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Subsurface Observations of Deformation Bands and Their Impact on Hydrocarbon Production within the Holstein Field, Gulf of Mexico, USA

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SUMMARY

The Holstein Field in the Gulf of Mexico consists of Pliocene, poorly lithified turbidite sands deposited in a ponded basin above an allochtonous salt tongue. Dense arrays of cataclastic deformation bands have been observed in core from wells that penetrate the K2 reservoir sand. The highest density of bands is located near the hinge of a monoclinal fold that divides the field into an up-dip terrace and a down-dip, steeply-dipping ramp. The predominant set of deformation bands strike parallel to the fold axis, and dip at both high and low angles to bedding. Their orientation, and offset of marker beds where present, suggest reverse shear. Restorations indicate that the deformation bands formed early during the burial process, and an inferred stress path suggests that high fluid pressures during the initial phase of burial was an important component. Reservoir permeability estimates from PTA well tests indicate a bulk permeability approximately one third of the reservoir core permeability. In comparison, the reservoir bulk permeability calculated on the basis of the deformation bands' actual permeabilities, thicknesses and densities, exceeds the well-test permeability by a factor of two. Additional factors are required to account for the well test results.

This paper summarizes a characterization of deformation bands in a poorly lithified Pliocene turbidite sand reservoir, and their impact on the production. The study is an effort to model the effect of deformation bands on reservoir performance in specific regions where pressure compartmentalization and well-test-based permeability are significantly lower than that expected from standard petrophysically-determined values from core. These model results are compared to well tests and pressure data to calibrate bulk permeability estimated for the arrays of deformation bands.

The Holstein Field in the Gulf of Mexico consists of poorly lithified turbidite sands deposited in a ponded basin formed above an allochtonous salt tongue. Dense arrays of cataclastic deformation bands have been observed in core from many wells that penetrate the K2 reservoir sand (Figure 1). The highest density of bands is located near the hinge of a monoclinal fold that divides the field into a up-dip terrace and down-dip, steeply-dipping ramp. The highest observed densities reach roughly 40 bands/meter. Observed deformation bands form in dense clusters, separated by relatively undeformed zones, rather than distributed evenly through the reservoir. The less defined areas are not shale breaks within this clean, 100ft. thick turbidite sheet sand. The along-hole width of these clusters ranges between 2 and ~20 feet, with the wider clusters generally, but not always, comprised of a greater density of bands. No slip-surfaces, interpreted as a later stage of deformation band development with layer slip in outcrop (Aydin and Johnson, 1978) were observed within these clusters.

The predominant sets of deformation bands strike parallel to the fold axis and dip at both high and low angles to bedding (Figure 1). These sets combine to form distinct ladder geometries that have been described by numerous authors (Davis et al., 1999; Schultz and Balasko, 2003). The high angle and low angle bands are mutually cross-cutting, indicating they formed contemporaneously. Their orientation, and offset of marker beds where present, suggest reverse shear. Restorations indicate that the deformation bands formed early during the burial process, and an inferred stress path and yield criterion suggests that high fluid pressures during the initial phase of burial was an important component.

Undeformed host sands are fine to very-fine grained, poorly sorted litharenites to sub-litharenites, with porosity and permeability of roughly 25-30% and 200-900 mD, respectively. SEM images show deformation bands as narrow zones with a fault rock of disaggregated and crushed grains which are significantly different than the adjacent host rock. Reduced grain sizes and fractured/cataclastic grains exist within the deformation bands. Grain sizes within the deformation bands were measured separately and compared to adjacent host rocks with laser grain size analysis. Deformation bands generally show an average reduction in median grain size of 0.05 mm relative to the host sands. In response to cataclasis, the deformation bands also experience a decrease in sorting, with a reduction in sorting of ~0.25 - 0.5 phi. The reduction in grain size is the main mechanism for porosity and permeability reductions within the bands. Cementation and clay smear were not identified.

Deformation band permeability, measured from laboratory flow experiments on 7 core plugs sampled from the field, average 45 +/- 29 mD (+/- one standard deviation) with a range of 11-93 mD. This average represents 11% of the average matrix permeability of the samples (381 mD), or an approximate order of magnitude reduction. Grid-cell effective permeability measurements can be estimated from the permeability of deformation bands in core plugs, and the measured deformation band density from core logging to estimate the volumetric fraction of deformation bands in grid cells for the models. The harmonic mean is used to estimate the effective permeability for fluid flow normal to the grid cells containing deformation bands and an arithmetic mean calculation to determine the effective permeability for flow parallel to the deformation bands. Bulk permeability estimates of permeability measurements across individual deformation bands convolved with their density and thickness measured from core are lower than the reservoir permeability, but exceed the permeability observed in the well tests by a factor of two. Relative permeability of oil to water for both the fault and host sands appears to present a reasonable match the well test permeability with that measured from core. The effective permeability of the deformation bands, however, is insufficient to account for the large pressure differences observed in the engineering production data.

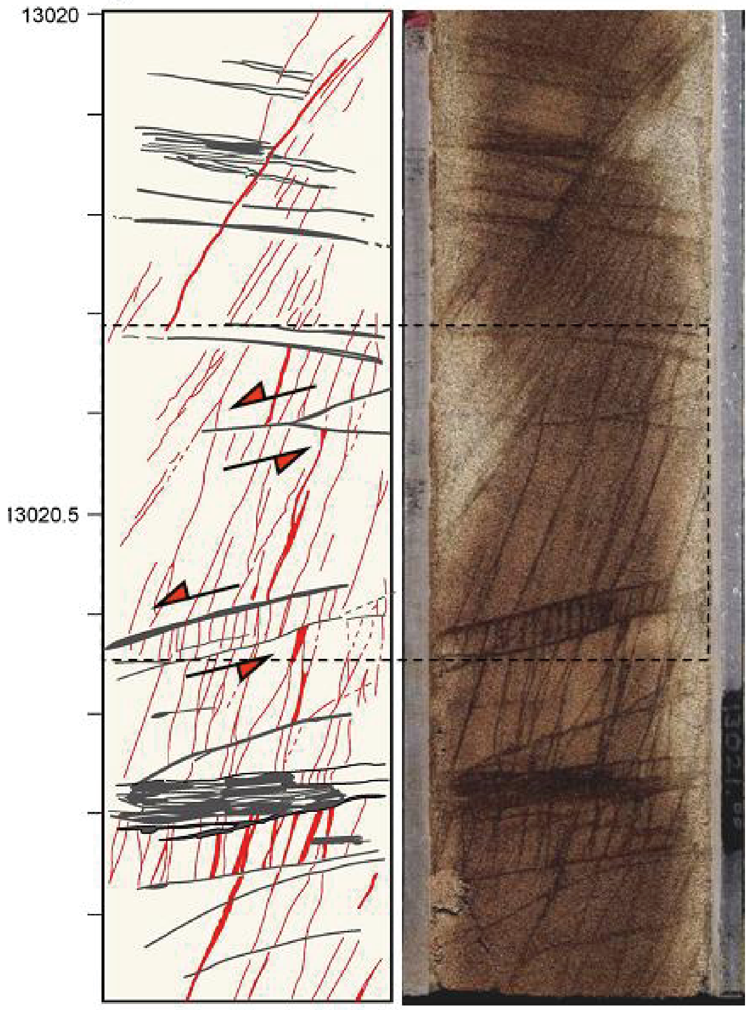

Figure 1 *Core photograph and interpretation from a deviated core. Bedding (not shown) is ~perpendicular to the core axis. A distinct high (gray) and low angle set (red) is present, with ladder structures forming predominantly between the low angle bands. Arrows indicate interpreted sense of apparent motion from a combination of ladder geometries or offset bands.*

Aydin, A. and Johnson, A.M. [1978] Development of faults as zones of deformation bands and as slip surfaces in sandstones. *Pure and Applied Geophysics*, **116**, 931–942.

Davis, G. H., Bump, A.P., Garcı´a, P.E., and Ahlgren, S.G. [1999] Conjugate Riedel deformation band shear zones. *Journal of Structural Geology*, **22**, 169 –190.

Schultz, R.A., and Balasko, C.M. [2003] Growth of deformation bands into echelon and ladder geometries. *Geophysical Research Letters*, **30**, 2033, doi:10.1029/2003GL018449.