Naturally Fractured Reservoirs and Compartments: A Predictive Basin Modeling Approach

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ABSTRACT

Phenomena in fractured reservoir genesis and dynamics are placed in the context of recent developments in compartmentation theory. Seals are important in isolating self-organized fracture-controlled reservoirs. These seals may be punctured by moving fracture fronts, and the interaction of fractured reservoirs with punctured seals affects the dynamics of compartmentation.

Requirements for a predictive model of fractured reservoir location and characteristics include:

- **3-D basin shape through time;**
- **fluid flow and chemistry;**
- **spatial and temporal thermal data; and**
- **lithologic data through time.**

The CIRF.B code incorporates these features into a new three-dimensional simulator, which is being used to develop an integrated remote sensing and modeling exploration strategy.

The Piceance and Anadarko Basins illustrate comparable yet different styles of compartmentation structure. The Piceance Basin is a primary example of petroleum production from fractures in otherwise tight reservoirs; it displays a complex mosaic of under- and overpressured compartments. The Anadarko Basin is an example of more conventional petroleum reservoirs; it houses larger spatial scale compartmentation with a mosaic zone in the general vicinity of the interface between the large scale over- and underpressured compartments.

Preliminary simulation results show the importance of grain size, textural heterogeneity, and depositional history in the development of fractured compartments.

Future developments and practical issues in the realization of this integrated scheme include complementation with seismic data and basement tectonic indicators, validation and calibration of rock rheologic, transport and chemical reaction rate laws, determining key data required for reliable predictions, and reducing computational times.

APPROACH

Predicting the location and characteristics of natural fractures is a challenging exploration and production problem. Our approach focuses on the use of three-dimensional basin modeling. The specific goals of this paper are to place fractured reservoirs within the wider context of basin compartmentation, to delineate the features that a viable basin model must have to make reliable predictions, and to give some preliminary examples of the predictions of such a model. We conclude with comments on the future prospects for such models and their integration into a program of remote detection for producible reserves.

The wider issue of fracturing will be limited to a discussion of perhaps the most interesting case of enclosed networks. Fracture networks that have good communication with overlying, high permeability strata are of less interest. Even if such fracture networks contained petroleum in the geological past, buoyancy or overpressuring would likely have led to its expulsion. Thus, fracture networks overlain or even completely enclosed by low permeability seals are of greatest interest as potentially producible reservoirs.

Compartments are, by definition, regions of preserved porosity and permeability enclosed in a three-dimensional shell or seal of very low permeability (Fig. 1) (Powley, 1975, 1990; Bradley, 1975; Bradley and Powley, 1994; Ortoleva, 1994a,b, 1996; Ortoleva et al., 1994). As fluids in a compartment cannot readily escape, their interiors are commonly overpressured. The overpressure can be developed via a number of mechanisms, including

- fluid thermal expansion in a subsiding basin;
- compaction (mechanical or from pressure solution);
- clay dewatering and devolitization of organic rich rocks;
- volume increasing reactions (notably those generating gases);
- desorption of surface-adsorbed gases; and
- matrix elastic compression/expansion from change of load (due to sediment infilling, erosion, basin compression, etc.).

When the compartment interior attains overpressures beyond least compressive stress, fracturing can occur within the compartment. As mechanisms generating overpressure are commonplace, it is likely that many fractured reservoirs are compartments with fractured interiors.

In Section II, the relation of fractured reservoirs and compartments is further developed and factors that affect fractured reservoir genesis, longevity and characteristics are delineated. In Section III the features of a three dimensional basin simulator that account for the hydrologic, reaction and mechanical processes needed to predict fractured reservoir location and characteristics are presented. A preliminary discussion of compartmentation structures of the Piceance and Anadarko basins is presented in Section IV. Over- and underpressured compartments in these basins are delineated in three dimensions. Preliminary simulation results of the genesis and dynamics of fracture networks are presented in Section V. Future developments and integration of the model into an exploration strategy are outlined in Section VI.

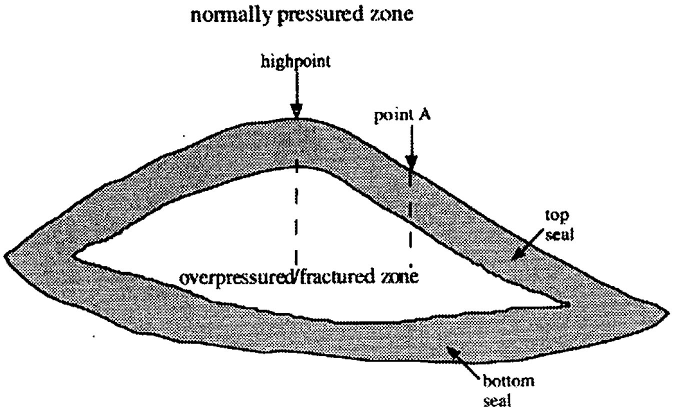


FIGURE 1. Schematic compartment cross-section showing interior and surrounding seal. Fracture induced breakthrough typically occurs at seal high-points, as noted in Section II.B2.

FRACTURES AND COMPARTMENTATION

Fractured Reservoirs

Hydrofracturing and tectonic fracturing play essential roles in compartmentation phenomena. Overpressured compartment interiors may have internal hydrologic connectivity maintained through a network of hydrofractures. Indeed, compartment interior pressures are commonly at a critical level for hydrofracture induction. On the other hand, fractures may compromise seals and thereby destroy compartment integrity. Thus, fractures may construct compartments by defining their interior hydraulic connectivity or destroy them by breaching their surrounding seal.

The petroleum industry has long had an interest in production from formations of low matrix permeability that contain sweet spots associated with a network of connected fractures. Without the fractures, these low permeability reservoirs would be subeconomic targets.

It seems reasonable to place these fracture sweet spots within the context of compartmentation theory. In a sense, a tight formation can constitute both the seal and the compartment interior. Such a fracture-related, intra-bed compartment is suggested in Figure 1. The genesis of such an intra-bed compartment is quite interesting. Suppose the interior is being overpressured. This overpressure can build up there but not near the periphery as the surroundings are, according to the situation of Figure 1, normally pressured. With time, the periphery can become increasingly tight through compaction due to the normal pressure there (elevated pressure represses compaction). However, in the interior, compaction is slowed by overpressure and permeability may be elevated through hydrofracturing. Over time, this permeability contrast between the interior and the surrounding rock can persist or even increase.

The rate of overpressuring plays a key role in geometry and timing of fractures. If it is large, fractures can extend out of the compartment and into the periphery and, thereby, compartment fluids can be expelled and the potential for interior overpressuring is lost. In time, such a system evolves to a tight, relatively unfractured bed. Thus, as fluid chemistry and rock temperatures can affect overpressuring rate, it is clear that basin stress history and sedimentary texture, mineralogy and geometry are not the only factors to be considered in predicting the location and characteristics of fracture sweet spots. A fully coupled, basin geochemical, hydrologic, mechanical and thermal model and computational simulator is required. Such a simulator is described in Section IV.

SEAL PUNCTURING

Moving Fracture Fronts

The puncture of a seal by fracturing through elevated pore fluid pressure plays a number of roles in compartment dynamics. Compartments can lose fluid through this process. In the case of nested or adjoining compartments, a fracturing of shared seals creates a larger (unified) compartment. Thus seal fracturing can be a mechanism for increasing the spatial scale of compartmentation.

Breaking through a seal by the overpressure it sequesters occurs via a fracture front that sweeps across the seal from the higher pressured side toward the lower pressured surroundings (Fig. 2). As fractures extend into the seal, they increase the local fluid pressure and thereby advance the incursion of fractures. This front may be arrested somewhere within the seal if leakage across the remaining unfractured layer of the seal can keep pace with the influx of fluid from the overpressured region. In this way the fractured zone, wherein the fluid pressure exceeds least compressive stress, is contained within the seal and the seal is not completely breached.

However, if the rate of overpressuring within the compartment interior is sufficiently large, the fracture front breaks through the seal into the relatively high permeability rock in the surroundings. This causes a relatively large fluid loss across the seal and, through fracture healing or closure, the seal can be brought back to viability. Thus one expects that the typical case of a seal enclosing a highly overpressured compartment interior is that the outer limit of the fractured domain lies somewhere within a region which, due to its small matrix permeability, would otherwise have been a seal.

The advancement of the fracture front into the seal followed by fluid pressure release and fracture healing can repeat if the mechanisms of overpressuring are still operating. This repetitive cycle and the notion of migrating seals are addressed in Chen et al. (1990), Dewers and Ortoleva (1994) and Ortoleva (1994a, 1996), and for cyclic methane expulsion from source rock in Ghaith et al. (1990).

Top Seal High Point Puncture Rule

Overpressure-instigated fracture breakout through a top seal is favored at the highest point in the seal. Consider a top seal as in Figure 1. The seal is assumed to cap an overpressured compartment. At the highest point along the bottom face of this seal, the difference between total fluid pressure over least compressive stress is greatest.

To demonstrate this, note that the least compressive stress minus hydrostatic fluid pressure generally increases with depth as suggested in Figure 3. Along a vertical profile at the high point in the top seal of Figure 1, the overpressure should be, qualitatively, as suggested in Figure 3. The overpressure along the line is zero until the top seal is encountered. It rapidly rises above zero with increasing depth, through the seal and into the compartment interior overpressure as the underside of the top seal is reached from above. Within the compartment, the overpressure is roughly constant, assuming this interior has relatively high permeability. At the top of the compartment, fluid pressure exceeds least compressive stress minus hydrostatic pressure, and thus fracturing is predicted to occur here. In the case suggested in Figure 3, the overpressure

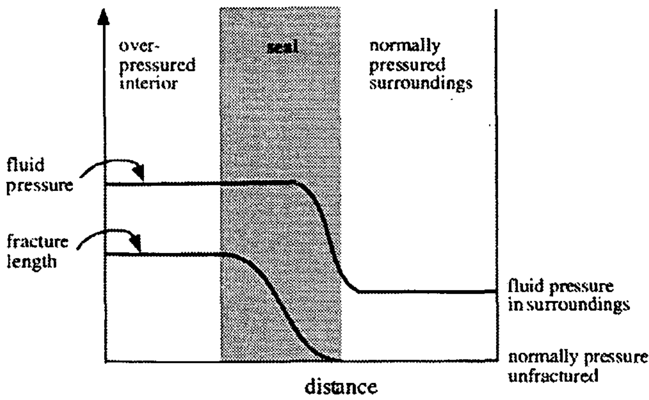


FIGURE 2. Schematic graph showing pressure and fracture length along a transect through an over-pressured zone through a seal to the surroundings.

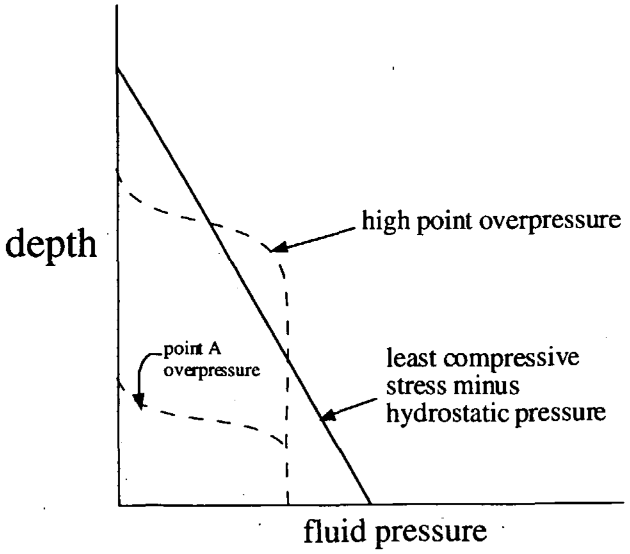


FIGURE 3. Schematic graph of least compressive stress minus hydrostatic pressure and overpressure with depth. Regions where overpressure is to the right of least compressive stress minus hydrostatic pressure indicates regions of fracturing.

profile at point A (away from the top seal high point) never reaches least compressive stress minus hydrostatic fluid pressure, and hence no fracture breakthrough is predicted to occur there. Thus, as overpressure develops, it is seen that fracture breakout through the seal should first occur at top seal high points.

The above simple assumptions may not apply, however. For example, if the seal at the high point is somewhat less efficient than elsewhere, the high point overpressure can be lower and fracturing might be repressed there. In general, heterogeneities in the effectiveness of the seal might lead to the violation of the high point breakout rule. Nevertheless, the high point rule is a general guideline suggesting where expulsion from overpressured source rock was or is favored.

A Primary Puncture Represses Neighboring Punctures

When a given puncture forms, leakage through it lowers pressure in the compartment interior as fluid flows laterally toward and out the primary puncture. Thus overpressure in regions neighboring a puncture may not develop to a sufficient degree to induce breakthrough near a primary puncture. In this way, an initial puncture represses the formation of neighboring punctures. The distance over which this repression is effective is expected to increase with increasing compartment interior permeability (and fluid flow rate out of the compartment), and decrease with an increase in the rate of overpressuring.

Flexure and Faulting

Flexure of brittle layers surrounded by relatively ductile, low permeability ones can lead to compartmentation. Consider such a three-layer package as in Figure 4. As the overall package bends, the top and bottom layers may relieve extensional stresses by a ductile response involving extension and concomitant thinning. However, extensional stress is relieved in the brittle layer by fracturing. If the brittle layer is, for example, a tight sandstone, then beyond the region of flexure the central bed serves as a lateral seal. If, in addition, the top and bottom layers are seals (for example, low permeability shales), then the ensemble constitutes a compartment.

Fracture Filling Precipitates

As fractures play a dual role in compartmentation, the filling of fractures by mineral cements or organic solids can foster or destroy compartmentation. A fracture provides a surface on which mineral grains may nucleate and grow away from the generally higher normal stress at grain-grain contacts in a matrix. Thus, there is always a driving force promoting dissolution from grain-grain contacts leading to nucleation and growth within fractures. Overgrowth at the free face of grains (experiencing pressure solution) neighboring the fracture will compete for these dissolution products. If these free faces are protected with clay or other coatings, then loss of solutes to fracture cementation will be promoted over free-face overgrowth. In addition, the fractures will be lined with fresh (broken) grain-free faces. Thus, grain coatings may not be a factor at the fracture faces. In this way, fracture infilling by mineral cements can destroy hydrologic connectivity in the compartment interior.

Fracture filling cements can also heal punctured seals (Chen et al., 1994). As fluids exit a compartment through such a puncture, changes in pressure, temperature or composition can cause mineral precipitation within the main flow conduit — the fractures. As flow is focused to these well-localized features, they may experience more cementation than would have been predicted from an overall flow (mass balance) analysis.

Precipitation of organic solid phases (e.g., asphaltenes or paraffins) may also heal punctured seals. On the other hand, through wetting of fracture faces with organic phases, fracture healing can be slowed or inhibited, and the nucleation of fracture-filling mineral cements (as from nearby pressure solution or infiltrating fluids) may be repressed. Thus the existence of petroleum in fractures can serve to inhibit intrafracture mineralization and thereby preserve hydrologic continuity within compartments with fractured interiors. Likewise, such cement inhibition by petroleum wetting of mineral grain surfaces may inhibit seal healing and hence allow for the loss of compartment interior fluid pressure.

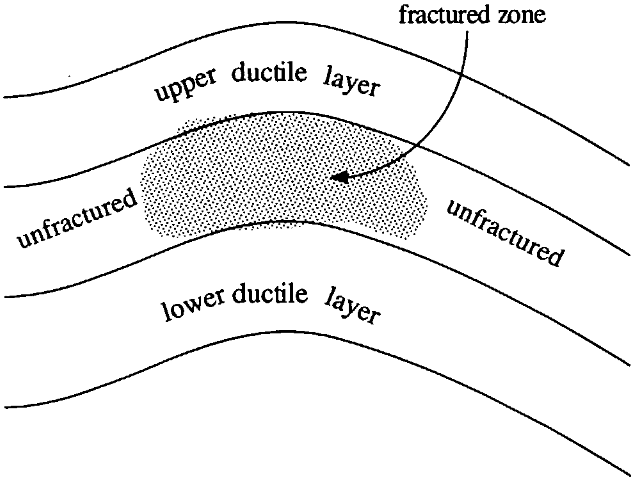


Figure 4. Flexure of a ductile/brittle/ductile layer package can lead to compartmentation.

Cleating

Cleats are fracture-like partings usually observed in coals. They are generally believed to be a result of a material contraction associated with the loss of mass from an organic-rich matrix due to the escape of volitilized components.

The origins of cleating can be understood in terms of incremental stress theory (see also Sect. III.B). Let $\dot{\underline{\underline{\varepsilon}}}$ be the total rate of strain, $\dot{\underline{\underline{\varepsilon}}}^{fr}$ be the contribution of fracturing to $\dot{\underline{\underline{\varepsilon}}}$, and $\dot{\Omega}$ be the relative rate of volume decrease from devolitization (i.e., the time derivative of the natural logarithm of rock volume). Neglecting elastic response and ductile yield, incremental stress theory (see also Sect. III.B) implies

$$\dot{\underline{\underline{\varepsilon}}} = \dot{\underline{\underline{\varepsilon}}}^{fr} + \tfrac{1}{3}\dot{\Omega}\underline{\underline{I}} \qquad \text{(II.E1)}$$

for unit tensor $\underline{\underline{I}}$. For vertical ($z$) shortening, without horizontal fractures, this implies

$$\frac{\partial u_z}{\partial z} = \tfrac{1}{3}\dot{\Omega} \qquad \text{(II.E2)}$$

for rock deformation vertical velocity u_z and depth z. As $\dot{\Omega}<0$ this shows that a horizontal bed undergoing devolitilization will shorten, as expected. However, friction with over- and underlying beds will make horizontal rock motion negligible. Hence $\dot{\varepsilon}_{xx} = \dot{\varepsilon}_{yy} \approx 0$. With this

$$\dot{\varepsilon}^{fr}_{xx} = -\tfrac{1}{3}\dot{\Omega} \qquad \text{(II.E3)}$$

and similarly for $\dot{\varepsilon}_{yy}$. Thus the devolitilization-induced contraction is taken up by fracture opening (cleating). In this way, generation of petroleum in very organic-rich beds can induce the internal formation of a fractured zone (compartment interior or sweet spot) that can house the petroleum, thereby not necessarily requiring an association between sweetspots and structures.

Episodic Fluid Flow and Self-Organized, Fracture Controlled Compartmentation

A cycle of overpressuring, fracturing, fluid escape and fracture closure and healing has been demonstrated to be possible in overpressured zones (Dewers and Ortoleva, 1994). Recently it was found that in association with this OFEC (overpressuring, fracturing, escape of fluids and closure of fractures) temporal cyclicity in regions of active burial, there is the possibility for the development of patchwork spatial patterns of fractured zones separated by low permeability seal zones, even in the absence of sedimentary features (Maxwell and Ortoleva, 1996). Such self-organized patterns of fracture sweet spots and seals is a truly novel finding that now allows for the understanding of the occurrence of such fractured reservoirs even in the absence of a direct correlation with coal beds, basement faults, flexure or other externally imposed spatial localization.

An example of a self-organized array of fracture sweet spots is seen in Fig. 5. The permeability (a) is dominated by fractures in the high permeability zones; between these zones seals cause large gradients of overpressure (b). The interesting point is that these patterns emerge spontaneously even in the

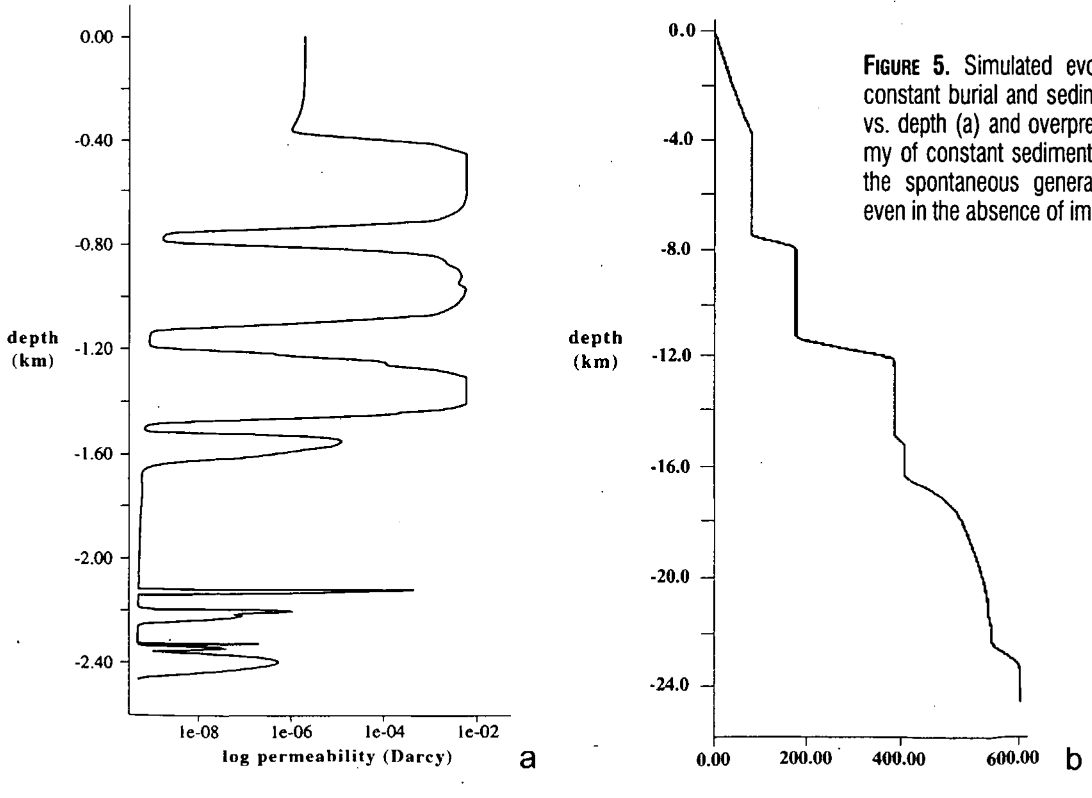


FIGURE 5. Simulated evolution of a basin subjected to constant burial and sediment input character. Permeability vs. depth (a) and overpressure vs. depth (b) shown at 50 my of constant sedimentation and subsidence, illustrating the spontaneous generation of stacked compartments, even in the absence of imposed sedimentary heterogeneity.

case shown of constant sedimentation rate and texture, as well as subsidence rate and sea level.

BASIN MODELING FOR FRACTURE PREDICTION

Overview

The complex network of coupled reaction, transport and mechanical (RTM) processes underlying the genesis and dynamics of fractures and compartments suggested above puts reliable prediction of their location and characteristics outside the realm of simple approaches. In particular, we believe that one must turn to a quantitative basin model capable of integrating all the relevant geological factors and the equations describing RTM processes. As reservoirs are fundamentally three dimensional in nature, the starting point of fractured reservoir theory should be three dimensional also.

CIRF.B (chemical interaction of rock and fluid simulator for basin analysis) is a fully coupled RTM simulator which accounts for the full range of processes commonly believed to be operating in a basin. The CIRF.B simulator is designed for full three dimensional modeling of a sedimentary basin. CIRF.B development was funded and guided by the petroleum industry, the Gas Research Institute and the U.S. Department of Energy (Maxwell and Ortoleva, 1994; Qin and Ortoleva, 1994; Sonnenthal and Ortoleva, 1994; Ortoleva, 1994a, 1996).

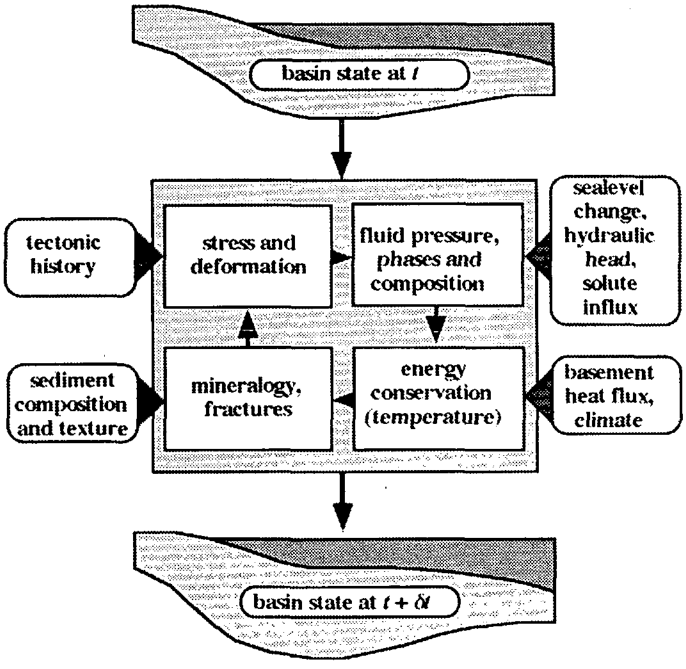


FIGURE 6. Flow chart showing how the interplay of geologic data and physico-chemical (i.e., reaction-transport-mechanical) process modules evolve the basin over a computational time interval dt.

The external influences such as sediment input, sea level, thermal and tectonic effects operate at the basin boundaries. Within the basin, the RTM processes are at work chemically and physically modifying the sediment to arrive at petroleum, mineral and potable water reserves and other basin features.

The CIRF.B approach for predicting the location and characteristics of petroleum reservoirs and other basin features is based on our novel basin model and computer simulation algorithms. CIRF.B provides a platform for integrating all available geological data into a basic scientific case study, or an exploration or reservoir development strategy, subjected to the laws of physics and chemistry.

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

CIRF.B simulations predict the windows of time during which formations along a putative migration pathway were free from compaction, formation collapse or cementation. Similarly, CIRF.B predicts whether formations bounding likely reservoirs compact before the reservoir became charged with petroleum, or if the sealing rock was breached due to natural fracturing or permeability-enhancing diagenetic reactions. It also can be used to predict reservoir producibility by estimating fracture network characteristics and effects on permeability due to diagenetic reactions. These considerations can be made in a completely self-consistent way through the inclusion of a multi-phase, organic and inorganic, reaction-transport module. Calculations of all effects are self-consistent so that all cross-coupling between processes is accounted for. The determination of temperature is affected by transport, which is in turn affected by the changes of porosity due to temperature-dependent reaction. The rate of kerogen decomposition depends on temperature, which depends on thermal transport, which in turn is affected by fluid buoyancy, thermal conductivity, capillarity and relative permeability, and the content and composition of organic material. Similar coupling relations between the full set of RTM processes is accounted for.

Other basin simulators lack the CIRF.B predictive power because they use statistical correlations. For example, they predict porosity based on a formula relating it to lithology and depth. However, porosity evolves due to the detailed stress, fluid composition and pressure and thermal histories. These histories are different for every basin. Thus a simple correlation of porosity with depth and lithology 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. While there are thousands of sedimentary basins for which the statistical correlations must account, the calibration required for our physico-chemically based approach involves fewer factors and, unlike the statistical approach, can be calibrated in principle. In short, the laws of physics and chemistry clearly hold in all basins and, furthermore, capture the individual character of every basin. Statistical approaches can only hope to capture the average character — i.e., can only predict a stereotypical basin's evolution.

To explain the interplay of geological and physico-chemical information in making CIRF.B predictions, consider one time step in its forward modeling as illustrated in Figure 6. 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 the 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 deformation) at the basin boundary. On the other hand, 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.

The CIRF.B geological input data is divided into four categories as shown in Figure 6. The tectonic data gives the change in the lateral extent and the shape of the basement-sediment interface during dt. As suggested in Figure 6, 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 a stress module that solves equations based on incremental stress rock rheology and force balance.

Another type of geological data is that affecting fluid transport, pressure and composition. This fluid data includes the history of sea level changes, recharge conditions and the composition of fluids injected from the ocean and meteoric sources at the domain boundary. This data is then used by the hydrologic and chemical modules to calculate the evolution in time of the spatial distribution of fluid pressure and composition within the basin. These physico-chemical calculations are based on single- or multi-phase flow in a porous medium and on conservation of mass of fluid phase molecular species (i.e., the reaction-transport equations). The physico-chemical equations draw on internal data banks for permeability-rock texture relations, relative permeability formulae, chemical reaction rate laws, and reaction and phase-equilibrium thermodynamics.

The spatial distribution of heat flux imposed at the bottom of the basin is another category of geological input. This data, as well as the temperature imposed at the top of the sediment pile (i.e., climate and ocean bottom temperature), is used to evolve the spatial distribution of temperature within the basin during the time interval dt. This evolution is computed using the equations of conservation of energy and formulae, and data for mineral and rock thermal properties (conductivities and specific heats).

The sedimentation data provides the detailed textural characteristics such as grain size, shape, mineralogy, mode and organic carbon content 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 grain free-face chemical kinetics, pressure solution, grain rotation or breakage, grain nucleation, and the laws of kerogen chemical kinetic transformation. Also used are the laws of fracture nucleation, extension and aperture dynamics, and the kinetics of cement infilling.

All this geological input data and the physico-chemical calculations are integrated in CIRF.B to allow it to predict the present-day internal state of the basin. The physico-chemical laws use the boundary constraints (geological data) to a predict the changes of internal basin state that take 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.

All the geological data noted above is commonly used in exploration and resource development. 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. In work in progress, we are developing methods for the input of geological data in the form of well logs, seismic data, core analysis and other "raw" data. Most of the physico-chemical data is available in data banks or the literature.

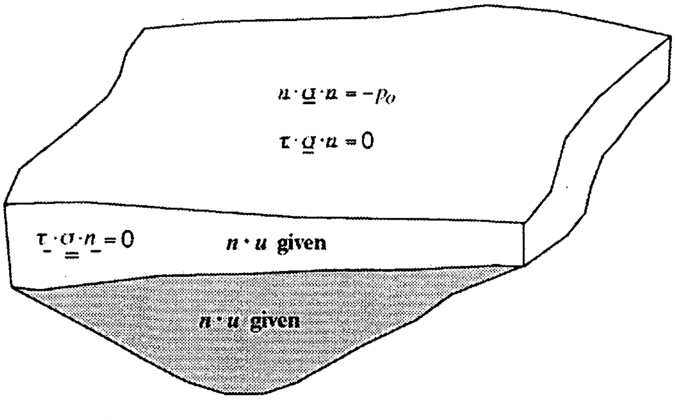


FIGURE 7. Conditions at boundary of basin simulation domain allow for imposition of ocean bottom normal pressure and no shear at the top (t being a unit vector and n being an outward pointing unit normal vector with respect to the basin boundary). At the bottom the tectonic history fixes the evolution of the deformation velocity u using slip conditions as on the sides (lightly shaded). The normal velocity n.u is imposed by the prescribed history of upheaval/subsidence and compression/extension.

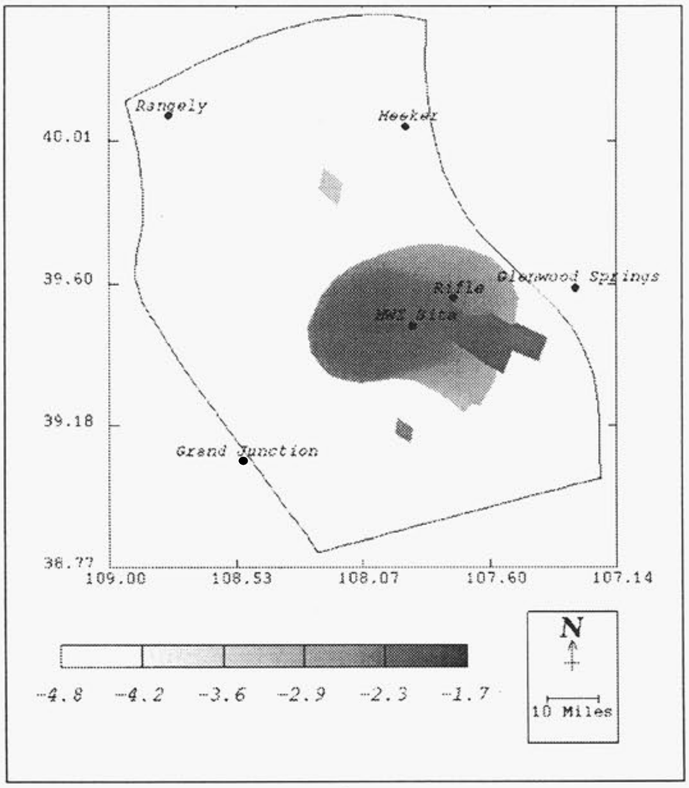


FIGURE 8. (a) Map view of 5 bar overpressure isosurface, shaded with depth, showing outline of domain. Latitude and longitude are indicated on the Y and X axes.

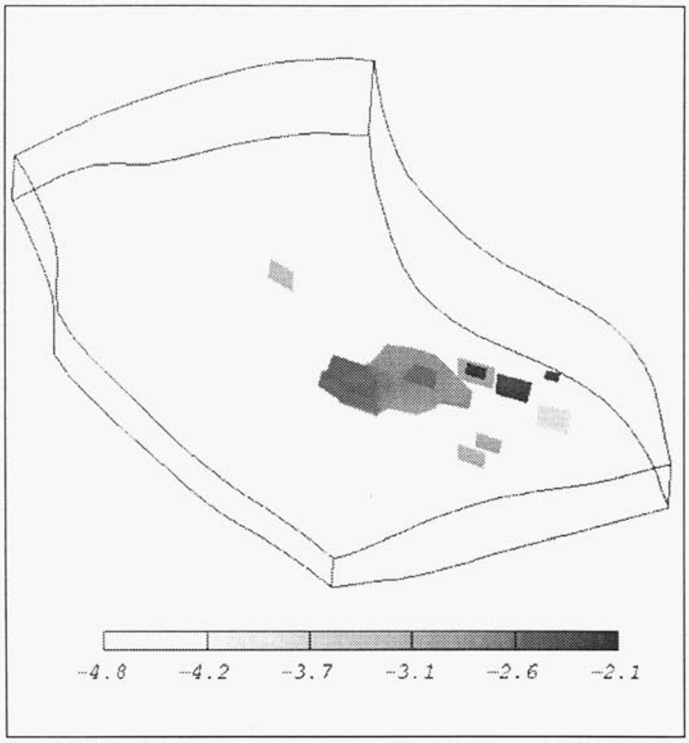


FIGURE 8. (b) 3-D view of 10 bar overpressure isosurface, shaded with depth, as viewed from the south; vertical exaggeration is 10x, and basin depth ranges from about 2 to 4 km.

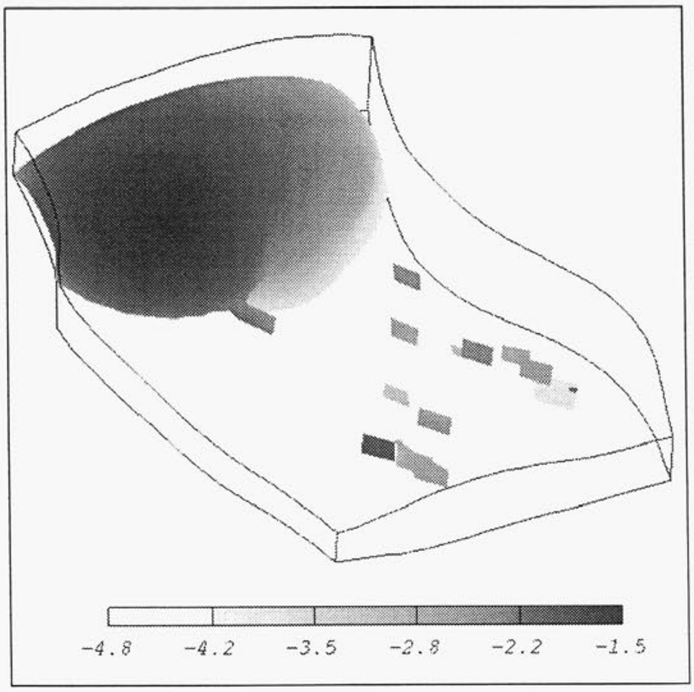


FIGURE 8. (c) 3-D view of 1 bar underpressure isosurface, shaded with depth; same dimensions and orientation as frame (b).

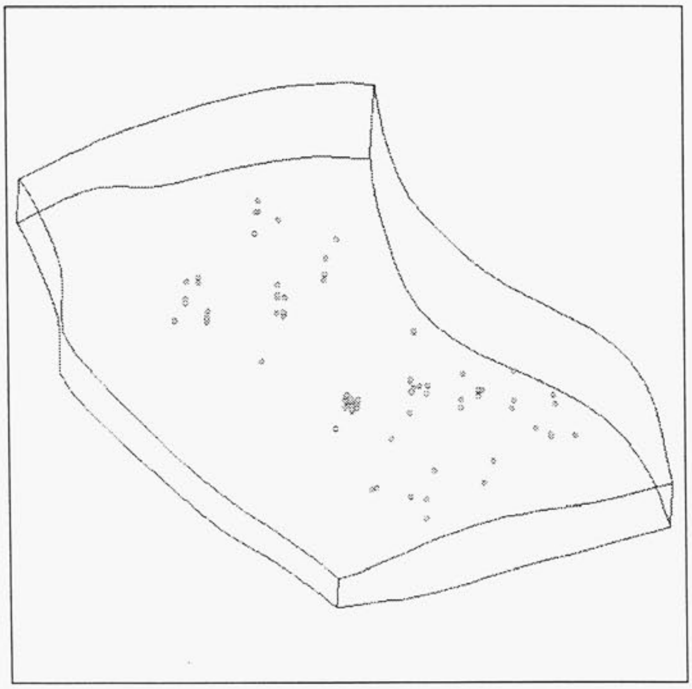


FIGURE 8. (d) Location of 96 Mesaverde pressure data points in the Piceance Basin, as evaluated by Texas Bureau of Economic Geology and Advanced Resources International; 3-D image has same dimensions and

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 this 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; estimating of the times of these events could be made more reliably when they are 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 inaccuracies in the simulation algorithms.

All of these discrepancies must be addressed in evaluating any predictions. 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 less well-constrained geological and physico-chemical data and those parameters controlling the numerical accuracy (time step, convergence criteria for iterative algorithms, etc.).

Clearly there is a variety of feedback loops that exist in the network of basin 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 Figure 6 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 fundamental and applied basin research.

Incremental Stress Computation

Key elements of abnormal pressure generation and preservation are compaction and fracturing. These processes depend strongly on basin stress. Thus, good estimates of stress distribution and its history are required to predict mechanical and chemical compaction and fracturing, essential aspects of compartment and seal genesis, structure and dynamics. As fracturing occurs when fluid pressure exceeds least compressive stress by rock strength, 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 affect overpressure through escape of fluids from overpressured zones, or can create economically important fractured reserves in conventionally tight reservoirs. Thus, the ability to estimate the history of the distribution of stress within a basin from available tectonic and sedimentary data is a key element of a predictive model of compartments and seals.

A rock rheological model has been developed for CIRF.B, based on incremental stress theory. This approach allows one to include fracturing and pressure solution into a unified theory that also accounts for elastic and viscous/plastic mechanical rock response. This rheology combined with the force balance condition predicts rock deformation and stress and their distribution in space and evolution over time. The stress solver is based on moving, second-order, finite element discretization and efficient iterative solution approaches.

The incremental stress rheology used to integrate all the strain mechanisms has the generic form

$$\underline{\underline{\dot{\varepsilon}}} = \underline{\underline{\dot{\varepsilon}}}^{el} + \underline{\underline{\dot{\varepsilon}}}^{in} + \underline{\underline{\dot{\varepsilon}}}^{ps} + \underline{\underline{\dot{\varepsilon}}}^{fr} + \underline{\underline{\dot{\varepsilon}}}^{misc} \quad \text{(III.A1)}$$

Here $\underline{\underline{\dot{\varepsilon}}}$ is the rate of strain while the terms on the right give the specific dependence of the contributions to $\underline{\underline{\dot{\varepsilon}}}$. These are poroelasticity (el), continuous inelastic mechanical (in), pressure solution (ps), fracturing (fr) and miscellaneous (misc) processes such as dewatering of clay and cleating. Expressions for each term used in CIRF.B are from either the literature or our earlier work.

The boundary conditions implemented in CIRF.B are indicated in Figure 7. They allow for a prescribed tectonic history at the bottom and sides of the basin. This data is input as a history of rock velocity at these boundaries. At the simulation domain sides, the vertical component of tangential shear is set to zero. This avoids artificial interference with the natural dynamics of compaction and fracturing. Normal stress at the top of the basin is set to ocean bottom or atmospheric pressure. Tangential shear on the top is set to zero to simulate the fluid-sediment interaction there.

The above boundary conditions allow for the full range of tectonic scenarios to which a basin is subjected. These include complex histories of subsidence and lift, compression or extension and the variation of these effects with map-view position along the basin periphery and basement-sediment interface. These features make the CIRF.B three dimensional stress solver a unique tool, powerful enough to address the important problems of basin deformation and the interplay of rock deformation, hydrology and geochemistry, and to predict naturally fractured reservoir phenomena.

Other Modules

In CIRF.B texture, stress, fluid phase and composition, temperature and fractures are co-evolved in time to preserve

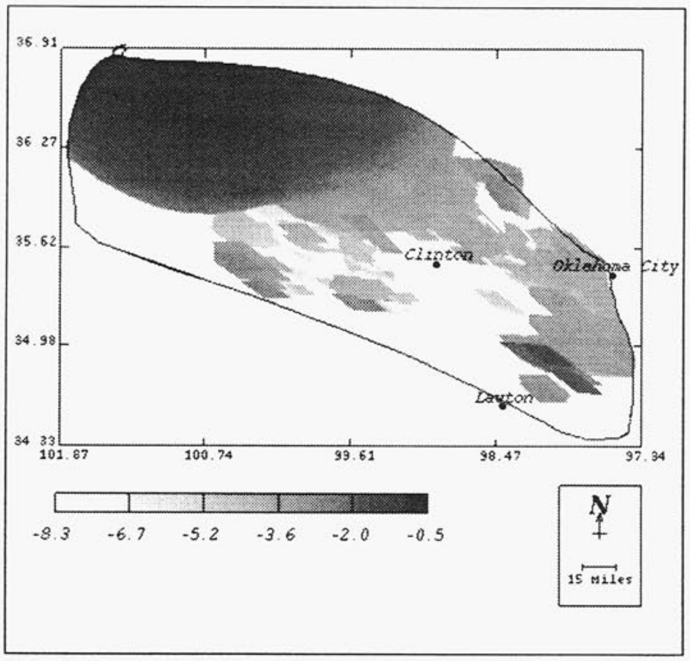


FIGURE 9. (a) Map view of 7 bar underpressure isosurface, shaded with depth, showing outline of domain. Latitude and longitude are indicated on the Y and X axes.

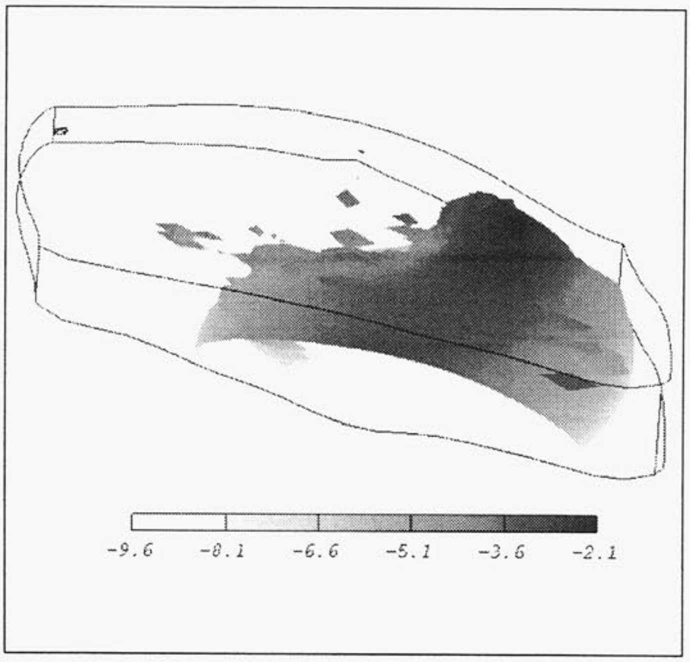


FIGURE 9. (b) 3-D view of 10 bar overpressure isosurface, shaded with depth; the basin domain is viewed from the south; vertical exaggeration is 10x, and the domain is over 2 km deep at its greatest depth.

FIGURE 9. (c) Location of over 2900 pressure data points in the Anadarko Basin. 3-D image has same dimensions and orientation as frame (b).

all the coupling of the underlying processes. Some of these modules are briefly described as follows.

A reservoir is defined by its spatial distribution of porosity and permeability. These factors are dictated by matrix texture (grain size, shape and packing) and fracture density, geometry and connectivity. In CIRF.B these properties are evolved via the texture evolution modules. The fracture nucleation, lengthening and aperture kinetics are based on subcritical, hydrofracture theory.

The textural description and kinetics model used in CIRF.B is the mean contact model (Park and Ortoleva, 1996). In that model, the grains of a given mineral are all assumed to be of the same size and shape — i.e., are represented by the average or mean grain of that mineral. The mean grain of mineral i (=1,2,...M) of the M mineral system is represented by a set of four lengths. The lengths are used to keep track of growth and dissolution at various facets of the grain.

The theory underlying the multi-phase reaction-transport approach implemented in CIRF.B is discussed in more detail in Chang and Ortoleva (1996) and Ortoleva (1996). Transport is via the black oil model. Formulae and data for relative permeability and capillary pressure, and equations of state, are taken from published literature and in-house industrial reports. The formulation implemented allows for the transport and spontaneous creation or disappearance of up to four phases (gas, aqueous, oil and CO_2-dominated) under the assumption that all processes transferring molecules between phases are at phase exchange equilibrium. Both rapid (equilibrated) intra-phase reactions and finite rate (kinetic law determined) intra-phase and fluid-rock reactions are accounted for. A simple kinetic law for kerogen thermal decomposition into organic fluid species is also implemented, while a more comprehensive model based on a new kinetic formulation calibrated using published experimental data is under development.

Sedimentary history is automatically constructed from petrology and age data at prescribed well sites. Seismic cross sections can also be used. A number of novel graphical

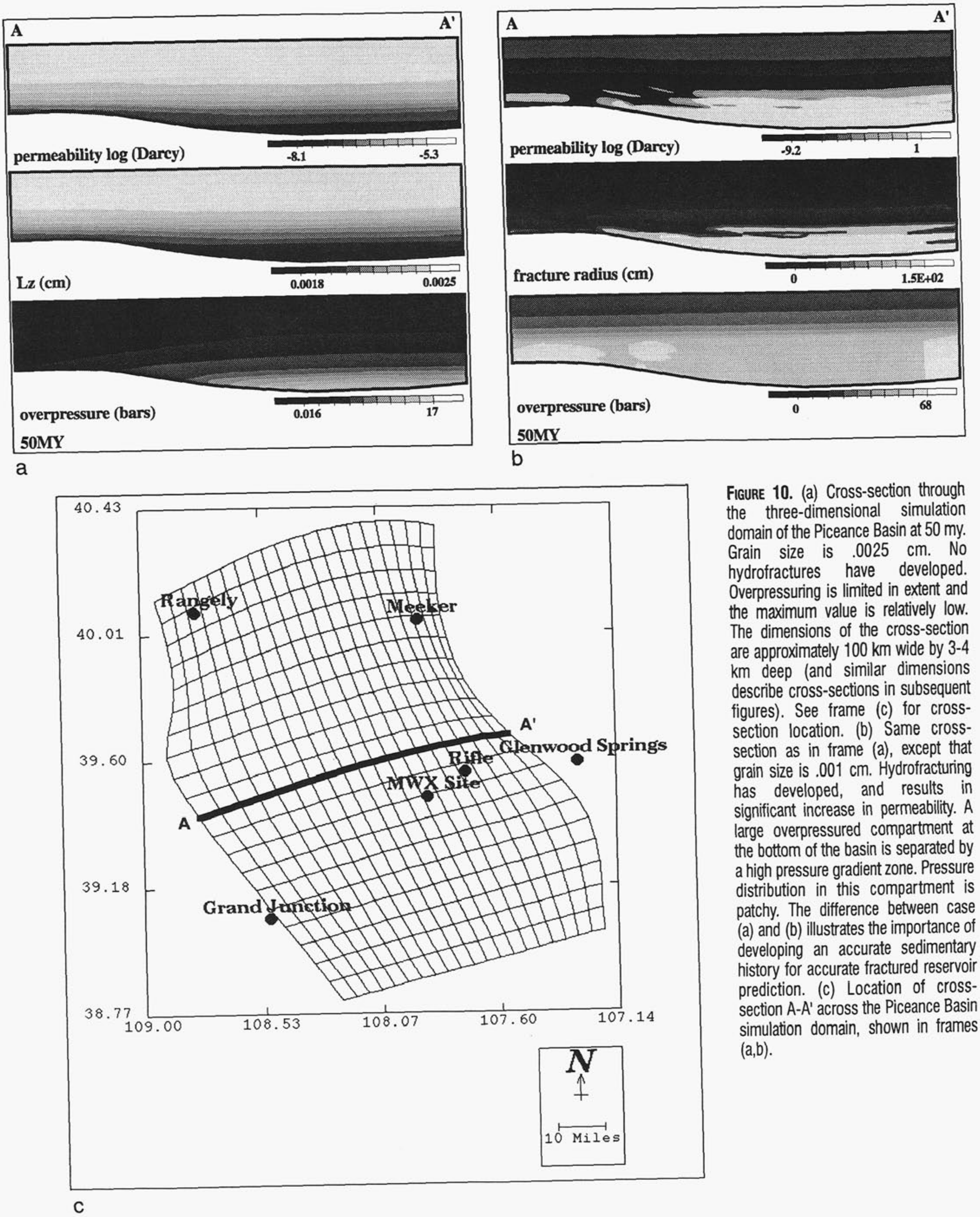
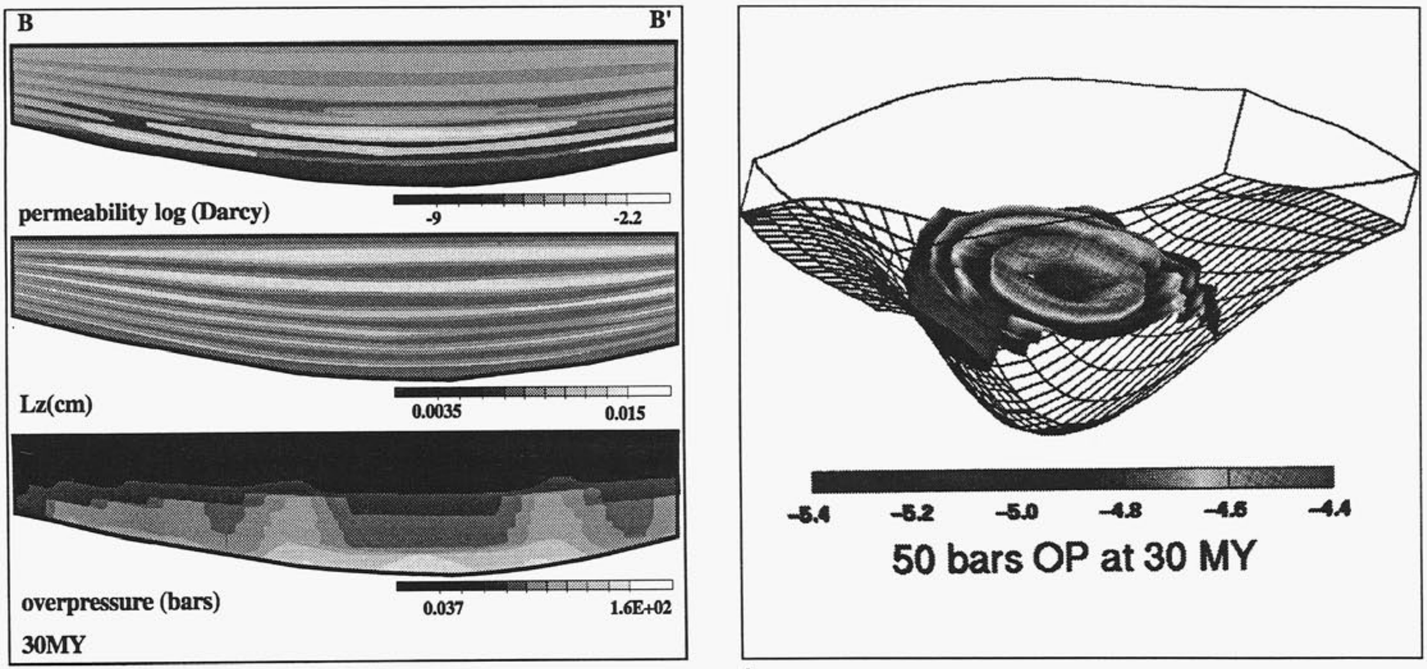
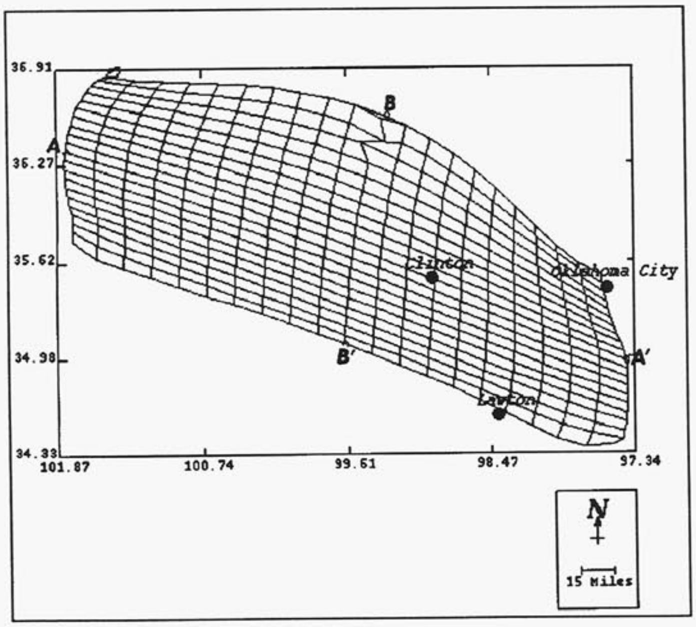


FIGURE 10. (a) Cross-section through the three-dimensional simulation domain of the Piceance Basin at 50 my. Grain size is .0025 cm. No hydrofractures have developed. Overpressuring is limited in extent and the maximum value is relatively low. The dimensions of the cross-section are approximately 100 km wide by 3-4 km deep (and similar dimensions describe cross-sections in subsequent figures). See frame (c) for cross-section location. (b) Same cross-section as in frame (a), except that grain size is .001 cm. Hydrofracturing has developed, and results in significant increase in permeability. A large overpressured compartment at the bottom of the basin is separated by a high pressure gradient zone. Pressure distribution in this compartment is patchy. The difference between case (a) and (b) illustrates the importance of developing an accurate sedimentary history for accurate fractured reservoir prediction. (c) Location of cross-section A-A' across the Piceance Basin simulation domain, shown in frames (a,b).



a

b



c

FIGURE 11. Cross-section through the 3-D simulation domain shown in Figure 11(c) at 30 my. The sediment grain size varied from 0.005 cm to 0.015 cm. The horizontal scale is 150 km along B-B', and the vertical scale is 10 km at the deepest part. Appreciable overpressures developed, resulting in hydrofracturing and enhanced permeability. (b) 3-D view of the Anadarko Basin simulation domain. The domain measures approximately 400 km along A-A' and 150 km along B-B'. Shown is an isosurface of 50 bars of overpressure at 30 my. The complicated surface represents overpressure build-up corresponding to the layered sedimentology. Also shown is one-fourth of the computational grid points along the bottom of the simulation domain. (c) Location of cross-section A-A' and B-B' across the Anadarko Basin simulation domain, shown in Figures 11(a,b) and 12(a-c). A-A' is approximately 400 km, and B-B' is approximately 150 km.

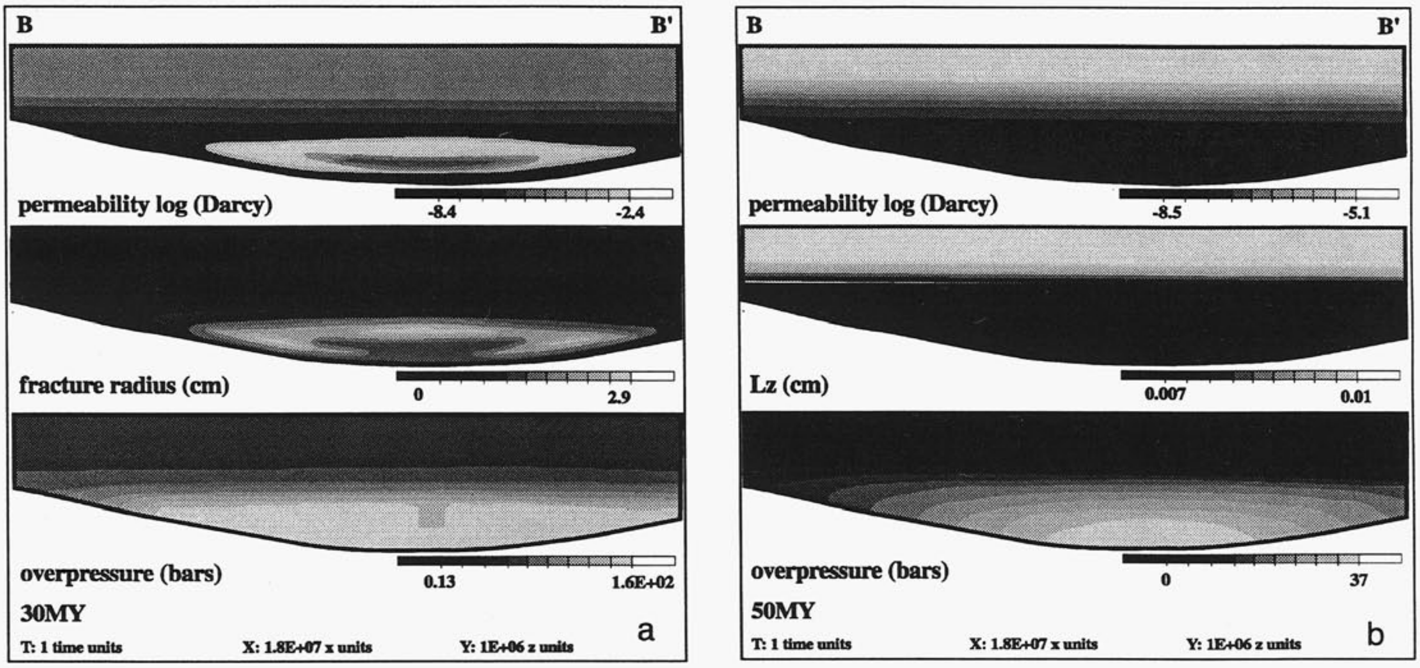
features allow for the viewing and editing of this computer-generated history. Basement heat flux, sea level and overall basin deformation histories may also be specified in CIRF.B.

OBSERVED COMPARTMENTATION

In this section, we examine the implications of fluid pressure data in the Piceance and Anadarko basins for abnormally pressured compartments. The approach used combined a data interpolation algorithm with a conjecture on the compartmentation structure of U.S. on-shore basin compartmentation. As overpressuring is a key indicator of fracturing, the analysis is an important aspect of fracture prediction. This factor, along with stratigraphy, flexure, basement faulting and coal beds, as well as their history, determine sweet spot location and characteristics.

Many on-shore U.S. basins contain a three-tiered hydrologic structure (Powley, 1990). A shallow, normally pressured zone is separated from a compartmented zone by a relatively flat top seal that can traverse stratigraphy. The compartmented zone generally supports overpressured and underpressured compartments. The latter tend to reside in uplifted areas. Below the compartmented zone often lies a second, normally pressured zone separated from the compartmented zone by a seal that tends to follow stratigraphy. In the Anadarko Basin, this three-tiered configuration is attained; the basal seal resides in the Woodford Shale (Al-Shaieb et al., 1994a,b).

An attempt was made to delineate compartmentation in the Piceance Basin using pressure data and some general notions of the hydrology of an on-shore U.S. basin. The



following procedure was used to develop a three dimensional view of basin-wide pressure regimes. A modified Gaussian formula was used to interpolate data from a set of shut-in pressure values at selected points (x,y,z) in the basin; the known pressure (1 atm) along the top surface of the basin and a normal pressure below the Woodford Shale for the Anadarko Basin and the Mancos Shale for the Piceance Basin was imposed (as observed and conjectured, respectively).

Let σ_L (>0) be least compressive stress and p be fluid pressure. Then the quantity ψ,

$$\psi = p - \sigma_L \tag{IV.1}$$

indicates potential for fracture networks. The domain $\psi > 0$ indicates the spatial location of possible fractures. Thus overpressure, and more precisely ψ, is a necessary (but not sufficient) indicator of fracture sweet spots.

Preliminary pressure distribution results for the Piceance Basin based on pressure data screened by the Texas Bureau of Economic Geology (TBEG) and Advanced Resources International (ARI) is seen in Figure 8. Normal pressure increases at about 98 bars/kilometer. The most striking feature of these over-and underpressured zones is that they form a patchwork. The overpressured zones are generally rather limited in spatial extent. The clustering of overpressured zones in the east central region of the basin correlates with the deeper (although somewhat south of the deepest) part of the basin. This suggests that open-fracturing is likely of limited extent if overpressure is the controlling factor in the development or preservation of fractures.

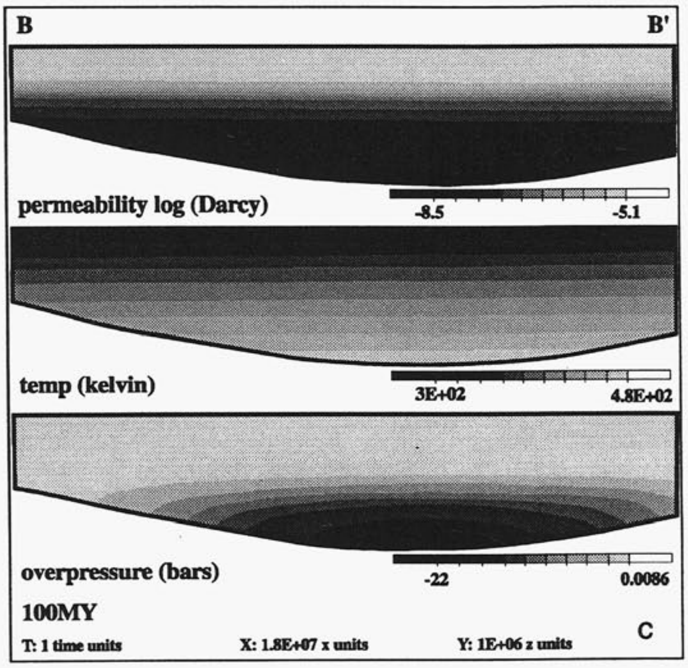


Figure 12. Cross-section through the 3-D domain at 30 my (a), 50 my (b), and 100 my (c). The scaling is the same as the cross-sections in Figure 11. At 30 my, the bottom heat flux of an equivalent geothermal gradient of 40°K/km was gradually decreased to an equivalent heat flux of 15°K/km at 100 my. At 30 my, there is an overpressured domain of 150 bars. Due to thermal contraction, this domain becomes underpressured at 100 my.

The similar analysis of the Anadarko Basin (see Fig. 9) shows a larger, continuous overpressured zone and two such underpressured zones. The latter generally lie north and south of the overpressured zone. Note that in the vicinity of the interface of the two pressure regimes there are a number of smaller scale compartments.

Differences in the abnormal pressure configurations (and implied compartmentation) between the two basins may be directly associated with fracturing. As production in the Piceance Basin tends to be from fractures, the matrix permeability typically being low, compartmentation tends to be shorter in length scale, coinciding with zones of fracturing plus surrounding unfractured seal rock. In the Anadarko Basin, many formations tend to have preserved matrix permeability and hence compartments tend to be larger scale. However, there is mosaic compartmentation in the Anadarko Basin in the interface between the under- and overpressured large scale compartments. Factors such as variability of the extent of small scale sedimentary features across the basin could also play a role. Thus, lithologic geometry and its scale of spatial variability may be reflected in the spatial scale of compartmentation.

A more accurate description of the compartment structure and, in particular, fracture sweet spots, awaits data on the spatial distribution of stress. The correlation of stress, flexure and deep fault geometry is invaluable in petroleum applications. The approach advocated here is to analyze and interpret remote sensing, well log and other classical data with basin evolution and fractured reservoir prediction models.

A key issue in the Piceance Basin and other low matrix permeability systems is whether fractures arise from overpressure or from flexure and other "tectonic" factors. If is sufficiently low, as for flexure (Subsection II.D), then y can be positive even though p is normal. Predicting fracturing requires a model of stress, fluid pressure and, as suggested in Section II, the diagenetics of fracture filling precipitation.

PRELIMINARY BASIN MODELING

Effect of Grain Size on Compartmentation

Simulations using the CIRF.B three dimensional simulator are being conducted. Initial simulations use a simplified quartz and water chemistry, constant grain size, and simplified burial and thermal histories. The three dimensional domain used was designed to capture the shape of the Piceance Basin, but not its detailed sedimentary and subsidence history.

Preliminary results show that grain size affects the development of fluid pressure compartments and hydro-fracturing. Figures 10(a-b) are cross sections through the three-dimensional simulation domain, along an east-west transect in the central part of the basin. Generally, finer-grained systems are more likely to develop abnormal pressure compartments and fracturing (Fig. 10(b)). Furthermore, because of their higher matrix permeability, coarser-grained systems may also develop abnormal pressures, but the pressure gradients are not as steep, making the boundaries between fluid pressure regimes more diffuse (Fig. 10(a)). It is interesting to note that even without grain size variation (i.e. sedimentary features imposed at deposition), overpressuring may develop a patchy distribution, as shown in Figure 10(b). With more detailed accounting of sedimentary features specific to the Piceance Basin, we believe that the model will predict an even more irregular distribution of abnormal pressures, like that demonstrated by the TBEG data.

Figure 10(b) also shows that in a system bearing fine silt-sized grains such as this simulation, significant permeability may be created as a result of hydro-fracturing. The greatest permeability correlates well with the largest fracture radius. This is significant as permeability and porosity in the Upper Cretaceous units of the Piceance Basin are believed to be fracture controlled.

Effect of Sedimentological Heterogeneity on Compartmentation

A simulation was carried out on the mono-mineralic (quartz) problem using a ±50% variation in grain size to illustrate the effect of sedimentological heterogeneity on abnormal pressuring and compartmentation. The most interesting finding is that even in the presence of regularly-spaced, interbedded fine-grained and coarse-grained strata, compartment geometry can have a strongly autonomous (self-organized) character.

A cross-section of a basin is shown in Figure 11(a) after 29 my of deposition and diagenesis. Note the variation of overpressure. This double maximum overpressure feature has interesting three dimensional implications, as suggested in Figure 11(b). The permeability (for example, of 3 Darcy) isosurface shows similar features to that of high overpressure due to permeability having been fracture controlled. These results show the complexity of fracture-defined compartmentation due to the interplay of sedimentological features and fracture dynamics.

Cooling and Overpressure Decline and Underpressuring

The widespread underpressuring in the Piceance Basin presents another challenge for basin modeling. To test CIRF.B in this context, we simulated a case wherein the heat flux at the bottom decreased from an equivalent 45°C/km to 15°C/km in 100 my. During the first 20 my, the grain size input was 0.7 mm; from 20 to 30 my, this was reduced to 0.05 mm; after 30 my, the sedimentation rate was essentially zero.

Figures 12(a-c) show depth shaded maps of overpressure at 30, 50 and 65 my. At 30 my, a large overpressured zone is observed. The pressuring mechanism here and in previous simulations and throughout is by compaction and fluid

(H_2O) thermal expansion. In subsequent periods (50 and 100 my), the overpressure declines and ultimately a large spatial scale underpressured zone is created.

FUTURE PROSPECTS

The application of a coupled basin diagenetic, hydrologic, mechanical model to hydrocarbon exploration and production holds great promise for the future. This type of modeling is an important complement to remote sensing activities in two ways. The modeling can be of assistance in guiding the selection of seismic surveys. It can also be used to aid in interpreting features detected by the latter.

Only a comprehensive fully coupled model such as CIRF.B can serve these purposes in the context of fractured reservoir exploration. As noted in this article, the existence and viability of a fracture network is dependent on and very sensitive to three factors — hydrology, chemistry and mechanics. Furthermore, these factors must be co-evolved over geological time to predict the present internal state of the basin (notably, the location and characteristics of fractured reservoirs). Decoupled models for basin hydrology, chemistry or mechanics cannot reliably address these problems. Mechanics requires fluid pressure through effective stress rheology. Mechanics affects permeability through fracturing and, finally, mechanics and hydrology are affected by diagenetic chemistry through mineral dissolution and precipitation and organic fluid phases. In short, the complex basin dynamics proceeds through a series of tightly coupled hydrologic, chemical and mechanical processes.

The success of the unique CIRF.B code as a practical tool for fundamental and applied basin studies depends strongly on two issues. First, the CIRF.B model is based on a number of rock rheologic, transport and chemical reaction rate laws. Thus, reliable prediction depends on a careful validation and calibration of these laws. Notable examples are the dependence on texture of rock failure criteria and nonlinear viscosity parameters, as well as permeability, relative permeability and capillary pressure. Also, the parameters for the dependence of the pressure solution and fluid phase chemical reaction rates on texture and fluid chemistry must be verified and calibrated. These activities are presently ongoing in our laboratory.

A basin simulation is only as accurate as the assumptions of overall tectonic, sedimentary and thermal histories. However, these factors play a role in any exploration strategy. The basin model provides a platform for integrating these factors under the constraint of the laws of physics and chemistry. Furthermore, the fully integrated basin model can be used to evaluate the sensitivity of, for example, the location and characteristics of fractured reservoirs on various, less well constrained factors. Thereby an effort can be focused on determining the key data required for reliable predictions.

A final consideration is a practical aspect of comprehensive basin modeling — i.e., the computational requirements. A typical exploration study involves a simulation on the 100 million year time frame. Our experience with CIRF.B is that a typical simulation of modest mineralogical sedimentary and chemical complexity takes about .1 CPU day per million years on a single R8000 Silicon Graphics Incorporated processor. However, the algorithms we have developed are executable on parallel computers. Thus, we expect to reduce simulation times to a few days or less. Also, in the next few years, single processor speeds should increase by a factor of two or more. Thus, modest and even more complex models should run in acceptable lengths of time.

In conclusion, we expect that CIRF.B should soon play a very critical role in exploration and field development analysis. This is only made possible because of its comprehensive physical, chemical and geological features and the fully coupled co-evolution of all processes in three spatial dimensions.

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