Developing Next Generation Natural Fracture Detection and Prediction Technology

Final Report
Phase III Report
Exploration Field Demonstration

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Abstract

The purpose of the "Next Generation" project was to develop technology that will provide a quantitative description of natural fracture properties and locations in low-permeability reservoirs. The development of this technology has consistently been ranked as one of the highest priority needs by industry. Numerous researchers and resource assessment groups have stated that the ability to identify area where intense clusters of natural fractures co-exist with gas-charged sands, the so called "sweet spots", will be the key to unlocking the vast quantities of gas in-place contained in these low-permeability gas basins.

To meet this technology need, the "Next Generation" project was undertaken with three performance criteria in mind: (1) provide an integrated assessment of the burial and tectonic stresses in a basin responsible for natural fracture genesis (using seismic data, a significantly modified application of geomechanics, and a discrete natural fracture generation model); (2) link the assessment of natural fracture properties and locations to the reservoir's fluid, storage and flow properties; and, (3) provide a reservoir simulation-based calculation of the gas (and water) production capacity of a naturally fractured reservoir system.

Phase III of the "Next Generation" project entailed the performance of a field demonstration of the software in an "exploration" setting. The search for an Industry Partner willing to host an exploratory field demonstration was unsuccessful and Phase III was cancelled effective May, 31, 2005. The failure to find an Industry Partner can be attributed to severe changes in the petroleum industry competitive environment between 1999 when the project was initiated and 2005 when further demonstration efforts were halted. The software was employed in portions of other, non-exploratory, projects underway during the development time period, and insights gained will be summarized here in lieu of a full field demonstration.

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Introduction

The goal of Phase III of the Next Generation software development project was to cooperatively demonstrate the software package in an exploratory setting. Efforts to identify a site mutually agreeable to willing Industry Partners and NETL were unsuccessful and Phase III was cancelled effective May, 31, 2005. The Phase III final report will discuss the cooperative research climate that led to the site identification failure and operational experience derived from using portions of the software package on related projects during the site selection timeframe.

Those participating in the project included the author, Vello Kuuskraa (ARI), Eugene Williams (Williams Consulting), Dr. David Campagna (ARI), and Lawrence Pekot(ARI). DOE Project Manager was William Gwilliam.

Site Selection Post Appraisal

Site selection efforts for Phase III encountered a difficult cooperative research environment. Twenty six companies received materials or onsite presentations after expressions of interest during the initial site selection canvas. A poster session was held at the 2003 AAPG National convention, personal solicitations were made at two successive North American Prospect Expositions and numerous local society meetings which resulted in a steady stream of leads. Site reviews or discussions encompassed seven basins where fractured tight gas sandstone and shale plays ranging in age from Paleozoic to Cretaceous in age were suggested and evaluated. Three companies and areas reached the final negotiation stage. Of those three sites, one was vetoed by a data vendor, one was vetoed by Partner upper management and one was vetoed by NETL immediately prior to project cancellation.

The two key underlying reasons for the failure of the site selection process were the changes in the industry business climate during the development phases and the strict adherence to an "exploratory" site selection criteria. Increasing product prices during the development phases fostered the emergence of an intensely competitive business environment that selected against corporate participation in cooperative research efforts in the project demonstration phase. Company exploratory philosophies changed from risk averse to risk tolerant and existing data, interpretations, and reservoir understanding became increasingly valuable as sources of potential commercial advantage. Exploration activities once again became extraordinarily sensitive. By late 2004, "publishable" and "exploratory" as selection criteria were mutually exclusive.

A further complication is an industry predilection for "direct detection" as an exploratory risk management tool. Industry feedback during the site selection effort suggests modeling technologies (as those upon which NextGen is based) are perceived to be more applicable to exploitation operations. Large scale field development is where moderate to large amounts of data are available to constrain the model building process and the potential economic benefits that might arise from successfully optimizing a drilling program are believed to justify the expense, effort and time invested in model construction and simulation.

A final issue affecting the overall site selection failure can be characterized as "resource allocation". NextGen became available for commercial demonstration during a time of intense, often crushing, industry activity. Existing prospects were being drilled at a pace that strained the limits of personnel and capital resources. During such periods companies expend their resources on familiar tools that are perceived to deliver predictable results within a predictable timeframe. Discussions at the most recent Hedberg Conference on tight gas resource development (Vail, Spring, 2005) indicate there is little concensus and much uncertainty regarding the role of natural fractures at the reservoir scale. Thus, in an over heated, frenetic E&P environment, there was little incentive to allocate scarce staff resources and project time to relatively unproven model based approaches. Only after the familiar tools are recognized and accepted as not delivering the needed results, will the environment be ready for new approaches.

The Phase III site selection process failed because the original exploratory criteria for the field demonstration site could not be satisfied by available opportunities within the overheated, intensely competitive industry environment at the time the tool became available for demonstration.

Operational Experience

The development of the NextGen software suite occurred simultaneously with other projects within ARI where opportunities existed to use geomechanical or other fractured reservoir tools and approaches contained within NextGen. As a result considerable practical experience has been gained in its use even if it hasn't received a full field demonstration. That practical knowledge will be the focus of the following discussion.

The Next Generation (NextGen) software package was conceived as an integrated suite of tools to facilitate the prediction of permeability fabrics related to natural fracturing in the subsurface. This was to be accomplished by building models of faults, simulating the distribution of stresses and strains generated in the target interval as a result of displacement along the faults, identification of failure envelopes, correlation of induced fracture styles to those envelopes, stochastic modeling of the fractures as discrete fracture networks (DFN), and converting the resultant DFN interpretation into gridded permeability arrays suitable for input into a reservoir model. This was an aggressive goal. Entire research programs have been designed around and Doctoral degrees earned performing individual subtasks of such a work flow. The NextGen system allows a sophisticated user with adequate background knowledge to accomplish the goal.

Baseline Requirements

As a practical matter, NextGen requires an individual (or team) to have a broad array of earth science, engineering and numerical skills in order to build the models, generate realistic simulations and process the results effectively in order to achieve meaningful results. Reducing the process to its simplest, NextGen forms a chain of mathematical dependencies from earth science inputs through reservoir simulation input. Poor quality earth science input interpretations will generate poor quality simulation inputs. An iterative process whereby input and internal consistency is increased by repetition, post appraisal and adjustment delivers the best result.

NextGen does not stand alone. A license to Surfer (Golden Software, Golden, CO) is required because NextGen relies upon Surfer for its gridding and contouring support. Availability of spreadsheet and text editing programs is highly reccomended to edit input files and generate calculations outside of the program. It is assumed appropriate geophysical, geological, geostatistical and petrophysical support is available to provide fault plane maps, reservoir horizon maps, descriptive geostatistical analyses and reservoir matrix parameters. Nearby production and reservoir engineering parameters are rquired to calibrate output permeability grids. GIS systems can be useful for cartographic manipulation, and detail input data editing. A final key requirement is the electronic data manipulation skillset to move data and interpretation files between packages.

Allow plenty of time to perform a project. The NextGen learning curve is steep, particularly for the first few projects. Iteration will be required before a good result is achieved. Two to four months is probably a reasonable estimate for the NextGen portion of the first project if the individual is a strong computer user with familiarity in the skill sets outlined previously.

Data Preparation

As in most modeling endeavors, background and input data preparation is paramount. The NextGen process is cumulative so initial problems with inputs will propagate through and compound their effect. It is much easier to be more thorough early and reduce complexity later than the reverse. The following areas are especially important:

1) Regional geology. Take the time to thoroughly understand the local geology from stratigraphic, structural and historical perspectives. Subsidence and uplift histories, orientations of present day and paleo stresses; estimates of

accumulated strain, orientations and types of fractures observed in core, image logs and outcrop. Collect any descriptive fracture statistics or rock property analyses that may be available.

2) Detailed seismic interpretation. Make sure the seismic interpretation (if any is available) is consistent internally and externally with the regional geology. If possible edit the faults within the seismic workstation to ensure the maximum possible initial interpretive consistency. If there are mechanical inconsistencies in the interpretation they will emerge during the structural modeling and force more iterations. In fact, you can check your structural interpretation through the modeling. Are the reservoir structures forming in the correct geometries and orientations? If not, why not? Is the depth conversion correct? All faults and horizons need to be in depth for modelng. Output available coherency or other attributes you feel may be important fracture indicators as x,y,z text files for later import into NextGen. Such attributes can be used as guides to constrain the distribution of fracture clusters or other distributions within Fracgen. Are there prominent structural trends in the seismic data? Can they be characterized with descriptive geostatistics?

3) Production analysis. Perform a thorough analysis of any production data available within or around the project area. If possible acquire a good petrophysical analysis of each well. Evaluate the production behavior using type curves or single well simulation to identify bulk permeability of the reservoir and any dual permeability behaviors. How does the bulk permeability from type curve work compare to that estimated from petrophysics? If they compare well, fractures may not be that significant in the reservoir and further NextGen modeling unneccessary. If there is considerable difference (several to several tens of fold difference) then the reservoir bulk permeability is significantly influenced by natural fractures. Early characterization of the impact of natural fractures on reservoir behavior builds team confidence in the process and supports the strategic technical direction of the project. Thoroughly explore the production data with descriptive geostatistics to identify any directional permeability fabric. This data will be extremely useful later on to calibrate the output permeability grids.

4) Evaluate the potential for covariance relationships between the production analysis and any geologic or geophysical data. Such relationships, if identified early, can greatly speed the interpretive process and improve the results.

Structural Modeling

The research program conducted by the Department of Energy at the MWX site in the Pieance Basin found pervasive networks of subsurface extensional fractures which greatly influenced the productivity of tight gas sands. Structural modeling capabilities were incorporated in NextGen as a first step in understanding and projecting these widespread elastic strain features. Other types of structural modeling can be performed outside NextGen and the results incorporated via import of gridded attributes. An example using visco-elastic modeling is described in the Phase II Final Report of this project. In fact, the interpreter is not compelled to use structural modeling at all if he/she has reason to believe they understand the origin and distribution of the pertinent fracture systems. Fracgen models can be built to distribute fracture permeability according to almost any scheme, from totally random to specifically related to a particular fault style or system. The primary objective, however, is to understand the nature and distribution of the fracture permeability. Validating an interpreted causal relationship through modeling can be an important confidence and credibility booster for both the interpreter and the final output permeability grids.

An early, public,version of Poly3D (Thomas), an elastic boundary element modeling program originally written at Stanford University, has been incorporated in NextGen to provide the capability to model elastic stresses around faults. Poly3D models and simulations will be the focus of this discussion but many of the observations can be more generally applied to other approaches.

A few key learnings about structural modeling as implemented in NextGen follow:

1) Distributions of computed stresses and strains from structural simulations are only as good as the technical quality of the input fault plane maps, horizons, displacements and imposed boundary conditions. Models of fault systems must be geometrically consistent internally and stylistically consistent with the interpreted tectonic setting and imposed boundary conditions.
2) Invalid results from data limited interpretations can be deceiving. A modeled fault at 20,000 ft subsurface will require nearly 64 square miles of 3D seismic data and mapping to generate 9 square miles of valid computed stresses along a reservoir horizon at 10,000 ft subsurface. Extreme care must be exercised when attempting correlations between simulated stress attributes and productivity indices to ensure that the computed results are valid across the target area.
3) Ensure that all fault planes, and horizons (seismic or well control generated) share a common datum and are referenced to local ground surface. The seismic processing datum is usually a good choice. The default Poly3D coordinate system has the local surface as Z=0. This makes anything subsurface a negative number and is consistent with the implementation of rock mechanics as practiced at Stanford. Load all fault plane and horizon data as negative values referenced to surface.

4) Take care to ensure that all cartographic units, depth units, constants and other input data are dimensionally consistent. Mixing x, y meters and z, feet guarantees invalid results.

5) Poly3d orientation and sign conventions follow those in use in the Stanford rock mechanics program. 0 azimuth is east. A compressional stress is negative by convention; extension is positive. These conventions are mathematically correct but counter to less rigorous usage common in industry. Without care, confusion can reign supreme.

6) Use dimensionally correct boundary conditions. Poly3D is a linear elastic model so output can be scaled later but it is easier and less confusing to be consistent from the start. It also makes it easier to present results to engineers and managers.

7) Provision has been made in NextGen to generate mean stress values incorporating reservoir pressure, depth etc. More elaborate calculations can be performed by using the gridded outputs in grid to grid operations in Surfer or pasting the raw Poly3D results into spreadsheets and using custom schemes for estimating lithostatic, thermoelastic or other stress components. Custom failure criteria such as those outlined by Bourne (2001) can be applied in the same fashion.

8) Poly3D results can be pasted into spreadsheets for calculation of stress vectors, Coulomb failure plane orientations etc. From there it is easy to move the data into a GIS or other workstation environment for attribute correlations, extraction of values around wellbores, geostatistics or other analytic schemes. Doing so also improves the interpreter's understanding of the calculations being performed behind the scenes and can serve as a quality control check on input/output values.

9) Fault systems are almost always oversimplified in the geophysical interpretation process. This effect will yield a fault plane that appears smooth from line to line but has several "kinks" when converted to depth and meshed in NextGen. Large fault systems are somewhat fractal in detail; composed of anastomosing swarms of smaller failure planes that scale up to give the appearance of a single fault at seismic scale. The best practical modeling approach to this issue has been to organize the observed faults into a causal heirarchy, identify the main driving fault system, edit it into a series of simplified, en echelon (usually) planar discontinuities which can then be imported into NextGen, meshed and simulated. Thus modeled, the main driving system (if the interpretation is correct) will generate stress and strain patterns consistent with location and orientation of the subsidiary faults. If the system behaves consistently, complexity can be added until a level of detail is achieved that shows a relationship to production. There are distinct computing limits (numbers of elements, etc) to the amount of complexity that can be modeled. A balance must be struck between incorporation of all the details available and an effective, executable model (or combination of models) that answers the problem at hand.

In the end, the interpreter should remember that the structural modeling portion of the project, no matter how complex or what kind of failure criteria have been applied, is only a validation (or not) of interpretational judgement and a guide to the follow on process of distributing a natural fracture related permeability fabric across the study area.

FracGen Modeling

The purpose of incorporating FracGen into NextGen is to support the generation of a statistically valid, geologically constrained, fracture network across the desired area of interest. Petroleum reservoirs of large areal extent may display fractal behavior at small to intermediate scales but also frequently contain larger features that may not be fractal in their distribution across the area; a single large fault, for example. FracGen affords the capability of honoring the irregularly distributed features as well as the fracture fabrics that are more penetrative in nature.

FracGen, itself, affords near infinite interpretational control for adjusting the statistics and relationships of the fracture populations it generates. Local fracture statistics, if available, can be used to condition the process or existing control files can be adapted using local stress orientations and observed fracture types as guides. Retention of the excellent internal descriptive statistics from the original example files (McKoy, 1996) is usually advisable. If the ultimate intent is to simulate the reservoir using a true discrete fracture network (DFN) model such as FracFlo (a DOE application), the result will be highly dependent on the fracture network generated and a high degree of care is warranted when constructing the control files. If the intent is to use the network in a more conventional simulator, the network will be gridded, scaled and otherwise transformed such that only the general patterns of natural fracture permeability will remain and less attention to detailed population statistics is needed.

NextGen provides a GUI interface for generating and modifying FracGen control files. The reader is referred to McKoy (1996 and FracGen User Guide, unpublished) for a detailed discussion of the DFN generation process. The version of FracGen contained in NextGen has been modified to run stochastically and have the output stored in a database for later analysis (Surf-Comet module).

Key learnings accumulated from FracGen modeling:

1) FracGen, at first encounter, is extraordinarily intimidating for the less mathematically inclined geologist. The blow may be softened if the various fracture sets and their dependencies are visualized as more akin to sedimentary facies than abstract mathematical descriptions of fracture populations (which they are). The interpreter's task is then to distribute the "facies" across the paleogeography using simulated paleo stress fields, seismic attributes or geostatistical characterization of the wellbore productivity as constraints. The

effort has been successful if the output generally ties the wellbore productivity control and reflects the variability of the control population.

2) Natural fractures can, indeed, be categorized into types ("facies") that have genetic meaning, much as sedimentary structures in core carry meaning for the sedimentologist. All too often they are discussed as "fractures" without any descriptive modifier. Dips, orientations, character, host lithology, displacement (or not), frequency, spacing, vertical density etc are all valuable information when attempting to build a FracGen model. Carefully search all available image logs, interpretation summaries, etc. for each and every tidbit of information and use it.
3) Large FracGen runs frequently fail to completely finish. If this happens, it is easier to find and modify the NextGen control file to begin the run at the next set than it will be to identify the exact issue within the input file that caused the interruption. Because NextGen runs Fracgen stochastically and adds the realizations, the final objective will be achieved regardless.
4) NextGen makes provision for examining the azimuthal distribution of the simulated fracture population at any point within the model area. Use it to post appraise the simulation and make sure it ties the available well control. Few things are more embarrasing than DFN's with population/orientation statistics radically out of step with the control wells on which the simulation was supposedly based.

No matter how well constrained the final FracGen model appears to be, if it doesn't fit the known control, it's not done.

Surf to Comet Module

The purpose of the NextGen Surf to Comet module is to facilitate the optimal layout of the simulation grid, condition (through scaling, addition, subtraction, boolean logic, etc) the gridded FracGen output, sample the grids, and output a formated simulator input file. Comet is a proprietary ARI reservoir simulator, hence the module name. Many of the functions for which the module was designed are being superceded by ongoing developments in petroleum workstation software. Almost all simulators use a proprietary input format and, as simulation becomes more commonplace, major vendors are writing I/O modules to perform the task. Scaling, transformation and output of the FracGen grids as permeability grids will most likely be the last interpretive operations performed in NextGen.

Several transformation schemes have been discussed in previous reports and will not be repeated here. The scheme actually employed should be the result of close cooperation between the NextGen interpreter and the simulation reservoir engineer. Aguilera (1995) reviews several general approaches and many more are to be found in the literature. Any available estimates of bulk wellbore permeability (and relative natural fracture contribution) should be used in the conditioning process. Time should be allowed for several iterations of the process (run simulation, adjust perms etc, run simulation) for the best results.

Summary

NextGen was conceived as a set of tools and concepts to facilitate the incorporation of natural fracture related permeability fabrics into conventional reservoir simulations. Integration of elastic structural modeling, discrete fracture network generation and streamlined grid to grid capabilities accomplish this goal. Hypotheses of natural fracture genesis governing the distribution of fractures are constantly evolving. Regardless of the genetic origin of a natural fracture network, if it can be described, its potential permeability impact in a reservoir can be tested through the tools and processes embodied in NextGen. Results of a recent Hedberg Conference on Tight Gas Development will show there remains considerable controversey around the role of natural fractures in tight gas reservoirs. The difficulties associated with testing the impact of natural fractures in mainstream reservoir simulators is a barrier and a significant reason the controversey remains. NextGen, as a system of tools and concepts, significantly lowers that barrier.

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