ANALYSIS OF OVER-PRESSURE MECHANISMS IN THE UINTA BASIN, UTAH

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Introduction

Extremely high pore fluid pressures exist in the area of the Altamont/Bluebell oil field in the Uinta basin, Utah. We discuss two possible mechanisms for the cause of these over-pressures in this paper: 1) compaction disequilibrium, and 2) conversion of kerogen to liquid hydrocarbon (oil). Compaction disequilibrium occurs during periods of rapid sedimentation. If the permeability of deeply buried strata is low, then connate water within the rock matrix does not escape rapidly enough as compaction occurs; as sedimentary deposition continues, high pore fluid pressures develop. Conversion of solid kerogen to a liquid generates both a liquid and additional pore space for the liquid to occupy. If the volume of the liquid generated is just sufficient to fill the pore space generated, then there will be no accompanying effect on the pore pressure. If the liquid is less dense than the solid it replaces, then there is more liquid than pore space created; pore pressure will increase, causing flow away from the area of the reaction (*Bredehoeft et al.*, 1994). Pore pressure is a sensitive measure of the balance between hydrocarbon generation and expulsion from the source into adjacent strata. If high pore pressures exist only where source rocks are thought to be generating oil, then kerogen conversion is a likely over-pressure mechanism. However, if over-pressures are found in low-permeability strata regardless of source rock proximity, then sedimentary compaction is probably a more dominant mechanism.

Maps of pore pressure gradients in the Uinta basin show some correlation between over-pressures and source rock occurrence. This is not sufficient evidence to conclude that over-pressures are a sole consequence of hydrocarbon generation. We examined the problem in more detail using numerical simulation. All of our simulations were performed using a modified version of TOUGH2.

The purpose of this paper is to provide an overview of how we adapted TOUGH2 as a basin analysis tool and to describe briefly the application of TOUGH2 for elucidating the causes of high pore pressure in the Uinta basin, Utah.

Basin Analysis Using TOUGH2

We used TOUGH2 to understand better the over-pressure mechanisms and the generation and migration of hydrocarbons within the Uinta basin. To improve TOUGH2 as a basin analysis tool, we added a compaction term to the governing equations. This allows strata to be deposited or exhumed and the model domain to be uplifted or subsided during model simulations of basin evolution. Layers of nodes are added during deposition and removed during erosion. The effective stress at each node in the solid skeleton is calculated at each time step, and the compaction of each node is determined. An independent coordinate system is used to determine the movement of all nodes relative to each other.

Other critical aspects of the basin model include:

-All transient effects of sedimentation, uplift, erosion and oil generation on the hydrogeological and thermal aspects of the basin are considered.

-Elastic and plastic strain are represented by constitutive relations between porosity and effective stress. Changes in effective stress are explicitly accounted for and facilitated by calculating elastic (reversible expansivity/compressibility) and inelastic (non-reversible) porosity changes. We also tested assigning porosity from empirical porosity versus depth curves (e.g. *Sclater and Christie*, 1980), and from effective-stress versus porosity curves discussed in *Schneider et al.* (1993).

-Absolute permeability is assigned based on correlation of measurements of permeability and porosity for 223 samples and 78 drill stem tests taken from the Uinta basin. We also tested assigning permeability from the Kozeny-Carmen formulation for permeability versus porosity (*Bear*, 1972).

-Oil generation is kinetically controlled by a first order Arrhenius, parallel reaction, in which heat is the driving force. Because the reaction is driven purely by heat the thermal history is important for the analysis.

-The thermal history is constrained by the present day heat flow observations and by vitrinite reflectance data published for the basin.

-Relative permeabilities (of different fluid phases) assigned to source strata are different than the relative permeabilities assigned to reservoir rocks. Relative permeability curves for reservoir strata are usually measured experimentally, and numerous "typical" relative permeability curves for sandstone are published in the literature. However, experimental relative permeability data for shales and other tight-permeability source rocks are not available. *Burrus et al.* (1992), *Okui and Waples* (1993), and *Wendebourg* (1994) proposed different relative permeability functions for source rocks (than those for reservoir strata) to improve hydrocarbon expulsion aspects in their modeling studies. We elected to test various relative permeability curves for shale and sandstone proposed by these workers in an effort to improve our understanding of expulsion and migration in the Uinta basin.

-Capillary pressures of oil-water interfaces assigned to reservoir (sandstone) and source (shale) strata are also different. We used functional relationships for capillary pressure published by *Parker et al.* (1987) with experimental parameters for sandstone published by *Essaid et al.* (1993). *Burrus et al.* (1992) estimated the capillary pressures for oil-water interfaces in source shales with permeability ~ 10^{-21} m^2 to be ~100 bars (10 MPa). For shale we used the *Parker et al.* (1987) capillary functions scaled to a maximum of 10 MPa.

Over-pressures by Compaction Disequilibrium

We conducted a sensitivity analysis to determine whether compaction disequilibrium could cause significant over-pressures in the Uinta basin. In the basin evolution model, we used the same geometry and dimensions of the Uinta basin, but rather than using the estimated sedimentation rates and other known geologic information for the basin, we used effective stress - porosity functions for shale and sandstone (*Schneider et al.*, 1993) in conjunction with various sedimentation rates.

The effective stress - porosity relationship for sandstones did not produce significant over-pressures except with unreasonably high sedimentation rates. However, the results corresponding to a model using the shale effective stress - porosity function and the Kozeny-Carmen permeability-porosity formulation for shale (*Bear*, 1972) illustrate that for model sedimentation rates in the range of observed Uinta sedimentation rates, especially the higher sedimentation rates, significant over-pressures can develop.

Assuming that compaction disequilibrium is a possible cause of over-pressures, we attempted to ascertain what range of permeability is necessary to maintain high pore pressures for tens of millions of years after they have developed. Our model results suggest that permeabilities of less than 10^{-19} m^2 for most of the stratigraphic column above and adjacent to the over-pressure region are required to maintain over-pressures for time scales on the order of tens of millions of years.

Over-pressures by Oil Generation

A volumetric expansion accompanies the conversion of kerogen to oil. Fluid pressures increase when the oil generation rate exceeds the rate oil can readily flow away. This mechanism can create high pore pressure, pressures approaching lithostatic, in a low permeability environment. We used the basin evolution model to test whether this mechanism is responsible for over-pressures observed in the Uinta basin.

The first step in the process is to backstrip all sediments (e.g. see *Miall,* 1990) with an assumed porosity distribution and estimate sedimentation rates. The basin is then reconstructed through time with estimated timing and rates of uplift. Vitrinite reflectance data are used to estimate the maximum depth of strata during deposition and subsequent erosion (e.g. see *Johnson and Nuccio*, 1993). Additional information needed to parameterize the thermal properties and boundary conditions through time are the background heat flow and the thermal conductivity distribution (*Willett and Chapman,* 1987) and the estimated surface temperature history (adapted from *Wolfe*, 1978). The resulting thermal history determines the hydrocarbon generation history.

Our results suggest that after time of maximum burial until present, hydrocarbon generation in the source strata (oil shale) is the most likely cause of over-pressures in the region of the Altamont-Bluebell and Duchesne oilfields in the northern part of the basin. Minor over-pressures due to compaction disequilibrium occur during periods of rapid deposition, but these over-pressures dissipate before significant oil generation begins.

The present day hydrodynamic state does not promote extensive regional migration. In our model, local migration of oil out of the Altamont-Bluebell and Duchesne fields occurs due to over-pressures. Fractures caused by over-pressures open higher permeability conduits in which oil moves. Our model suggests that most regional migration probably occurred prior to late Miocene time (before 10 Mya), which is when most uplift and erosion of the southern, western and eastern basin flanks began (*Johnson and Nuccio* (1993) and *Johnson and Finn* (1986). We found that both the over-pressures and migration are extremely sensitive to the permeability distribution and viscosity of the oil phase. For over-pressures to develop, marginal lacustrine and open lacustrine facies (source strata) must have very low permeability (~10^{-18} m^2 or lower). For regional migration to occur, at least portions of the alluvial facies (reservoir strata) must have permeability ~10^{-15} m^2 or higher.

We also determined that diagenetic porosity loss may augment over-pressures; applying assumed porosity reduction rates associated with diagenesis increased over-pressures.

Summary

1. We used TOUGH2 to understand better the over-pressure mechanisms and the generation and migration of hydrocarbons (oil phase) within the Uinta basin, Utah.

2. To improve TOUGH2 as a basin analysis tool, we added compaction to the governing equations; strata can be deposited or exhumed and the model domain can be uplifted or subsided during model simulations of basin evolution. All transient effects of sedimentation, uplift, erosion and oil generation on the hydrogeologic and thermal aspects of the basin are considered. Elastic (reversible expansivity/compressibility) and plastic (non-reversible) strain are represented by constitutive relations between porosity and effective stress. Permeability in the basin evolution model is predicted by empirical correlations of permeability and porosity that are constrained by core and drill stem test data.

3. Basin history simulations suggest that compaction disequilibrium was likely a cause of over-pressure during periods of rapid deposition. Both analytical and numerical calculations suggest that, depending upon the permeability of the sediments, the over-pressure produced by sedimentary loading alone should dissipate within 10,000 to 1 million years following the maximum depth of burial. Hydrocarbon generation in the source strata (oil shale) is the most likely cause of current over-pressures observed in the area of the Altamont-Bluebell oilfields.

4. Model results suggest that the present-day hydrodynamic state does not promote extensive regional migration of hydrocarbons out of the Altamont-Duchesne source region. Model results also suggest that most migration of oil probably occurred prior to late Miocene time (before 10 Mya), when uplift and erosion of the basin flanks began.

5. We found that the over-pressure plus migration system is extremely sensitive to hydraulic conductivity. For over-pressures to develop, marginal and open lacustrine facies (source strata) must have very low permeability ($\sim 10^{-18}$ m^2 or lower). For regional migration to occur, at least portions of the alluvial facies (reservoir strata) must have permeability $\sim 10^{-15}$ m^2 or higher.

6. We conclude that diagenetic porosity loss may augment over-pressures because applying assumed porosity reduction rates associated with diagenesis increased over-pressures.

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