Fault Damage Zones in 3D with Active-Source Seismic Data

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Abstract

Damage zones are important to the rupture dynamics, evolution and fluid coupling of earthquakes. However, information about the damage zone at depth is limited. It is unclear if damage zones increase or decrease in intensity with depth. Here we use marine 3-D seismic surveys and modern fault detection methods to address the depth-dependent structure of damage zones. We use two overlapping legacy industry seismic volumes collected offshore of Los Angeles span approximately 20 km of the Palos Verdes strike-slip fault. The data here allows visibility of the damage zone in the sedimentary formations to 2,200 meters depth, which is comparable to the constraints provided by SAFOD and other studies. Using both interpreted mapped primary fault strands and seismic attributes to identify subsidiary faults, we map and quantify spatial variations in damage zone size and intensity. The damage zone consists of subsidiary faults, or linked discontinuities in the seismics selected within assigned ranges of geometries to the primary strands. Damage was identified using a variation of the seismic attribute semblance, or multi-trace similarity. This method allows interrogation of damage zone in response to changes sedimentary lithology and fault geometry. Subsidiary faults delineate the damage zone to approximately 1 km in width and fracture density decays with distance from the primary fault strands for all sedimentary lithologies in the study area. The damage zone narrows with depth, but fracture density increases because the intensity of fracturing more than compensates for the decreased width. In the thickest formation we find that fracture density increases as Z1.8, where Z is depth in meters. These results are then compared to resolution changes with depth. The damage intensity increase and localization potentially provides a strong constraint for efforts to determine an appropriate rheology for producing damage zones and studying their effects.

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Rock Damage in Fault Zones
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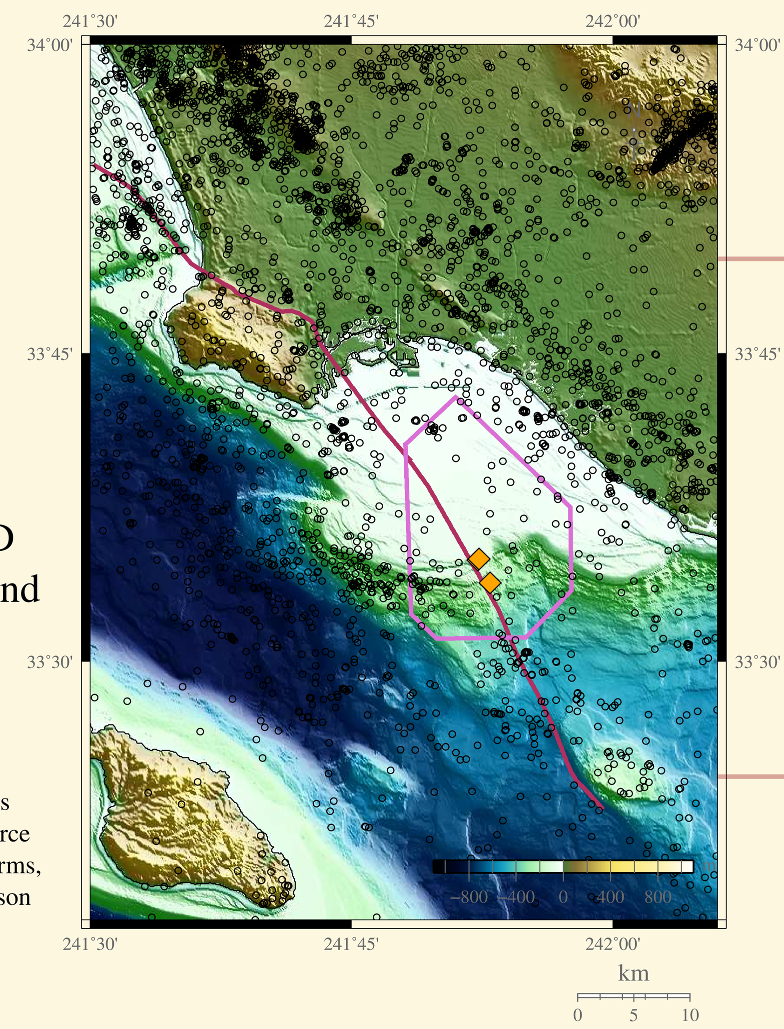
Introduction

Can we measure fault damage in 3D seismic data?

Why it's important:
◉ Damage zones are important to rupture dynamics, evolution, and fluid coupling of earthquakes.

Motivation:
◉ The Palos Verdes strike-slip fault and the recently release of industry collected marine 3D seismic data provides an opportunity to study and quantify in-situ spatial variation in damage associated with the fault.



Seismic Reflection Survey Details:

C-01-76-SC
3D multichannel seismic
Source: Airgun
Collected by: Chevron
Sample Rate: 4ms
Area: 230 km^2
Resolution: 50 x 25 m bins

B-388-84-SC
3D multichannel seismic
Source: Airgun
Collected by: Shell
Sample Rate: 4ms
Area: 46.4 km^2
Resolution: 26 x 13 m bins

(Data available through the USGS - National Archive of Marine Seismic Surveys)

Figure 1. Map of study area. Maroon line indicates the trace of Palos Verdes Fault, and purple polygon indicates the bounds of the 3D marine active source data sets. Orange Squares are the locations of offshore Beta-field oil platforms, and gray circles are earthquake epicenters (SCSN alternate catalog [Haukkson et al., 2012]).

Methods

Use mapped primary fault strands and seismic attributes to identify subsidiary faults and quantify damage spatially.

Manual Fault Mapping:
◉ Three distinct primary fault strands were manually mapped through both seismic volumes.
Mapping was done on vertical slices oriented perpendicular to fault strike, with higher resolution 2D seismic lines as an aid.

Seismic Attribute Analysis
◉ Attribute analysis was applied to seismic volumes in order to identify seismic discontinuities between traces. The Thinned fault likelihood attribute [Hale 2013] was used to identify discontinuities using a variation of semblance (a measure of trace similarity) which is structurally (s) oriented and smoothed (f).

$$semblance = \frac{<< image >_s^2 >_f}{<< image^2 >_s >_f}$$

$$fault\ likelihood \equiv 1 - semblance^8$$

‣ The volumetric local maxima of fault likelihood is preserved and the surrounding region are collapsed to the maxima, thinning the attribute.
‣ The thinned discontinuities voxels (3D pixels) are then scanned over strikes and dips with in reasonable ranges for linkages (with in 60 degrees of the Palos Verdes fault strike and dips in the 45- 89 range).
‣ The result is a seismic attribute identified fault and fracture network.

$$fracture\ density = \frac{N_{traces}[TFL > threshold]}{N_{traces\ total}}$$

Results

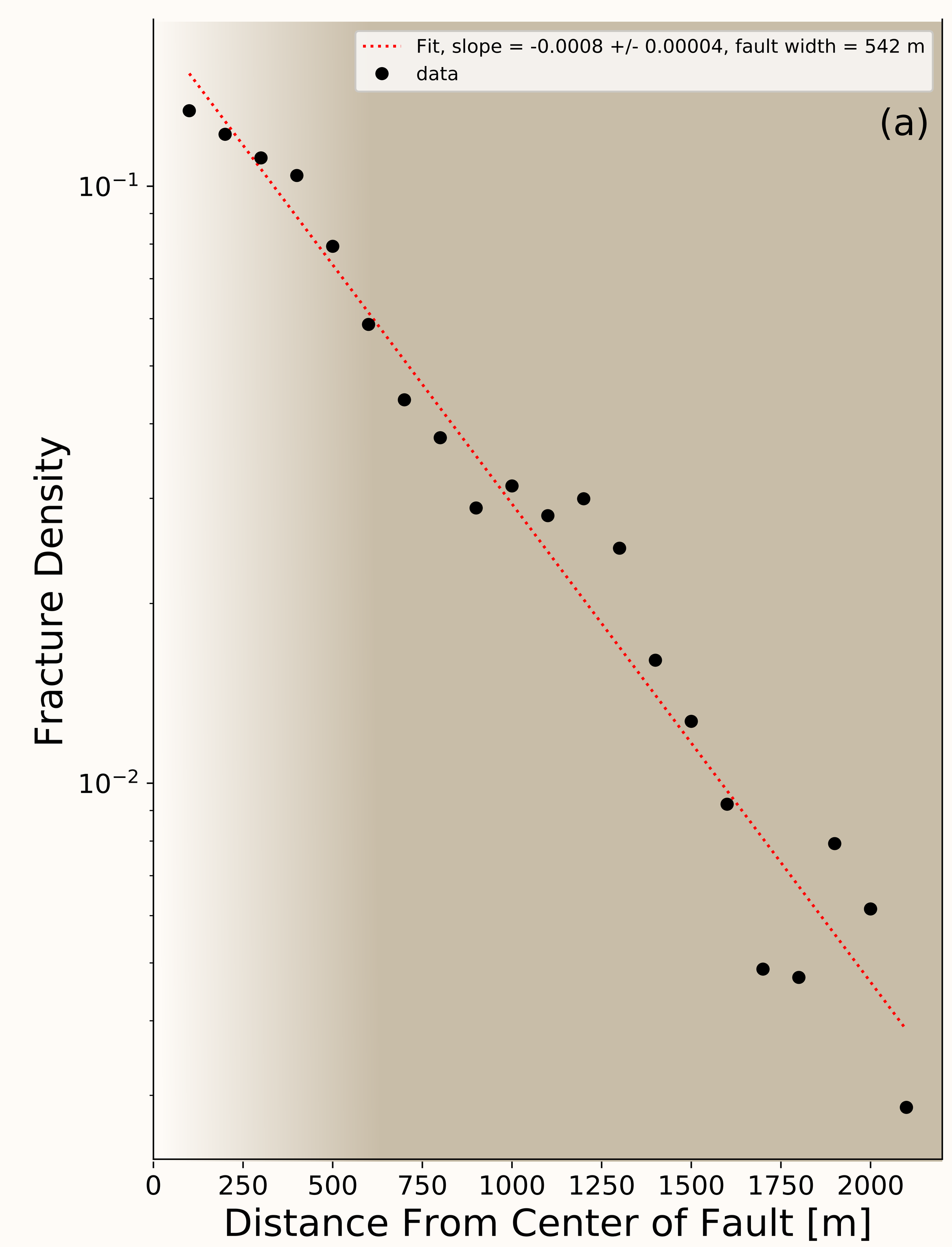
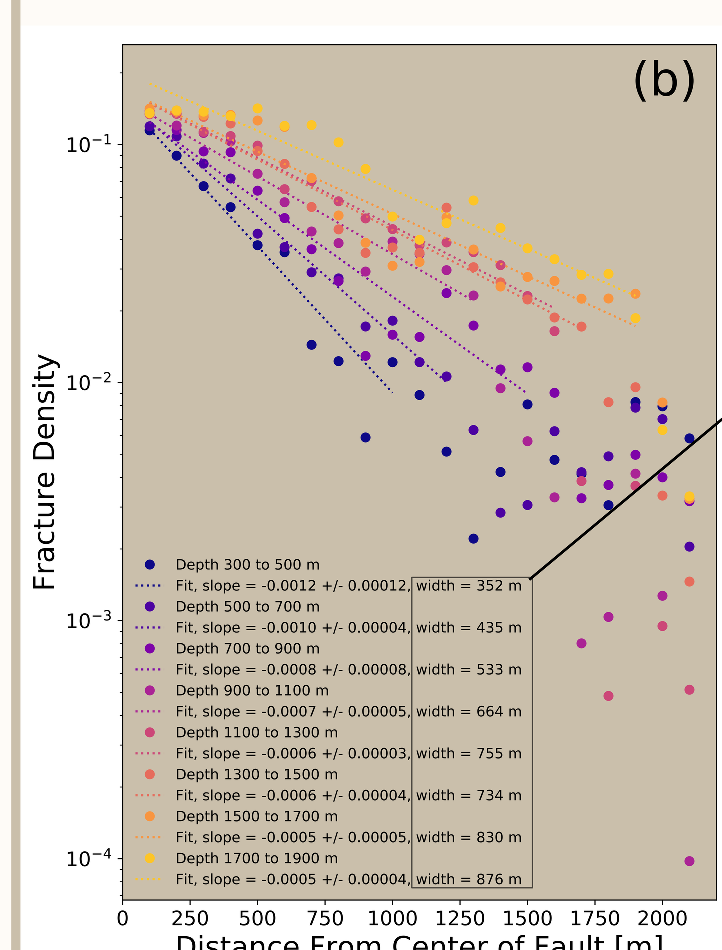
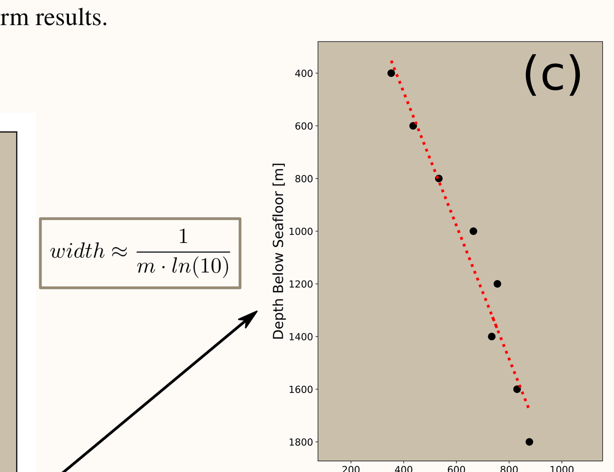


Figure 2. (a) Plot showing the exponential relationship of fracture density with increasing distance from the center of the central fault strand. Analysis was performed on larger volume (Chevron C-01-76-SC). Each point is a median value of fracture density binned by distance from fault. (b) Similar figure, further binned by depth below seafloor as shown in color scale. Widths are inferred as the e-folding distances. (c) Plot showing the depth vs width relation, notice the apparent widening with depth. More tests are needed to confirm results.





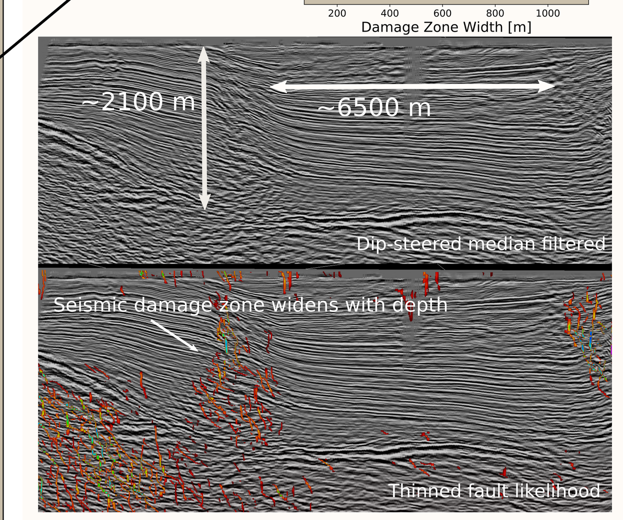


Figure 3. Visual example of thinned fault likelihood, Note the widening relationship with depth as shown in 2b & 2c.

Interpretation

Fault damage can be identified & quantified in 3D seismic data.

1. Damage decays exponentially with distance form the fault.
2. Lithology & age are a significant control on damage.
3. Damage increases with depth.

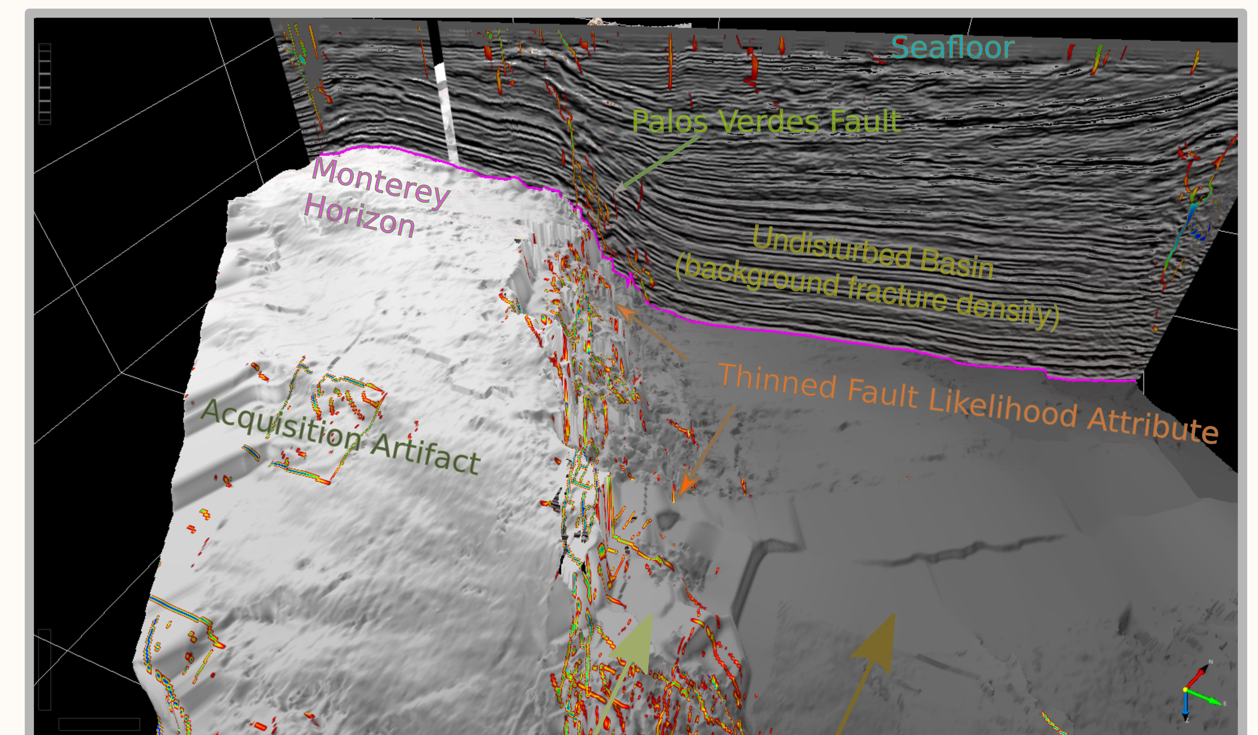
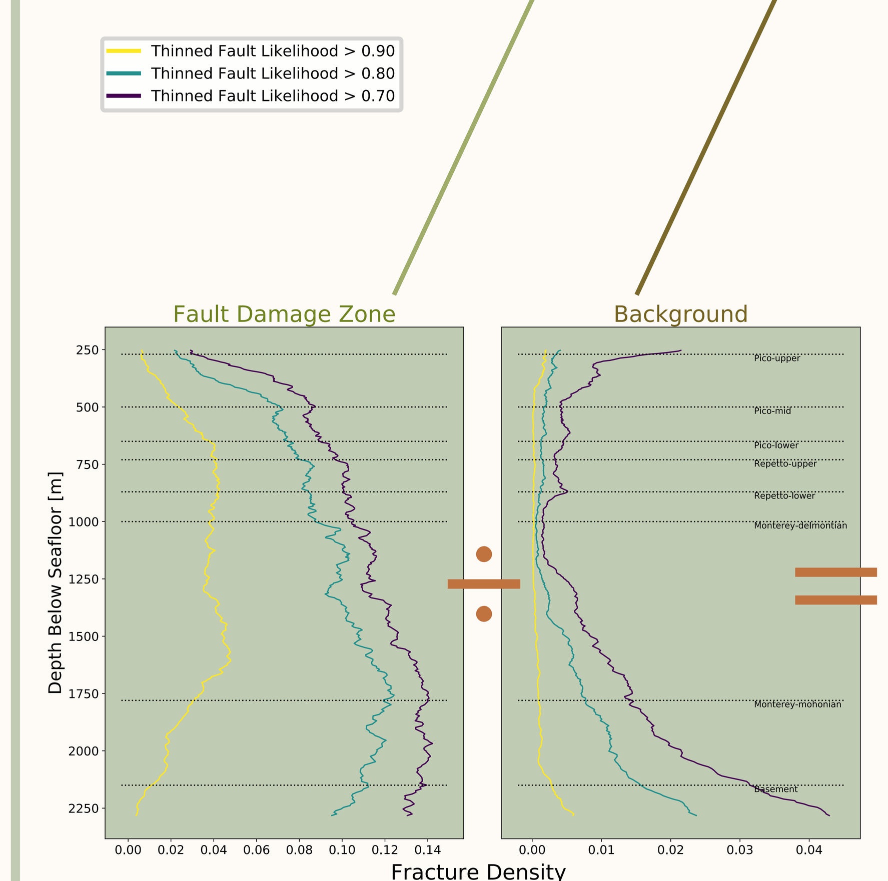


Figure 4. Perspective view of Thinned Fault Likelihood attribute results in high confidence ranges (0.75 - 1.00) along the Palos Verdes fault zone. The rainbow color-map ranges from red to violet, where violet is greatest probability of a fault. The attribute is projected on an strike-perpendicular line and an interpreted and interpolated horizon. Note the variable width of the damage zone along strike.



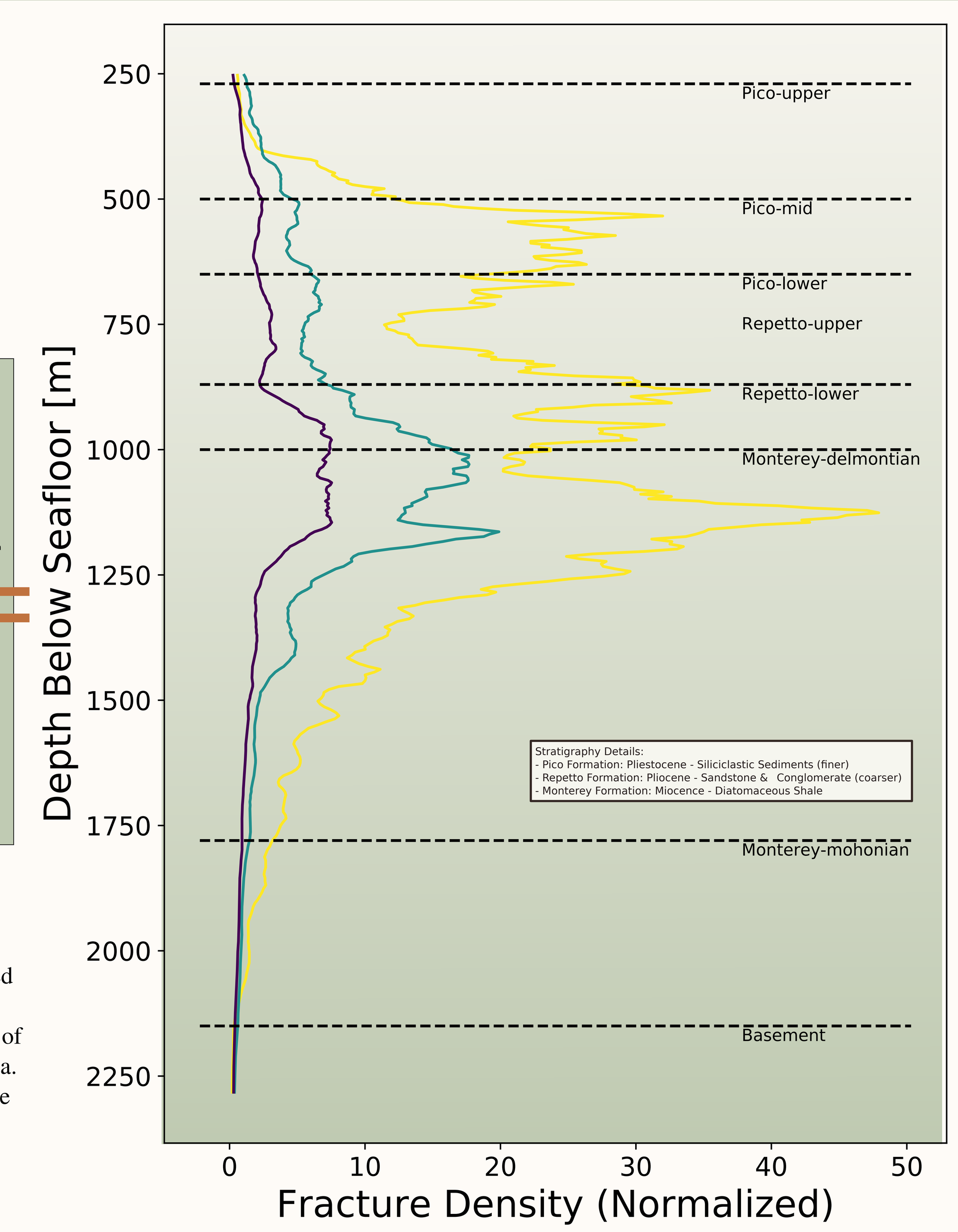


Figure 5. Fracture density variation with depth at three threshold values for thinned fault likelihood. (above) Fault damage zone - fracture density calculated within 650 meters east of the fault. Background - fracture density calculated within a range of 1500 - 3000 meters eastward of fault. Approximate locations of unit boundaries indicated as mean values of well tops logged within survey area. (right) Values for fault zone fracture density normalized by background fracture density. Note the influence of the unit boundaries.

References:
1. Hauksson, E., W. Yang, and P. M. Shearer. “Waveform Relocated Earthquake Catalog for Southern California (1981 to June 2011).” Bulletin of the Seismological Society of America 102, no. 5 (October 1, 2012): 2239–44.
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3. Savage, Heather M., and Emily E. Brodsky. “Collateral Damage: Evolution with Displacement of Fracture Distribution and Secondary Fault Strands in Fault Damage Zones.” Journal of Geophysical Research 116, no. B3 (March 31, 2011).