Liu, Y., Zhang, H., Kendall, M., & Wookey, J. (2021). Conjugate fault deformation revealed by aftershocks of the 2013 Mw6.6 Lushan earthquake and seismic anisotropy tomography. *Geophysical Research Letters*, 48(14), [e2021GL092563].
<https://doi.org/10.1029/2021GL092563>

Peer reviewed version

License (if available):
CC BY-NC-ND

Link to published version (if available):
[10.1029/2021GL092563](https://doi.org/10.1029/2021GL092563)

[Link to publication record in Explore Bristol Research](#)
PDF-document

This is the accepted author manuscript (AAM). The final published version (version of record) is available online via Wiley at 10.1029/2021GL092563. Please refer to any applicable terms of use of the publisher.

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:
<http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/>

Conjugate fault deformation revealed by aftershocks of the 2013 Mw6.6 Lushan earthquake and seismic anisotropy tomography

Ying Liu^{1,2}, Haijiang Zhang^{1,2,3*}, Michael Kendall⁴, James Wookey⁵

¹Laboratory of Seismology and Physics of Earth's Interior, School of Earth and Space Sciences, University of Science and Technology, 96 Jinzhai Road, Hefei, Anhui, China

²Mengcheng National Geophysical Observatory, University of Science and Technology of China, Hefei, Anhui 230026, China

³CAS Center for Excellence in Comparative Planetology, University of Science and Technology of China, Hefei, Anhui 230026, China

⁴University of Oxford, Department of Earth Sciences, South Parks Road, Oxford, OX1 3AN, United Kingdom

⁵University of Bristol, Department of Earth Sciences, Queens Road, Bristol, BS8 1RJ, United Kingdom

*Corresponding email: zhang11@ustc.edu.cn

Geophysical Research Letters

June 11, 2021

Key Points:

- P-wave traveltime anisotropy tomography is used to study fault deformation in the upper crust by aftershocks of the 2013 Lushan earthquake
- Two stripes of structure controlled anisotropy anomalies are imaged above conjugate faults delineated by the distribution of aftershocks
- The anisotropy strength distribution suggests the fault deformation extends to the aseismic layer in the shallow crust from seismogenic zone

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as [doi: 10.1029/2021GL092563](https://doi.org/10.1029/2021GL092563).

This article is protected by copyright. All rights reserved.

Abstract

Seismic anisotropy is sensitive to the alignment of minerals, fluid-filled cracks and fractures caused by fault deformation, thus providing a signature of fault deformation, especially in the aseismic layer. In this study, we use seismic travelttime anisotropy tomography to study the spatial distribution of azimuthal anisotropy in the region of the 2013 Mw 6.6 Lushan earthquake. Our analysis reveals both stress-induced and structure-controlled seismic anisotropy mechanisms. The distribution of seismicity and anisotropy clearly delineates conjugate faults in the seismogenic zone between depths of 8 and 15 km. Two near-vertical stripes or zones of strong seismic anisotropy reveal the continuation of these faults into the diagenetic or overlying aseismic crust. The anisotropic corridors associated with the conjugate faults are interpreted in terms of the crystal preferred orientation of fault rock minerals, which may be enhanced by shear-band compaction. Our results demonstrate how seismic anisotropy can provide new insights into fault deformation.

Plain Language Summary

Fault deformation can be characterized by the distribution of seismicity in fault zones. However, failure in the shallow crust is often aseismic due to the velocity strengthening friction behavior of fault zone materials. Isotropic velocity tomography can be used to delineate fault deformation in the aseismic or diagenetic layer, but only when there is a sharp velocity variation across the fault. In comparison, seismic anisotropy is sensitive to the alignment of minerals, fluid-filled cracks and fractures caused by fault deformation, thus providing a signature of fault deformation, especially in the aseismic layer. In this study, we use seismic travelttime anisotropy tomography to study the spatial distribution of

azimuthal anisotropy in the region of the 2013 Mw 6.6 Lushan earthquake. A regional array of 29 temporary seismic stations captured a rich aftershock sequence, which we use to image the fault system through the seismogenic zone and overlying aseismic region. In this way, the fault deformation in the aseismic layer may be inferred. Compared to isotropic velocity variations, two anisotropic stripes associated with the conjugate faults do a much better job of delineating fault deformation along two faults, extending from deeper seismogenic zone to the shallower aseismic zone.

1. Introduction

Faults move on time scales from centimeters per year to meters per second. How faults respond to stress, through creep or earthquakes, depends on a range of factors including geometry, stress, mineralogy, pressure, temperature and fluids. As a result, patterns of failure vary along the length of large tectonic faults, and with depth in the crust (e.g. [Zoback et al., 1987](#); [Pei et al., 2019](#)). It is generally accepted that frictional faulting and large earthquakes nucleate in the seismogenic zone, but rupture may extend into the overlying diagenetic zone ([Sibson, 1983](#)). Surface rupture is seen for many large earthquakes, but not all. Blind faults can cause significant damages with little previous evidence of their existence (e.g., the Northridge earthquake: [Shaw and Shearer, 1999](#)). For earthquakes that do not show clear rupture on the surface (e.g., the Haiti earthquake: [Hayes et al., 2010](#)), there is a question of how deformation extends into the shallow crust and can we observe in-situ evidence of this strain?

The Longmenshan fault system (LFS) is a thrust fault system which runs along the base of the Longmen Mountains in Sichuan Province in southwestern China, between the Eastern Tibetan Plateau and the Sichuan Basin. In the LFS, deformation is mostly accommodated by thrust faults, but there also exist variable amounts of strike-slip movements, which transitions from sinistral in the south to more dextral in the north. This region was thought to be of low seismic hazard, but on the 12th May, 2008, a devastating earthquake of magnitude Mw 7.9 occurred in Wenchuan County, Sichuan Province, along the LFS, and led to a substantial loss of human life. Five years later, on the 20th April, 2013, another strong earthquake of magnitude Mw 6.6 occurred in the Lushan County of Sichuan Province, towards the southern end of the LFS. Its epicenter was about 80 km south of the 2008 Mw 7.9 Wenchuan earthquake, near the triple junction between the Longmenshan Fault, the Anninghe Fault and the Xianshuihe Fault (Fig. 1a). Unlike the Wenchuan earthquake, the Lushan earthquake occurred with little surface rupture (Hao et al., 2013; Xu et al., 2013; Lu et al., 2017). Both the Wenchuan and Lushan earthquakes led to rich aftershock sequences. It is worth noting that there is a gap in aftershocks in a ~60 km segment between the Wenchuan earthquake and the Lushan earthquake on the LFS, the potential seismic hazard of which has been debated (Pei et al., 2014; Liu et al., 2018).

Extensive researches have been published on the Lushan earthquake, including locating the mainshock and aftershocks, determining their focal mechanisms, and revealing fault geometry and rupture process. These studies show that the mainshock of the Lushan earthquake occurred at a depth of about 13 km and the aftershocks were mainly distributed at depths below 8 km (Zhang et al., 2013; Pei et al., 2014). The geometry of the Lushan earthquake fault has the character of conjugate faulting, revealed by a “y” type of

Accepted Article
aftershock locations; the mainshock is a thrust-type earthquake that occurred on the southeast blind reverse fault of the conjugate faults (Han et al., 2014; Li et al., 2014). The rupture process revealed by coseismic slip distribution suggests that the mainshock of the Lushan earthquake ruptured in the depth range of 5-20 km on a fault plane oriented N210°E with dipping angle N40°W and that there was no apparent rupture at the surface (Hao et al., 2013).

There are a number of seismic methods that can be used to image a fault and its stress regime. Perhaps the most obvious approach is through the location of earthquakes on the fault, especially aftershock sequences (e.g., Carena and Suppe, 2002). Solutions for focal mechanisms offer insights into the stress regime and how it can vary through the earthquake cycle. However, seismicity distribution does not illuminate regions where the crust slips in a ductile manner, for example in the shallow crust. Seismic velocity tomography is another approach that has been used extensively to characterize fault zone structure (e.g., Eberhart-Phillips and Michael, 1993; Zhang et al., 2009a; Allam et al., 2014). If the fault separates two different tectonic blocks, as in the case of the San Andreas Fault, seismic velocity tomography can be used to image the strong velocity contrast across the fault (Thurber et al., 2004; Zhang et al., 2009a). In some cases, even the fault damage zone can be imaged as a low velocity zone (Zhang et al., 2009a; Yang et al., 2014; Wang et al., 2019). However, in many cases, seismic velocity tomography cannot image a clear velocity contrast across the fault or low velocity anomalies near the fault (e.g., Bleibinhaus et al., 2007; Zhang et al., 2009b). One possible reason is the lack of large velocity contrast across the fault.

Another approach is to look for evidence of seismic anisotropy in regions of faults. Through laboratory measurements, Kelly et al. (2017) demonstrated the anisotropic effect

on velocities of fault zone rocks are about 10~15% in the Carboneras fault zone. Both seismic and aseismic deformation will lead to the preferred orientation of rock forming minerals (crystal preferred orientation or CPO) in the vicinity of faults, which leads to seismic anisotropy (e.g., [Lloyd and Kendall, 2005](#)). This is sometimes called intrinsic or structural anisotropy (e.g., [Boness and Zoback, 2006](#)). High stress will also lead to the alignment of open cracks and fractures in the direction of maximum horizontal compressive stress, which is also very effective in generating anisotropy in the shallow crust ($< \sim 7\text{km}$, e.g., [Maher and Kendall, 2018](#)). This is a more extrinsic form of anisotropy, commonly referred to as stress anisotropy or extensive dilatancy anisotropy (EDA) ([Crampin, 1987](#)). The observations of two independent shear waves (i.e., shear wave splitting) is perhaps the most unambiguous indicator of anisotropy. A range of seismic methods can be used to study spatial distributions in anisotropy. For example, [Kendall et al. \(2006\)](#) used body waves (teleseismic and local) and surface waves (Love and Rayleigh) to infer depth variations in anisotropy in the Ethiopian Rift. [Audet \(2015\)](#) used teleseismic receiver functions to evaluate anisotropy in the crust near the SAF. He interprets EDA in the upper crust and a fossil or inherited CPO anisotropy in the deeper crust. With dense seismic arrays and rich aftershock sequences, tomographic methods to estimate spatial variations in anisotropy are now possible. This can be done using variations in shear wave splitting data (e.g., [Zhang et al., 2007](#); [Hammond et al., 2014](#)) or travel times (e.g., [Toshiki et al., 1996](#); [Eberhart-Phillips and Henderson, 2004](#)). [Li et al. \(2014\)](#) applied the shear wave splitting tomography method of [Zhang et al. \(2007\)](#) to determine the seismic anisotropy structure of the north Anatolian fault. The fault is delineated by a corridor of strong, but asymmetrical, seismic anisotropy. In recent years, body wave travel time anisotropy tomography methods

have been broadly applied to study variations in anisotropy structures. [Wei et al. \(2013\)](#) applied P-wave anisotropy tomography method to a dataset from southeast Tibet. Their results reveal a localized distribution of fast directions in different areas, indicating complex geological structure and active faults.

The anisotropy in the LFS fault region has been previously studied by using shear wave splitting analysis ([Chang et al., 2014](#); [Gao et al., 2014](#); [Liu et al., 2015](#)), revealing a complex pattern of anisotropy with orientations both parallel and perpendicular to faults. [Liu et al. \(2015\)](#) also used shear wave splitting tomography based on the delay times between slow and fast shear wave to study the 3D distribution of the magnitude of anisotropy in the upper crust, showing that the anisotropy is shallow (<8 km) and caused by both the regional stress and fault-zone processes. These studies consider the accumulated anisotropy along near-vertically travelling raypaths and cannot image the spatial variations of anisotropy polarizations. Furthermore, this method is subject to the number of the high-quality shear wave splitting data that is often available in limited quantities, and therefore the resolution of shear wave splitting based tomography (e.g. [Zhang et al., 2007](#); [Li et al., 2014](#); [Liu et al., 2015](#)) can be limited.

In order to better characterize the spatial variations of the anisotropic structure in the upper crust in vicinity of the 2013 Lushan earthquake and infer the fault deformation pattern, we apply 3D P-wave traveltimes anisotropy tomography based on the aftershock sequence of the 2013 Lushan earthquake in a region roughly 35 km x 35 km in extent. The dense raypath coverage leads to a high-resolution 3D model of the azimuthal anisotropic structure (both in orientation and magnitude). The results provide new insights into the previously unknown deformation of the conjugated blind faults in the aseismic layer and

present new opportunities to study the stress distribution around the faults. This is also the first time the two different anisotropic tomography methods can be directly compared and evaluated.

2. Data and Method

Within one week of the 2013 Lushan Mw 6.6 earthquake, 29 short-period three-component seismometers were deployed around the epicenter of the Lushan mainshock (Fig. 1b; Liu et al., 2015). Almost 4200 aftershocks were recorded over a continuous 3-week period between 04/24/2013 and 05/19/2013 (Fig. 1b). The aftershocks mostly occurred below a depth of 8 km and are mainly distributed along the fault strike direction. Nearly 53000 P-wave arrival times were manually picked. To ensure the quality of arrival time picks in our anisotropy tomography, we only use reliable P-wave arrival time picks within the main trend of travel time curves. In total, about 49500 P-wave arrival times were selected for seismic anisotropy tomography (Fig. S1).

Assuming weak anisotropy, Hearn (1996) followed the Pn velocity expression of Backus (1965) to develop a 2D Pn wave traveltime anisotropy tomography method and applied it to the Western United States. Considering the dipping angle of direct P-wave raypath, Eberhart-Phillips and Henderson (2004) derived a more general azimuthal anisotropic P-wave velocity formula and developed 3D direct P-wave traveltime anisotropy tomography method. With some assumptions, Liu and Zhao (2016) extended this approach to a joint P- and S-wave traveltime anisotropy tomography method and applied it to the Japan subduction zone. In small scale problems, the reliability of anisotropy tomography results highly depends on the quality and accuracy of arrival picks. In general, the S-wave picks have larger uncertainties than P-wave picks. In addition, S-

wave picks may differ significantly at different components of waveforms. For this reason, here we only consider the P-wave azimuth anisotropy following the same approach taken by [Eberhart-Phillips and Henderson \(2004\)](#).

The P-wave slowness u_p can be written as following:

$$u_p = u_{p0} + P \sin^2 \delta \sqrt{A^2 + B^2} + \cos^2 \delta (A \cos 2\phi + B \sin 2\phi), \quad (1)$$

where u_{p0} is the isotropic P-wave slowness, A and B are the anisotropic parameters, δ is the angle between the ray path and horizontal direction, and ϕ is the back azimuth angle. P is the parameter that controls the P-wave velocity in the vertical direction.

We build the inversion system following the scheme in [Eberhart-Phillips and Henderson \(2004\)](#), and use the LSQR algorithm of [Paige and Saunders \(1982\)](#) to solve the equation. The fast direction, ψ_p , and magnitude, Mag_p , of P-wave azimuthal anisotropy can be calculated from the inverted anisotropic parameters A and B :

$$\psi_p = \frac{1}{2} \tan^{-1} \left(\frac{B}{A} \right) + \begin{cases} \pi/2, & A > 0; \\ 0, & A < 0. \end{cases} \quad (2)$$

$$Mag_p = \frac{V_{pf} - V_{ps}}{V_{p0}} = \frac{2\sqrt{A^2 + B^2}}{1/V_{p0} - V_{p0}(A^2 + B^2)} \quad (3)$$

where V_{pf} and V_{ps} are the P-wave velocity in the fast and slow directions, respectively.

3. Results

We used P-wave arrival times to simultaneously determine the P-wave azimuthal anisotropy structure, the isotropic V_p model and event locations. Tomographic details can be found in the Supporting Information ([Text S1, Figs. S1-S4](#)). Fault-normal cross-sections,

horizontal sections and 3D view of the azimuthal anisotropy structures are shown in Figs. 2c, 3a and 4, respectively. We comprehensively analyzed the model resolution (Text S2, Figs. S5-S8, Fig. 3b) and uncertainty (Test S3, Figs. S9-S13, Table S1). These tests show the derived models in the central regions are well resolved and robust.

Similar to Zhang et al. (2013), our derived Vp model (Fig. 2a) shows a predominantly one-dimensional pattern, with low Vp in the aseismic zone and high Vp in the seismogenic zone. The Vs model of Zhang et al. (2013) also shows similar one-dimensional pattern. Aftershocks are mainly located below 8 km depth and their locations clearly delineate the “y” shape of the conjugated thrust faults. In comparison, the azimuthal anisotropy strength distribution does not show a similar 1D pattern as the isotropic velocity models (Fig. 2a & 2b). The strength of the azimuthal anisotropy is highest in the aseismic zone (above 8 km depth), and it is also significant in the seismogenic zone (below 8 km depth). Fault-normal cross-sections and 3D view (Fig. 2c & 4) show that the strong azimuthal anisotropy in the seismogenic zone is located between the two conjugated faults delineated from aftershock locations. From seismogenic zone to aseismic zone, the high anisotropy area is separated into two stripes from deeper to shallower depths, which are also associated with two conjugated faults, respectively. Compared to azimuthal anisotropy model inverted from shear wave splitting tomography using the similar aftershock dataset (Liu et al., 2015), seismic traveltime anisotropy tomography shows similarly high anisotropy anomalies above ~9 km but more clearly separated stripes (Fig. S14). In addition, seismic traveltime anisotropy tomography also better resolves the anisotropic anomalies in the seismogenic region (Fig. 3b). This is likely because the number of high-quality shear wave splitting

times is limited, which adversely affects the model resolution from shear wave splitting tomography (Fig. S14).

Horizontal sections and 3D view (Fig. 3a & 4) show that the areas of high anisotropy are separated into two along-fault stripes at shallow depth (0~6 km), which converge at a depth of about 9~12 km. The anisotropy decays sharply below the location of the 2013 Mw 6.6 Lushan earthquake. The fast directions of azimuthal anisotropy are nearly parallel to the trend of the LFS especially in the areas of high anisotropy (Fig. 3a & 4, Fig. S15a). In areas of moderate anisotropy, fast directions are distributed between the fault-parallel direction and fault-normal direction (Fig. S15b). In areas of low anisotropy, fast directions are deviated from the fault strike and some are nearly perpendicular to the fault strike (i.e., nearly parallel to the maximum horizontal compressive stress direction; Fig. S15c). The distribution of fast directions in high anisotropic areas from P-wave anisotropy tomography shows similar patterns with the shear wave splitting measurements (Fig. S15).

4. Discussions

4.1. Formation mechanisms of the azimuthal anisotropy in the upper crust

Generally, two major mechanisms are known to be responsible for seismic anisotropy in the crust: stress-induced anisotropy due to the preferential alignment of fluid-saturated cracks that are sub-parallel to the direction of maximum horizontal compressive stress, and the structure-controlled anisotropy where the fast polarization direction parallels to the strike of the structural fabric and is due to the alignment of parallel planar features including macroscopic fractures, sedimentary bedding planes, or minerals/grains (Boness and

Zoback, 2006). Within the fault zones, structure-controlled anisotropy is likely dominated by the rock fabric caused by the relative movement between two fault blocks (Lloyd and Kendall, 2005).

The direction of maximum horizontal compressive stress (N55°W, Zhao et al., 2013) in this region is nearly perpendicular to the trend of the LFS. The P-wave anisotropy tomography shows that the fast directions in the areas of low anisotropy clearly deviate from the main fault trend and are much closer to the direction of the maximum horizontal compressive stress (Fig. 3-4, Fig. S15). This indicates that stress-induced anisotropy exists around the aftershock zone of the 2013 Lushan earthquake. However, both the SWS observations (Liu et al., 2015) and P-wave anisotropy tomography results reveal nearly fault-parallel fast directions of anisotropy, dominant in both the aseismic and seismogenic layers. Thus, we conclude that the azimuthal anisotropy in the Lushan aftershock zone is mainly structurally controlled and is likely due to the alignment of the fabric caused by fault deformation extending from the deeper to shallower zones.

4.2. Fault deformation delineated by seismic anisotropy

The Lushan earthquake occurred on a blind fault, and although there was little evidence of a clear surface rupture zone (Xu et al., 2013), local damage was seen at the surface in some places. If there also exists fault deformation in the aseismic layer in the shallow part, the azimuthal anisotropy can be used to delineate it. Around the aftershock zone of the Lushan earthquake, the strongest anisotropy is observed in the aseismic zone at shallower depths, directly above the deeper conjugate faults mapped by relocated earthquakes. Furthermore, above the depth of 6 km, the strength of anisotropy in the

northwest (stripe 1) is greater than that in the southeast (stripe 2). At face value, the anisotropy appears to map the aseismic parts of the conjugated faults as they rotate to a more vertical direction near the surface. It is likely that this reveals a damage zone of fractured rocks in the aseismic zone due to the fault deformation, which may or may not be fluid rich. This aligned damage zone will be very effective in generating seismic anisotropy with a fast direction parallel to the plane of the fractures, especially if they are water rich. This is because slip on the faults aligns the fault materials, including fluid-filled cracks and fractures. In this case, the anisotropy should be strongest near the more heavily damaged region. This explains why the two high anisotropy stripes are associated with conjugated faults, which extend from deep to shallow in the crust. Furthermore, the more localized deeper conjugated faults may splay into more minor faults towards the near surface, further enhancing the magnitude of the anisotropy. Therefore, our results show that deformation around the conjugate faults does not stop in the seismogenic zone. The faults are listric-like, extending to the surface in an aseismic zone. The shallow anisotropic stripes reveal the conjugated faults in the subsurface aseismic zone.

4.3. The importance of delineating fault deformation from seismic anisotropy

Aftershock locations are often used to study the fault deformation ([Carena and Suppe, 2002](#)). But in the Lushan aftershock zone, it was not possible to investigate fault deformation in the aseismic shallow crust above ~8 km depth from aftershocks ([Li et al., 2013](#); [Zhang et al., 2013](#); [Fang et al., 2015](#)). Similarly, many other fault zones are generally aseismic in the shallow zone because the materials there have the slip characteristics of velocity strengthening, prohibiting the occurrence of earthquakes ([Liu and Rice, 2005](#); [Harbord et al., 2017](#)). Another approach is to use isotropic V_p and V_s models to

Accepted Article

characterize fault zone structure where there is a sharp velocity contrast across the fault (Zhang et al., 2009a; Yang et al., 2014; Wang et al., 2019). However, not all fault deformation leads to a velocity contrast. At Lushan, no clear velocity contrast is observed across the faults (Fig. 2, Zhang et al., 2013). In comparison, seismic anisotropy in the crust is very sensitive to fault-related fabric, and is thus more sensitive to fault deformation. This can be due to the alignment of phyllosilicate minerals in the deeper fault zone or the alignment of fluid rich cracks and fractures in shallower regions. Therefore, seismic anisotropy provides a means of delineating fault deformation even in the aseismic layer. In this study we have benefitted from the dense ray path coverage from a rich aftershock sequence and strong lateral variations in seismic P-wave anisotropy. Cumulatively, this has provided high-resolution of 3D azimuthal anisotropy structure and fault deformation, even in the shallow aseismic layer. This has not been previously inferred.

5. Conclusions

Relocated aftershocks from the 2013 Mw6.6 Lushan earthquake reveal a conjugate set of hidden faults along the Longmenshan fault system. The seismicity is confined to the seismogenic zone between 8 and 15 km in depth. A rich aftershock sequence of ~4200 events were recorded by a local array of 29 stations. Using these aftershocks, we apply seismic P-wave traveltimes anisotropy tomography to study the three-dimensional distribution of seismic anisotropy in the upper crust around these faults. The tomographic results characterized by P-wave traveltimes anisotropy tomography show a dominant fault-parallel fast azimuthal anisotropy direction, indicating seismic anisotropy in the aftershock

zone is controlled by fault zone structure. There exist two stripes of fault-parallel anisotropy up to 3% in magnitude above the conjugate faults mapped by the aftershocks. The anisotropy maps the locations of the faults even into the aseismic diagenic zone. The anisotropy is strongest in the aseismic layer of the shallow crust, which may be due to the enhanced effects of cracks and fracture alignments. The P-wave anisotropy decreases away from the faults.

Cumulatively, these results indicate that the regions of high anisotropy correlate with deformation associated with the conjugated faults. Long term slip on the faults causes the development of rock fabric and crystal preferred orientation of phyllosilicate minerals in fault zones, which is further enhanced by aligned cracks and fractures in the shallow aseismic region. Isotropic velocity inversions do not delineate the fault deformation revealed in seismic anisotropy models. This study suggests that fault deformation can occur in both seismogenic zone and aseismic zone, and it can be more diffusive and stronger in the shallow part. Collectively, these results show how the distribution of aftershocks and images of seismic anisotropy can be used to better understand fault geometry and fault deformation, especially in the aseismic layer.

Acknowledgements

We are grateful for Donna Eberhart-Phillips for sharing her original seismic traveltime anisotropy code with us, which is adapted for our study. We also thank Associate Editor Victor Tsai and two anonymous reviewers for their helpful comments. This work is supported by the National Key R&D Program of China under Grant 2018YFC1504102, the National Natural Science Foundation of China (grants 42004034 and U1839205) and

the China Scholarship Council award 201606340073. The seismic arrival times used in this study can be accessible via <https://doi.org/10.5281/zenodo.4444505>.

Figure Captions

Fig. 1. (a) Topography map of Sichuan Basin and adjacent areas. Blue circles represent earthquakes occurring between 1980 and 2016 with $M_w \geq 5.0$. Black thick lines denote main faults in the area: GZF, Ganzi Fault; LTF, Litang Fault; XSHF, Xianshuihe Fault; LXJF, Lijiang-xiaojinhe Fault; ANHF, Anninghe Fault; ZMHF, Zemehe Fault; LZJF, Lvzhijiang Fault; LMSF, Longmenshan Fault. White rectangle box outlines the study area as shown in (b). Grey and yellow filled stars represent the mainshocks of the 2008 Wenchuan M_w 7.9 earthquake and the 2013 Lushan M_w 6.6 earthquake, respectively. (b) Distribution of aftershocks and stations used in this study. The 2013 Lushan M_w 6.6 mainshock is marked as a yellow star. Aftershocks are shown as dots with color indicating event depth. Stations are marked as green triangles. Main faults (Xu et al., 2013) are plotted as black lines: YJWLF, Yanjin-Wulong Fault; SHDF, Shuangshi-Dachuan Fault; SHDF1, Shuangshi-Dachuan Fault Branch; YJF, Yingjing Fault; and MSDYF, Mingshan-Dayi Blind Fault.

Fig. 2. Fault-normal cross sections of V_p (left column), V_s (middle column) and 3-D P-wave azimuthal anisotropy strength model (right column) at $Y = -10, -5, 0$, and 5 km, respectively. The X-Y coordinate is shown in the supporting information (Fig. S3). Red star indicates the mainshock of 2013 Lushan M_w 6.6 earthquake. Black dots represent aftershocks within ± 2.5 km to each cross section. Note that V_p and P-wave anisotropy

models are derived from P-wave travel time anisotropy tomography. The V_s model is from the double difference tomography of Zhang et al. (2013).

Fig. 3. (a) Horizontal sections of 3-D P-wave azimuthal anisotropy model derived from P-wave travel time anisotropy tomography at $Z=0, 3, 6, 9, 12$ km depth, respectively. The length and orientation of black short line indicate the anisotropy strength and fast direction of azimuthal anisotropy. Grey thick lines represent the main faults in the study area. (b) The associated checkerboard resolution test at $Z=0, 3, 6, 9, 12$ km depth, respectively. Red and grey bars represent the recovered and true azimuthal anisotropy model. White open circles show fast direction differences between two models.

Fig. 4. 3D view of P-wave azimuthal anisotropy model with horizontal sections at $Z=0, 3, 6, 9$ km and normal-fault section at $Y=5$ km. Other Symbols are the same as Fig. 3a.

References

- Allam, A. A., Ben-Zion, Y., Kurzon, I., Vernon, F., 2014. Seismic velocity structure in the Hot Springs and Trifurcation areas of the San Jacinto fault zone, California, from double-difference tomography. *Geophysical Journal International*, 198(2), 978-999.
- Audet, P., 2015. Layered crustal anisotropy around the San Andreas Fault near Parkfield, California. *Journal of Geophysical Research*, 120(5), 3527-3543.
- Backus, G. E., 1965. Possible forms of seismic anisotropy of the uppermost mantle under oceans. *Journal of Geophysical Research*, 70(14), 3429-3439.
- Bleibinhaus, F., Hole, J. A., Ryberg, T., & Fuis, G. S., 2007. Structure of the California Coast Ranges and San Andreas Fault at SAFOD from seismic waveform inversion and reflection imaging. *Journal of Geophysical Research: Solid Earth*, 112(B6).
- Boness, N. L., & Zoback, M. D., 2006. A multiscale study of the mechanisms controlling shear velocity anisotropy in the San Andreas Fault Observatory at Depth, *Geophysics*, 71, F131–F146, doi:10.1190/1.2231107.

- Carena, S., & Suppe, J., 2002. Three-dimensional imaging of active structures using earthquake aftershocks: the Northridge thrust, California. *Journal of Structural Geology*, 24(4), 887-904.
- Chang, L., Ding, Z. & Wang, C., 2014. Variations of shear wave splitting in the 2013 Lushan Ms7.0 earthquake region. *Sci. China Earth Sci.* **57**, 2045–2052. <https://doi.org/10.1007/s11430-014-4866-8>
- Crampin, S., 1987. Geological and industrial implications of extensive-dilatancy anisotropy, *Nature*, 328, 491-496.
- Eberhart-Phillips, D., Henderson, C. M., 2004. Including anisotropy in 3-D velocity inversion and application to Marlborough, New Zealand. *Geophysical Journal International*, 156(2), 237-254.
- Eberhart-Phillips, D., Michael, A. J., 1993. Three-dimensional velocity structure, seismicity, and fault structure in the Parkfield Region, central California. *Journal of Geophysical Research*, 15737-15758.
- Fang, L., Wu, J., Wang, W., Du, W., Su, J., Wang, C., Yang, T., Cai, Y. (2015). Aftershock observation and analysis of the 2013 Ms 7.0 Lushan earthquake. *Seismological Research Letters*, 86(4), 1135-1142.
- Gao, Y., Wang, Q., Zhao, B., Shi, Y., 2014. A Rupture Blank Zone in Middle South Part of Longmenshan Faults: Effect After Lushan Ms 7.0 Earthquake of 20 April 2013 in Sichuan, China. *Science China Earth Sciences*, 57(9): 2036–2044.
- Hammond, J. O., Kendall, J. M., Wookey, J., Stuart, G. W., Keir, D., Ayele, A., 2014. Differentiating flow, melt, or fossil seismic anisotropy beneath Ethiopia. *Geochemistry Geophysics Geosystems*, 15(5), 1878-1894.
- Han, L., Zeng, X., Jiang, C., Ni, S., Zhang, H., & Long, F. (2014). Focal Mechanisms of the 2013 Mw 6.6 Lushan, China Earthquake and High-Resolution Aftershock Relocations. *Seismological Research Letters*, 85(1), 8-14.
- Hao, J., Ji, C., Wang, W., Yao, Z., 2013. Rupture history of the 2013 Mw 6.6 Lushan earthquake constrained with local strong motion and teleseismic body and surface waves. *Geophysical Research Letters*, 40(20), 5371-5376.
- Harbord, C. W., Nielsen, S. B., De Paola, N., & Holdsworth, R. E. (2017). Earthquake nucleation on rough faults. *Geology*, 45(10), 931-934.
- Hayes, G. P., Briggs, R. W., Sladen, A., Fielding, E. J., Prentice, C., Hudnut, K., ... & Ito, T. (2010). Complex rupture during the 12 January 2010 Haiti earthquake. *Nature Geoscience*, 3(11), 800-805.
- Hearn, T., 1996. Anisotropic Pn Tomography in the Western United States. *Journal of Geophysical Research*, 101(B4): 8403.
- Kelly, C. M., Faulkner, D. R., and Rietbrock, A. (2017), Seismically invisible fault zones: Laboratory insights into imaging faults in anisotropic rocks, *Geophys. Res. Lett.*, 44, 8205– 8212, doi:10.1002/2017GL073726.

- Kendall, J. M., Pilidou, S., Keir, D., Bastow, I. D., Stuart, G. W., Ayele, A., 2006. Mantle upwellings, melt migration and the rifting of Africa: insights from seismic anisotropy. *Geological Society, London, Special Publications*, 259(1), 55-72.
- Li, Y., Jia, D., Wang, M., Shaw, J. H., He, J., Lin, A., ... & Rao, G. (2014). Structural geometry of the source region for the 2013 Mw 6.6 Lushan earthquake: Implication for earthquake hazard assessment along the Longmen Shan. *Earth and Planetary Science Letters*, 390, 275-286.
- Li, Z., Tian, B., Liu, S., & Yang, J. (2013). Asperity of the 2013 Lushan earthquake in the eastern margin of Tibetan Plateau from seismic tomography and aftershock relocation. *Geophysical Journal International*, 195(3), 2016-2022.
- Li, Z., Zhang, H., Peng, Z., 2014. Structure-controlled seismic anisotropy along the Karadere-Düzce branch of the North Anatolian Fault revealed by shear-wave splitting tomography. *Earth and Planetary Science Letters*, 319-326.
- Liu, X., Zhao, D., 2016. Seismic velocity azimuthal anisotropy of the Japan subduction zone: Constraints from P and S wave traveltimes. *Journal of Geophysical Research*, 121(7), 5086-5115.
- Liu, Y., & Rice, J. R. (2005). Aseismic slip transients emerge spontaneously in three-dimensional rate and state modeling of subduction earthquake sequences. *Journal of Geophysical Research: Solid Earth*, 110(B8).
- Liu, Y., Zhang, H., Zhang, X., Pei, S., An, M., Dong, S., 2015. Anisotropic upper crust above the aftershock zone of the 2013 Ms 7.0 Lushan earthquake from the shear wave splitting analysis. *Geochemistry Geophysics Geosystems*, 16(10), 3679-3696.
- Liu, Z., Liang, C., Hua, Q., Li, Y., Yang, Y., He, F., & Fang, L. (2018). The seismic potential in the seismic gap between the Wenchuan and Lushan earthquakes revealed by the joint inversion of receiver functions and ambient noise data. *Tectonics*, 37(11), 4226-4238.
- Lloyd, G. E., Kendall, J. M., 2005. Petrofabric-derived seismic properties of a mylonitic quartz simple shear zone: implications for seismic reflection profiling. *Geological Society, London, Special Publications*, 240(1), 75-94.
- Lu, R., Xu, X., He, D., John, S., Liu, B., Wang, F., Tan, X., Li, Y., 2017. Seismotectonics of the 2013 Lushan M w 6.7 earthquake: Inversion tectonics in the eastern margin of the Tibetan Plateau: The 2013 Lushan M w 6.7 Earthquake. *Geophysical Research Letters*, 44(16), 8236-8243.
- Paige, C. C., Saunders, M. A., 1982. LSQR: An Algorithm for Sparse Linear Equations and Sparse Least Squares. *ACM Transactions on Mathematical Software*, 8(1), 43-71.
- Pei, S., Zhang, H., Su, J., & Cui, Z. (2014). Ductile gap between the Wenchuan and Lushan earthquakes revealed from the two-dimensional Pg seismic tomography. *Scientific reports*, 4(1), 1-6.
- Pei, S., Niu, F., Ben-Zion, Y., Sun, Q., Liu, Y., Xue, X., ... & Shao, Z., 2019. Seismic velocity reduction and accelerated recovery due to earthquakes on the Longmenshan fault. *Nature Geoscience*, 12(5), 387-392.

- Sean Maher, J.-Michael Kendall, Crustal anisotropy and state of stress at Uturuncu Volcano, Bolivia, from shear-wave splitting measurements and magnitude–frequency distributions in seismicity, *Earth and Planetary Science Letters*, Volume 495, 2018, Pages 38–49, ISSN 0012-821X, doi: [10.1016/j.epsl.2018.04.060](https://doi.org/10.1016/j.epsl.2018.04.060).
- Shaw, J. H., Shearer, P. M., 1999. An elusive blind-thrust fault beneath metropolitan Los Angeles. *Science*, 283(5407), 1516–1518.
- Sibson, R. H., 1983. Continental Fault Structure and the Shallow Earthquake Source. *Journal of the Geological Society*, 140(5), 741–67.
- Thurber, C., Roecker, S., Zhang, H., Baher, S., & Ellsworth, W., 2004. Fine-scale structure of the San Andreas fault zone and location of the SAFOD target earthquakes. *Geophysical Research Letters*, 31(12).
- Toshiki Watanabe, Toshiyuki Hirai, Koichi Sassa, 1996. Seismic traveltome tomography in anisotropic heterogeneous media, *Journal of Applied Geophysics*, 35(2–3), 133–143.
- Wang, Y., Allam, A., Lin, F. C., 2019. Imaging the fault damage zone of the San Jacinto Fault near Anza with ambient noise tomography using a dense nodal Array. *Geophysical Research Letters*, 46(22), 12938–12948.
- Wei, W., Zhao, D., & Xu, J., 2013. P-wave anisotropic tomography in Southeast Tibet: New insight into the lower crustal flow and seismotectonics. *Physics of the Earth and Planetary Interiors*, 222, 47–57.
- Xu, X., Wen, X., Han, Z., et al., 2013. Lushan $M_s7.0$ earthquake: A blind reserve-fault event. *Chinese Science Bulletin*, 58: 3437–3443.
- Yang, H., Z. Li, Z. Peng, Y. Ben-Zion, and F. Vernon, 2014. Low velocity zones along the San Jacinto Fault, Southern California, inferred from body waves, *J. Geophys. Res.*, doi: 10.1002/2014JB011548.
- Zhang, H., Liu, Y., Thurber, C. H., Roecker, S. W., 2007. Three-dimensional shear-wave splitting tomography in the Parkfield, California, region. *Geophysical Research Letters*, 34(24).
- Zhang, H., Thurber, C. H., Bedrosian, P. A., 2009a. Joint inversion for V_p , V_s , and V_p/V_s at SAFOD, Parkfield, California. *Geochemistry Geophysics Geosystems*, 10(11).
- Zhang, H., Wang, P., van der Hilst, R. D., et al., 2009b. Three-dimensional passive seismic waveform imaging around the SAFOD site, California, using the generalized radon transform, *Geophysical Research Letters*, 36(23).
- Zhang, X., Zhang, H., Wang, H., Pei, S., 2013. Seismic Velocity Imaging of the Aftershock Zone of the 2013 Mw 6.6 Lushan Earthquake, China. In *AGU Fall Meeting Abstracts*.
- Zhao, B., Gao, Y., Huang, Z., Zhao, X., Li, D., 2013. Double difference relocation, focal mechanism and stress inversion of Lushan $M_s7.0$ earthquake sequence. *Chinese Journal of Geophysics*, 56(10): 3385–3395.

Zoback, M. D., Zoback, M. L., Mount, V. S., Suppe, J., Eaton, J. P., Healy, J. H., ... & Wong, I. G. (1987). New evidence on the state of stress of the San Andreas fault system. *Science*, 238(4830), 1105-1111.

(a) Isotropic V_p (b) Isotropic V_s

(c) P Anisotropy

(a) **(b)**