Curvature-fracture relations in clay experiments
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Summary
Layer curvature is often used as a proxy for fracture intensity (FI) in subsurface seismic analyses (e.g. Chopra and Marfurt 2010). This usage is based on beam bending calculations in which tensile strain, and the resulting FI, is proportional to the beam curvature. We experimentally tested this hypothesis by deforming clay models that are 3-5 cm thick and subjected to basement compression (thrusting) or extension (normal faulting). The FI (total fracture length/area) and the clay surface curvature were determined in 10-20 intervals during each experiment. Clear correlation is observed between the FI and the corresponding measured magnitude of the local clay curvature under both compressional settings ($r^2=0.95$) and extensional setting ($r^2=0.61$). These experimental results support the use of layer curvature as an indicator for FI in subsurface analysis.

Introduction
The detection of common rock fractures typically falls below seismic resolution, yet fractures are often critical to porosity and permeability in hydrocarbon reservoirs. Multiple studies link fractures to structural curvature following the assumption that extension fractures are generated on the extending side of flexed and folded. For example, curvature calculations from 3D seismic data were correlated with fractures presence in borehole image logs by Hunt et al. (2010), Nissen et al (2009), and Ericsson et al. (1998). Potential fracture zones seen by lineaments in the subsurface were identified using the curvature attribute in 3D seismic surveys by Chopra and Marfurt (2010, 2008, 2007), Nahari et al. (2009), and Hart (2006).

Beam theory (Manaker, 2007) indicates that the tensile strain, $\varepsilon$, at the convex part of a beam with thickness, $h$, that is flexed with radius of curvature, $R_c$, is linearly proportional to the curvature magnitude, $k_c$:

$$\varepsilon = \frac{h}{2R_c} = k \frac{h}{2}$$  (1)

We hypothesized that clay model experiments will exhibit similar relationships.

Methods
We report here the result of clay model experiments in which we used homogenous clay cakes (1.22 g/cm$^3$, or 76.2 lb/ft$^3$) with approximate dimensions of 7.87 in (20 cm) long, 5.91 in (15 cm) wide, and 1.97 in (5 cm) thick. A laser scanner positioned above the clay cakes captured 3D-surface images at vertical and horizontal resolution of 75 DPI (~0.015 in, or 0.0381 cm point density) every two minutes. A typical experiment lasted approximately 30 min.

The experimental apparatus consists of a horizontal table with one moveable side-wall, one stationary side-wall and a deforming base. We ran four experiments. In the extensional experiment, the clay cake was placed on top of two rigid, thin metal plates that were moved away from each other (Fig. 1, left). In the compressional experiments, the clay cake was placed on two metal wedges with inclinations 45°, 30°, and 15° that moved toward each other to simulate reverse basement faulting (Fig. 1, right).

The curvature of the clay surface was calculated from the laser scans using commercial software and the fractures were mapped on digital photographs of the clay surface. Curvature over the area of deformation was calculated in each stage by placing three polygons at fixed locations and averaging the curvature within each polygon. FI was calculated for these polygons by dividing total fracture length in each polygon by the polygon area.
Clay models and curvature

Results

In the extensional experiment, a basin formed in the center of the clay cake with a main listric-normal fault on the right side and normal faulting, fracturing, and flexure occurring on the left side of the basin; curvature and FI calculations were measured on the left side of the basin (Figure 2). Fractures were first visible at clay curvature of $2.53 \times 10^{-3}$ cm$^{-1}$ and later are linearly related to the progressing curvature with $r^2=0.61$. Figure 3 shows positive curvature applied to the final stage of extension.

In all three compressional experiments, an anticline developed with fractures on the crest parallel to the axial plane (Figure 4). Fractures were first visible at clay curvature of $1.40 \times 10^{-2}$ cm$^{-1}$ – $1.90 \times 10^{-1}$ cm$^{-1}$ and are strongly linearly related to the advancing curvature with $r^2=0.98$, $r^2=0.97$, and $r^2=0.91$. It is important to note that curvature values increased as the fault ramp became steeper (15°, 30°, and 45°). Figure 5 shows positive curvature applied to the final stage of deformation for the 30° ramp.

Conclusions

1. The experiments indicate that FI in clay models is linearly related to the curvature in agreement with our hypothesis which is based on beam theory calculations (Figure 6).

2. Fractures become visible only after a finite curvature suggesting that yielding occurs at a critical strain (strength?).

3. The noted difference of the FI-curvature relation between extension and compression tests requires further investigation.

4. These results suggest that seismic determined layer curvature above a (yet unknown) critical minimum is a good proxy for fracture intensity.

Figure 1: Experimental set up for the extensional (left) and compressional (right) clay cake experiments. Metal wedge angles used included 45°, 30°, and 15°.

Figure 2: General view of extensional experiment. Note flexure on graben left side where the curvature was correlated to fracture density.
Clay models and curvature

Figure 3: Most-positive curvature computed from the final stage of extension experiment (Fig. 2). Subtle curvature anomalies parallel and perpendicular to the fault correlate to tool marks made in the initial clay model construction.

Figure 4: Photograph from above demonstrating fractures on the top of the deformed anticline in the 30° compressional experiment.
Clay models and curvature

**Figure 5**: Curvature computation of the final stage of deformation for the 30° compressional ramp experiment. Subtle curvature anomalies parallel and perpendicular to the anticline correlate to tool marks made in the initial clay model construction.

**Figure 6** – Graph showing linear relationship between fracture intensity and curvature with standard error bars for all four experiments.