[PS]Fault Damage Zones at Reservoir Depths: Observations from a Gas Field in Southeast Asia and SAFOD*

Madhur Johri[1], Mark Zoback[1] and Peter Hennings[2]

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[1]Geophysics, Stanford University, Stanford, CA. (johri@stanford.edu)
[2]Subsurface Technology, ConocoPhillips, Houston, TX.

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Abstract

We report a study on fault damage zones associated with second-order faults in two different regions - one adjacent to the San Andreas Fault in central California and the other adjacent to a major fault in a gas field in Southeast Asia. The importance of characterizing damage zones arises from the pivotal role that fractures play in governing fluid flow through fractured, low permeability reservoirs. Damage zones studied adjacent to the San Andreas Fault are encountered in well-cemented arkosic sandstones immediately southwest of the main fault at the SAFOD site. Fifteen second-order faults have been identified in electric image logs on the basis of changes in lithology, orientation of bedding planes and anomalous physical properties such as decreased seismic-wave velocities. Most second-order faults have identifiable damage zones in which the density of smaller-scale faults and fractures (third order features) within the damage zones is anomalously high. Damage zone widths associated with second-order faults are typically on the order of 50-100 meters. The damage zone associated with the San Andreas Fault is about 250 meters wide. Within the damage zones of second-order faults, there are approximately two to three identifiable third-order features per meter. The density of these third-order features decreases rapidly with distance. The faults in the arkosic section have a variety of orientations, but many appear to be southwest-dipping reverse faults. The conjugate set of these is missing. However, this may be due to a sampling bias.

The second region of study is a fault zone in a gas reservoir in Southeast Asia. Twenty-seven seismically-resolvable second-order faults are observed. The peak fracture density is approximately two to three fractures per meter. While most of the wells do not intersect the second-order faults, several peaks of increased fracture density are observed, leading us to suspect the presence of sub-seismic second-order faults. Production data indicates poor correlation of production with the reservoir-borehole contact length, but a strong correlation with the number of critically stressed fractures that the borehole intersects. Production data also indicates significantly larger production from a non-vertical well as compared to vertical wells. Majority of the fractures are steeply dipping and fail to be sampled by vertical wells. A correction to remove the sampling bias is applied to characterize the fractures correctly.

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Madhur Johri and Mark Zoback, Department of Geophysics, Stanford University, Stanford, CA-94305. johri@stanford.edu, zoback@stanford.edu
Peter Hennings, ConocoPhillips, Houston, TX-77079. peter.hennings@conocophillips.com

1. Introduction

● A fault system comprises of a fault core surrounded by a damage zone. The fault core which comprises of high strain products (breccias, cataclasites etc.) having low permeability and porosity acts as a barrier to fluid flow. The damage zone (DZ), however, comprises of fractures which induce permeability anisotropy by increasing the permeability along the fault plane (Paul et al, 2007).

● The fault core permeability is governed by the grain scale matrix permeability of the fault rock, while the damage zone permeability is governed by the hydraulic properties of the fracture network,

● Hydraulic properties of the fracture network depend on fracture density, fracture orientation and hydraulic and mechanical characteristics of fractures. Most hydraulically conductive fractures are *critically stressed* in the present day stress fiield(Barton et al , 1995).

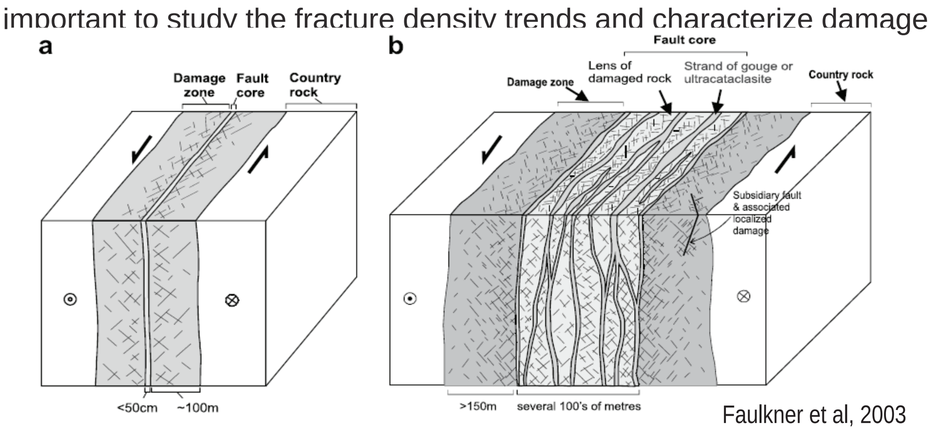
Motivation: Since fractures strongly affect fluid flow, it is important to study the fracture density trends and characterize damage

Damage Zone Attributes:

● *Damage Zone Width:* DZ width scales with slip across the fault (Faulkner et al, 2008)

● *Fracture density variation:* Fracture density decreases exponentially with distance from the fault

● *Assymetry:* Damage zone formed by dynamic rupture across the fault plane may give rise to asymmetric damage on the two sides of the fault depending on the direction of propagation.



Faulkner et al, 2003

2. Areas of study

Sub-surface damage zones present at depth are characterized indirectly using fault and fracture information derived from geophysical logs such as image logs, sonic and resistivity logs. Damage zones have been characterized in two regions:

1. Gas field in Southeast Asia.

2. Arkosic section adjacent to the San Andreas Fault in central California.

3. Gas Field in Southeast Asia

● Produces wet gas from compressionally uplifted, fractured, crystalline and metamorphic basement rocks.

● Second order faults have reverse separation.

West of master (first order) fault- Strke-slip regime.

East of the master fault-Reverse faulting regime.

● Wells A, E, G and I are vertical. Wells B and C are deviated wells.

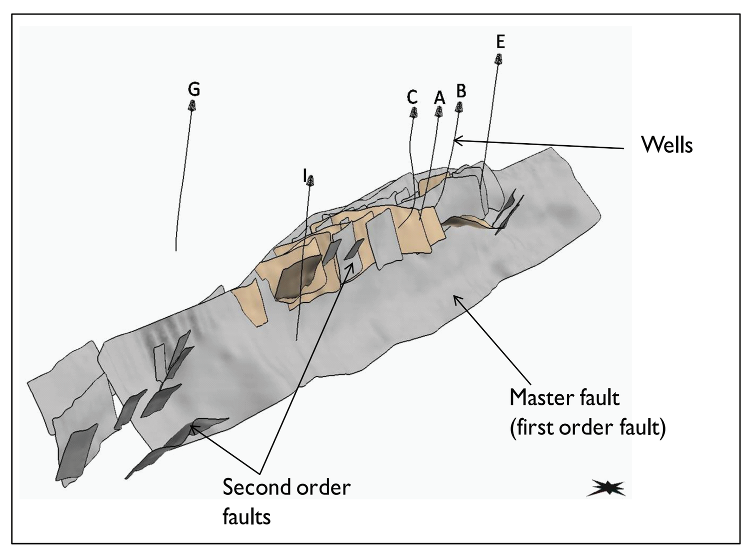
● Results from well tests:

-> Weak correlation between production and reservoir-wellbore contact length.

-> Weak correlation between production and number of fractures intersected.

-> *Strong correlation* between *production* and *number of critically-stressed fractures* intersected by the borehole

● The critically stressed fractures are steeply dipping, hence fail to be adequately sampled by near-vertical wells.



Structural map of the gas field showing the master (first-order) fault, second-order faults and wells

4. Characterization of Natural Fractures and Damage Zones in the Gas Field in Southeast Asia

● Peak fracture density: ~2-3 fractures/meter. DZ width ~ 50-80 m

● Most wells do not intersect seismically identified second order faults.

● Fracture peaks could represent damage zones associated with ***sub-seismic*** faults.

● Numbered arrows represent suspected sub-seismic second order faults - Inferrred by change in orientation of bedding plane. These depths are marked by increase in fracture densities.

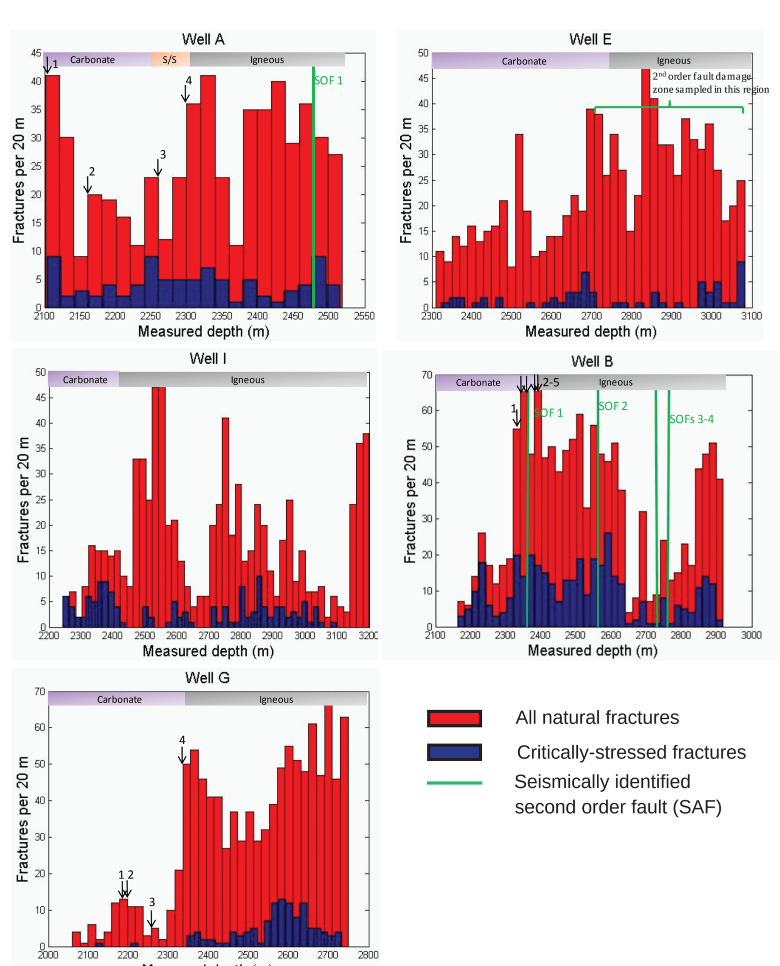
● Fracture density in the igneous section is greater than in carbonate. More brittle nature of igneous rocks could be the reason.

Critically-stressed fractures

● Peak critically stressed fracture intensity and number of critically stressed fractures intersected by well B (deviated well) is larger than other wells (vertical).

● Critically stressed fractures are steeply dipping and not sampled adequately by vertical wells.

● Important to design wellbore trajectory so it intersects maximum number of critically stressed fractures.

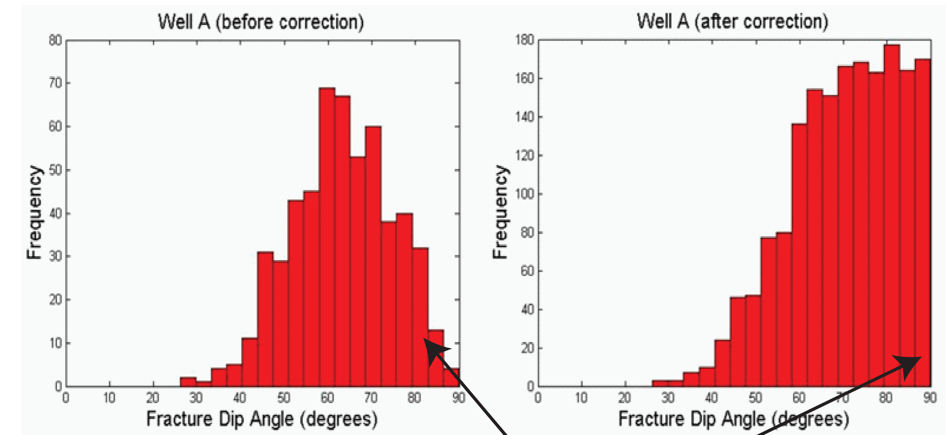


5. Removal of Sampling Bias

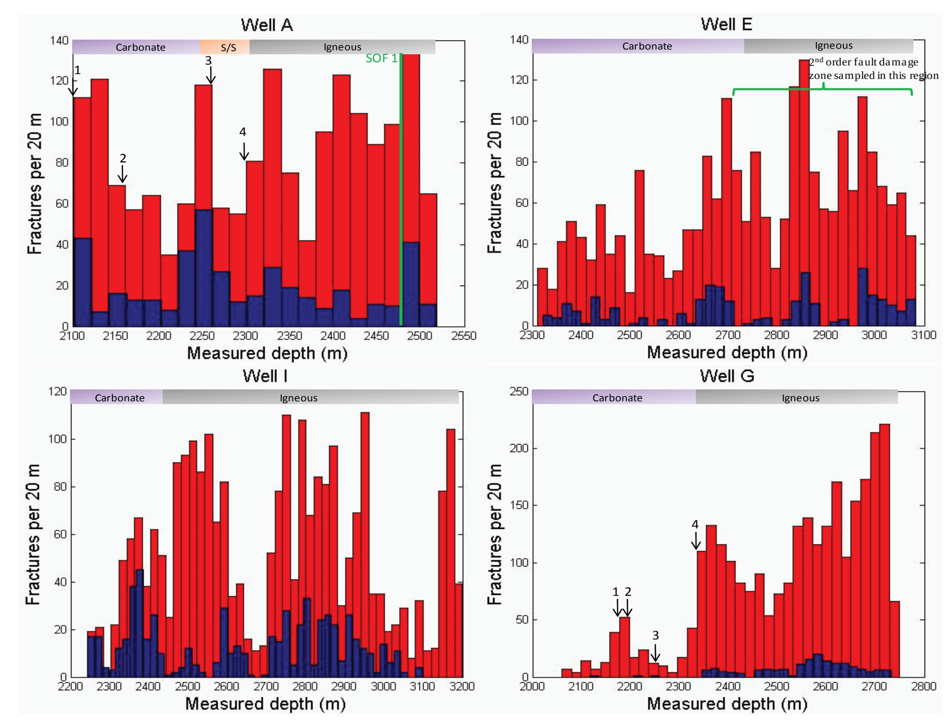
● Boreholes fail to sample fractures oriented sub-parallel to the borehole.

● Fracture information obtained from image logs needs to be corrected for sampling bias in order to correctly characterize damage zones at depth (Terzaghi, 1965)

● Peak fracture intensity increases to ~ 5-7 fractures/m



The number of steeply dipping fractures increases very significantly after correction is applied. Well A being a vertical well fails to sample steeply dipping fractures adequately



Well	Before application of correction		After application of correction	
	Total number of fractures intersected by the well	Number of critically stressed fractures intersected by the well	Total number of fractures intersected by the well	Number of critically stressed fractures intersected by the well
A	547	91	1781	414
E	903	63	2286	263
G	1055	117	2602	175
I	800	140	2547	607

6. Arkosic section adjacent the San Andreas Fault

● Arkosic section -> well-cemented sandstones, bound by the San Andreas Fault and Buzzard Canyon Fault.

● Arkosic sandstones are juxtaposed against the granitic rocks of Salinian block to the Southwest and fine-grained Great Valley Group and Jurassic Franciscan rocks to the Northeast.

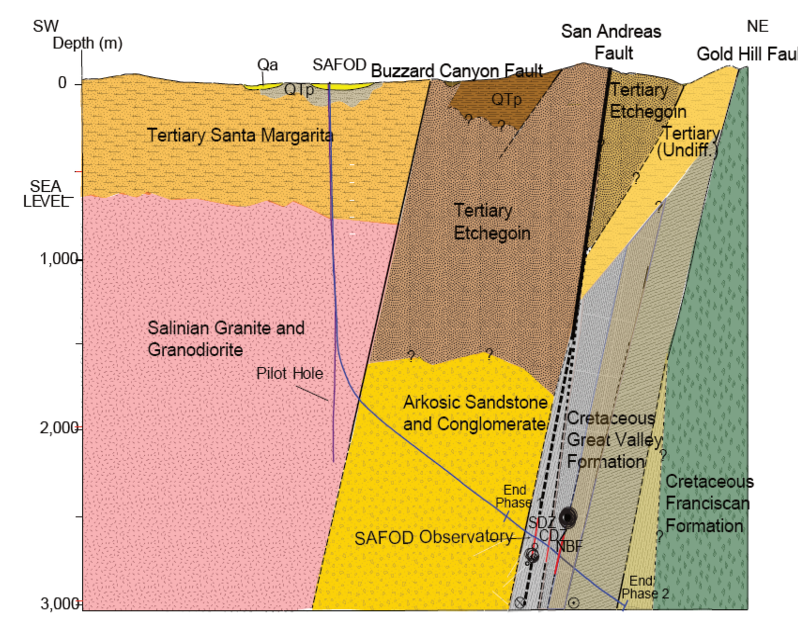
● Arkosic section extends from 1920-3157m along borehole.

● Nomenclature:

First order faults: The San Andreas Fault and Buzzard Canyon Fault

Second-order faults: Smaller, sub-seismic faults identified by changes in orientation of bedding planes.

Third-order faults: Fractures and smaller faults identified in the image logs



Zoback et al, 2011

7. Characterization of Natural Fractures and Damage Zones in the Arkosic section, SAFOD

● Second order faults are identified by abrupt changes in orientation of bedding planes.

● 14 structural blocks ('a'-'n') are identified. The bedding plane orientation in each block is distinctly different from that in the adjacent blocks.

● The block boundaries could represent second order faults since most boundaries are marked by increased fracture density and decreased sonic velocities and resistivity.

● Damage Zone widths:

Buzzard Canton Fault: 120m.

Faults 1, 9, 12 and 14: 50-80m.

Faults 3-8: Their damage zones overlap.

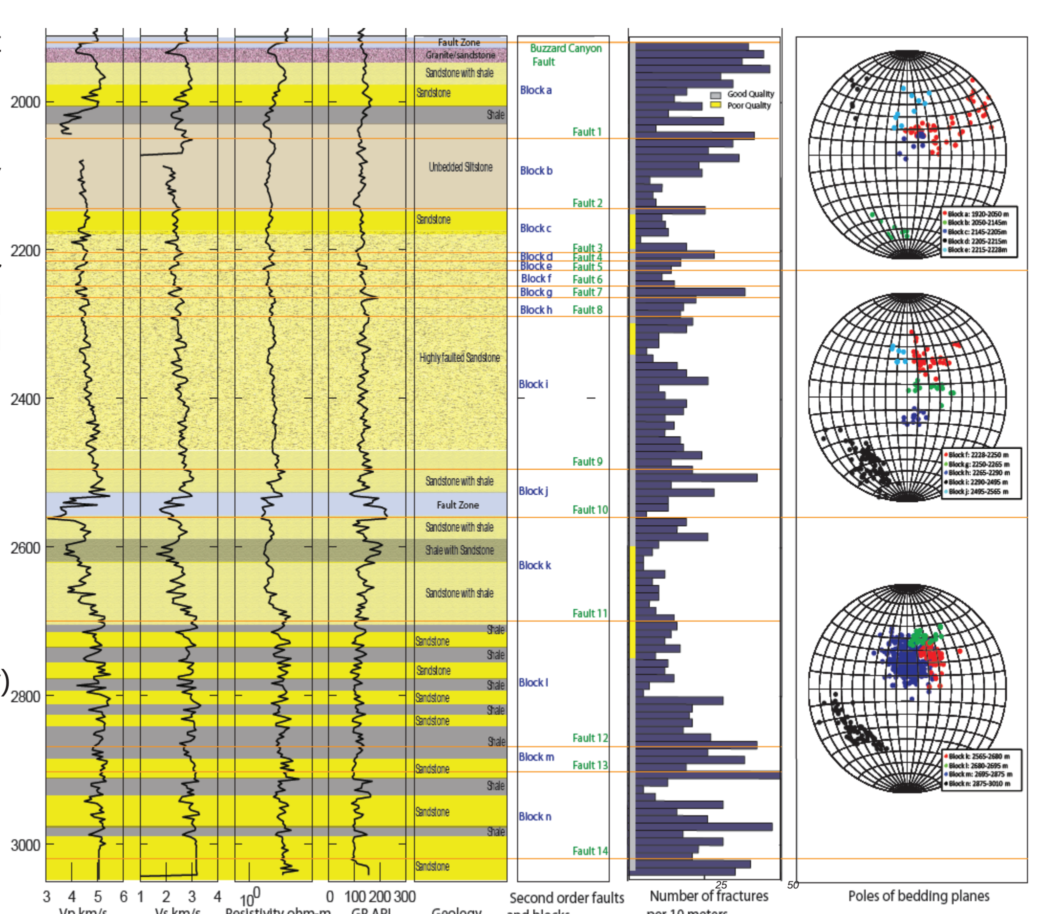
Faults 2, 10, 11: Ill-defined DZs. (Bad data quality)

● Peak fracture intensity:

Faults 1,3,6,7,9,12,13 and 14: ~3-4 fractures/m

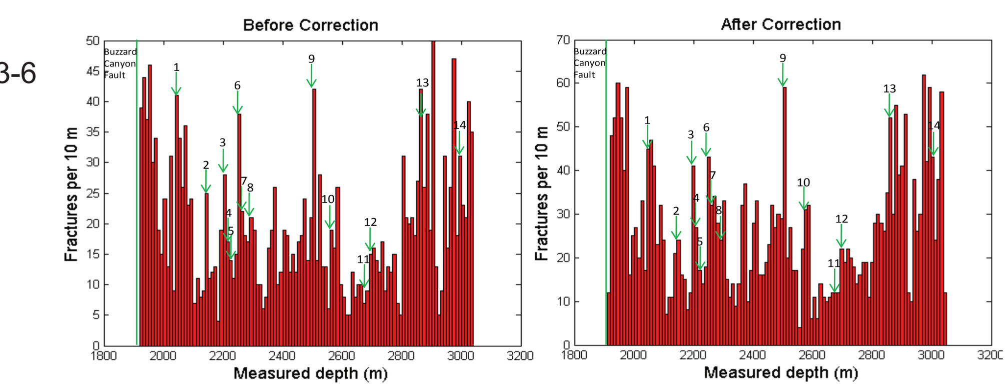
Faults 2,4,5,8,10,11: 1.5-2 fractures/m

● Fracture density decreases rapidly with distance



8. Removal of Sampling Bias

● Peak fracture intensity increases to approximately 3-6 fractures per meter after correction is applied.



9. Variation of Fracture Density with Distance from a Fault Plane

● Only the well-defined and isolated damage zones are selected.

● The fracture density decreases exponentially with distance.

● ln(F(0)) lies between 0.5 and 1.5 before correction and between 1.5 and 1.9 after correction. Critical fracture density does not depend upon the size of the fault or slip across it (Mitchell and Faulkner, 2009).

● Peak fracture intensity:

Gas field: ~6-7.5 fractures/meter

Arkosic section: ~ 4.5-6.5 fractures/meter

Background fracture intensity: ~ 1.5-2 fractures/meter

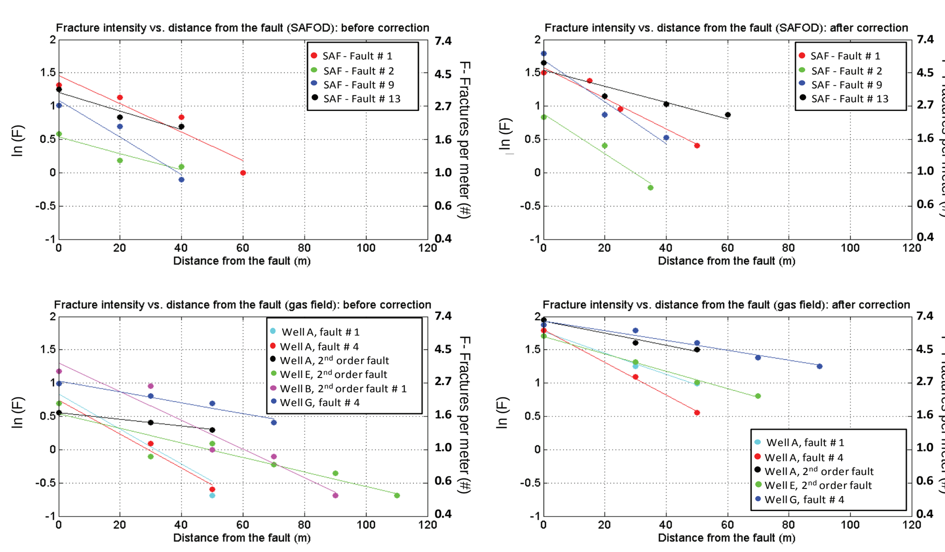
● Damage zone width:

Gas field: ~ 50-100 meters.

Arkosic section: ~ 40-60 meters

● Rate of decrease in fracture density α:

Greater for carbonate and sandstone than for granite. Brittle nature of granite could be a reason.



$$F = F_0 e^{-\alpha x} \quad \Rightarrow \quad \ln(F) = \ln(F_0) - \alpha x$$

F: Fracture Density

F₀: Critical fracture density (at the fault core-damage zone interface)

α: gradient of decrease in fracture density

x: distance from the fault plane

10. Conclusion and Future Work

● The position of sub-seismic second order faults and their associated damage zones is constrained by abrupt changes in bedding planes and changes in sonic velocities and resistivity.

● Damage zones observed in the gas field are quite similar to those observed in the arkosic section in terms of widths of damage zones, peak fracture density and rate of decrease of fracture density with distance.

● Damage zones are typically 50-80 meters wide.

● Peak fracture intensity is approximately 2-3 fractures per meter. A correction to remove sampling bias is applied. On correcting for sampling bias, the peak fracture intensity increases to ~ 4-7 fractures per meter.

● Fracture density decreases exponentially with distance from the fault. The rate of decrease in fracture density is smaller in granite than in arkosic sandstone and carbonates.

● The critically stressed fractures have been found to be the most productive fractures in the gas field. This concept of potentially active fractures and faults, and halos (damage zones) rich with critically stressed fractures forms the basis for the drilling strategy.

● Having an understanding of damage zone characteristics and attributes can greatly assist us in building more realistic flow simulation models and designing borehole trajectories.

● Future work comprises modeling the formation of a damage zone by simulating a dynamic rupture propagation. As a fault slips, stress concentrations at the tip of the propagating slip pulse cause inelastic deformation in the rock leading to the formation of damage zone.

11. Acknowledgements

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12. References

● Barton C.A., M.D.Zoback, and D. Moos. 1995. Fluid flow along potentially active faults in crystalline rock. Geology 23: 683-686

● Faulkner, D.R., A.C.Lewis, and E.H.Rutter. 2003. On the internal structure and mechanics of large strike slip fault zones.: field observations from Carboneras fault in southeastern Spain. Tectonophysics 367 (3-4): 235-251

● Paul, P., M.D.Zoback and P. Hennings. 2007. Fluid flow in a fractured reservoir using a geomechanically constrained fault zone damage model for reservoir simulation. Society of Petroleum Engineers Reservoir Evaluation and Engineering 12, No.4: 562-575

● Terzaghi, R.D. 1965. Sources of error in joint surveys. Geotechnique 15: 287-304

● Zoback, M.D., S. Hickman, William Ellsworth and the SAFOD Science Team. 2011. Scientific drilling into the San Andreas Fault Zone - An overview of SAFOD's first five years. Scientific Drilling 11: 14-28