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June 4, 2001

U.S. Nuclear Regulatory Commission
ATTN: Mrs. Deborah A. DeMarco
Office of Nuclear Material Safety and Safeguards
TWFN Mail Stop 8 A23
Washington, DC 20555

Subject: Submittal of Posters: (1) Synthetic Layer Dip Adjacent to Normal Faults, and (2) Influence of Fault Geometry on Reservoir Connectivity

Dear Mrs. DeMarco:

Attached are two posters for presentation at the American Association of Petroleum Geologists (AAPG) 2001 National Meeting. These posters describe work performed for the Japan National Oil Corporation. The work described did not use any NRC funds, and the posters are sent for information only.

Let me take this opportunity to point out how these work for other projects benefit NRC. The first poster, Synthetic Layer Dip Adjacent to Normal Faults, describes and characterizes five models that provide a basis for interpreting the synthetic dip panel that shows up in the Day et al., cross sections through Solatario Canyon fault system. Also, the fault block impingement and contraction faulting mechanism may explain the four contractional faults mapped in the Yucca Mountain normal fault system. In summary, this work provided additional ideas regarding faulting at Yucca Mountain that could not have been obtained exclusively at Yucca Mountain without significant additional expense.

The results described in the second poster, Influence of Fault Geometry on Reservoir Connectivity, are not as directly applicable to current NRC work except that they provide a broader base to consider structural control of hydrologic flow.

In addition, both posters provide an opportunity to receive peer comments on the work and resulting understandings of the origin and significance of geologic structures. This work and its presentation also enhances the reputation and credibility of the CNWRA staff and, thereby, their usefulness to NRC.

If you have any questions please contact Dr. David Ferrill at 210-522-6082 or me at 210-522-5252.

Sincerely,

Budhi Sagar
Technical Director

BS/rae
Attachment
cc: J. Linehan, W. Reamer, B. Leslie, E. Whitt, B. Meehan, J. Greeves, J. Piccone, S. Wastler, T. Essig, P. Justus, W. Patrick, CNWRA Dirs/EMs, D. Ferrill, D. Sims, D. Waiting, T. Nagy (SwRI Contracts)

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SYNTHETIC LAYER DIP ADJACENT TO NORMAL FAULTS

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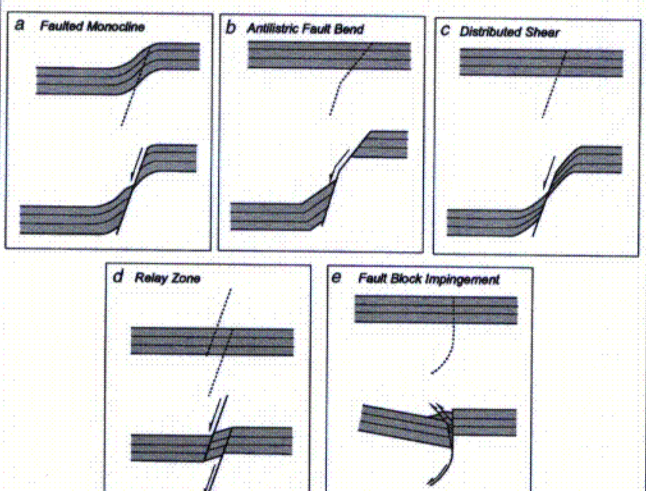
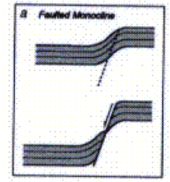
Abstract

Field and analog modeling studies of normal faulting illustrate the importance of synthetic layer dip associated with normal faults. These synthetic dip panels are developed where layers on upthrown, downthrown, or both sides of a normal fault dip in the same direction as the fault. Synthetic dip panels adjacent to normal faults should be expected at some scale in all normal fault systems. In addition to faults developed in strata with a regional dip, five fault-related mechanisms for the development of synthetic dip are: faulted monocline, antilistric fault bend, distributed shear, shear in overlap between vertically or laterally segmented faults (i.e., relay zone), and fault block impingement and contraction. Development of synthetic dip accommodates a component of throw by tilting or folding, thereby reducing the offset or true displacement on the related normal faults. Fault block deformation is strongly dependent on the mechanisms that produce synthetic dip panels, and may influence fault zone and fault block permeability. Depending on stratigraphic and structural relationships, synthetic dip panels can produce downthrown closure for hydrocarbon trapping, provide fluid migration and/or production communication pathways across faults, or produce barriers to fluid communication across faults.

Mechanisms for development of synthetic layer dip adjacent to normal faults



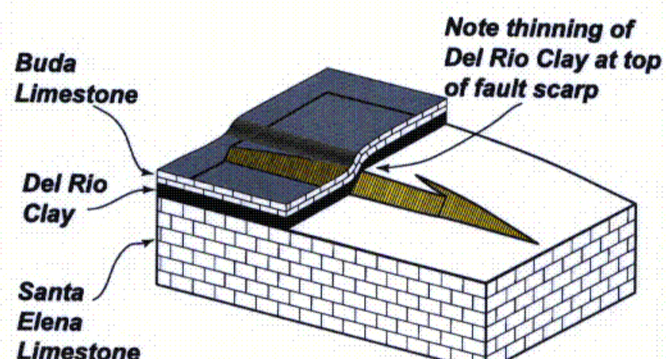
Example 1: Big Brushy Canyon Monocline, Sierra Del Carmen, Texas

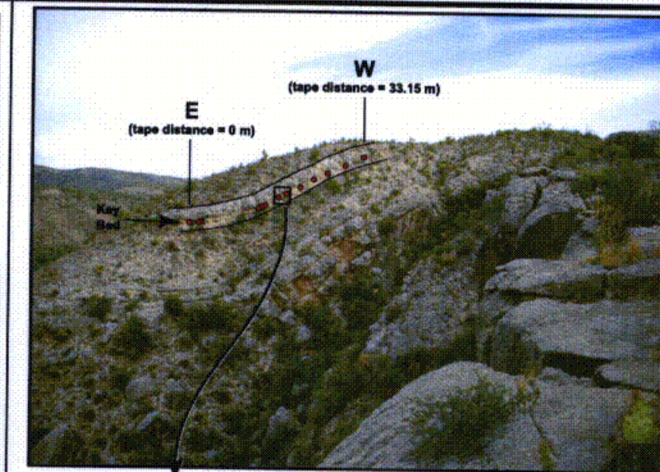


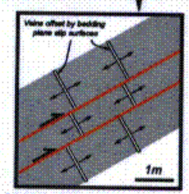
Influence of stratigraphy on structural style:

- *Fault displacement in massive Santa Elena Limestone is damped by the overlying Del Rio Clay.*

- *Displacement at the Buda Limestone level is accommodated by formation of a monocline.*







MESOSTRUCTURAL ANALYSIS OF BUDA LIMESTONE IN MONOCLINE:

Layer Extension:

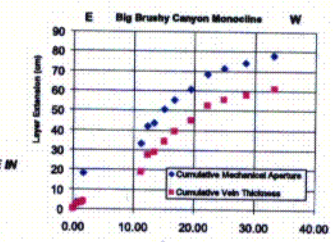
Formation of 0.5 - 15 cm-thick, layer-perpendicular coarse calcite veins accommodated 2% extension parallel to layering (in dip direction). Dilation along vein margins accommodated an additional 0.5% layer-parallel extension.

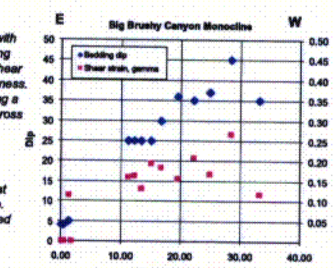
Bedding Plane Slip:

Bedding plane slip occurred with a consistent slip sense, with top moving in up-dip direction. Slip along individual bedding planes offset veins as much as 63 cm. Bedding-parallel shear strain (gamma) = total bedding-plane slip / total layer thickness. Shear strain measurements were made at 14 stations along a single limestone layer in the Buda Limestone exposed in cross section.

Timing Relationships:

Deformation of veins adjacent to slip surfaces indicates that veins were present early with respect to bedding-plane slip. Localized development of unfilled fracture voids, and unfilled aperture development along offset vein segment margins suggests that layer-parallel extension may have continued during bedding plane slip. Relationship of greatest layer extension and shear to steepest dips in monocline limb indicates that layer extension and shear are directly related to monocline formation. Patterns in graphs show less change in layer extension with distance and smaller shear strain at lower dips, suggesting that deformation is localized in monocline limb.





C01

SYNTHETIC LAYER DIP ADJACENT TO NORMAL FAULTS

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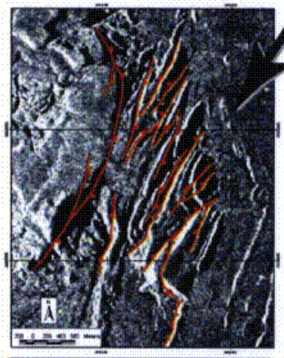
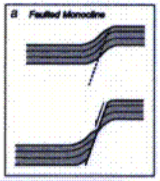
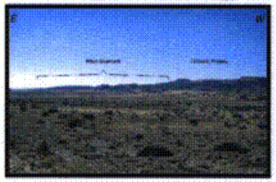
Example 2: Mesa Quebrada, western Rio Grande Rift, New Mexico





Stratigraphic Control: Faulting in the Dakota Sandstone above very weak shale of the Morrison Formation.

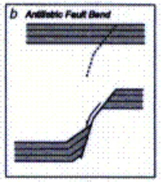


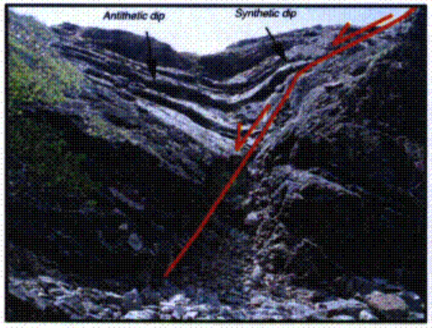
Strata dip consistently to east, faults cutting Dakota Sandstone in monocline dip both east and west.

Predominance of west-dipping faults in monocline indicates that monocline faulting is not simply accommodated distributed down-to-the-basin faulting, but is instead accommodating bending strain above Morrison Formation shale, which decouples deformation in Dakota Sandstone from

Mesa Quebrada, which means "broken mesa" is along the western margin of the Rio Puerco fault system west of Albuquerque, New Mexico. The Rio Puerco fault system is a down-to-the-east fault system located along the boundary between the Colorado Plateau to the west, and the N-S trending Rio Grande Rift to the east.

Example 3: Galera Point, Trinidad



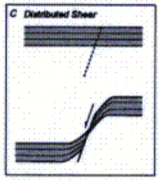


Fault geometry control: Slip on normal fault with antilistric bend.

Galera Point, northeasternmost Trinidad. Normal fault cuts a massive coarse-grained sandstone layer overlain by thinly bedded interlayered sandstone and shale. Although hanging wall dip is primarily toward (antithetic to) the normal fault, the interbedded sandstone and shale layers locally dip in the same direction as the fault.

Example 4: Cedar Pocket, Arizona

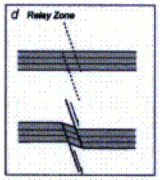
Normal faults in road cut along Interstate 15 in the northeastern corner of Arizona. Light-blue lines show enveloping surfaces through fault system. Note that steepening of lower enveloping surface is accomplished by slip on a swarm of small-displacement faults shown in detail in bottom photograph.

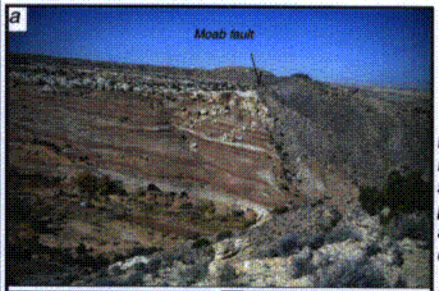


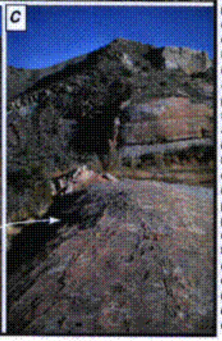
Distributed shear produces envelope dip that is synthetic to overall fault dip.

Distributed shear is accomplished by slip on discrete faults at more than one scale.

Example 5: Moab Fault, Bartlett Wash, Utah



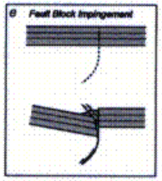




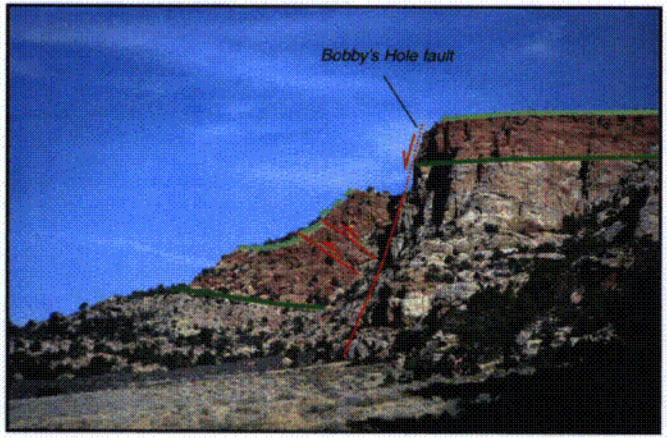
Fault geometry control: Relay zone in vertically segmented fault produces dip changes to accomplish displacement transfer.

(a) View to west showing Moab fault at Bartlett Wash. Hanging wall strata consist of Brush Basin Member of the Morrison Formation, footwall is Moab Tongue Member of the Entrada Sandstone. (b) Annotated photograph of footwall of fault shown in (a). Note person for scale. Synthetic dip panels in footwall of Moab fault rest above upwardly tipping fault segments. (c) System of deformation bands in footwall of Moab fault is visible in foreground of photo [view is to the east, area of photo is shown in (b)]. System is dominated by deformation bands that are synthetic to the main fault and accommodate synthetic dip development. However, antithetic bands are also common and mutually cross cut synthetic deformation bands.

Example 6: Bobby's Hole fault, Utah



The Bobby's Hole fault is a nearly vertical, northwest dipping normal fault in the southeastern part of the Grabens area, south of Canyonlands National Park. Hanging wall strata dip gently southeastward, toward the Bobby's Hole fault. In a sandstone knob in the hanging wall of the fault, layering adjacent to the fault dips to the northwest, synthetic to the Bobby's Hole fault. A red sandstone layer at this location is thickened and laterally contracted by two reverse faults. The contractional faults have moderate dips, antithetic to the Bobby's Hole fault.



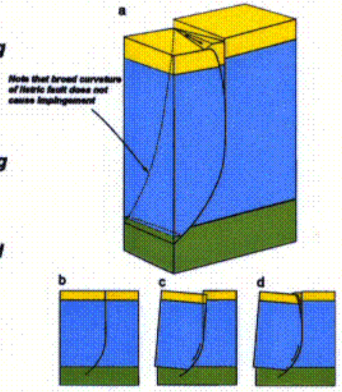
Fault geometry control: Fault block impingement and contraction faulting in normal fault hanging wall.

Steep fault at ground surface.

Predominant antithetic dip of hanging wall strata indicates listric fault geometry.

Synthetic dip panel locally developed in uppermost hanging wall strata - restricted to hanging wall.

Synthetic dip panel contains reverse faults that are antithetic to the Bobby's Hole fault.



C02

SYNTHETIC LAYER DIP ADJACENT TO NORMAL FAULTS

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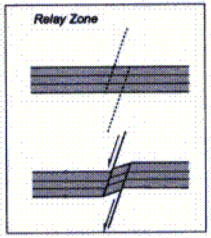
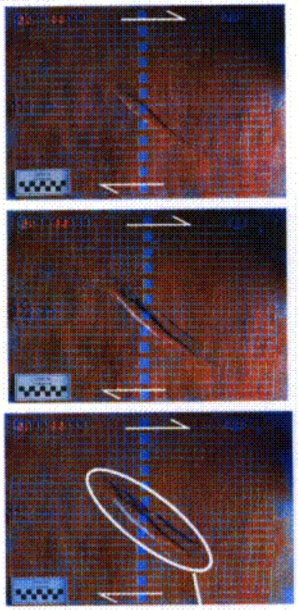
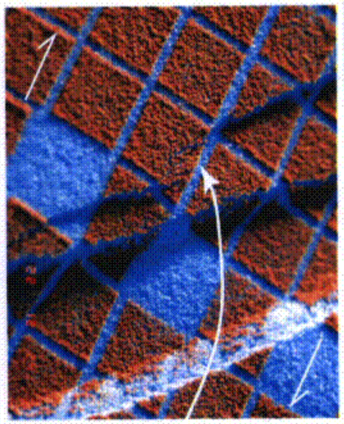
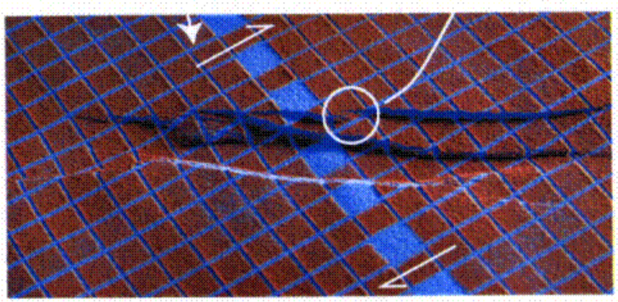
[3]Technology Research Center, Japan National Oil Corporation, Mihamaku, Chiba, 261-0025, Japan

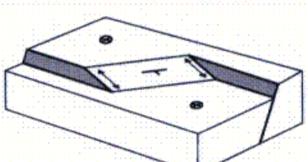
Example 7: Sandbox Model of Pull-Apart Basin Development











Displacement transfer between two underlapping faults produces obliquely dipping panel (relay ramp) that accommodates fault throw in underlapping region.

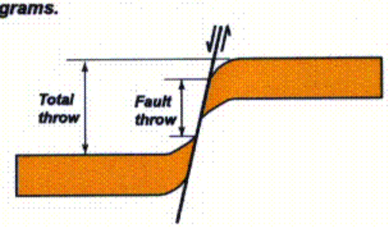
Importance of Synthetic Dip Panels for Hydrocarbon Movement and Accumulation

The following characteristics apply to all five mechanisms (a through e) of synthetic dip panel development :

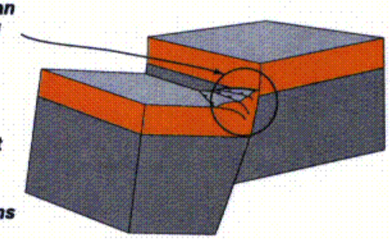
1. Total throw includes both folding and faulting components - fault throw may under-represent total throw.

2. Seismic data may image total throw rather than actual fault throw, especially on small-displacement faults.

3. Synthetic dip panels show up as displacement minima on distance-displacement diagrams.

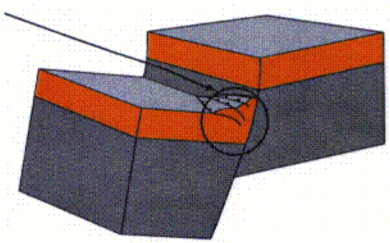


4. Reservoir communication across faults may be better than expected based on interpreted total displacement.



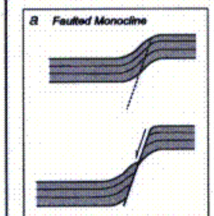
Fault block impingement and hanging wall contraction mechanism is shown here, but same geometric relationships influence trapping and migration for other mechanisms of synthetic dip panel development.

5. Downthrown synthetic dip panels are potential trapping locations.



6. Locally intense deformation in synthetic dip panels formed by all mechanisms may strongly influence reservoir quality. Specific effects on reservoir quality depend on rock type and deformation conditions.

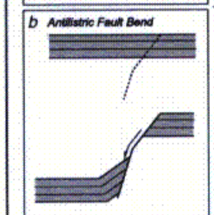
Summary



Stratigraphically controlled - presence of relatively thick weak mechanical layer.

Folding before faulting.

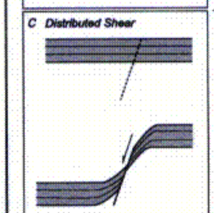
Synthetic dip panel contains distributed folding-related deformation features.



Fault-geometry controlled - associated with antilistric (downward steepening) fault.

Fault shape may be stratigraphically controlled - failure angle controlled by mechanical layering.

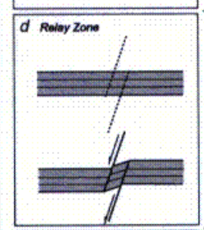
Folding during faulting.



Structurally or stratigraphically controlled.

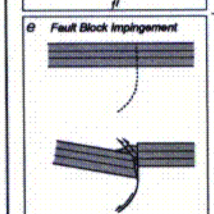
Folding before or during faulting.

Common in zones of displacement transfer between fault segments.



Displacement transfer between fault segments.

Folding during faulting.



Fault-geometry controlled - associated with rigid fault block above listric (upward steepening) fault.

Listric fault with long straight segment and relatively small radius of curvature.

This work was funded by the Japan National Oil Corporation. We thank Uko Suzuki, Rasoul Sorkhabi, Daichi Sato, and Kiyofumi Suzuki for their contributions to project planning, coordination, and field work. We thank Larry McKague and Wes Patrick for their technical reviews of this presentation.

C03

INFLUENCE OF FAULT GEOMETRY ON RESERVOIR CONNECTIVITY

Darrell W. Sims[1], David A. Ferrill[1], Alan P. Morris[2], Michael Ferguson[1], and Rasoul Sorkhabi[3]
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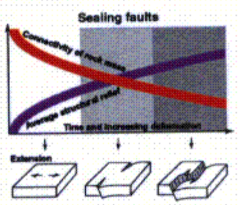
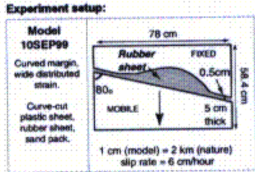
Abstract:

Sandbox analog modeling experiments provide new insights into the effects of structural geometry on reservoir connectivity. Progressive deformation of the models indicates that the potential for hydrocarbon trapping and compartmentalization increases and that the potential for reservoir communication decreases as fault systems mature. For example, experiments of distributed extension (deformation over a rubber sheet) demonstrate that geometrically simple faults nucleate at a large number of sites throughout the deforming region. Initially, relay ramps and forced folds over blind faults form potential hydrocarbon pathways. As deformation proceeds, structural relief increases and potential reservoir communication pathways are severed as faults merge by lateral and upward propagation or ramp breaching. This structural evolution progressively creates more opportunities for trapping and compartmentalization, and results in decreased reservoir connectivity. The experiments demonstrate that this geometric evolution occurs at many scales. Large-displacement faults show clear, large-scale examples of this geometric maturation of potential hydrocarbon communication pathways (e.g., relay structures) into potential hydrocarbon traps (e.g., breached relay ramps or faults merged by lateral propagation). In the models, these same processes also occur within the deformed region at smaller scales. Analog models of contractional and strike-slip deformation exhibit similar relationships between degree of structural development and reservoir connectivity.

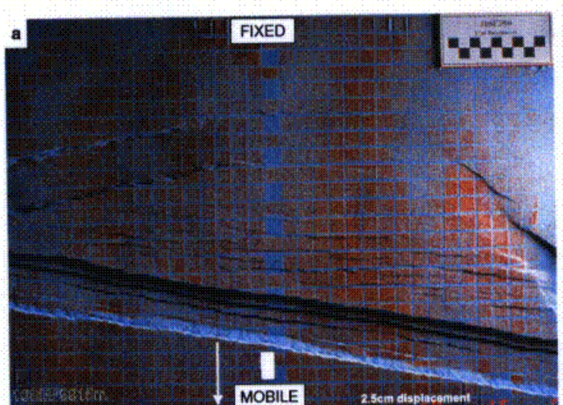
Extension:



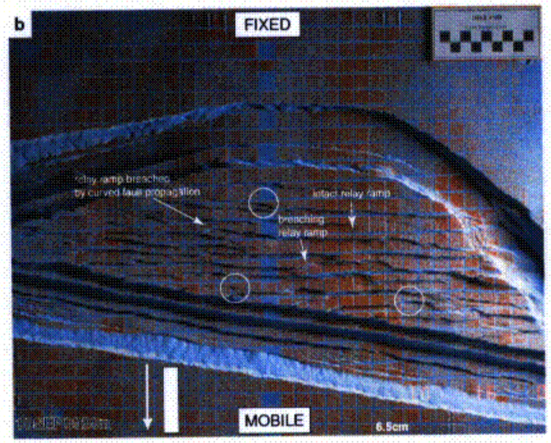
Experiment setup:



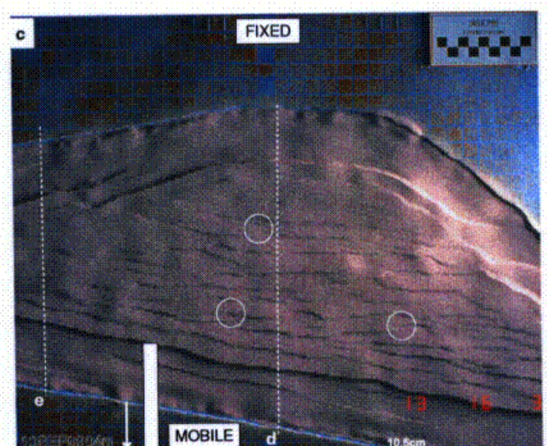
Not all faults seal: While the examples shown are interpreted for the case of sealing faults, the geometric progression as described can be applied to both sealing or leaking faults.



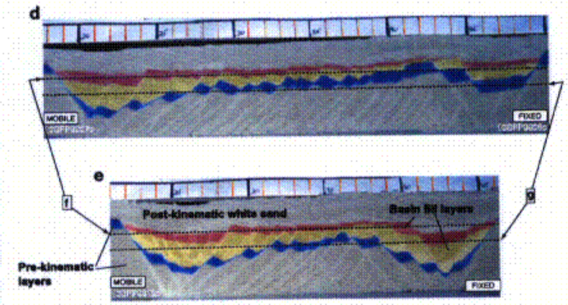
1) Faults form by linking of initially separate fault segments.
2) Relay ramps and monoclines serve as potential hydrocarbon communication pathways across the basin and across basin-bounding faults in some locations.



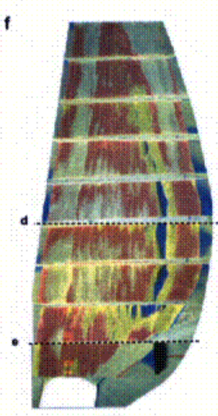
1) Connectivity between the hanging wall and footwall is localized or terminated.
2) Relay structures exist at various scales and geometries.
3) Connectivity across the basin remains high. Compare highlighted features with (c) below.

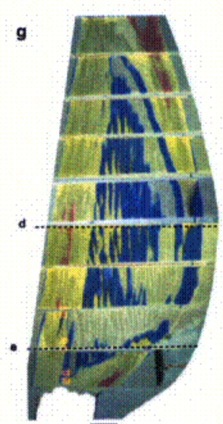


1) Relay structures are inherited by basin fill layers, and inherited structures in the fill repeat the evolution of underlying older structures.



1) Cross sections (d) and (e) above show domino appearance of fault systems developed as relay structures.
2) In the case of relay structures, dip of panels is into or out-of the plane of section, with leak points, spill points, or traps located up or down ramp-dip.





1) Horizontal sections (f) and (g) show anastomosing pattern created by fault system development.
2) Results from the modelling reveals that the potential for rock mass connectivity exists at all stages of development.

C04

INFLUENCE OF FAULT GEOMETRY ON RESERVOIR CONNECTIVITY

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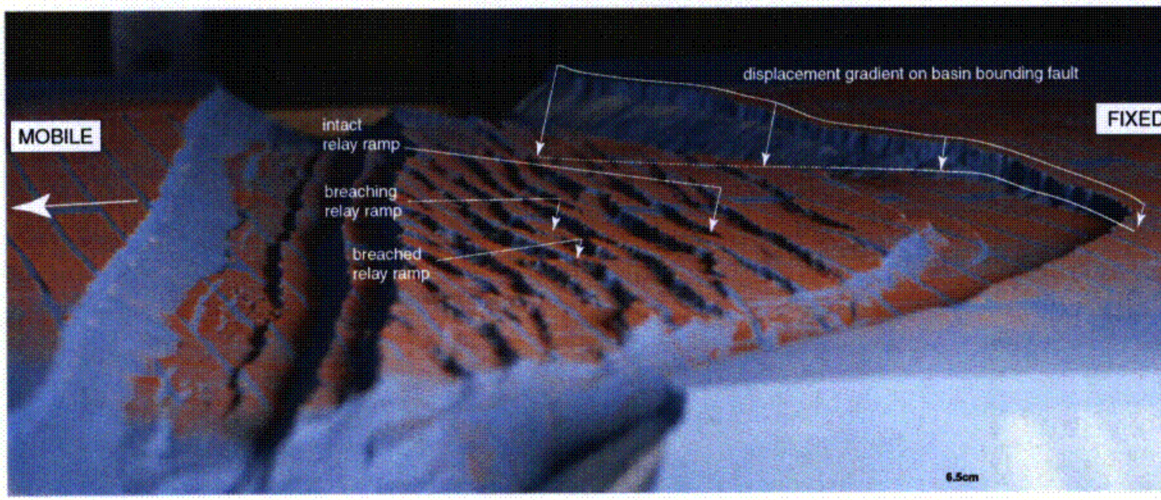
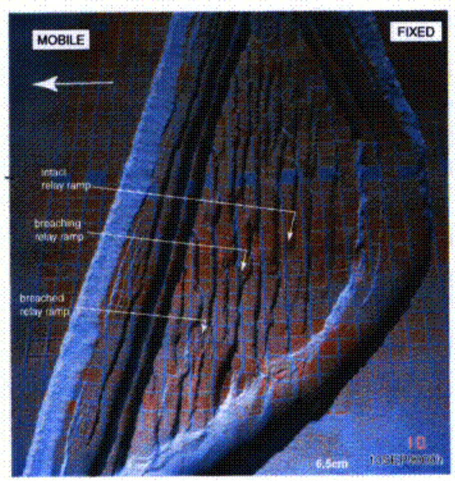
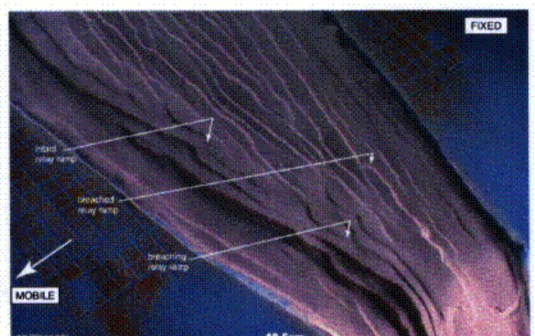
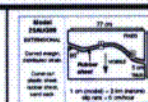
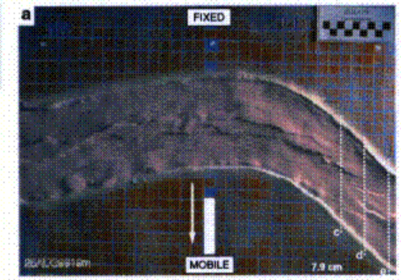


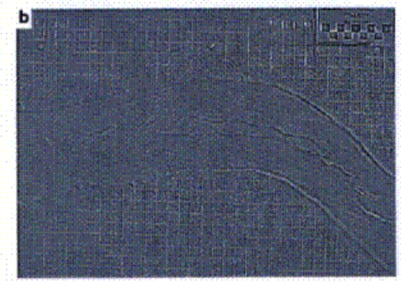


1) Oblique views show clear evidence of connectivity across the exposed fault system.
2) Localized traps associated with relay structures or footwall "uplift" of small faults are common within the fault system.
3) Relay structures exist at a range of scales and geometries, and at a range of evolutionary stages from intact ramps to cut or breached relay structures.
4) Smaller scale deformation observed within mature relay ramps may strongly influence reservoir permeability within ramps.

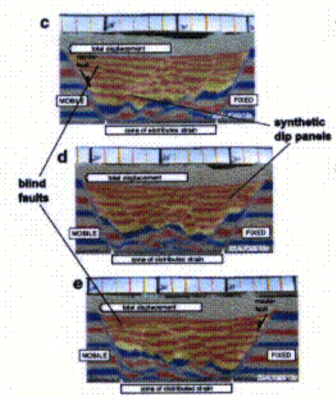








(a) Fault systems, including relay structures, occur at a range of scales within a basin. Figure (b) is the same image as figure (a) after edge detection filtering, which is similar in appearance to output from fault detection algorithms applied to 3D seismic data. Relay structures appear as overlapping *en echelon* fault traces.



1) In cross section (and assuming sealing faults) most faulted layers show apparent closure against a fault. However, the models show that relay structures with dips parallel to the bounding faults appear as anti- or synthetically dipping panels, and flow would be potentially into or out of the section.

2) Where sections are subparallel with extension direction relay structures may be detected as closely-spaced subparallel faults, synthetically dipping panels, and blind faults.

3) Sections show that some relay structures persist after several episodes of simulated basin fill (alternating yellow-red layers), and that the newly deposited layers inherit pre-depositional structures from underlying rocks.

C05

INFLUENCE OF FAULT GEOMETRY ON RESERVOIR CONNECTIVITY

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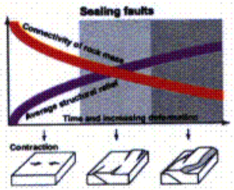
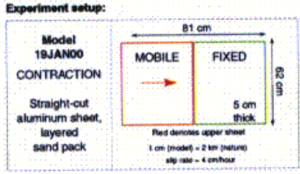
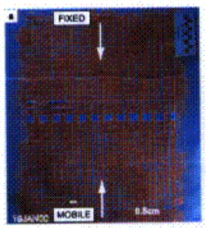
Contraction:

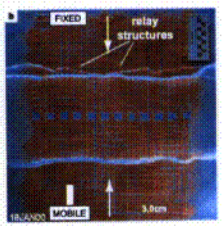


Experiment setup:

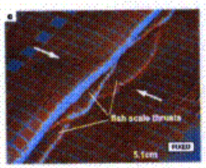


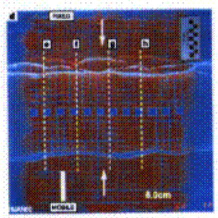


1) First thrusts form by linking of initially separate fault segments

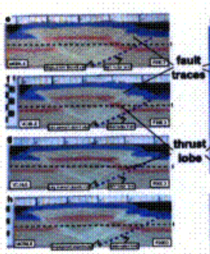


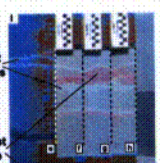
2) "Fish scale" thrust lobes (b) exist at various scales (c).
3) Relay structures flanking nascent thrust lobes (b) maintain connectivity with footwall.
4) Potential for local traps increases.
5) Connectivity is reduced for the case of sealing faults.





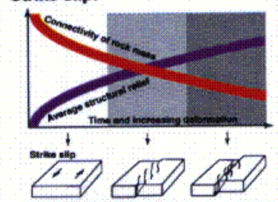
6) Trapping opportunities increase (c,d).
7) In the case of sealing faults, connectivity between thrust lobes is severed.
8) Structural traps (highs) are created in the upper thrust sheet by stacking of thrust lobes.
9) Spill points for structural highs migrate as thrust lobes stack.



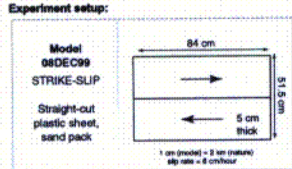


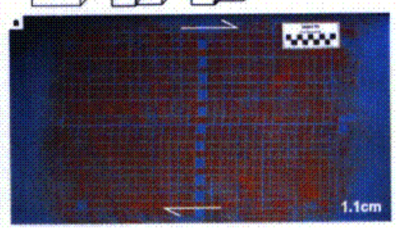
10) In the case of sealing faults, connectivity between fault blocks is severed.
11) In most cases, maximum dip of faulted layers is perpendicular to the section.
12) Correlation of thrust lobes between adjacent cross sections is difficult.

Strike slip:

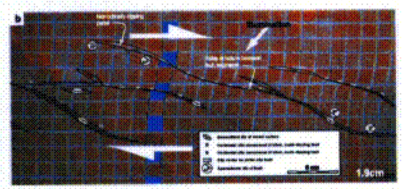


Experiment setup:

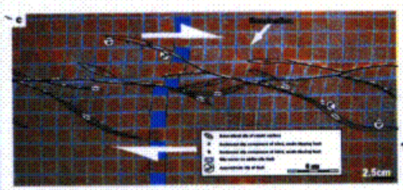




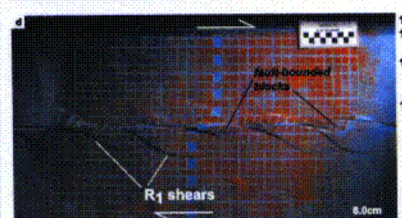
1) Distributed shear across incipient fault zone. Potential for fracture formation high.
2) Connectivity continuous across entire structure. No observable structural traps.



3) Faults form by linking of fault segments and by lateral propagation.
4) Relay structures serve as potential hydrocarbon communication pathways.
5) Localized reduction in connectivity.
6) Potential for local traps increases.



7) Relay structures maintain connectivity across the developing shear zone.
8) In the case of sealing faults and where relay structures are cut, connectivity across the shear zone is locally severed.
9) Potential for localized traps increases.
10) Potential for reservoir



11) Connectivity continues to decrease.
12) Relay structures are cut and fault-bounded blocks increase in number.
13) In the case of sealing faults, opposing sides of the shear zone are disconnected.
14) Potential for local traps and reservoir compartmentalization continues to increase.

Conclusions:

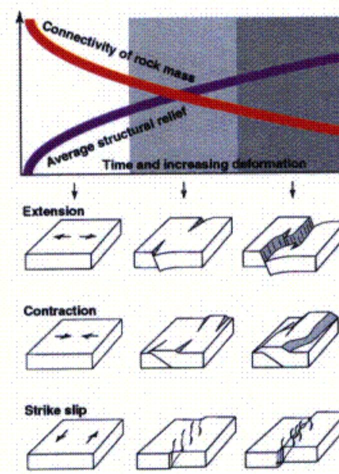
1) Fault systems form by nucleation of geometrically simple faults at a large number of sites throughout the deforming region.

2) As fault systems grow by segment interaction, relay structures and forced folds over blind faults form potential hydrocarbon pathways.

3) As faults lengthen by segment linking or lateral propagation, structural relief increases and, in the case of sealing faults, potential hydrocarbon communication pathways are severed.

4) Structural evolution progressively creates more opportunities for trapping and reservoir compartmentalization, and, in the case of sealing faults, progressively decreases reservoir connectivity.

5) Similar structures occur at various scales within the deformation system.



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