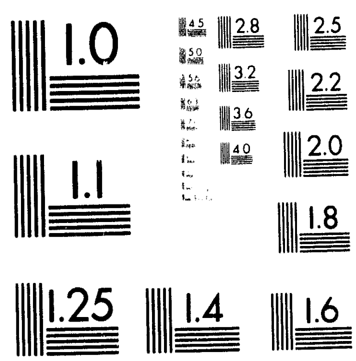
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Geotechnology for Low Permeability Gas Reservoirs

CONTRACT INFORMATION

Contract Number	DE-AC04-~~76DP00789~~ 94AL85000 (FEW-2086)	
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METC Project Manager	Royal J. Watts	
Period of Performance	April 1, 1992 to September 30, 1993	
Schedule and Milestones	**FY93 - FY94 Tasks**	

	| FY93 | FY94 | O N D J F M A M J J A S O N D J F M A M J J A S
Slant Hole Completion Test	--------|
Fractured Reservoirs:	
Green River Basin	--
Support to Industry	--
Geomechanics:	
Lab Studies	--
Effective Stress Analyses	--
Methodology Report	------------------------------|
Geophysical Data Set	(FY94) |-------------------------------|
Support to METC	--

OBJECTIVES

The objectives of this program are (1) to use and refine a basinal analysis methodology for natural fracture exploration and exploitation, and (2) to determine the important characteristics of natural fracture systems for their use in completion, stimulation and production operations.

BACKGROUND INFORMATION

Natural fractures are the critical production mechanism in most of the low permeability gas reservoirs in the western United States. Of particular interest are the regional fracture systems that are pervasive in western US tight sand basins. Regional fractures are created by anisotropic stress fields, usually under conditions of high pore pressure (Lorenz et al., 1991). In such systems, fractures tend to be primarily unidirectional, and thus poorly interconnected (Lorenz and Finley, 1991). This facet of western US tight gas reservoirs has been one of the primary causes of poor success in obtaining economic production from these tight reservoirs.

If these fracture systems are to be economically exploited, it is necessary to determine where fractures exist, what their characteristics are, and how the fractures interact with the reservoir geometry, in situ stresses, and other factors. Natural fracture basinal analysis, which integrates core, log, outcrop, and well test data into a tectonic and fracturing framework, provides a means for obtaining a useful characterization of the natural fracture system. Results from seismic analyses, if proven to be effective in detecting fracture systems, can also be incorporated within this framework.

Successful stimulation and production of these reservoirs also requires a knowledge of the properties of the fracture systems, such as the stress sensitivity and damage propensity. The factors need to be evaluated through a combination of field and laboratory studies, in which individual fractures (lab) and fracture systems (field) are studied. Such studies provide the necessary information for optimizing reservoir management strategies.

PROJECT DESCRIPTION

Continuing work (Lorenz et al., 1993) on this project has demonstrated that natural fracture systems and their flow characteristics can be defined by a thorough study of well and outcrop data within a basin. Outcrop data provides key information on fracture sets and lithologic controls, but some fracture sets found in the outcrop may not exist at depth. Well log and core data provide the important reservoir information to obtain the correct synthesis of the fracture data. In situ stress information is then linked with the natural fracture studies to define permeability anisotropy and stimulation effectiveness. All of these elements require field data, and in the cases of logs, core, and well test data, the cooperation of an operator.

Such a systematic study has been performed in the southern Piceance basin, with the Multiwell Experiment (MWX) providing the key subsurface information. Other wells in the surrounding region have confirmed the MWX data and supported the findings. Currently, a similar effort is ongoing in the Green River basin and in other fractured reservoirs. Through such studies, these procedures can be refined, but a key need is access to more and better field data. Thus, cooperating with industry to obtain non-routine, extra data on "wells of opportunity" are an important part of this project. The result is a better understanding of the dynamics of fractured reservoir behavior.

Laboratory studies of the stress sensitivity and permanent damage to natural fractures have aided in interpreting reservoir response. Such lab studies require conductivity measurements of single natural fractures under a wide range of stresses and pore pressures. Matrix poroelastic studies are also required to estimate the stress change within a reservoir as pressure drawdown occurs. Special laboratory procedures were developed previously in this project, and are now being applied to a wide variety of rocks. These detailed lab measurements are required to understand the flow characteristics of the matrix rock and fracture system throughout the life of a reservoir.

RESULTS

The following three sections present brief examples of the types of information gained from some different parts of this project.

Natural Fracture Characterization

Figure 1 shows data on natural fracture orientations and locations as revealed in horizontal core from the Slant Hole Completion Test (SHCT) core. This fracture system is a

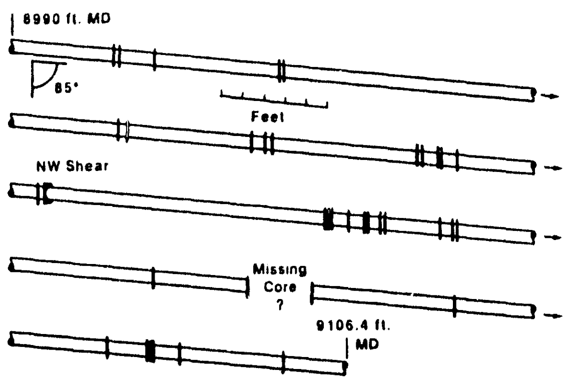


Figure 1. Fractures in SHCT-1 Core

regional, unidirectional, system, whose existence was essentially inferred during MWX and confirmed in this SHCT core. Of note are the non-regular spacings of fractures, which appear in a series of groups or swarms. Thus "Average Fracture Spacing" is not a useful number. Rather, the typical spacings of fracture groups is a better number to use in simulation models, as these give a more realistic value for the distribution of the permeable fracture conduits for gas. This spacing seen in core is similar to the spacing of gas shows observed while drilling (Lorenz and Hill, 1991).

These natural fractures are vertical and thus they have a minimum probability of being intersected by the typical vertical well. So little information is gained about the fracture system. This project addressed how to optimize the amount of natural fracture data from a pilot well. If the pilot well is deviated by 30 degree from vertical, the probability of intersecting a vertical fracture in a 35-ft thick pay increases by up to 6200% where the wellbore's azimuth is oriented normal to the fracture strike. However, even if the fracture strike is unknown, there is a two-thirds chance of intersecting at least half of this percentage with a randomly oriented wellbore azimuth (Lorenz, 1992). A company, based on Sandia recommendations, recently drilled a 30-degree deviated pilot well in order to assess natural fracture orientation and characterization at a site in the Green River basin. This slanted pilot well was successful in providing the data required to determine the regional fracture system's azimuth, and the company confidently drilled a horizontal well at this location.

Effective Stress

The effective stress law of a material defines a relation for the interplay of confining stress and internal pore pressure on a given property or process. The stress law is usually expressed in the form:

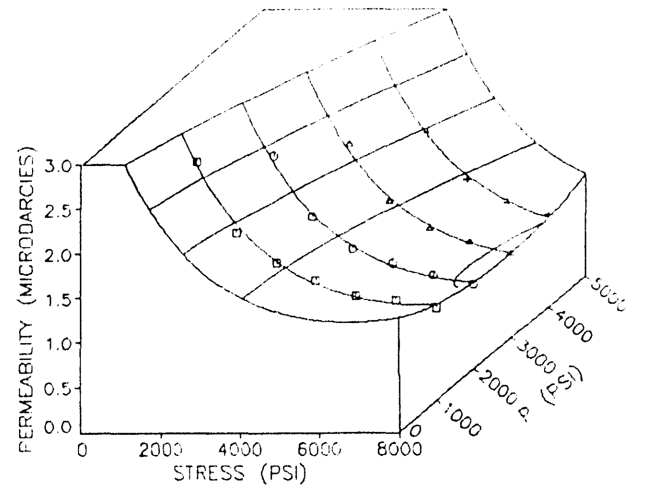
$$P = G(\sigma - \alpha p),$$

where the property or process, P, may include, for example, permeability or deformation, G( ) is some generalized function that describes the effect of stress on P, σ is the external confining stress on the sample, p is the internal pore pressure, and α is the poroelastic parameter that relates stress and pore pressure. Generally, α is assumed to be a constant and equal to 1.0. However, an accurate knowledge of α as a function of σ and p is required for confident understanding and modeling of reservoir behavior during such normal operations as drawdown, water flooding, and stimulation. Unfortunately, few studies of α are available. This project has focused upon determinations of α for tight sandstones and carbonates (e.g., Warpinski and Teufel, 1992).

An experimental apparatus and analytical procedures have been developed that allow for the routine determination of α. Figure 2 shows the measured permeability (k)-stress (σ)-pore pressure (p) relationships, as well as the resulting α for permeability, for a Mesaverde Cozzette sandstone. Of note is the large decrease in α at high effective stress. This shows that the common assumption of α=1 is not very good for such low permeability rocks.

Figure 3 shows the α for deformation as a function of depth at the MWX site. Again, the divergence between measured and theory indicates that α needs to be measured for tight rocks as simple theory is not adequate.

Similar measurements have been made on samples containing single natural fractures. The experimental procedures are complicated by the need to correct for turbulence and to note any irreversible closure behavior. Two Mesaverde Cozzette samples showed relatively little stress sensitivity, and nearby mudstones showed irreversible closure behavior.



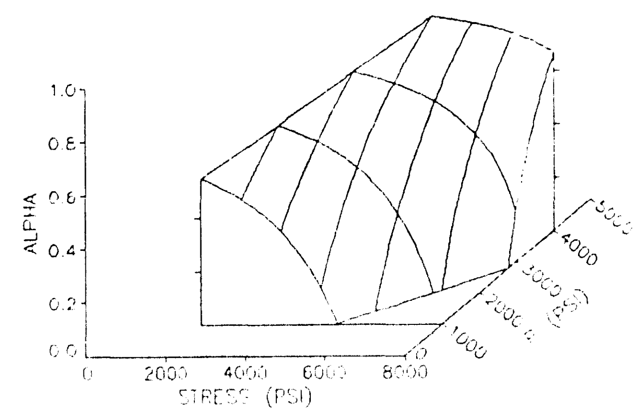


Figure 2. Effective Stress for Permeability

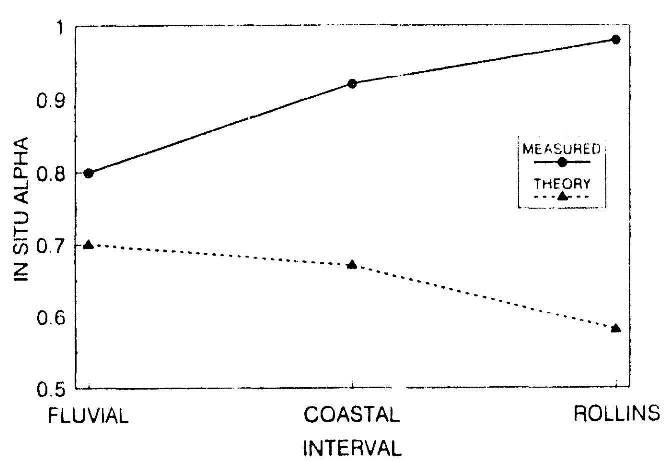


Figure 3. Alpha for Deformation vs. Depth

Stress Path

Knowledge of in situ stress and how stress changes with reservoir depletion and pore pressure drawdown is important in a multi-disciplinary approach to reservoir characterization and management. Stress affects nearly all petrophysical properties and hence the measurement and interpretation of laboratory, well test, and geophysical data. Hydrostatic (isotropic) loading is the conventional test procedure followed by the petroleum industry to determine the stress dependence of reservoir properties. However, hydrostatic tests do not truly reflect the stress anisotropy and deviatoric stress state that exists in most reservoirs and do not adequately simulate the changing stresses in a reservoir during production (e.g., Teufel et al., 1993) In situ stress measurements made in wells during pore pressure drawdown show that many reservoirs follow a stress path (defined as the change in effective horizontal stress/change in effective overburden stress from initial reservoir conditions) that is significantly different than either a constant total-stress boundary condition (hydrostatic loading) or a uniaxial-strain boundary condition (i.e., no lateral displacement of the reservoir boundaries).

Triaxial compression laboratory tests on a variety of reservoir rocks show that compressibility, permeability, and sonic velocity vary markedly with stress path (Rhett and Teufel, 1992). Thus, changes in properties measured under hydrostatic loading conditions to predict reservoir response during production and pore pressure drawdown can be inaccurate and very misleading if applied to a reservoir that follows a non-hydrostatic stress path. Realistic predictions of reservoir behavior require petrophysical property measurements of reservoir matrix rock and fractures made in the laboratory under loading paths that duplicate the stress path followed by the reservoir during production.

For example, analysis of MWX data shows that this reservoir (in the Rulison field) followed a relatively high stress path of 0.76 (Figure 4). This path is less than isotropic loading (K=1.0) and considerably greater than K=0.25 predicted by uniaxial strain tests. Fracture closure and large reductions in reservoir permeability and productivity can occur in reservoirs that follow high stress paths. In sharp contrast, permeability and productivity are maintained in reservoirs with low stress paths (Figure 5), such as the Ekofisk field, because there is only a relatively small increase in the horizontal stress across steeply dipping fractures.

FUTURE WORK

Future work in FY 94 will consist of three main efforts:

- We will continue its geologic field work and its efforts with industry on wells-of-opportunity in order to obtain high-quality information on natural fractures and stresses and reservoirs of interest.

- We will also continue our geomechanics-related measurements and analyses (stress sensitivity, damage, poroelasticity, stress path, etc.) on appropriate reservoir rocks where information is lacking.

- We will analyze a unique in-situ, seismic data set that will be obtained as part of the DOE-Gas Research Institute's M-Sites Experiment to determine the ability of seismic techniques to define a typical regional fracture system.

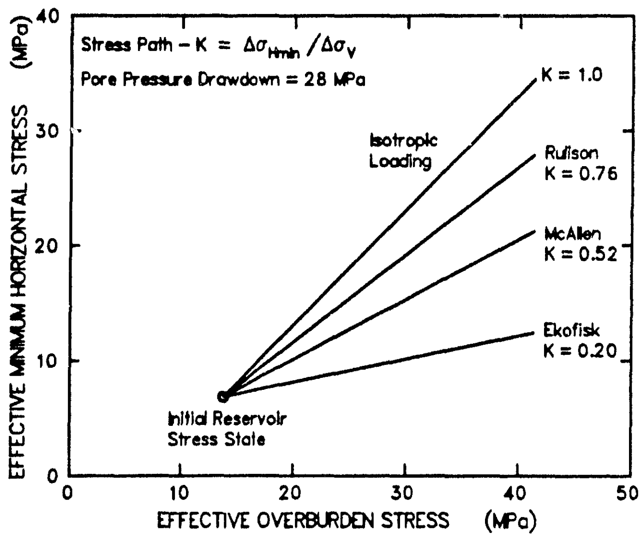


Figure 4. Examples of Different Stress Paths (from Teufel et al., 1993)

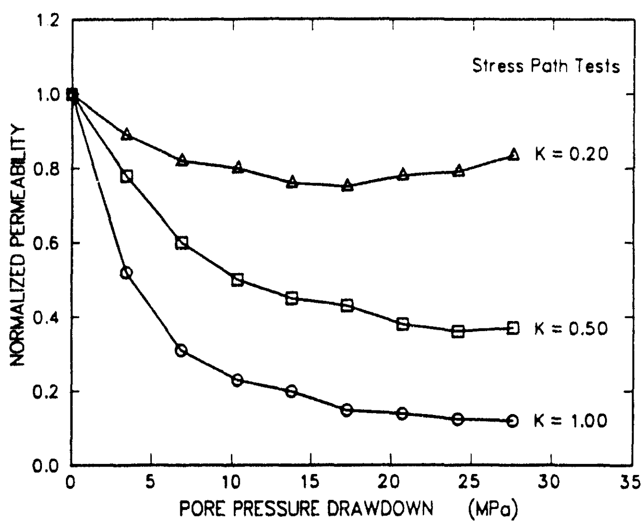


Figure 5. Effect of Stress Path on Permeability (from Teufel et al., 1993)

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