Naturally Fractured Tight Gas Reservoir Detection Optimization

Quarterly Report

April 1 - June 30, 1995

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**U. S. DEPARTMENT OF ENERGY
MORGANTOWN ENERGY TECHNOLOGY CENTER
QUARTERLY STATUS REPORT
FOR THE PERIOD
April 1, 1995 - June 30, 1995
DATE OF SUBMISSION: 7/31/95**

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Naturally Fractured Tight Gas
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CONTRACT PERIOD:

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CONTRACT OBJECTIVE: No Change

TECHNICAL APPROACH CHANGES: No Change

A. GEOLOGIC ASSESSMENT OF THE PICEANCE BASIN

High Resolution Aeromagnetic Survey:

Analysis concentrated on the high-resolution aeromagnetic data acquired by World Geoscience, but the interpretation was supplemented by examination of regional published gravity and magnetic data, as well as surface geology and subsurface geology.

THE DATA SETS

The high-resolution aeromagnetic survey provides an excellent data set. Close line spacing (1/4 x 1 mile) and low aircraft flight elevation (500 feet above mean terrain) provide abundant information about shallow magnetic sources that are important to interpretation of faulting and fracturing in the prospective section. Traverse lines were flown north-south, an appropriate orientation for both basement and shallow-source anomalies, which have typical east-west to NW-SE orientations. The 2 1/2-nT contour interval of the 1:100,000-scale maps probably shows virtually all anomalies of geological significance.

World Geoscience acquired and processed the data between September 1994 and January 1995. In addition to the total magnetic intensity map (reduced to the pole), World Geoscience prepared three Pseudo-Depth Slice Maps, which are used to enhance trends that arise from anomalies at depth intervals identified through spectral analysis. The interpretation was based primarily on the reduced-to-the-pole total field map, but the Depth Slice Maps provided significant useful information regarding details of specific interpreted features, particularly in terms of disruptions in the shallow-source anomalies.

Published data used for the regional tectonic interpretation included the Gravity Map of the U.S. (SEG, 1982), the Magnetic Anomaly Map of the U.S. (Bond and Zietz, 1987), and 1:500,000-scale maps of the Piceance Creek Basin area (Abrams, Grauch, and Bankey, 1990; Grauch and Plesha, 1989). Many surface geologic maps were consulted.

GRAVITY AND MAGNETICS

A few basic principals of gravity and magnetic interpretation are included here for the benefit of those who may not have had any exposure to these methods. For a more thorough treatment, you are referred to any good geophysics textbook, such as Nettleton's *Gravity and Magnetism in Oil Prospecting* (McGraw-Hill, 1976). Two qualities of potential-field data which are important to both quantitative and qualitative interpretation are *amplitude* and *frequency*.

Amplitude, or intensity, refers to the value of a gravity or magnetic anomaly in milligals or gammas. In hydrocarbon exploration, gravity and magnetic anomalies are typically measured to 0.01 milligal and 0.01 gamma (1 gamma = 1 nanoTesla, nT), respectively, or better than one part in 5,000,000 of the earth's fields. In general, the value is proportional to the density or magnetic susceptibility contrast in the rocks beneath the sensor. (Susceptibility is a measure of the ease with which a material can be magnetized. Geologically, it can be thought of as a measure of magnetite content, although there are a few other minerals that contribute to bulk rock magnetization under special circumstances.) Again generally, gravity highs indicate the presence of relatively dense rocks, and magnetic highs are caused by rocks with abundant magnetite in them. Thus lithologies are implied, but statements about lithology in the subsurface are usually interpretations. Sometimes the data are nearly inescapable in their implication of certain rock types (especially when diverse data are interpreted synergistically), but more often several alternatives are possible and should be constrained as much as possible with other information. Very high intensity anomalies usually (but not always) in basement rocks. Such changes are commonly clearer in magnetic data, reflecting the fact that magnetite content varies much more in basement rocks than does density. Structural features, such as folds and faults, usually cause much smaller anomalies. The observed anomaly is of course the result of both structural and lithologic effects; if a small anomaly caused by a large structure is superimposed upon a large anomaly caused by a lithologic contrast, the two features may be inseparable. Zones of lithologic contrast are often loci of structural disturbance.

Frequency is a measure of how narrow or broad anomalies are, and is a quantity which is mathematically proportional to the depth to sources. High-frequency, narrow anomalies come from sources that are relatively shallow, and broad, low-frequency anomalies are caused by contrasts at

greater depths. This quality of these data is irrespective of intensity; that is, a magnetic high that is very broad almost certainly comes from great depth. It is a mistake to equate magnetic highs with topographic or structural highs, just as magnetic highs should not necessarily be expected to coincide with gravity highs.

Because magnetic anomalies come from contrasts between relatively few rock types, quantitative analysis such as computing a depth to source is appropriate (if specifications of the data acquisition are known; in this study such necessary parameters as magnetometer altitude were not known with certainty). Gravity anomalies, as mentioned above, are caused by contrasts in all parts of the rock section (from the below the base of the crust to the surface) and can therefore be misleading. It is possible for relatively shallow sources to be distributed in a way that produces a broad gravity anomaly which would be expected to come from deep bodies of rock.

INTERPRETATION

Overview of Data

The data contain anomalies from two immediately obvious depth ranges: very broad (on the order of several miles) features that arise from the magnetic basement, and very narrow (small fractions of a mile) anomalies that come from shallow, near-surface sources. All of the basement anomalies are evident in published data, but this survey reveals a wealth of detail that could never be inferred from the regional maps. These broad anomalies are also high-intensity features. The high in the middle of the survey has an amplitude of more than 500 nT. Such anomalies are typical of cratonic magnetic basement and are fundamentally intrabasement lithologic contrasts of Precambrian age. In areas of tectonic activity, such contacts serve as weak zones that are often rejuvenated as structures. This appears to have occurred in the basement of the Piceance Creek Basin.

Further examination of the data, especially in conjunction with the Depth Slice Maps, revealed an additional category of anomaly. These intermediate-depth anomalies are most evident just south of the Colorado River near Rifle. Their amplitudes and frequencies suggest moderately deep basement sources, but deep magnetic material other than basement cannot be ruled out. They are discussed further in the section on Specific Basement Features.

Regional Interpretation

Basement in the Piceance Creek Basin deepens from the west (Douglas Creek Arch) into the survey area. Basement crops out in the Uncompahgre and White River Uplifts to the southwest and northeast, respectively. Within the basement, lithologic contacts exist that give rise to the high-intensity magnetic anomalies observed on regional maps. In many parts of the Rocky Mountain region, basement magnetic highs reflect granitic and/or granodioritic basement, while lows typify metamorphic rocks in the basement, and this is a reasonable concept for the basement in this area. All of the basement rocks in the survey area are expected to be early to middle proterozoic crystalline rocks; the edge of the Archean Wyoming Craton lies much nearer the northern border of Colorado.

These intrabasement lithologic contacts are transected by regional disruptions in gravity and magnetic data that may be structural zones with Precambrian heritage. Some of the disruptions in this region have prominent northeast-southwest orientations that correlate with mylonite zones and faults within outcropping basement in the Park Range, and this direction is parallel to the Colorado Mineral Belt trend that can be traced in magnetic data from northeastern Colorado into Arizona.

All of these weak zones - intrabasement lithologic contacts and old structural zones - are likely sites for later Laramide structural rejuvenation. Thus the regional interpretation (Map 3) provides a framework for suggesting particular basement zones that may have had impact on the prospective section. That impact may have been specific basement faults of various types, or a focus for fracturing in the section. In particular, the east-west magnetic gradient near the Garfield-Mesa County line is a zone that may have had structural reactivation along it. Sales (1968) suggested that the zone was an east-west left-lateral basement fault that produced en echelon anticlines in the section above it. NW-SE trending anticlines do exist in this area, but many of the ones Sales described were defined from single wells, so their orientation is unclear. Nonetheless, this possible fault zone fits well with postulated Laramide rotation of the Colorado Plateau Craton, and the intense linear magnetic gradient certainly represents a major intrabasement contact.

Basin-scale Interpretation and Specific Basement Features

This interpretation shown on figure 1 is largely self-explanatory. Note that specific basement faults were drawn on steep gradients in the total field magnetic map, modified (usually, only slightly) using especially Depth Slice #4. Sense of throw on these faults was inferred by subjective estimations of frequency variations, but since these variations are small and in some locations heavily interfered with (by the shallow-source anomalies), this postulated throw is questionable. "Small" throw means probably hundreds of feet rather than thousands, although the aggregate throw between major basement blocks may be several thousand feet or more.

Preliminary Depth estimates tend to support the idea of small throws totaling a few thousand feet over multiple faults. Interference (both from shallow sources and from low-intensity broad features), poor orientations, and lack of two-dimensionality all reduce the value of the depth estimates that are shown. Values in the 6800-8200-foot range (sub-sea level) are consistent with generally projected basement surface elevations in the basin. A detailed depth to basement in preparation will be included within the next quarterly report.

The interpretation shows the magnetic high in the middle of the survey to represent a slightly uplifted block of basement. This area is certainly shallower than the basement beneath the wide gradient in the south-central and southwest part of the survey, and the high is subjectively inferred to be shallower than the basement to the northeast and east. This is also consistent with geologic information that indicates thinned or absent Paleozoic rocks in the vicinity of the magnetic high, as well as with the limited information from the depth estimates.

The high block in the middle of the survey appears to represent an area of fundamentally different basement behavior from the area to the east and northeast, which is inferred to be

underlain by less-magnetic metamorphic rocks. Inferred deformation style in the central and western block appears to be more brittle and high-angle, while thrust faulting appears to be confined to the east and northeast part of the survey. At least thrusting that is inferred to involved the magnetic basement (most evident south of the river near Rifle, and at Divide Creek) appears to be limited to this eastern area. It is difficult to define the boundary between these two blocks with certainty, but the major basement fault zone along the east and northeast side of the intense magnetic high is the favored area.

The difference in structural behavior of the basement (brittle and high-angle vs. basement-involved thrusts) may relate to the presence or absence of Proterozoic sedimentary rocks (Uinta Mountain Group equivalent) as well as to differences in crystalline basement lithology, but because the distribution of Proterozoic sediments is poorly known this conclusion cannot be considered definitive.

The summary basement blocks shown on figure 1 represent one attempt to generalize and group the basement faults, and they should be thought of as approximate boundary zones rather than as single "master" faults. Variations in precise position are possible, and it is likely that some zones that are shown to terminate against others (e.g., the boundary at the southern edge of the Parachute-De Beque Basement High) may actually have effects beyond that termination (i.e., east of the NNW-trending boundary zone on figure 1). The summary basement blocks should be used to suggest regions of somewhat independent movement, but confirmation of such tectonism should rely on careful integration with subsurface data.

Intermediate-Depth Features

South of the Colorado River near Rifle, anomalies of moderate intensity and intermediate frequency are interpreted to represent basement-involved thrust faults and tear fault zones associated with them. These anomalies are distinctly different (and of deeper source) than the shallow-source anomalies discussed below. They can be discerned in the Total Field map, but they are enhanced considerably by Depth Slices 3 and 4. The idea that they are thrust faults comes from local subsurface geology provided by Advanced Resources (seismic data showing thrusting), but the specific locations shown on Map 1 are derived entirely from the magnetic data.

The inferred tear faults show up as disruptions in the magnetic data. The one along the river delimits the zone of inferred basement-involved thrusting, with possibly no continuation of basement involvement to the north. Map one shows possible continuity of faults across the river, but in fact the anomalies there are very much more subtle than on the south side of the river, and it would be a viable interpretation that the faults end at the river. An alternative is that the faults continue, but pass out of magnetic crystalline basement south of the river into nonmagnetic Proterozoic sediments to the north.

Of the other possible tear fault zones, the best-defined one is the one that extends from Battlement Mesa toward New Castle on the Colorado River. It is marked by disruptions of the intermediate-depth anomalies north of it, and it also marks the northwestern termination of the

REGIONAL HIGH-RESOLUTION TOTAL FIELD MAGNETIC INTENSITY

broad anomaly associated with the end of the Divide Creek Anticline, a basement-involved thrust feature. Discerning the broad anomaly that comes from the basement at Divide Creek is difficult because of the interference by shallow-source anomalies, but Depth Slice 4 shows this feature (and its termination to the northwest) quite clearly. Regional gravity data also show a high along the Divide Creek Anticline.

Shallow Interpretation

The abundant shallow-source anomalies have intensities as high as 150 nT. Careful correlation of their locations with surface geology revealed a moderately good correlation with certain stratigraphic horizons. Some of the most intense anomalies correlate very well with the upper part of the Mesa Verde Group, and in the Grand Hogback, they correlate with clinker in that part of the section. Isolated intense anomalies in the northwest and southwest corners of the survey also correlate with outcrops of the mesa Verde and are suspected to represent clinker as well. Most of the rest of the isolated anomalies in the western two-thirds of the survey are very near the contact between the Parachute Creek Member of the Green River Formation and rocks of the lower part of that formation (*Tgp/Tgl* on Map 1). Generally, the anomalies parallel strike of the contact, which suggests that whatever they are they have a stratigraphic origin. Comparison with the most detailed geologic maps available (GQ and MF maps) confirmed the position near or at this contact, but revealed no suggestion of clinker or any other potentially magnetic material. A possible exception is "*numerous thin yellowish-brown tuff beds...rusty weathering*" on the south side of Long Point (sec. 7, 18, 19, T7S, R97W; Geologic Map of Long Point Quad) in the Parachute Creek Member.

The fact that the anomalies are discontinuous as well as quite variable in intensity indicates that they do not arise from something consistently stratified in the rocks. Igneous material such as sills is a possibility, but it would be expected that at least some would have been mapped geologically. Thus the ultimate origin of these anomalies is not resolved. Field examination of outcrops is recommended to determine the cause. The observation that many of the most intense anomalies in the western part of the survey appear to lie at intersections of basement lineaments suggests the possibility of tectonic and/or igneous control.

In the eastern part of the survey (as well as in places in the south-central part), most of the anomalies correlate with mapped Wasatch and Ohio Creek strata (*Two* on Map 1). Several locations show correlations with surficial deposits - Quaternary alluvium and/or gravels, or glacial deposits. While it is possible that some material such as basaltic boulders in alluvium or gravel could produce magnetic anomalies, it is highly improbable that they could cause anomalies of the intensity found in this survey. In this area (especially around Divide Creek Anticline and points to the north), the shallow-source anomalies are typically elongate, suggesting strata-bound origin, and this is the premise for the interpretation of disruptions in the anomalies as small faults or fracture zones in the sedimentary section. These disruptions are predominantly oriented NE-SW, but in such high-frequency data it is possible to find orientations in virtually any direction one chooses. The mapped fault-fracture zones are essentially parallel to the interpreted tear faults associated with thrusting near Rifle, which makes them consistent with other tectonic features in the area.

Some of the NE-SW disruptions are mapped on Map 1, but most are shown on Map 2 because specifics of their location and orientation were derived more from Depth Slices 2 and 3 than from the total field map. The clearer expression in the Depth Slice maps also lends considerable confidence to the interpretation of orientations.

At Divide Creek Anticline, a particularly intense, continuous, linear shallow-source anomaly zone is nearly parallel to and just stratigraphically above the contact between Mesa Verde and Wasatch rocks. The source may lie within the Mesa Verde (broken or breached magnetic strata just below overlying Wasatch rocks) or within the Wasatch essentially at the source.

The anomalies southwest of Divide Creek Anticline differ somewhat in character from other shallow-source anomalies in the eastern part of the survey. Apart from two relatively intense anomalies that correlate with Wasatch on the surface (but which may be dikes), most of the anomalies in this area are relatively low intensity, and most have an east-west grain. The NE-SW trending fault/fractures from Divide Creek can easily be construed to continue in this area, but the disruptions are less easy to see (even on Depth Slice 2) in these lower-intensity anomalies. These anomalies may be coming from sources similar to those to the northeast, but at a slightly greater depth (a few hundreds of feet, probably), or they may arise from different strata or from small dikes. Of the two dikes mapped in the area, the one east of Battlement Mesa has a clear magnetic expression, while the one west of the middle of Divide Creek Anticline has very little. It is possible that east-west basement structures in the western part of the survey have an impact in this area, accounting for the east-west orientation of the anomalies. This interpretation suggests that whatever the source of the anomalies southwest of Divide Creek, they have probably been affected by the same NE-SW disruptions that are evident in most of the eastern part of the survey.

FIELD PERFORMANCE TEST PLAN:

During the last quarter a preliminary integration of the imagery lineament analysis, high resolution aeromagnetics, stratigraphic and structural modeling was completed. It was concluded that the identified NW - SE trending basement faulting was the primary control on open fracture systems. Enhanced production is developed NW - SE along the anticline axis whereas poor production was associated with NW - SE trending synclinal axis. Updip gas migration increasing gas saturation, in conjunction with dilation of fracture systems is a likely cause of the NW - SE anticline production fairways. Geologic mapping indicates that extensive undrilled areas have similar structural settings that would permit extending existing field boundaries and locations for exploratory drilling. To confirm the geologic model a 3D 3C seismic shot is required.

The Rulison Field lies along the most prominent NW - SE trending basement fault. The field operator, Barrett Resources Corp. is in complete agreement with geologic model for the Rulison Field. Infield drilling on 40 acre spacing is designed along the NW - SE trending production fairway. The 3D - 3C seismic program will be used to identify the most fractured portion of the field for targeting development wells and locating the western most boundary of the

production fairway. Ideally the shot will be performed over the southern portion of the field underlain by two horizontal wells. Fracture data from the horizontal wells will be used to calibrate seismic anisotropy trends.

On May 10, 1995, Royal Watts, Heloise Lynn, and David Decker traveled to the Rulison Field site to inspect it for suitability for a multicomponent 3D survey. Two possible sites are identified: the relatively flat desert scrub-brush area north of I-70 and the relatively flat grassy meadow mesa-highland south of the Colorado River, which contains the MWX site. These two sites are possible locations for the 3C geophone patch (stationary, not rolling), and the seismic sources (dynamite or vibroseis). There are various cultural noises to contend with on both sites: the northern site has the Interstate and some N/S power lines and some compressors and generators associated with producing gas wells; while the southern site has a power line running approximately east-west across the flat open space suitable for the geophone patch, various pipelines and/or equipment associated with producing gas wells.

It is necessary to surround the geophone patch with seismic sources up to 4000-5000' offsets. The southern site can be ringed with seismic sources with probably less than 20% dropout for the whole survey. The ability to put sources west and north of the northern site is greatly restricted by the rough terrain. If the northern site were selected, a heli-portable drill would probably be employed, thus driving up costs for the source effort. Therefore, the southern site is deemed logistically better.

A basemap containing all noise generating objects and objects requiring standoff of seismic sources: pipelines, generators, power lines, well heads, roads, houses, waterwells, etc. will be generated. This basemap will greatly assist the seismic contractors in laying out the desired program and in preparing, and comparing bids. A NEPA report, and if appropriate archeological reports will be filed.

In preparation for the seismic program at Rulison Field a review of all existing seismic data was conducted. This report will summarize the information describing successful surface seismic data acquisition in the Rulison Field area. Initial seismic interpretation efforts were focused on structure, with primary emphasis on basement tectonics. For the present acquisition design the focus shifts to the shallower Cameo-Rollins interval and characterization of fractures. A review of the available seismic data in the vicinity of Rulison Field suggests that good to excellent seismic data is possible. Optimal acquisition parameters for the Cameo-Rollins interval, however, may fall short in the quest to delineate structural variation in the interval from Dakota to Basement.

The earlier data (SSC, Terra) suffers from low frequency and in the case of the SSC data, broad group and shot spacing. Low fold of 24 also hurts the imaging potential of these data for very shallow and the deepest horizons. Both data sets are adequate for imaging the Cameo-Rollins interval, however. Meridian has reprocessed selected Terra Resources lines with good improvement in the Cameo-Rollins interval. Given the Good-Fair imaging of the basement on the Terra Resources data, Vibriosis should be a viable source in this area. The Grant-Norpac and Mobil data show good penetration and overall, good imaging at all depths. The large charge size (35-60#) appears to reduce overall frequency near the Mesaverde when compared to the Meridian

dynamite data (5-10#). All three of these data sets benefit from modern processing and higher fold. These data also provide excellent imaging of the Cameo-Rollins interval. The swath lines acquired by Meridian are the best data in the area for the Cameo-Rollins interval with upper frequencies in the 90 hertz range. Penetration through to Dakota and Basement are weak for these data showing the tradeoff between charge size, frequency content in the Cameo-Rollins interval and deeper imaging.

Meridian also provided information on a 3D survey they had planned to acquire for their Southwest Rifle Prospect overlying the Rulison Field. The design covers 15 square miles and averages 15 fold. The design covers areas both north and south of the river. Meridian is very much interested in acquiring a portion of this survey and may co-fund the DOE acquisition if their goals can be met along with the DOE's. Their current area of interest for a P-wave receivers live (in patches) throughout the surrounding 10-15 square miles. This would create a large P-wave 3D overlying the converted wave 3D survey tied to the 2D shear wave data. We will arrange a meeting with Meridian to further discuss the potential joint shoot, establish a preliminary understanding for data sharing, and technology development.

The CIRF.B Basin Simulator

While structural elements are important to fracturing in tight gas sands, rock properties and fluid overpressuring determine the nature, location and orientation of fractured rock. These properties are significantly affected by the degree of cementation and compaction, pore fluid composition and phase, paleostress, basement tectonics and overpressuring from hydrocarbon generation, compaction and fluid thermal expansion. What is needed is a predictive basin model that incorporates these factors so as to predict the extent, character, location and compartmentation of NFTR's.

Stresses affect mechanical and pressure-solution mediated compaction which, in turn, affect the distribution of fluid pressure and the rate of diagenetic reactions and hence porosity and other textural variables. The latter affect the distribution of rock mechanical properties and hence stress and fracturing. Thus, the network of reaction-transport-mechanical (RTM) processes is very strongly coupled and the phenomena of interest here can only be properly understood in terms of the fully interacting network.

Our premise is that multiple, overlapping and integrated geological methods and remote sensing tools can substantially increase the probability of detecting subsurface fractures. Furthermore, theories on fracture genesis coupled with a numerical rock properties simulator can quantify the process of fracture mapping. We are carrying out a coordinated petrological, geological and RTM modeling study to produce a predictive fracture mapping approach.

B. Approach

Our RTM model and data interpretation strategy in prospecting for naturally fractured petroleum reservoirs provides an economical strategy for targeting areas for more extensive and definitive exploration efforts. Our model and computer simulator CIRF.B can be used to

predict the location of linear, partially-healed natural fractures. Such a predictive method can lead to better placement of wells and increased accuracy in exploration for productive fracture zones. The required predictive power is provided by integrating seismic, geostatistical, production engineering data, basin sedimentological and tectonic reconstruction history data using the CIRF.B code. Unlike other approaches where seismic data is interpreted by traditional means and then used as input to run a model, our approach directly uses raw seismic data via an optimal control, history matching algorithm.

The CIRF.B model is being calibrated at the MWX site in the Rulison field located in the Piceance Basin of northwest Colorado. Research at the MWX site has resulted in a wealth of data critical for calibrating the model. The model's capability to map subsurface lateral and vertical fracture extension is being compared: 1) locally with *in-situ* fracture characterization data at the MWX site and 2) regionally to structural and basement fault block maps derived from integrated imagery, aeromagnetics and 2-D seismic interpretations as well as maps of methane-producing coal beds and other potential sources of overpressuring. The model will be fully calibrated when a good match between predicted and observed fractures is achieved.

There are two mechanisms which are believed to strongly contribute to fracture generation in general and in the Piceance Basin. Tectonics are important because of their external control on sedimentation and lateral basin stresses. The development of overpressure from processes internal to the basin, such as hydrocarbon generation and other diagenetic and hydrologic processes, may also contribute to fracturing. Both mechanisms are considered and incorporated into the CIRF.B model.

As a first step in calibration and testing of the model, a review and evaluation and compilation of the available data on tight gas sand reservoirs in the Piceance Basin has been performed. We have collected the necessary geological, geochemical, and geophysical data for model calibration and testing. New data is also being acquired. In developing CIRF.B, we have integrated the existing hydrologic, pore fluid and mineral mass conservation, fracture mechanics, pressure-solution and poro-elasticity simulators into a unified model (taking advantage of our integration approaches used in other codes).

The final calibration and testing of CIRF.B is being made by comparing CIRF.B predicted with observed fracture maps. CIRF.B predicts fracture dimensions, heterogeneity, connectivity, extent and quality of fracture networks, likely petroleum reserves and hydrologic properties of the surrounding rock. A sensitivity analysis is being performed to estimate error bounds on the prediction as a measure of its use from a probabilistic sense. An evaluation of how the model improves exploration strategies over the success rate of conventional approaches is also being performed.

Thus, the model can be used in a number of distinct ways:

1. Delineate the types of NFTR's that can exist and the tectonic and sedimentary conditions favoring them;

2. Predict the locations where NFTR's are likely to exist in basins of various type;
3. Model the Piceance Basin where knowledge of the sedimentology and tectonics has been worked out, predict the likely locations of NFTR's and their likely extent and petroleum content and producibility;
4. Predict engineering properties (brittleness, porosity/permeability, cementation, fluid pressure) of a formation in one part of the basin based on its physical properties (petrologic, organic and fracture network analysis, etc.) in another;
5. Predict fracture styles in different lithologies using rock rheological data.

In these ways, the model can be used to develop exploration and production strategies and predict the location of prospective NFTR's. Our ultimate goal is that our model is calibrated such that it can reliably be used for any basin.

II. The CIRF.B Basin Simulator

A. Purpose

Our basin simulator accounts for the intimate coupling of mechanical and chemical processes which may result in the kind of fracturing required for NFTR's. The processes included and the effects that accounting for them in the model allows us to capture are as follows:

- Grain reactions can cause the infilling of fractures near the periphery of a developing NFTR (thereby retaining the gas in the interior); these reactions can also yield brittle behavior needed to allow for fracturing or create a limited number of cement crystals within a fracture, thereby propping it open.
- Aqueous reactions affect the pore fluid composition that mediates grain reactions (and hence texture evolution).
- Unified viscous-plastic-elastic-brittle rock rheology that allows for the prediction of the timing of the transition to fracturing relative to that of petroleum generation and migration (Chen et al., 1990; Ghaith et al., 1990; Dewers and Ortoleva, 1994b; Ortoleva, 1994a).
- Pressure solution and supra-grain scale diffusion (Dewers and Ortoleva, 1990a,b, 1992, 1994a; Ortoleva, 1994a) allows for the development of banded diagenetic seals at the reservoir periphery and stylolites and diagenetic bedding observed within the NFTR. This has been observed in the Anadarko basin (Ortoleva et al., 1994). These diagenetic features can significantly affect the characteristics of a fracture network.

- Pore fluid overpressuring can preserve porosity and keep fractures open (Ghaith et al., 1990).
- Kinetics of petroleum generation fix the timing of generation relative to that for fracturing; these reactions can also cause overpressures which could induce fracturing (Chen et al., 1990; Ghaith et al., 1990; Park et al., 1990; Dewers and Ortoleva, 1988, 1994b).
- The variation of rock rheology accounts for the dependence on mineralogy, texture, organic content, inorganic chemistry, temperature and fluid pressure and permits the coupling of the chemical and mechanical processes (Dewers and Ortoleva, 1989, 1990a).
- Basin-scale variations of the mechano-chemical environment influence the prediction of the location in the basin where stress, thermal and chemical conditions favorable for NFTR's are obtained (Dewers and Ortoleva, 1994b; Sonnenthal and Ortoleva, 1994).
- The coupling of reaction and transport can lead to highly localized sites of dissolution and precipitation through flow self-focusing (Chadam et al., 1986, 1988, 1990; Chadam and Ortoleva, 1990, 1991; Chen et al., 1990) and other geochemical feedback processes (Ortoleva et al., 1987; Ortoleva, 1994a,b).

B. Physical, Chemical and Geological Basis of the Model

The CIRF.B simulator is designed for full three dimensional modeling of a sedimentary basin so as to meet the E&P needs of the petroleum industry. Its development was funded and guided by the petroleum industry, the Gas Research Institute and the U.S. Department of Energy. CIRF.B (chemical interaction of rock and fluid simulator for basin analysis) accounts for the full range of reaction, transport and mechanical processes commonly believed to be important to the formation of petroleum reservoirs.

The CIRF.B approach for predicting the location and characteristics of petroleum reservoirs is based on our novel basin model and computer simulation algorithms. CIRF.B provides a platform for integrating all available geological data into an exploration or reservoir development strategy under the umbrella of the laws of physics and chemistry.

Available information can be divided into geological data and the physico-chemical laws and parameters. The former give the information that makes a basin simulation tailored to a specific basin. The physico-chemical information gives our model the power to predict resource location and characteristics.

To explain the interplay of these two types of information in making CIRF.B predictions, consider first one time step in our forward modeling as illustrated in Fig. 1. The purpose of

the incremental evolution step is to advance the state of the basin from a time t in the past to a later time $t + dt$. In our simulator, two distinct operations are taking place simultaneously during this time interval dt . The geological information is used to 1) fix the input/output of energy and mass at the basin boundaries and 2) impose, through the tectonic history, the strain history (i.e., overall basin deformation) at the basin boundary. The physico-chemical processes determine the evolution in time during dt of the spatial distribution of the local state variables. The latter include stress, fluid properties, mineralogy, porosity, permeability, fracture characteristics and temperature.

These unique predictions are a natural and necessary complement to other simulators that focus on petroleum generation, expulsion and migration. CIRF.B output shows the windows of time during which formations along a putative migration pathway were actually open and not closed due to compaction, formation collapse or cementation. Similarly, CIRF.B predicts whether formations bounding likely reservoirs formed in time (before the reservoir became charged with petroleum) or if the sealing rock was breached due to natural fracturing or permeability-enhancing diagenetic reactions. Finally, CIRF.B can be used to predict reservoir producibility by estimating fracture network characteristics and permeability enhancement from diagenetic reactions.

Other basin simulators lack the CIRF.B predictive power because they are solely based on statistical correlations. For example, they predict porosity based on a formula relating it to mineralogy and depth. However, porosity evolves due to the detailed stress, fluid composition and pressure and thermal history. These histories are different for every basin. Thus a simple correlation of porosity and depth and lithology type does not exist in principle. CIRF.B avoids such problems by actually solving the fully coupled rock deformation, fluid and mineral reactions and fluid transport problem.

The geological input data is divided into four categories as shown in Fig. 1. The "tectonic data" gives the change in the lateral extent, shape of the basement-sediment interface and the amount of sediment loading or erosion during dt . As suggested in Fig. 1, this data provides the conditions at the basin boundary needed to calculate the change in the spatial distribution of stress and rock deformation within the basin. This latter physico-chemical calculation is carried out by our stress module that solves equations based on incremental stress rheology and force balance.

The sedimentation data provides the detailed textural characteristics such as grain size, shape, mineralogy, mode and carbon content (i.e., inorganic and organic texture) of the sediment being deposited during dt. The physico-chemical laws and data are used to calculate the change of the spatial distribution of texture within the basin during dt. These physico-chemical calculations involve the rate laws and data for free face grain chemical kinetics, pressure solution and grain rotation or breakage, grain nucleation and the laws of kerogen chemical kinetic transformation. Also used are the laws of fracture nucleation, extension, aperture dynamics and the kinetics of cement infilling.

All this geological input data and the physico-chemical calculations are integrated in our basin simulator to uniquely give us the power to predict the present-day internal state of the basin. The physico-chemical laws translate the boundary constraints (geological data) into a prediction of the changes of internal basin state that took place during dt. The incremental time advancement is repeated until the evolution of the basin internal state, from the inception of the basin (or other chosen initial state) to the present, is computed.

The above procedure can only be considered useful in a practical context if the required geological data is the same or less than that presently used in exploration and resource development. In fact, all the geological data noted above is in common usage. It is derived from well log analysis, seismic data, general basin tectonic history re-creation studies, vitrinite reflectance and other temperature indicators, stress and strain indicators, core analysis and production data. Most of the physico-chemical data is available in data banks or the literature.

An important perspective is that the physico-chemical computations provide another way of integrating the presently-used geological data. In a real sense these calculations put constraints on the interpretation of the geological data. For example, an interpretation of the geological data without the benefit of our model is subject to some assumptions on the relative timing of events which could be made more reliably when the timing of these events is predicted based on the known rates of the underlying physico-chemical processes.

Like any analysis of the geological data (including those presently used in other approaches) our model-based data integration and predictions are subject to some uncertainties. These are of three types:

- Variations among the interpretations of the geological data;
- Incomplete physico-chemical phenomenologies or required data; and
- Numerical difficulties in the simulation algorithms

All these discrepancies must be addressed in evaluating our or any predictions. Interestingly, our simulator itself provides an important tool for analysis of the above potential errors. By carrying out sensitivity studies, one can determine the contributions of uncertainties in the various factors. To accomplish this one needs to vary the geological and the physico-

chemical data and those parameters controlling the numerical accuracy (time and space step, convergence criteria for iterative algorithms, etc.).

The enormity of the physico-chemical calculation may at first sight make the computations seem impractical. However, the rapid improvements in computer hardware surmount this difficulty. These improvements are in CPU speed, large memory and parallel computation. Advancements in modeling techniques also are bringing in great reductions in the computations. These include homogenization techniques whereby small spatial scale features can be embedded into large (here basin) scale simulations. The latter is done in such a way that the details of the small scale features are not lost in a crude averaging. Also, advances in numerical techniques, notably adaptive gridding, higher order discretization schemes and iterative, sparse linear solvers, also make the computations fast, accurate and robust.

Past basin modeling efforts have only focused on one or two factors, such as hydrology, stress, or mineral or organic reactions. While these decoupled models have given insights into specific aspects of the evolving basin, they cannot answer many of the key questions at hand. This is because many of the phenomena of interest involve several processes that are very strongly coupled. For example, hydrofracturing depends on stress and fluid pressure. These depend on texture through mechanical and transport (namely permeabilities) parameters and hence on hydrofracturing. Textural evolution is also effected by stress and fluid pressure (through pressure solution) and through fluid flow (by the import of ions affecting grain growth rate laws).

Clearly there is a variety of such feedback loops that exist in the network of basin reaction-transport-mechanical (RTM) processes. Fracturing plays a key role in many of these feedback loops as it depends on a number of effects (stress, fluid pressure, and mineral infilling reactions) and, in turn, modulates these effects. Thus predicting the timing of the development of petroleum and its emplacement in quality reservoirs (and similarly for water and mineral resources) requires a fully coupled model and simulator. In CIRF.B, the solver modules of Fig. 1 are not run independently. Rather, the system of fully coupled equations are solved iteratively for each time step advancement so that all cross coupling relationships between processes are accounted for. This full self-consistency of our RTM simulator gives it the unique character needed to make the predictions required for practical petroleum applications.

In order to have the potential for reliable and comprehensive predictions, CIRF.B has the following features:

- generalized chemistry and mineralogical composition;
- kinetically controlled mineral dissolution reaction rates depending on pressure, temperature, stress and fluid composition;

- pressure solution-mediated compaction using the water film diffusion (WFD) mechanism;
- fluid flow using modified multiphase Darcy laws;
- basin subsidence, sea level curve, and stress history;
- thermal history; and
- the time-course of the rate, texture, and fluid composition of the sediment added.

The WFD mechanism accounts for the effect of stress at grain-grain contacts, the width of the water film layer within the contact, and the diffusion rate along the water film, as well as temperature, fluid pressure and fluid composition. Free face dissolution/overgrowth reactions are also accounted for. The formulation used incorporates temperature, fluid pressure and ionic strength effects.

In the model as presently developed, porosity reduction and overpressuring in the pore occurs through (1) pressure solution-induced and mechanical compaction of pore space, (2) thermal expansion of the fluid and (3) volume increasing reactions. When a large overpressure accumulates and the fluid pressure approaches lithostatic pressure, the pressure solution rate diminishes, so that no further chemical compaction of the sediment takes place. A model accounting for hydrofracturing using a subcritical fracture nucleation and growth theory augmented with a model of fracture cement infilling has also been developed. A grain nucleation module has also been included.

C. Three Dimensional Incremental Stress Module

A key element of overpressure generation and preservation, compaction and fracturing is basin stress. Good estimates of stress distribution and its history are required to calculate mechanical and chemical compaction that can overpressure a formation and create seals. As fracturing occurs when fluid pressure exceeds least compressive stress, estimates of the time of creation, growth, healing or closure as well as orientation of fractures rely on estimates of the stress distribution and its history. In turn, resulting fracture permeability can lead to overpressure loss through escape of fluids from the overpressured zones or the creation of economic petroleum reserves in otherwise tight reservoirs. In short, the ability to estimate the history of the internal distribution of stress within the basin from available data on the overall tectonic and sedimentary history of a basin is a key element of a predictive model of reservoir location, fluid pressure, heterogeneity and producibility.

In CIRF.B we have developed a rock rheological model based on incremental stress theory. This approach allows us to include fracturing and pressure solution naturally into a theory that also accounts for elastic and visco-elastic mechanical rock response. This rheology combined with the force balance condition allows for the calculation of rock deformation and

stress and their distribution in space and evolution over time. The stress problem is solved by a moving, second order finite element approach.

The incremental rheology has the generic form

$$\underline{\underline{\dot{\epsilon}}} = \underline{\underline{\dot{\epsilon}}}^{el.} + \underline{\underline{\dot{\epsilon}}}^{mec.} + \underline{\underline{\dot{\epsilon}}}^{ps} + \underline{\underline{\dot{\epsilon}}}^{fr.} \quad (1)$$

Here $\underline{\underline{\dot{\epsilon}}}$ is the rate of strain while the terms on the RHS give the specific dependence of the contribution to $\underline{\underline{\dot{\epsilon}}}$ from four processes. These are poroelasticity (el.), continuous mechanical (mec.), pressure solution (ps) and fracturing (fr.). We have implemented specific expressions for each term adopted from the literature or as derived by us. The stress solver has undergone rigorous testing by comparing results to both analytical solutions and published studies in the structural analysis literature. These tests have been very successful as have simultaneous work on optimizing the code by trying a range of linear solvers to find the best one for the stress problem.

The boundary conditions implemented in our basin stress solver are indicated in Fig. 2. They allow for a prescribed tectonic history at the bottom and sides of the basin, input as a history of rock velocity at these boundaries. Note that at the basin simulation domain sides the vertical component of tangential shear is set to zero so as not to interfere with the natural dynamics of compaction there. Finally, normal stress at the top of the basin is set to ocean bottom or atmospheric pressure and tangential shear is set to zero so as to capture the essence of the fluid-sediment interface.

Fig. 2. Conditions at boundary of basin simulation domain allow for imposition of ocean bottom normal pressure p_o and no shear at the top ($\underline{t}$ being a tangent vector and $\underline{n}$ being a normal vector). At the bottom the tectonic history fixes the evolution of the deformation velocity $\underline{u}$. On the sides (lightly shaded) the horizontal deformation velocity (u_x, u_y) is imposed, to allow for specification of epochs of basin compression or extension; the vertical component of shear is set to zero to allow for the natural compactional dynamics to take place there.

A basin-scale simulation using the finite element stress solver is seen in Fig. 3. In this 80 km $\times$ 80 km basin originally 5 km thick, a tectonic event leading to the dropping of the center of the basin occurred. This led to simulated failure along developed faults and near the bottom of the basin due to overburden-induced mechanical compaction.

Our boundary conditions allow for the full range of tectonic conditions to which a basin is subjected. These include complex histories of subsidence and upheaval, compression or extension and the variation of these effects with map-view position along the basin periphery and basement-sediment interface. These features make our three dimensional stress solver a unique tool powerful enough to address the important problems of basin deformation and the interplay of rock deformation with fluid transport and diagenetic reactions. These aspects of basin evolution are of great interest to basic and E&P research.

Fig. 3(a) Half basin originally $80 \times 80 \times 5$ km after 35 MY of deformation. Colors indicate shear stress σ_{xz} with blue indicating the maximum absolute value of shear.

Fig. 3(b) Quarter section of basin as in (a) showing frame indicating basin boundaries. Below the indicated surface is the domain in which stress indicates that yield was exceeded by 15%. Values of parameters were taken from the literature and are as follows (increasing from top to bottom): shear viscosity = $10^{16} - 10^{18}$ P; bulk viscosity = $10^{16} - 10^{18}$ P; yield = 7 MPa; elastic bulk modules = 10^4 MPa; and Poisson ratio of .3.

III. Direct Integration of Seismic and Other Data

The use of seismic and other remote data and well logs for basin simulations involves a great deal of interpretation that usually depend on a number of quantitative assumptions. The ideal situation would be to directly use the raw data and have a basin simulator process it by automatically creating the sedimentation, tectonic and other histories and to evolve the basin over the time of interest.

That such a completely automated approach is possible is yet to be demonstrated. In our approach we attempt to use the raw data so as to constrain its interpretation with the laws of reaction, transport and mechanics on which CIRF.B is based.

The specific approach we are developing is to use more traditional methods for fixing sedimentation, tectonic and heat flux data except that the least well constrained parameters of this history reconstruction are left as undetermined parameters. These parameters are then fixed with the raw remote or well log data in an error minimization scheme as follows.

Our primary goal to start with is the use of seismic data. This is being done via a module added to CIRF.B. This module takes seismic data directly, and interprets it quantitatively, in an effort to improve upon the traditional, more qualitative interpretation methods. This method removes several steps in being able to use the seismic data as input into the CIRF.B (or other basin) program, as well as the subjectivity of an individual's data interpretation.

In our CIRF.B seismic matching optimization mode, certain parameters that are key to the predictions and which are less well-known are identified. Next, an optimization is carried out so as to find the best values of these parameters. As suggested in Fig. 4, this is done by generating a least-squares error function that represents the difference between the actual seismic data and that obtained from our program-predicted rock property distributions. The predicted seismic data is obtained using the internal distribution of rock properties predicted by CIRF.B and synthetic seismic algorithms such as the codes developed by Alterman and Karal (1968), Alford et al. (1974), Vidal et al. (1985), Mallick and Frazer (1987), Vidal and Helberger (1988) and Rudman et al. (1993). Finally the error function is minimized using a conjugate gradient approach. This optimization is the most efficient way to get the best choice of less well-controlled parameters, notably those characterizing sediment, thermal and tectonic history.

Fig. 4 Flow chart illustrating basin history matching optimization using seismic data.

The specific implementation is as follows. The real and simulated seismic data is in the form of a sequence of N response times t_i and t_i^s , $i = 1, 2, \dots, N$. The error E is then defined via

$$E = \sum_{i=1}^N (t_i - t_i^s)^2 \quad (2)$$

The simulated times depend on a set of parameters $l_1, l_2, \dots, l_M$; the M parameters are to be varied to get the best representation. Hence $E(l_1, l_2, \dots, l_M)$ is to be minimized with respect to the M l -parameters. Our simulator and the seismic recreation program provide the implicit dependence on the l 's when they are run. This implicit dependence yields the implicit dependence of E on the l 's so that an optimum-search numerical simulator can be invoked. We have developed such a procedure using a conjugate gradient squared (CGS) algorithm and will apply it here.

IV. The Piceance Basin Test Case

A. Rationale for the Piceance Basin

The Piceance Basin is an ideal test case for this study. The basin is rich in natural gas that is housed in tight sandstones. The Piceance Basin progressed from a marine environment in the Cretaceous, characterized by blanket marine sandstones and interbedded marine shales; to a fluvial/coastal plain environment during the Paleocene characterized by lenticular or laterally discontinuous fluvial sandstones interspersed with fluvial plain siltstones and mudstones; to an intermontane lacustrine environment during the Eocene, characterized by variable lake-bed and lake margin deposits. The tectonic history of the basin is sufficiently

rich to yield a spectrum of local stress histories and hence test a range of conditions for the genesis of NFTR's.

The Upper Cretaceous Mesaverde Formation contains good examples of NFTR's. It is a well-studied and generally well-understood basin, and because of this, there is an abundance of available data. In addition to the MWX site, set-up and operated by the DOE, there are numerous operators in the area with claims/prospects in various stages of development. Thus our approach could be tested with historical data and could serve to influence and be tested with ongoing and future drilling results.

The fractures in the system apparently contain most of the producible natural gas. They are believed to be formed as a result of 1) external stresses, including lateral tectonic and mountain-building stresses and basement deformation and/or 2) internally developed fluid pressures, from diagenetic geochemical reactions or hydrocarbon maturation (and the release of gas-phase methane from coal). To understand these factors and their relative importance, we are simulating the full basin using a wide variety of published and industry data.

B. Data Availability and History Recreation

Well data from over 40 wells in the Piceance Basin are being used by us to create depositional and burial histories. For a description of the available well information and composite stratigraphy, see Appendix A. Our focus now is on the southern half of the basin so that detailed analysis will not be limited to the wells as indicated in Fig. 5. This data is being correlated and interpolated across the basin to provide a three-dimensional view of the present state of the basin. This state is specified by the distribution in space of the formation identity, texture (i.e., grain size and shape, porosity and fracture characteristics) and stress, fluid pressure and composition and mineralogy and other variables. This internal state is the basis for comparison used to test the model. An example of our recreated basin state is seen in Fig. 6.

Fig. 5 Distribution of wells in the southern half of the Piceance Basin presently being used for CIRF.B model calibration and testing.

Red = Marine Shale
Yellow = Marine Sandstone
Green = Paludal, Coal-bearing Units
Blue and Yellow-Green = Terrestrial Fluvial Units
Orange = Hiatus

Fig. 6 Our interpolation scheme automatically creates the basin state from well data. (a) Three-dimensional block diagram of the southern Piceance Basin simulation domain; and (b) Present-day geometry of the Rollins S.S. in the Mesaverde Formation.

Fig. 6b

Our inter-well interpolation scheme is also used to automatically recreate the sedimentation history. The information on stratigraphic contacts from these wells is taken from density, gamma and electric logs. The element of time required for history recreation comes from the ages of the formations as estimated in the literature from the fossil record. A convenient way to examine our computer generated sedimentation history is an "isochron map". As seen in Fig. 7, these maps show for a given time the location where each formation is being deposited.

Fig. 7 Isochron maps of the southern half of the Piceance Basin showing formations being deposited at (a) 75, (b) 73.75 and (c) 72.75 MA in the past as automatically generated from well data using our sedimentation history recreation module.

For a complete sedimentation history simulation see Appendix B.

The MWX site provides valuable petrologic information on some of the important Mesaverde reservoir units. Data on composition, grain size and reservoir properties are available and are being extrapolated to parts of the basin, where such data is generally unavailable.

There is much remote data available, including seismic, aeromagnetic, imagery and SLAR (side-looking airborne radar). Most of this data has been collected and/or interpreted by ARI (Advanced Resources International) with whom we collaborate on Piceance data aspects of this project. The purpose of this data is to gain an understanding of the sub-surface structure and its history.

The methane in the units of interest in the Piceance Basin is believed to have arisen from coal maturation processes. Coal data for the Piceance data has been collected from the US Geological Survey Coal Quality Database (USGS, 1994).

The suite of available data types being used is summarized in the Table. It is the broad spectrum and adequate spatial density of this data that makes the Piceance Basin an ideal test case for our study.

Table

<u>Organic Geochemistry</u> Total organic carbon Organic matter type and composition Thermal maturity <u>Water/Rock Data</u> Porosity Permeability Aqueous fluid composition Whole rock mineralogy Size and shape of grains Mineralogy and volume of cements and overgrowths Volume and type of minerals dissolved by pressure solution Volume of pore space lost by compaction Timing of diagenetic events	<u>Fracture Analysis</u> Fracture density, morphology, length and volume Fracture filling material (cements, organics) Mineralogy and texture of fracture-bearing zones Changes of fracture network with texture, mineralogy and diagenetic features <u>Production History</u> Quantities produced Petroleum compositions <u>Tectonics and Sedimentology</u> Sedimentation and erosion history Magnitude and timing of tectonic movements Heat flow Basin stresses Conventional and 3D seismic data Well logs
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C. Rheological Parameters

Reliable prediction of fracture phenomena is predicated on the availability of rock rheological parameters both as they are at present and as they were from the time of fracture creation to the present. Instantaneous rock strength, poroelastic constants and other mechanical properties depend on rock texture. In our modeling approach we are using rock mechanics experiments to determine this texture dependence. Such a compilation and

formulation in terms of rheologic laws for the suite of sedimentary rock types is not readily available in the open literature so that we are developing this data in this project.

As an example, data on the failure of shales and claystones was used to calibrate our nonlinear rheologic model. According to the latter, failure occurs when the stress invariants J_1 and J_{2D} are related by

$$J_{2D}^{1/2} = aJ_1 + b \quad (3)$$

Using published data on shales and claystones we find a and b to depend strongly on porosity—see Fig. 8 for examples (Hoshino et al., 1971). This type of fitting yields rock rheologic parameter dependence on texture. Then CIRF.B calculates the temporal evolution of texture, we can thereby estimate the rock rheological properties as they evolve over the life of the basin. As a consequence we can know these important properties at the inception and during the life of the fractures. Hence we can determine if the fracture network was open for petroleum import from source rocks or if fractures closed or were cemented.

Fig. 8 (a) Mechanical parameter a plotted as a function of porosity for a group of Japanese tertiary rock shales. (b) As in (a) except using parameter b . (c) Mechanical parameter a plotted as a function of porosity for a group of Japanese tertiary claystones. (d) As in (c) except using parameter b .

D. Preliminary Piceance Basin Simulations

A number of simulations are being carried out to test aspects of CIRF.B in the context of the Piceance Basin problem. In order of complexity, they are as follows.

1. Simple Mineralogy - Inorganically Generated Overpressure Test

A test of the fluid flow module was carried out on a Piceance Basin grid to examine its stability in difficult problems where many orders of magnitude of permeability are encountered. This allowed for pressure solution-mediated compaction and thermal expansion with burial to generate large (suprafracture) overpressures over long periods of time.

An example is seen in Fig. 9. There we see the isosurfaces of fluid overpressure (OP) and "over fracture pressure" (OFP). This is fluid pressure minus the least compressive stress which in this simulation was taken to be $-.4 s_{zz}$; s_{zz} being vertical stress, here taken to simply be from overburden. Shown are the evolution of OP and OFP via results at 13 and 31 MY after basin inception. Note the development of a basin-wide region of OP and of regions of OFP, the latter suggesting where fractures could be found in this simple test problem.

2. Organically Generated Overpressure

A test of the methane-production generated OP was carried out. In this simple test a kerogen-rich layer was placed in the basin and the reaction kerogen (solid organic residue) + CH_4 was allowed to take place. In the CH_4 generating layer CH_4 first was produced and resided as a solute in the aqueous solution. After a critical time the aqueous fluid became saturated and a gaseous phase appeared. In Fig. 10 we see the resulting fluid pressure OFP and gas saturation after 5.5 MY.

3. Piceance Basin Sedimentary History

Well data from the Piceance Basin was used to generate a full sedimentary infilling history for the southern half of the Piceance Basin. This history is shown and discussed in Appendix B.

A. David Decker, Vice President

(a)

OP, 13 MY, 100 bars

(b)

OFP, 13 MY, 100 bars

OP, 31 MY, 100 bars

OFP, 31 MY, 100 bars

Fig. 9 Map view of (a) fluid overpressure (OP) and (b) "over fracture pressure" (OFP) isosurfaces. The latter is the fluid pressure minus the least compressive stress which is taken to be $-0.4 \sigma_{zz}$. Shown are the evolution of OP and OFP at 13 and 31 MY after basin inception. The development of OFP suggests where fractures would be found. The colorless regions on the right and in the middle are of high permeability (10^{-3} Darcy on the right and 10^{-5} Darcy in the middle). Elsewhere the permeability is on the order of 10^{-9} Darcy.

Fig. 10a Pressure produced after 5.5 MY in the area of methane being generated.

Fig 10b Gas saturation has been increased from 0 to 0.013 in the area of methane being generated.

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