A scaling law to characterize fault-damage zones at reservoir depths

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ABSTRACT
We analyze fracture-density variations in subsurface fault-damage zones in two distinct geologic environments, adjacent to faults in the granitic SSC reservoir and adjacent to faults in arkosic sandstones near the San Andreas fault in central California. These damage zones are similar in terms of width, peak fracture or fault (FF) density, and the rate of FF density decay with distance from the main fault. Seismic images from the SSC reservoir exhibit a large basement master fault associated with 27 seismically resolvable second-order faults. A maximum of 5 to 6 FF/m (1.5 to 1.8 FF/ft) are observed in the 50 to 80 m (164 to 262 ft) wide damage zones associated with second-order faults that are identified in image logs from four wells. Damage zones associated with second-order faults immediately southwest of the San Andreas Fault are also interpreted using image logs from the San Andreas Fault Observatory at Depth (SAFOD) borehole. These damage zones are also 50–80 m wide (164 to 262 ft) with peak FF density of 2.5 to 6 FF/m (0.8 to 1.8 FF/ft). The FF density in damage zones observed in both the study areas is found to decay with distance according to a power law $F = F_0 r^{-n}$. The fault constant $F_0$ is the FF density at unit distance from the fault, which is about 10–30 FF/m (3.1–9.1 FF/ft) in the SSC reservoir and 6–17 FF/m (1.8–5.2 FF/ft) in the arkose. The decay rate $n$ ranges from 0.68 to 1.06 in the SSC reservoir, and from 0.4 to 0.75 in the arkosic section. This quantification of damage-zone attributes can facilitate the incorporation of the geometry and properties of damage zones in reservoir flow simulation models.

INTRODUCTION AND MOTIVATION
Field observations of relatively large-scale faults and damage zones frequently show that fault zones consist of a fault core
surrounded by damaged rock. The fault core, in which most of the displacement is accommodated, commonly occurs as a narrow, localized slip zone containing structures that are formed because of high strain (Figure 1), such as breccias, cataclasites, veins, and gouge (Aydin, 1978; Chester et al., 1993; Caine et al., 1996). Damage zones that are mechanically related to the growth of the fault zones exhibit a network of subsidiary structures including smaller faults, fractures, cleavage, and folds surrounding the fault core (Chester and Logan, 1986; Smith et al., 1990; Scholz and Anders, 1994; Goddard and Evans, 1995). Wide damage zones may represent the manifestation of multiple fault-slip events and the overprinting of successive stages of deformation (Caine et al., 1996). The damage zones are, in turn, surrounded by relatively undeformed host rock mostly devoid of any fault-associated fractures. Understanding the geometry and composition of the components of fault structure is critical to understanding the mechanical, seismological, and fluid-flow properties of the fault system.

Fault cores and damage zones are distinct hydrogeological units, which reflect the material properties and deformation conditions within a fault zone (Caine et al., 1996). Typically, the fault core, which is composed of structures related to high strain, has low permeability and porosity and acts as a barrier to fluid flow (Goddard and Evans, 1995; Caine et al, 1996). Because the degree of brittle deformation is significantly larger in the fault core (Andersson et al., 1991; Chester et al., 1993), the low fault-core permeability is governed by grain-scale (or smaller) matrix deformation of the fault rock (lowered further by clay gouge development). However, damage zones comprising higher permeability fractures and faults produce bulk permeability anisotropy related to higher permeabilities along the fault plane, thus enhancing fluid flow (Zhang and Sanderson, 1995; Paul et al., 2009). Lockner et al. (2000) and Wibberley and Shimamoto (2003) reported experimentally measured permeabilities and showed that the permeability of core samples from the damage zone is several orders higher than that of samples taken from the fault core. Although these results are more representative of the microfracture (length scale of microns to millimeters) characteristics and their spatial heterogeneity inside the damage zones, we expect a similar observation for macrofractures (length scale of meters). In fact, we speculate that the impact of macrofractures in damage zones would be more pronounced given their large-scale impact on bulk flow properties, and the fact that microfractures seal more readily making their impact ephemeral in most rock types and thermal histories. The bulk permeability of damage zones, however, is governed by the properties of the fracture network that include the fracture density and orientation, along with the hydraulic and

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mechanical characteristics of the fractures themselves, and whether the fractures are sealed (Laubach, 2003; Olson et al., 2009).

The primary difficulty in predicting or modeling the movement of hydrocarbons through damage zones arises because the permeability enhancement varies significantly as a function of distance from the fault core as a result of the change in fracture density with distance. Thus, understanding the spatial variability of fracture density inside damage zones is one of the key aspects in evaluating their impact on flow. In addition, damage zones create spatial permeability anisotropy because of increased flow paths (greater fracture density) and preferential flow directions (along the fracture plane). In a fractured, low-matrix-permeability reservoir, fluid drains from the fractures present in the surrounding rock mass into the highly permeable damage zones where large flow rates can be maintained when the well-perforation interval lies within the damage zone (Figure 1).

Several studies have documented the influence of damage zones on hydrocarbon production. Paul et al. (2009) studied a gas field in the Timor Sea where it was only possible to explain large gas production rates by introducing spatially variable permeability anisotropy associated with damage zones adjacent to faults in the reservoir. Hennings et al. (2012) showed that the wells that intersect damage zones, especially those with a large population of critically stressed fractures and faults in the Suban gas field (a fractured gas reservoir with very low matrix permeability) in Southeast Asia are most productive. Two wells with trajectories that intersected the highest number of fractures and faults in the damage zones of larger faults showed an increase in well performance by factors of 3 and 7 compared to wells not designed to intersect damage zones (Hennings et al., 2012).

Figure 1. A schematic of a fault zone showing the relatively impermeable fault core surrounded by the highly fractured damage zone. In a fractured, low matrix permeability reservoir, fluid from the fractures in the surrounding rock mass drains into the highly permeable damage zones.
Despite their importance, the occurrence of permeable fractures and small faults in damage zones have not traditionally been incorporated in reservoir simulation models because of the inability of geologists to provide damage-zone characteristics in a quantified manner that is practical to assimilate in flow-simulation models. In addition, the reluctance of reservoir engineers to include more geologic complexity and associated uncertainty (regarding the spatial location, clustering, size, geometry, and flow properties of fractures) contributed. However, we are beginning to see this improve as a result of increased collaboration between the two communities (Pasala et al, 2013; Zhang et al, 2013).

Flow-simulation models that do incorporate damage zones are usually generated by assigning effective permeability tensors to reservoir grid blocks. The permeability tensor of each grid block depends on the characteristics of fractures inside the grid block, such as fracture density, orientation, and fracture permeability. The outstanding question, therefore, is how do we estimate the spatial extent and heterogeneity of permeability anisotropy at reservoir scale using the available subsurface data? This issue can be addressed by studying properties of damage zones, such as the spatial extent of damage zones and variation of fracture density with distance from the fault surface in damage zones using subsurface data such as image logs. Paul et al. (2009) adopted this methodology to study the decay of fracture density inside damage zones. However, because all the wells in that study were outside the fault-damage zones, they had no direct data constraint on damage-zone characteristics and the variability of fracture density with distance from the fault.

We focus our attention on three primary damage-zone attributes: the spatial extent (width) of damage zones, the peak fracture density within damage zones, and the spatial heterogeneity of fracture density within damage zones. These attributes are functions of a wide range of factors, such as the amount of slip across the fault, size of the fault (Mitchell and Faulkner, 2009), lithology, rupture processes, and movement history (Caine et al., 1996). Various outcrop studies in the past have shown that fracture density inside damage zones decreases with distance from a fault (Schulz and Evans, 1998, 2000; Vermilye and Scholz, 1998; Shipton et al., 2005; Mitchell and Faulkner, 2009; Savage and Brodsky, 2011). Savage and Brodsky (2011) have suggested that the fracture density decays with distance from isolated faults according to a power law \( F = F_0 r^{-n} \) in which \( F_0 \) is the fault constant (the fracture density at unit distance from the fault), \( r \) is the distance from the fault, and \( n \) is an exponent describing the decay (Figure 2A). Compiling various published fracture-density profiles, Savage and Brodsky (2011) find the decay rate \( n \) is ∼0.8 for smaller faults (with slip less than ∼150 m [∼492 ft]), and it decreases for larger faults with greater displacements. The authors also report that the fault constant \( F_0 \) is fault specific and seems to depend on lithology and fault displacement. However, an alternate study by Mitchell and Faulkner (2009) suggests that this fracture density at unit distance is constant (∼100 fractures/m [30.5 fractures/ft]), independent of the size of the fault, and represents a critical level of fracturing before fracture damage is so intense that brecciation and cataclasis begin. Previous studies have also reported that fracture-density decay can be expressed by exponential and logarithmic laws (Chester et al., 2005; Faulkner et al, 2008). However, power law decay with distance seems more reasonable because the stress perturbations, which eventually lead to damage, decay with the inverse of distance from a propagating crack tip during dynamic rupture propagation (Love, 1927; Freund, 1979). Several field studies and compilations have also shown that damage zones grow linearly with displacement, but not at all locations (Shipton and Cowie, 2001), with most damage-zone growth occurring early in the fault-slip history (Childs et al., 2009). Savage and Brodsky (2011) have reported that the fault zone width scales with cumulative fault displacement up to a threshold value of approximately 2400 meters (7874 ft), beyond which the scaling breaks down and further growth in the damage-zone width is more gradual (Figure 2B).

The presence and attributes of damage zones at depth can be studied directly with ultrasonic and resistivity image logs, whereas sonic, resistivity, and porosity logs indicate changes in physical properties related to the presence of fractures. In this paper, we characterize subsurface damage zones at depth using fault and fracture information derived from image logs, and then compare our observations with those
summarized above, which are based on outcrop studies. We only consider macroscopic-scale fractures visible in the image logs. For reference, we refer to very large faults, such as the San Andreas fault and the large master fault in the SSC reservoir, as first-order faults, the relatively smaller faults that are seismically resolvable as second-order faults (SOFs), and the still smaller subsidiary fractures and faults seen only in image logs as third-order features. These features seen only in image logs could be fractures (planar discontinuities) or small faults (fractures with a finite shear displacement), although we suspect that most of these features are small faults (because most fractures at depth probably have a finite slip across their surface). We refer to these third-order features as fractures and faults (FF). First-order faults are expected to be associated with well-developed fault systems with complex and mature damage zones, and several generations of splaying faults and fault cores formed by overprinting of successive stages of slip and deformation. Thus, the fault core may be a single structure or occur as a wider zone containing multiple strands and fault cores (Faulkner et al., 2003, 2008; Mitchell and Faulkner, 2009; Zoback et al., 2011). The SOFs represent relatively isolated faults with relatively smaller displacement and having relatively simpler damage zones. In this paper, we specifically investigate damage zones associated with these SOFs primarily because these are more frequently encountered in reservoirs and are, therefore, more relevant to influencing the bulk flow properties of reservoirs.

We report observations from two distinctly different regions. The first area of study is the faulted SSC reservoir where we characterize damage zones encountered in five wells drilled in the reservoir. We then discuss damage zones associated with SOFs that occur in a well-cemented arkosic sandstone section adjacent to the San Andreas fault in central California. We compare these subsurface damage zones with those identified in the outcrop studies summarized previously in terms of fracture density and the decay rate of fracture density with distance from the fault. In a companion study (Johri et al., 2014), we also compare damage-zone attributes observed in this study with those theoretically predicted by dynamic rupture-propagation models.

**Damage Zones Associated with Faults in the SSC Reservoir**

The SSC reservoir (Figure 3) produces hydrocarbons principally from compressionally uplifted, fractured,
crystalline, and metamorphic basement rocks and overlying clastic and reefal carbonate rocks. Interpretation of the prestack depth-migrated three-dimensional (3-D) seismic volume across the domain of the field yielded a large thrust master fault (with a throw of \( \sim 700 \) m \( \sim 2297 \) ft) and strike length of \( \sim 13 \) km \( \sim 8 \) mi) and several second-order reverse faults (Figure 3). The map lengths of these faults range from 50 to 3000 m (164 to 9843 ft), whereas the maximum throw ranges from 8 to 180 m (26 to

Figure 3. Three-dimensional structural model of the southwestern domain of the SSC reservoir viewed from the north. The model shows the master fault, reservoir-scale second-order faults, well trajectories, and the depth structure of the reservoir-bottom horizon. Contour interval is 100 meters (328 ft).
591 ft). All SOFs have a reverse separation. They strike subparallel to the master fault and are concentrated in a 1×8 km (0.6×5 mi) area along the crest of the anticline. The region of interest is in the hanging wall of the master fault that is characterized by a strike-slip stress regime.

We examine five wells (Figure 3): A, B, C, E, and I. Wells A, E, and I are near-vertical wells, and wells B and C are deviated wells. Well tests suggested that poor correlation exists between wellbore–reservoir contact length and well performance, and also, a very weak correlation exists between well performance and the total number of FF that the wells intersect. However, the well performance correlates strongly with the total number of critically stressed FF transected by the well.

According to the critically stressed-fault hypothesis, FF that are mechanically active are hydraulically conductive, and those that are mechanically dead are hydraulically dead (Barton et al., 1995; Zoback, 2007). This means that faults on which the ratio of resolved shear to effective normal stress is greater than the coefficient of sliding friction (normally about 0.6; Byerlee, 1978) are expected to be mechanically active and to slip. Fault slip may lead to dilatancy and brecciation (Dholakia et al., 1998), which in turn imparts enhanced permeability to the fracture. However, it is important to note that whereas the critically stressed-fault hypothesis may help us identify which FF are likely to be permeable, and other geologic factors, such as degree of alteration and cementation of the brecciated rock within the fracture, and its diagenetic history (Fisher and Knipe, 1998; Fisher et al., 2003), determine the actual permeability. Of course, other viewpoints suggest that diagenesis may be a critical factor that controls fracture permeability. For example, Laubach (2003) and Laubach et al. (2004) provide evidence that mechanically stable or dead fractures are not necessarily hydraulically dead and vice-versa. However, the critically stressed hypothesis appears to explain the hydraulic properties of fractures fairly well in the SSC reservoir.

Characterization of FF identified in image logs in terms of local state of stress reveals that critically stressed FF in the SSC reservoir are steeply dipping. Directing the well path through fault-damage zones increases the FF population that the well intersects, whereas deviating them increases the probability of wells intersecting a larger population of steeply dipping critically stressed FF. Wells B and C were purposely deviated to target fault-damage zones and have potential well performance ranging from 3 to 7 times higher than non-deviated wells.

Regions of anomalously high FF density (identified in image logs) around SOFs encountered along the wells are interpreted as damage zones associated with those SOFs (Figure 4). The depths at which wells intersect seismically interpreted SOFs are constrained from seismic images whereas the positions of subseismic SOFs are constrained by identifying abrupt changes in bedding-plane orientations or concentrations in FF identified in image logs (in intervals where bedding planes are absent or uninterpretable). For subseismic SOFs identified purely on the basis of regional concentrations in FF density, we observe a high FF density that decays sharply with distance on either side along the well—a significant damage-zone character. The geomechanical modeling essential to constraining the stress state and identifying critically stressed FF is not reported here for proprietary reasons. The peak FF density and peak critically stressed FF density in most damage zones identified in these wells is approximately 1.5–2 FF/m (0.5–0.6 FF/ft) and 0.25–0.5 FF/m (0.07–0.15 FF/ft), respectively (Figure 4). Many apparent damage zones appear to overlap, making it difficult to identify their width. However, most damage zones appear to be approximately 50–80 m (164–262 ft) wide (Figure 4). The FF density is larger in the deviated well (well B) as compared to the vertical wells. Most of the wells do not intersect the seismically identified SOFs. Well A intersects only one of those faults (at 2490 m [8169 ft]), although we observe well-defined concentrations of FF that resemble damage zones in image logs around positions marked by arrows in Figure 4. Well E does not intersect any seismically identified SOF, but it passes near one between 2700 and 3100 m (8858 and 10171 ft). Thus, although it does not intersect the fault, it samples the damage zone along an extended length. Several other well-defined damage-zone-like features are observed around positions marked by dotted blue arrows in well E (Figure 4), but direct evidence is lacking, suggesting the presence of a fault. Well I is also not interpreted
to intersect any SOF, yet the FF histogram reveals well-defined damage zones and FF peaks around positions marked by dotted blue arrows (Figure 4), again suggesting the presence of seismically unresolvable SOFs. This well terminates close to the master fault (~10 m [~32.8 ft]), which may be the reason for an elevated FF density at the bottom of the well. Well B was drilled with the intention of intersecting a large number of natural FF in damage zones, and is also the well with the highest production. It intersects three seismically identified second-order faults. Although the regions where the well intersects the first two faults are marked by increase in FF density, a high FF density is not observed around the third fault as a result of poor data quality in an area of extremely large FF density, which prevents identification of individual FFs. High FF density is also observed at the bottom of this well because it terminates close (<10 m [<32.8 ft]) to the first-order master fault.

**Removal of Sampling Bias from the Well FF Data**

To characterize the number of FF at depth using image logs, we correct for the sampling bias resulting
from the inability of the wells to sample FF oriented subparallel to the wells (Terzaghi, 1965; Einstein and Baecher, 1983; Appendix). As wells A, E, and I are near-vertical wells, they undersample steeply dipping FF significantly. As expected, a significant increase occurs in the number of FF dipping steeply after the correction is applied (Figure 5). For example, only four FF dip between 85 and 90° in the original FF population. However, this number increases to 160 in the corrected FF population. This clearly demonstrates that undersampling of FF subparallel to the well is an important concern to obtain an appropriate and representative fracture characterization within the reservoirs.

A significant increase also occurs in the total and critically stressed FF population after correcting for the sampling bias (Figure 6). The peak FF density in most damage zones in wells A, E, and I is approximately 5–6 FF/m (1.5–1.8 FF/ft), whereas the original peak FF intensities were approximately 2–3 FF/m (0.6–0.9 FF/ft). The percentage increase in the peak critically stressed FF population (from ~0.25–0.5 to 1–3 FF/m [~0.07–0.15 to 0.3–0.9 FF/ft]) is greater because the critically stressed FF are steeply dipping, the orientations that are most strongly biased against by the vertical wells. The peak FF density in damage zones in well B increases from ~2.5–3.5 to ~6–7 FF/m (~0.8–1.1 to ~1.8–2.1 FF/ft) after bias correction. The difference in the FF population between the vertical and deviated wells before the correction is significant; however, that difference is only modest after the correction is applied. This is expected because the corrected fracture population is meant to be representative of fractures in the rock volume and independent of the well trajectory along which fractures are sampled. Table 1 lists the number of FF intersected by the wells before and after correcting for the sampling bias. From the corrected FF population, we notice that the regional density of critically stressed FF around well A is 1.58 FF/m (0.48 FF/ft), which is larger than that around other wells (0.36, 0.59, and 0.52 critically stressed FF/m [0.11, 0.18, and 0.16 FF/ft] around wells E, I, and B, respectively). We can perhaps argue that, if an appropriately deviated well was drilled in the region around well A, it could potentially have been even more productive than the prolific well B.

In the above method, however, a danger exists of amplifying the number of steeply dipping FF. Observation of a few FF subparallel to the well turns into a large number of corrected FF. By analogy, missing a few of these FF oriented subparallel to the well would lead to a discrepancy in the corrected FF data set. Therefore, it is critical that fractures and faults are picked with care in the FMI image logs so that the uncorrected FF population and their orientation distribution are consistent.

Figure 5. Histograms of FF dips before and after the correction of sampling bias for well A.
We also studied the damage zones that are encountered in well-cemented arkosic sandstones and conglomerates immediately southwest of the San Andreas fault zone at the SAFOD site near Parkfield, California (Figure 7, after Zoback et al., 2011). The previously unknown arkosic sandstones and conglomerates, with some interbedded shales (Boness and Zoback, 2006; Solum et al., 2007) are juxtaposed against granitic rocks of the Salinian block to the southwest and against fine-grained Great Valley Group and Jurassic Franciscan rocks to the northeast (Figure 7). These rocks are strongly cemented, and their seismic velocities and resistivity are similar to the fractured Salinian granites and granodiorites from which they were likely derived. Petrographic details of cores from the arkosic section are provided in Springer et al. (2009). The Buzzard Canyon fault is subparallel to the San Andreas fault (Rymer et al., 2003; Thayer and Arrowsmith, 2005). In the main SAFOD borehole, the Buzzard Canyon fault separates the granodiorite from the arkosic rocks. This section of arkose is present from 1920 to 3157 m (6299 to 10358 ft; measured depth) along the main hole drilled at SAFOD (Boness and Zoback, 2006; Solum et al., 2007). The San Andreas and Buzzard Canyon faults are the first-order faults in this region.

The arkosic section is divided into several structural blocks. Springer et al. (2009) have identified

**Figure 6.** Same as Figure 4, but for a fractures and faults population corrected for sampling bias. SOF = second-order fault.
Table 1. Contact Length of Wells A, B, E, and I with the Reservoir along with the Number of All Fractures and Critically Stressed Fractures That the Wells Intersect Prior to and after the Fracture Population Has Been Corrected for the Sampling Bias

<table>
<thead>
<tr>
<th>Well (Suban)</th>
<th>Reservoir Wellbore Contact Length (m)</th>
<th>Before Correction</th>
<th>After Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>All Fractures</td>
<td>Critically Stressed Fractures</td>
</tr>
<tr>
<td>Well A</td>
<td>234</td>
<td>547</td>
<td>91</td>
</tr>
<tr>
<td>Well B</td>
<td>758</td>
<td>1261</td>
<td>194</td>
</tr>
<tr>
<td>Well E</td>
<td>772</td>
<td>903</td>
<td>63</td>
</tr>
<tr>
<td>Well I</td>
<td>957</td>
<td>800</td>
<td>140</td>
</tr>
</tbody>
</table>

Figure 7. Simplified geologic cross section parallel to the trajectory of the San Andreas Fault Observatory at Depth (SAFOD) borehole. The geologic units are constrained by surface mapping and the rock units encountered along both the main borehole and the pilot hole (Zoback et al., 2011).
three main lithologic units within the arkosic section, which have further been subdivided into 11 structural domains based on bedding orientations determined from the analysis of the electrical image log data. Our first objective is to constrain the position of second-order faults that divide the arkosic section into several structural domains. We do so by identifying abrupt changes in bedding-plane orientations observed in the image logs (Figure 8). The second objective is to study the damage zones associated with these SOFs.

Dynamically normalized electrical image logs were collected in the arkosic section and analyzed to identify third-order features and bedding planes, and evaluate their orientations. We also examine primary (P) wave velocity logs derived from sonic monopole velocity logs, dipole secondary (S) wave velocity, resistivity, and neutron porosity logs to determine the signature of damage zones because highly fractured depth intervals would have a low-velocity, low-resistivity, and high-porosity response (Figure 9). Fourteen blocks (referred to as blocks a–n) were identified on the basis of changes in orientation of bedding planes (Figure 8). We suspect that these blocks are separated by subseismic SOFs for many of these block boundaries have well-defined damage zones around them marked by an increase in observed FF density (as do Springer et al., 2009). Several of these boundaries are also indicated by decreases in sonic velocities and resistivity and increase in porosity (Boness and Zoback, 2006).

Blocks a–i compose the upper arkose as defined by Springer et al. (2009). These rocks are quartz and feldspar rich and are relatively homogeneous. A clay-rich region with a marked increase in gamma-ray and porosity logs and a decrease in sonic velocities extends from 2530 to 2680 m (8301 to 8793 ft) measured along the borehole (Boness and Zoback, 2006). We identify two blocks (j and k) lying in this region. Blocks l, m, and n lie in the lower arkose region (Springer et al., 2009). The average porosity in this region is less than that in the upper arkose. The amount of quartz in the lower arkose is also less than in the upper arkose, and most of the quartz that is present is plastically deformed (as evidenced by full grains present in the crystal structure [Springer et al., 2009]), which could be indicative of creep behavior and relatively less faulting. Of the 14 block boundaries that we identified (Figures 8, 9), 9 are similar to those identified by Springer et al. (2009). The depths of bedding block interfaces identified in Springer et al. (2009) are 1920, 2145, 2225, 2250, 2290, 2530, 2565, 2680, 2880, 3010, and 3157 m (6299, 7037, 7300, 7382, 7513, 8301, 8415, 8793, 9449, 9875, and 10358 ft).

The histogram of FF identified along the borehole shows the positions of various interpreted subseismic SOFs and their damage zones (Figure 9). These SOFs are numbered 1–14, in which fault number 1 separates block a from block b and so on. The widths of damage zones associated with the SOFs are typically on the order of 50 to 80 meters (164 to
The Buzzard Canyon fault, the major near-vertical fault striking subparallel to the San Andreas fault at the western boundary of the arkosic section has a width of approximately 200 m (656 ft) wide (Zoback et al., 2011).

Figure 9. The $P$-wave, $S$-wave, resistivity, and gamma-ray logs and geology in the arkosic section encountered by the borehole at San Andreas Fault Observatory at Depth. The histogram on the far right represents the FF identified in the formation micro-imager (FMI) logs. The orange horizontal lines (numbered 1–14) indicate the block boundaries that may represent second-order subseismic faults. Gray and yellow bars in the histogram represent good and poor quality of the image log. Well-developed damage zones (evidenced by the histogram peaks) around most of the block interfaces strengthens our conviction that these are second-order faults (modified from Boness and Zoback, 2006).
damage zone ∼120 m (∼394 ft) in width (Figure 9). The width of damage zones associated with the SOFs are again interpreted as the interval along the borehole having a FF density larger than the background FF density. Damage zones around faults 1, 9, 12, and 14 are approximately 60–80 m (197–262 ft) wide, whereas those around faults 12 and 13 appear to overlap each other. The peak FF density around these faults is approximately 3–4 FF/m (0.91–1.22 FF/ft). Damage zones around faults 3 to 8 overlap each other. This may, perhaps, be a fault with multiple strands. The peak FF density in their damage zone is approximately 2 FF/m (0.61 FF/ft). Damage zones around faults 2, 10, and 11 are fairly well defined, but they have a relatively lower peak FF density. Poor image quality (probably caused by very intense damage) could prevent identification of discrete fractures. Damage zones around these faults are approximately 40–50 meters (131–164 ft) wide and their peak FF density is approximately 1.5–2 FF/m. We also observe a sharp decay in the density of FF with distance from the fault. Several authors have shown that the width of damage zones scales with slip across the fault (Mitchell and Faulkner, 2009; Johri et al., 2014). If this is true, faults 1, 9, 12, 13, and 14 may have a relatively greater slip. The P- and S-wave velocities, as expected, are usually low in the vicinity of most suspected SOFs (Figure 9). A marked decrease in velocities and resistivity occurs around SOFs numbered 1 and 10. However, damage-zone signatures around most of the other SOFs on the geophysical logs are only subtle, marked by a modest local decrease in velocities and resistivity.

**Removal of Sampling Bias from the SAFOD FF Data**

We correct the FF population for the sampling bias (Appendix) similar to what we did for the fracture data set from the SSC reservoir (Figure 10). The peak FF density in damage zones after correcting for sampling bias is approximately 2.5–6 FF/m (0.76–1.8 FF/ft). The increase in the FF population after correction is not very significant. This may be due to the following reasons. First, FF oriented subparallel to the borehole are very few. Second, the sampling-bias-removal algorithm upscales the number of FF with a certain orientation identified in the image logs by an upscaling factor. If no FF are identified within a certain orientation range, no upscaling is performed and an increase in FF population is observed associated with that range of orientations (Figures 14, 15). The FF orientations subparallel to the well identified in the image logs are completely absent, hence the minimal increase in FF population.
VARIATION OF FF DENSITY WITH DISTANCE FROM FAULTS IN DAMAGE ZONES

We investigate the trend of decreasing FF density with distance from SOFs to compare them with observations from outcrop studies. However, at least three inherent difficulties exist in performing this analysis using image logs. First, as the borehole in SAFOD and most wells in the SSC reservoir did not intersect seismically resolvable SOFs, the orientation of the SOFs is unknown. Thus, calculating the perpendicular distance of FF from the second-order fault plane is difficult. Second, most damage zones observed in the image logs overlap, so it is difficult to associate certain FF with a unique fault. Finally, varying image log quality at various intervals greatly affects the identifiable FF, and hence the damage-zone characteristics. These caveats should be kept in mind while drawing conclusions.

To investigate relationships of FF density with distance from a fault, we have selected only those damage zones that appear well defined (in the FF histograms) and relatively isolated from other damage zones. The FF densities reported at various distances (Figures 11, 12) is the average in a 10 m (32.8 ft) binning performed to obtain histograms in Figures 6, 10.

**Figure 11.** Decay of FF density with distance from the fault inside various damage zones encountered in the four wells in the SSC reservoir. The decreasing FF density trends (shown by solid lines) are extrapolated back to unit distance (dotted lines) to obtain the fault constant $F_0$. The red horizontal line represents the approximate background FF density ($\sim 0.5$ FF/m ($\sim 0.15$ FF/ft)). SOF = second-order fault.
The decay of FF density with distance can be described by a power law $F(r) = F_0 r^{-n}$, consistent with observations reported by Savage and Brodsky (2011) from outcrop studies (Figures 11, 12). The FF densities in most damage zones shown in Figures 11 and 12 do not completely decay to background density levels because of the merging of the peripheries of adjacent damage zones. The sections below discuss various damage-zone attributes.

**Damage-Zone Width**

Damage-zone width is identified as the region around the fault where the FF density is greater than the background FF density. Because considerable overlap exists in damage zones identified in this paper, it is difficult to identify a specific background FF density. The background FF density (i.e., FF density away from the damage zones) in the wells in the SSC reservoir appears to be $\sim0.5$–1 FF/m ($\sim0.15$–0.3 FF/ft) (Figure 6), whereas that in the arkosic section adjacent the San Andreas fault is $\sim0.4$–0.5 FF/m ($\sim0.12$–0.15 FF/ft) (Figure 10). The damage zones are approximately 50–80 m (164–262 ft) wide in the arkosic section and the SSC reservoir (Figures 6, 10). The hyperbolic model suggested by Mitchell and Faulkner (2009) predicts that a finite limit exists to the damage-zone width, and the rate of damage-zone growth decreases with fault displacement. Savage and Brodsky (2011) suggest that the fault-zone width scales with fault displacement up to a threshold slip value of approximately 2400 m (7874 ft), beyond which the scaling breaks down and the fault-zone width stabilizes (Figure 2B). The scaling in Figure 2B suggests that faults with 50 to 80 m (164 to 262 ft) wide damage zones (as those in the SSC reservoir) have a displacement of 30 to 60 m (98.4–197 ft). This value matches well with the 8 to 180 m (26–591 ft) of displacement observed across the faults in the SSC reservoir from seismic images.

**Fault Constant**

As the FF population has been binned into intervals of 10 m (32.8 ft), the fault constant (fracture density at unit distance of 1 m [3.28 ft]) cannot be read directly from the histograms. Therefore, the fault constant $F_0$ is calculated by extrapolating the power law fit to unit distance from the fault plane. Most damage zones in the SSC reservoir exhibit $F_0$ values from 10 to 30 FF/m (3 to 9 FF/ft), whereas those in the arkosic section are characterized by $F_0$ values of 6 to 17 FF/m (1.8 to 5.2 FF/ft) (Table 2).
The decay exponent $n$ is approximated by fitting a power law to the fracture-density decay profile. The values of $n$ for each of the damage zones (Figures 11, 12) are reported in Table 2. Damage zones in the SSC reservoir are characterized by decay rates ranging from 0.68 to 1.06 (average $\sim$0.8), whereas those in the arkosic section show relatively lower decay rates of $\sim$0.4 to 0.75 (average $\sim$0.56). Usually, the decay rate appears to decrease in relatively mature damage zones (Savage and Brodsky, 2011). If true, we could speculate that the SOFs in the arkosic section are older and have relatively more mature damage zones.

Although we have limited data for analysis in this paper, the damage-zone attributes identified are consistent with those reported from several field studies (Savage and Brodsky, 2011). In another paper, we model the formation of damage zones around the SOFs in the SSC reservoir using principles of dynamic rupture propagation (Johri et al., 2014). The damage-zone attributes identified in this study are also consistent with those found by modeling numerically.

**DISCUSSION**

We quantify the three main attributes for characterizing damage zones associated with SOFs: the damage-zone width, fault constant, and rate of fracture-density decay with distance from the fault. In this paper, we specifically investigate damage zones associated with SOFs primarily because these are more frequently encountered in reservoirs and are, therefore, more relevant for addressing the bulk flow properties of reservoirs. We do not suggest that the damage-zones attributes identified in this study

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Table 2. Fault Constant $F_0$ and Decay Rate $n$ Obtained by Fitting a Power Law Curve to Describe the Decay of Fracture Density with Distance from the Fault

<table>
<thead>
<tr>
<th>Fault</th>
<th>$n$</th>
<th>$F_0$</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault 1</td>
<td>$-0.89$</td>
<td>10</td>
<td>0.75</td>
</tr>
<tr>
<td>Fault 2</td>
<td>$-0.74$</td>
<td>8.64</td>
<td>0.82</td>
</tr>
<tr>
<td>Fault 3</td>
<td>$-0.55$</td>
<td>5.48</td>
<td>0.83</td>
</tr>
</tbody>
</table>

*The coefficients of determination $r^2$ (for the linear fit between the logarithms of fracture density and distance from the fault) are also listed.
are exactly representative of all damage zones associated with SOFs. These attributes may be a complex function of lithology, stress-state, regional tectonics, fault slip, and slip history, further complicated by overprinting of multiple damage zones. Evidence also exists of asymmetric damage zones around undulating faults (Flodin and Aydin, 2004), which violate our inference of a steady decay in FF density. However, we speculate that these attributes represent damage zones at a scale that affects the bulk flow properties and may be used as reasonable anchor points while building reservoir models that include damage zones.

One of the shortcomings of this paper is the failure to address the distribution of fracture length or size within damage zones because we are limited primarily to image logs, which do not provide any information on the size of fractures. Image logs do provide a size filter in terms of the minimum fracture cross-sectional response that can be resolved on the image log, but this is sensitive to whether the fracture is conducting or non-conducting. It is largely believed that power-law models describe the length distribution of fractures. A large number of studies have been devoted to analyzing the length distribution of fractures (Segall and Pollard, 1983; Gudmundsson, 1987; Villemin and Sunwoo, 1987; Childs et al., 1990; Scholz and Cowie, 1990; Davy, 1993; Odling, 1997; Main et al., 1999) to test the power-law scaling model. However, despite numerous analyses and efforts, the statistical relevance of power-law models is not established among the scientific community, primarily due to difficulties in obtaining a robust statistical analysis on severely limited data sets (Pickering et al., 1995; Bonnet et al., 2001). In the absence of a more established opinion and analysis in this study, we can perhaps speculate that power-law models can also describe the length distribution of FF within damage zones.

The quantified damage-zone attributes can help incorporate the geometry and properties of damage zones in flow simulation models by assigning appropriate effective permeability tensor values to various reservoir grid blocks depending on fracture density in those grid blocks, and the flow properties of those fractures (Johri, 2012). For example, because the fracture-density decay with distance from the fault can be described by a power law, the reservoir grid blocks close to the fault have larger permeability that decreases in grid blocks away from the fault surface in accordance with the power-law decay relationship. We also notice that the damage-zone attributes in both the SSC reservoir and arkosic sandstones are very similar despite the difference in lithology. This could suggest that damage-zone attributes in other lithologies may be very similar, at least to first order. Such a result can be useful in the event of data scarcity. In the absence of image logs and other relevant fracture information, reasonable estimates of damage zones associated with reservoir-scale faults (the positions of which are constrained from seismic images) can be made assuming their characteristics are similar to those identified in the current paper (Pasala et al., 2013). Once the fracture network comprising fault-damage zones is modeled, fluid flow can be simulated by either upscaling fractures using effective media modeling methods or directly using finite-element schemes for discrete fracture flow modeling (Dershowitz, 2000; Johri, 2012). Because simulating flow through discrete fractures using finite-element methods is computationally expensive (especially in a dense fracture network typical of damage zones), the fracture population is usually upscaled to obtain effective continuum grid flow properties using methods, such as Oda’s method (Oda, 1985), and so on. Commercial simulators such as Eclipse can then be used for modeling flow. A methodology for including damage zones in building geologically representative reservoir discrete fracture network (DFN) models and modeling flow through them is described in Johri (2012). Considering several realizations of damage zones using a range of values of fault constant and decay rates can help perform uncertainty analysis in flow predictions.

We also demonstrate the importance of correcting the FF population (obtained from image logs) for the sampling bias introduced caused by the undersampling of FF subparallel to the well. Significant increase exists in the FF population, especially in the SSC reservoir in which the FF data set obtained from image logs is statistically corrected to remove the sampling bias. The corrected FF population represents the number of FF that are expected to be present in the rock mass, as opposed to the number observed in
the image logs because of spatial sampling along a one-dimensional (1-D) linear well. The purpose of this statistical correction is to extrapolate a 3-D perspective of the regional FF population from 1-D data acquisition, and hence obtain a more meaningful fracture characterization. A well-constrained reservoir fracture characterization, along with knowledge of prominent fracture sets, locations of SOFs, their damage-zone characteristics, and critically stressed FF orientations can help us design well trajectories that could exploit damage zones and the more productive critically stressed faults by orienting wells perpendicular to them, in the process sampling most of those FF and hence optimizing production. As previously mentioned, it can also assist us in making more geologically informed reservoir models for simulating fluid flow, and hence predicting production rates and reservoir performance with greater accuracy.

CONCLUSIONS

We have identified the attributes of fault-damage zones associated with second-order faults (SOFs) at reservoir depths in two regions, the arkosic section adjacent to the San Andreas fault and the SSC reservoirs. The SOFs and their damage zones are characterized using image and other geophysical logs. The positions of subseismic-resolution SOFs at depth are constrained by noting changes in the orientation of bedding planes and anomalous changes in geophysical properties. Damage zones observed in both the regions are similar in terms of damage-zone widths and fault constant \( F_0 \) despite the geologic differences. These damage-zone characteristics are also very similar to those observed in outcrop studies. The decay of fracture density with distance from faults can be described by a power law \( F = F_0 r^{-n} \). Such a decay rate has been reported from outcrop field studies (Savage and Brodsky, 2011), and we have extended it to damage zones at reservoir depths. The decay rate \( n \) from 0.68 to 1.06 (average \( \sim 0.8 \)) is observed in damage zones in the SSC reservoir, whereas \( n \) from 0.4 to 0.75 (average \( \sim 0.56 \)) is observed in damage zones in the arkosic sandstone section. Damage zones in both the regions are typically 50–80 m (164–262 ft) wide. The extrapolated value of the fault constant ranges from 10 to 30 FF/m (3 to 9 FF/ft) for damage zones in the SSC reservoir and from 6 to 17 FF/m (1.8 to 5.2 FF/ft) in those in the arkosic section. \( F_0 \) for damage zones in the arkosic section may have been underestimated because of poor data quality and intense fracturing.

APPENDIX: REMOVAL OF SAMPLING BIAS

To characterize subsurface natural fractures and damage zones using geophysical logs such as image logs, it is necessary to correct for the sampling bias introduced by the inability of wells to sample fractures oriented subparallel to them (Terzaghi, 1965; Einstein and Baecher, 1983). If we consider a set of fractures intersecting a vertical well dipping at angle \( \theta \), and \( d \) is the actual average spacing between two fractures, the apparent fracture spacing as seen in the image log would be \( d/ \cos \theta \) (Figure 13; Terzaghi, 1965). Consequently, if \( N \) is the number of fractures intersecting this vertical well per unit length along the well, the actual fracture density of this fracture set would be \( N \sec \theta \) per unit length measured along the normal to this fracture set. This approach can be extended to nonvertical wells (Figure 13). If we consider a set of fractures striking \( \alpha_1 \) and dipping \( \phi_1 \), the trend and plunge of the normal to this fracture set would be \((\alpha_1 - 90)° \) and \((90 - \phi_1)° \). If the trend and plunge of the well are \( \alpha_2 \) and \( \phi_2 \), then the unit vectors along the normal to the fracture set \((u)\) and along the well \((v)\) would be

\[
\begin{align*}
\vec{u} &= \sin(\alpha_1 - 90) \cos(90 - \phi_1) \vec{e}_x \\
&\quad + \cos(\alpha_1 - 90) \cos(90 - \phi_1) \vec{e}_y - \sin(90 - \phi_1) \vec{e}_z \\
\vec{v} &= \sin(\alpha_2) \cos(\phi_2) \vec{e}_x + \cos(\alpha_2) \cos(\phi_2) \vec{e}_y - \sin(\phi_2) \vec{e}_z
\end{align*}
\]

Figure 13. Geometry of correction for the systematic undersampling of steeply dipping fractures in a deviated well.
If the average distance between the fractures in this fracture set is \( d \), the apparent distance between these fractures seen along the well would be \( d \sec \theta \). We define bias factor as the projection of the normal to a fracture of a certain orientation along the well (\( \cos \theta \)). Larger values of the bias factor represent lower bias, whereas lower values represent a larger bias.

\[
\text{bias factor} = \cos \theta = \frac{\mathbf{u} \cdot \mathbf{v}}{|\mathbf{u}| |\mathbf{v}|}
\]

Using this concept, we adopt the following approach to remove the sampling bias. Continuous intervals of a certain length along the well are selected. For each interval, the FF striking and dipping within a certain interval are identified, and their number is upscaled by a factor of \( \sec \theta \). The new fractures introduced in the synthetic data set are distributed along that depth interval, and assigned strike and dip values according to the distribution of the spatial location and orientation of FF present in the original FF population in that depth–strike–dip window. The depth interval considered in this study is 10 m (32.8 ft), whereas the strike and dip intervals used are 10°. The corrected population predicts the actual fracture population present.

The orientation of the well in the arkosic section is variable but the deviation from vertical lies largely between 53 and 55°, whereas the deviation direction lies largely between 36 and 39°. The apparent fracture density of a certain fracture set measured along a well when divided by the bias factor gives the actual fracture density. Figure 14 shows the bias factors introduced in a well for all possible orientations of fractures. Such a plot is valid only for a certain well orientation. Because the well orientation changes continuously, different plots of bias factors at different intervals along the well are obtained. The plot in Figure 14 represents the bias factors at a measured depth of 2270 m (7448 ft) at which the deviation and deviation direction of the well are 55 and 36°, respectively. The warmer colors represent higher values of the bias factor. These occur for fractures with an approximate dip direction of 305° and dip of 55°. This is expected because such a fracture set would be perpendicular to the well and present maximum probability of being sampled or intersected. On the other hand, the cooler colors represent the lowest values of the bias factor. Fracture sets with such orientations are subparallel to the well and will present a minimum probability of being intersected by the well.

The distribution of the orientation of FFs identified in the arkosic section before and after correcting for the sampling bias can be seen in Figure 15. We notice that the number of FF with a dip direction of 305° and dipping 35° (subparallel to the well; a red spot in Figure 15A) remains almost the same after a correction is applied. However, the population of FF with a dip direction of 140° and dipping 55° increases from 6 FF/m (1.8 FF/ft) before correction to 20 FF/m (6.1 FF/ft) after correction. The dark blue regions in Figure 15A representing fracture orientations, which are completely missing in the original fracture set, remain missing in the updated fracture set as well (Figure 15B) because no fracture population exists to correct.

**Figure 14.** Values of the bias factor (BF) for fractures with various orientations with respect to a well the deviations from vertical and deviation directions of which are 35° and 36°. These values are shown in a planar plot (left) and a stereonet (to the right). Warmer colors represent larger values of BF (lower bias), whereas the cooler colors represent lower values of BF (greater bias).
Figure 15. The number of fractures of various orientations present in (A) original FF data set and (B) updated fracture data set (after correcting for sampling bias) from the arkosic section of San Andreas Fault Observatory at Depth. Circle regions show the increase in the population of FF with a dip direction of 50° and dipping 55° from 6 before correction to ~20 after corrections.

REFERENCES CITED


