Application of high resolution DEM data to detect rock damage from geomorphic signals along the central San Jacinto Fault

Neta Wechsler a,⁎, Thomas K. Rockwell b, Yehuda Ben-Zion a

a Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740, USA
b Department of Geological Sciences, San Diego State University, San Diego, CA 92182, USA

A R T I C L E   I N F O

Article history:
Received 17 September 2008
Received in revised form 22 January 2009
Accepted 8 June 2009
Available online 21 June 2009

Keywords:
Drainage density
Fault zone structure
LiDAR
Rock damage
Earthquake ruptures

A B S T R A C T

We analyze geomorphic properties extracted from LiDAR and SRTM (Shuttle Radar Topography Mission) data to test whether the damage zone along the central San Jacinto Fault (SJF) zone can be resolved with remotely-sensed data in a quantitative fashion. The SJF is one of the most active faults in southern California, with well expressed geomorphology and a fast slip rate, as seen in the geology and by GPS. We use ArcMap and the TauDEM toolbox to compare several morphometric parameters, including drainage density (Dd), on both sides of the fault, using a 1 km and a 5 km buffer for the LiDAR and SRTM data, respectively. We also analyze the spatial patterns of Dd near the fault, using two different definitions of spatial Dd. The high resolution of the LiDAR data allows us to focus on a single fault, eliminating the effects of parallel nearby faults. From the LiDAR data we find that the highest Dd values occur in areas between two fault strands, followed generally by rocks on the northeast side of the fault, with the lowest Dd values occurring on the southwest side of the fault. The SRTM data shows a band of high Dd values centered on the main fault trace with ~1 km width. Our results indicate that there is a strong correlation between drainage density and proximity to the fault, with zones of structural complexity along the fault displaying the highest Dd. We interpret this to largely be an effect of degree of rock damage, as these are areas that are expected to be more damaged, and field observations support this contention. If we are correct, then it appears that the northeast side of the SJF is generally more damaged. South of the trifurcation area there is evidence that the signal is reversed on the larger scale, with more damage on the southwest side of the fault inferred from the SRTM data, possibly caused by extension between the Coyote Creek and Clark faults. The implications of the observed asymmetry could be geological evidence for rupture propagation direction, because a preferred propagation direction is predicted to produce asymmetric damage structure that would be recorded in the volume of rock surrounding a fault.

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1. Introduction

Understanding the structure of active fault zones is important for many branches of earth sciences, including earthquake and fault mechanics and crustal hydrology. Because faults grow and evolve as a result of crustal stresses generated by multiple earthquakes, there are many connections between the processes that govern earthquake ruptures and the structural properties of fault zones. In a typical fault structure, the principal slip zone is surrounded by gouge and embedded within a tabular or wedge shaped damage zone which can extend to several kilometers depth and several hundred meters width (Ben-Zion and Sammis, 2003, and references therein). However, most of the movement across the fault is accommodated within the narrow localized principal slip zone (Rockwell and Ben-Zion, 2007). The broad damage zones are observed in gravity and geodetic surveys around active faults (e.g., Stierman, 1984; Hamiel and Fialko, 2007), and are also seen in numerical modeling of evolving fault zone structures (Finzi et al., 2009), but they appear to accommodate only minor adjustments in the long term motion of faults (e.g., Chester and Chester, 1998; Rockwell and Ben-Zion, 2007). Clarifying the in-situ properties of fault zone structures can provide important information on the mechanisms that generate each structural component, as well as the stress fields that are operative during and between earthquakes.

In this paper we examine the effect of seismic-induced rock damage on the development of drainages near an active fault zone. In the past, studies that looked at the interaction between active faults and geomorphology (e.g. Whipple, 2004; Densmore et al., 2007) used the tectonic factor only as the source of relief, which caused increased erosion as a result of the increased elevation difference. It was recently suggested by Molnar et al. (2007) that tectonics play an important role in causing rapid erosion of hillslopes by fragmenting the upper crust down to the scale of boulders or smaller. They suggested that fracture
density is an important factor affecting rock erodibility. It was shown that both micro- and macrofracture density increase in proximity to faults (Chester and Chester, 1998; Wilson et al., 2003), and that along active faults there is a low-velocity zone that is seen in fault zone trapped waves and is associated with intense damage (Li et al., 1999).

Another recent observation regarding fault zones was the existence of highly damaged or pulverized bodies of rock along active strike-slip faults, at distances of up to hundreds of meters away from the fault (Dor et al., 2006a) and with increasing intensity of pulverization closer to the fault (Rockwell et al., 2009). The pulverized rocks undergo intense fracturing in the microscale which reduces their grain size significantly (Rockwell et al., 2009). This reduction in grain size can have an effect of decreasing the rock permeability by increasing moisture retention in the near surface, thereby decreasing infiltration capacity, which in turn increases runoff and promotes the initiation of channels. Along with the general decrease in the strength of the “rock”, the end result may be to cause higher drainage density where damage is more intense, i.e. close to the fault.

Theoretical results indicate that on a fault that separates different elastic solids, ruptures tend to propagate in a wrinkly-like pulse predominately in the direction of slip on the compliant side of the fault (e.g. Weertman, 1980; Ampuero and Ben-Zion, 2008). Such ruptures produce dynamic dilation at the tip that propagates in the direction of motion on the more compliant side of the fault, and dynamic compression at the tip propagating in the other direction. Due to these opposite rupture tip changes in normal stresses, ruptures tend to propagate in the direction of motion of the block with slower seismic velocities at depth, which is referred to as the preferred direction. On bimaterial faults that produce a preferred propagation direction for earthquake ruptures, most of the rock damage is expected to accumulate on the stiffer side, which persistently experiences a tensile stress field during earthquake ruptures (Ben-Zion and Shi, 2005), as it is easier to damage rocks under tension than under compression (Fig. 1). If there is no preferred rupture direction, such as in a homogenous solid, superposition of the damage generated by many earthquakes is expected to be approximately symmetric across the fault. The existence of a preferred propagation direction for ruptures on large faults can have fundamental consequences for many aspects of earthquake physics and estimates of seismic shaking hazard in major metropolitan areas near large faults (e.g. Ben-Zion, 2001).

Asymmetric patterns of rock damage across large strike-slip faults have recently been documented at several localities over several scales. In southern California, Dor et al. (2006b) observed significant asymmetric distribution of damage elements on one side of the principle slip surfaces of the San Jacinto, Punchbowl and San Andreas faults at a scale of a few meters. Lewis et al. (2005, 2007) found clear asymmetry of low-velocity damaged fault zone layers from analysis of seismic fault zone trapped and head waves along sections of the San Jacinto and San Andreas faults. The fault zone layers imaged in these studies are about 100 m wide and extend through the top few km of the crust. Dor et al. (2008) observed damage asymmetry at scales ranging from sub-meter to over a km across parts of the North Anatolian Fault in Turkey, consistent with the (opposite) rupture directions of the 1943 and 1944 earthquakes on the fault, which are thought to represent long term preferred propagation directions on the corresponding sections of the North Anatolian Fault.

The asymmetry of rock damage across faults may be expressed by differences in the surface hydrology of the drainage systems on the opposite sides of the fault. The increase in damage to the rocks is expected to correlate with more erosion on the one hand, and higher drainage density on the other hand. If indeed the damage is significantly higher on one side compared to the other, then we expect to see the influence of the damage asymmetry in the drainages on both sides of the fault. In general, the erosion intensity and drainage density are affected by many other intrinsic and extrinsic parameters, which include climate, rock unit, soil type, slope, aspect, relief, land use, basin development stage, etc. However, in cases where those variables are similar across terrains, the different levels of rock damage across the fault may be the influential factor on erosion and the development of drainage patterns.

In this paper, we study two neighboring terrains, which lay on the two sides of a major fault — the San Jacinto Fault. Quantitative comparison of geomorphic parameters related to erosion and drainage patterns is used to study the underlying distribution of rock damage, and to examine the symmetry properties of damage across the fault. Because the chosen terrains are approximately similar in their generic parameters that may affect erosion, having similar climate, geology and geomorphic history, earthquake-induced damage may be invoked to explain any observed differences in the erosion intensity and drainage patterns that are indicated by the analyses done in this work.

2. Regional setting

The San Jacinto Fault (SJF) is one of the major branches of the San Andreas Fault (SAF) system in southern California, and extends from the Transverse Ranges southeastward into the Salton Trough (Fig. 2). It is presently the most seismically active fault in southern California, with a geologic slip rate of 12–14 mm/yr (Rockwell et al., 1990) and post-Cretaceous cumulative offset of ~24 km (Sharp, 1967). The SJF is a young fault, but its age is poorly constrained to 1–2.5 Ma (Matti and Morton, 1993; Dorsey and Roering, 2006). Becker et al. (2005) found a strong GPS strain signal of 15 mm/yr across the fault. Fialko (2006) used InSAR to study the interseismic strain across the southern SAF system and showed that there is nearly equal interseismic strain accumulation on the SAF and the SJF, with ~19 mm/yr inferred slip rate for the SJF on the Borrego Mountain section.

The Anza section of the San Jacinto Fault zone has been termed the “Anza Seismic Gap” due to its dearth of microseismicity, and is one of the segments of the fault zone that may not have ruptured in historical times (Sanders and Kanamori, 1984), although paleoseismic observations suggest it may have ruptured in the November 22, 1800 earthquake (Rockwell et al., 2006; Rockwell and Seitz, 2008). The San Jacinto Fault is well expressed geomorphically near Anza, and there is apparently only one major active strand — the Clark Fault (Rockwell et al., 1990). Other faults in the area to the south include the Coyote Creek and Buck Ridge faults, both of which are sub-parallel to the main strand and both terminate their north ends in the Anza area — the trification zone. The slip distribution is ~22 km of cumulative slip on the Clark strand northwest of Anza, with a few kilometers maximum displacement on the Hot Springs Fault to the northeast. South of the trification zone, the cumulative slip on the Clark Fault drops to about 14.5 km, there is about 5 km of cumulative slip on the Coyote Creek Fault and only minor slip on
the Buck Ridge fault (Le et al., in review). Two left jogs in the SJF main strand create areas of compression, northwest and southeast of Anza. The subsurface structure of the fault is dipping steeply to the NE throughout the area (Sanders and Kanamori, 1984; Lewis et al., 2005).

Several studies have focused on fault related damage in the area. Dorsey and Roering (2006) studied basin evolution northeast of the Clark fault, along Horse canyon and Buck ridge, and showed that as basins move through the restraining bend in Horse canyon they change their profiles from convex to concave. North of the bifurcation area, Dor et al. (2006b) studied three outcrops of the fault core and described its asymmetry, as well as asymmetry in the damage of the adjacent Pleistocene sediments, and concluded that the northeast side of the fault is more damaged northwest of Anza. Lewis et al. (2005) used fault zone trapped waves to image the internal structure of the different branches of the SJF south of the bifurcation area. They interpreted the existence of ~100 meter wide trapping structures that extend to a depth of 3–5 km and are offset to the northeast from the surface trace of each fault branch. These results suggest a broad damage zone along the northeast side of the Clark segment south of the bifurcation at depth. However, Stilings (2007) mapped the Horse Canyon area southeast of Anza and observed more damage in the form of pulverization on the southwest side of the fault’s primary northern strand, extending out several tens of meters but with greatest damage proximal to the active fault core. This relationship argues that the pulverization is related to slip on the Clark fault. The northeast side of the fault in the Horse Canyon area only expresses intense damage outwards for a few meters from the fault core at the surface, in apparent contrast to the observations of Lewis et al. (2005) at depth, although the country rock is highly fractured for a greater distance.

The SJF bifurcation area is ideal for a hydrological analysis, being a semi-arid region where the climate is generally similar, and the vegetation cover is relatively sparse, consisting mostly of succulents at low elevations with some juniper trees at higher elevations (above 1 km). The relatively minor total fault offset ensures that until the initiation of slip on the fault, the rocks on both sides probably experienced similar geological and climate histories. An observed difference between corresponding rock bodies would therefore be related to the more recent fault activity, which is believed to have initiated in the early Quaternary (Kirby et al., 2007).

3. Data and methods

3.1. Data

We use two datasets with different resolutions to examine the geomorphic parameters of the study area. The first is a 30 m pixel DEM derived from SRTM (Shuttle Radar Topography Mission) data, obtained from the USGS seamless server (http://seamless.usgs.gov). This will be referred to as the SRTM dataset. The second is a 1 m pixel...
DEM derived from the point cloud data of the B4 LiDAR (Light Distance And Ranging, a.k.a. ALSM (Airborne Laser Swath Mapping)) project, obtained from the GEON portal (http://www.geongrid.org). This will be referred to as the LiDAR dataset. The B4 LiDAR data covers the southern part of the SAF and the SJF. The data were acquired in 2005 and cover the main fault traces with ~1 km combined swath width. The swaths usually overlap, so that the ground is sampled at multiple points per square meter. LiDAR has the advantage of the ability to penetrate through vegetation, so that some of the recorded returns are from vegetation and others are from the ground.

The point cloud data were converted into grid using a local binning algorithm with a radius of 1 m and choosing the local minimum (Arrowsmith and Crosby, 2006; Kim et al., 2006). The local minimum approach is smoothing some of the more con- voluted portions of the topography, thus helping the later determination of flow path. By using a local minima binning scheme, we managed to eliminate most of the vegetation returns, but not all. The vegetation in the study area consists mainly of desert shrubs and succulents, whose canopy is locally dense at higher elevations, and therefore harder to penetrate using LiDAR. However, at lower elevations, it is quite sparse and therefore less disrupting to geomorphic analysis. Missing elevation values, where the point cloud density was smaller than the search radius, were filled by using a larger (2 m) search radius to estimate the elevation. Thus, holes larger than 1 pixel were left without values, but most of the study area was indeed covered.

With the SRTM dataset, we use the geological map of California, obtained in GIS format from the California Dept. of Conservation, Division of Mines and Geology, and based on Jennings (1977, 1985, 1994). The map scale is stated to be 1:750,000 so that the margin of error for a location of a line is about 250 m, according to the metadata. We focus on igneous and metamorphic rocks, assuming that most of the surface damage was caused by the activity of the San Jacinto Fault. Sharp (1967) notes that where the fault traverses crystalline rocks, it generally occupies a central position in a crowded zone of several tens of meters in width, along which a rift valley has been eroded. This rift valley is visible in the shaded relief topography effectively buffered to a ~1 km wide zone surrounding the main fault, which means a 5 km wide zone. The LiDAR dataset is already disrupted to geomorphic analysis. Missing elevation values, where the point cloud density was smaller than the search radius, were filled by using a larger (2 m) search radius to estimate the elevation. Thus, holes larger than 1 pixel were left without values, but most of the study area was indeed covered.

3.2. Analysis methods

Both the SRTM and the LiDAR datasets were analyzed using ESRI ArcGIS 9.2 with the TauDEM toolbox (Tarboton, 1997). The overall drainage delineation scheme is summarized in Stepinski and Collier (2004). Stream networks were derived using the Strahler classification method (Strahler, 1952) with a threshold value of stream order = 3 for the SRTM data, and verified using air photos. For the LiDAR data, the Slope–Area method was used with a threshold value of \( A/b \) such that the absolute value of the t-statistic is less than 2. This selects the highest resolution network consistent with the “constant drop law” (Tarboton et al., 1991, 1992). The choice of different delineation methods for the stream networks for the two datasets (stream order for the SRTM dataset, slope–area for the LiDAR dataset) was a result of unsatisfying delineation results when one method was applied for both datasets. Fig. 4 is an example of the result of the drainage delineation using the LiDAR dataset.

For the SRTM dataset, we use a 2.5 km buffer around the main fault, which means a 5 km wide zone. The LiDAR dataset is already effectively buffered to a ~1 km wide zone surrounding the main fault. We divide the study area into two parts — NW of the trifurcation and SE of the trifurcation, which will be called NW of Anza and SE of Anza. Each side of the fault is studied separately and compared to the other side (NE, SW) in both parts, as well as for the entire study area.

We approach the problem of measuring damage with drainage networks in two ways. The first is to look at various drainage parameters of chosen drainages and to compare them across the fault. A similar approach was used by Dor et al. (2008) for a study along the North Anatolian Fault. The second approach is to look for spatial patterns of variations in the drainage network. This approach was used by Tucker et al. (2001) but for a different purpose. Both methods are not infallible, although we think they are complimentary. Fig. 4 demonstrates how the drainage networks can differ in character and density on both sides of the fault.

3.2.1. Chosen drainages approach

For each type of rock unit and for each side of the fault, we chose several drainages that are completely or almost completely contained within the fault buffer zone, on one side of the fault (do not cross it). Areas with a high degree of human activity (mainly near Anza) are ignored. For all the chosen drainages, several geomorphic and geographic parameters are calculated and a comparison of drainages at different locations is made.

We calculate the following for each of the drainages: Average slope, average aspect, area, perimeter, and the following hydrological parameters: Hypsometric Integral (Hi) and Drainage Density (Dd). Hi is an integral of the dimensionless area–altitude distribution curve, which relates the horizontal cross-sectional area of a drainage basin to the relative elevation above the basin mouth (Strahler, 1952). Hi can
range between 0 and 1, usually ranging 0.25–0.75, and lower values are associated with higher levels of erosion, since more material is removed from the basin. Drainages with similar area–slope–elevation relations can still have different hypsometric curves, if their drainage networks are different (Willgoose and Hancock, 1998). Dd is the ratio between the total stream lengths (L) and the drainage basin area (A) (Horton, 1945). Dd is associated with rates of erosion (higher where erosion is more intense) and so can potentially be used to infer tectonic and geomorphic history (Tucker et al., 2001). In contrast to Dor et al. (2008), we do not use the Horton–Strahler parameters (Horton, 1945; Strahler, 1964) of bifurcation ration, slope ratio, etc. because it has been shown that Strahler's network statistics do not necessarily reflect differences in drainage properties (Kirchner, 1993; Hancock, 2005).

All of the above parameters are expected to change as a function of slope, aspect, rock unit, and climate. If there is indeed more damage on one side of the fault, this side will presumably be more erodible, promoting the transport of material downstream (lower hypsometric integral) and encouraging the formation of badland topography (high drainage density). By choosing drainage systems on different sides of the fault and controlling for rock unit, slope, aspect and climate, it may be possible to isolate the differences in drainage parameters that occur simply due to the damage asymmetry. If the damage asymmetry indeed exists, we expect that the Dd values will be higher on the damaged side, and the Hi values are expected to be lower.

3.2.2. Spatial approach

We examine the drainage density as a spatially varying function and compare it across similar terrains that are located on both sides of the fault. First we compute spatial Dd simply as the total length of streams in a certain area, following the definition of Horton (1945). For this we use a raster of the area where pixels with streams are of value 1 and pixels without streams are of value 0 (one of the products of TauDEM). A summation of pixels within an area is then performed, and the result is divided by the area to give a number that represents the drainage density. This action is similar to counting the length of the stream per area.

Tucker et al. (2001) claimed that Dd is not a continuous terrain property and therefore does not reflect the large spatial variability of hillslope lengths, but when considered as the hillslope flow path, its spatial variation can tell something about various geomorphic processes. They suggested using the down-slope distance to the nearest channel as a spatial quantity related to drainage density. Following Tucker et al. (2001), we look at the variation of the drainage density in space, using the down-slope distance to the nearest channel. A spatial average can be performed either for a certain area, or for the entire dataset using a moving averaging filter with a radius determined by the spatial covariance method, as described by Tucker et al. (2001). For the SRTM data, the filter radius is found to be 1000 m (Fig. 5A), similar to the value found by Tucker et al. (2001) for a similar dataset. For the LiDAR data, the value is 100 m (Fig. 5B). In this approach, shorter distances to the nearest channel (a lower value of down-slope distance) correspond to higher drainage density.

Use of the averaging filter can give smoothed Dd images in both methods, but it does not differentiate between different rock types. We therefore perform another averaging, this time taking the rock unit polygons and computing the mean values for each rock type at each location. Both methods enable us to look at the spatial variations in the drainage density near the fault, without the limitation of singling out drainages.

4. Results

4.1. Chosen drainages approach

4.1.1. SRTM dataset

We select 19 drainages NE of the fault and 15 drainages SW of the fault for the comparison of parameters. The chosen drainages are all contained within the buffer area and the igneous–metamorphic rock units. Fig. 6 illustrates the drainage locations, the rock units and the Hi values. The comparison results are summarized in Table 2. Two parameters are compared across the fault for each rock unit — the hypsometric integral (Hi) and Drainage Density (Dd). Looking at the study area as a whole, the Hi values are a bit higher on the SW side of the fault for the grMz rock unit, but the opposite is true for the gr-m rock unit, where Hi values are higher on the northeast side. We use the Kolmogorov–Smirnov (K–S) method (Chakravarti et al., 1967) to test if there is a statistically significant difference between the populations of Hi values in different rock units and different sides of the fault. The results indicate that the Hi values of drainages in both rock units are from different populations, with more than 95% confidence. From this we can conclude that Hi values are significantly affected by rock type. However, the hypothesis that the Hi values are different across the fault is not rejected by the K–S test, which means that the differences in Hi values across the fault are not significant enough to imply different erosion rates. From this we conclude that it is possible that the small differences in Hi values do not reflect differences in damage, and are likely due to averaging values from drainages of various slopes. Another possibility is that by averaging values for each side of the fault we are obscuring any spatial variability in Hi values that may be caused by variability of damage along the fault trace.

To study the possibility of damage varying along the fault, we separate the study area into two parts, northwest and southeast of Anza. The K–S method indicates there’s a statistically significant difference between the populations of Hi values for drainages in the two areas. Southeast of Anza, the Hi values are consistently lower on the southwest side of the fault, which may point to more damage on this side. In the grMz rock unit, the average slope is almost equal for both sides of the fault, but the average Hi value is significantly lower on the southwest side, meaning that the difference in Hi values cannot be attributed to slope differences. In the gr-m rock unit, the average Hi value is lower on the southwest side, while the average slope is also lower on the SW side. Higher slope is usually considered to promote erosion, therefore it is expected that the differences in slope would result in lower Hi values where the slope is steeper. This relation does not hold for the gr-m drainages, where even though the average slope is much higher on the northeast side, the southwest side still has the lower average Hi value. This discrepancy can be explained by our damage asymmetry hypothesis — the southwest side suffered more damage which made it more susceptible to erosion, causing the Hi values to be overall higher.

To the northwest of Anza, a direct comparison is not possible due to differences in rock units. However, taking into account that values of Hi in the grMz unit are usually higher, and that the average slope is similar for both sides, the small difference between the average Hi values on the two sides of the fault may indicate more damage on the northeast side, consistent with the observations of Dor et al. (2006a). The above results suggest an asymmetric distribution of damage across the fault, so that northwest of Anza the northeast side of the fault is more damaged, while southeast of Anza the southwest side of the fault is more damaged.

Comparisons of drainage density values show consistently higher Dd values on the southwest side (Table 2). It is important to note that
drainage density is correlated to the drainage area, so that higher Dd values occur in drainages with smaller areas. This correlation is evident from the Dd definition and the fact that it has a dimension. Taking that into account sheds doubt on the higher values of Dd on the southwest side, especially since the differences are so small. One exception may be the average Dd value of drainages in the grMz rock unit to the southeast of Anza, which is equal for both sides of the fault despite the larger average drainage area on the southwest side. This may indicate higher damage on the southwest side, which causes a higher Dd value than expected for the larger area. This result is compatible with the Hi comparison result that southeast of Anza the southwest side displays more damage.

4.1.2. LiDAR dataset

We select 18 drainages SW of the fault, 42 drainages NE of the fault and 14 drainages that are in between two fault strands using the LiDAR dataset. The comparisons of results from the analysis are summarized in Table 3. Two parameters are compared across the fault for each rock unit — the hypsometric integral (Hi) and Drainage Density (Dd). Due to the distribution of rock types in the study area, we are able to compare only drainages from three different lithologic groups — pKm, Kt and Qb (see Table 1). The Qb unit is the Bautista Formation sandstone and conglomerate and is not directly comparable to the other two rock units, as it is largely derived from them. The higher resolution of the LiDAR dataset enabled us to choose drainages that fall in between the two main strands of the fault in an area where a thrust component is present, so the locations of some drainages is defined as C for “center”.

The average Hi values for drainages in the pKm rock unit clearly show a progressive change, where the center has the lowest value, followed by the northeast side of the fault, and finally the southwest side has the highest Hi values. However, the average slope values follow the same progression, and may be invoked to explain the change in Hi values. The average Dd values are higher in the northeast, even though the average area is similar. Assuming that higher Dd and lower Hi values correspond to higher degree of damage, the results imply that the center and NE side are more damaged compared with the SW side of the fault. The locations of the pKm drainages are distributed such that most of the northeastern drainages fall southeast of Anza, and most of the southwest drainages fall northwest of Anza. From this we conclude that the northeast side has more damage southeast of Anza than the southwest side northwest of Anza.

Drainages in the Kt rock unit have similar Hi values across the fault, and when considering the average slope, no significant difference is apparent. However, the drainage density is higher on the northeast side, while the average area is similar. A comparison focusing on the...
area southeast of Anza hints to a slight difference, with lower Hi values on the southwest, but higher Dd values on the northeast. The Dd value is probably affected by smaller drainage areas in the northeast, while the Hi value may be affected by steeper slope in the northeast, making the comparison less useful for inferring damage signal.

In the Qb rock unit, the average Hi value is slightly lower on the northeast side of the fault northwest of Anza, and lower on the southwest side southeast of Anza. The average slope southeast of Anza is higher on the SW side, so that the difference in Hi cannot be explained by it. It can be explained by higher damage on the northeast side of the fault, consistent with the results from the pKm unit. The Dd values are less useful due to different drainage area values.

The results of comparing drainages using the LiDAR dataset are compatible with the results from the SRTM data to the northwest of the trifurcation, implying more damage on the northeast side. Southeast of Anza, the LiDAR results imply more damage on the northeast side, which is the opposite of what the SRTM data imply.

4.2. Spatial approach

The spatial approach is driven by the observed correlation between the drainage density and the drainage area for individual drainages. We compute spatial drainage density that is not related to specific drainages using the two methods. The first uses the down-slope distance to the nearest channel (Tucker et al., 2001), and the second uses the sum of the length of streams divided by area, but is not limited to specific drainages. The two methods are referred to as the down-slope distance and the streams-sum methods, respectively. We analyze the spatial patterns by using a circular averaging filter with size chosen according to the data autocorrelation (see Section 3.2.2). We also compare drainage densities for each rock unit separately, using the geological map shapefiles. In the first method, small downslope distance corresponds to high drainage density.

4.1.1. SRTM dataset

Fig. 7 shows the results of a 1000 m radius averaging filter applied to the down-slope distance and streams-sum rasters, as well as to the slope raster. To determine how much the pattern is influenced by the slope, we calculate the spatial correlation between the three rasters. The correlation between the slope and the down-slope distance rasters is $-0.05$, and the correlation between the slope and the streams-sum rasters is $-0.2$ (a value of 0 indicate no correlation, while a value of 1 indicates direct correlation and a value of $-1$ indicates reverse correlation). Therefore, the slope does not seem to have much effect on the pattern. We mask the areas that do not correspond to bedrock (either grMz or gr-m), but we expect that the fringes of the bedrock area would be affected because of the filter radius.

Looking at the spatial patterns, we see that down-slope and stream-sum rasters are similar but not identical. Northwest of Anza,
there is a higher drainage density zone near the fault, but it is slightly off-center to the northeast. The width of the high Dd band seems to be about 1 km. In the trifurcation area, there seems to be higher Dd between the Clark and the Buck Ridge strands, and between the Clark and the Thomas Mountain strands. Southeast of the trifurcation, the higher Dd concentrates in the areas where the fault bends or splays. The streams-sum data show a band of high Dd centered on the Clark strand and north of the normal faults that cut Coyote Ridge (Fig. 7A). The higher drainage density spot on the southeast is related to the Jackass flats, a large area of late Quaternary alluvium which is masked but still has an effect on the Dd because of the filter size. The minor dependency on slope can be seen by comparing parts A and B of Fig. 7 to part C.

It is important to note that this method does not distinguish between rock units, so it is only useful for looking at general spatial patterns. The averaging filter does not discriminate between bedrock and alluvium, and “smears” the drainage density between rock units. Even masking the data so that only Dd data for bedrock is available does not entirely remove the affects of large areas of alluvial cover that can have high Dd values due to the multiple streams and braiding that occur in such flat areas. The resolution of the data enables us to see general patterns of drainage density using the two different methods. If indeed the higher Dd band near the fault is an expression of damage to the rocks, it appears that the best scale to search for fault related damage is a kilometer wide band around the fault, which is what the LiDAR data provides us.

4.1.2. LiDAR dataset

Fig. 8 shows the results of a 100 m radius averaging filter applied to the streams-sum raster for part of the LiDAR dataset. The SJF in this area bends into a thrust and splays into several segments. The south side is the hanging block, where more damage is expected in the rocks. The higher drainage density is evident on the south side of the fault, as well as between the strands, consistent with the thrust component on the fault at this location. However, there are different rock types across the fault which prevents us from a direct comparison (see Fig. 4). In order to catalog the data according to different rock units and locations, we divide each rock type into groups according to location (NE or SW of the fault, NW or SE of Anza) and compute the spatial average of drainage density obtained by the two methods for each rock unit in each group. The results are summarized in Fig. 9 and Table 4. When looking at the overall averages, without partition with relation to the trifurcation zone, for most rock units, the northeast side of the fault has higher Dd values, except for the pKm rock type, where the Dd value derived from the down-slope distance is similar for both sides (the center has the highest Dd values), and the Dd value derived from the stream-sum is a bit higher on the southwest side. When focusing only on outcrops that are southeast of Anza, the northeast side again displays higher Dd, except for the Kt rock unit, where the Dd value derived from down-slope distance is slightly lower on the northwest side. There are not enough outcrops of similar rock types to compare to northwest of Anza.

It is worth noting that the Qb and Ka outcrops display the highest difference in down-slope distance values. While outcrops of pKm rock unit that fall in the center have the highest damage, this is not true for the Qb outcrops, which may be due to their unconsolidated nature. It is also likely that some areas of highly damaged rock are more deeply eroded, and therefore are overlain by young alluvium and could not be used in this analysis.

Using the LiDAR data to focus on the area close to the fault, we see a similar sense of damage asymmetry, as reflected in the drainage density southeast of the trifurcation, to what the individual drainage approach shows. The results of the LiDAR data point to the northeast side as having higher Dd values and therefore being more damaged across the study area, which is contrary to some field observations. However, when averaging for rock units, we disregard difference in distance from the fault, which is known to affect the degree of damage. Some units occur closer to the fault on one side, which might skew the results. Another concern is the lithological difference within...
each rock unit, which may affect its strength and the amount of damage it sustained.

Another approach is therefore taken, where similar areas in corresponding offset bodies of rock are compared. Using the known cumulative offset on the San Jacinto Fault, we locate two outcrops of the same rock body and compare the Dd of two similarly shaped areas at similar distance from the fault trace. Thus we eliminate possible lithological differences that can occur within each rock unit, and ensure that we are indeed comparing similar rocks with similar histories. The results are summarized in Table 5 and Fig. 10.

The large offset on the Clark Fault makes it difficult to find a pair of outcrops to compare northwest of Anza, so most of the pairs either come from southeast of the trifurcation, or they are “split” — the outcrop on the SW side is northwest of the trifurcation, and the outcrop on the NE side is southeast of the trifurcation. The results of the down-slope distance method do not yield conclusive results as there is no consistent side that displays lower values. The results of the streams-sum method consistently show higher values of Dd on the northeast side of the fault, regardless of slope, with one exception in the SRTM data. Since the down-slope distance method is being affected by streams outside the chosen outcrop polygon, because a pixel close to the edge can have a lower down-slope distance value if it is closest to a channel that is outside the polygon, thus reducing the average value and increasing the measure of Dd.

5. Discussion

We have presented an analysis of the geomorphology near the San Jacinto Fault using several different methods to explore drainage properties. We show that drainage density increases in close proximity to the fault, and demonstrate that some geomorphic differences between the drainages on the two sides of the fault cannot be explained by the usual factors that control drainage morphology. This suggests that fault related damage is a likely factor that can produce those differences. Here we discuss some concerns and limitations we encountered while conducting the analysis and how they may have affected our results. We also examine the interpretation of some drainage properties as damage proxies and how the results correspond to field observations.

When choosing drainages for comparison, we were limited by several factors. The drainages should be inside the zone of interest, they should mainly lie within one rock unit, and the sizes of the drainages should be similar. It was therefore difficult to choose a large enough population of drainages for the results to be statistically significant, if damage is the principal factor to be compared and the rest of the affecting parameters discarded. We conclude that the hypsometric integral seems to be the best quantity for comparing individual drainages across the fault, being non-dimensional and least correlated to the drainage size. Drainage density is less suited for this type of comparison, when used on individual drainages, unless there is high similarity in drainage areas. We tried to choose drainages that have similar aspects, and succeeded to do so in the SRTM case, where most of the drainages face southwest (Fig. 6). This was not possible in the LiDAR dataset, because the active fault is controlling the geomorphology and creating a valley into which the streams are draining from both sides. Another limiting factor in the LiDAR data was its limited extent, determined by the fault locality and not by geomorphology, which caused some drainage basins to be only partially mapped and therefore unsuited for analysis.

When choosing the spatial approach, we conclude that the meaningful scale to look for fault related damage is at most a 1 km wide zone around the fault. The spatial analysis of drainage density using the SRTM data demonstrates higher Dd near the fault, with width of ~1 km (Fig. 8).

It seems that the scale of 5 km width across the fault, used with the SRTM data, is too wide and is only partly capturing fault related damage. A damage zone width of ~1 km is best reflected in the hydrology, and is supported by field observations of badland morphology around the fault (Stillings, 2007). Therefore, the use of high resolution LiDAR data is more suited for looking at fault related damage, because it is a representation of the surface at a more appropriate scale for our purpose. The best validation of the spatial approach comes from the result that outcrops of rock occurring between two strands exhibit the highest drainage density, which correlates to the highest damaged zone (Table 4). The spatial approach, while having the advantage of smoothing and eliminating the need to choose drainages, is not without its problems. There is still a need to differentiate between rock units, and even though the area dependency is easily overcome by choosing regions with equal area, the slope and aspect contributions are harder to control due to the area’s geomorphology. We find that using the classical definition of drainage density (sum of streams length per area) produces better results than using the down-slope distance proxy of Tucker et al. (2001), and that focusing on offset correlative bodies of rock yields the best results in that case.

The chosen drainages approach gave better results southeast of Anza, possibly because the smaller total offset of rock units allows for an easier comparison between the two sides of the fault in that region. There is some disagreement between the SRTM and the LiDAR data results, where the SRTM data indicate more damage on the southwest side, southeast of Anza, while the LiDAR data indicate more damage on the northeast side throughout the fault zone. This damage asymmetry is also indicated by the spatial approach results. It may be that the SRTM data, which is using a larger buffer, is recording the effects of the activity on the Coyote Creek fault and the extension in the Coyote Ridge area southeast of the trifurcation. The rocks in the Coyote Ridge area are possibly more fractured as it is easier to damage rocks in an extensional regime. The narrower focus of the LiDAR dataset allowed us to eliminate most of the influence of the extensional step-over between the Coyote Creek and Clark faults which may have influenced the observations from the SRTM data. However, we note that the inference on higher damage on the southwest side of the fault does not match the results of the LiDAR analysis, nor those of Lewis et al.

![Fig. 8. A map of spatial Dd (streams-sum method) using an averaging filter with 100 m radius on the LiDAR data. The area in the map is the same as in Fig. 4. The filtering action smoothes out the data and makes it easier to see regional patterns. In this map, the central and southern parts have visibly higher Dd.](image-url)
This may reflect, in part, the nature and scale of the damage field as it is reflected in the drainage geomorphology.

Field observations show that highly pulverized granites are mostly located in areas that are between two fault strands, as well as on the hanging wall of the fault where it bends, resulting in areas where thrusting is the main slip component. This is in agreement with the observed high values of Dd in the spatial SRTM data near fault kinks, double strands, and fault junctions (Fig. 7). Stillings (2007) observed

**Fig. 9.** Results of the spatial approach using the LiDAR dataset and comparing drainage density in four different geological units, calculated by two methods — the down-slope distance and the streams-sum methods. The corresponding data is presented in Table 4. On the left are the results for the entire study area, whereas on the right are the results for the area southeast of Anza. Distance — the down-slope distance method. Lower values correspond to higher Dd. The values are consistently lower on the NE side, which we interpret as more damage to the rocks. Values are divided by the maximum value to scale them between 0 and 1.

**Table 4**
Comparisons of drainage density in different geological units, calculated by the two methods — the down-slope distance and the streams-sum per area.

<table>
<thead>
<tr>
<th>Rock unit</th>
<th>Location relative to fault</th>
<th>Down-slope distance (all)</th>
<th>Stream length sum/area (10^{-2}) (all)</th>
<th>Down-slope distance (SE)</th>
<th>Stream length sum/area (10^{-2}) (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qb</td>
<td>NE</td>
<td>31.67</td>
<td>3.41</td>
<td>34.90</td>
<td>3.20</td>
</tr>
<tr>
<td></td>
<td>SW</td>
<td>40.86</td>
<td>2.88</td>
<td>50.67</td>
<td>2.84</td>
</tr>
<tr>
<td>pKm</td>
<td>NE</td>
<td>29.37</td>
<td>3.78</td>
<td>29.37</td>
<td>3.78</td>
</tr>
<tr>
<td></td>
<td>SW</td>
<td>29.56</td>
<td>4.18</td>
<td>30.56</td>
<td>2.53</td>
</tr>
<tr>
<td>Ka</td>
<td>NE</td>
<td>23.95</td>
<td>3.37</td>
<td>23.95</td>
<td>3.37</td>
</tr>
<tr>
<td></td>
<td>SW</td>
<td>69.80</td>
<td>3.26</td>
<td>113.02</td>
<td>1.35</td>
</tr>
<tr>
<td>Kt</td>
<td>NE</td>
<td>34.09</td>
<td>4.29</td>
<td>33.18</td>
<td>4.63</td>
</tr>
<tr>
<td></td>
<td>SW</td>
<td>35.81</td>
<td>4.71</td>
<td>39.51</td>
<td>4.37</td>
</tr>
</tbody>
</table>

**Table 5**
Comparisons of drainage density between offset rock bodies along the fault, calculated by the two methods — the down-slope distance and the streams-sum per area.

<table>
<thead>
<tr>
<th>Rock unit and location relative to Anza</th>
<th>Id</th>
<th>Location relative to fault</th>
<th>Area (10^5) m(^2)</th>
<th>Average slope</th>
<th>Down-slope distance</th>
<th>Stream length sum/area (10^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qb SE</td>
<td>1</td>
<td>NE</td>
<td>1.37</td>
<td>18.52</td>
<td>51.83</td>
<td>2.53</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>SW</td>
<td>1.35</td>
<td>32.33</td>
<td>56.76</td>
<td>2.10</td>
</tr>
<tr>
<td>Qb SE</td>
<td>6</td>
<td>NE</td>
<td>1.78</td>
<td>28.39</td>
<td>32.98</td>
<td>4.60</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>SW</td>
<td>1.77</td>
<td>23.11</td>
<td>26.36</td>
<td>3.79</td>
</tr>
<tr>
<td>Qb Split</td>
<td>14</td>
<td>NE</td>
<td>2.87</td>
<td>28.40</td>
<td>15.40</td>
<td>3.50</td>
</tr>
<tr>
<td></td>
<td>19</td>
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<td>2.94</td>
<td>25.81</td>
<td>20.24</td>
<td>3.22</td>
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<tr>
<td>Ka SE</td>
<td>2</td>
<td>NE</td>
<td>2.94</td>
<td>35.00</td>
<td>20.03</td>
<td>8.60</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>SW</td>
<td>3.07</td>
<td>40.25</td>
<td>13.89</td>
<td>5.22</td>
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<tr>
<td>Ka SE</td>
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<td>NE</td>
<td>3.12</td>
<td>27.47</td>
<td>25.66</td>
<td>4.62</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>SW</td>
<td>3.16</td>
<td>24.41</td>
<td>29.98</td>
<td>2.55</td>
</tr>
<tr>
<td>pKm SE</td>
<td>7</td>
<td>NE</td>
<td>2.62</td>
<td>26.39</td>
<td>22.71</td>
<td>3.01</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>SW</td>
<td>2.57</td>
<td>18.83</td>
<td>29.32</td>
<td>2.83</td>
</tr>
<tr>
<td>pKm Split</td>
<td>17</td>
<td>NE</td>
<td>2.71</td>
<td>20.57</td>
<td>30.68</td>
<td>1.94</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>SW</td>
<td>2.72</td>
<td>24.18</td>
<td>22.46</td>
<td>4.07</td>
</tr>
<tr>
<td>pKm Split</td>
<td>18</td>
<td>NE</td>
<td>3.00</td>
<td>25.83</td>
<td>22.32</td>
<td>3.64</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>SW</td>
<td>2.92</td>
<td>25.60</td>
<td>20.25</td>
<td>3.39</td>
</tr>
<tr>
<td>pKm NW</td>
<td>22</td>
<td>SW</td>
<td>4.06</td>
<td>31.91</td>
<td>20.37</td>
<td>6.97</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>NE</td>
<td>4.02</td>
<td>25.43</td>
<td>23.12</td>
<td>3.25</td>
</tr>
</tbody>
</table>

The rock units were chosen such that their area and distance from the fault would be as similar as possible.

Table 5 corresponds to Fig. 10. Each pair has one outcrop NE of the fault and one outcrop SW of the fault. The pair’s location relative to the trifurcation (or Anza) is indicated. Split means that one outcrop is NW of Anza and the other is SE of Anza. Id is the outcrop identifying number.
that in some locations, the most intensely damaged rock occurs outward at a distance of tens of meters on the southwest side of the fault, with pulverization localized between the two fault strands. Our analysis methods focused on larger scales than tens of meters, and we were limited by the data resolution, so we were not able to detect this type of observed damage. We are probably observing a mix of signals from an evolving damage structure. The more widely-spaced fracturing north-east of the fault probably controls the signal, with a smaller influence from the pulverization zones in areas of fault trace complexity.

It is possible that the zones with the highest damage are also the ones that are the most eroded, and are now covered with alluvium, which are areas that we eliminated from the dataset. One such area is Jackass flat, where the fault crosses a wide basin with Quaternary alluvial fill, and is not exposed in bedrock. In the Jackass flat area the bedrock on the northeast side is farther away from the active fault trace than on the southwest side (and out of the LiDAR data extent), which could indicate more erosion and therefore more damage on the northeast. However, the situation is reversed in Horse canyon, where bedrock abuts the fault on the northeast, and on the southwest there is a wide alluvial flat underlain by the damage zone and a secondary fault.

6. Conclusions

The rock damage signal along the Clark strand of the San Jacinto Fault was inferred from observations derived from two elevation datasets and a suit of hydrological and GIS tools, and there appears to be a correlation between the amount of damage across and within the fault zone and the drainage properties in those areas. The results from the lower resolution SRTM data point to a ~1 km wide damage zone centered on the main strand of the San Jacinto Fault. The use of high resolution topography from LiDAR data enabled us to narrow our focus to the fault of interest and remove influences from nearby faults.
The LiDAR data proved more useful for observations at the scales of the fault process zone than the low-resolution SRTM data. The fault damage zone, as inferred from drainage properties, is more pronounced near areas of complexities in the surface trace, such as kinks, double strands and fault junctions. The results from the LiDAR spatial analysis indicate that the highest damage occurs in between fault strands, followed by higher overall damage to the northeast. The damage that we infer is probably in the form of widely-spaced fracturing at the 5–20 cm scale, as described by Molnar et al. (2007), as opposed to pulverization which occurs at the tens of microns scale and is thought to be a marker for preferred propagation direction (Dor et al., 2006a; Lewis et al., 2007). If indeed the signal that is registered in the LiDAR data is related to the macro-fracturing of rock, then we are left with the problem of resolving which damage signal is more representative of the overall preferred rupture direction, as they seem to give opposite results. From field observation, pulverization along the SJF occurs mostly in areas of compression or between two fault strands, which may indicate that pulverization is more related to structural complexities rather than rupture direction, and that the overall higher drainage density in those areas reflects that relationship.

The higher damage on the northeast compared to the southwest side of the fault throughout the study area may point to a consistent propagation direction along the entire studied length of the fault, from southeast to northwest, consistent with the observations of Lewis et al. (2005) of a higher level of damage on the northeast side of each branch of the SJF. A southeast to northwest rupture propagation on the Clark segment of the SJF, means more energy will propagate towards the more populated areas of San Bernardino and Riverside. This is also important for hazard assessment for the Los Angeles basin area, because it has been shown by simulations that a northward propagating earthquake will cause much more shaking in the basin (Olson et al., 2008).

While trying to quantify observed asymmetry in the drainage morphology across the fault, we encountered many difficulties, such as removing the affects of slope and aspect, finding appropriate areas to compare, and taking into account other possible sources of damage besides the preferred propagation direction hypothesis. Our results are by no means conclusive as to the sense of asymmetry on the fault, and further work needs to be done in order to resolve those issues. If indeed the two sides of the fault have a significant difference in rock damage, it should be reflected in the slope–area relation of different drainages, which we have yet to explore. Even higher resolution datasets can be derived from the LiDAR point cloud, which would allow one to focus on a narrower zone and perhaps detect different damage signatures, such as rock pulverization and seismic trapping structures which typically occur only within 100 m from the fault. Looking at several different faults at various stages of development, and conducting the same type of analysis for comparison, should help determine if damage and damage intensity are indeed affecting drainage patterns. Faults of the Eastern California Shear Zone could be ideal for this purpose, being in an arid location and having accessible LiDAR data.

Acknowledgements

We thank Ken Hudnut, the GEON portal website and the people behind it (www.geongrid.org) for access to the B4 LiDAR data. This paper benefited greatly from the comments of Ramon Arrowsmith and an anonymous reviewer.

References


Jennings, C.W., 1985. An explanatory text to accompany the 1:750,000 scale fault and geologic maps of California, California Department of Conservation, Division of Mines and Geology.


