed reducing numerical rounding error. Also, coordinates were changed from elliptical to rectilinear in order to agree with the coordinate systems of other program modules being developed. An improvement was made on the water-film diffusion pressure solution rate law. By developing an expression for the diffusion coefficient, this accounts for the difference between surface bound and free water at the grain-grain contact. In addition, the code is being parallelized in order to have the capacity to account for more complex internal sediment geometry within the basin.

Testing is completed on the pressure solver using an improved curvilinear coordinate method. The routine is working correctly. Work has begun on improving the accuracy of the pressure solver by solving for a five-diagonal matrix, instead of a three-diagonal matrix. These improvement techniques will be applied to the temperature solver once they have been verified. A new algorithm for calculating the numerical derivatives, based on a curvilinear coordinate method, has been developed for the pressure solver. This algorithm allows for nine orders of magnitude better resolution than the previously used algorithm and accurately accounts for changes between fine-scale grid spacing and coarser-scale grid spacing at sharp lithologic contacts, to which the grid has been adapted. This allows for successful computation of fluid pressure across lithologic contacts.

2. Stress Solver:

A smoothing technique has been implemented in the stress solver in order to reduce numerical noise. Extremely-fine grid spacing is required for accurate simulation and improvement of the grid optimization algorithm appears necessary. The code is being methodically reworked to determine if errors in code construction are contributing to numerical inaccuracy. The elastic module of the finite element stress solver has been completed. Preliminary comparison between the predictions of the finite element code, and analytical solutions for simple and/or published results, suggests that the second order finite element method in use is ideal for simulating basin stresses and deformation. The next step will involve stress analysis of the Piceance Basin and refinement of the code to reduce computing time.

The visco-elastic module of the finite element stress solver has been completed and agrees with published results. An effort is currently being placed on determining the best linear solver for efficiently analyzing more heterogeneous media. An improved iterative solver for the visco-plastic module of the finite element stress solver has been implemented. Work has started on testing of the solver using Piceance Basin stratified rheology and realistic basin compressional and extensional forces. When testing is completed, work will commence on refining the code to operate with a variable gridding density. Several faster iterative solvers were tested for the visco-plastic module of the finite element stress solver. A satisfactory solver improves the speed and efficiency of computations over the direct solver originally used, and is currently being implemented.

Boundary condition discretization for the finite difference stress solver has been redesigned to have second order accuracy. Originally, the boundary conditions were numerically modeled using first order numerical difference approximations, whereas the interior of the simulation domain was discretized using the more accurate second order numerical discretization. The new approach avoids inaccuracies in the boundary conditions propagating into the interior, and allows more consistent and accurate calculations throughout the entire domain.

3. Two-Dimensional Basin Simulator:

Coding of the fracture mechanics module has been completed. The module was calibrated by matching simulation results with published experimental results. The infilling module is 25% completed and will simulate the precipitation of authigenic phases in fractures. Work has recommenced on the solute transport module, with emphasis placed on finding appropriate numerical methods. The planned approach is the one shown to be successful for the pressure solver, which is based on a curvilinear coordinate approach. Additional improvements have been made to the user interface module in order to facilitate creating chemical and geological input files.

4. Organic Reactions and Multi-Phase Flow

Work continues on solving the mass-balance and chemistry of the system, combined with two-phase flow, and should be completed shortly, assuming no fundamental problems with the

algorithm. The algorithm for the multi-phase flow module has been significantly accelerated by changing the parameters for relative permeabilities of gas and water in the rock and for reaction rates of organic phases. Time step sizes have increased from approximately 500 to 10,000 years. Work is beginning on using another algorithm, based on the Newton-Raphson method, for solving multi-phase flow. Its generality allows for a wider range of gas saturations, and more complete aqueous-gas-oil and other phase compositions and reaction processes. Improvements in the multi-phase equilibrium solver, based on simulated annealing, have been made, greatly improving the efficiency of convergence. This module is to be embedded in the multi-phase reaction-transport code.

5. Grid Optimization:

The routine to adapt a grid to a digitized image, or one created by using a standard desktop graphics package, has been completed. It can take irregularly shaped boundaries in a cross-section and increase the number of grids in those locations to enhance resolution at lithologic contacts and boundaries. As the routine was originally prohibitively slow (requiring several days of computation), it has been redesigned to operate much faster (less than one hour of computation). In addition, a method of partial splitting of grids is being developed. This will allow gridding to be refined even more intensely in areas of interest (e.g. the MWX site), and allows better control on local grid density. This should further increase the computation speed when the grid is used to solve differential equations. To make the interface more user-friendly, a routine is being developed to adapt a grid to a digitized image, using images created by standard desktop graphical packages or scanned images.

6. Database Calibration and Data Input:

Work continues on establishing histories and compiling lithologic information for various sites within the basin. Input files for several sites were created for three-dimensional simulation. The sediment input module was modified to dynamically add grid points in three dimensions. Work continues on the program which interpolates input data between wells for use in CIRF.B sediment input and computational format. The burial history interpolation algorithm has been completed, and additional work is being expended on development of an interpolation algorithm for

the lithologic data. Work continues on the program which interpolates input data between wells for the CIRF.B3 sediment and tectonic history input format. Input files for the Piceance Basin for the combined general chemistry and pressure solver are being created, and preliminary runs with these files should begin in the next month. In order to allow for greater flexibility in the computational grid (including the possibility of dynamically adding new grids) the code was arranged to make both the sediment input and calculation grids computationally independent.

A graphical interface for the CIRF.B* codes is almost completed, and should be completed in the next month. The database manager "Sybase" will be installed next month. The system manager is currently learning how to operate it and is customizing simple commands to make it easier to use for those entering and retrieving data for simulation input.

Several published cross sections were collected, representing different areas of the basin and different stratigraphic intervals, in order to facilitate constructing a three-dimensional image of the basin at a sequence of times. In addition, research and collection of publications containing lithologic information continues, with special emphasis on the Tertiary and younger units (e.g. the Wasatch Formation and the Green River Formation). In addition, physico-chemical data (e.g. rock mechanics data) is being collected on a variety of sedimentary rock types and degrees of lithification. This data will be used to develop and parameterize phenomenological laws relating elasticities, viscosities, and yield criteria to grain size, shape, number density and mineralogy, for use by the three-dimensional stress modules.

7. Piceance Basin Initial Simulations:

A preliminary one-dimensional simulation has been successfully completed. This simulation utilized a four-mineral system (quartz, microcline, albite, and kaolinite) taken from the Mesaverde units lithologic composition data from the MWX site. Lithologic compositions for other units were chosen based on generic lithology types. Results show that porosity trends do not correspond well with those at the MWX site, although the relative mineral modes are similar. We believe that simulations to improve less well defined parameter values, such as those affecting water film thickness, as well as the inclusion of a more complete suite of minerals, will give better agreement.

World Geoscience:

The aeromagnetic survey commenced in October and was completed in mid-November. There were significant amounts of aircraft downtime, primarily caused by adverse weather conditions that made flying hazardous. Because the contract is fixed-price, this downtime did not affect the cost of the survey. Overall, data quality is excellent. A preliminary data set of two maps (total magnetic intensity and total magnetic residual) was made available in late December for comparison with seismic-mapped faults and structures. Detailed data and analyses will be available near the first of February. Preliminary study of the data sets indicates that the aeromagnetic survey accurately images basement geometry and reveals the location of several basement fault zones. Work in progress is continuing with the interpretation and integration of this data set with seismic and other subsurface control.

B. GEOLOGIC ASSESSMENT OF THE PICEANCE BASIN

The geologic assessment phase of the project involved several primary sub-tasks as discussed below.

Geologic Interpretation:

Structural Analysis:

Final revisions were made to the tectonic evolution chart. A regional synthesis map of all tectonic structures was created by digitizing all USGS Geologic Quadrangle (GQ-series) and USGS Miscellaneous Field Investigations (MF-series) maps throughout the basin. This information was integrated with other published sources to recognize the dominant trends and timing relationships of these structures throughout the basin. This information will also be used to determine the character of many of the remote sensing interpreted linear features to minimize the need for field-verification of all linear features interpreted for this study.

Structural analysis of the basin has initially focused on delineating the timing of deformation on the major structures within and around the basin from the Precambrian to the Present-day. Work in progress is attempting to delineate the orientation of fractures that were

produced during each tectonic phase and the relationship between pre-existing structures and later fractures.

A more complete modern-day stress map of the basin was generated that shows the orientation of the principal horizontal stress throughout the basin. This map is extremely important because it is the modern-day stress that dictates which fractures are open or closed in the subsurface. The orientation of hydraulic stimulation fractures also parallels the maximum horizontal stress so that possessing the stress orientation *a priori* will allow some estimation to be made of the likelihood of intersecting natural fracture sets with the stimulation.

Research effort has concluded on the creation of a new structural map of the southeastern Piceance Basin to update the earlier work of Johnson (1983). This new map contains updated structural data obtained during the past ten years of exploration and development drilling. This map area expands from the Parachute-Rulison area to better define regional trends. In addition, it serves to fully delineate the NW-trends in the eastern basin. In the process of making this map for the top of the Rollins Sandstone member of the Iles Formation, additional stratigraphic picks were made for the Cozzette and Corcoran members and for the top of the Mesaverde Group. The collection of this additional data will allow us to contrast the differences between structural datums and will provide insight into the structural evolution of the basin. The top of the Mesaverde (Cretaceous-Tertiary unconformity boundary) will be especially informative because it has not been previously studied with as much well control as we have for this area. The planarity of this surface and its suitability as a structural datum will be more fully documented as a result of our work. Work in progress is revising these maps to eliminate sources of error from incorrect kelly bushings, incorrect stratigraphic picks and other problems. It is estimated that final versions will be completed by the end of October. In addition the collected data will allow isopach/isochore maps to be made of the Corcoran, Cozzette, Rollins and total Mesaverde Group package. These maps can be used to determine depositional systems evolution for each of these various intervals.

A fortuitous additional benefit realized by this mapping was the ability to completely update our existing computer databases, merging various data sets to create a unified system available for basin analysis. In the process, extensive error checking was performed to insure data accuracy and database integrity.

Reservoir Characterization:

Detailed production maps were made of Grand Valley, Parachute and Rulison fields. Detailed cross-sections of these fields have been constructed to recognize the producing intervals in these fields. Detailed structure maps have also been constructed for these fields. Future work will examine production controls in Plateau, Divide Creek and White River Dome fields. Preliminary relationships indicate that the strong relationship between production and structure does extend to basement features observable on aeromagnetic and seismic maps. Additional effort will attempt to fully demonstrate the minimal influence of stratigraphy on production trends. Earlier work clearly demonstrated these relationships in Parachute and Rulison fields. New effort will address production controls in other fields.

Well test and production data from Parachute and Rulison fields have been analyzed to determine the effectiveness of hydraulic stimulations used by the various operators (Barrett Resources, CER, and Northwest Exploration) in the two fields. Work in progress is attempting to delineate the reason for the variable effectiveness of the stimulations and the controlling geologic influences.

Because of the undocumented presence of fractured reservoir conditions in many gas fields in the Piceance Basin, we are also conducting several detailed field studies to document production trends in these fields and the relationship between production, structure and depositional trends. Preliminary emphasis has been placed on Grand Valley Field (located just west of Parachute and Rulison fields) to augment our previous study completed in Parachute and Rulison fields. Upon completion of this study, we will concentrate our efforts on Plateau-Shire Gulch fields in the southwest basin. It is anticipated that White River Dome (in the northern basin) and Divide and Wolf Creek structures in the eastern basin will be studied to contrast fractured production controls and trends in thrust-cored fault-propagation anticlines.

Stratigraphic Interpretation:

An extensive grid was constructed throughout the southern Piceance Basin to conduct a detailed investigation of the subsurface stratigraphy. This analysis will examine the interval from the top of the Mancos "B" shale up through the lower Tertiary-age Wasatch Formation. It will

include producing horizons of the Cozzette, Corcoran and Rollins sandstones, Cameo coals and sands and Mesaverde or Williams Fork fluvial channels, in addition to the lowermost Wasatch sands. Work in progress involves correlating stratigraphic picks throughout the grid and preparing to tie wells in infill areas to the grid system. The data used for these picks will be added to the digital database system used for geologic interpretation.

Recurrent movement of basement blocks during basin evolution has been recognized to generate paleo-lineaments along basement block boundaries. Block boundaries are commonly associated with zones of high fracture permeability and thicker sections of reservoir rocks. In these lineaments, fracture development is enhanced that creates favorable reservoir conditions for the development of prolific production fairways. These lineaments possessing enhanced fracturing and related reservoir quality have recently been recognized in the San Juan Basin (Decker et al, 1994; DOE-METC SBIR Final Report), the Green River Basin (Forster, 1994) and the Powder River Basin (Forster, 1994). As part of the integrated fracture detection approach, stratigraphic mapping is expected to delineate paleo-lineaments and related enhanced fracture fairways. It may also be possible to develop a predictive model for fracture intensity based on favorable rock mechanical properties identified using high-resolution stratigraphic analysis. This predictive model would be further enhanced by the use of stratigraphic data calibrated using petrophysical information from cored wells, including the MWX site.

Seismic Interpretation:

The seismic database at Barrett Resources for the Piceance Basin was inventoried and reviewed for applicability to basement and shallower structural analysis. The synthetic seismogram control has been discussed and appears to provide good coverage based on available borehole information. The central Basin has extensive seismic control. Additional seismic control at the north end of the basin is available through published lines through most of the major structures. Basemaps and CDP seismic sections have been prepared and structural interpretations are nearly completed. The overall objective is to generate time-structure maps that clearly demonstrate the link between basement and shallower-level structures. These maps and related 2D interpretations will be integrated with the high-resolution aeromagnetic data and

the regional tectonic interpretation to determine the basement controls on shallower-level structures that control fractured reservoir production.

The following seismic data were inventoried and available for analysis:

Mobil-3 lines (CDP)

Grant Norpac Spec lines-3 lines (CDP)

UPRC-5 lines (CDP)

SSC-6 lines (CDP)

North Divide Creek (Shot by Barrett Contractor)-3 lines (CDP)

Grand Valley (Shot by Barrett Contractor)-12 lines (CDP)

Terra Resources-14 lines (CDP)

Geofile (100%)-10 lines

(highest quality lines at top, lower quality at bottom)

The seismic data quality crosses a broad spectrum ranging from poor to excellent. Data quality is directly proportional to acquisition date and time of processing or reprocessing. Data quality is better in the eastern portion of the basin and decreases toward the west. Although the data appears adequate in its present form for shallow structural and stratigraphic interpretation, sub-Dakota (Cretaceous) reflectors are weak or absent in a significant portion of the data set. The explanation for this is probably that the sub-Dakota section is markedly thinned on the edge of a Precambrian-age uplift that has been extensively eroded at its top. Because of this erosion, the acoustic contrast between the overlying sediments and the basement is low. To the east, where Paleozoic sediments are present, the basement and sub-Dakota sediments and structure are much more clearly imaged. It may be possible to reprocess some of the non-exclusive data (e.g. Barrett lines) in the western basin to more clearly image the sub-Dakota structure. This data is approximately ten years old and considerable new technology exists to increase the resolution of older data using advanced reprocessing techniques. These techniques include refraction statics, DMO, and prestack migration to enhance deeper reflectors.

The seismic data available at Barrett Resources has been interpreted and data entered into a digital format for importation into the mapping software used by Advanced Resources International. Horizons picked include a Fort Union marker (Tertiary-age), a Rollins Sandstone (to facilitate comparison with conventional subsurface structure maps), the Dakota sandstone (to

recognize sub-Mancos shale detachment surfaces) and Basement. A basement fault interpretation is underway and will be compared with fault maps constructed for each of the overlying seismic horizons. Data quality for the Dakota, Rollins and Fort Union picks are very good. Basement horizons are difficult to unequivocally delineate. Combined with difficult calibration with subsurface well control, the process is extremely tedious. Work in progress involves working downward from shallower levels to recognize deeper structures.

Remote Sensing Interpretation:

Analysis of linear features from various regions of the basin shows that the basin has experienced a complex structural history. From this preliminary analysis, it appears certain that we will need to delineate distinct domains based on some criteria (e.g. lithology, basement structural domain, timing of structural development, and/or geographic location) that permits ready distinction of the different sets. Work in progress is attempting to determine the most suitable parameter to use to break out the different structural domains.

Overall, there appears to be a close relationship between observed linears (interpreted from both SLAR and TM data) and surface-mapped fractures. TM, because it lacks the look-direction bias, is preferable to SLAR and shows a close correspondence to surface-mapped faults. Surface-mapped joints, however, do not show such a close correspondence. At present, it is thought that faults exert a greater control on the development of geomorphic features than do joints. The reason for this relationship is under investigation.

The final stages of imagery analysis are nearing completion. Work in progress involves attempting to determine the structural significance of interpreted linears. Initial attempts have been made to separate linears based on structural domain. Additional effort has focused on interpretation based on host rock lithology. Using digital basin geologic maps, the outcrop polygons are used to partition the linear features data sets by bedrock geology. This information will allow us to see the differences in linear features between surficial host rock lithology. Previous fracture work in the basin has suggested that there is a difference in fracture characteristics between the Mesaverde, Wasatch and the Green River (oil shale) formations. Upon completion of the structural interpretation, the remote sensing interpretation can be finalized. Completion of the remote sensing interpretation is scheduled for late February.

We are in the process of defining additional domains based on the boundaries of basement and shallower fault blocks. Final completion of the structural interpretation will allow the remote sensing data to be integrated with the structural data and the overall interpretation can be finalized. Completion of the remote sensing interpretation is scheduled for late February, upon final integration of the aeromagnetic data set with the surficial and seismic interpretation

Project Review Meetings:

Efforts this quarter focused on coordinating activities between the various subcontractors and the operator participating in the study, Barrett Resources. To further these objectives, two meetings were held.

The first meeting was held in October between Advanced Resources staff and Indiana University. David Decker and Thomas Hoak traveled to Bloomington, Indiana for this meeting. During this meeting, ARI presented an overview of the overall objectives of the project and outlined how the numerical modeling effort ties into the activities being performed by other subcontractors. This was particularly important information to convey to the programmers at Indiana University who were not fully aware of the supporting data available and the implications of their own efforts. Indiana University presented an overview of the project accomplishments to date, the personnel responsible for each of the different subtasks, and described in detail the preliminary results that had been obtained. The most critical accomplishment was the clear communication between the different groups and the development of a more complete recognition of the abilities that each of the different groups can bring to bear on the problem. This recognition will allow us to greatly facilitate the transfer of technology between the different groups and interested groups, especially industry, outside the project.

The second meeting in October involved Advanced Resources staff and Barrett Resources staff. Because of new staff added to both organizations, a project overview was presented to Barrett Resources staff. Barrett staff were able to pose questions about the data acquisition and analysis efforts and generously offered significant amounts of company data to aid the project. ARI staff will have access to all Barrett Resources seismic and well data from throughout the basin. In addition, ARI will be able to freely access company files. Barrett Resources staff will assist in these tasks as necessary. Follow-up meetings with Barrett Resources staff have yielded

additional insight into the development and exploration strategies for fractured reservoirs currently being undertaken throughout the basin.

Professional Meetings:

David Decker and Thomas Hoak were authors of a talk presented by David Decker at the RMAG Biennial Gas Conference held in Denver. The talk focused on the development of a integrated fracture detection methodology and used the example of the DOE-METC Fracture Detection Program in the Piceance Basin. Response to the talk was highly favorable and several Piceance Basin operators subsequently contacted ARI regarding application of the techniques to detection of fractured reservoirs in the Green River Basin and to characterization of their reservoirs in the Piceance Basin.

Two abstracts of papers were accepted for publication and presentation at the Intergas '95 conference to be held in Tuscaloosa, Alabama. The first paper will discuss the gas and water saturated areas of the Piceance Basin. The second paper addresses the results of the remote sensing and geophysics studies of the basin. Final manuscripts will be completed shortly after the new year.

An abstract was submitted and has also been accepted to the AAPG Annual Meeting to be held in Houston. This abstract outlines some of the preliminary results of the fracture detection program in the Piceance Basin.

Several ARI staff members attended the Green River Basin Workshop (11/7/94) in Denver. This meeting showcased the methodologies being used for fracture detection in the Green River Basin. Many of these ideas are transferable to the Piceance Basin project.

Royal Watts (DOE Project Manager) visited the offices of ARI in early November and viewed the progress to date on the project. An annual review meeting at Morgantown is scheduled for January 10, 1995 and will be reported in the next quarterly.

C. REVIEW OF REGIONAL LITERATURE

Additional references of topical importance were collected this quarter with particular emphasis on regional syntheses of western Colorado geology, mechanics of fractured sandstone

reservoirs and methods of determining regional stress magnitudes. Future literature review will continue along topical lines.

OPEN ITEMS: None

SUMMARY STATUS AND FORECAST

All work is proceeding on schedule. Significant efforts in the next quarter will be addressed toward integration of the various data sets into a coherent, unifying interpretation. A critical output of this integration and the ultimate objective of the project is the delineation of fractured areas in the basin.

A handwritten signature in black ink, consisting of a stylized 'A' and 'D' followed by a horizontal line.

A. David Decker, Project Manager