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Models for Naturally Fractured, Carbonate Reservoir Simulations

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Abstract

This report outlines the need for new tools for the simulation of fractured carbonate reservoirs. Several problems are identified that call for the development of new reservoir simulation physical models and numerical techniques. These include:

- karst and vuggy media wherein Darcy's and traditional multi-phase flow laws do not apply;
- the need for predicting the preproduction state of fracturing and stress so that the later response of effective stress-dependent reservoirs can be predicted; and
- methods for predicting the fracturing and collapse of vuggy and karst reservoirs in response to draw-down pressure created during production.

Specific research directions for addressing each problem are outlined and preliminary results are noted.

I Challenges

Producing carbonate reservoirs presents special challenges that are not found in sandstone reservoirs. As a result, only limited success can be obtained using available reservoir simulators. In this section, we summarize some of these modeling challenges while in the next section we present new modeling tools that we have tested for addressing these problems.

Perhaps the main challenges encountered in carbonate reservoir simulation is their karst or void textures (macroporosity) and their stress/fluid pressure sensitivity. They are as depicted in Figs. 1 through 4.

Local regions of macroporosity (vugs and karst) or connected, large aperture fractures can serve as superior reservoirs. However, as suggested in Fig. 1, they may lead to bypassed reserves.

Present-day reservoir simulators do not incorporate the physical flow laws that can model such systems. As suggested in Fig. 2, flow in these systems involves a composite of free flow zones (for which Darcy's or black oil models do not hold) and classical porous medium flow zones. Thus, what is needed are new flow laws that unify free fluid and porous medium multi-phase flows. In the free flow zones there is a strong tendency for density stratification of the phases (gas over oil over water) while in the porous medium surface forces usually dominate. These two distinct types of flows must be unified in a new generation of reservoir simulators.

Carbonate reservoirs can be particularly stress/fluid pressure sensitive. Predicting the response of such reservoirs requires the following:

- a knowledge (observed or predicted) state of the preproduction stress within and at the periphery of the reservoir;
- a knowledge of fracture intensity and orientation; and
- a way to determine the fluid pressure at which voids will collapse or induce fractures.

The preproduction stress state is needed to start any simulation purporting to follow the scenario of evolving effective stress and associated continuous or discontinuous deformation. Knowledge of fracture orientation and geometry is needed to predict their closure as pressure draw-down may cause closure and, hence, loss of producibility. In contrast, Fig. 3 shows the potential conflicting roles of rock failure in the presence of macroporosity. If fracturing but not void collapse results, connectivity between voids may be created and, hence, overall permeability and producibility can be increased. Alternatively, void collapse can lead to loss of producibility.

Flow and deformation laws describing these phenomena are not in present-day reservoir simulators. Both development of the correct physical laws and their implementation as numerical simulators are required.

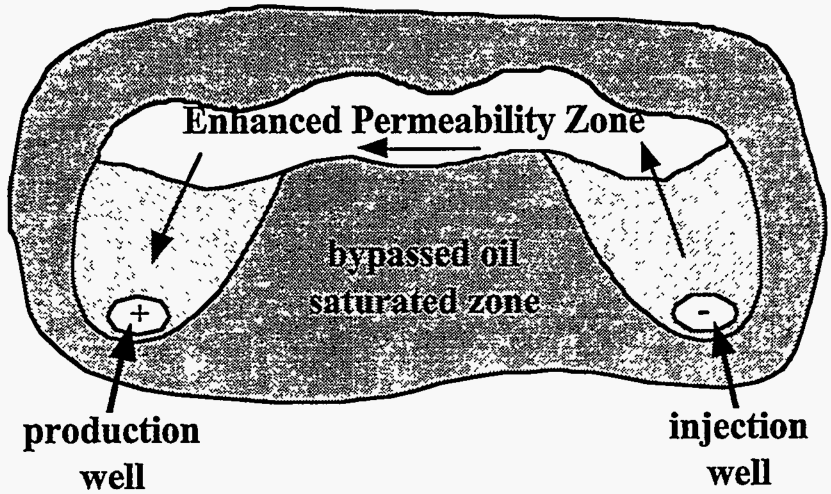

Fig. 1 A zone of very efficient flow (due to macroporosity or large open fractures) can direct the flow so that large areas of reserves are missed and early water breakthrough occurs.

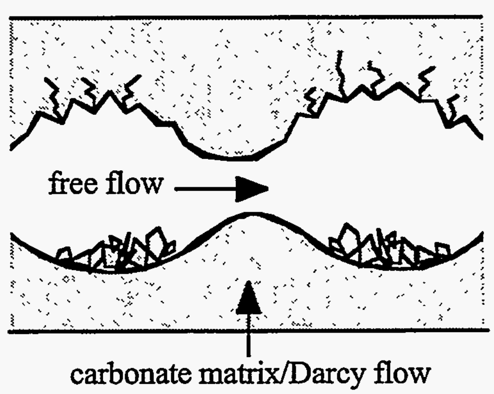

Fig. 2 Flow through karst or connected vug zones can involve large regions of free flow not accurately described by Darcy or classical black oil ("multi-Darcy") flow laws.

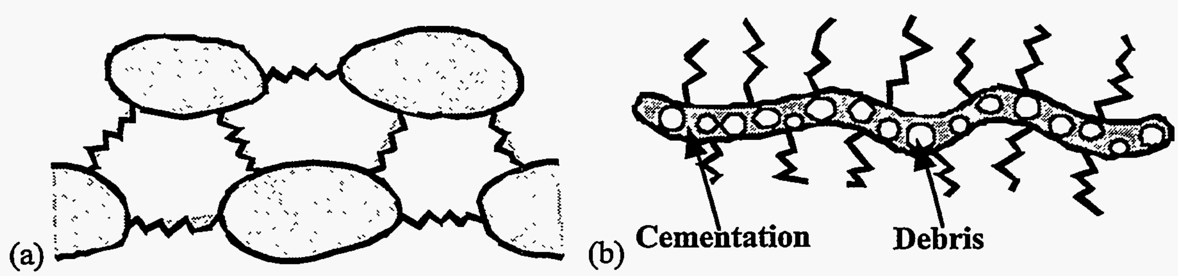

Fig. 3 (a) Fracture may connect voids and thereby enhance producibility. (b) Collapse (and diagenetic) cementation may destroy it.

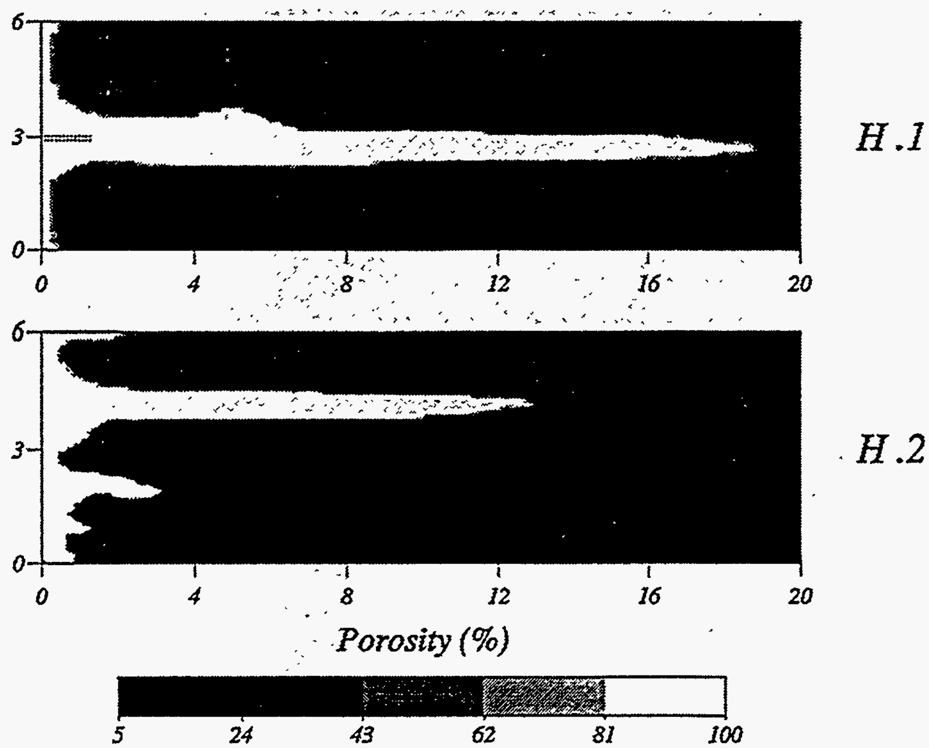

Fig. 4 The coupling of Brinkman flow with dissolution reactions was used to generate wormholes in carbonate rocks injected with acid. These two simulations show that the creation of a single, flow capturing channel results even for rather different initial data (from Ormond and Ortoleva 1998).

II Remedies

The challenges set forth in the above discussion must be addressed using new models and simulation tools. Below, we review those solutions which we have outlined based on our investigations in this project.

A. New Flow Laws

A flow law bridging free and Darcy flow for single phase systems has been set forth by Brinkman (1946). In a preliminary study (Ormond and Ortoleva 1998; Liu et al. 1997), we have investigated this law. The work of Ormond and Ortoleva (see Fig. 4) shows how mixed Darcy and free flows can be simulated even for a case wherein the free flow zone is changing with time (here, due to matrix dissolution).

What is needed for reservoir simulation in macroporosity systems is the generalization of the (single-phase) Brinkman law for multi-phase systems. We have investigated such a model (Tuncay, Zhan, and Ortoleva 1998). It generalizes the black oil model in the matrix so as to make a more natural matching with the free flow zones. Three-dimensional finite element simulation approaches have also been developed.

B. Preproduction Stress-Strain State and Coupled Deformation/Flow Modeling

Over geological or production timescales, so many processes are interacting with each other that only fully coupled, comprehensive models are likely to achieve reliable predictive capability. Fig. 5 shows a set of cross-coupling relationships that operate in a basin or reservoir. It is clear that there are a large number of reaction, transport, mechanical (RTM) processes and that they are very strongly coupled.

A fully coupled model accounting of all the processes suggested in Fig. 5 is reviewed in the companion paper in this report ("Predicting the Natural State of Fractured Reservoirs: An Andector Field, West Texas Test of a 3-D RTM Simulator"). To our knowledge, there is no other such simulator. Its application to predicting the preproduction state of the reservoir is outlined in the aforementioned report.

The next task for simulation of production in carbonate reservoirs is to implement features for reservoir simulation (name, wells and injection/production features) and to include macroporosity flow (noted above) and macroporosity failure (noted below) phenomenologies.

A key aspect of the simulation of fractured reservoirs is a model that can describe the dynamics of fracture network initiation, growth, geometry and orientation statistics. We have developed such a dynamical fracture network statistical model (Tuncay and Ortoleva 1998) that predicts the effect of the fracture swarm on rock properties (notably permeability), and in turn fluid pressure and thereby the developing fracture network. Such a dynamical model is needed to predict fracture changes as effective stress changes during draw-down.

An important aspect of the above model is its richness in effects, i.e., sufficient to predict evolving fracturing intensity and rose diagrams. The latter are essential for testing the validity of

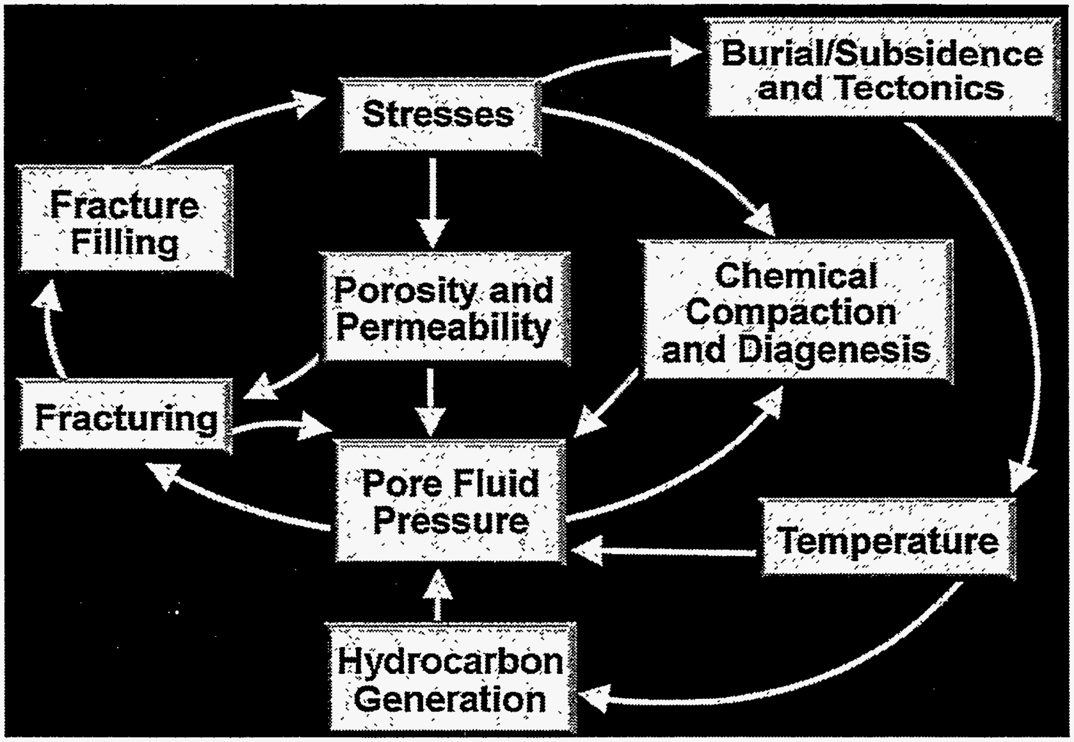

Fig. 5 Complex network of coupled processes underlying the dynamics of a sedimentary basin or evolving reservoir.

predictions across a reservoir knowing their values at the surface or from core.

C. Void Collapse and Fracture Interconnectivity

Void failure is suggested in Fig. 3 to have several distinct modes and implications. Fig. 6 shows a preliminary study for the present project wherein the failure of variably shaped and oriented ellipsoidal voids was considered (Ozkan and Ortoleva 1998). The study demonstrated that use of exact results for isolated ellipsoidal voids could predict stresses near a void and can be used to indicate failure.

The above void failure prediction can be developed into a practical reservoir analysis tool if

- the rheology of the matrix was generalized to include irreversible (in addition to poroelastic) behavior;
- various failure modes be tested in addition to that of Drucker-Prager; and
- more complex void shapes and void-void interactions be considered.

This will follow from the full collapse of voids and of the interconnectivity by fractures to be investigated so that the more precise reservoir dynamical consequences can be predicted.

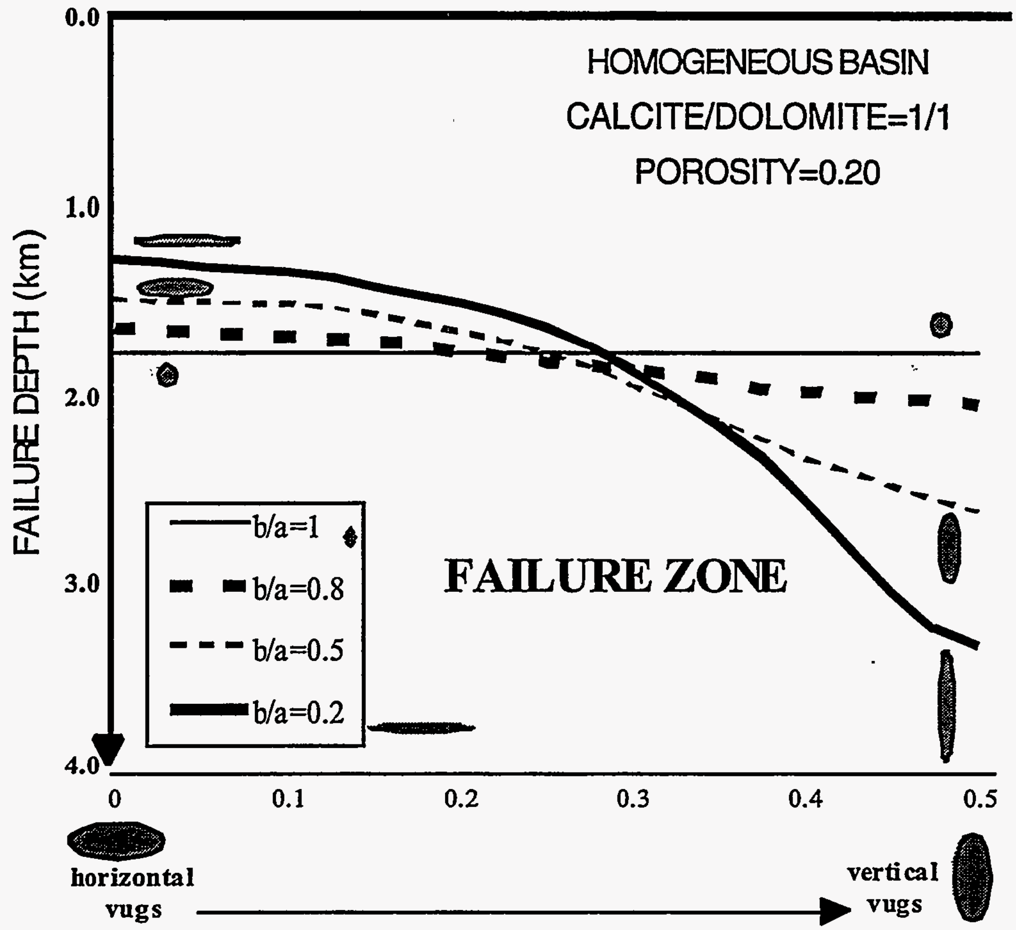

Fig. 6 In a texturally and mineralogically uniform basin, vugs will stand the overburden loads up to different depths according to their shapes and orientations. Failure-depth curves of vugs in a uniformly textured dolomite-calcite basin with porosity of 0.20. The stresses are normal overburden stress and fluid pressure is hydrostatic with water table at the surface. Highly asymmetric vugs oriented vertically may survive below 3,000 meters. Horizontally oriented ones will fail after 1,100 meters.

III Future Work

One of the objectives of the production facet of this project was to set forth the modeling challenges and solutions needed to obtain fractured carbonate reservoir simulation. These challenges have been identified and a number of specific solutions (physical/mathematical models and simulation approaches) have been set forth and tested.

The goal of integrating all these new tools into a new generation reservoir simulator was not explicitly met. This rather ambitious goals can, however, be met by using the unique tools developed in this project. This future integration is a natural follow-on project which can comfortably be achieved in three years in a scope of about $600,000 by the team at the Laboratory for Computational Geodynamics (LCG) at Indiana University. The next generation simulator can be cost-effectively built on LCG's 3-d, finite element basin/reservoir geological evolution simulator Basin RTM. Updates on this and related basin and reservoir simulation projects can be found at the LCG website (http://www.indiana.edu/~lcgiu).

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