

Rupture process of the 2021 M7.4 Maduo earthquake and implication for deformation mode of the Songpan-Ganzi terrane in Tibetan Plateau

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The deformation mode of the Tibetan Plateau is of crucial importance for understanding its construction and extrusion processes, as well as for the assessment of regional earthquake potential. Block motion and viscous flow models have been proposed to describe the deformation field but are not fully supported by modern geophysical observations. The 2021 Mw 7.4 Maduo earthquake, which occurred inside the Songpan-Ganzi terrane (SGT) in central-east Tibet, provides a chance to evaluate the associated deformation mode of the region. We conduct a joint inversion for this earthquake and resolve a bilateral rupture process, which is characterized by super- and subshear rupture velocities, respectively. We interpret this distinct rupture behavior to be the result of the respective slip concentration depths of the two ruptured segments. We analyze geological, seismic, and geodetic evidence and find that the SGT upper crust shows distributed shear deformation and distinct transverse anisotropy, which are associated with folded structures originating from compression of the paleo-Tethys ocean accretional prism realigned by following shear deformation. The SGT receives lateral shear loading from its NS boundary and accommodates a right-step sinistral motion across the terrane boundary faults. The unique tectonic setting of the SGT defines locations and behaviors of internal faulting and strong earthquakes such as the 2021 Maduo earthquake, with the latter occurring on slow-moving faults at intervals of several thousands of years.

Maduo earthquake | Songpan-Ganzi terrane | deformation mechanism | seismic anisotropy | Tibetan Plateau

As the highest plateau in the world, the Tibetan Plateau (TP) attracts broad attention from Earth scientists. One outstanding issue is the mechanism that built this large area (2,500,000 km²), high elevation (~5 km), and relatively top-flat plateau (Fig. 1). The TP is a consequence of the collision between the Indian Plate and the Eurasia Plate that began ~55 Ma (1). The continental collision has resulted in the TP growing toward the northeast and caused the movement of several blocks, including the Tarim Basin, Sichuan Basin, and Ordos block (Fig. 1). While the northeast deformation front is building the Qilian Mountains, the central plateau involves eastward extrusion (2, 3). Deformation is distributed over the plateau in several geological units, including the Lhasa (LS) terrane, Qiangtang (QT) terrane, Songpan-Ganzi (SG) terrane, and Qaidam (QDM) basin, which are bounded by several suture zones and faults, including the Bangong-Nujiang suture (BNS), Jinsha suture (JSS), and Kunlun fault (KLF), respectively (Fig. 1). It is generally recognized that the deformation mode transits from dilatational in central Tibet to compressional at the northeast plateau margin, and yet how this transition occurs and its long-term impact on the plateau growth are not well understood. Understanding this problem will also provide insights into the building and deformation mechanism of the plateau.

Various dynamic models have been proposed to explain the uplift and faulting behaviors of the TP. Two major mechanisms, i.e., crustal viscosity (4, 5) and brittle block motion (6, 7), are considered to describe the motion and construction history of the plateau. The viscous model assumes a "soft" lithosphere of the plateau, which includes a delaminated lithosphere (3) or an intruded lower crust (8) to elevate the plateau. Lateral motions of the viscous lower crust are used to explain the surface velocity field and boundary topography (9). On the other hand, the block model attributes the lateral motion of coherent blocks as the dominant deformation and explains the surface faulting at block boundaries (6). Thrust motion along major mountain building zones accounts for the building and shortening of the plateau (1, 10). A more specific "active

Significance

The Songpan-Ganzi terrane lies in the central-east of the Tibetan Plateau, which was considered a stable block in some tectonic models. Its deformation mode is of crucial importance for understanding the evolutionary history and seismic hazard of the plateau. The recent Maduo earthquake occurred inside the terrane. We resolve a bilateral rupture process with distinct super- and subshear rupture modes for this event. We also find that pervasive folding structures that are aligned by shear deformation in the current Songpan-Ganzi terrane are responsible for the seismic wave anisotropy and shear strain orientation in its upper crust. Its deformation mode can be classified as distributed simple shear, which receives shear loads from side walls and produces internal earthquakes.

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Fig. 1. Regional tectonic setting. The study area is identified in the *Top Right Inset* map. Terranes of the TP and surrounding blocks are plotted as red- and blackbounded polygons. Mountain ranges are filled in gray. A dashed line in the southwest-northeast direction marks the sidewall of Fig. 5. (A) The distribution of maximum shear strain rates (14) is plotted as a colored map in the background. Terrane boundaries, i.e., sutures and major faults, are plotted as thick red and white curves. Regional normal, strike-slip, and thrust faults are plotted as red, white, and black curves (68), respectively. Historical events and the 2021 Maduo earthquake are plotted as black and red focal mechanisms, respectively. Fault slip rates along the Altyn Tagh fault (ATF), KLF, ELKF, GYF, and XSHF (15, 54–56) are labeled. (*B*) Regional strain regimes. Red and blue-filled patches are regions with predominantly lateral dilatational and compressional strain rates. Focal mechanisms (GCMT M_W > 4.0 1980 to 2021 and ref. 69) of normal, strike-slip, and thrust events are plotted as red-, black-, and blue-filled back balls, respectively.

block model" is further proposed to explain the surface deformation of China (11). This model is a small-scale version of plate tectonics, which identifies block boundaries by active faults. To the first order, it successfully explains the fault belts and locations of major historical earthquakes in China (12). As defined by the active block model, the region between the Kunlun-East KLF (KLF+EKLF) and Ganzi-Yushu-Xianshuihe fault (GYF+XSHF) is identified as the Bayanhar block, which is considered to be the block with most active boundaries in China. In the past 100 y, boundaries of the Bayanhar block have been ruptured by about 20 M earthquakes with magnitudes of >6.5 (Fig. 1A), among which the 1997 $M_W7.6$ Manyi, 2001 M_W7.8 Kokoxili, and 2010 M_W6.9 Yushu earthquakes have been investigated by modern seismological and geodetic methods. The eastern margin of the Bayanhar block is the collision front between the plateau and the Sichuan basin, which has built the Longmenshan Mountains and produced the devastating 2008 M_W7.9 Wenchuan earthquake. This is the most destructive earthquake in China of this century, causing more than 80,000 fatalities (13). Therefore, understanding the deformation behavior of the plateau is of key importance as well to evaluate the seismic hazard of the plateau and its surrounding areas.

Deformation modes are distinct in various TP terranes, which is evident in global positioning system (GPS) observations and earthquake and faulting mechanisms (Fig. 1B) (14). The spatial distribution of the strain field demonstrates that the dominant strain mode changes from east-west extension in the central plateau (LS+QT terranes) to north-south differential shear in the central-east plateau (Songpan-Ganzi terrane [SGT]) and to NS shortening in northeast front (QDM and QL). The SGT lies between dilatational and compressional regimes with an elongated shape in the EW direction, which accommodates the eastward extrusion of the QT terrane and northward motion of the QDM basin and Qilian Mountains. However, discrepancies exist between the observed earthquake activity and strain rate distribution. Large earthquakes in the SGT mostly occurred on the boundary faults of the Bayanhar block, i.e., the EKLF and GYF. On the other hand, the shear strain is distributed over the entire SGT (Fig. 1B). This discrepancy raises a question to re-evaluate the seismic hazard of the Bayanhar block, namely, whether the strains within the block are seismogenic and capable of producing large earthquakes. Historical intraterrane events, such as the 1947 Dari earthquake, suggest that the answer is yes, but its rupture mechanism and faulting details lack modern geophysical observation, so as to its association with the tectonic process and deformation mechanism of the SGT.

On May 22, 2021, at a local time of 02:04:13 AM, an $M_w7.4$ strike-slip event, namely, the Maduo earthquake, ruptured the Jiangcuo fault, which is located about 70 km south of the EKLF (15) within the Bayanhar block. This event occurred in a low populated area and caused five fatalities and hundreds of injuries (Fig. 2*A*), while its location is of particular importance to evaluate the rupture behavior of intrablock events. In this study, we investigate the rupture characteristics of this earthquake and resolve a bilateral rupture process with distinct rupture velocities. We further discuss the current and long-term deformation behavior of the SGT from geological, geodetic, and seismic evidence. Our analysis suggests that the deformation mode of the SGT is "distributed shearing," which draws further implications for the crustal structure and strength of the SGT.

Data, Methods, and Results

We adopt a joint inversion technique to investigate the rupture process of the 2021 Maduo earthquake. This inversion involves coseismic GPS measurements, synthetic aperture radar (SAR) images, and teleseismic body waves and exploits complementary spatial, temporal, and seismic moment resolution lain in different data to achieve comprehensive model resolution (16). Details of data processing and inversion techniques are described as follows.

Campaign GPS Data. We use coseismic ground displacements measured by 106 campaign GPS stations. Original data collection and processing were made by two studies (17, 18). We only use horizontal displacements of stations located within 200 km from the hypocenter in the inversion (Fig. 2) because vertical displacements have significantly larger uncertainties



Fig. 2. Coseismic slip solution of the 2021 Maduo earthquake. (*A*) InSAR detected coseismic ground displacements of the earthquake in the line-of-sight direction, plotted in a blue-red color scale. Lateral ground displacements observed by GPS stations are denoted as black arrows. The red curve marks the identified fault trace. Aftershock locations are marked as gray-filled circles. Dynamic energy bursts recovered by the BP method are plotted as circles with the time indicated by the filling color. (*B*) Coseismic slip distribution plotted in a precip color scale in the background, with the slip directions indicated by white arrows. Aftershocks are marked as black dots. Slip concentration areas (asperities) and slip voids are marked. (*C*) Data postfit residual curves of the westward and eastward rupture velocities, plotted in the two *Left* panels, respectively. Teleseismic, SAR, GPS, and total residual curves from joint kinematic inversions are color coded in red, magenta, blue, and black, respectively. Optimal rupture velocities are marked as a lack curve in the *Right* panel. Rupture concentration depths are marked as a red box. East- and westward rupture velocities are denoted as red dashed lines. (*D*) Energy bursts projected to the fault strike direction for Australian (red dots) and European (blue dots) arrays, respectively. West- and eastward propagations are shown in the *Left* and *Right* panels. Reference rupture velocities are marked as dashed lines.

than the horizontal components and the observations are usually buried in their uncertainties and hardly to have meaningful contributions.

SAR Data Processing. We use two pairs of Sentinel-1 SAR images (Ascending Track 99 and Descending Track 106) and one pair of ALOS-2 SAR images (Ascending Track 149) to map the surface deformation caused by the earthquake (*SI Appendix*, Table S1). Image pairs are firstly coregistered using a geometric approach with precise orbit ephemerides and the Shuttle Radar Topography Mission digital elevation model. Burst-based interferograms are merged, with an azimuth phase ramp correction using the burst-overlap interferometry (19). We calculate cross-correlation between uniformly distributed nonoverlapping 64-by-64 subimages on the coregistered radar amplitude images (20). For the inversion, the derived displacements are down-sampled using uniformly distributed 4-km grids in the near field and quadtree structures in the far-field for the InSAR data. Details of SAR data processing are available in *SI Appendix*.

Teleseismic Data Processing. We use 34 P wave and 36 S wave recordings recorded by the Global Seismic Network. Instrumental responses are removed from the original data to recover displacement recordings. We adopt a band-passed filter of 0.01 to 0.95 Hz to filter the data. We then use the down-sampled (2 sps) data in the finite fault model inversion.

Joint Inversion of Fault Slip Using GPS, InSAR, and Teleseismic Data. We parameterize the fault plane with respect to the mainshock focal mechanism reported by the Global Centroid Moment Tensor (GCMT) project (21). The fault surface trace is identified from the SAR images (Fig. 2A), and a northward dipping angle of 83° is assigned to parameterize the fault plane. The fault plane is parameterized with 40 and 8 subfaults in the along strike and dip directions, respectively, with an averaged scale of 3.9×2.9 km. We set the National Earthquake Information Center hypocenter (34.586°N, 98.255°E, 10 km) at the 23rd and 4th subfault in the along strike and dip directions, respectively. We adopt a multitime-window (MTW) parameterization method, which approximates the source time function with multiple triangles (22) and nonnegative linear least-squares inversion to deduce the rupture kinematics. For each subfault, we use six triangles to parameterize the source time function, each having a 2-s duration. We invert for slips along two directions with a rake uncertainty of $\pm 15^{\circ}$ from the point source rake angle (0°). We parameterize a bilateral propagation with different rupture velocities and select the preferred rupture velocity (Vr) for each side through trade-off curves (Fig. 2D). An empirical weighting technique (23) is adopted to determine the relative weighting between data sets, and Laplacian smoothing is applied in the inversion (SI Appendix, Fig. S2).

Seismic Back-Projection for the Earthquake Rupture Process. The vertical components of the teleseismic P waves of two regional networks, namely, the Australian Network (AU) and European Network (EU), are used in our back-projection study. As shown in *SI Appendix*, Fig. S1, 41 stations in AU and 51 stations in EU are used. The source area centered by the epicenter (98.2548°E, 34.5864°N) is parameterized into $0.1^{\circ} \times 0.1^{\circ}$ grids with a fixed depth of 10 km. The normalized P waveforms are band-pass filtered with the frequency range of 0.5 to 2.0 Hz. The waveforms are aligned using multichannel cross-correlation of 10-s-long segments of waveforms starting from 5 s prior to the theoretical P arrival time, to account for the travel time anomalies caused by the three dimensional Earth

structure. A 10-s-long sliding window with a time-step of 1 s is applied to the whole waveform to attain the rupture process of the earthquake. For each window, linear stacking is used in beamforming to obtain the true amplitude.

Results and Discussion

Rupture Process of the 2021 Maduo Earthquake. The slip model of the 2021 Maduo earthquake is plotted in Fig. 2B. As predicted from the surface deformation, the rupture is bilateral and dominated by eastward propagation. Three concentrated slip patches (asperities) are obtained, which are composed of one at 60 km to the west and two others at \sim 30 and \sim 75 km to the east of the epicenter, respectively. The peak slips of three asperities are about 3, 4, and 5 m, respectively, located above 5-km depths yielding the total seismic moment release of 1.43×10^{20} N-m, which is equivalent to a moment magnitude of $M_w = 7.37$. We obtain a moderate amount (~10%) of shallow slip deficits above the second row of asperity 2, which is smaller than that reported by ref. 24. It needs to be noted that we use a relatively large subfault size with an \sim 3-km depth scale, and the slips resolved in the first and second rows of subfaults are averaged between 0 to 3 km and 3 to 6 km; thus, we could not recover fine-scale shallow slip deficits, e.g., above 3 km depth as that reported by ref. 24. Coseismic slip models were also investigated by refs. 17 and 25 using different data and techniques, which resolved similar bilateral slip patterns although their spatial resolutions vary. Three voids of slips (Fig. 2B) located between the rupture asperities show different intensities of aftershocks. The first and second slip voids located on two sides of the hypocenter are filled with dense aftershocks, which generally meet the complementary pattern between coseismic slips and aftershocks observed for other strike-slip events (e.g., refs. 26 and 27). The third slip void between the second and third rupture asperities shows a moderate amount of slip (~ 1 m) and low aftershock activities. The depth of rupture concentration areas appears to influence the distinct Vr for the bilateral ruptures, as discussed in the following section.

We obtain distinct rupture kinematics, i.e., sub- and supershear, for the west- and eastward ruptures. The adopted MTW inversion uses a prescribed Vr to determine the rupture kinematics; thus, by testing with different Vr, we can determine the realistic Vr from the residual curve as a function of Vr (28). Ideally, the location and timing of each asperity receive constraints from geodetic and teleseismic data, respectively, and the joint inversion technique can recover rupture kinematics by exploiting information lain in both data. The Vr of westward and eastward ruptures are determined as 2.0 and 4.6 km/s, respectively, which are in the subshear and supershear domains in comparison with the averaged shear velocity (Vs, ~3.4 km/s) for the rupture concentration depth (above 15 km) (Fig. 2C). This distinct rupture propagation behavior is also consistent with that obtained by BP images; coherent radiators are imaged between a Vr range of \sim 2 to 3 km/s and 3 to 5 km/s for the west- and eastward ruptures in the multiple array back-projection (BP) image results (Fig. 2D). The BP method images the rupture kinematics by beam-forming techniques with little a priori assumptions, which is independent of the rupture model inversions. Thus, the consistency of results reported by the two techniques confirms the reliability of different rupture velocities of the bilateral rupture.

It is noted that the Vr postfit residual curve variation is most significant in the GPS residuals (Fig. 2B), which is not intuitive since GPS data only recover coseismic ruptures. Our test shows

that different rupture velocities place asperities at different locations and predict different GPS displacement vector directions. The spatial locations of GPS displacement vectors appear to be the key to differentiating the models and precisely determining Vr. A similar super- and subshear bilateral rupture pattern is resolved for the Maduo earthquake by BP and Mach wave methods (29). When regional high rate GPS (hr-GPS) data are adopted, however, a uniform subshear Vr of 2.6 to 2.8 km/s is obtained by Chen et al. (30). It is noted, nevertheless, that Chen et al. (30) assume the bilateral ruptures share identical velocity, which may recover only the averaged Vr. These discrepancies reflect the influence of parameter assumptions and a priori constraints in resolving rupture kinematics, and we consider that the sub- and supershear Vr in the bilateral rupture is a soundly recovered phenomenon discerned using several techniques.

Most supershear ruptures were reported for unilateral strikeslip events, for example, the 2001 Kokoxili (31-33), the 2013 Craig (28), and the 2019 Palu (34) earthquakes, while supershear rupture of bilateral strike-slip events is rarely reported. The equivalent moment magnitude of the west- and eastward ruptures are $M_w = 7.05$ and 7.25, respectively, which is above the magnitude threshold (M_w of ~6.9) that supershear ruptures are commonly reported (35). If the stress environments and fault properties are similar for fault planes in two directions, a direct question to raise is why supershear only occurred in the eastward rupture. Theoretical studies demonstrate that supershear rupture has a preferred direction when materials on two sides of a fault show strong velocity contrast (36, 37). This mechanism can produce bilateral ruptures with sub- and supershear velocities in laboratory experiments (36). The velocity contrast mechanism is more suitable to explain the supershear phenomena of plate boundary faults. However, as a fault inside a geological unit, a strong wave velocity contrast across the Jiangcuo fault is not expected. We suggest that the distinct Vr contrast may arise from the difference in slip concentration depths of ruptures in two directions. The rupture pathway west of the hypocenter is limited to above 5 km, while the rupture east of the hypocenter is distributed within a 10-km depth. The distinction of Vr may directly reflect the contrast of Vs at the slip concentration depths. The shallow depths may be subject to sediment layers, and the uppermost crust commonly shows stable or conditionally stable sliding properties (38), which release, at least partially, interseismic stress loading through creeping. Dynamic weakening mechanisms (39) may drive the rupture to go through such a regime, while the low initial shear stress and enhanced friction at low Vr may prevent the rupture to go supershear (40). In contrast, the eastward rupture went through seismogenic depth and quickly received the energy input of asperity 2 and thus is more likely to grow into supershear. The supershear segment may have produced limited aftershock activities (33), which is related to the complete stress release with its fast rupture. This feature is consistent with the absence of aftershocks in the third slip void. It is noted that our inversion is performed with a single curved fault plane, which is the first-order estimation of the fault geometry. Other factors, including fault branches, more reliable hypocenter location (41), and extra regional seismic and hr-GPS data (30), are needed in future works to reveal more detailed rupture kinematics.

Deformation Features of SGT. The present strain rate is obtained by a 30-y observation of GPS networks; it is nevertheless still a snapshot in comparison with the geological time of the TP construction and mostly reflects an elastic deformation.

To assess the relationship between the present and long-term deformation, we compare patterns of geodetic strain rate with seismic anisotropy and surface faulting distribution. We use the upper crust (top 15 to 30 km) anisotropic seismic velocity model of the northeast plateau (42) obtained by measuring azimuth-dependent propagation velocity of surface waves. We interpolate azimuthal anisotropy vectors at sample points inside the SGT and compare the fast axis direction with the nearest fault strike direction. The comparison reveals a consistency between anisotropy fast direction and fault orientation within an acceptable range $(\pm 20^\circ)$, which suggests that the anisotropy direction is related to the faulting orientation (Fig. 3F). The anisotropy level inside the SGT (3 to 5%) is significantly higher than that ($\sim 1\%$) in other parts of the plateau, including the QT, LS, and QDM terranes (Fig. 3B) (42). Wang et al. (17) demonstrated that the maximum shear direction in the SGT is consistent with the fault orientation near several major faults, which, as shown in Fig. 3B, also correlates with the orientation of seismic anisotropy. This comparison, therefore, shows that shear strain, fault orientation, and anisotropy directions are correlated over the SGT.

Geological evidence shows that majority of the SGT is composed of the accretional prism of the closed paleo-Tethys that experienced two stages of shortening during the late Triassic and Tertiary periods (43, 44). The SGT is a fold belt, on which fold and thrust structures related to its shortening history are pervasively observed by satellite images and field mapping (10). Subvertical strata are observed in several profiles in the terrane-cutting directions and also bore-hole core samples, which shows that the original horizontal layering of sedimentary rocks are deformed as foliated steep strata (10, 44). This appears to be the dominant material structure introducing the observed azimuthal anisotropy in the upper crust. Overlapping of sedimentary layers above horizontal décollement interfaces also accommodates the prism shortening, which will increase the thickness of sedimentary layers yet not influence its anisotropic pattern.

The seismic anisotropy result we adopted for this study was derived using different frequency contents of surface waves to resolve anisotropic features at different depths (42). Results from other anisotropic studies, such as those using data of SKS splitting (45), are not discussed in this study since they usually lack depth resolution. We plot the depth distribution of the anisotropy model along two profiles, as follows: one north-south trending profile cutting the western SGT and another southwest-northeast profile through the 2021 Maduo and 2010 Yushu earthquake rupture area (Fig. 3A). Taking the averaged crustal thickness of \sim 70 km in the SG and QT terranes (46), we found that their entire lower crust has a relatively low shear velocity and low anisotropy level. We also compare the along-profile distribution of geodetic maximum shear strain rate with the anisotropy level in Fig. 3 C and D. Both profiles reveal a shallow depth concentration (15 to 30 km) of anisotropy level, which is correlated with the surface distribution of maximum shear strain rate. The depth dependence of the anisotropic feature suggests that the folding structure observed on the surface of the SGT extends to about a 15- to 30-km depth, which reflects the amount of thickening of the original prism wedge (Fig. 3C) from a typical original thickness of 1 to 7 km for ongoing subductions (47) and is accompanied with heavy denudation during the process (48).

The above comparison exhibits the correlation between deformation rate, seismic anisotropy, and geological structures and sheds light on the relationship between the evolutionary history of the SGT and its geological structure and current deformation mode. We introduce a physical model to unite the



Fig. 3. Shear strain rate (14) and anisotropy observations (42) in the region. (*A*) Two profiles (Prof 1 and 2) are plotted as black lines on the background of the maximum shear strain rate map. Averaged anisotropic levels in the upper 30 km are plotted as black contours. Focal mechanisms of the 2001 Kunlun, 2013 Yushu, and 2021 Maduo earthquakes are plotted. (*B*) The fast anisotropy axis and maximum shear directions are plotted as magenta and black lines, respectively. The area with low-anisotropy level is masked in opaque. (*C* and *D*) Velocity and deformation features along Prof 1 and 2. The topography and shear strain rate and anisotropy level distributions are plotted in the *Top* two panels. Depth distribution of anisotropy level and shear velocity perturbation are plotted in the *Bottom* two panels using different color scales. EQ stands for earthquake, and QLS stands for Qilianshan Mountain. (*E*) Shear strain rate and anisotropy levels are sampled at the same spatial points and plotted as black and gray dots for samples inside and outside SGT, respectively. Theoretic cal relationships between the simple shear rate and anisotropy level are plotted as red and blue contours, with respect to the two TI parameters R_L (length ratio) and dVs (shear velocity change), which are labeled for each curve. (*F*) Azimuthal differences between anisotropy fast axes and fault strikes are plotted along longitude for spatial sample points, with the anisotropy level represented by the filling color.

three observations. A homogeneous transversely isotropic medium is assumed with a horizontal symmetry axis (HTI) to represent the SGT upper crust, which essentially resembles finely distributed vertical strata with azimuthal-dependent elastic strengths (SI Appendix, Fig. S9). The TI medium is commonly used to present anisotropic features of sediment layers and, thus, can be directly adopted to represent folded sedimentary rocks (49) when its symmetric axis is rotated to be horizontal. The anisotropy level of a sedimentary basin is around 8% (50), which is high enough to explain the folded sediments of SGT. Under the HTI assumption, the anisotropy and shear strain rate behavior can be theoretically calculated. The theoretical solution of shear strain rate and anisotropy level depends on two dimensionless TI parameters, namely, R_L and R_µ, which define the thickness ratio and velocity reduction ratio between characteristic strong and weak layers of sediments. A detailed calculation is provided in SI Appendix. We calculate the theoretical trade-off curve between the level of anisotropy and shear strain rate with respect to different combinations of TI parameters and compare the theoretical and observed values in Fig. 3D. It is noted that TI shear strain rate uses a simple shear approximation, which is twice the pure-shear amplitude (Fig. 3D) (14). The comparison shows that the observed shear strain rate and anisotropy level can be well predicted by a velocity perturbation of 21 to 29% and R_L between 30 to 65%, which are reasonable ranges for strength and thickness variation of sedimentary rocks. Damage zones of strike-slip and thrust faults may also contribute to the anisotropy pattern, but considering their spatial density, their contribution should be much smaller than folding structures.

Our simplified physical model is a first-order approximation, which explains the observed velocity anisotropy and shear strain rate features. The strain rate reflects the elastic deformation of the current epoch, which is consistent with the direction of strike slip faults (17), while in the geological time scale, the plastic effect of shear loading needs to be considered. Particularly, the initial folding is not necessarily formed along the current strike-slip faults, while it is observed that the anisotropy direction follows the clockwise (~30°) rotation of strike-slip faults along the SGT within $\pm 20^{\circ}$ variation (Fig. 3*F*). The match between anisotropy and shear directions suggests a connection between their driving mechanisms. In other words, plastic shear deformation, which is required to rotate and align the fold structures, also shaped the anisotropic structure that manifests the modern elastic deformation of the SGT.

Implications for Large Earthquake Potential. The occurrence of the Maduo earthquake calls for a re-evaluation of the potential for large earthquakes in the SGT. As evident in the strain rate map, shear strain rates are distributed within a region of a 100-to 400-km width, which defines a "shear zone" with a potential of intrablock large earthquakes. We consider 10 profiles across the SGT and integrate rates of simple shear to produce cumulative differential shear velocity (Fig. 4; *SI Appendix* for the calculation). Our comparison finds that the cumulative shear velocity is about 20 to 30 mm/y across the SGT, with some levels of spatial variation. A field investigation of the fault slip rate is not complete in the SGT, which is mostly focused on the KLF, EKLF, GYF, and XSHF (Fig. 4). The slip rate of the Anyemagen Shan,



Fig. 4. Slip budget of the SGT. (*A*) Locations of 10 profiles across the SGT are plotted as colored lines in the mapview. Slip rates along the KLF-EKLF and GYF-XSHF systems are labeled. ZBS stands for Zangbo Suture, and ANHF and DLSF stand for the Anninghe and Daliangshan faults, respectively. (*B*) Cumulative shear velocities along the 10 profiles denoted in *A* are plotted at the central longitude of each profile. Estimated slip rates on the KLF-EKLF and GYF-XSHF are plotted as black and red bars. At the SE end of the XSHF, its slip rate is calculated by summing slip rates on the ANHF and DLSF. (*C*) Strain rate distribution along each profile is plotted as colored curves. (*D*) Conceptual figures showing surface shear rate and displacement velocity for slip on boundary faults and distributed inside a terrane are plotted in the *Left* and *Right* panels, respectively. Anti-plane movements of strike-slip faults are denoted as dotted and crossed circles.

which is gradually reduced and down to $\sim 2 \text{ mm/y}$ east the Anyemagen Shan on EKLF (53, 54). On the south side of the SGT, the slip rate on the GYF is 5 to 8 mm/y (55), which increases to 8 to \sim 13 mm/y along the XSHF and is partitioned between the Anninhe and Daliangshan faults south of the XSHF (56). On each profile, we take the summation of northern (KLF+EKLF) and southern (GYF+XSHF) boundary faults of the SGT to account for slip rates on block boundaries, which account for 60 to 90% of the accumulated differential motion of GPS observations (Fig. 4B). The slip contribution of boundary faults reduces from the central SGT (about 90% when adding that of the KLF and GYF) to the eastern SGT (about 60% when adding that of the ELKF and XSHF). The change of boundary slip contribution is accompanied with slip transition from the northern boundary to the southern boundary. Although shear rates may vary over a cycle of interseismic loading with spatial and temporal variations, we assume that the crust deforms approximately at the current observed rate over the interseismic period and the remaining 10 to 40% of the strain accumulation needs to be released within the body of the Bayanhar block. Thus, the in-block area is subject to the potential of large earthquakes. Besides the Jiangcuo fault, other terrane interior strike-slip faults, such as the Dari, Wudaoliang-Changshagongma (7, 17), and possibly some unmapped faults, have to contribute to this slip budget. We assume an equal allocation of slip deficits on these faults and estimate their averaged loading rate as 0.5 to 2 mm/y. Considering the averaged slip amount of the Maduo earthquake (~2 m) as a reference, intervals for characteristic earthquakes, like the 1947 Dari and 2021 Maduo earthquakes, on these faults should be about several thousands of years.

Although the SGT experiences a distributed shearing, it is noted that the slip rates on its boundary faults, such as the EKLF and XSHF (~10 mm/y), are about one order of magnitude higher than that on the terrane interior faults (0 to 2 mm/y). If the SGT receives shear loading from side walls, the stress loading rate should be similar across the SGT and produce similar slip rates on boundary and interior faults unless their properties are different. Besides the upper-crustal faults, geophysical observations resolve that the lower crust of the SGT has a wide spread of low shear velocity (42), high conductivity (57, 58), and regular viscosity ($\sim 10^{19}$ Pas) (59), indicating a ductile material property. The strength of a continental crust is controlled by the frictional strength in the upper crust and ductile strength in the lower crust (60). We evaluate the rupture patterns of the 2001 Kokoxili (61), 2010 Yushu (62), and 2020 Maduo earthquakes and find that their coseismic slips are mostly limited to above a 10-km depth, indicating similar seismogenic depths and similar upper crust strengths. For the lower crust, the viscous strength also depends on shear rates because shear heating further weakens the medium and produces positive feedbacks to form a localized shear zone (63). The shear rate difference suggests that the lower crust beneath the boundary faults may have more localized shear concentration and lower viscosity (64), which in turn explains the shear rate difference between the boundary and interior faults. Seismic evidence also shows Moho offsets beneath the KLF and XSHF, suggesting that these boundary faults probably cut through the entire lithosphere (46, 65). This is in contrast to the relatively flat Moho within the SGT, indicating that localized shear bands may not have been developed in the lower crust beneath the intraterrane faults to disturb the Moho.

Deformation Mechanism of the Eastern TP. The above synthesis suggests that a thin brittle upper crust (upper 30 km) underlain a viscous lower crust best describes the material strength of



Fig. 5. A schematic diagram for the regional tectonic deformation model of Tibet. (A) A simplified model for the SGT is plotted in the Top Left corner, showing distributed shear within deformation zone of a right-step sinistral fault system, with terrane shape and displacement rotation features neglected. (B) Regional tectonic setting and deformation mode are plotted in a perspective map view, and the sidewall is cut along a profile shown in the inserted map of Fig. 1. Lateral motions of the Indian plate and QDM basin relative to the Eurasia plate are indicated by thick white arrows. Dilatation and shear motions are plotted as white and black arrow pairs. Identified strike-slip faults in the SGT are plotted as black curves with the relative motion marked. Inferred folding structures and thrust faulting are denoted as double-headed arrow lines and barbed lines in white, respectively. The Main Himalaya Thrust (MHT), KLF, GYF, ATF, and DN-HYF (Danghe-Nanshan and Haiyuan fault) are labeled. On the east-side wall, the location of a ductile lower crust is indicated. Folding structures in the SGT upper crust are denoted as green curves. The geometry of subducted slabs and fault geometry are referenced to refs. 1 and 10, with inferred slab boundaries marked as dashed lines.

the SGT (Fig. 5). As an overall picture of the current deformation field, the compressional and dilatational modes dominate the deformation mechanism in the collision fronts (Himalava and Qilian mountains) and central plateau (QT+LS terranes) (1), while currently distributed elastic shear dominates the elongated SGT (17), which accommodates the differential motion between central extrusion and northeast collision of the plateau. The eastward movement of the SGT is impeded by the Sichuan basin at its eastern margin, building the Longmenshan Mountains. The shear motion decreases gradually along the KLF+EKLF from the central section to the east section (15) (Fig. 4) and terminates near the Longmenshan (54). The shear motion transmits from the KLF and EKLF to the GYF and XSHF through the SGT east of 98°E. The first-order deformation of eastern Tibet could then be understood as a left-lateral èn echelon fault system with a right step change (Fig. 5A) (66).

One striking deformation feature of the SGT is the current distributed elastic shear motion inside this geological unit (Fig. 5). As the remnant of the Tethys accretional prism, the compressional evolution of the SGT introduced pervasive folding structures in its upper crust, while the long-term plastic shear motion modified the trend of fold structures along the shear direction to accommodate an eastward extrusion of the central plateau. The SGT upper crust is comprised of HTI medium, which well explains its seismic anisotropic and shear deformation features. Ruptures of the SGT faults, e.g., during the Kokoxili, Yushu, and Maduo earthquakes, are mostly confined within the top 10-km depth. This relatively shallow seismogenic depth and other geophysical observations suggest a hot and ductile lower crust.

Another important inference of deformation analysis is that the loading force of the SGT should be lateral shear instead of bottom drag, which suggests that the SGT motion is passively driven by the eastward extrusion of central Tibet. If the SGT is driven by lower crust flow as some previous models suggested (e.g., ref. 9), the deformation and faulting pattern would be more like an outward flow originated from central Tibet plus narrow shear motions across a few boundary faults, not the broad lateral shear motion as we observe in the SGT. Our modeling analysis uses simple lateral shear to explain the faulting and strain rate observations, which is evident in both current elastic and long-term plastic deformations. Although this is a simplified model, two important properties are pivotal in controlling the mechanism, i.e., viscous strength in the lower crust and brittle strength of the upper crust. We suggest that both should be considered when quantitatively investigating the deformation behavior of the plateau. The general dilatational, shearing, and compressional mode of deformation can be accounted for by numerical modeling (67). With the constraints from the recently available strain rate map (14), numerical modeling that considers both upper and lower crustal strength with a quantitative comparison of surface strain rates and other geophysical and geological constraints, may shed light on the material strength variation over the entire plateau.

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Data Availability. Seismic data used to perform slip model inversion of the Maduo earthquake is recorded by Global Seismic Network and accessed through Incorporated Research Institutions for Seismology. Sentinel-1 SAR data are copyrighted by the European Space Agency and are additionally distributed by the Alaska Satellite Facility (from https://ast.alaska.edu). ALOS-2 SAR images are provided by Japan Aerospace Exploration Agency via Research Project ER2A2N050. Analysis code is written with Matlab, and readers can communicate with the authors to access the source code. Teleseismic Waveforms data have been deposited in IRIS (Incorporated Research Institutions for Seismology).

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