Application of GOHFER® in a Petroleum Engineering Curriculum

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Introduction

To many people GOHFER is "just a frac model". GOHFER has grown over more than 30 years of development into an integrated well design and optimization package that covers a broad spectrum of disciplines involved in petroleum engineering. It is our belief that GOHFER can be used throughout the curriculum to bring together multiple disciplines and a large amount of diverse but interconnected information impacting well performance efficiency and development planning.

Although many universities have access to GOHFER at no cost, through the GOHFER/B&A University Outreach Program, is has become apparent that the software is not being used to its full potential as a teaching aid. This document presents some of the features GOHFER, along with suggestions as to how it can be used to supplement a curriculum that is more focused on development of unconventional reservoirs, which seems to be the outlook for our industry in the near future.

Log Analysis

The log analysis portion of GOHFER (LAS Processing) imports multiple LAS files that conform to the standard for version 2 certification. It provides a means to process conventional logs (triple-combo, platform express, etc.) and acoustic logs (BHC sonic, acoustic anisotropy, dipole sonic). Logs can be displayed over any depth range, and at many standard log depth scales, for both oilfield (English or Imperial), and metric units. Unit conversion for all input log tracks is available, along with the ability to generate graphical equation processing on each curve, or pairs of curves. The mathematical functions allowed are Cartesian shift of the curve, multiplier or scaling, summing of curves, averaging of curves, logarithm of input curve, and exponentiation of the input curve. These functions can be used to transform any input log curve, and to generate a new curve that may be an input to another generated curve or function.

The package also includes a crossplot, or scatter-plot function that allows generation of correlation functions between any pair of input log tracks or curves. These regression results can then be used to produce a desired output log curve from any available input curve. Similarly, there are pre-defined correlations to generate synthetic sonic logs and dynamic rock mechanical properties, Poisson's Ratio and Young's Modulus) from multiple inputs, as well as from conventional shear and compressional acoustic slowness. Correlation of the generated sonic log curves have been shown to be good indicators of total organic content and hydrocarbon potential of zones. The derived curves also provide mechanical properties estimates that are corrected for the slowing effect of hydrocarbons on the raw sonic data.
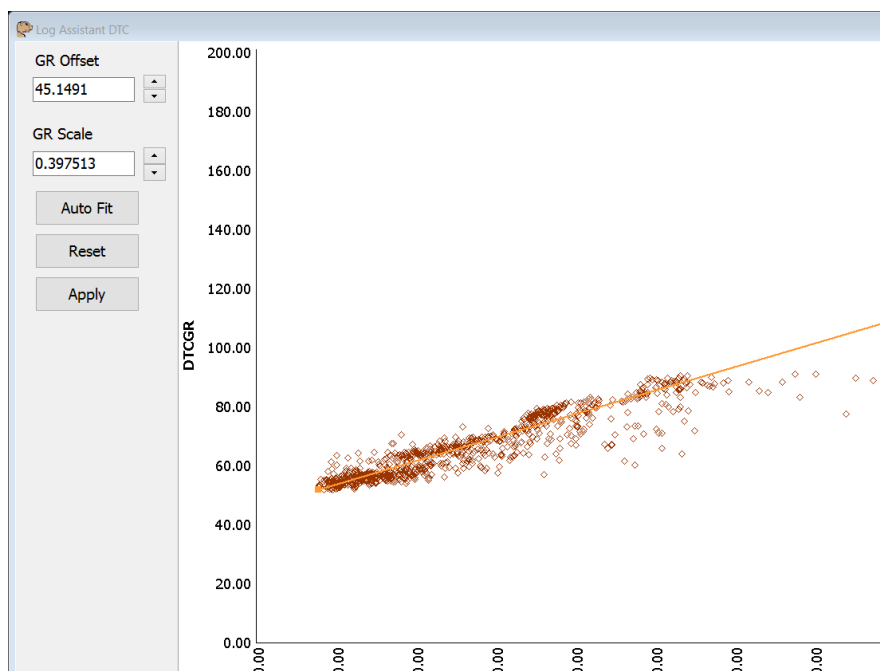
Crossplot correlation for DTC derived from GR log data.

The mechanical properties and derived Biot's poroelastic coefficient are combined with true vertical depth, overburden gradient, pore pressure profile, and imposed tectonic stress and strain boundary conditions, to compute a curve of minimum in-situ stress. This curve can be calibrated to field measured

fracture closure stress to generate a representative mechanical earth model. The stress profile can also be used to generate a maximum horizontal stress estimate, when sufficient data are available. These two curves then define a horizontal stress anisotropy that is spatially variable, and tied to lithology and local rock properties.

A lithologic model can also be generated based on a 6 component model. The model includes volume fraction of clay (or shale), sand (quartz, feldspars, mica), lime, dolomite, anhydrite (including other heavy minerals), and coal (or kerogen). The model parameters can be adjusted to match available XRD/XRF data when available.

Core data can be input to the model, and depth shifted to align core and log depths. Any core properties tabulated versus depth can be input, and plotted, along with any appropriate log curve. This provides a means for calibrating derived log curves or quality assurance of core and log data for consistency. Logs from offset wells can also be imported n the same project, and each log can be depth-shifted to a common datum plane for comparison.

The processed log functions are also used to generate a net-pay curve based on effective porosity, resistivity, and shale (clay) fraction. This process provides an effective "quick look" to find potential pay targets. The net pay analysis also includes the generated "brittleness" curve. Archie water saturation is also computed and displayed as a separate log curve.

All processed and generated curves are output to a LAS (log ascii standard) filed for use in any other log analysis package, or for input to a simulator. There are pre-defined output curves that are used within GOHFER, but any derived curve can be added to the output LAS.

The GOHFER LAS processing package can be used to teach conventional log analysis, geomechanics, response and comparison of different logging tools, and normalization of logs. The impact of changes in any input parameter on the resulting stress profile can be examined, including use of mechanical properties from multiple sources. Local pore pressure depletion and overpressure can be modeled in the logs, and shown to affect in-situ stress. Similarly, the difference between a constant stress and strain boundary condition on calibration of the stress profile can be easily illustrated. This leads to a more general discussion of tectonics and development of a calibrated 3D stress tensor for a geomechanical model.

Drilling and Wellbore Stability

A detailed wellbore deviation survey can be input to GOHFER in the form of MD, Inclination, and azimuth. The well northing, easting, and TVD are computed using the minimum radius of curvature method. The azimuth of maximum horizontal stress can also be specified. Using the derived mechanical earth model, spatially variable stress anisotropy, and relative azimuth of the well and maximum stress, the tangential stress is computed around the deviated well at any point in the model. Data are available at each point along the well trajectory to compute the safe mud weight window to avoid well collapse or tensile failure of the borehole. The computation of the safe mud weight window will be added in an upcoming version of GOHFER, and is currently done in an external application.

The well directional survey is displayed in a rotatable 3D view, and in an x-z vertical earth cross-section through the variable lithology derived from the log processing. Geologic structure, including folds, bed dips, and faults, can be built into the cross-section. Each shift of TVD of any rock unit changes the stress tensor, relative to the overburden and pore pressure gradients, so that the stress tensor at each point are recomputed. Any point on the vertical cross-section, on or off the wellbore trajectory, can be selected to evaluate well breakdown conditions.
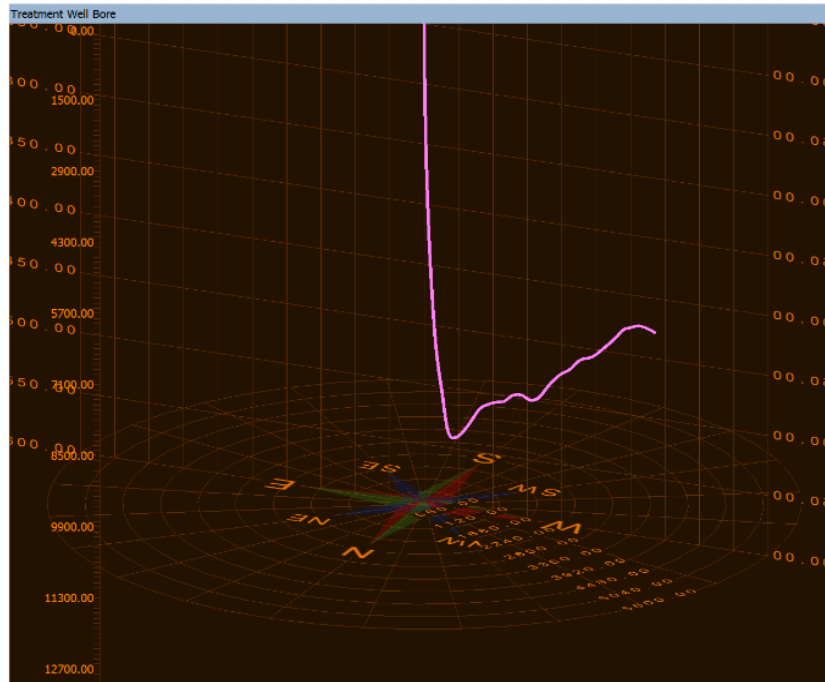

Well directional survey in 3D view.

The selection of a point in the earth section generates a pair of polar coordinate plots, showing the well trajectory in terms of inclination and azimuth and the tensile failure (breakdown) pressure gradient in psi/ft or kpa/m. The second plot shows the angle of inclination around the wellbore circumference where the minimum tangential stress exists. This is the angle of departure of an induced tensile fracture for a homogeneous medium (over the diameter of the hole), with no pre-existing flaws or cracks. In these plots any of the parameters affecting breakdown pressure can ba varied for "what if" analysis. These parameters include the maximum stress azimuth, stress anisotropy, pore pressure, Biot's coefficient, Poisson's Ratio, Young's Modulus, and stress or strain boundary conditions on the earth model. This analysis easily demonstrates the potential problems encountered when traversing the build section of a high-angle well, especially when drilled orthogonal to the maximum horizontal stress.
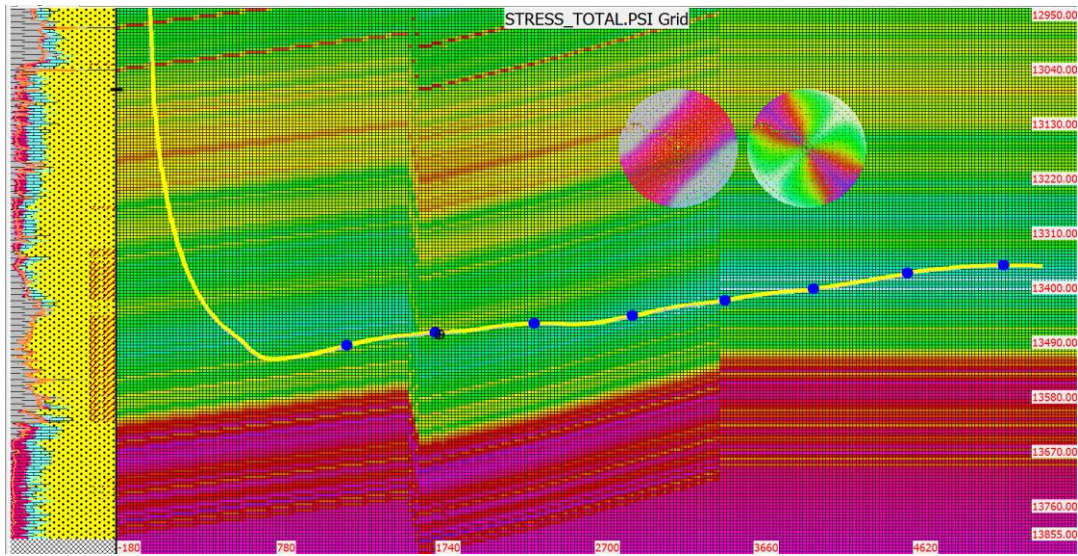
Model grid showing total closure stress and well breakdown conditions.

Along with the general polar plots of breakdown gradient, a second analysis and plot shows the tangential stress distribution around the well at any point along the directional survey. Rapid changes in the tangential stress profile can occur over short distances along the well, when the wellbore cuts layers of variable rock type or changes angle of attack. The analysis can be used to select optimal points for breakdown, or fracture placement, and to avoid sections of the well where adverse breakdown conditions may exist.
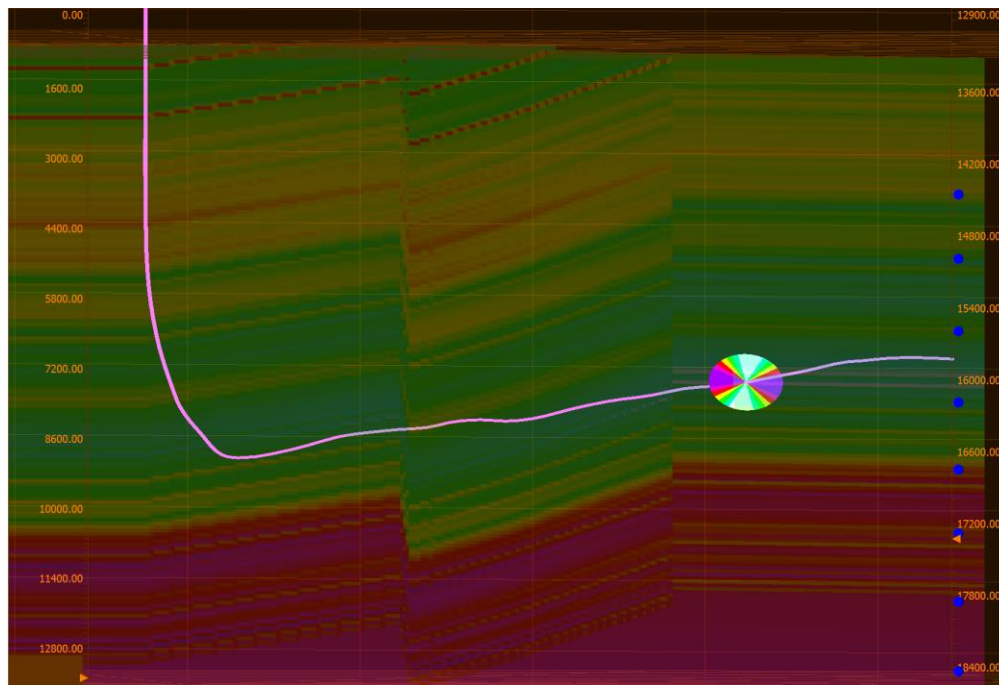

Tangential stress around borehole for breakdown conditions.

Geosteering and Selective Completions

GOHFER provides for import of well logs for both a vertical reference well, to provide data for construction of the mechanical earth model above and below the treatment well, and for the treatment well itself. The treatment well logs may be LWD/MWD or post-drill logs. Any logs can be imported and processed for the treatment well, including GR, mud logs, density, porosity, resistivity, and sonic. All the log processing, generation of synthetic sonic and mechanical properties available for the vertical reference well can be performed in the treatment well.

In the vertical earth cross-section view, with the treatment well trajectory displayed (based on the input survey), a log curve from the treatment well and a corresponding log from the reference well can be displayed. As the user moves a cursor along the wellbore the two logs can be correlated by vertically shifting the lithology column at each point. This allows the well to be located correctly within the vertical cross-section, and builds the geologic structure necessary to describe well surroundings.
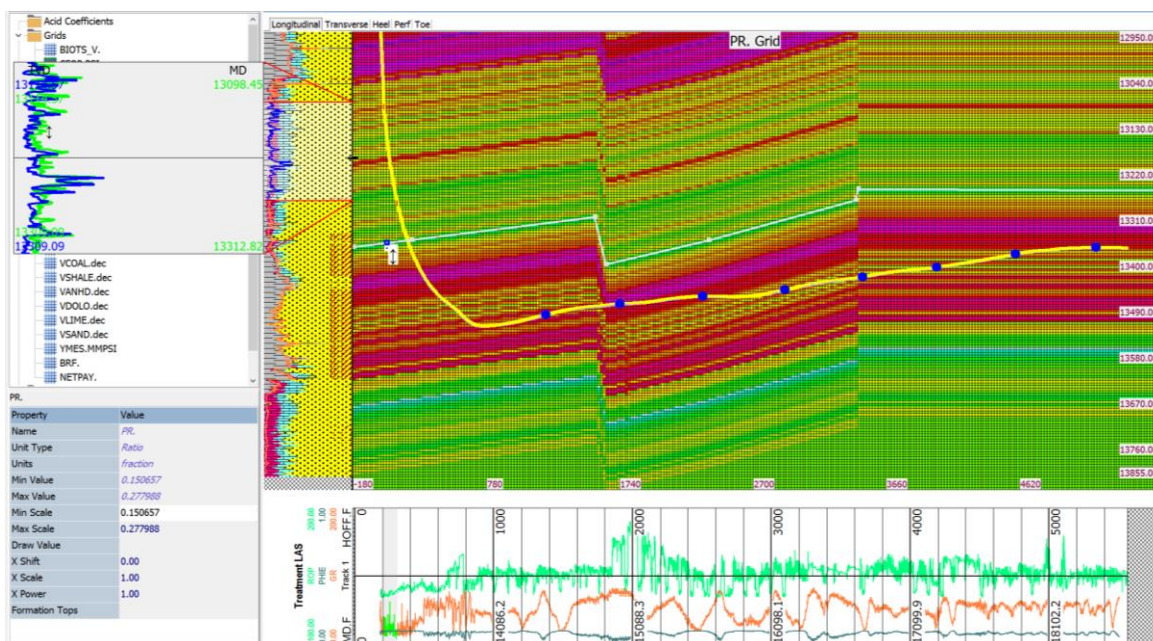
Vertical reference well and treatment well logs with geosteering application.

This process can be frustrating when the well is nearly parallel to the bed dip, as there is no change in the log character over a range of well MD. Exercises in log correlation, pattern recognition, and an understanding of the difficulties in locating a well in the geologic section are valuable. The impact on wellbore stability, breakdown pressure, and ultimate fracture geometry that can result from incorrect placement of a well can also be illustrated. Putting the well in the wrong vertical position can, in some cases, completely change the section of pay contacted by an induced hydraulic fracture.

Having the log suite along the treatment well, including processing for mechanical properties and derived stress profile, can also provide insights for an engineered completion, instead of random or uniform perforation placement. Areas of adverse breakdown conditions, or non-pay sections can be readily

identified, and marked for potential exclusion from perforating or stimulation. Placement of selective perforations can be evaluated in terms of fracture coverage and completion economic optimization.

Pre-Frac Diagnostic Injection Test Analysis

The diagnostics package in GOHFER includes step-rate analysis, G-function, Sqrt(time), and log0log type-curve derivative analysis, non-linear leakoff determination, and wellbore storage and decompression analysis. Familiarization with the analysis and interpretation of these data allow determination of total closure stress and pore pressure, for calibration of the minimum in-situ stress profile. The data can also be used to determine reservoir flow capacity, for appropriate design of stimulation and completions as well as post-frac production forecasting.
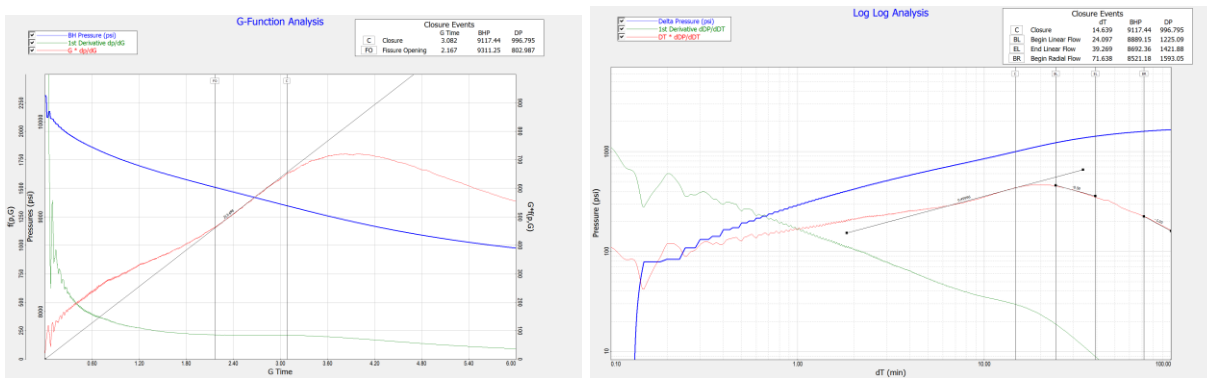
Example of diagnostic G-function and log-log plot analyses.

Results of a complete, and proper DFIT analysis, coupled with the fracture geometry and proppant placement model, then tied to fracture cleanup driven by reservoir transient behavior, have been shown to accurately predict well production in every type of reservoir and geologic environment. The production forecast and derived reservoir properties are consistent with production rate-transient analysis and static pressure buildup data.

Input to the calibration of the in-situ stress tensor and subsequent development of a calibrated mechanical earth model requires direct measurement of pore pressure and stress. These properties cannot be computed from available log data. The same is true for pore pressure and reservoir flow capacity. Without this information it is not possible to design an appropriate or optimum completion for a well.

Reservoir pore pressure and estimated permeability, combined with porosity, saturation, and net pay analysis from the log processing will allow a production decline forecast to be run for any proposed fracture design. This process leads naturally to development of an economic value model which can illustrate the merits of initial production (IP), net present value (NPV), internal rate of return (IROR), and other value indicators in making development decisions. Without an accurate estimate of the reservoir properties, this exercise can be almost useless. An accurate analysis also requires a realistic assessment of fracture conductivity and flowing length, which will be discussed later.

Fracturing Fluid Rheology

Although most fracture treatments in unconventional reservoirs are now conducted with some form of polyacrylamide friction reducer (slick-water), complex non-Newtonian linear and crosslinked polymer-based fluids are still used. Understanding the time, shear, temperature, and complex breaker effects on these fluids is important in overall stimulation design. How long should the fluid last? What temperature should it be designed and tested at? How do all the chemical additives interact to produce a suitable stimulation fluid? These questions can be answered with appropriate laboratory rheology and break testing.

GOHFER includes a fluid database, and the ability to generate a shear-rate and time dependent model of complex fluid rheology, based on specific laboratory test data. Lab rheometer test results can be imported and processed to generate a consistent description of a job-specific fluid. The newly developed fluid model can be added to the user fluid database, then used in fracture geometry and proppant transport modeling to determine the impact of rheology on geometry and economic value of the stimulation.
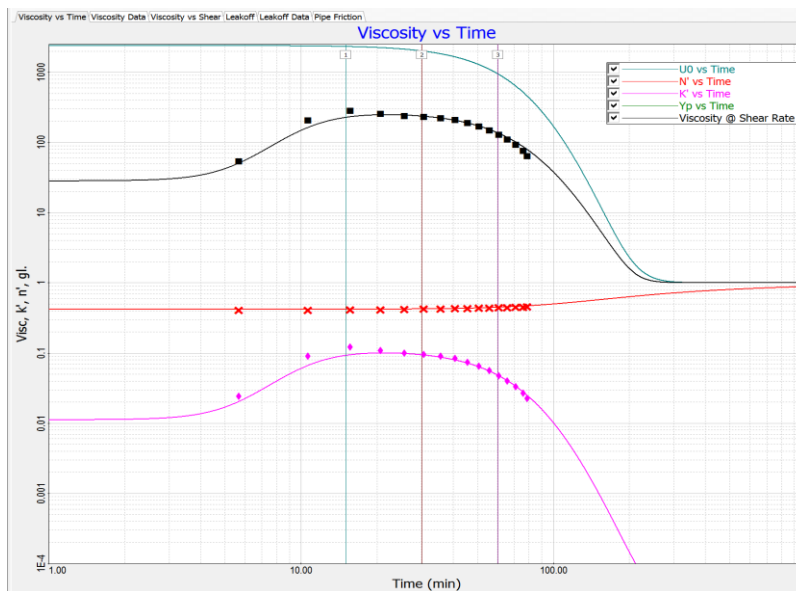
Fluid rheology model and import of lab data.

Proppant Material Properties and Transport

Complete models of proppant conductivity and crush under field confining stress conditions have been developed based on 30 years of consistent laboratory measurements at the Stim-Lab Proppant Consortium. The results of the entire Stim-Lab proppant library are available in GOHFER for comparison of baseline and effective conductivity, and economic value of all commercially available proppants. Careful analysis of well performance with similar fracture designs, or pumping schedules, shows that productivity is not only controlled by the strength or baseline conductivity of proppants. The effects of multiphase flow and inertial losses in the proppant pack, along with the energy supplied by the reservoir, often dominate production. Accurate coupling of proppant behavior with transient reservoir performance is required to assess the true economic value of proppants with varying costs and availability.

The proppant model allows computation and direct comparison of baseline conductivity of any number and size of proppants, at any specified concentration, substrate modulus, and temperature. Various proppants can be selected for use in fracture treatment designs. Integration of the proppant pack created by the design with the log-derived and calibrated reservoir pore pressure, closure stress, and transient production profile, allow each proppant to be evaluated in terms of its cost-benefit ratio. Use of the proppant model provides valuable insights into the selection and cost justification of materials for stimulation design and execution.

The proppant transport model in GOHFER has been verified by years of testing in large and small scale slot flow cells. Fluids including borate and metallic crosslinked gels, linear polymer system, and slickwater have been modeled, both physically and numerically. The model performs transport and settling computations for any size and density of proppant. Up to ten proppants and ten fluids may be used within a single design model. GOHFER provides insights into the actual economic value and placement efficiency for commercially marketed propping agents.

Fracture Geometry Evolution and Job Design

Prediction of fracture geometry is one of the primary purposes of GOHFER, and involves developing a correctly calibrated and representative mechanical earth model. From a teaching standpoint, GOHFER can be used to evaluate the fracture geometry generated by different fluids, pump rates, perforation spacing, proppant schedules, and many other "design" variables. Common metrics such as gallons per foot, or pounds of proppant per foot of pay or lateral, can be evaluated versus their impact on cost and production.

More importantly, the impact of changes in log processing and assumptions about pay quality, pore pressure, stress anisotropy, and other geomechanical inputs can be easily evaluated. Critical observation of the sensitivity of results to geologic inputs, rather than to changes in fluid, proppant, and job size may add support to multi-disciplinary team building. Consistent input to describe the reservoir and mechanical properties and pressure/stress state are more important than simply pumping bigger jobs, if economic value and efficient use of resources are important to the industry, shareholders, and community at large.

The model is also useful to demonstrate fracture containment and isolation from potable water sources. It provides a good visual reference for comparing probable fracture extent, especially height growth, to sources of drinking water. The model will also take 3D microseismic event locations as input, for comparison to the predicted fracture geometry. The distribution of shear events can be related to the predicted fracture deformation field.

When available, radio-active tracer data can be imported for comparison to the predicted fracture height in vertical wells. These data can be imported as LAS or text files, and plotted with the simulator output of proppant concentration or other state variables.

Fracture Cleanup, Conductivity, and Effective Length

A critical output for any fracture treatment design is an realistic estimate of the resulting fracture conductivity and effective producing length. This goes far beyond modeling the created fracture geometry and baseline conductivity of the proppant pack. GOHFER incorporates the results of 30 years' effort by the Stim-Lab consortium to understand proppant pack conductivity and fracture cleanup under actual field producing conditions. To estimate effective conductivity, the fracture must be coupled to a transient reservoir production simulator. The energy supplied by the reservoir, in the form of flow velocity and potential gradient in the fracture, drives the cleanup. With limited production, there will be limited fracture conductivity. Fracture conductivity also depends more on reservoir producing conditions, such as water cut, liquid yield, and applied drawdown, than on the fracture geometry and proppant selection.

The ability to model fracture conductivity, cleanup, and production for various scenarios can be used to demonstrate sensitivity to the critical parameters governing post-frac productivity. The model can easily show the effect of changing proppant type, size, strength, and cost, on development economics. The impact of water cut, GOR, and condensate yield can also be demonstrated. In the current economy, being able to identify what actually impacts project economics, and to make positive changes that add value to a development is a useful, if not necessary, ability.
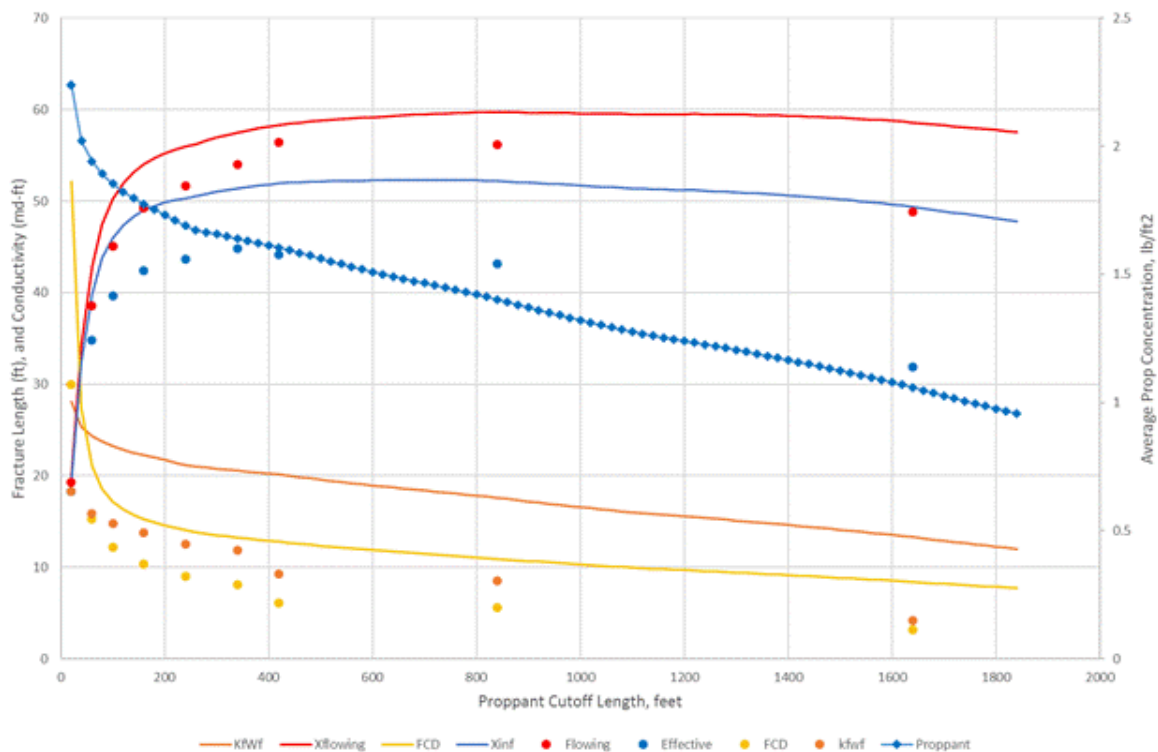

Output of various predicted fracture lengths: Cutoff, Flowing, and Effective, from the GOHFER simulator.

Well and Fracture Spacing, Interference, Well Bashing

With the prevalence of multi-stage horizontal well fracturing, it is necessary to understand the stress and strain interference between fractures in a stage, and from one stage to the next. Similarly, for "zipper frac" operations, the impact of stress/strain transmitted from one well in the pattern to another must be understood. GOHFER can be used to illustrate the impact of fracture and well spacing, time between stage (as the fractures leak-off and close), fluid rheology, pump rate, emplaced proppant pack width, and other variables that impact stress shadowing.

When infill-drilling, or offsetting a producing well, the pore pressure depletion resulting from production of the existing offset well affects fracture placement, wing asymmetry, conductivity, and damage to the offset well by invasion of frac fluids. The effect of local depletion zones can be modeled and illustrated. Degree of depletion, effect of shut-in of the offset well, re-injection into the well, well spacing, and other variables can be studied with relative ease.

The industry is entering a phase of development where infill drilling and re-fracturing are a major concern. The ability to model fracture placement and performance in an environment of highly variable pore pressure and earth stress, and to account for likely operational interventions, such as pressure buildup and re-injection, is a relatively new area of study. It is an area that will become increasingly important and valuable in the near future.
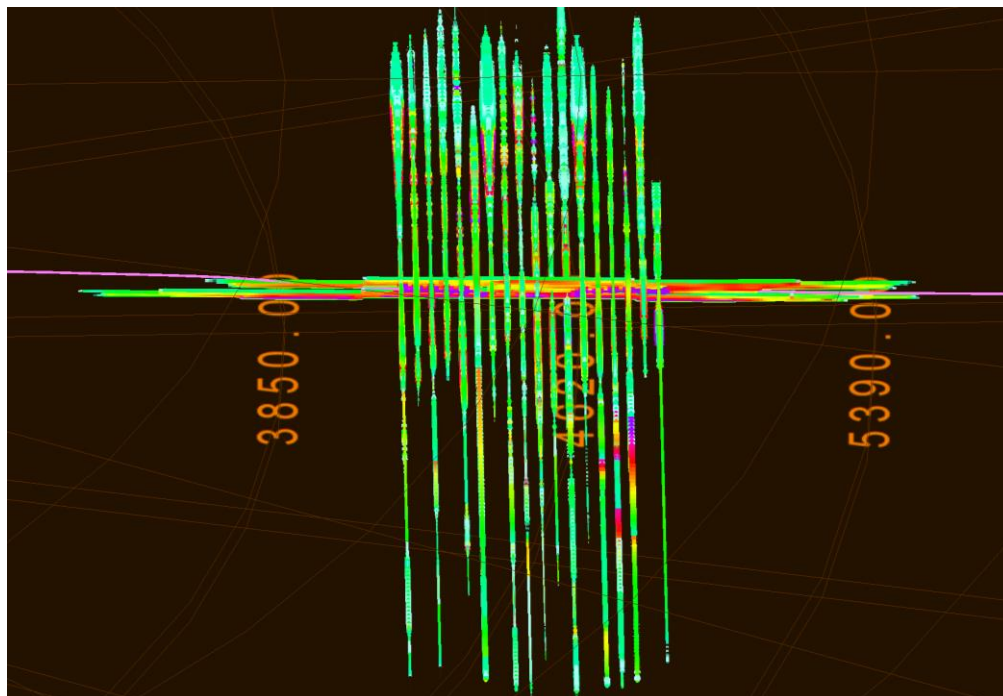

Multiple stage stress shadow and impact of offset well depletion causing fracture asymmetry.

Production Forecasting and Economic Optimization

An accurate production forecast requires accurate reservoir descriptions, knowledge of reservoir producing fractional flows, and a valid fracture conductivity profile that responds to changes in producing conditions over time. The effective fracture length and conductivity are never constant, but change with production rate, fractional flow, and bottomhole pressure, as well as time-dependent degradation of the proppant itself. Using a model that accounts for all these makes it possible to demonstrate the relative economic value of those parameters that can be controlled by the stimulation design, and those that are dependent on accurate reservoir and PVT characterization.

GOHFER makes it easy to compare multiple production forecasts, NPV, IP, EUR, and other production metrics for many cases. Fracture treatment design, fluid cleanup, proppant selection, and reservoir properties can be quickly changed to show the relative sensitivity to each. An interesting exercise is to construct a reservoir realization, with fixed reservoir and geomechanical properties, then challenge the students to maximize the NPV or IROR for a completion design. This may involve all the possible design parameters including frac spacing, number of entry points per stage, lateral length, proppant and fluid selection, pump rate, perforation design, fluid volume, proppant mass, well spacing, and others.

For multi-stage horizontal wells, production can be modeled wither for the entire well, or by replicating the production generated from a single archetypical stage. In the latter case the production is not simply multiplied by the number of stages. Transient interference and overlap of drainage area is considered in the production forecast and resulting economics.
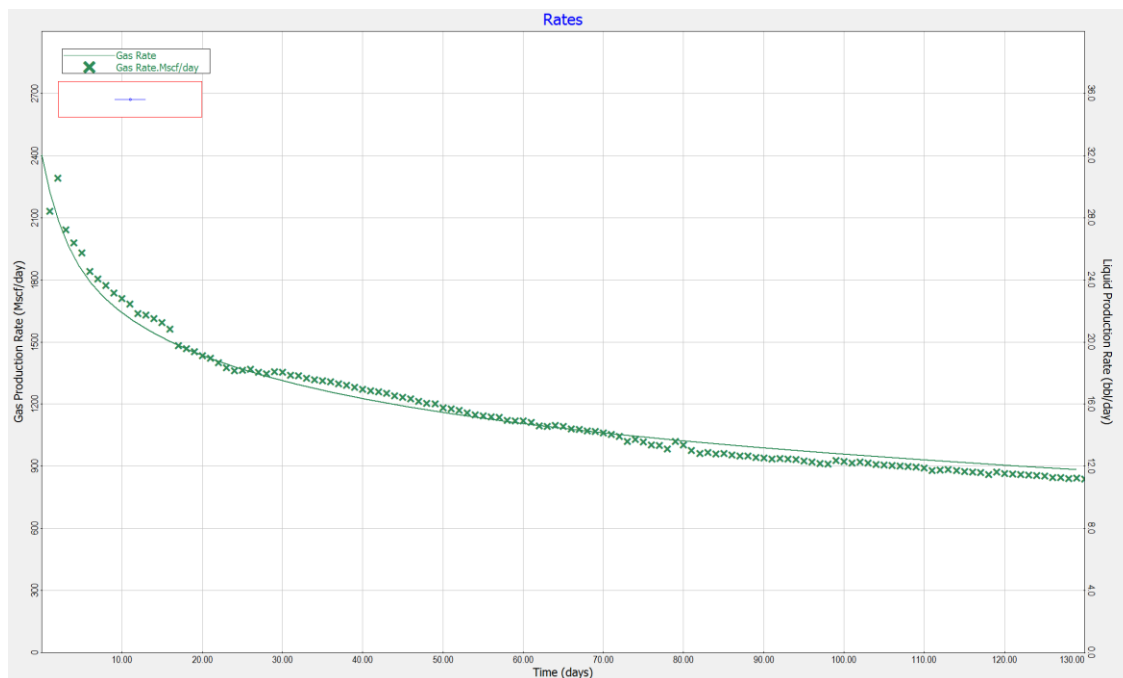
Comparison of actual and model predicted post-frac production using input reservoir properties and modeled fracture geometry and conductivity.

Rate-transient Production Analysis and Decline Curves

Reservoir engineering relies heavily on analysis of production decline, and assessment of reserves and economic value of a well. GOHFE includes a fast, efficient, and accurate production analysis package. The analysis types include flowing material balance for determination of drainage volume, area, and aspect ratio. These results depend heavily on a correct assessment of reservoir fluid mobility and compressibility. To aid in the analysis, a complete PVT correlation package is part of the production analysis. This makes evaluation of the impact on production of changes in oil and gas gravity, GOR, yield, and other properties possible.

To determine the size and shape of the drainage area, the time for each pressure transient to reach each successive boundary must be determined. To accomplish this, the reservoir permeability and effective fracture length and conductivity must be determined. A diagnostic plot is provided to determine these parameters, but the solution requires iteration with the flowing material balance. Both these analyses are linked, and the correct results require satisfaction of both analyses.

Once the drainage area, perm, and frac length are defined, the software generates am Agarwal-Gardner type curve in terms of PWD and TDA. For either a horizontal or vertical well, a diagram of well length, fracture effective length, and drainage area for each fracture is displayed. The type curve can be then be used, with the input flowing pressure history of the well, to produce a model "history match" of the entire production decline for all phases. Once a history m attach is achieved, the model can be used for various production forecasts.

The production forecasting ability in GOHFER provides many opportunities for evaluation of well operating plans. Starting from the end of the existing production history, the future production can be modeled with changing BHFP or fracture length, to simulate the effect of re-frac treatment, installation of a pump, gas lift, or other change in production mechanism. The re-frac model will also simulate the relative impact of a change in effective fracture length with the existing pressure transient in the reservoir, resulting from the previous production, or the effect of a shut-in with or without a re-frac. The shut-in, or "new transient" mode assumes that the reservoir builds up to the current average reservoir pressure based on the volumetric depletion of the preceding production.

The economic value, in terms of acceleration and added reserves, of various changes in fracture length, shut-in, and operating conditions can be readily demonstrated. Re-fracturing is thought by many to be next step in unconventional resource development. The ability to assess re-frac candidates quickly, efficiently, and correctly, is a valuable asset.
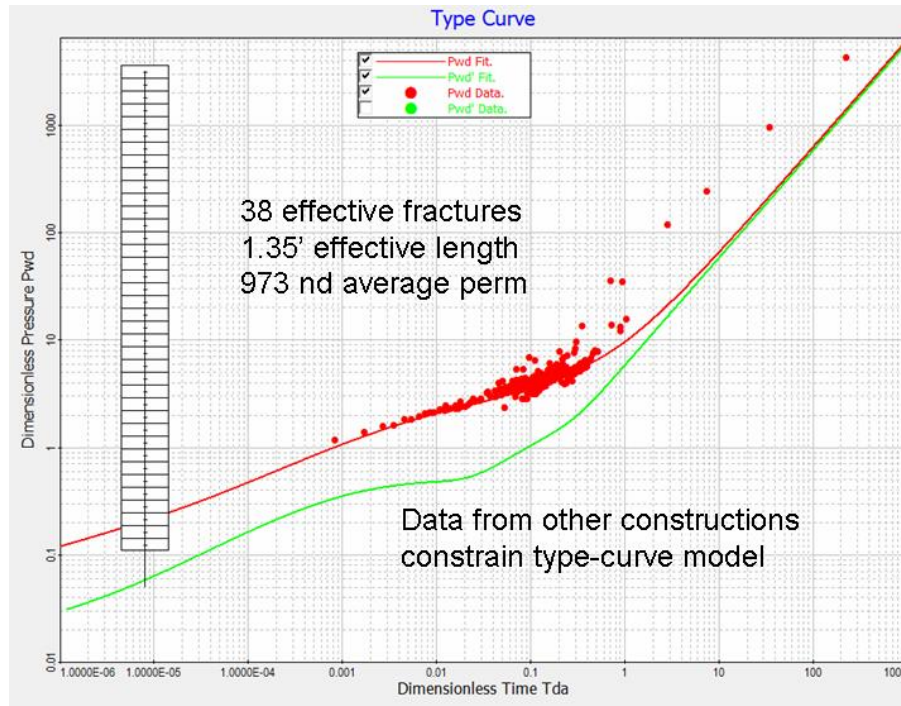
Type-curve model derived from production data and used for production forecasting, economics, and re-frac analysis.

Team Integration:
Geology – Geophysics – Petrophysics – Drilling – Completion – Operations – Reservoir – Management

The entire development of GOHFER, over the past nearly four decades, has been based on the requirement of input from all disciplines involved in petroleum engineering. Log analysis and petrophysics is required to understand rock properties, mineralogy, and geomechanical inputs, as well as reservoir properties derived from core and log measurements. Just integrating core data with the logs, and developing a calibrated model, sometimes requires specialized input and expertise.

Geophysical input is needed for interpretation of local tectonic conditions, deformational history, fault activation, and to understand the relationships between seismic or acoustic velocity, saturation, stress, lithology, and other properties. An understanding of local and regional depositional, and subsequent diagenetic and deformational impacts on the present day stress field is needed to understand fracture orientation, geometry, and interaction.

All aspects of reservoir engineering apply to the problem of economic development of unconventional reserves. This includes reservoir flow capacity, determination of effective drainage area as a function of time, PVT characterization of complex fluid systems, changes in flow capacity due to condensate dropout or gas liberation, capillary and relative permeability effects, and production economics. Without complete ties to the reservoir and economic conditions, it is impossible to even attempt an optimized stimulation design or field development plan.

The overall design of a GOHFER project integrates all these disciplines, and leads to a coherent and consistent development of a predictive three-dimensional reservoir and geomechanical model. Rather than spending excessive time running full field numerical reservoir simulators, that may not correctly represent fracture conductivity, cleanup, and flow capacity, an entire GOHFER project can be built on a time schedule that is appropriate for a university setting. Multiple production sensitivity runs can be accomplished quickly, once the model is built. The software package is ideal for integrating data and input from multiple disciplines, and building an appreciation for an integrated development team that is sought after by many companies.

Regards,

Robert D. Barree

President,

Barree & Associates LLC