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A Uniform Database of Teleseismic Shear-Wave Splitting Measurements for the Western and Central United States: December 2014 Update

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ABSTRACT

We present a new version of a shear-wave splitting (SWS) database for the western and central United States (WCUS) using broadband seismic data recorded up to the end of 2014 to update a previous version that used data recorded prior to the end of 2012, when the USArray Transportable Array stations were still recording in the easternmost region of the WCUS. A total of 7452 pairs of additional measurements recorded by 1202 digital broadband seismic stations are obtained, and all the measurements in the previous database are rechecked. The resulting uniform SWS database contains a total of 23,448 pairs of well-defined *SKS*, *SKKS*, and *PKS* splitting parameters. Relative to the previous version of the database, the additional measurements notably improved the spatial and azimuthal coverages of the measurements, providing an improved dataset for constraining geodynamic models related to lithospheric deformation and asthenospheric flow, as well as for complex anisotropy recognition and characterization.

Online Material: Tables of individual shear-wave splitting measurements, station-averaged measurements, and averaged splitting parameters.

INTRODUCTION

Shear-wave splitting (SWS) parameters, including the polarization orientation of the fast wave and the splitting time between the fast and slow waves traveling in an anisotropic medium, are among the most fundamental observables in structural seismology (Silver and Chan, 1991). Numerous SWS studies over the past several decades demonstrated that SWS measurements, especially those obtained using the *XKS* phases (which are *P*-to-*S* conversions at the core–mantle boundary on the receiver side, such as *SKS*, *SKKS*, and *PKS*), can provide important direct information regarding the direction and magnitude of finite strain associated with lithospheric deformation and asthenospheric flow (Silver, 1996). They are also widely used as invaluable constraints for numerical modeling of mantle dynamics (Becker *et al.*, 2006; Bird *et al.*, 2008; Kreemer, 2009), as well as for investigating structure and dynamics in the core–mantle boundary region (Lay *et al.*, 1998).

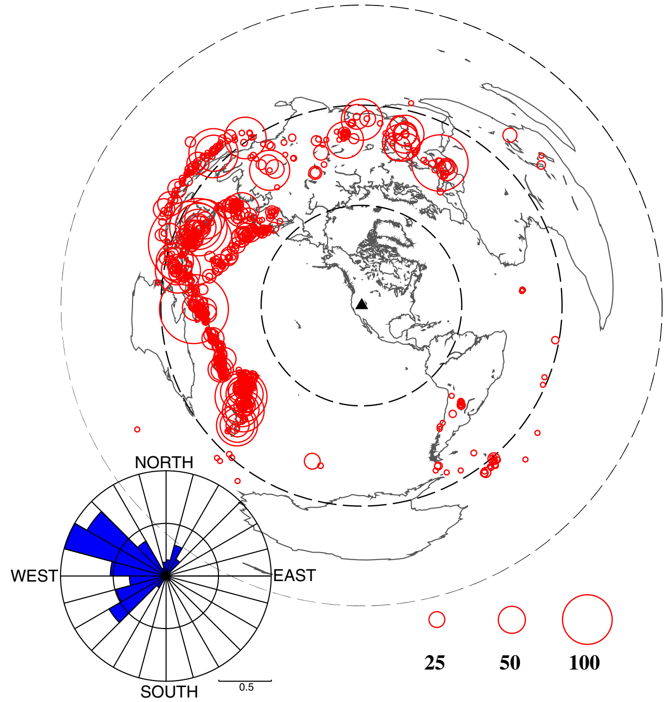
As recently suggested by Liu and Gao (2013) and others (e.g., Wustefeld *et al.*, 2009), however, significant discrepancies exist in the reported splitting parameters obtained at the same stations due to the different measuring techniques and data processing and ranking procedures used by different groups, resulting in compilations of heterogeneous datasets (e.g., see shear-wave splitting database B inData and Resources). Additionally, the vast majority of the splitting parameters are reported in the form of station-averaged parameters, which are in principle only valid for areas with simple anisotropy (i.e., a single layer of anisotropy with a horizontal axis of symmetry) and cannot accurately reflect the true anisotropic structure for areas dominated by complex anisotropy. A recent synthetic study (Kong *et al.*, 2015a) suggested that station-averaged splitting times obtained using the multiple-event stacking procedure (Wolfe and Silver, 1998) are systematically underestimated for areas with complex anisotropy. The resulting fast orientation obtained by stacking all the events at a station seating on a two-layer anisotropic structure, which is the most common form of complex anisotropy, is dominated by the fast orientation of the top layer (Kong *et al.*, 2015a).

Using pre–USArray data and a set of splitting-parameter measuring and ranking procedures (Liu and Gao, 2013), Liu (2009) produced the first comprehensive (in the sense that all the available data were used) uniform SWS database of 6224 pairs of individual (rather than station-averaged) splitting parameters for North America. The western and central United States (WCUS, which herein refers to the area of the contiguous United States west of 90° W) portion of the database was updated later (Liu *et al.*, 2014) in response to the dramatically increased spatial coverage as a result of the deployment of the USArray Transportable Array (TA) stations. The database, which can be found as a Data Product at the Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC; see Data and Resources), includes 16,105 pairs of splitting parameters obtained using data recorded prior to the end of 2012 or even earlier, during which some of the USArray TA stations in the eastern portion of the region were still recording. The earliest TA stations started recording in 2004 at the west-most portion of the contiguous United States.

All the TA stations completed their two-year recording period and were moved out of the WCUS prior to the end of 2014. Furthermore, outstanding *XKS* waveforms that were not used by the previous version of the SWS database have been recorded by numerous permanent and non-TA portable broadband stations in the study area over the past several years. To improve both the spatial and azimuthal coverages of the SWS measurements and produce an SWS database utilizing all the TA data in the WCUS, we conducted SWS analysis using data recorded prior to the end of 2014 that were not used in Liu *et al.* (2014). To produce a database that is as uniform as possible, we also rechecked all the measurements in the previous version and made necessary modifications to about 0.7% of the 16,105 pairs of SWS measurements. The updated database contains a total of 23,448 pairs of manually checked splitting parameters and can be found in Ⓔ Table S1, available in the electronic supplement to this article.

DATA AND METHOD

The broadband seismic data used in the study were obtained from the IRIS-DMC (see Data and Resources) for the area of 125° W–90° W, and 24° N–52° N, which is the same as the study area of the previous version of the database (Liu *et al.*, 2014). The useful epicentral distance range for *SKS*, *PKS*, and *SKKS* is 84°–180°, 120°–180°, and 90°–180°, respectively, and the generic cutoff magnitude is 5.6, which is reduced to 5.5 for earthquakes with focal depths greater than 100 km to take advantage of the sharper waveform. The seismic stations belong to one (or more than one, for some stations shared by different networks) of the following networks: the U.S. National Seismic Network (network code US), GEOSCOPE (G), USArray Transportable Array (TA), IRIS/U.S. Geological Survey Global Seismographic Network (IU), and various campaign-style seismic arrays. Seismograms that were recorded prior to 31 December 2014 and that were not included in the previous version of the database were requested from the DMC; these were processed and manually checked using the same data selection and processing standards and procedure used by Liu *et al.* (2014) to ensure homogeneity of the resulting database. Similar to the events used for the previous version, the vast majority of the events used to produce the new measurements have a back azimuth in the 90° range of 225°–315° (Fig. 1) as the result of the uneven distribution of the world's seismicity at the present time.

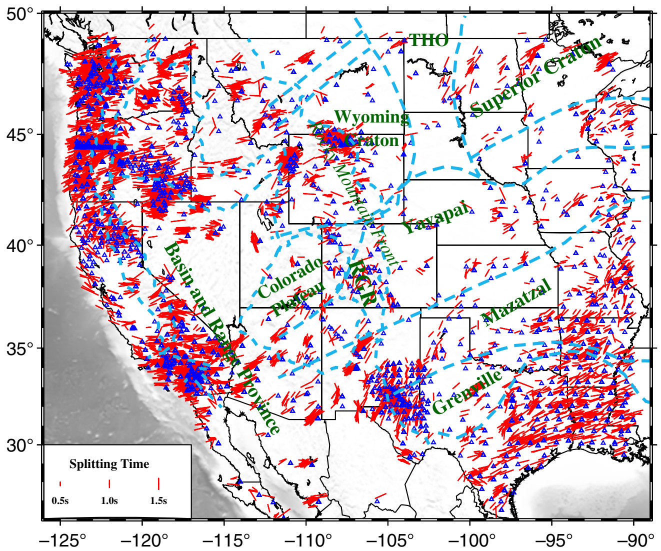


▲ **Figure 1.** Distribution of earthquakes used in the study. The inset rose diagram shows the distribution of the back azimuth of the events. The color version of this figure is available only in the electronic edition.

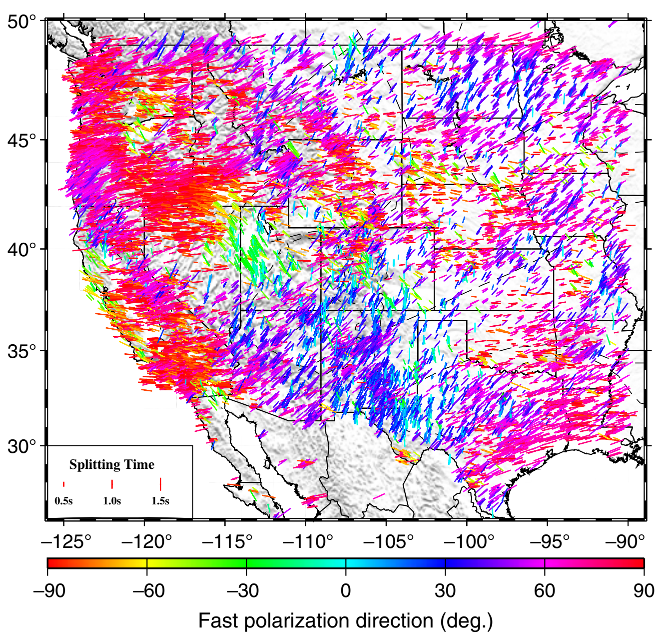
A band-pass filter with corner frequencies of 0.04 and 0.5 Hz is applied to the requested traces. The SWS measurements are made using the minimization of transverse energy technique of Silver and Chan (1991), which is considered to be the most reliable technique by some previous studies using synthetic and recorded data (Vecsey *et al.*, 2008; Kong *et al.*, 2015b). The results are ranked as A (outstanding), B (good), C (poor), and N (null) based on the combination of the signal-to-noise ratios on the original and corrected radial and transverse components (Liu *et al.*, 2008), and only A- and B-quality measurements are included in the database. A detailed description of the splitting-parameter measuring and ranking procedures can be found in Liu and Gao (2013).

THE UPDATED DATABASE

A total of 7452 well-defined (A- or B-quality) new measurements recorded by 1202 stations have been added to the updated database, including 536 *PKS*, 1070 *SKKS*, and 5846 *SKS* measurements (Fig. 2). Most of the new measurements are in southern and northern California due to the numerous permanent stations, the Pacific Northwest due to both permanent and portable stations, southwestern United States and the upper Midwest due to USArray Flexible Array experiments, and the eastern margin of WCUS due to new data from the TA stations. We also visually verified all the measurements in

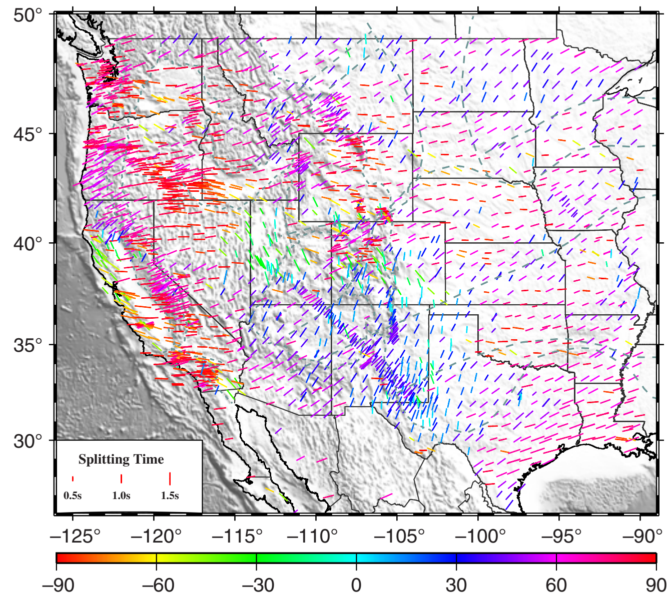


▲ **Figure 2.** New *XKS* splitting measurements recorded by 1202 stations for the western and central United States. The results are plotted above the *XKS* ray-piercing points at 200 km depth. The orientation of the bars represents the fast orientation, and the length is proportional to the splitting time. Major tectonic and basement provinces are marked by the dashed lines. Stations are shown as triangles. THO, Trans-Hudson orogeny; RGR, Rio Grande rift. The color version of this figure is available only in the electronic edition.

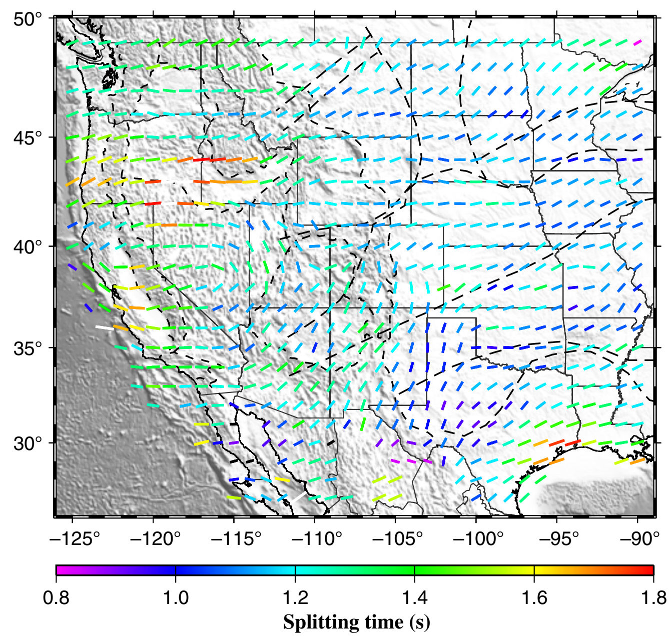


▲ **Figure 3.** Locations of the 23,448 pairs of *XKS* shear-wave splitting measurements in the updated database, plotted at the surface projection of ray-piercing points at 200 km depth. The color version of this figure is available only in the electronic edition.

the previous version and made adjustments to the measuring parameters (e.g., *XKS* window selection and ranking) of about 110 (~0.7%) of the 16,105 measurements. The final product is

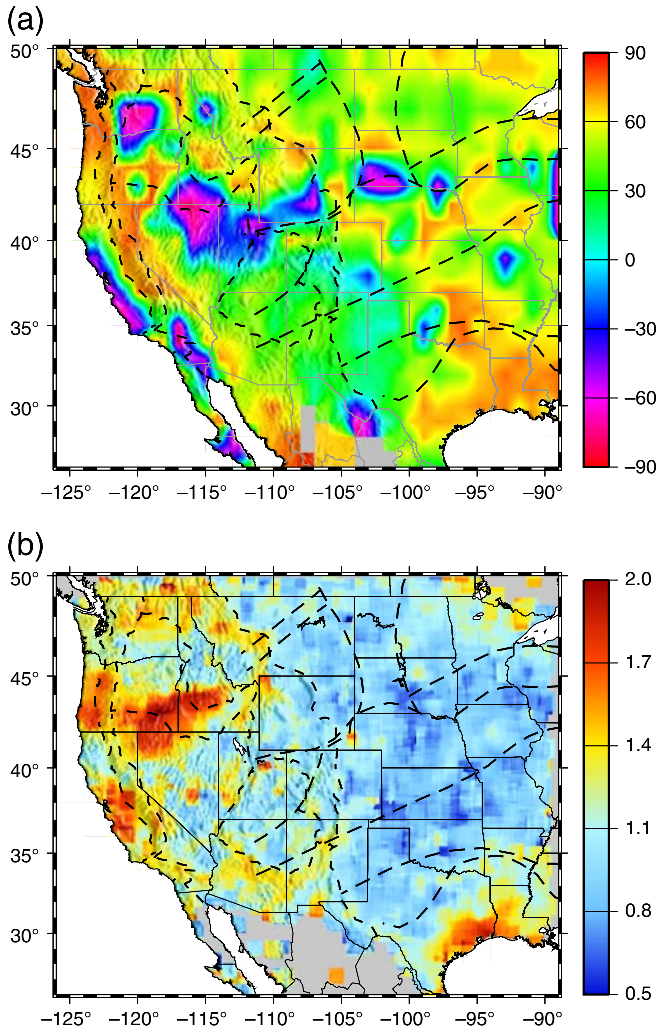


▲ **Figure 4.** Station-averaged splitting parameters. The results are plotted at the location of the stations. The color version of this figure is available only in the electronic edition.

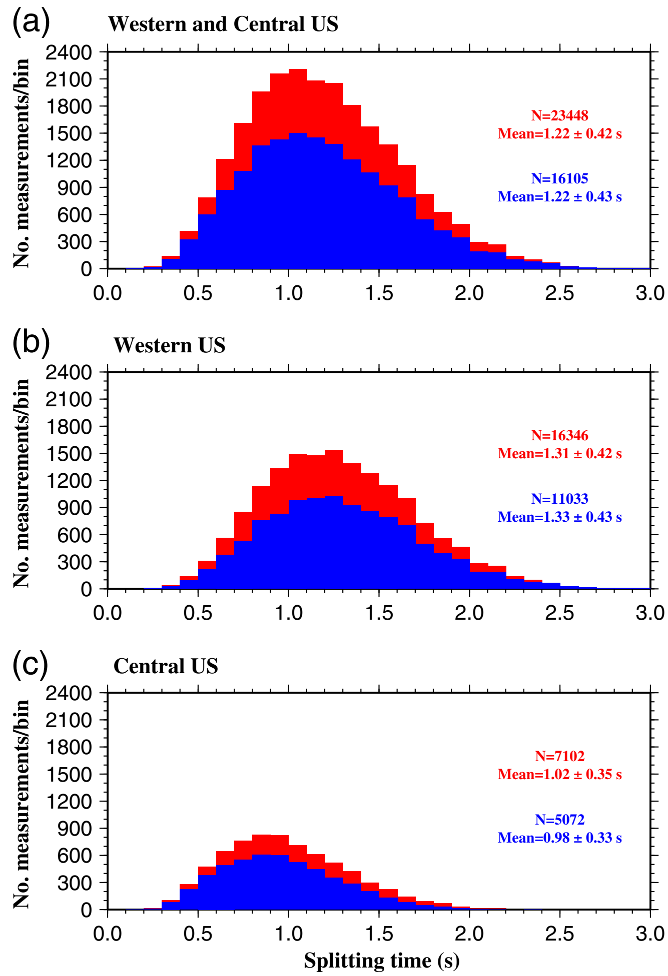


▲ **Figure 5.** Spatially averaged (in 1°-radius circles) shear-wave splitting (SWS) parameters. The color version of this figure is available only in the electronic edition.

a uniform database of 23,448 pairs of well-defined splitting parameters (Fig. 3), among which 11,646 (49.7%) are from the USArray TA stations. The number of stations with one or more measurements is 2400, including 1144 (47.7%) TA stations. The updated database represents a 45.6% increase in the number of measurements over the previous version.



▲ **Figure 6.** Spatially averaged (in overlapping 1 × 1 degree^2 blocks with a moving step of 0.1°) for (a) fast orientations and (b) splitting times. The color version of this figure is available only in the electronic edition.



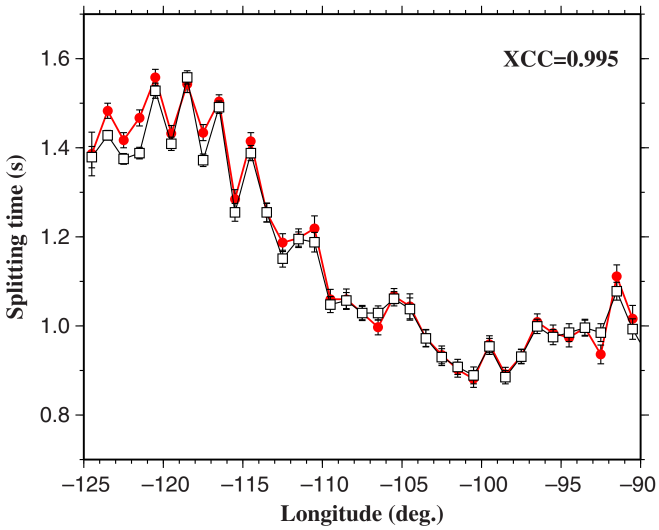
▲ **Figure 7.** The distribution of the *XKS* splitting times for (a) the entire area, (b) western United States, and (c) central United States for the previous (dark) and updated (light) databases. The color version of this figure is available only in the electronic edition.

The updated database is included as Ⓔ Table S1 and, for each event, consists of station name, phase name (including *PKS*, *SKK* for *SKKS*, and *SKS*), event name, station latitude, station longitude, fast orientation, standard deviation of fast orientation, splitting time, standard deviation of splitting time, back azimuth (BAZ), modulo-90° of the BAZ, epicentral latitude, epicentral longitude, focal depth, rank of the measurements, and the latitude and longitude of the ray-piercing points at 200 km depth.

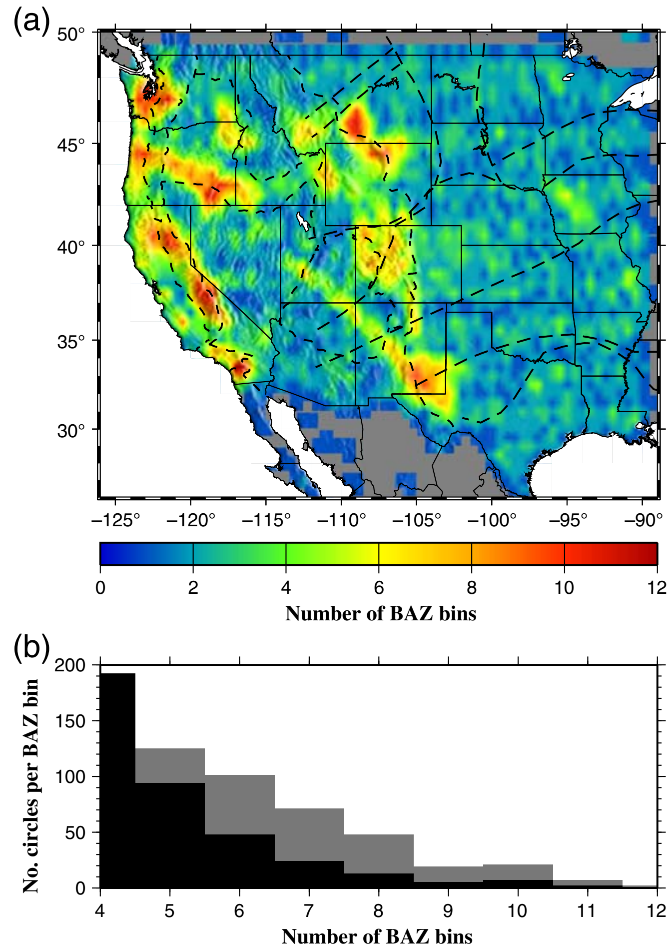
The station-averaged measurements are plotted in Figure 4. Ⓔ Table S2 shows the station name, station latitude, station longitude, mean fast orientation for the station and its standard deviation, mean splitting time and its standard deviation, and the number of observed measurements for each station. In this study, the averaged fast orientations are calculated as the circular mean of the individual fast orientations (Mardia and Jupp, 2000), whereas the averaged splitting times are reported as arithmetic means.

To create an evenly spaced dataset of spatially averaged splitting parameters, we first determine the coordinates of the piercing point of the individual measurements at 200 km depth, and then compute the averaged splitting parameters in 1°-radius circles. The distance between the neighboring circles is one geographic degree. Figure 5 shows the resulting splitting parameters, which can also be found in Ⓔ Table S3. Table S3 includes the latitude and longitude of the center of the circles, mean fast orientation and its standard deviation, mean splitting time and its standard deviation, and the number of individual measurements in the circle.

Figure 6 shows averaged splitting parameters in 1 × 1 geographic degree^2 blocks with a moving interval of 0.1°. Virtually all of the features summarized in Liu *et al.* (2014) for the previous version of the database can still be observed. The same is true for the distribution of splitting times in the entire WCUS (Fig. 7a), western United States (Fig. 7b), and central United States (Fig. 7c). The slight increase (1.02 versus 0.98 s) in the



▲ **Figure 8.** Splitting times averaged over 1°-wide longitudinal bands. Circles linked by the thick line represent results computed from the previous database (Liu *et al.*, 2014), and squares linked by the thin lines are those from the updated databases. The cross-correlation coefficient (XCC) value shows the high similarity between the two curves. The color version of this figure is available only in the electronic edition.



▲ **Figure 9.** (a) Spatial distribution of the number of 30°-wide back-azimuthal bins using the updated database, and (b) histogram showing the number of 1°-radius circles per back-azimuth (BAZ) bin produced using the previous (dark) and updated (light) databases. The color version of this figure is available only in the electronic edition.

mean splitting time in the central United States is mostly caused by the addition of TA stations in the southeast corner of the study area (Fig. 2), in which the splitting times are larger than most other areas in the central United States (Fig. 6b).

In spite of the nearly 50% increase in the number of SWS measurements in the updated database, the two databases are highly similar. To quantify the similarities, we compute the cross-correlation coefficient (XCC) between the spatially averaged splitting parameters in 1°-radius circles produced using the previous and updated (Fig. 5) databases. The resulting XCC is 0.954 for the fast orientations and 0.832 for the splitting times. The high similarity is also demonstrated in the cross sections of splitting times over 1°-wide longitudinal bands across the study area (Fig. 8).

As the result of the increased number of events, especially those at the permanent stations, the azimuthal coverage by the events shows a notable increase over the previous version. To specify the increase, we follow the procedure of Liu *et al.* (2014) to divide the study area into overlapping 0.5°- radius circles and compute the number of 30°-wide BAZ bins per circle. Relative to the previous version, the number of circles with six or more BAZ bands, which can be used for complex anisotropy studies, are more than doubled (Fig. 9). Such an increase improves the capability of the database in future research efforts for the recognition and characterization of complex anisotropy (e.g., Liu *et al.*, 2014; Yang *et al.*, 2014), which is identifiable by systematic variations of the splitting parameters with regard to the BAZ of the XKS events.

CONCLUSIONS

We produced a new version of a uniformly created SWS database for the western and central United States, using broadband seismic data recorded before the end of 2014, for the purpose of updating a previous version that used data recorded prior to the end of 2012, when the USArray TA stations were still recording in the easternmost region of the WCUS. A total of 7452 pairs of new measurements recorded by 1202 digital broadband seismic stations are obtained, and all the measurements in the previous database are reverified. The resulting uniform SWS database contains a total of 23,448 pairs of well-defined and manually checked *XKS* splitting parameters. Relative to the previous version of the database, the additional measurements significantly improved the spatial and azimuthal coverages of the measurements, providing an excellent dataset for constraining geodynamic models related to lithospheric deformation and asthenospheric flow, as well as for complex anisotropy recognition and characterization.

DATA AND RESOURCES

All the data used in the study are openly accessible from the Incorporated Research Institutions for Seismology Data Management Center (IRIS DMC; http://ds.iris.edu/ds/nodes/dmc/data/, last accessed March 2015. Data Product at IRIS DMC can be available at http://ds.iris.edu/ds/products/sws-db-mst (last accessed December 2015). Shear-wave splitting database B can be available at http://splitting.gm.univ-montp2.fr/DB/index.html (last accessed December 2015).

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