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**MECHANICAL PROPERTIES AND MODELING
OF SEAL-FORMING LITHOLOGIES**

A.K. Kronenberg, J.E. Russell, N.L. Carter,
W. Shea, W. Ibanez, R. Mazariegos, and O. Kwon

Center for Tectonophysics
Dept. of Geology and Geophysics
Texas A&M University
College Station, TX 77843
(409) 845-0132

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FINAL TECHNICAL PROGRESS REPORT

Research Objectives and Summary

The focus of this research supported by DOE Basic Energy Sciences for a three year period and extended one additional year at no extra cost, has been on the mechanical and transport properties of two sedimentary lithologies, rocksalt and phyllosilicate clay-bearing shale, that commonly serve as structural traps to hydrocarbons. Experimental determinations of physical properties of these rock types have been combined with numerical modeling to examine the development of structural traps and the roles of fluids in natural deformations, applying depositional and tectonic loading conditions and entertaining different histories for the presence of fluids. Laboratory efforts have been directed towards determining realistic constitutive relationships that are accurate over a wide range of strain rates and improving our understanding of the physics and micromechanics of deformation. Modeling efforts have applied these laboratory-based relationships to follow the initiation and evolution of salt structures and overlying stratigraphic units for structures with well-constrained geologic histories, stratigraphic controls on loading and timing, and microstructural information relevant to flow stresses.

Many of the research objectives defined by our original proposal have been completed and we have addressed new questions that emerged during the course of our investigations. The nonlinear relationships between strength and strain rate for rocksalt and illite-bearing shale have been evaluated over a wide range of experimental conditions ($21^{\circ} \leq T \leq 200^{\circ}\text{C}$, $3 \leq P_e \leq 400 \text{ MPa}$, $10^{-9} \leq \dot{\epsilon} \leq 10^{-3} \text{ s}^{-1}$) and numerical modeling of salt diapirs with geologic constraints on loading and ascent rates has extended predictions of mechanical response of rocksalt to strain rates of 10^{-15} s^{-1} . Fluids are extremely important to the mechanical behavior of both rock types. Experimental results for shale include its behavior in the absence of pore fluids, with only structural and adsorbed H_2O layers on clays, as well as its drained and undrained response when saturated with brines of varying composition. Models of salt diapir development have compared incubation times for diapir initiation and ascent velocities that are constrained by geologic observations and those predicted by power law, dislocation creep laws determined in our laboratory for relatively dry rocksalt and the linear, solution-transfer creep law of *Spiers et al.* (1988, 1990) for wet rocksalt.

Shale Deformation

Failure strength and permeability measurements for Wilcox shale have been made with 1 molar solutions of NaCl, KCl, and CaCl_2 as well as with distilled H_2O . Both the mechanical and transport properties of shale are strongly dependent on effective mean stress, exhibiting significant non-recoverable changes with increasing effective pressure P_e associated with inelastic changes in pore geometry and structure, and smaller reversible poro-elastic changes for decreasing pressure. In addition, failure strengths are weakly dependent on strain rate and can be described by an exponential law of the form $\dot{\epsilon} = A(T, P_e) \exp \{ \beta (\sigma_1 - \sigma_3) \}$, both when samples are essentially dry and when they are saturated with fluids. Inelastic yield strengths depend on temperature for dry samples at elevated P_e through an Arrhenius expression.

From transient pulse permeability measurements and calculations of internal pore pressures based on one-dimensional diffusion we conclude that triaxial compression experiments over strain rates of 10^{-8} s^{-1} to 10^{-3} s^{-1} include time scales that represent drained and effectively undrained conditions. Having established the time scales for drained response, we have determined effective stress laws for permeability and failure strength of shale. Much as expected for soils and weak materials in which the fractional cross-sectional area of pore space in contact with fluid is near unity, α values for permeability and failure are nearly equal to one. While effects of fluid chemistry on failure strength under drained conditions appear to be small, permeabilities are affected significantly by exchange of divalent cations for monovalent cations at clay mineral surfaces. Thus, time scales for which drained versus undrained mechanical behavior are observed may change with fluid chemistry, as will strength-strain rate relationships that result from time-dependent perturbations in local pore pressure. Time scales over which deformation can be considered drained are further complicated by dilatant volumetric strains during experiments and measured changes in permeability at differential stresses near failure.

Compressive failure strengths of Wilcox shale show only subtle anisotropy, with maximum and minimum peak differential stresses that differ by only 20% for samples with different orientations, whereas permeabilities for flow parallel to bedding are 10^2 greater than those measured perpendicular to bedding at low effective pressures. With increasing effective pressure, though, permeabilities measured parallel to bedding decrease more rapidly than those measured perpendicular to bedding, reaching $\sim 10^{-21} \text{ m}^2$ (~ 1 nanodarcy) at $P_e = 8 \text{ MPa}$ and permeabilities approach similar, isotropic values.

Our permeability and deformation experiments suggest interesting and important effects that adsorbed surface layers at fluid-clay interfaces have on the properties of shale. While illite is less reactive with fluids than most other clays and basal layer d-spacings of clays in Wilcox shale do not exhibit any expansion or contraction with exposure to fluids of varying composition, the macroscopic dimensions of Wilcox shale samples immersed in differing aqueous fluids prior to experiments change significantly. Permeabilities depend on the composition of the pore fluid and sequence of exposure to strongly adsorbing cations. Permeability of Wilcox shale is virtually identical for distilled H_2O and 1 molar brines of NaCl and KCl for samples that have been pre-treated with these same fluids to prevent ion exchange between clays and fluids during the experiments. However, permeability is enhanced by more than an order of magnitude for CaCl_2 brine transport in exchanged samples, suggesting an important effect of the clay-fluid electrical double-layer on the effective dimensions and connectedness of pores available for bulk fluid flow. By altering fluid compositions during permeability experiments, interesting effects of ion exchange and adsorption hydration at clay-fluid interfaces can be examined. Permeabilities of Wilcox shale increase significantly upon changing the fluid from 1 molar solutions of NaCl to CaCl_2 but remain large upon changing the fluid back to 1 molar NaCl . Permeabilities of Wilcox shale remain the same upon changing the pore fluid from distilled H_2O to 1 molar NaCl but decrease by 20% upon changing the fluid back to H_2O .

Failure strengths of Wilcox shale show only weak effects of pore fluid composition by comparison to our permeability results. However, shale strengths appear to depend on the presence of pore fluids by the effective stress law as well as chemical hydration states of clay surfaces by processes that we have not identified. These effects originally complicated our efforts to determine an effective stress law for shale deformation since variations in adsorbed surface layers of water can give rise to

differences in strength as well. However, we believe that these effects are minimized once fluid pressures are large.

Salt Tectonics Modeling

Our numerical studies of salt structure development have led to insights into the initiation, evolution, and timing of complex salt structures of the northern continental shelf of the Gulf of Mexico, as well as the sensitivities of salt structure development to subsurface conditions, viscosity contrasts between salt bodies and overlying sediments, and degrees of nonlinearity in rheology. These model studies have been accompanied by studies of deformation microstructures of natural salt structures of the Gulf of Mexico using cores recovered from actively deforming allochthonous salt nappes. Equivalent stress levels within these structures, as determined from stress-dependent microstructures offer important constraints for the models and the rheologies upon which our models are based.

Differential loading of evaporites in the subsurface is a natural consequence of deltaic depositional cycles and are considered to have been responsible for the formation and contemporaneous evolution of salt structures of the East Texas Basin and the Northern Gulf of Mexico. Algorithms to handle multiple interfaces and sequential depositional loading histories have addressed salt structure development due to realistic though generic depositional histories. In addition, we have examined the roles of extensional basement faults at continental margins on the initiation and morphologic development of salt structures.

As part of the comparison of results obtained for power law creep associated with dislocation creep of dry rocksalt and linear, fluid-assisted creep of wet rocksalt, we have examined model sensitivities to degrees of nonlinearity in rheology of rocksalt. In addition, we examined the effects of varying viscosity contrasts between salt units and overlying sediments and of highly nonlinear sediment behavior, using sediment mechanical properties that closely approximate those determined experimentally for shale. In both geometric comparisons of vertical and horizontal velocities and timing of salt structure development, the models closely approximate what we know from stratigraphic and microstructural constraints for salt diapirs and shallow allochthonous salt sheets.

This project has supported the graduate research of three students, leading to two doctoral dissertations and one masters thesis. One of these dissertations, that of Ruben Mazariegos, was recognized by the U.S. National Committee on Rock Mechanics with the 1995 Award for the "Best Dissertation in Rock Mechanics." Dr. Mazariegos is now an Assistant Professor of Geophysics at the University of Texas-Pan American where he serves as mentor to a large number of minority students and proves to them tangibly that their cultural heritage and a successful scientific/technical career are not mutually exclusive. William Ibanez is currently working on a doctoral dissertation within our department and Ohmyoung Kwon is expected to defend his dissertation by May of 1998.

Results obtained over the last four year period have been presented at twelve national and international meetings in the form of abstracts and oral presentations. Six papers have been published and five manuscripts are in preparation or have been submitted for publication.

MASTERS THESES AND DOCTORAL DISSERTATIONS

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Journal Publications

Kwon, O., and Kronenberg, A.K. (in preparation) Permeability of Wilcox shale: mechanical and chemical effects of fluids, intended for publication in *Amer. Assoc. Petrol. Geol. Bull.*

Kwon, O., and Kronenberg, A.K. (in preparation) Roles of fluids and volume changes on the failure of Wilcox shale, intended for publication in *Tectonophysics*.

Spiers, C.J., and Carter, N.L. (in preparation). Offshore salt sheets - Gulf of Mexico, intended for publication in *Tectonophysics*.

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