**AAPG Annual Meeting 2013**

**INFLUENCE OF PRE-EXISTING STRIKE-SLIP FAULTS ON FAULT DEVELOPMENT DURING SUBSEQUENT PHASES OF DEFORMATION**

**Putra, Christian; Schlische, Roy W.; Withjack, Martha O.**

We used scaled experimental (analog) models with wet clay to investigate how conjugate sets of steeply dipping strike-slip faults affect deformation patterns during a subsequent phase of extension. In all two-phase experiments, an initial phase of strike-slip deformation produces a long, wide deformation zone consisting of subvertical Riedel shears; synthetic R-shears and antithetic R'-shears trend at ~15° and ~85°, respectively, relative to the long axis of the deformation zone. The second phase of deformation is extensional with extension directions trending 60° to 120° from the long axis of the deformation zone. Reactivation of the pre-existing R-shears only occurs in models in which the second-phase extension direction is subperpendicular to the R-shears. Reactivation includes changes in the sense of slip (strike-slip faults reactivated as oblique-slip faults) and length (propagation of pre-existing faults). In all models, new normal faults also form during the second phase of deformation. These new normal faults also form during the second phase of deformation. These new normal faults crosscut, terminate against, and/or initiate at pre-existing Riedel shears, creating zigzag geometries or "ladder" structures (normal faults bounded by subparallel strike-slip faults). In models where the extension direction is oblique to both sets of Riedel shears, the second-phase fault orientations resemble those that develop in models without a first phase of strike-slip deformation. In models where the extension direction is subperpendicular to the R-shears, the second-phase fault orientations resemble those of the R-shears. Although the new faults have the same strike as the R-shears, their moderate dip angles are more typical of normal faults. Layered models suggest that these faults develop when some steeply dipping R-shears, present only near the base of the model, are reactivated during the second phase of extension. As the faults propagate upward toward the surface, their dip angle decreases. In summary, reactivation of steeply dipping strike-slip faults can occur during extension, depending on the orientation of the extension direction relative to that of the strike-slip faults; additionally, the presence of pre-existing strike-slip faults can affect the geometry and spatial distribution of new normal faults.

**AAPG Annual Meeting 2013**

**THE INFLUENCE OF SYNrift SALT ON DEFORMATION DURING AND AFTER RIFTING: EXAMPLES FROM THE ORPHEUS RIFT BASIN, OFFSHORE NOVA SCOTIA AND NEWFOUNDLAND, CANADA**

**Hanafi, Bari R.; Withjack, Martha O.; Schlische, Roy W.; Syamsir, Zulfriadi; Durcanin, Michael A.**

The Orpheus rift basin is part of the eastern North American (ENA) rift system that formed prior to the opening of the Atlantic Ocean. Like many of the northern ENA rift basins, a considerable thickness of salt (i.e., the Late Triassic/Early Jurassic Argo Formation) accumulated within the Orpheus basin during rifting. We have used a dense grid of public and proprietary 2-D seismic data, industry well data, and information from the adjacent Fundy rift basin to better understand how the presence of synrift salt influenced rift-basin development. Our work shows that the stratigraphic distribution, thickness, and composition of the synrift salt significantly influenced deformation patterns during and after rifting. The lower Argo Formation consists of massive halite. Salt deposition was widespread, but accumulation
varied, controlled by basement-involved faulting. Generally, the basal halite is thin or absent above shallow fault blocks and thick above deep fault blocks. The upper Argo Formation consists of halite and interbedded clastic sedimentary rocks. In parts of the basin, the upper Argo Formation is predominantly halite with few shale beds. In other parts of the basin, however, the halite is interbedded with numerous, thick shale beds. Growth beds in the upper Argo Formation associated with extensional fault-propagation folds reflect continued activity on basement-involved faults below the salt during the deposition of this unit. During the later phases of rifting, focused deposition near the northern border-fault zone caused the underlying salt to move. Paired minibasins and salt walls/columns preferentially formed where the lower Argo salt was thick and/or where the upper Argo Formation had a high proportion of halite. Immediately after rifting, shortening associated with basin inversion reactivated the basement-involved faults and produced broad sub-salt folds similar to those in the adjacent Fundy basin, which shares its border-fault zone with the Orpheus basin. In response, detached structures formed above thin salt, and the existing salt walls/columns narrowed to accommodate the shortening. Additional postrift deformation during the Late Jurassic/Early Cretaceous and Oligocene/Miocene again reactivated basement-involved faults and shortened the buried salt walls/columns, producing domes in the sedimentary cover above them.

AAPG Annual Meeting 2013
EVOLUTION OF THE JEANNE D'ARC BASIN, OFFSHORE NEWFOUNDLAND, CANADA: 3-D SEISMIC EVIDENCE FOR >100 MILLION YEARS OF RIFTING

Serrano-Suarez, Beatriz E.; Withjack, Martha O.; Schlische, Roy W.

The petroliferous Jeanne d'Arc rift basin formed during the breakup of Pangea from Late Triassic through Early Cretaceous time. Previous studies concluded that rifting was episodic, occurring during two or three distinct events with intervening periods of thermal subsidence. To test these conclusions, we used 3-D seismic data, well data, and restoration techniques to determine the spatial and temporal evolution of the Flying Foam region in the northwestern part of the basin. The Flying Foam region lies between the NNE-striking, E-dipping Mercury and Murre border faults of the basin. In the southern Flying Foam region, a series of basement-involved faults are present between the Mercury and Murre faults. In the north, a major anticline (the Flying Foam anticline) overlies the Murre fault. We have identified three syn-rift tectonostratigraphic packages, none of which are present in the footwall of the Mercury fault. Strata within the basal Late Triassic/Early Jurassic syn-rift package thicken toward basement-involved faults. This package contains salt of the Argo Formation, which decouples the basement-involved faults from shallow structures. The overlying Jurassic package lacks evident fanning toward the Murre and Mercury faults. However, changes in thickness across the Murre fault and along-strike thickness variations in the hanging wall of the Mercury fault reflect displacement on the faults during deposition. The overlying Early Cretaceous package thins toward the Flying Foam anticline, a structure produced by a combination of forced folding above the Murre fault and fault-bend folding associated with a listric fault that detaches within the Argo salt. Thus, the Early Cretaceous package is also a syn-rift unit. In conclusion, our work indicates that extension in the Jeanne d'Arc basin was not episodic, but rather rifting was continuous, occurring from the Late Triassic through the Early Cretaceous. The intensity and extension directions could have changed through time.

AAPG Annual Meeting 2013
GEOLOGICAL PREDICTION OF SUBSEISMIC DEFORMATION FROM SEISMIC-REFLECTION PROFILES OF CONTRACTIONAL STRUCTURES

Groshong, Richard H.; Withjack, Martha O.; Schlische, Roy W.
Recent Abstracts

Subseismic (subresolution) deformation can significantly influence reservoir continuity, porosity, and permeability. The area-depth-strain (ADS) method is a rapid and inexpensive screening technique for recognizing potential locations and magnitudes of subseismic deformation. With this method, a graph of excess area vs. depth yields the boundary displacement. The displacement, together with measured bed lengths and widths of the structure at regional, allow for the calculation of subseismic strain for each marker. We present ADS results for three seismic profiles from fold-thrust belts: 1) a regional profile from the central Appalachian Valley and Ridge fold-thrust belt, 2) an oil-field-scale fault-bend fold from deep water offshore Nigeria, and 3) the fault-bend fold that produced the Rosario oil field in Venezuela. The results show that the ADS method permits the quantification of subseismic deformation at numerous stratigraphic horizons (including growth horizons) within the structures. For the Appalachian profile, the ADS method predicts a subresolution layer-parallel shortening of ~40% at the level of the basal Silurian strata. Outcrop and map data provide information about the character of this deformation and indicate at least two scales of substantial deformation not included on the regional profile: outcrop-scale folds and faults and small map-scale folds. The Nigerian example is a single thrust-ramp anticline with growth strata. ADS analysis indicates that layer-parallel strain varies considerably with substantial shortening (13-23%) at some stratigraphic levels and little at other levels. The differences are probably related to lithology, with stiffer, brittle units having less subseismic deformation. Horizons with high subseismic strains are likely to be thin-bedded or consist of an inherently more ductile lithology. The predicted subresolution strain is inversely proportional to the separation on the fault, suggesting a partitioning of displacement between layer-parallel shortening/thickening and fault slip. For the fault-bend fold forming the Rosario oil field, the ADS analysis indicates that layer-parallel shortening strains are small at all stratigraphic levels. Thus, the ADS analysis predicts that the Rosario structure has little subseismic deformation, in contrast to the Nigerian and Appalachian examples.

2012 GSA Annual Meeting

RIFTING, BREAKUP, AND POST-RIFT DEFORMATION ON THE ‘PASSIVE-AGGRESSIVE’ MARGIN OF EASTERN NORTH AMERICA

M. O. Withjack, R. W. Schlische, P. E. Olsen, and M. L. Malinconico

Seismic, field, borehole, core, and vitrinite-reflectance data indicate that the tectonic evolution of the continental margin of eastern North America was complex, involving rifting, breakup, and post-rift deformation. The onset of rifting, from Florida to the Canadian Grand Banks, was approximately synchronous, occurring by Late Triassic time. The resulting eastern North American (ENAM) rift system was characterized by a broad zone of upper crustal extension in which a few, wide (>100 km), deep (5-10 km), long-lived (>30 m.y.), fault-bounded basins accommodated much of the extension. The border-fault zones (BFZs) of the rift basins were mostly reactivated, pre-existing Paleozoic and older structures with gentle to moderate dips. The cessation of rifting (and presumably the onset of breakup) was diachronous, occurring first in the southeastern United States (latest Triassic), then in the northeastern United States and southeastern Canada (Early Jurassic), and finally in the Grand Banks (Early Cretaceous). The Central Atlantic Magmatic Province (CAMP) developed simultaneously (latest Triassic / earliest Jurassic, ~200 Ma) throughout eastern North America. Thus, CAMP magmatic activity occurred shortly after rifting in the southeastern United States and during rifting in the northeastern United States and maritime Canada. Much of the current geometry of the ENAM rift system reflects deformation that occurred after rifting, including: 1) reactivation of BFZs and intrabasin faults with reverse and/or strike-slip components of displacement; 2) folding near BFZs and intrabasin faults; and 3) very broad arching that produced regional tilting and uplift, leading to locally >5 km of erosion. This post-rift erosion considerably reduced the size (depth and width) of the ENAM rift basins. Although the timing of the post-rift deformation is poorly constrained, a growing body of evidence suggests that some occurred during breakup and/or the early stages of seafloor spreading whereas some occurred during Cenozoic time.
2012 GSA Annual Meeting

INTERPRETING DISPLACEMENT AND STRAIN IN GROWING THRUST-RAMP ANTICLINES: FROM MODEL TO SEISMIC REFLECTION PROFILE

Richard H. Groshong, Jr., Roy W. Schlische, Martha Oliver Withjack, Triyani N. Hidayah

Thrust-ramp anticlines are the characteristic structures in most foreland fold-thrust belts. Typical interpretation questions include: Is the structure balanced? What is the orogenic shortening? What is the growth history? Can subresolution strain be inferred? We address these issues for growing thrust-ramp anticlines with three examples: a geometric (kinematic) model, an experimental (analogue) model, and a seismic-reflection profile of a thrust-ramp anticline from offshore Nigeria. We show that the area-depth-strain (ADS) method, an area-balance technique, yields accurate quantitative information without assuming a kinematic model and which avoids the problems that may arise in interpretations based on the assumption of constant bed length. The ADS method makes it possible to clearly discriminate between growth and pregrowth units at a change in slope on a graph of excess area versus depth. For pregrowth horizons, the inverse slope of the line through the data points gives the total displacement and the depth to the lower detachment. For a growth horizon, the displacement since deposition is given by the inverse slope of the line connecting its area-depth point to that of the lower detachment. From this information, it is possible to calculate displacement rates, subresolution strain and, for the experimental model with known boundary displacement, the dilation. The experimental model shows layer-parallel shortening of up to ~17% with corresponding layer-normal thickening. The differences between calculated and imposed displacement indicate positive dilation up to +5%, not tectonic compaction as inferred from methods assuming constant bed lengths. The measured displacement on the thrust ramp is ~30% less than the boundary displacement. The strain magnitudes are sensitive to the specific interpretation of bed length vs. fault length but the other values (detachment depth, displacements, dilation) are relatively insensitive to this. The seismic profile is balanced, with layer-parallel shortening up to 23%. The pregrowth interval shows a partitioning between internal strain and fault separation in which the lowest-strain markers have fault separations only 2% less than the calculated total.

2012 GAC Meeting, St. John’s, Newfoundland

THE MESOZOIC ORPHEUS RIFT BASIN, OFFSHORE NOVA SCOTIA AND NEWFOUNDLAND, CANADA: THE INFLUENCE OF BASIN ARCHITECTURE ON SALT TECTONICS AND BASIN INVERSION

Hanafi, B.R., Withjack, M.O., Syamsir, Z., Durcanin, M.A. and Schlische, R.W.

The Orpheus rift basin is the part of the Mesozoic rift system of eastern North America that formed prior to the opening of the North Atlantic Ocean. The Cobequid-Chedabucto fault system (CCFS) bounds the Orpheus and Fundy rift basins on the north; thus, it is likely that both basins have a common tectonic evolution. Our study area, imaged by a grid of 2D seismic-reflection profiles, covers the eastern part of the Orpheus basin. Based on data from nearby wells, comparisons to the Fundy basin, tectonostratigraphic packages bounded by unconformities, the presence/absence of growth beds, and cross-cutting igneous intrusions, we recognize four major tectonic episodes for the Orpheus rift basin: Triassic to Early Jurassic rifting, Early Jurassic basin inversion during the transition from rifting to drifting, Early Cretaceous uplift and erosion, and Oligocene/Miocene uplift and erosion. In the study area, the Orpheus basin has two distinct basin architectures based on the geometry of basement-involved extensional faults. In the eastern part of the study area, most basement-involved faults dip toward the south. In the western part of the study area, however, the basement-involved faults dip toward the south and the north, producing a horst-and-graben geometry. The synrift Argo salt is thicker in the full grabens
near the CCFS and in the fault blocks far from the CCFS; thus, the fault geometries controlled the initial thickness/distribution of the Argo salt. In areas with thinner salt, basin inversion reactivated the basement-involved extensional faults below the salt, and produced supra-salt compressional structures such as salt-cored buckle folds and detached thrust faults. Thus, the salt layer decoupled the shallow and deep deformation. In areas with thicker salt, salt structures developed during rifting, producing salt walls/columns and wedged-shaped mini basins. Basin inversion reactivated the basement-involved extensional faults below the salt. In response, the salt columns narrowed, accommodating most of the supra-salt shortening. Our work shows that the style of post-rift basin inversion on the passive margin of eastern Canada depends, at least in part, on the basin architecture and the distribution of salt within the basin.

2012 IGC Meeting, Brisbane, Australia
EXPERIMENTAL PHYSICAL MODELLING OF RELEASE FAULTS IN EXTENSIONAL SYSTEMS AND IMPLICATIONS FOR HYDROCARBON EXPLORATION

Destro, N., Withjack, M.O., Schlische, R.W., Henza, A.A., and Durcanin, M.A.

We have used scaled experimental models to define the conditions that promote the formation of release faults during extension. Release faults develop to accommodate the variable displacement along the strike of a normal fault, named a parent fault. As observed in outcrops and subsurface structural contour maps, release faults die out away from their parent fault, have strikes that range from orthogonal to oblique to the strike of their parent fault, have normal displacements, and form in strike ramps of parent faults.

We have produced release faults with wet clay using orthogonal extension. In one set of models, a homogeneous layer of wet clay covered either a stretching rubber sheet or a thin layer of silicone polymer above a stretching rubber sheet. In a second set of models, a layer of wet clay covered two diverging, overlapping plates. In models with two phases of non-coaxial, oblique extension (45° and 135°), many of the second-phase normal faults resembled release faults as they commonly nucleated at and died out away from the first-phase faults (i.e., the parent faults). However, they differed from release faults in that they were widespread and not exclusively associated with a single parent fault.

Release faults have been documented in several extensional settings, and release faults in either the hangingwall or footwall of the parent fault are favorable for the development of structures bearing hydrocarbon accumulations. Examples presented are from the Cretaceous Recôncavo and Sergipe-Alagoas basins in Northeast Brazil.

2011 AGU Meeting
SUBSURFACE IMAGES OF THE NORTHERN NEWARK BASIN, NEW YORK, USA AND THEIR IMPLICATIONS FOR CARBON SEQUESTRATION.

Olsen, P.E., Withjack, M.O., Schlische, R.W., Goldberg, D., Kent, D.V., Tamulonis, K., Couësland, M., Collins, D.J.

The Triassic-Jurassic Newark rift, a large onshore sedimentary basin close to northeast US metropolitan areas, may have potential for safe geological storage of CO2 in a suitably deep formation overlain by appropriate confining units. Filled with continental synrift sedimentary rocks and CAMP (Central Atlantic Magmatic Province) basaltic intrusions and flows, the basin is bounded on the NW by the NE-striking, SE-dipping Ramapo fault. Funded by the Department of Energy's (DOE) National Energy Technology Laboratory's (NETL) Carbon Sequestration Program's portion of the American Recovery and Reinvestment Act of 2009 (ARRA) and NYSERDA, the TriCarb Consortium for Carbon Sequestration acquired two seismic-reflection profiles in Rockland County, NY that were processed to obtain depth-
migrated images of the basin's subsurface geometry. The E-trending dip profile crosses most of the basin, while the shorter N-trending profile provides a strike-view. Five seismic facies are present: (1) shallow continuous, closely spaced, W-dipping reflections suggestive of lacustrine deposits; (2) short, non-coherent reflections suggestive of conglomeritic fluvial strata; (3) high-amplitude parallel reflections, locally exhibiting reverse separation, suggestive of prerift early Paleozoic strata Cambro-Ordovician carbonates; (4) a facies at the bottom of both lines and the western end of the ESE-trending line that lacks reflections, suggestive of prerift metamorphic rocks such as Precambrian gneiss, and/or highly deformed Taconic (Ordovician) phyllites; and (5) a seismically transparent band commonly bounded by high-amplitude reflections that cuts across the stratigraphy of facies 1-3, suggestive of a scoop-shaped intrusive diabase sheet that projects to the surface to outcrops of the CAMP-related Palisade sill. Basin geometry is well-imaged conforming to a deeply eroded half graben. Reflections of facies 3 are truncated by facies 2 marking the angular pre-rift unconformity. Distinct fanning in facies 1 suggests syndepositional faulting with reflections dipping and thickening toward the poorly imaged Ramapo fault to the NW. Because Jurassic CAMP lavas crop out at the NW edge of the basin, the full thickness of Triassic strata are imaged on the seismic data. Our favored interpretation has the Palisades sheet intruding the pre-rift unconformity in the axis of the basin, climbing up-section into Triassic strata to the NW, NE, and SE. The base of the intrusion and the contact with prerift strata appears to be at a depth of ~ 2 km (6600 ft) in the location of a planned basin-characterization core hole to be drilled in late summer/early fall of 2011. In this location, our favored interpretation has the intrusion underlying Triassic sandstones and conglomerates of the Stockton Formation (best reservoir candidate), in turn overlain by mudstones of the Lockatong Formation (best confining unit candidate), overlain by upwardly coarsening mudstones, sandstones, and conglomerates of the Passaic Formation. These hypotheses should be tested by "ground truth" from the borehole by the time of this presentation.

Groshong, R.H., Jr., Hidayah, T.N., Withjack, M.O., and Schlische, R.W., 2011, New insights into fault-bend folding revealed by area-depth relationships in physical models, the Rosario oil field, Venezuela, and an outcrop example from the Canadian Rockies, AAPG Annual Meeting, Houston.

2010 AAPG Annual Meeting, New Orleans.
PRE-EXISTING ZONES OF WEAKNESS: AN EXPERIMENTAL STUDY OF THEIR INFLUENCE ON THE DEVELOPMENT OF EXTENSIONAL FAULTS

Alissa A. Henza, Martha O. Withjack, Roy W. Schlische

We use scaled experimental (analog) models to investigate how the properties of pre-existing zones of weakness influence deformation patterns during extension. In the models, a homogeneous layer of wet clay (simulating brittle rock) undergoes two phases of extension whose directions differ by 45°. To vary the properties of the first-phase fault fabric, we vary the magnitude of the first-phase extension. Specifically, as the extension magnitude increases, the number, average length, and average displacement of the first-phase normal faults increase. Deformation during the second phase of extension depends on the properties of the first-phase fault fabric (and, thus, on the magnitude of the first-phase extension). For a poorly developed pre-existing fault fabric, new normal faults (which strike perpendicular to the second-phase extension direction) accommodate most of the extension during the second phase. For a well-developed pre-existing fault fabric, many of the first-phase normal faults are reactivated as oblique-slip faults during the second phase of extension. New normal faults also form. These second-phase normal faults are shorter and more likely to strike obliquely to the second-phase extension direction. They are also less likely to cut pre-existing faults than the second-phase normal faults that form in models with a poorly developed fabric. In all models, the pre-existing faults act as nucleation sites for the second-phase normal faults. In models with a well-developed fabric, however, the pre-existing faults also act as obstacles to the lateral and vertical propagation of the second-phase normal faults. We classify the faults patterns as first-phase dominant, second-phase dominant, or neither phase dominant, depending on which
fault population (if any) controls the final deformation pattern. The relative magnitude of extension during the two phases of deformation determines the dominance of a particular fault population. Intersecting fault patterns result when first-phase faults are dominant, parallel fault patterns result when second-phase faults are dominant, and zigzag fault patterns result when neither the first-phase nor the second-phase faults are dominant. These fault patterns are common in many extensional basins (e.g., the Jeanne d’Arc basin of eastern Canada, the Suez rift of Egypt, the Pattani basin of Thailand), and likely reflect the influence of a pre-existing fabric.

QUANTITATIVE COMPARISONS OF ANALOGUE MODELS OF BRITTLE CONTRACTIONAL DEFORMATION

Schreurs, G. and the GeoMod2008 Analogue Team

Analogue model experiments are widely used to gain insights into the evolution of geological structures. In this study, we present a direct comparison of model results from different analogue laboratories for identical set-ups. A quantitative analysis of the results will document the variability among models and has direct implications for comparisons between structures in analogue models and natural field examples. All 14 participating laboratories used the same analogue materials and identical model-building techniques. In addition, all laboratories used the same type of self-adhesive foil to cover the base and all walls of the experimental apparatus; this guaranteed identical base and wall frictional properties. Each laboratory used its own experimental apparatus. Three experimental set-ups using only brittle frictional materials were examined. In each of the three set-ups, the model was shortened by inward translation of a mobile wall.

In the first experimental set-up, a quartz sand wedge with a surface slope of \( \sim 20^\circ \) was translated by a mobile wall. All models conformed to the critical taper theory, maintained a stable surface slope and did not show internal deformation. In the next two experimental set-ups, a horizontal sandpack consisting of alternating quartz sand and corundum sand layers was shortened by inward translation of a mobile wall. In one of the set-ups a rigid sheet covered part of the model base and was attached to the mobile wall. In the other set-up this sheet was absent. In both types of experiments, models accommodated initial shortening by forward- and a backward-verging thrusts. Further shortening was taken up by in-sequence formation of forward-verging thrusts. In all experiments, lateral friction created important drag of structures along the sidewalls. We therefore compared surface slope and the location, dip angle and spacing of thrusts in sections through the central part of the model.

All models show an encouraging overall agreement in their cross-sectional evolution. Nevertheless, along-strike variations of structures in map view remain important and may relate to sidewall friction and/or to the properties of the granular materials used. [Comment: All labs used the same granular materials, but temperature and especially humidity may have affected their mechanical properties.]


AAPG 2010 International Conference and Exhibit.
SYNRIFT, POSTRIFT, AND SALT-RELATED DEFORMATION ON THE PASSIVE MARGIN OF NOVA SCOTIA AND SOUTHERN NEWFOUNDLAND, CANADA: IS IT REALLY
PASSIVE?

Durcanin, M., Syamsir, Z., Withjack, M., and Schlische, R.

Like the Fundy rift basin of southeastern Canada, the Orpheus basin formed by reactivation of the Cobequid-Chedabucto fault zone during early Mesozoic rifting (i.e., the breakup of Pangea). The Fundy basin has undergone significant post-rift shortening, the timing of which is poorly constrained because post-rift strata are absent. Jurassic to Quaternary post-rift strata, however, overlie the Orpheus basin. We use newly reprocessed seismic-reflection data to better define the geometry and temporal evolution of post-rift deformation in the Orpheus basin. Here, we focus on the post-rift succession between two major angular unconformities, an Oligocene (?) unconformity and the latest Jurassic/early Cretaceous Avalon unconformity.

Strata above the Avalon unconformity are deformed into broad anticlines and synlines, which generally overlie either pre-rift and/or syn-rift salt. Cretaceous strata directly above the Avalon unconformity show minor thinning over the crests of anticlines, suggesting that the rate of sediment aggradation exceeded the rate of anticlinal growth. Higher in the section, strata show greater thickness variations with respect to the anticlines. Most anticlinal growth occurred during the latter half of the Cenozoic and is associated with widespread erosion and, at least locally, uplift. Faults with normal separation cut the post-Avalon strata at the crests of anticlines and elsewhere.

Two hypotheses can explain the post-rift deformation within the Orpheus basin. One hypothesis is that salt movement triggered by gravity-driven processes such as differential loading caused the formation of the post-Avalon structures. The second hypothesis is that post-Avalon structures are related, at least partially, to basement-involved deformation. Results of experimental modeling suggest that the rate of anticlinal growth--if related to gravity-driven processes--would decrease through time as the thickness of the sedimentary cover increased. However, the rate of anticlinal growth in the Orpheus basin has increased through time, favoring some basement-involved deformation.


2008 AGU Annual Meeting

PORE-PRESSURE VARIATIONS: A POSSIBLE EXPLANATION FOR STRAIN-RATE-DEPENDENT FAULTING IN ANALOG MODELS WITH WET CLAY

Thorsten J. Nagel, W. Roger Buck, Roy W. Schlische³, and Martha O. Withjack³

Localized shear zones (i.e., faults) develop in extensional analog models with wet clay only after a significant amount of extension has occurred. The amount of strain needed for localization, as well as the proportion of strain accommodated by shear zones, depends on the strain rate. With higher strain rates, more strain is needed before localized shear zones appear (i.e., less strain is accommodated by visible faults). With lower strain rates, less strain is needed before localized shear zones appear (i.e., more strain is accommodated by visible faults). Fewer faults with larger displacements form with lower strain rates. It is unclear what process controls this rate-dependent behavior in wet clay.

Thin sections from extensional analog models show that: (1) clay minerals, when not faulted, are aligned horizontally, i.e., parallel to the upper and lower boundaries of the experiment; (2) clay minerals
in shear zones have a strong preferred orientation with clay minerals aligned slightly oblique to the shear-zone boundary; and (3) shear zones are discrete and extremely narrow, i.e., 30 microns wide. These observations lead us to consider the possible role of pore-pressure changes in the development of shear zones in clay models. The reorientation of clay minerals in the shear zones would produce a period of dilation and related localized decrease in pore-pressure, thereby inhibiting localized deformation. Experiments with lower strain rates would have more time to restore pore pressures in shear zones through permeable flow and, thus, promote strain localization.

We use a 2D numerical model to investigate how pore-pressure changes and permeable flow would affect fault growth in extensional models with wet clay. As in many previous numerical studies, brittle strain localization is achieved through reduction of cohesion and friction with increasing strain. In addition, an arbitrary reduction of initially high pore pressure with increasing strain suppresses localization. Permeable flow along pore-pressure gradients leads to a diffusional restoration of pore pressures with time. With these numerical material properties, we can reproduce the above-mentioned strain-rate dependency of (1) the onset of faulting and (2) the portion of extension accommodated along discrete faults. However, because our numerical shear zones are two orders of magnitude wider then the actual shear zones in wet clay, we have to use artificially high permeabilities to produce numerical results that look similar to the clay models. We propose that strain-related, dilational, pore-pressure drops in wet clay might cause the observed rate-dependent faulting.


EXPERIMENTAL MODELING OF EXTENSIONAL FAULT DOMAINS AND FAULT-DOMAIN BOUNDARIES (TRANSFER ZONES / ACCOMMODATION ZONES)

Roy W. Schlische and Martha Oliver Withjack

Fault domains, in which all or most normal faults dip in the same direction, are common in many extensional provinces. Fault-domain boundaries are zones that separate adjacent fault domains, and are variously referred to as transfer zones or accommodation zones. We have used experimental (analog) models of uniform extension to study the origin, geometry, and evolution of fault domains and their boundaries. Our models show that fault domains and their boundaries develop with both orthogonal and oblique extension and with both dry sand and wet clay as the modeling material. The size and shape of the fault domains and the number and orientation of their boundaries is highly variable, even for identical models. Generally, fault-domain boundaries are broad zones of deformation, consisting of overlapping tips of normal faults from adjacent fault domains, fault-displacement folds, and numerous small-scale normal faults. The fault-domain boundaries in our models differ significantly from those in published conceptual models of transfer zones / accommodation zones. Specifically, the fault-domain boundaries in our models are broad zones of deformation, not discrete strike-slip or oblique-slip faults; their orientations are not systematically related to the extension direction; and they can form spontaneously without any prescribed pre-existing zones of weakness.

We infer that the fault domains in our models result from the self-organized growth of fault populations in which the stress-reduction zones of large, parallel faults are less likely to overlap and
inhibit fault growth. The spatial arrangement of fault domains and their boundaries is governed by the spatial distribution and dip direction of the earliest formed large normal faults, the locations of which are, at least in part, controlled by a random distribution of flaws (nucleation points). Our models show that the presence of multiple fault domains affects the size of normal faults because the length of an individual fault cannot exceed the fault-parallel width of its fault domain. Consequently, fault lengths are more likely to be constrained as strain increases and fault domains interact. Additionally, although the fault population as a whole will show a positive relationship between fault length and displacement, the displacement-length scaling relationship may change with increasing strain. The presence of fault domains may contribute, in part, to the large scatter in length-displacement data observed for natural fault populations.


**FAULT-SURFACE CORRUGATIONS: INSIGHTS FROM SCALED EXPERIMENTAL MODELS OF EXTENSION**

**Amber B. Granger, Martha Oliver Withjack and Roy W. Schlische**

Many fault surfaces, observed in outcrop and 3D seismic data, have complex morphologies with numerous corrugations that trend parallel to the slip direction. We have used scaled experimental (analog) models with wet clay to study these features. Our models have simulated extensional deformation (i.e., normal faulting) using three common basal boundary conditions: two diverging, overlapping plates; a stretching, basal rubber sheet; and a stretching, basal layer of silicone polymer. During the experiments, we photographed the top surface of the models at regular time increments. After the experiments, we constructed structure-contour maps for several normal-fault surfaces using closely spaced (1-mm apart) serial sections. The surface photographs, showing exposed fault scarps, and the structure-contour maps, showing subsurface features, clearly demonstrate that the normal-fault surfaces in all models are corrugated at various scales. The surface photographs indicate that many of the large-scale corrugations formed during the linkage of originally separate fault segments. The origin of small-scale corrugations, however, remains enigmatic. These corrugations are subparallel to the slip direction, and are present along the entire extent of the fault surfaces. These observations suggest that the original small-scale corrugations are not tool-and-groove features because their lengths exceed the net slip. Furthermore, small, relatively isolated normal faults exhibit the same small-scale corrugations as larger normal faults.

Experimental models with two non-coaxial phases of extension provide insight into the origin of the small-scale corrugations. During the second phase of extension, many of the first-phase normal faults reactivate as oblique-slip faults. New small-scale corrugations develop on the exposed fault scarps of these reactivated faults. These new small-scale corrugations overprint the original corrugations, are less well defined than the original corrugations, and are subparallel to the new slip direction. They are not related to fault propagation and linkage because they develop on pre-existing, through-going fault surfaces. Does the same process produce the small-scale corrugations during the first and second phases of extension? We hypothesize that the small-scale corrugations are related to incremental differential slip along fault-segment surfaces, both during initial fault development and fault reactivation.

**INFLUENCE OF PRE-EXISTING FABRIC ON NORMAL-FAULT DEVELOPMENT: AN EXPERIMENTAL STUDY**

**Alissa A. Henza, Martha O. Withjack, Roy W. Schlische, Iain K. Sinclair**
Many rift basins have undergone multiple episodes of extension with differing extension directions. Do the normal faults that form during an early episode influence the development of normal faults that form during subsequent episodes? Does this influence depend on the characteristics of the early-formed faults (i.e., their number, density, length, displacement)? To address these questions, we have conducted a series of scaled experimental (analog) models with wet clay. Each model had two phases of distributed extension, and the extension directions during the first and second phases differed by 45°. Because the characteristics of the fault populations at the end of the first phase depended on the total magnitude of extension, we incrementally varied the total magnitude of the first-phase extension from 18 to 35%. As the magnitude of extension increased, the number, density, length, and displacement of the normal faults that formed during the first phase also increased. In all models, the total magnitude of extension was 35% during the second phase of extension.

The experimental models show that the characteristics of the fault populations that formed during the first phase of extension profoundly affected the fault patterns that developed during the second phase of extension. When the total magnitude of the first-phase extension was small (~18%), only a few short normal faults developed during the first phase. This poorly developed fabric associated with these first-phase faults had little influence on the subsequent deformation. Specifically, the normal faults that formed during the second phase of extension had orientations, lengths, and displacements similar to those in models without a first phase of extension. When the total magnitude of the first-phase extension was greater than ~20%, numerous large normal faults developed during the first phase, and they significantly affected the subsequent deformation. Many of the first-phase normal faults were reactivated as oblique-slip faults during the second phase of extension. Additionally, numerous new normal faults developed during the second phase of extension. The second-phase normal faults were most likely to cut the first-phase normal faults when the magnitude of the first-phase extension was small. Otherwise, most of the second-phase normal faults nucleated at the first-phase faults or terminated against them. Generally, the second-phase normal faults had anomalously short lengths compared to the first-phase faults, indicating that the presence of the first-phase faults had inhibited the propagation and growth of the second-phase faults. Interestingly, the orientations of the second-phase normal faults were both orthogonal and oblique to the direction of the second-phase extension. This suggests that the formation of the second-phase normal faults was influenced by local perturbations of the stress state associated with first-phase faults.

The model fault patterns resemble those observed on 3D seismic data from the Grand Banks (e.g., Jeanne d’Arc basin), an area hypothesized to have undergone two non-coaxial extensional phases. Thus, the models may provide templates for interpreting the fault patterns and interactions in the Grand Banks as well as other regions with multiple phases of extension.

**Geological Society of London, Rifts Renaissance: Stretching the Crust and Extending Exploration Frontiers, p. 100.**

**OBLIQUE INVERSION OF THE FUNDY RIFT BASIN ON THE PASSIVE MARGIN OF SOUTHEASTERN CANADA**

Mark S. Baum, Martha Oliver Withjack, and Roy W. Schlische

Rift-basin inversion involves a reversal in deformational style, specifically an extensional phase followed by a shortening phase. Orthogonal inversion occurs when the directions of the extension and shortening are coaxial, whereas oblique inversion occurs when the directions of the extension and shortening are non-coaxial. Our goal is to better understand the structural characteristics of oblique inversion by studying a natural example, the inverted Fundy rift basin of southeastern Canada. We have defined the 3D geometry and kinematics of inversion structures in the Fundy rift basin using seismic (offshore and onshore), field, aeromagnetic and DEM data. Of critical importance are the contrasting structural styles associated with differently oriented segments of the border-fault system. NE-striking border faults are
gently dipping, whereas ENE-striking border faults are steeply dipping at the surface but gently dipping at depth. All segments were active during Late Triassic – Early Jurassic sedimentation.

The hinges of most post-depositional, shortening-related folds parallel the major border faults. The tightest and narrowest folds occur adjacent to the most steeply dipping upper fault segments, whereas broader folds occur adjacent to the more gently dipping upper fault segments. Some of the folds are traditional anticlinal buttress folds. Others, however, consist of trains of hanging-wall anticlines and synclines and are a combination of buttress and detachment (buckle) folds, with the low-angle fault surface or evaporites acting as the detachment surface. In outcrop, the folds are bounded and/or cut by high-angle faults with mostly left-lateral strike-slip. The inversion-related deformation is, at least partially, partitioned into pure-shear and simple-shear components. The fault-parallel buttress/detachment folds accommodate the pure-shear component, whereas the left-lateral strike-slip or gently raking oblique-slip faults accommodate the simple-shear component. Thus, the buttress/detachment folds do not necessarily indicate the regional shortening direction but rather reflect the variable local shortening direction associated with the pure-shear component of the deformation. Based on kinematically compatible slip vectors on differently oriented border-fault segments and the results of experimental models of oblique inversion, the regional shortening direction during inversion of the Fundy rift basin was NNE-SSW to ENE-WSW, which is moderately oblique to sub-parallel to the passive margin. In contrast, the likely shortening direction for inverted rift basins in the southeastern United States was sub- perpendicular to the margin.

2008, Central Atlantic Conjugate Margins
THE INS AND OUTS OF BUTTRESS FOLDS: EXAMPLES FROM THE INVERTED FUNDY RIFT BASIN, NOVA SCOTIA AND NEW BRUNSWICK, CANADA

Baum, M.S., Withjack, M.O., and Schlische, R.W.

Buttress folds form in the hanging walls of non-planar normal faults during inversion. Slip occurs more easily along the lower, more gently dipping fault segments of the normal faults, whereas the upper, more steeply dipping fault segments act as buttresses, inhibiting slip and causing the hanging-wall strata to shorten and fold. Seismic and field data from the inverted Fundy rift basin, Nova Scotia and New Brunswick, Canada, show that buttress folds can have a great variety of geometries. Generally, the trends of the buttress folds parallel the trends of the adjacent normal faults. The tightest and narrowest folds occur adjacent to the most steeply dipping upper fault segments. Many buttress folds are hanging-wall anticlines; other buttress folds are trains of hanging-wall anticlines and synclines. In the latter case, the buttress folds do not affect the gently dipping, lower segment of the adjacent normal fault, indicating that a detachment level exists above the normal-fault surface. Potential detachment levels include the normal-fault surface itself and/or evaporite units in the hanging wall. Thus, many of the buttress folds in the inverted Fundy rift basin are combination buttress/detachment folds. The inversion-related deformation in the Fundy rift basin is, at least partially, partitioned into a pure-shear and simple-shear component. The fault-parallel, buttress/detachment folds accommodate the pure-shear component, whereas left-lateral strike-slip faults accommodate the simple-shear component. Thus, the buttress/detachment folds in the Fundy rift basin are biased indicators of the regional shortening direction. Their trends reflect the local shortening direction associated with the pure-shear component of deformation, not the regional (NE-SW) shortening direction.

2008 AAPG Annual Meeting
DEFORMATION DURING MULTIPLE PHASES OF EXTENSION: COMPLEX FAULT PATTERNS AND RESERVOIR COMPARTMENTALIZATION

Alissa A. Henza, Martha O. Withjack, Roy W. Schlische
Recent Abstracts

Multiple episodes of extension, commonly with different extension directions, affect many rift basins. We have used scaled experimental models with wet clay to study the fault patterns that develop during two sequential non-coaxial episodes of extension. The models show that both the angle between the two extension directions and the magnitude of the first-phase extension strongly affect fault development during the second extensional phase. In the models, fault reactivation occurs during the second extensional phase even if the angle between the two extension directions is large (i.e., 45° or greater). As the angle between the extension directions decreases, fault reactivation accommodates more deformation, and fewer and shorter normal faults form during the second extensional phase. An increase in the magnitude of the first-phase extension (and, thus, the displacement and length of the first-phase normal faults) also results in fewer and shorter normal faults during the second extensional phase. The interactions between the first-phase normal faults and the second-phase normal faults vary considerably. Newly formed normal faults cut and offset pre-existing normal faults, they emanate from the tips of pre-existing faults, and they terminate against the surfaces of pre-existing faults. Model fault patterns closely resemble fault patterns observed on 3D seismic data from the Grand Banks (Jeanne d’Arc basin) and the North Sea (Viking graben). Thus, the models may provide templates for interpreting complex fault patterns, constraining fault interactions, and estimating the magnitude of reservoir compartmentalization in regions with multiple phases of extension.

2007 GSA Annual Meeting
DEFORMATION DURING MULTIPLE PHASES OF EXTENSION: KINEMATICALLY SIMPLE, MECHANICALLY COMPLEX

Alissa A. Henza, Martha O. Withjack and Roy W. Schlische

We use scaled experimental models with two phases of extension to investigate the influence of pre-existing normal faults on subsequent normal-fault development. The models show that, although the strain states and particle-displacement paths are simple, the strain is accommodated by a complex fault pattern. The pre-existing normal faults create mechanical inhomogeneities throughout the model, influencing both the number and geometry of subsequent normal faults. The exact influence depends on the magnitude of extension during the first phase and the angle between the extension directions during the first and second phases. As the magnitude of extension during the first phase increases, fewer and shorter normal faults form during the second phase. In addition, the strike of the second phase faults differs by 10-20° from expected fault orientations and therefore are not orthogonal to the extension direction. As the angle between the extension directions during the first and second phases decreases, fewer and shorter normal faults form during the second phase and reactivation of pre-existing normal faults increases. Pre-existing faults reactivate with both a dip-slip and right lateral strike-slip component, and reactivation occurs when extensional phases are as much as 45° apart. The interactions between the pre-existing faults and new faults vary considerably. Newly formed normal faults can cut and offset pre-existing normal faults, they can emanate from the tips of pre-existing faults, and they can terminate on the surface of pre-existing faults. The modeling results suggest that map-view fault patterns do not necessarily reflect the timing, directions, and intensities of extensional episodes.

Geological Society of America Annual Meeting 2006
FOUR DAYS A WEEK: A HANDS-ON STRUCTURAL GEOLOGY COURSE EMPHASIZING SEISMIC-REFLECTION AND EXPERIMENTAL MODELING DATA

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Our 4-credit Structural Geology course (enrolling 2nd- and 3rd-year majors) meets for 80-minute periods on four consecutive days per week for 14 weeks. We make no distinction between lectures and labs, and cover topics in the order best-suited for learning, rather than for fitting into a rigid lecture / lab format. Each class session is a mixture of 1) reviews and/or quizzes; 2) brief lectures; and 3) a series of hands-on exercises. These exercises involve topics covered in most traditional courses: description and attitude of geologic structures, geologic maps and cross sections, stereographic projections, etc. In addition, many exercises involve interpretation of seismic-reflection data. Widely used in industry and academic research, these data allow students to study the geometry of structures in 3-D (vertical profiles plus “map-view” time slices) and to unravel geologic history using cross-cutting relationships, recognition of unconformities, and the presence or absence of syn-deformational units. Many exercises use the results of scaled experimental models. Students also run and analyze their own experiments involving extension, shortening, and strike-slip or oblique deformation. Students complete short exercises during class and orally report on their results; they complete other exercises for homework. In total, there are over 50 graded assignments, including four written reports on the experiments and field trips. The final exam is cumulative and open-book. Many students, accustomed to passive learning in 80-minute doses, are uncomfortable with our hands-on, interactive style, but almost all prefer it by the end of the semester. Because many of these students also take our subsequent Field Geology course, we have determined that students retain more knowledge compared to students who took earlier, more traditional versions of the course. This positive result more than compensates for the extra effort required to prepare and grade all those exercises.

**Geological Society of America Annual Meeting 2006**

**UNDULATIONS ON NORMAL-FAULT SURFACES: INSIGHT INTO FAULT GROWTH USING SCALED PHYSICAL MODELS OF EXTENSION**

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We have used scaled experimental models with wet clay to study undulations on normal-fault surfaces; similar undulations or grooves occur on many natural normal-fault surfaces. The models simulate extensional deformation using three common basal boundary conditions: overlapping plates simulate a detached normal fault, a rubber sheet simulates distributed deformation above a thin ductile layer, and a layer of putty simulates distributed deformation above a thick ductile layer. For selected faults within each model, we produced structure-contour maps of fault surfaces using closely spaced serial sections. Fault surfaces in all models have two types of undulations. Large-scale variations in fault strike are likely due to the linkage of originally separate fault segments. Small-scale undulations trend subperpendicular to fault strike, parallel to the slip direction, and are present along the entire extent of fault surfaces. The undulations are not tool-and-groove slickenlines because the length of the undulations exceeds the net slip. We observed the undulations on exposed fault scarps during the model run; thus, they are not artifacts resulting from the construction of the structure-contour maps. Many researchers ascribe the curvature of normal-fault segments in map and cross-section views primarily to lithologic variations. However, lithologic changes cannot be the cause of the undulations in our models because the clay is virtually homogenous. Additionally, fault-segment linkage cannot fully explain the small-scale undulations because a small, relatively isolated fault exhibits the same type of undulations as the larger faults. These undulations may be a result of a fundamental aspect of fault growth: the incorporation of non-coplanar, small-scale fractures onto the expanding fault surface, which has a nearly rectangular geometry (not the commonly assumed elliptical geometry) with lateral tip lines subparallel to the slip direction.
Recent Abstracts

Geological Society of America Annual Meeting 2006

SCALED EXPERIMENTAL MODELS OF EXTENSION: DRY SAND VS. WET CLAY

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For more than a century, geologists have used scaled experimental models to simulate extensional deformation. Today, dry sand and wet clay are the most common modeling materials. Three common basal boundary conditions are pre-cut blocks that simulate a dipping normal fault at depth, overlapping plates that simulate a detached normal fault at depth, and a rubber strip that simulates distributed extension at depth. We have conducted identical experiments with these three boundary conditions using sand and clay, the results of which show broad similarities and significant differences. In both sand and clay models, normal faults generally strike perpendicular to the extension direction. However, the faults are steeper and more planar in sand models than in clay models. Fault spacing and fault-zone width are greater in sand models compared to clay models. Faults rapidly propagate upward and along strike in sand models, whereas fault growth is gradual and involves more linkage in clay models. Folds (e.g., faultpropagation folds and relay ramps) are poorly developed in sand models compared to clay models. Deformation is more localized in sand models and more distributed in clay models. For example, in models with overlapping plates, visible faults accommodate 85% of the deformation in sand models, compared to 44% in clay models. In the sand models, a few major antithetic normal faults accommodate most hanging-wall deformation. Most layers, although faulted, remain flat. The effective shear angle (60 - 65°) is the same as the dip of the antithetic faults. In the identical clay models, numerous minor normal faults (antithetic and synthetic) and cataclastic flow accommodate most hanging-wall deformation. The deformed layers are faulted and folded. The effective shear angle (35 - 50°) is considerably less than the dip of the antithetic normal faults.

Geological Society of America Annual Meeting 2006

GROUNDWATER FLOW AND GROUNDWATER-STREAM INTERACTION IN FRACTURED AND DIPPING SEDIMENTARY ROCKS: INSIGHTS FROM NUMERICAL MODELS

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Groundwater flow in unconfined aquifers is influenced by topography, but in fractured and dipping sedimentary rocks, it is also influenced by structure. Field evidence indicates that groundwater is older on the down-dip side of a stream (asymmetry) and that dipaligned streams receive more baseflow than strike-aligned streams (anisotropy). We present detailed numerical models to evaluate the effects of various factors that influence groundwater flow pathways. The models simulate a small watershed drained by headwater streams and underlain by dipping strata. Groundwater flow can be characterized by three components: down the hydraulic gradient, down-dip, and along-strike. The degree of anisotropy and asymmetry depends on several factors: bedding anisotropy, efficiency of the weathered horizon, fracture depth, and bedding dip angle. Whereas anisotropy increases linearly with dip angle, asymmetry is
greatest at a threshold angle. This threshold angle is related to the mean groundwater flow direction in an equivalent homogeneous and isotropic system.


**EVOLUTION OF THE PASSIVE MARGIN OF EASTERN NORTH AMERICA: DIACHRONOUS RIFT-DRIFT TRANSITION AND INVERSION**

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Geological and geophysical data, together with the results of experimental models of basin inversion, suggest a complex tectonic evolution for the passive margin of eastern North America. Firstly, the transition from rifting to drifting was diachronous. In the southeastern United States, the rift-drift transition occurred ~200 Ma immediately before or during the development of the Central Atlantic Magmatic Province (CAMP), a large igneous province. In the northeastern United States and southeastern Canada, the rift-drift transition occurred ~185 Ma after CAMP-related magmatism and synrift deposition in Early Jurassic time and before postrift deposition in early Middle Jurassic time. Secondly, compressional activity inverted rift basins in both segments of the passive margin during or shortly after the rift-drift transition. Thus, inversion was also diachronous, occurring first in the southeastern United States and later in the northeastern United States and southeastern Canada. During inversion in the southeastern United States, many of the NE-striking rift-basin border faults were reactivated as reverse faults. New NE-striking reverse faults developed, and NW-striking CAMP-related dikes intruded the attenuated continental crust. These deformation patterns resemble those in scaled experimental models of orthogonal inversion. Thus, we infer that the southeastern United States moved orthogonally (i.e., northwest) relative to the margin of the North American craton. During inversion in the northeastern United States and southeastern Canada, NE- and E-striking rift-basin border faults were reactivated as oblique-slip faults with left-lateral and reverse components of displacement. New WNW-striking reverse faults and NNE-striking strike-slip faults formed. WNW-trending folds not directly related to pre-existing extensional faults also developed. These deformation patterns resemble those in experimental models of oblique inversion. Thus, we infer that the northeastern United States and southeastern Canada moved obliquely (i.e., north-northeast) relative to the margin of the North American craton. Ridge push and/or asthenospheric upwelling may have produced the first compressional episode in the southeastern United States. The second compressional episode in the northeastern United States and southeastern Canada is likely related to a fundamental change in plate motions.

**AAPG Annual Meeting 2005**

**EXPERIMENTAL INSIGHTS INTO THE ORIGIN, GEOMETRY, AND EVOLUTION OF DIP DOMAINS AND TRANSFER ZONES IN EXTENSIONAL PROVINCES**

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In many extensional provinces, large normal faults dip in the same direction, forming dip domains. Features named transfer faults, transfer zones, and accommodation zones (hereafter called transfer zones for brevity) separate adjacent dip domains. It is commonly assumed that transfer zones follow preexisting zones of weakness or that their orientation is systematically related to the extension direction.
Experimental modeling provides insights into the origin, geometry, and evolution of dip domains and transfer zones and raises questions about the validity of the above assumptions.

In our scaled models, a homogeneous layer of wet clay overlies a rubber sheet that is stretched orthogonally or obliquely between two rigid plates. Dip domains and transfer zones develop in all models. These dip domains and transfer zones form spontaneously without any prescribed preexisting zones of weakness. The number of dip domains as well as the number and orientation of transfer zones are variable, even for identical models. Thus, the orientation of the transfer zones is not systematically related to the extension direction. We propose that dip domains develop because early-formed faults perturb the stress field, causing new nearby faults to dip in the same direction. As extension continues, faults from adjacent dip domains propagate toward each other. Because opposite-dipping faults ultimately interfere with each other in the zone of overlap, the faults stop propagating. Numerous smaller faults then form to accommodate the strain. The transfer zones result from the alignment of small faults and partially overlapping tips of faults from the adjacent dip domains.

**AAPG Annual Meeting 2005**

**DIFFICULTIES IN IDENTIFYING SYNRIFT GROWTH BEDS**

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Growth beds constrain the timing of rifting, providing critical temporal information about trap development, source-rock maturation, and hydrocarbon migration. Synrift growth beds commonly fan or thicken toward active normal faults. Field, seismic, and experimental studies, however, show that not all synrift growth beds share this characteristic. In asymmetric rift basins bounded on one side by a low-angle fault zone (e.g., the Newark basin, the Fundy basin), most growth beds have a subtle fanning geometry. Without regional seismic lines and ample well/outcrop data, it is easy to mistake these synrift growth beds for prerift or postrift rocks. In symmetric rift basins bounded on both sides by fault zones (e.g., the Rhine graben), most growth beds do not thicken appreciably toward either boundary fault zone. The presence of salt also affects the characteristics of growth beds in rift basins. Basement-involved normal faults cannot propagate upward through thick salt. Instead, fault-propagation folds develop in the sedimentary cover in rift basins with salt (e.g., the Suez rift, Haltenbanken region of offshore Norway). Growth beds, deposited during movement on basement-involved normal faults, thin toward the crests of the folds rather than thicken toward the active, underlying faults. Postrift salt movement, triggered by differential sediment loading and/or regional tilting, creates detached normal faults in rift basins with salt (e.g., the Jeanne d’Arc basin, Orpheus graben). Without high-quality seismic data, it is easy to mistake these postrift growth beds associated with detached normal faulting for synrift growth beds associated with basement-involved normal faulting.

**AAPG Annual Meeting 2005**

**HOW DO MODES OF EXTENSION AFFECT NORMAL-FAULT GEOMETRY, DISPLACEMENT VARIATIONS AND POPULATION DYNAMICS?**

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Knowledge of normal-fault geometries, displacement variations and spatial distribution is crucial for understanding hydrocarbon trap development. We constructed three scaled experimental clay models that simulate different extensional modes: block translation with no internal deformation, block translation with internal deformation above a thin ductile layer, and block translation with internal deformation
above a thick ductile layer. The normal faults in all three extensional modes strike subperpendicular to the displacement direction and are initially segmented, with maximum displacement at segment centers and minimum displacement at segment tips. The extensional mode profoundly affects fault shape, the number of faults with depth, the displacement distribution with depth, and the style of deformation. With block translation alone, all faults form at the block edge. The main fault zone is listric, movement on which creates a rollover fold cut by antithetic faults. Fault segments are soft-linked at the surface and hard-linked at depth, the greatest number of faults occurs near the base, and fault displacement increases with depth. Deformation is similar for the other two modes of extension. Domino-style faults develop. Faults are planar, the greatest number of faults occurs near the base, and fault displacement increases and then decreases with depth. Fault displacement values approach zero near the base of the block overlying a thin ductile layer, whereas fault displacement values are finite at the base of the block overlying a thick ductile layer. Thus, with only shallow data, it would be difficult to distinguish between these two extensional modes.

**The Hydrogeology of the Newark Basin—A Regional Workshop, Rutgers University, New Brunswick, NJ, November 11-12, 2004**

**GROUNDWATER FLOW AND INTERACTION WITH STREAMS IN DIPPING SEDIMENTARY ROCKS: A MODELING STUDY**

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In this modeling exercise, we examine the anisotropy and asymmetry in groundwater flow and groundwater-stream interaction, as a result of the two competing factors that control groundwater flow: the structure of the fractures (i.e., bedding plane orientation), and the topography-stream system. The model domain is a small watershed underlain by dipping beds of contrasting permeability. These beds are explicitly modeled using Visual Modflow by Waterloo Hydrogeologic Inc. A symmetric topography-stream system drains the groundwater in the fractured media. We observed that groundwater flow tends to be deflected along the strike on their way to local streams, and that this flow anisotropy also leads to an anisotropy in groundwater-stream interaction, that is, streams aligned with the dip receives more baseflow than streams along the strike, given the same surface drainage area. In addition, we observed that, if a stream is aligned with the strike, then in general the groundwater head is higher and the age is older on the down-dip side of the stream, that is, there is a flow asymmetry on opposite side of a stream aligned with the strike. The degree of this anisotropy and asymmetry depends on several factors, among them the thickness of the weathered zone, the bed dipping angle, and the permeability contrast in along-bed and cross-bed directions. The effect of each of these factors is evaluated systematically using the 3-D numerical model. Implications to field characterization and numerical modeling are explored.

**The Hydrogeology of the Newark Basin—A Regional Workshop, Rutgers University, New Brunswick, NJ, November 11-12, 2004**

**TECTONIC HISTORY OF THE NEWARK RIFT BASIN AND THE EASTERN NORTH AMERICAN PASSIVE CONTINENTAL MARGIN**

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Field, seismic, and drill-hole data constrain the tectonic history of the Newark rift basin, which formed during continental extension preceding the diachronous (northward-younging) opening of the North Atlantic Ocean. (1) **Middle (?) to Late Triassic.** The oldest synrift deposits, which are not exposed at the surface, accumulated in a narrow basin formed by reactivation of typically low-angle Paleozoic compressional faults. These strata exhibit pronounced growth, i.e., thickening toward the border-fault system (BFS), which consisted of isolated fault segments bounding small basins or subbasins. (2) **Late Triassic.** The BFS consisted of fully linked fault segments. The Stockton through Passaic formations accumulated in a progressively widening basin (as wide or wider than the current width) and exhibit increasingly subtle growth. (3) **Early Jurassic.** Synrift strata and lava flows of the Central Atlantic Magmatic Province (CAMP) accumulated in a basin undergoing accelerated subsidence and tilting along with intrabasinal faulting. CAMP dikes strike NNE, similar to major segments of the Flemington and Hopewell intrabasinal faults; thus, extension was oblique to the generally NE-striking BFS. At least some NE-striking, high-angle-to-bedding extension fractures in the Passaic Formation were present prior to this time. (4) **Early to Middle Jurassic.** Rifting ceased, seafloor spreading started, and postrift compressional deformation (basin inversion) began. This inversion (a) produced significant uplift and erosion; (b) amplified and possibly rotated NW-trending, extensional fault-displacement folds adjacent to the BFS; (c) produced axial-planar cleavage in some buttress folds; and (d) was associated with a basin-wide hydrothermal event that produced a synfolding paleomagnetic overprint. Basin inversion likely produced additional tilting of synrift strata, bedding-subparallel extension fractures, and N- to NE-striking strike-slip faults. The shortening direction is difficult to constrain because of bias from preexisting extensional structures. However, scaled physical modeling suggests that the shortening direction was oriented N-S to NNE-SSW, consistent with the attitude of some postrift structures.

**AAPG Annual Meeting 2004**

**OBLIQUE SHORTENING FOLLOWING OBLIQUE EXTENSION: AN EXPERIMENTAL STUDY OF THEIR RELATIVE INFLUENCE ON THE GEOMETRY OF INVERSION STRUCTURES**

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Inversion structures result from two phases of deformation: an extensional phase and an ensuing shortening phase. We conducted a series of scaled experimental models in which we independently varied the obliquity for both stages of deformation. In our models, a layer of wet clay covered two overlapping metal plates: one fixed and one mobile. The edge of the fixed plate represents a preexisting zone of weakness. The angles between the displacement direction of the mobile plate and the edge of the fixed plate for the extensional phase and the shortening phase are $\alpha_e$ and $\alpha_s$, respectively.

Our work shows that the degree of obliquity during both tectonic episodes influences the final deformation pattern. Obliquity during the extensional phase produces a fault zone that parallels the preexisting zone of weakness, with secondary normal faults subperpendicular to the displacement direction. All major through-going faults reactivate during inversion. Secondary normal faults striking obliquely to the major fault zone show varying degrees of reactivation, depending on their orientation relative to $\alpha_e$. For any initial $\alpha_e$, deformation patterns are similar for all $\alpha_s > 45^\circ$: new large-scale folds and thrust faults form subparallel to the preexisting zone of weakness. For all $\alpha_s < 30^\circ$, no new large-scale folds and few new thrust faults form. Instead, strike-slip faults develop subparallel to the preexisting zone of weakness. We conclude that the inversion deformation pattern is more sensitive to variations in $\alpha_e$ than to variations in $\alpha_s$. The modeling results resemble deformation patterns in inverted rift basins of eastern North America.
AGU Fall Meeting 2003

CONTROLS ON THE GROWTH AND MAXIMUM SIZE OF FAULT ARRAYS AND FAULT SEGMENTS--INSIGHTS FROM EXPERIMENTAL CLAY MODELS

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We have used a series of scaled experimental models with clay to study the nucleation, growth and linkage of fault arrays and their constituent fault segments. We have varied the clay thickness and the magnitude, rate, width, and obliquity of deformation. We have also varied the basal boundary conditions: 1) focussed deformation associated with the edges of moving metal plates or metal blocks, simulating the effects of fault reactivation on a cover sequence, and 2) deformation above a rubber sheet, simulating distributed deformation. For small amounts of strain, the lengths of fault arrays and segments increase with increasing deformation and increase with decreasing deformation rate. Most fault arrays and segments ultimately achieve a 'maximum' length. This length depends on mechanical-layer thickness (increasing as thickness increases), deformation-zone width (increasing as width increases), and obliquity (decreasing as obliquity increases). Mechanical-layer thickness and deformation-zone width have an especially strong influence on the 'maximum' length of fault segments.

The length of the fault array that develops during fault reactivation is strongly controlled by the length of the underlying reactivated fault, whereas the length of the constituent fault segments is controlled by the factors discussed above. Although a hard-linked fault array ultimately develops from these segments (given enough displacement on the reactivated fault), evidence of the location of former segment boundaries is long-lived. This evidence includes breached relay ramps, fault-displacement folds, and fault strands. The persistence of these features decreases with increasing displacement on the reactivated fault, decreasing thickness of the cover sequence, and decreasing obliquity.

As most fault populations have a 'maximum' length, we expect that power-law size distributions will be uncommon. Our experimental models indicate that an exponential size distribution describes most fault populations. An exception is fault populations that form during orthogonal deformation at low strains. At higher strains, these fault populations also exhibit an exponential size distribution, with a power-law to exponential transition occurring at higher strains in thicker mechanical layers. As the maximum length of faults is limited in the experimental models, we expect that the scaling law between length and displacement will change with increasing strain. This may contribute to the large scatter in experimental and natural length-displacement data.

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CONTROLS OF STRUCTURAL GEOMETRIES ASSOCIATED WITH RIFT-BASIN INVERSION

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Rift-basin inversion occurs during a post-extension episode of shortening and can affect the hydrocarbon potential of rift basins by creating late-stage structural traps. Therefore, it is important to understand the development of inversion structures, specifically how the preexisting extensional fault system influenced their formation. The Mesozoic Fundy rift basin in Maritime Canada is part of the eastern North American
rift system and presents an excellent opportunity to study inversion structures in both the subsurface and in outcrop. Observed inversion structures include normal faults reactivated as reverse faults, fault-bend and detached compressional folds, and folds associated with restraining bends. Seismic data indicate that inversion-related folds post-date the youngest synrift sediments. The seismic data also show that most inversion-related folds are fault-bend folds that trend subparallel to the preexisting border faults. In addition, the folds are broader where associated with lower-angle faults and tighter where associated with higher-angle faults. Therefore, most inversion-related fold geometries are not indicative of the far-field state of stress during shortening, but rather are controlled by the preexisting extensional fault geometries. However, the geometries of detachment folds and folds associated with fortuitously oriented restraining bends in the border fault system likely reflect the state of stress during shortening and suggest that, in the Fundy basin, maximum horizontal compression was oriented NE-SW. Field evidence supporting this shortening direction includes East-striking sinistral-reverse-oblique faults and NW-trending folds. NE-SW shortening is also consistent with structural analyses by other workers and the current state of stress in eastern North America.

**AAPG Annual Meeting 2003**

**RIFT-BASIN INVERSION: EVIDENCE FROM SMALL-SCALE STRUCTURES**

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Geologists have recognized evidence of rift-basin inversion from seismic and outcrop studies worldwide (e.g., northwest shelf of Australia, northeastern Europe, offshore Brazil, eastern North America, and Morocco). Rift-basin inversion can be difficult to identify because many inversion structures are subtle, even with large amounts of shortening. Furthermore, widespread erosion caused by uplift associated with basin inversion may remove evidence of inversion. Our work shows that the structural geometry and spatial distribution of small-scale structures may provide critical information about the tectonic evolution of a rift basin, including basin inversion. Data collection and analysis of small-scale structures from ten field areas in the Fundy rift basin of Maritime Canada provide strong evidence of a common extensional history. Structures studied in the field include faults and slickenlines, deformation bands, calcite veins, and folds. Structures in syn-rift strata along the NE-trending, low-angle, dip-slip faulted margin of the northwestern Fundy basin; the E-trending, variable angle, oblique-slip faulted margin of the northern Fundy basin; and the hinged margin of the southern Fundy basin all indicate NW-SE extension during Mesozoic rifting. Anomalous orientations of bedding, fault, and slickenline orientations along the E-trending faulted margin, however, indicate a second episode of deformation after rifting. Evidence includes steep to overturned beds, tight folds, rotated bedding and fault populations, faults with reverse separation, cross-cutting relationships, and overprinted slickenlines. We interpret these features as products of an episode of NE-SW shortening that affected the Fundy rift basin sometime after deposition of the youngest syn-rift strata.

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**EFFECT OF DEFORMATION RATE ON FAULT POPULATIONS**

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We used scaled clay models to investigate how deformation rate affects the geometry, size, and spacing of faults. In the models, a layer of wet clay covered a rectangular latex sheet. Displacing one of the long edges of the latex sheet deformed the sheet and the overlying clay layer. We varied the angle (alpha) between the deformed-zone trend and the displacement direction in 15-degree increments from 90 degrees (regional orthogonal extension) to 0 degrees (regional shearing). Independently, we varied the displacement rate from 3 to 36 cm/hr. For all alpha angles, as the displacement rate increased, the number of faults cutting the top surface of the clay generally increased, the maximum displacement on these faults generally decreased, and the fault spacing generally decreased. Regardless of displacement rate, normal faults developed in models with alpha greater than 30 degrees, and two sets of oblique-to-strike-slip faults developed in the other models. In these latter models where two sets of faults developed, one set of faults was subparallel to and had the same sense of shear as the deformed zone, and the other set of faults was at a high angle to and had the opposite sense of shear as the deformed zone. For alpha angles of 30 degrees and less, the displacement rate also affected the geometry of the faults. Specifically, oblique-to-strike-slip faults that were subparallel to and had the same sense of shear as the deformed zone became more dominant as the deformation rate increased.

The modeling results, if applicable to nature, suggest that deformation rate affects fault-population characteristics. In the Triassic Danville rift basin of eastern North America, lacustrine strata contain two populations of normal faults. Set 1 consists of widely spaced meter-scale faults; Set 2 consists of much more closely spaced centimeter-scale faults. Set 2 faults are ubiquitous except for the stress-reduction zones surrounding Set 1 faults. Thus, Set 2 faults formed after Set 1 faults. Because both sets of faults cut the same rocks and formed after lithification but before tilting, we infer that the deformation rate was lower for Set 1 faults and higher for Set 2 faults.

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THREE-DIMENSIONAL STRUCTURAL ANALYSIS OF A POPULATION OF NORMAL FAULTS IN A SCALED PHYSICAL MODEL

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We used map-view photographs and serial cross sections spaced 1 mm apart to study the 3D geometry of normal faults in a scaled clay model. In the models, a 4-cm-thick layer of wet clay (consisting of colored sublayers) covered a rectangular latex sheet. Displacing one of the long edges of the latex sheet deformed the sheet and the overlying clay layer. After displacement of 2.5 cm, the clay thinned to ~3.6 cm. The deformation produced a population of normal faults with dip-slip slickenlines; the strike of these faults was subperpendicular to the displacement direction. Photographs of the top surface of the clay taken during deformation showed the nucleation, propagation, and linkage of the faults to produce segmented fault systems in which displacement varied considerably along strike. Offsets of the colored sublayers in cross-sectional view allowed us to recognize faults and to measure their displacements. The faults exhibit conjugate dip directions with dip angles averaging 68 degrees. The number of faults within the model generally increases with depth, and the distance between faults generally decreases with depth. The average displacement of the faults also generally decreases with depth. The base of the clay appears unfaulted, yet probably consists of many very small faults whose offsets are smaller than our detection ability. We analyzed the fault-surface geometry and displacement geometry of two faults in detail. Both fault surfaces are irregular, curving in three dimensions, which is consistent with the complex trace of faults cutting the top of the clay. For the small, relatively isolated fault, maximum displacement occurs near the center of the fault and decreases toward the fault tips; contours of fault displacement are approximately elliptical. The larger, more complex fault has three displacement maxima with intervening minima. Fault-segment linkage likely explains the complex displacement geometry. The areas of higher
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displacement could be the centers of originally smaller, isolated faults that linked together, and the areas of lower displacement could be fault-segment boundaries.

**Geological Society of America Annual Meeting 2002**

**EVOLUTION OF RIFT BASINS: NEWARK RIFT BASIN, EASTERN NORTH AMERICA**

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We have interpreted and restored seismic line NB-1 through the Newark rift basin of eastern North America. Our seismic interpretation, together with well and field data, show that the rift basin is asymmetric, bordered on the northwest by a low-angle, SE-dipping normal-fault zone. Our restoration suggests that the rift basin experienced several distinct stages of development: rift-basin initiation (Stage 1), widening (Stage 2), and dissection (Stage 3). During Stage 1 (Late Triassic), regional NW-SE extension reactivated a pre-existing contractional fabric to form the low-angle border-fault zone. During Stage 1, the embryonic rift basin was relatively narrow, and the synrift strata noticeably thickened toward the border-fault zone. Displacement on the border-fault zone exceeded 4 km. During Stage 2 (Late Triassic), the rift basin became much wider, and the synrift strata gradually thickened toward the border-fault zone. Without a regional perspective, these synrift strata can be mistaken for postrift strata because of their gradual thickening toward the border-fault zone (i.e., their lack of growth). During Stage 2, displacement on the border-fault zone exceeded 11 km. During Stage 3 (Early Jurassic), several kilometers of additional synrift strata and volcanics filled the rift basin, deeply burying and compacting the older synrift strata. Displacement on the border-fault zone exceeded 22 km. Several large intrabasin normal faults dissected the rift basin during Stage 3. Stage 4 occurred either during the final stages of rifting or after rifting. During Stage 4, the synrift strata were tilted 10 to 15 degrees toward the border-fault zone. Considerable uplift led to the erosion and removal of about 5 km of section. It is unclear whether synrift extension and/or postrift shortening produced the deformation associated with Stage 4.

**Geological Society of America Annual Meeting 2001**

**RIFTING, DRIFTING, MAGMATIC ACTIVITY, AND BASIN INVERSION ON THE PASSIVE MARGIN OF EASTERN NORTH AMERICA**

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The tectonic development of the passive margin of eastern North America between the Carolina trough and Scotian basin was considerably more complex than the classical two-stage, rift-drift model. Firstly, the transition from rifting to drifting was diachronous. In the southeastern United States, the rift-drift transition occurred after Late Triassic synrift deposition and before CAMP (Central Atlantic Magmatic Province) magmatism in earliest Jurassic time (~200 Ma). In maritime Canada, the rift-drift transition occurred after CAMP magmatism and synrift deposition in Early Jurassic time and before postrift deposition in early Middle Jurassic time (~185 Ma). Secondly, on both the southern and northern segments of the margin, the deformational regime changed substantially after rifting. Generally, NW-SE postrift shortening replaced NW-SE synrift extension. NE-striking reverse faults formed, and many of the rift-basin boundary faults had reverse displacements (inversion). In the southeastern United States, the
change in the deformational regime occurred in Late Triassic/Early Jurassic time during the rift-drift transition. Simultaneously, diabase sills and dikes, many striking perpendicular to the trend of the rift basins, intruded the attenuated continental crust, and a massive wedge of presumed volcanic or volcaniclastic rocks developed near the continent-ocean boundary. In maritime Canada, the change in the deformational regime occurred during or after Early Jurassic time and before or during Early Cretaceous time (i.e., during the rift-drift transition and/or early stages of seafloor spreading).

**AAPG Annual Meeting 2001**

**STYLES OF SECONDARY FAULTING AND FOLDING ASSOCIATED WITH OBLIQUE DEFORMATION**

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We used scaled experimental models to investigate two styles of oblique deformation. In the models, a cover sequence composed of wet clay overlies either a basement-involved, oblique-slip normal fault or a detached, oblique-slip normal fault. We also compared our results with published results from experiments with a cover sequence composed of dry sand.

The modeling results demonstrate that three styles of deformation can develop within the cover sequence above an oblique-slip normal fault. With partitioned deformation, dip-slip and strike-slip faults strike subparallel to the strike of the master fault. With focused deformation, oblique-slip faults strike subparallel to the strike of the master fault. With distributed deformation, an extensional forced fold develops above and parallel to the master fault. Numerous secondary normal faults cut the forced fold and strike obliquely to the master-fault strike. Distributed deformation gives way to focused or partitioned deformation as the displacement on the master fault increases, as the depth within the cover sequence increases, and as the thickness of the cover sequence decreases. With a basement-involved fault, the regional level of beds within the cover sequence changes across the master fault. With a detached fault, the regional level drops locally within an asymmetric graben above the master fault. Other notable modeling results include: 1) A single episode of oblique-slip faulting can produce two distinct fault populations with somewhat different trends and ages. 2) Fault patterns vary significantly with depth. Secondary faults become less oblique to the master-fault trend with increasing depth in the cover sequence.

**AAPG Annual Meeting 2001**

**STRUCTURAL STYLES OF RIFT BASINS**

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The structural geometries of rift basins vary significantly, depending on the mechanical behavior of the prerift and synrift packages, the tectonic activity before and after rifting, and the obliquity of rifting. The following rift-basin classification is based on these factors. Type 1 basins have salt or thick shale in the prerift or synrift packages. They are characterized by forced folds above basement-involved normal faults, diapiric structures, and detached normal faults and associated fault-bend folds. In Type 2 basins, one or more major contractional events preceded rifting. Many of the normal faults in Type 2 basins are reactivated basement-involved thrust faults. These faults are commonly low angle. In Type 3 basins, one or more contractional events followed rifting. These inverted rift basins are affected by late-formed contractional structures including normal faults reactivated as reverse faults, newly formed reverse faults, and contractional fault-bend and fault-propagation folds. Type 4 basins are produced by oblique rifting. They are characterized by faults with strike-slip, normal, and oblique-slip displacement and with multiple
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trends (i.e., parallel and oblique to the rift trend). The eastern Vøring basin is a Type 1 basin; the Fundy rift basin is a composite Type 2/Type 3 basin; and the Dampier rift basin is a composite Type 1/Type 4 basin. Rift-basin type strongly affects petroleum potential. The timing and geometry of potential structural traps differ for the rift-basin types. Also, the distinct structural geometries in the rift-basin types influence depositional patterns and, thus, the distribution of potential reservoir and source rocks.

Geological Society of America Northeast Section Meeting 2000
NORMAL FAULT POPULATIONS AND SCALING LAWS: AN OVERVIEW

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In the last 15 years, the field of fault-population studies has experienced remarkable growth. This presentation will review key aspects of fault population research and highlight some unresolved issues and opportunities for further research.

The scaling law for fault length (L) and displacement (D) is of the form D=\(cL^n\), where \(n\) is the scaling exponent and \(c\) is related to tectonic setting and rock properties. Although some datasets show linear scaling (\(n=1\)) over a large scale range, non-linear scaling may arise as a result of fault linkage or mechanical layer effects. Objective statistical criteria for distinguishing between linear and non-linear scaling still need to be developed.

Fault size in continental settings is widely considered or assumed to follow a power-law distribution, but few studies have demonstrated self-similar distributions over a large scale range. Sampling dimension and the type of data collected profoundly affect the power-law exponent, as does fault linkage. The thickness of the seismogenic layer (the largest mechanical layer) imposes an upper limit on fault displacements and hence lengths, resulting in departures from power-law scaling for large faults. Experimental models of orthogonal extension show that power-law scaling gives way to exponential scaling with increasing strain; the transition occurs at higher strains for thicker mechanical layers. Fault populations in experimental models of oblique extension show mainly exponential distributions, possibly because the oblique rift zone limits the maximum length of faults. Faults at oceanic spreading centers follow an exponential distribution. These deviations from power-law scaling suggest that extrapolations from the sampled population to larger or smaller scales using a power law can be problematic.

Fault populations exhibit both spatial clustering and anticlustering related to stress enhancement and reduction zones, respectively, surrounding normal faults. Spatial clustering occurs near fault tips and in zones of fault linkage. Determining the scaling laws for the spatial distribution of faults has lagged behind the formulation of scaling laws related to fault size distribution and length-displacement relationships.