Fault Damage Zones-Observations, Dynamic Rupture Modeling and Implications on Fluid Flow*

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Abstract

We present a methodology that accounts for the effect of permeability heterogeneity and anisotropy introduced by fault damage zones on the flow characteristics of fractured reservoirs. In this study, we carry out an integrated observational and modeling study of sub-surface fault damage zones in a gas field and adjacent to the San Andreas Fault in central California. We compare observations (from image logs) with theoretically-predicted damage zones from dynamic rupture propagation modeling. Flow simulations are then performed on reservoir models containing damage zones to illustrate the impact of the damage zones on fluid flow.

Despite the geologic differences, damage zones in both the gas field and the arkosic sandstone (adjacent the San Andreas Fault) have a number of similar characteristics. The decay of fracture density with distance can be described by a power law F(r)=F0 r-n in the 50-80 m wide damage zones. F0 (Fault constant) is the fracture density 1 meter from the fault. It ranges from 6-30 fractures/m. The rate of decay n ranges from 0.4-1.

Damage zone modeling utilizes two-dimensional plane-strain dynamic rupture models with strong rate-weakening fault friction and off-fault Drucker-Prager plasticity. The number of induced fractures is calculated by assuming that the dilatational plastic strain is manifested as discrete fracture planes. Theoretical results obtained post model calibration with field observations suggests that the damage zones are approximately 60-100 meters wide and the fracture density decreases with distance from the fault according to a power law with the rate of decrease approximately 0.8, both predictions in good agreement with our observations and outcrop studies of fault damage zones.

Finally, the damage zone observations and modeling results are used to build a reservoir model of the gas field using a discrete fracture network framework. The model is upscaled, and flow simulations performed (in a dual porosity framework) to highlight the hydraulic impact of damage zones on flow. Flow simulations show that pressure drawdown due to production is significantly larger in the absence of damage zones. This is due to higher flow rates facilitated by damage zones. These results show that considering the presence of damage zones is important in modeling flow and optimizing production.

Selected References

Hennings, P., P. Allwardt, P. Paul, C. Zahm, R. Reid, H. Alley, R. Kirschner, B. Lee, and E. Hough, 2012, Relationship between fractures, fault zones, stress, and reservoir productivity in the Suban gas field, Sumatra, Indonesia: AAPG Bulletin, v. 96/4, p. 753-772.

Paul, P., M.D. Zoback, and P. Hennings, 2009, Fluid flow in a fractured reservoir using a geomechanically constrained fault-zone-damage model for reservoir simulation: SPE #110542, Reservoir Evaluation & Engineering, v. 12/3, p. 562-575.

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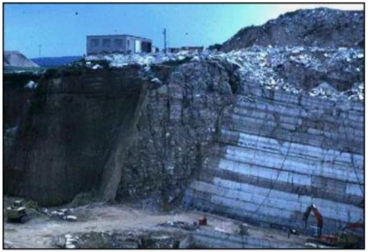
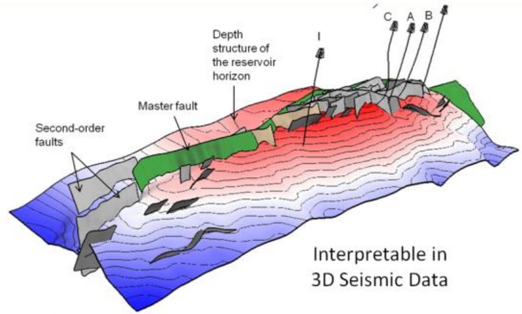
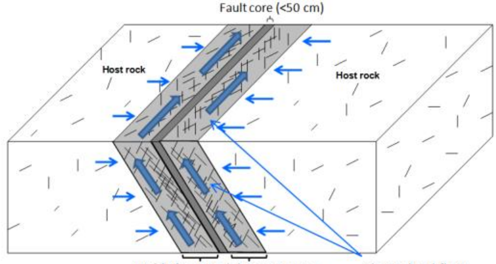
Faults and Fault Damage Zones

Second-order faults (~ 100s m - kms)



Courtesy of Peter Hennings





Presenter's notes: In this study, we are specifically looking at 2nd order faults on scales of 100s m –km (as shown), smaller than the large 1st order faults such as SAF, but large enough to be interpreted in seismic images as shown in this structural map showing the reservoir in this study.
Regardless of the size, a fault zone comprises of a fault core in the center surrounded by an intensely damaged region containing a large fracture population (DZ) usually formed due to stresses induced during slip across the fault plane.
The reason we are interested in studying of damage zones is in context of their impact on fluid flow when embedded in reservoirs. The fault core containing high strain products usually act as barriers to flow, but damage zones comprising of a large population of fractures facilitate fluid flow. So, if there are damage zones present in reservoirs, fluid flows from the host rock drains into the damage zone and gets channelized along it, thereby dramatically affecting the flow properties of the reservoir.

Importance, Challenges, Objective

- Importance: Field studies documenting the impact of damage zones on production
  – CS gas field (Paul et al., 2009)
  – Suban gas field (Hennings et al., 2012)

- Challenge: Lack of a quantitative understanding of damage zone characteristics in an easy-to-assimilate manner in reservoir models

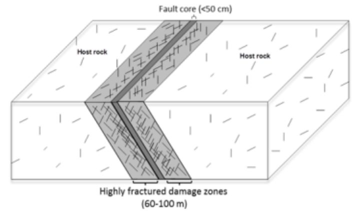
- Objective:
  - Quantitative characterization of damage zones
  - Incorporating damage zones in reservoir models illustrating their impact on flow and production

Presenter’s notes:

- Studies including those by Paul et al and Hennings et al have shown the dramatic impact of damage zones on flow of HC within a reservoir– they have shown that the wells that intersect damage zones are significantly more productive than the wells which do not.
- But although the impact of damage zones on flow is appreciated, conventional practices do not incorporated in generating reservoir models mainly due to an insufficient quantitative understanding on damage zone characteristics in a manner which facilitates their assimilation in reservoir models.
- Therefore, the objective of this work is to develop a quantitative understanding of reservoir-scale fault damage zones and incorporate them in reservoir models to illustrate their impact on production, and how ignoring their presence could lead to grossly erroneous predictions of flow.

Outline

1. Observations of Damage Zones at Reservoir Depths – SSC gas field and SAFOD
   - Width
   - Fault constant F_0 (Fracture density 1 m from the fault)
   - Decay of fracture density with distance from the fault



2. Modeling Damage Zones using Dynamic Rupture Propagation

3. Fluid Flow through Fault Damage Zones

Presenter's notes: We adopt a 3-pronged strategy in addressing this problem.

- First we identify 2nd order faults present in the reservoir and their damage zones from image logs, and then characterize those damage zones in terms of their width and spatial hetereogeneity in fracture density within the damage zone, essentially how the fracture density decays with distance from the fault. This study is performed in 2 areas, a gas field (SSC) and the arkosic sandstone section encountered around the borehole at SAFOD adjacent the SAF.
- Next, because image and other relevant data to identify damage zones is usually not available, we model damage zones in order to predict damage zones around 2nd order faults whose positions are well known from seismic images. We compare model results with observations for check and consistency.
- Finally, we integrate all information of faults from seismic images, damage zone attributes from modeling, and major fracture orientations from image logs to build a reservoir DFN model, and simulate flow through the model.

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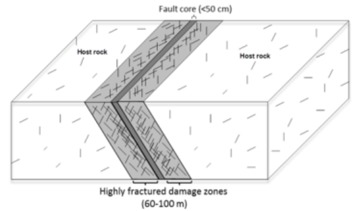

2. Modeling Damage Zones using Dynamic Rupture Propagation

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Conclusions*

- Decay of fracture density with distance can be described by a power law – similar to reports from outcrop studies

$$F = F_0 x^{-n}$$

- Decay rates (n)
  - Arkosic section: 0.4-0.75 (average ~ 0.56)
  - CPE gas field: 0.68-1.06 (average ~ 0.8)
- Fault Constant (F_0)
  - Arkosic section: 6-17 fractures/m
  - CPE gas field: 10-30 fractures/m
- Damage Zone widths: 50-80 meters

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*A Scaling Law to Characterize Fault Damage Zones at Reservoir Depths

Madhur Johri, Mark D. Zoback, and Peter Hennings – AAPG bulletin (submitted)

Presenter's notes: We concluded that – points 1, 2, 3, and 4.
These damage zone attributes have been obtained by interpreting and characterizing damage zones observed in image logs. In the next section, we will model damage zones and compare their attributes to these that are observed here.

Outline

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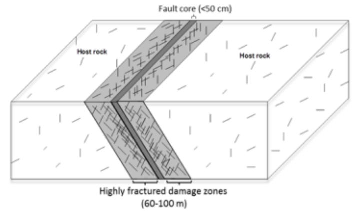


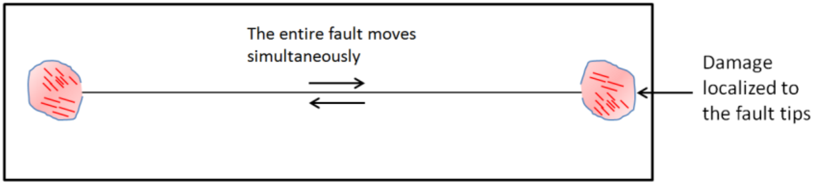
2. Modeling Damage Zones using Dynamic Rupture Propagation

3. Fluid Flow through Fault Damage Zones

Presenter's notes: Next, I'll discuss a methodology for modeling DZs and predicting DZ attributes that we observe.

Static Dislocation vs. Dynamic Model

Static Dislocation model:



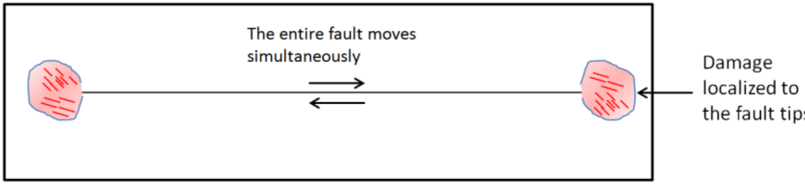
Presenter's notes: There are 2 popular approaches of modeling damage zones – the static dislocation approach and the dynamic model.

- In a static dislocation model, a uniform stress drop is considered along the slip surface, and stress concentrations are present only at fracture tips or fracture bends.
- In contrast, a dynamic rupture propagation model considers stress perturbations due to a slip pulse that propagates along the fault surface, and as the slip pulse propagates, it creates damage all along the length of the fault (consistent with field observations).

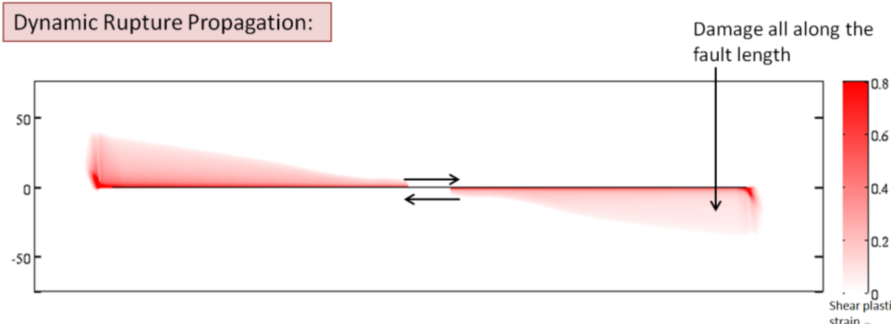
In this study, we adopt the dynamic rupture propagation model to model fault damage zones.

Static Dislocation vs. Dynamic Model

Static Dislocation model:

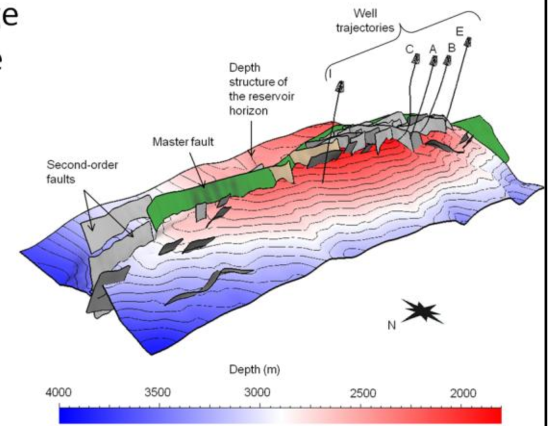


Dynamic Rupture Propagation:



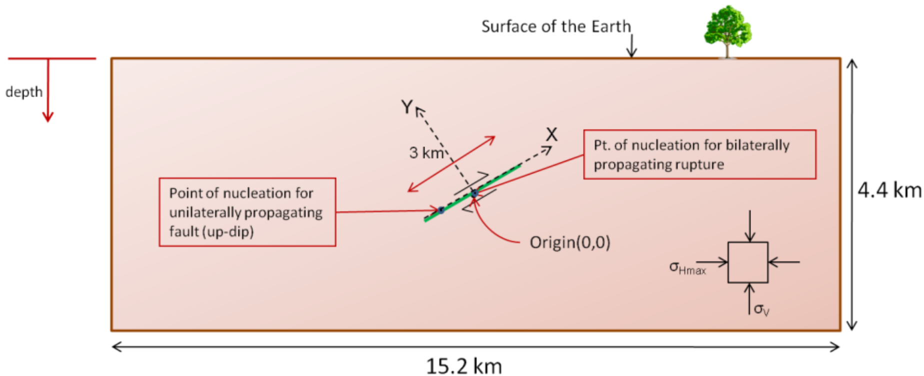
SSC Gas Field - Structural Map

- Objective: Model damage zone associated with the second-order faults
- 27 second order faults
  - Thrust faults
  - Reverse separation: 8-180m
  - Map lengths: 50m-3 km



Presenter's notes: This is the structural map of the gas field in our study – our objective is to model DZs around these 2nd-order faults and predict their attributes, and then compare them to DZ attributes observed (shown a couple of slides ago) to check whether the modeling is consistent.

Model Development



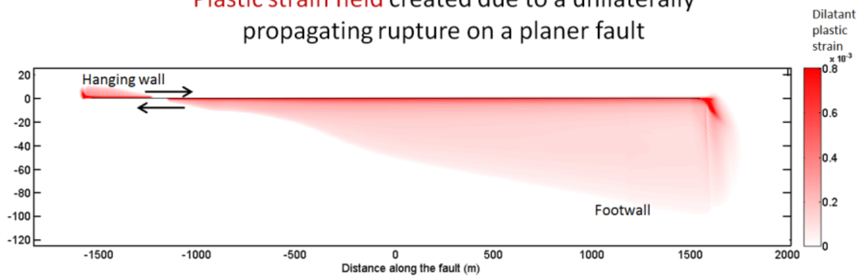
- 2-D plane strain models
- Fault Friction - Strongly rate weakening fault friction (in a rate and state framework)
- Off fault material : Drucker-Prager elastic plastic

Presenter's notes: Rupture propagation on the fault is studied using 2D plane strain models as shown in the figure. This is how we set up our model in 2D. We consider a 3 km fault shown in green. Surface of the Earth, origin. We consider the X axis to be along the fault while the Y axis is perpendicular to the fault. In the thesis, I have discussed two kinds of ruptures, one that nucleates at the fault center and propagates bilaterally while the other which nucleates towards the lower extent of the fault and travels unilaterally upwards. We have also discussed non-planer faults. However, in this presentation, I will only discuss ruptures that nucleate at greater depths and propagate unilaterally upwards on planer faults.

That was the geometric set-up. As far as the physical laws are concerned, the friction law on the fault surface is assumed to be strongly rate-weakening, while the material around the fault is assumed to be a Drucker Prager elastic plastic solid, and we follow the Drucker-Prager yield criteria to evaluate failure and then calculate the associated plastic strains. Details are provided in the thesis.

Plastic Strain field – Single Slip Model

Plastic strain field created due to a unilaterally propagating rupture on a planer fault



Region undergoing inelastic deformation assumed to be the damage zone created due to slip

Volume balancing: Dilatant Plastic Strain => Fracture Density

- Volume created by plastic strains is manifested in the formation of new fractures

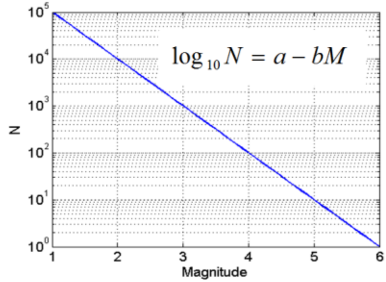
Presenter's notes: This figure shows the plastic strain field generated due to a rupture that nucleates at this point and propagates unilaterally in the up-dip direction. The X axis represents the surface of the fault (which dips at 30 degrees), but I have rotated it for better visualization. It is a thrust fault, so the part above is the hanging wall while the part below is the footwall. We call this region undergoing inelastic deformation the damage zone associated with the fault.

The dilatant plastic strains essentially create new volume, so we convert this plastic strain field into a fracture density field by assuming that the volume created by strains is manifested in the formation of new fractures, so by a volume balancing we can obtain the fracture density at each point.

At this point, we have modeled one event, but DZs are the cumulative result of several events occurring over geologic time scales.

Multiple Slip Model and Calibration

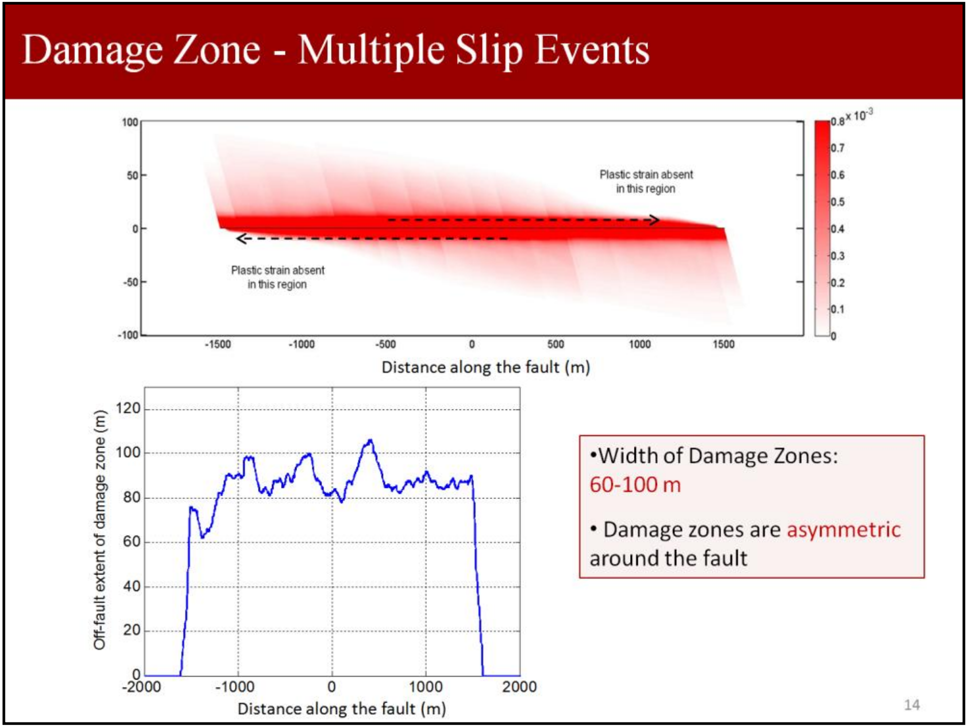
- Effect of multiple slip events - superimposing plastic strain field due to multiple slip events
- Distribution on slip events of various magnitudes – Gutenberg Richter Relationship
- How many slip events?
- Model Calibration
  - 'a' parameter (regional seismicity)
  - Fault constant (model)= Observed fault constant (image logs or scaling relationships)
  - F_0=20 fractures/m
  - Calibrated a = 6.3



Presenter's notes: The effect of multiple slip events on the formation of damage zone is considered by superimposing the plastic strain field obtained from multiple events of various size such that the distribution of slip events of various sizes is consistent with the GR relationship, shown graphically in this plot. I'm sure most of you know about it, it basically says that there are 10 times more events of a certain magnitude as compared to events of magnitude a unit larger.

Ok, so we are superimposing strain field due to multiple events- but the question is how many? And that how many is fixed by the parameter 'a' which actually is representative of the total seismicity rate of the region. We take that value of 'a' such that the fault constant (FD at unit distance) obtained after superimposing individual plastic strain fields matches the observed FC (from image logs, or scaling relationships between fault constant and fault displacement given by outcrop studies).

For the example shown which is a 3 km fault, the F0 observed is 20 fracs/m, for which we calculate the a value to be 6.3. For a different fault, we could have a different f0, and hence a different a.

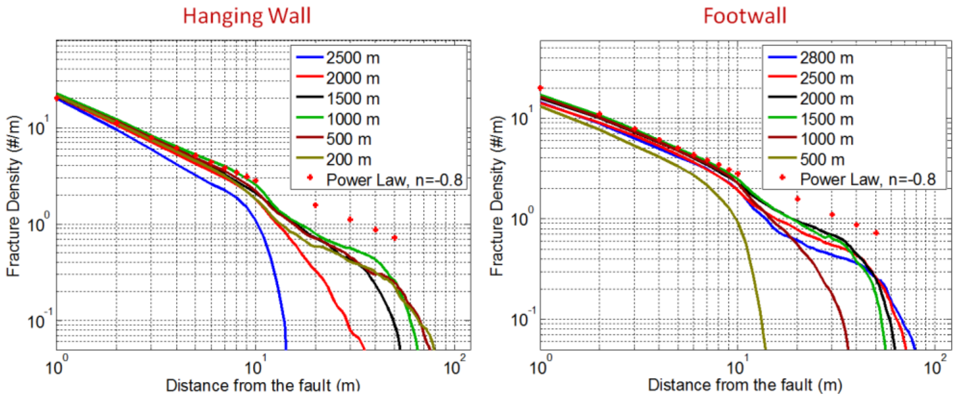


Presenter's notes: This figure shows the plastic strain field obtained by superimposing plastic strains due to several slip events. The plot below shows the width of the damage zone along the fault length.

These damage zones are 60-100meters wide, again consistent with field observations.

However, we should note that these damage zones are not symmetric around the fault, i.e. they are not necessarily of equal widths on either side (in the HW and FW).

Fracture Density Decay with Distance – Multiple Ruptures



- Decay of fracture density with distance can be described by a power law
- Rate of decay
  - Up to 10-20 m: 0.8
  - Beyond: larger decay
- Consistent with field observations (but truncated)

Presenter's notes: These 2 plots show the decay of fracture density with distance in the hanging wall and the footwall. Various colors in both the plots represent variation along different transects at the mentioned distances form the base of the fault. The dotted line for reference represents a power law decay with a rate of -0.8…which is a sort of an average decay reported from outcrop studies and observations.

1. The decay of fracture density with distance in the modeled DZs seems to follow a power law, the rate of decay is almost 0.8 upto 10-20 meters, after which the rate increases.
2. Fault constant fixed at 20 fractures/meter.

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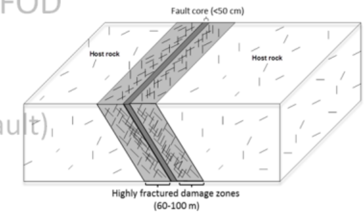


2. Modeling Damage Zones using Dynamic Rupture Propagation

3. Fluid Flow through Fault Damage Zones

Presenter's notes: So, the modeling of DZs is consistent with field observations. Next, we use information derived from modeling and observations to build a reservoir model containing DZS and modeling flow through those DZs.

Discrete Fracture Network (DFN) Models

- DFN models are more representative of fractured reservoirs
  - Flow simulated discretely through individual fractures
  - Channeling and preferential flow paths
  - Geomechanical coupling of fracture flow properties

- Computationally expensive and time consuming
- Hybrid models – DFN + Dual continuum models

Presenter’s notes: We build a reservoir model in the framework of DFNs, primarily because they provide a better framework for modeling phenomenon such as channeling and preferential flow paths, typically observed in fractured reservoirs. However, modeling flow through each fracture (in FE) is computationally very expensive, so DFNs are used in conjunction with the significantly faster dual continuum (DP) models, and that’s what we use n this study.

Since we don’t have enough data to predict production, we only generate a sector model of the reservoir containing a well that intersects 3 damage zones.

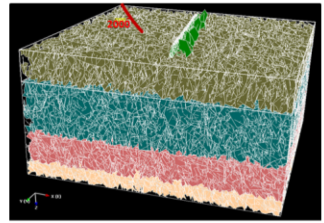
Workflow – DFN Generation, Dual Porosity Upscaling and Flow Simulations (FracMan and Eclipse)

Fracture location
- Background - Stochastic
- Damage Zones - Modeling

Geometric properties
- Length, shape
- Orientation

Flow properties
- Aperture
- Permeability

DFN generation



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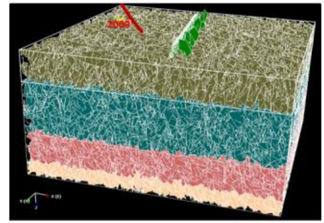
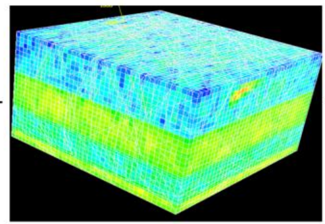
DFN generation



Upscaling (Oda)
- Permeability
- Shape factor



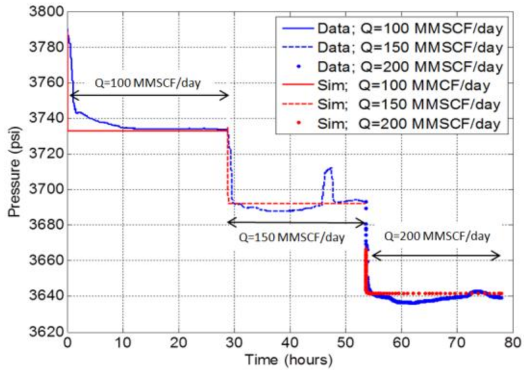
Well test simulation

Dual porosity

Model Calibration
- Flow after flow test

Flow Simulations

Well Test and Model Calibration

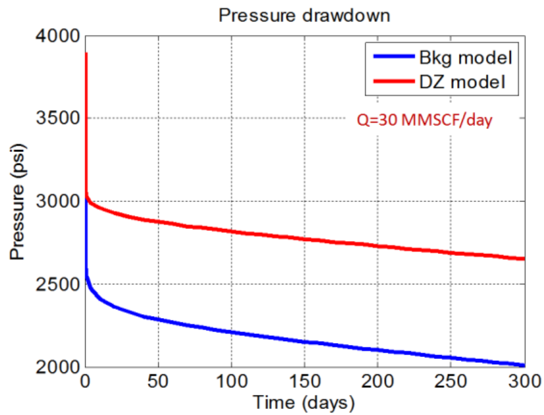


- Drawdown at 100 MMSCF/day – Model Calibration
- Drawdowns at 150 and 200 MMSCF/day – Model Validation

Presenter's notes: This plot shows the pressure drawdown observed during a flow after flow well test performed over a period of 80 hours, at 3 different flow rates of 100, 150 and 200 MMSCF/day. The blue line represents the actual drawdown observed while the red line represents the simulated pressure drawdown. The match is good enough for us to consider the fracture flow properties calibrated.

Next, we perform flow simulations. Since we do not have enough data to predict production, we basically just aim to show the impact of damage zones on flow.

Flow Simulation – Impact of Damage Zones on Flow



Bkg model: Only the background fracture population

DZ model: Background fractures and damage zones

Larger pressure decay in the absence of damage zones:

- Higher permeability and channelization
- High fracture density facilitates flow from matrix into the fracture system

Presenter's notes: For that, we consider 2 models, the BKG model containing only the background fractures and the DZ model containing both the background fractures and DZs. We produce the well in both the models at a rate of 30 MMSCF/day for a period of 300 days. The plot represents the simulated pressure drawdown. We observe that the pressure decay in the absence of DZs (in blue) is a lot larger than that in their presence (red), essentially because fluid gets channelised along DZs and can flow towards the well at significantly larger rates, thereby preventing as large BHP decays as observed in the absence of DZs.

This clearly shows the impact of DZs on flow, and how ignoring them can lead to erroneous conclusions and interpretations.

Conclusions

- Developed a methodology for
  - Modeling fault damage zones
  - Incorporating damage zones in reservoir models
  - Simulating flow through damage zone models
- Damage zone attributes modeled are consistent with those observed from field data and reported from outcrop studies
- Damage zones impact fluid flow
  - Good understanding can help optimize production

Presenter's notes: The 3 elements of this work – observations, DZ modeling, and flow simulations are really 3 independent pieces of work in 3 different papers, but I attempted to present all of them together just to give a flavor of how different applications including structural geology, earthquake seismology, geomodeling and flow modeling really come together to address a single problem which in my opinion is pretty important.

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