Near-orthogonal orientations of active conjugate faults in the Anza-Borrego shear zone, Southern California

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Key Points:

- We use a new algorithm to identify quasi-linear clusters of micro-earthquakes associated with active strike-slip faults in a trans-tensional region south of the Salton Sea, Southern California.
- The observed dihedral angles between right- and left-lateral faults show a broad distribution with a peak around 80°.
- Near-orthogonal fault orientations can be explained by tectonic rotation due to a long-term slip on a more mature system of right-lateral faults.

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Abstract

We investigate orientations of small active faults in the Anza-Borrego shear zone to the south of the Salton Sea, Southern California. We use LINSCAN, a new algorithm for identifying quasi-linear clusters of earthquakes, to identify seismogenic strike-slip faults in the study area. LINSCAN, a derivative of OPTICS, is an unsupervised learning algorithm which uses a distance function based on Kullback-Leibler divergence rather than Euclidean distance to find clusters of points that are not only geometrically close, but also have a preferred orientation. We evaluate dihedral angles between the identified sets of left- and right-lateral faults. The dihedral angles are normally distributed around $\sim 80°$, much larger than expected assuming optimal fault orientations and the coefficient of friction of 0.6–0.8. We show that the observed fault orientations are best explained by fault rotation away from the principal shortening axis due to a cumulated tectonic strain.

Plain Language Summary

Small earthquakes can highlight the location and attitude of active faults at depth. We use a large set of earthquake locations and a novel algorithm to identify small faults, along with their orientations, and sense of slip. We find that faults with opposite sense of slip (the so-called antithetic, or conjugate faults) are at nearly right angles to each other. For newly created faults, such a configuration would imply that friction is almost negligible. We suggest that the high-angle conjugate faults instead result from fault rotation due to long-term tectonic deformation.

Introduction

According to the Mohr-Coulomb failure theory, new or pre-existing faults should be preferentially activated at an angle $\pm\theta_0$ to the principal compression axis (Anderson, 1951; Sibson, 1974; Scholz, 2019). The two antithetic fault orientations are known as conjugate faults (e.g., Twiss & Moores, 1992, p. 141). For typical laboratory values of the static coefficient of friction μ of 0.6–0.8 (Byerlee, 1978), the dihedral angle between optimally oriented conjugate faults is $2\theta_0 = \arctan(\mu^{-1}) \approx 50 - 60$ degrees (Anderson, 1951; Sibson, 1974). While in some cases there is good agreement between predictions of the Mohr-Coulomb theory and the observed fault orientations (Walsh & Watterson, 1988; Collettini & Sibson, 2001; Alt & Zoback, 2017), there are also ample examples of conjugate faults that are not optimally oriented with respect to each other and/or the

inferred principal stress axes, assuming the Byerlee's friction. In fact, many active conjugate faults exhibit dihedral angles close to 90 degrees, considerably greater than $2\theta_0$ (McGill et al., 1989; Thatcher & Hill, 1991; Yue et al., 2012; Jin & Fialko, 2020; Fialko & Jin, 2021; Hatch-Ibarra et al., 2022). Proposed explanations include anomalously low in situ friction (e.g., Middleton & Copley, 2014; Ross et al., 2019), a dominant control of deep fault roots in the ductile lower crust (Thatcher & Hill, 1991; Scholz & Choi, 2022; Liang et al., 2021), and fault rotation due to finite tectonic strain (Cloos, 1955; Freund, 1970; Nur et al., 1986; Fialko & Jin, 2021). A low frictional strength is often inferred in case of mature well-slipped faults (Mount & Suppe, 1987; Wernicke, 1995; Sibson, 1994), presumably due to activation of various weakening mechanisms (Rice, 2006; Di Toro et al., 2011; Brown & Fialko, 2012). However, the bulk of the seismogenic upper crust is unlikely extremely weak, as evidenced by optimal orientations of at least some active faults (Walsh & Watterson, 1988; Collettini & Sibson, 2001; Alt & Zoback, 2017), stress measurements in deep boreholes (Townend & Zoback, 2000), and long-term support of topography (Coblentz et al., 1994; Burov, 2011). Deep ductile roots could possibly control the orientation of faults that originate at the bottom of the seismogenic zone and/or cut through the entire brittle crust (Scholz & Choi, 2022), but not of the abundant small faults having characteristic dimensions of less than $\sim$10 km that are unlikely connected to the ductile substrate (Fialko & Jin, 2021). It was also suggested that faults may typically form at near-optimal angles, but be subsequently rotated away from the axis of maximum compressive stress due to finite tectonic strain (Cloos, 1955; Freund, 1970; Fialko & Jin, 2021). The maximum rotation angle is limited by a fault lock-up, and is on the order of θ_0 (Nur et al., 1986; Sibson, 1990).

These hypotheses can be discriminated by quantifying relative orientations of small active faults. Fialko and Jin (2021) noted that lineated clusters of microseismicity in the Eastern California Shear Zone near Ridgecrest reveal multiple high-angle conjugate faults consistent with the rupture geometry of the M6.4 foreshock and M7.1 mainshock of the 2019 Ridgecrest earthquake sequence (Ross et al., 2019; Jin & Fialko, 2020; Fialko, 2021). Fialko and Jin (2021) further showed that the observed fault geometries are consistent with finite strain and rotation since the inception of the Eastern California Shear Zone. It is of interest to quantify relative orientations of conjugate faults in different regions undergoing active deformation (Fialko, 2021). However, identifying and systematically

mapping active fault structures is a challenging task, especially in case of relatively small faults that typically do not have a surface expression.

In this paper, we apply a new algorithm to map out a population of active strike-slip faults in the Anza-Borrego shear zone in Southern California, and evaluate the distribution of dihedral angles between the identified sets of antithetic (i.e., left- and right-lateral) faults. We then use the observed fault orientations to evaluate possible controlling mechanisms.

1 Data and Methods

Active faults are often expressed in microseismicity (Valoroso et al., 2009; Nadeau & McEvilly, 1999). In case of strike-slip faults, the associated microearthquakes appear as localized streaks of epicenters in a map view (e.g., Alt & Zoback, 2017; Fialko, 2021). The respective quasi-linear clusters (QLCs) of events can be used to map active fault structures (Skoumal et al., 2019; Fialko, 2021). Several algorithms were proposed to identify lineated structures in highly scattered point clouds, all based on the point density and/or Euclidian distance between candidate points (Skoumal et al., 2019; Cochran et al., 2020; Fialko, 2021). In particular, Fialko (2021) used a non-parametric unsupervised learning algorithm OPTICS (Ordering Points To Identify the Clustering Structure; Ankerst et al., 1999), a variant of DBSCAN (Schubert et al., 2017), to separate clustered events from the background seismicity. One of the drawbacks of proximity-based algorithms such as OPTICS and DBSCAN is that the selected clusters can be of arbitrary shape, and additional screening is needed to cull out clusters having isometric or irregular geometries. Oftentimes such clusters contain smaller-scale lineated features that could be sensibly associated with active faults but would be missed by the search algorithm if the parental cluster is culled out. A robust procedure for multi-scale identification of quasi-linear sets of epicenters is therefore highly warranted.

1.1 LINSCAN Algorithm

We use LINSCAN, a new algorithm based on OPTICS, in which the Euclidean distance metric is replaced with a distance function $D(P, Q)$ derived from Kullback-Leibler (KL) divergence. The KL divergence is a measure of how similar two given distributions are. For two groups of points P and Q, the distance function $D(P, Q)$ is minimized when

points in both groups are distributed along similar directions (see Supplementary Information for details). This ensures that only specific geometric shapes (in this case, QLCs) are selected. We evaluated the accuracy and robustness of the algorithm using a synthetic catalog of earthquake epicenters. The synthetic catalog consists of (i) arbitrarily oriented QLCs of various sizes, (ii) quasi-isometric clusters, and (iii) randomly distributed "background seismicity" (see Figure S1a in the Supplementary Information). The LINSCAN algorithm is able to efficiently identify and separate QLCs from the rest of the data (Figure S1b). Occasionally, some of the original QLCs are split into co-linear subsegments (Figure S1b). This is not a major issue since we are interested in accurate estimation of the fault strike angles. If needed, adjacent QLCs can be merged by considering their proximity and along-strike continuity. More importantly, the algorithm is able to identify overlapping and intersecting clusters that are ubiquitous in the case of complex fault systems (e.g., Fialko, 2021), although for some of the overlapping clusters the selection choices are non-unique. In the test shown in Figure S1, the number of points identified as belonging to QLCs (Figure S1b) is about 82% of the total number of "true" QLC points in the input data set (Figure S1a). A small fraction of points was identified as QLCs even though they did not belong to any of the input QLCs, due to either false detections or spontaneous quasi-linear patterns in the randomly generated "background seismicity".

1.2 Data analysis

We apply LINSCAN to quantify relative orientations of small strike-slip faults in a region of active deformation to the south of the Salton Sea, Southern California (Figure 1). This region accommodates ∼20 mm/yr of strike-slip motion between the North American and Pacific plates (Tymofyeyeva & Fialko, 2018), and hosts a number of active faults of various degrees of maturity (Jennings & Bryant, 2010), as well as abundant microseismicity (Yang & Hauksson, 2013). This region, hereafter referred to as the Anza-Borrego shear zone, is part of a transtensional transition zone connecting the Southern San Andreas Fault system to the Cerro Prieto fault system, and ultimately to the Gulf of California (Herzig & Jacobs, 1994; Crowell et al., 2013; Gonzalez-Ortega et al., 2014). We use a recently published catalog of precisely located events with focal mechanisms that spans 1981–2021 (Cheng et al., 2023). The event locations are shown in Figure 1. We convert geographic coordinates to the local Cartesian (UTM) coordinates using a lo-

cal origin at 117°W, 32°N. The catalog epicenters and the QLCs selected by LINSCAN are shown in Figure 2 (blue and orange dots, respectively).

To ensure that the selected QLCs are robust, we perform several quality checks. As spurious linear patterns may emerge at the boundaries of the area of interest (due to the discarding of data outside of the bounding box), we removed all east-west and north-south striking clusters near the respective boundaries. For each "inside" cluster, we compute the Pearson correlation coefficient (Artusi et al., 2002), and retain clusters for which the absolute value of the correlation coefficient is greater or equal to 0.5. We further fit a straight line segment to the respective sets of points for each cluster, and compute the mean normalized distance δ between the points and the best-fit line as the mean of distances from the points to the line, divided by the line length. We discard clusters for which $\delta > 0.1$. Since we are interested in strike-slip faults, we compute composite focal mechanisms and discard clusters for which the dip angle of either P or T axis is greater than 40° (Fialko, 2021). Finally, we perform a visual check to discard clusters in which the events are too sparse, unevenly distributed, hard to distinguish from the background seismicity, or organized in sub-clusters with significantly different orientations. Figure S2 shows several examples of the culled out "low quality" clusters, and Figures 3 and S5–S15 show QLCs that satisfy the above criteria.

Based on the identified fault planes and polarity of composite focal mechanisms, we determine the sense of slip on each identified fault (Fialko, 2021). Figure 4 shows the distribution of fault orientations, and Figure 5 shows the distribution of dihedral angles between all possible pairs of right- and left-lateral faults (for technical details, see Fialko, 2021).

2 Discussion

Dihedral angles between the identified conjugate faults (Figure S4) are nearly normally distributed with a peak around 80° (Figure 5). The near-orthogonal orientations of the majority of conjugate faults are distinctly different from the near-optimal orientations of strike-slip faults activated by fluid injection in the central US (e.g., Alt & Zoback, 2017; Schoenball & Ellsworth, 2017; Skoumal et al., 2019), but similar to those observed in the Ridgecrest area of the Eastern California Shear Zone (e.g., Ross et al., 2019; Fialko & Jin, 2021; Fialko, 2021). The characteristic dimensions of faults or active fault

patches used in our analysis vary from 80 m to 3 km, with the mean value of 0.6 km (Figures S4–S15). Rupture dimensions of individual earthquakes comprising the respective earthquake clusters are smaller still. The small rupture size has several implications. First, a large fraction of the identified small-scale ruptures are not associated with mature well-slipped faults, and thus not linked to the ductile substrate, precluding a possibility that their orientations are controlled by localized shear zones below the brittle-ductile transition (e.g., Takeuchi & Fialko, 2012, 2013; Fialko & Jin, 2021; Scholz & Choi, 2022; Liang et al., 2021). Second, small ruptures are not expected to produce strong dynamic weakening, so that their strength may be to the first order governed by quasi-static friction (e.g., Lapusta & Rice, 2003; Fialko, 2015).

An optimal fault orientation due to very low static friction may also be ruled out as the cause of large dihedral angles observed in the study area (Figure 5). In the area of interest, the principal axes of both the maximum horizontal shortening rate (Figure S3) and maximum compressive stress (Yang & Hauksson, 2013) are oriented approximately north-south. Results shown in Figure 4 indicate that populations of right- and left-lateral faults are not symmetrically distributed around the axis of the maximum shortening rate and/or compression. While most of the right-lateral faults are at angles of 45±15 degrees to the principal strain rate/stress axis (Figure 4), most of the left-lateral faults are at more acute angles of 20–30°, nearly optimally oriented assuming the Byerlee's law (i.e., the coefficient of friction of 0.6–0.8). This is different from the observed fault orientations in Ridgecrest, where the dihedral angles between conjugate faults are approximately bisected by the principal strain rate and stress axes (Fialko & Jin, 2021; Fialko, 2021).

We argue that the observed orientations of small active faults in the Anza-Borrego shear zone can be explained by a long-term fault rotation. It is known that slip on a fault embedded in an elastic medium results in fault rotation,

$$\omega = \arctan\left(\frac{1-2\nu}{2G}\Delta\tau\right), \tag{1}$$

where ω is the rotation angle in radians, G the shear modulus, ν the Poisson's ratio, and $\Delta\tau$ the stress drop (Martel, 1999). For an infinitely long strike-slip fault with a constant stress drop, the relation between the stress drop $\Delta\tau$ and surface fault slip s is:

$$\Delta\tau = \frac{1}{2}\frac{sG}{D}, \tag{2}$$

where D is the fault locking depth (e.g., Segall, 2010, p. 96). From equations 1 and 2, a strike-slip fault with a total offset s rotates by an angle

$$\omega = \arctan\left(\frac{1-2\nu}{4}\frac{s}{D}\right). \tag{3}$$

For right-lateral slip, the predicted sense of rotation is counter-clockwise (Martel, 1999). The estimated total offset on the San Jacinto Fault system that dominates interseismic deformation in the study area is 20–25 km (e.g., Morton & Matti, 1993). For $\nu = 0.25$ and $D = 12$ km (Lindsey et al., 2014; Tymofyeyeva & Fialko, 2018), equation 3 suggests a rotation of 12–15 degrees. Using a depth-averaged slip instead of surface slip in equation 3 reduces the estimated rotation by a few degrees. This is a lower bound on the total possible rotation amount because it neglects contributions from other major faults such as the Elsinore fault, as well as distributed deformation due to numerous small faults in the bulk of the brittle upper crust (e.g., Fialko & Jin, 2021). Thus an apparent $\sim 20^\circ$ counter-clockwise deviation of the majority of right-lateral faults from the optimal orientation (Figure 4) is consistent with a progressive rotation since the inception of the Anza-Borrego shear zone. The left-lateral faults are smaller/less mature and therefore experienced relatively little rotation. Note that the observed distribution of strike angles of a population of right-lateral faults is fairly broad, and some fraction of right-lateral faults is indeed optimally oriented assuming Byerlee's law (Figure 4).

We interpret differences between the observed distributions of dihedral angles in different tectonic areas in terms of the amount of a total accommodated strain. In case of injection-induced seismicity in the central US (Alt & Zoback, 2017; Schoenball & Ellsworth, 2017; Skoumal et al., 2019), pre-existing faults are brought to failure due to increases in the pore fluid pressure, resulting in a preferential activation of faults that are optimally oriented with respect to the background stress. The Ridgecrest, eastern California region is a developing shear zone, where new and pre-existing faults are continually activated and rotated primarily via distributed failure and simple shear (Fialko & Jin, 2021). The Anza-Borrego shear zone exemplifies a "high strain" end-member, whereby much of the deformation and rotation (Hauksson et al., 2022) is accommodated by well-developed plate boundary faults. The main difference between the observed orientations of small active faults in the Ridgecrest area of the Eastern California Shear Zone and the Anza-Borrego Shear Zone is that the latter features the average dihedral angles (Figure 5) that are about $\sim 10^\circ$ larger than those in the Ridgecrest area (Fialko, 2021), and a non-symmetric distribution of conjugate faults with respect to the principal compres-

sion and shortening rate axes (Figure 4), likely due to different amounts of slip accommodated by the respective fault systems.

3 Conclusions

We used a new algorithm to quantify orientations of small active faults at the southern end of the San Andreas-San Jacinto fault system, referred to as the Anza-Borrego shear zone. The dihedral angles between conjugate strike-slip faults are nearly normally distributed with a mean value of ∼80°. The fault strikes are asymmetrically distributed with respect to the principal strain rate and stress axes, with left-lateral faults optimally oriented for failure assuming the Byerlee's law, and right-lateral faults rotated by ∼20° counter-clockwise from the optimal orientation. We argue that the inferred near-orthogonal orientations between conjugate faults are not due to either low coefficient of friction or ductile shear zones in the lower crust, but can instead be explained by rotation due to a long-term tectonic deformation. Faults may form or be activated at near-optimal orientations, and subsequently rotate away from the principle shortening axis. A comparison to other areas of well-documented small active faults reveals an increase in the average dihedral angle with the total accumulated tectonic strain. We attribute the observed asymmetric distribution of conjugate faults with respect to the principal strain rate axis to a difference in the total amount of slip accommodated by the right- and left-lateral fault systems.

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Data Availability Statement

LINSCAN source codes with examples are available at `https://zenodo.org/badge/latestdoi/672119597`

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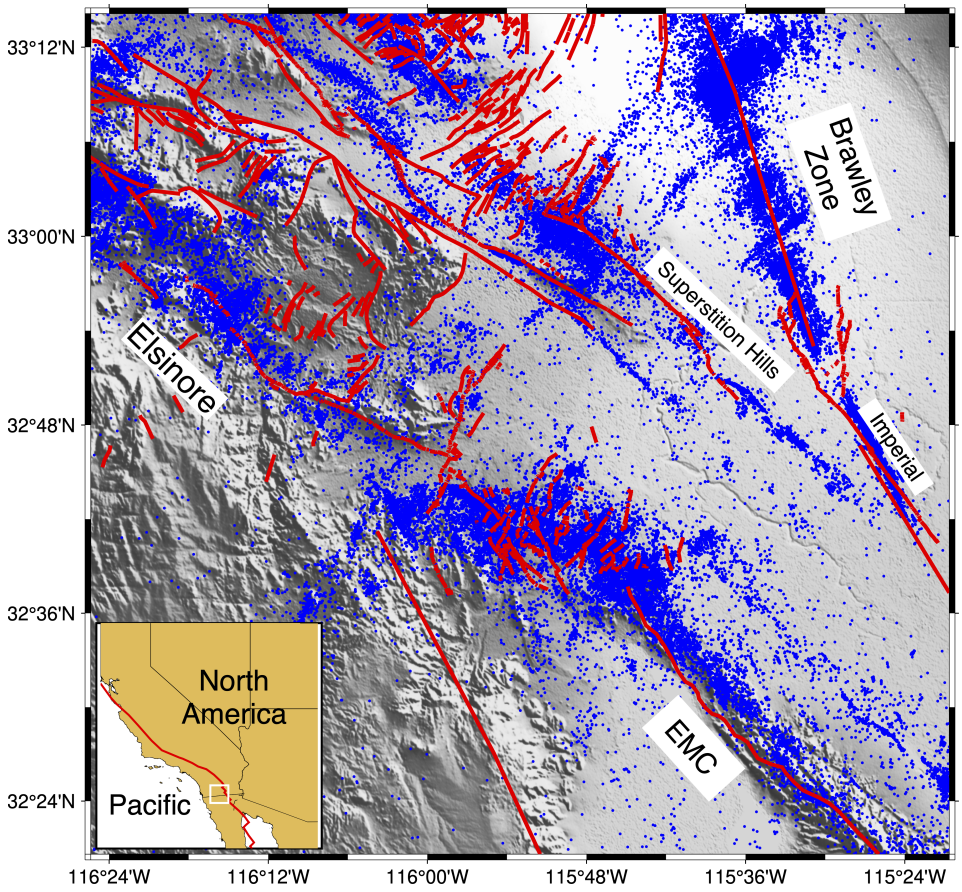


Figure 1. Map of the study area, with shaded relief. Red lines denote traces of Quaternary faults (Jennings & Bryant, 2010). Blue dots denote earthquake epicenters from Cheng et al. (2023) catalog. EMC="El Mayor-Cucapah". The inset shows the regional setting with respect to the North America-Pacific plate boundary (red line).

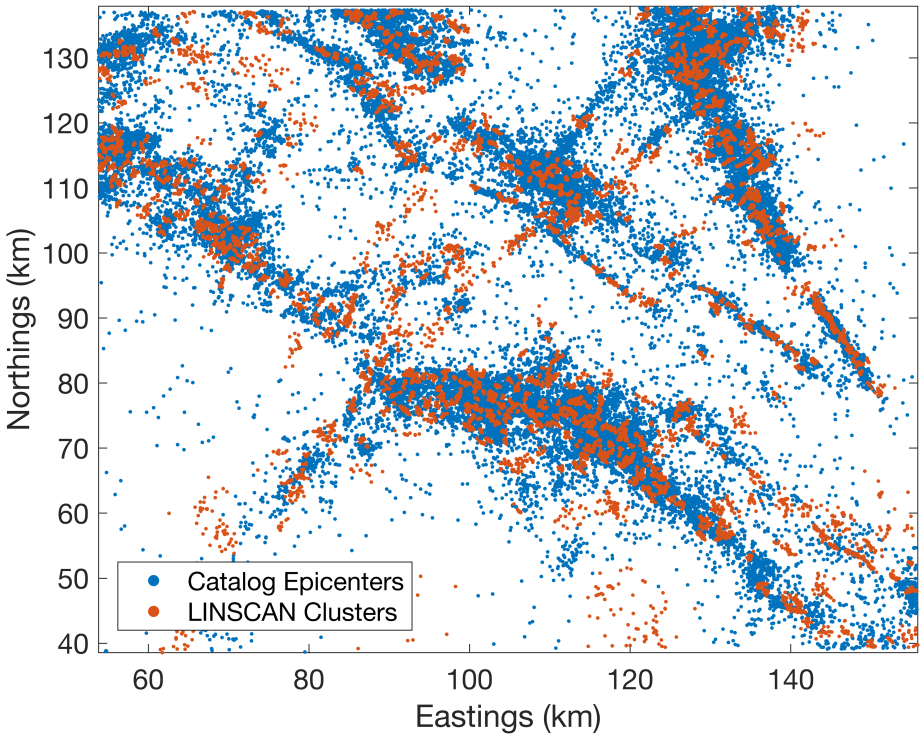


Figure 2. Catalog seismicity (blue dots, same as in Figure 1), and quasi-linear clusters (QLCs) of seismicity identified by the LINSCAN algorithm (orange dots). The total number of QLCs identified by LINSCAN is 1181.

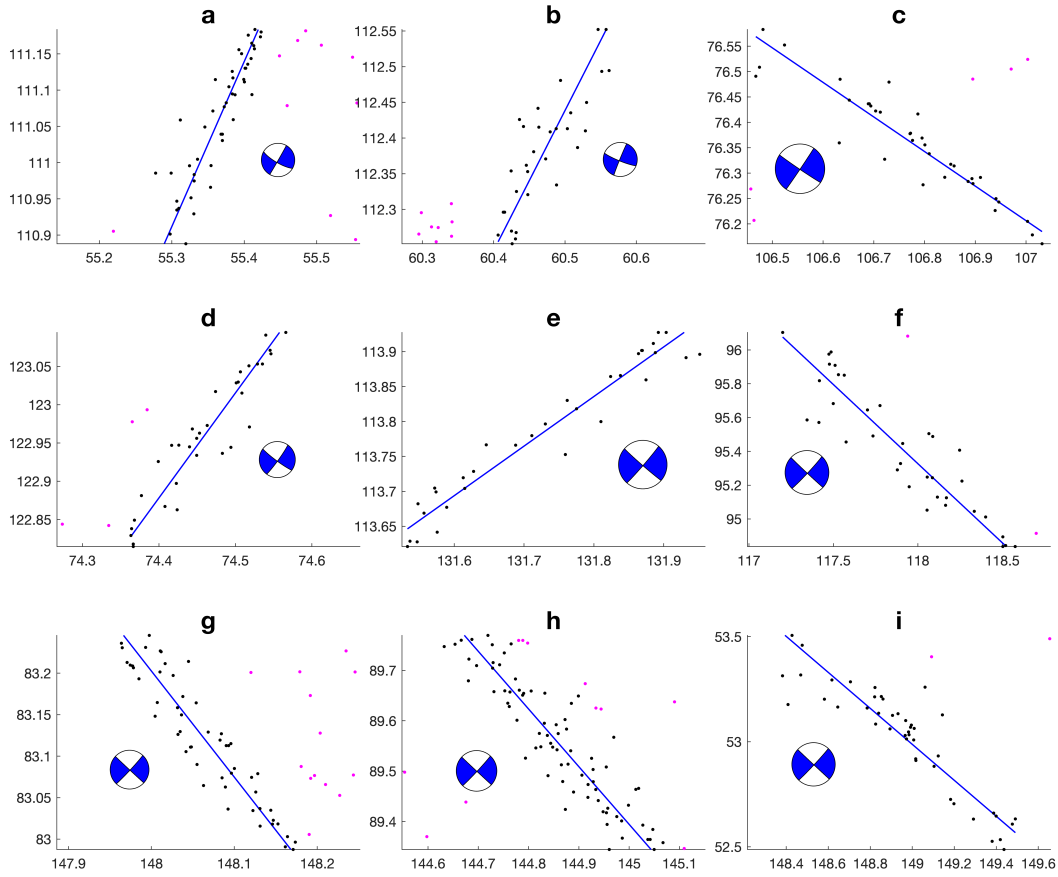


Figure 3. Examples of quasi-linear clusters that passed the quality control checks. Black dots denote earthquakes constituting a cluster, and magenta dots denote the background seismicity. Blue lines denote best-fitting linear segments. Blue beach balls denote composite focal mechanisms. Axes represent northing and easting coordinates, in km.

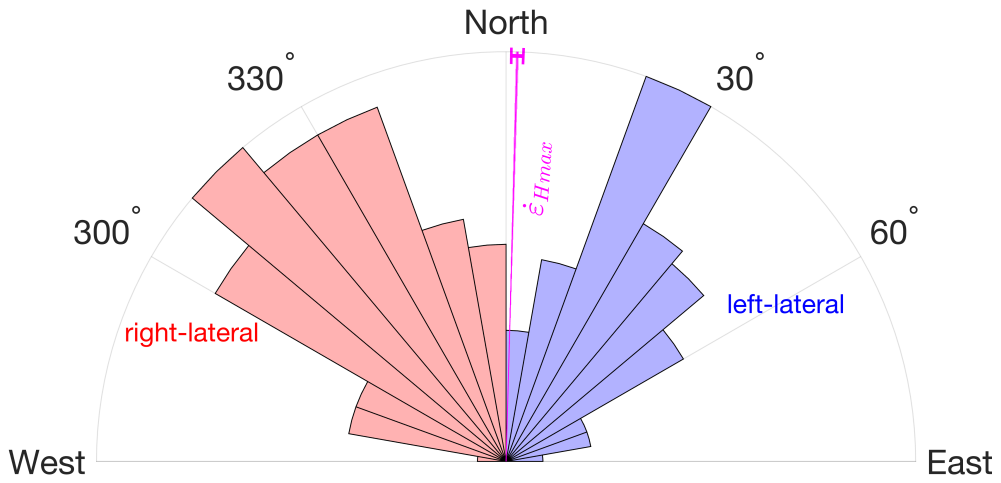


Figure 4. A distribution of strike angles of high-quality QLCs shown in Figures 3 and S4-S15. Red histogram corresponds to right-lateral faults (total of 159 samples), and blue histogram corresponds to left-lateral faults (total of 216 samples). Thin magenta line denotes the average orientation of the principal shortening rate axis (see Figure S1?). The magenta error bar denotes 4 standard deviations.

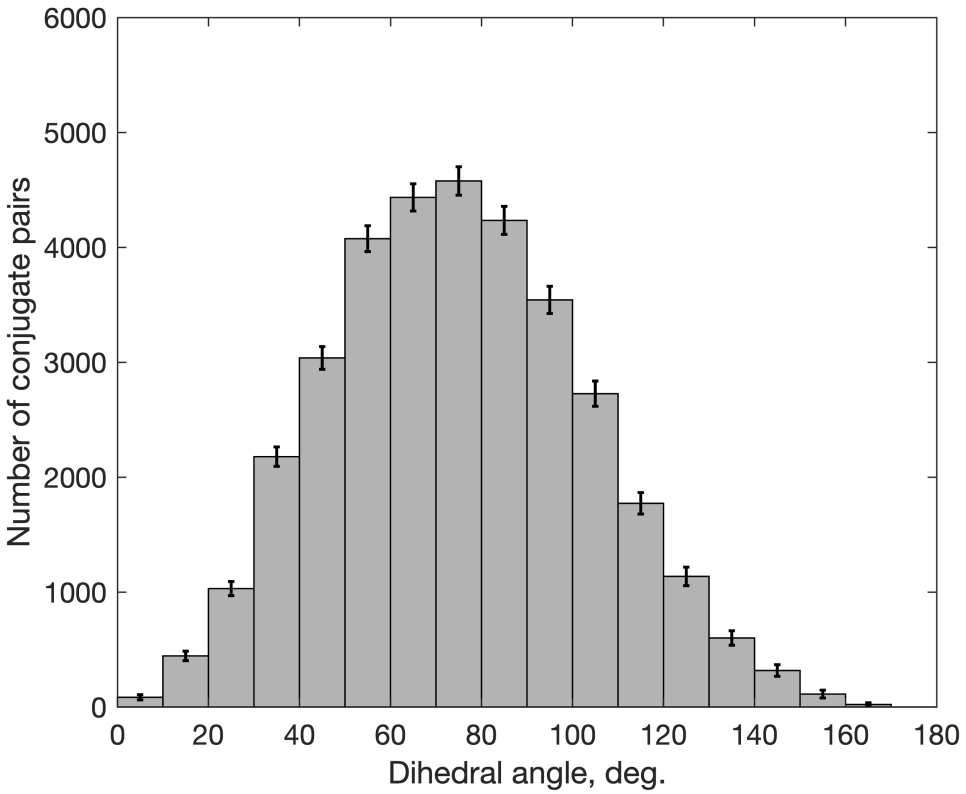


Figure 5. A histogram of dihedral angles between the conjugate strike-slip faults shown in Figure 4. Dihedral angles were computed between every possible pair of right- and left-lateral faults. Error bars denote 2σ uncertainty (see Fialko (2021) for details of the error analysis).

Figure 3.

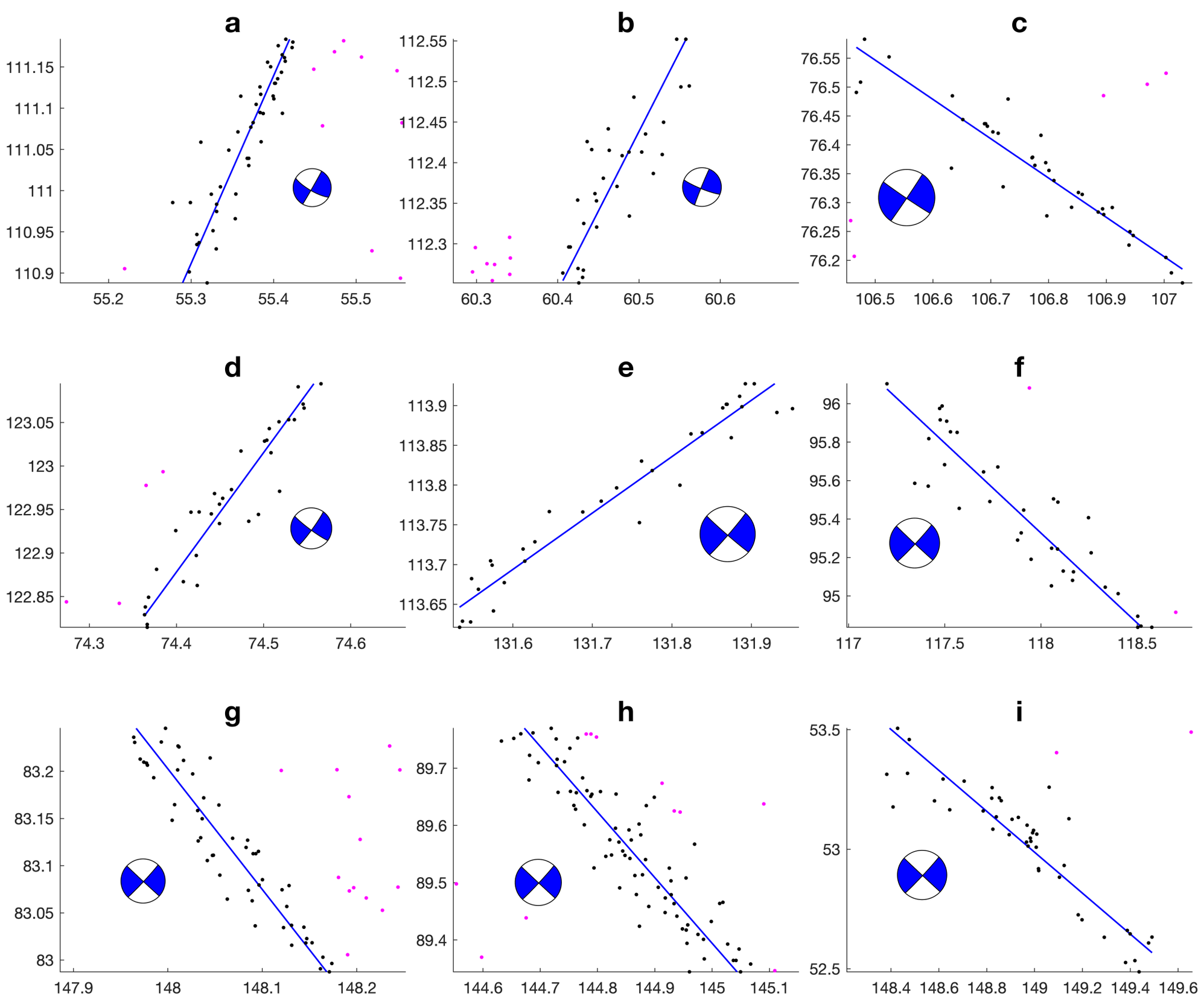

a
111.15
111.1
111.05
111
110.95
110.9
55.2
55.3
55.4
55.5
b
112.55
112.5
112.45
112.4
112.35
112.3
60.3
60.4
60.5
60.6
c
76.55
76.5
76.45
76.4
76.35
76.3
76.25
76.2
106.5
106.6
106.7
106.8
106.9
107
d
123.05
123
122.95
122.9
122.85
74.3
74.4
74.5
74.6
e
113.9
113.85
113.8
113.75
113.7
113.65
131.6
131.7
131.8
131.9
f
96
95.8
95.6
95.4
95.2
95
117
117.5
118
118.5
g
83.2
83.15
83.1
83.05
83
147.9
148
148.1
148.2
h
89.7
89.6
89.5
89.4
144.6
144.7
144.8
144.9
145
145.1
i
53.5
53
52.5
148.4
148.6
148.8
149
149.2
149.4
149.6

Figure 4.

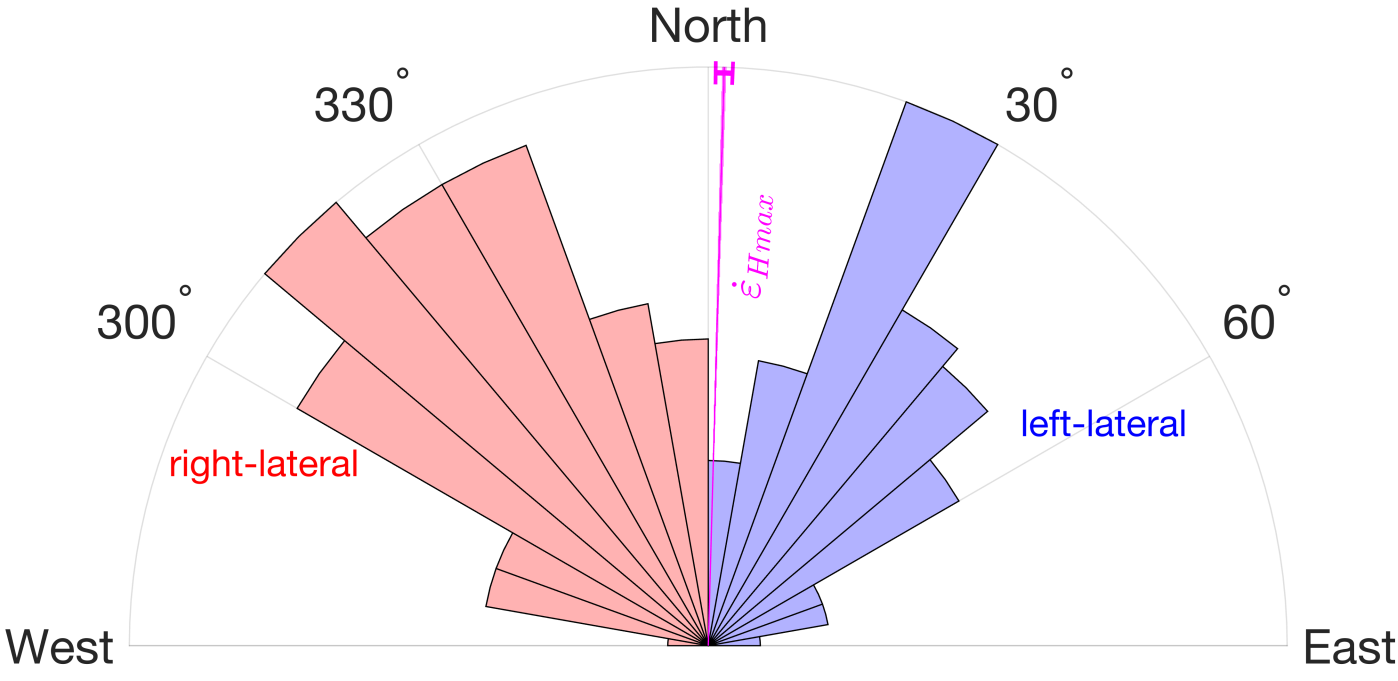

North
330°
30°
300°
60°
West
East
$\dot{\varepsilon}_{Hmax}$
right-lateral
left-lateral

Figure 2.

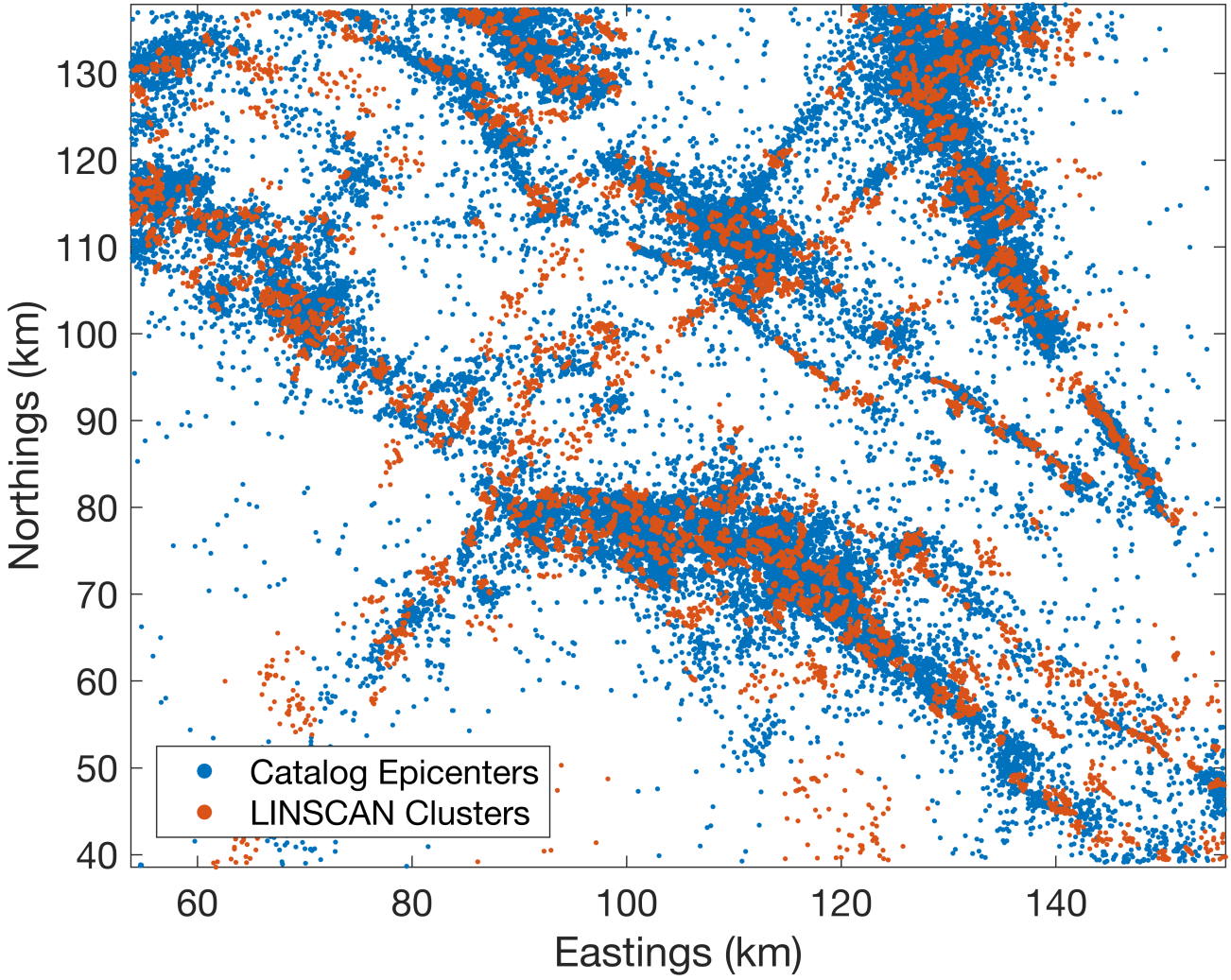
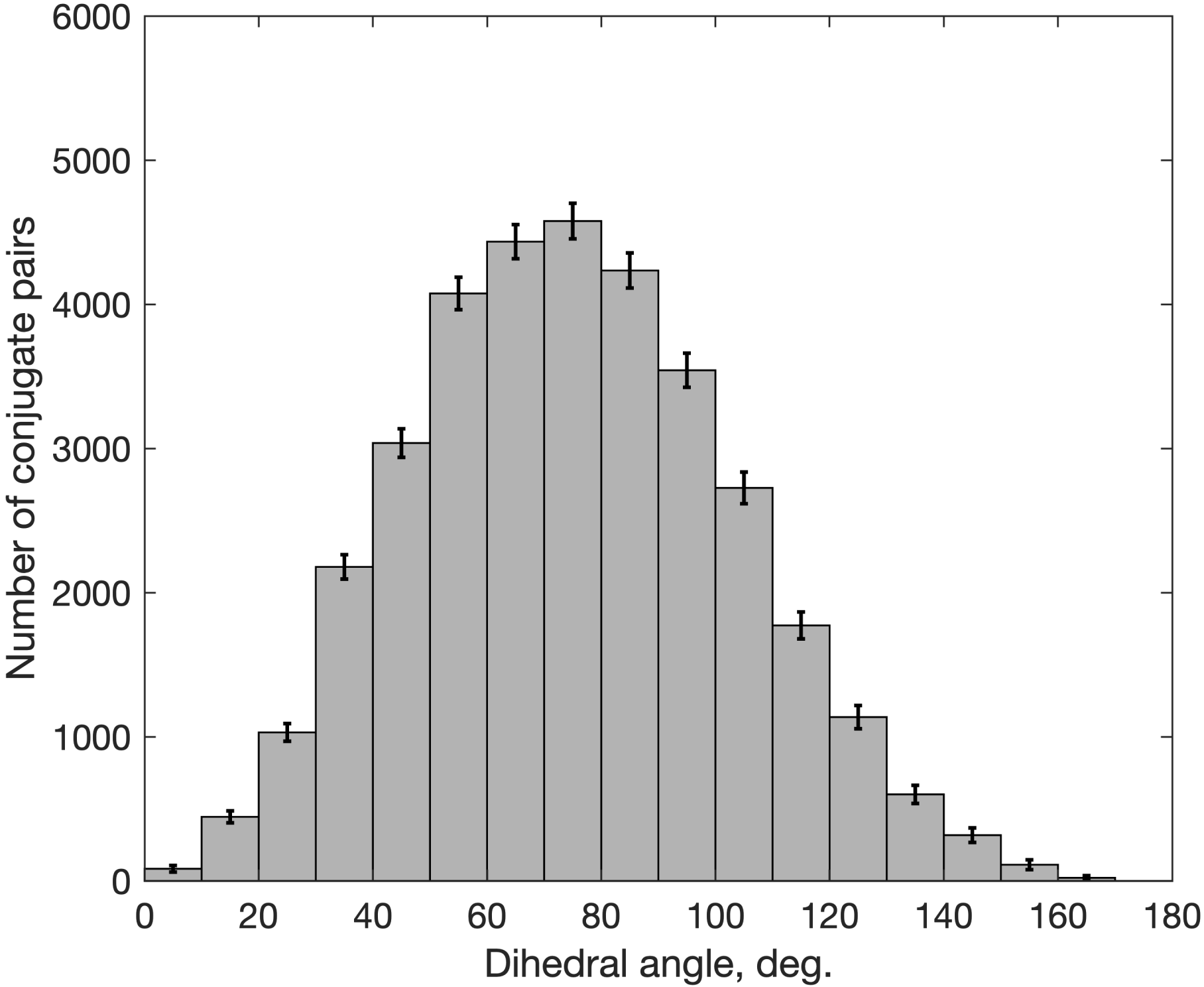

Catalog Epicenters
LINSCAN Clusters
Northings (km)
Eastings (km)
130
120
110
100
90
80
70
60
50
40
60
80
100
120
140

Figure 1.

33°12'N
33°00'N
32°48'N
32°36'N
32°24'N
116°24'W
116°12'W
116°00'W
115°48'W
115°36'W
115°24'W
Elsinore
Brawley Zone
Superstition Hills
Imperial
EMC
North America
Pacific

Figure 5.


6000
5000
4000
3000
2000
1000
0
Number of conjugate pairs
0
20
40
60
80
100
120
140
160
180
Dihedral angle, deg.