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

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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.
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, cataclastics etc.), having low permeability and porosity acts as a barrier to fluid flow. The damage zone (DZ) however comprises of fractures which have a low permeability anisotropy due to 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 hydric 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 field (Barton et al., 1985).

**Motivation:** Since fracture strongly affect fluid flow, it is important to study the fault damage and characterize fractured zones of interest.

**Damage Zone Attributes:**
- Damage Zone Width: CZ width scales with slip across the fault (Aplin et al., 1998).
- Fracture density variation: Fracture density decreases exponentially with distance from the fault.
- Asymmetry: Damage zone formed by dynamic rupture across the fault plane may give rise to asymmetry on the two sides of the fault depending on the direction of propagation.

2. Areas of study

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

1. Gas field in Southeast Asia
2. Arkoic section adjacent to the San Andreas Fault in central California.

3. Gas Field in Southeast Asia

- Produces wet gas from compressionally uplifted, fractured, and altered carbonate igneous basement rocks.
- Second order faults have reverse separation.
- Wells A, E, G and I are vertical. Wells B and C are deviated wells.

3.1 Wells A, B, C, E, G, I: Orientation of faults and damage zones:

<table>
<thead>
<tr>
<th>Fault ID</th>
<th>Orientation</th>
<th>Damage Zone Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well A</td>
<td>horizontal</td>
<td>10</td>
</tr>
<tr>
<td>Well B</td>
<td>horizontal</td>
<td>15</td>
</tr>
<tr>
<td>Well C</td>
<td>horizontal</td>
<td>20</td>
</tr>
<tr>
<td>Well E</td>
<td>horizontal</td>
<td>25</td>
</tr>
</tbody>
</table>

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

- Peak fracture density: ~2.3 fractures/meter. CZ width: ~50-100 m.
- Most wells do not intersect sub-seismic identifiable second order faults.
- Fracture peaks could represent damage zones associated with sub-seismic faults.
- Northward arrow represents expected sub-seismic second order faults, inferred by changes in orientation of bedding planes. These depths are marked by increase in fracture densities.
- Fracture density in the igneous section is greater than in carbonates. More brittle nature of igneous rocks could be the reason.

4.1 Characteristic of Natural Fractures:

- Critical fracture density: Peak critically stressed fractures and number of critically stressed fractures decreases exponentially with distance by 0.6 (deviated well) is larger than other wells (vertical).
- Critical stress fractures are critically dipping and not sampled adequately by vertical wells.
- Important to design wellbore trajectory as it intersects maximum number of critically stressed fractures.

5. Removal of Sampling Bias

- Important to design wellbore trajectory so it intersects fractures which induce permeability anisotropy by increasing the permeability along the fault plane (Paul et al., 2007).

6. Arkosic section adjacent the San Andreas Fault

- This section of geologic interest has been found to be the most productive fractures in the gas field. The critically stressed fractures have been found to be the most productive fractures in the gas field.
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6.1 Detailed structural logs of selected faults:

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<td>25</td>
</tr>
</tbody>
</table>

7. Characterization of Natural Fractures and Damage Zones in the Gas Field, San Andreas Fault

- Second order faults are identified by abrupt change in orientation of bedding planes.
- 14 structural blocks (V-I) are identified. The bedding plane orientation in each block is distinctly different from that in the adjacent block.
- The block boundaries could represent second order faults since most boundaries are marked by increases in fracture density and decreased sonic velocities and resistivity.

7.1 Damage Zones:

- Buzzard Canyon Fault: 120m.

8. Removal of Sampling Bias

- Peak fracture density 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.

9.1 Fracture density decreases exponentially with distance.

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 50-60 meters wide.
- Peak fracture density is typically 0.2 fractures per meter. A correction to remove sampling bias is applied. On correcting for sampling bias, the peak fracture density 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 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 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 metastable deformation in the rock leading to the formation of damage zone.

11. Acknowledgements

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- We would also like to thank the Stanford Rock Physics and Geophysics (SRP) consortium for their constant support.

12. References