

Crustal response to water loads and expansion of triggered seismicity around the Xiluodu Reservoir, Southwest China

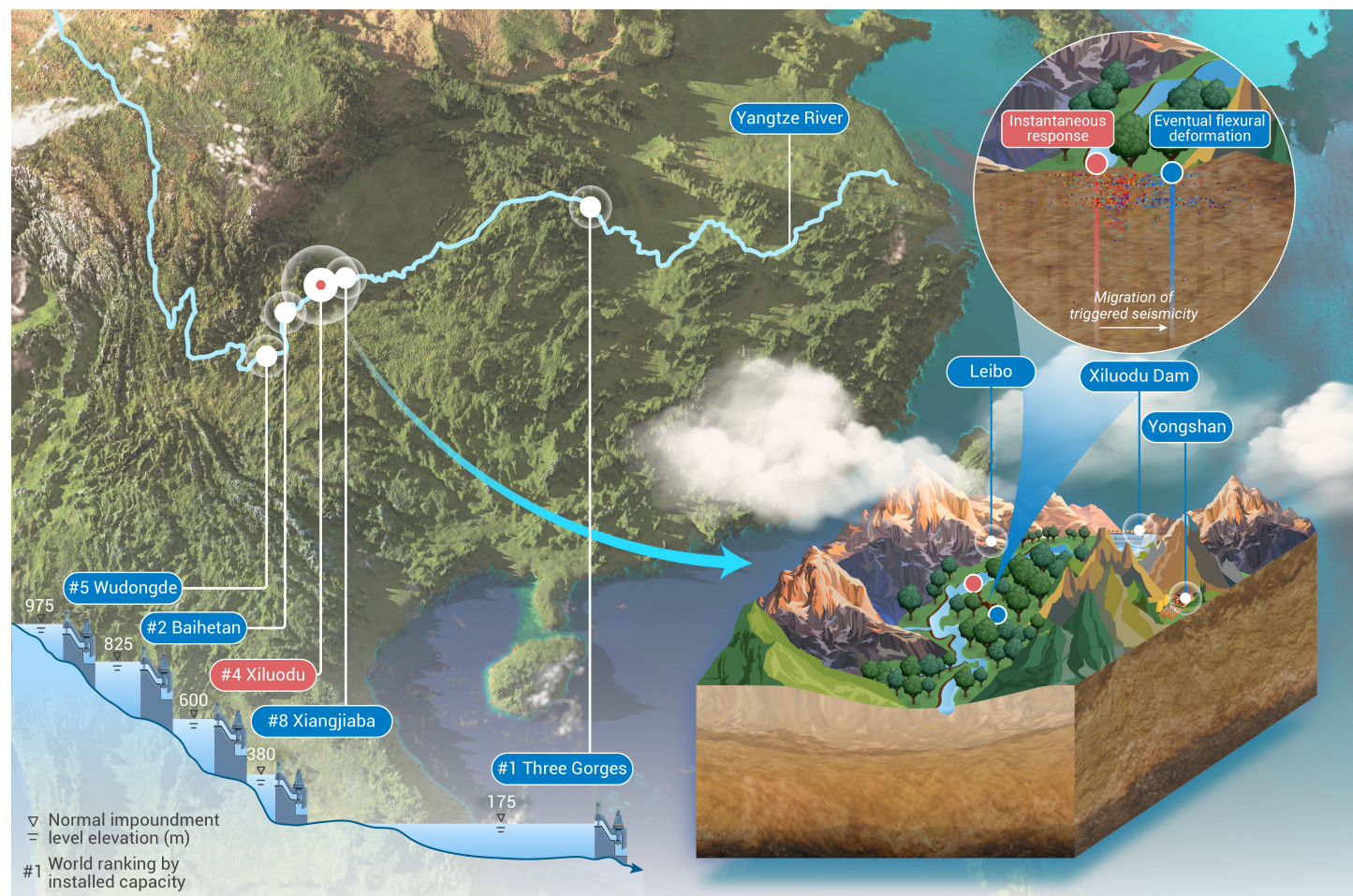
Xuhua Shi,^{1,10,*} Yuanhai Shu,^{1,10} Roland Bürgmann,² Lei Xie,³ Libo Han,⁴ Zhongcheng Cao,⁵ Wenbin Xu,³ Teng Wang,⁵ Hanlin Chen,^{1,*} Austin Madson,⁶ Eric Kirby,⁷ Guojie Meng,⁸ Renqi Lu,⁹ Qi Yao,⁸ Xiaogan Cheng,¹ and Shufeng Yang¹

*Correspondence: shixuhua@zju.edu.cn (X. S.); hlchen@zju.edu.cn (H. C.)

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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- The impoundment of the Xiluodu and Xiangjiaba Reservoirs results in crustal subsidence.
- About 81% of triggered seismicity is located within 15 km of the subsidence center of rapid crustal response.
- Triggered seismicity temporally relates to rapid hydrologic loading/unloading.
- Viscous relaxation effect leads to the spatiotemporal migration of triggered earthquakes.
- Enhanced geohazard monitoring efforts are urgently needed around subsidence centers.

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Xuhua Shi,^{1,10,*} Yuanhai Shu,^{1,10} Roland Bürgmann,² Lei Xie,³ Libo Han,⁴ Zhongcheng Cao,⁵ Wenbin Xu,³ Teng Wang,⁵ Hanlin Chen,^{1,*} Austin Madson,⁶ Eric Kirby,⁷ Guojie Meng,⁸ Renqi Lu,⁹ Qi Yao,⁸ Xiaogan Cheng,¹ and Shufeng Yang¹

¹Key Laboratory of Geoscience Big Data and Deep Resource of Zhejiang Province, School of Earth Sciences, Zhejiang University, Hangzhou 310058, China

²Berkeley Seismological Laboratory and Department of Earth and Planetary Science, University of California, Berkeley 94720, USA

³School of Geosciences and Info-Physics, Central South University, Changsha 410083, China

⁴Institute of Geophysics, China Earthquake Administration, Beijing 100081, China

⁵School of Earth and Space Sciences, Peking University, Beijing 100080, China

⁶Wyoming Geographic Information Science Center, University of Wyoming, Laramie 82071, USA

⁷Department of Earth, Marine, and Environmental Sciences, University of North Carolina, Chapel Hill 27514, USA

⁸Institute of Earthquake Forecasting, China Earthquake Administration, Beijing 100036, China

⁹Institute of Geology, China Earthquake Administration, Beijing 100029, China

¹⁰These authors contributed equally

*Correspondence: shixuhua@zju.edu.cn (X. S.); hlchen@zju.edu.cn (H. C.)

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The transition to low-carbon energy generation requires a diverse portfolio of energy sources. Large hydropower stations play a crucial role in providing eco-friendly energy but can lead to crustal deformation and seismic activity due to reservoir impoundment and discharge. The mechanism behind how impoundment-induced deformation influences reservoir-triggered seismicity remains unclear. We investigate this at the world's 4th largest hydropower station in Xiluodu, China, using interdisciplinary analyses of relocated earthquakes, geodetic data, and numerical simulations. Geodetic observations confirm both a linear elastic response to hydrologic loading and the transition towards a relaxed and flexural response. Notably, approximately 81% of the earthquakes since impoundment occurred within ~15 km of the subsidence center. These events temporally relate to rapid hydrologic loading/unloading periods, with their spatiotemporal outward migration potentially caused by viscous relaxation of load stresses in the lower crust and upper mantle. The reservoir-induced flexural deformation and subsequent viscous relaxation may control the distribution and expansion of triggered seismicity. This research highlights the urgent need to enhance geohazard monitoring efforts around the subsidence center and emphasizes the vital importance of carefully considering this factor during the construction of large reservoirs to mitigate potential seismic risks.

INTRODUCTION

Large artificial reservoirs can produce large amounts of hydropower, representing the world's leading sustainable energy source,^{1,2} and help to mitigate anthropogenic water supply issues (for irrigation, residential and industrial usage) and downstream flooding.³ However, the impoundment of large reservoirs can also pose significant geohazards, such as earthquakes and induced surficial slope failures that affect nearby human populations.⁴ For instance, earthquakes following the impoundment of the Koyna Reservoir in India caused 200 deaths and several thousand injuries.⁵ Previous reservoir geohazard research mainly focused on 1) the characteristics, monitoring, and preventative countermeasures of surficial geohazards (e.g., slope failures),⁶⁻⁸ 2) the evolution and mechanisms of triggered earthquakes,⁹⁻¹³ and 3) valley contractions across reservoir dam infrastructure and their associated causes.^{14,15} However, due to the complexity of seismic mechanisms and the limitation of data analysis, relatively few studies have systematically evaluated the spatiotemporal distribution of earthquakes and underlying processes,^{16,17} and thus their causal mechanisms remain largely uncertain.

From a new perspective of the relationship between crustal deformation and seismicity, we seek to address how earthquakes are spatiotemporally distributed at the world's 4th largest hydropower station (by installed capacity), the Xiluodu Reservoir in southwestern China. It is one of the world's largest cascade hydropower stations and is located between Leibo in the Sichuan Province and Yongshan in the Yunnan Province on the upper

Yangtze River (Figure 1A-C). The concrete double-curvature arch dam has an overall height of 285.5 m. The first major water impoundment began on May 4, 2013 and saw the water level rise from 440 to 540 m above sea level (a.s.l.) in a span of 50 days. The second major impoundment event began on May 20, 2014 and saw the water level rise to a historical high of 600 m a.s.l. on Sept. 29, 2014. This high-water level corresponds to a total water storage capacity of 12.7 billion m³. The reservoir experienced eight filling and draw-down phases between May 2014 and Feb. 2022, with a typical seasonal water level cycle between 540 and 600 m a.s.l. (Figure 1D).^{13,14} A nearby reservoir, the Xiangjiaba Reservoir (located ~90 km northeast of the Xiluodu Reservoir) began impounding water on Oct. 10, 2012 and the water level rose from 280 m a.s.l. to an operational storage level of 380 m a.s.l. on Sept. 12, 2014 (Figure 1D).¹⁸

Geologically, the Xiluodu Reservoir was built in a basin with folded Permian basalt and limestone bedrock with pre-existing joints and fractures at its center,¹⁹ with the active Leibo and Lianfeng strike-slip and the Ebian-Jinyang reverse faults located to its north, south and west, respectively (Figure 1B).²⁰ This area constitutes the easternmost part of the topographic gradient extending from the Tibetan Plateau to the Sichuan Basin. It's characterized by southeast-directed geodetic surface motions²¹ and compressional stress patterns,²² and active-faulting-related geohazards.^{23,24} Additionally, it displays low shear-wave speeds indicative of a low-viscosity (10¹⁷-10¹⁸ Pa s) lower crust.^{25,26}

RESULTS

Magnitudes and patterns of crustal deformation in response to changing water loads

We use layered elastic half-space and plate-flexure models to estimate both the instantaneous elastic deformation and the deformation following complete relaxation below an elastic upper-crustal layer following impoundment. Modeling results from the layered elastic model (LEM) show that the maximum vertical displacement, due to the 60 m load difference of the Xiluodu, and the total loads of the Xiluodu and Xiangjiaba, are ~18 and ~64 mm at the subsidence center, respectively. The deformation mostly occurs in the upper crust and in the head area of the Xiluodu Reservoir, and the modeled deflection contours closely follow the load geometry (Figure 2A-B). Horizontal contraction is centered on the two reservoirs, and the maximum horizontal displacements reach ~3 and 10 mm under the 60 m load difference and total loads, respectively, in the Xiluodu area (Figure 2A-B; Figure S7).

Modeling results from the elastic plate models (EPM) with similar elastic moduli to the LEM (Figure S1; Table S1) show a sub-concentric pattern of isostatic deformation with the subsidence center located near the town of Wuji, ~20 km southwest of the Xiluodu Reservoir dam, regardless of the choice of T_e (Figure 2C-E). This fully relaxed flexure produces substantially larger peak subsidence (with the maximum displacement reaching 400 mm)

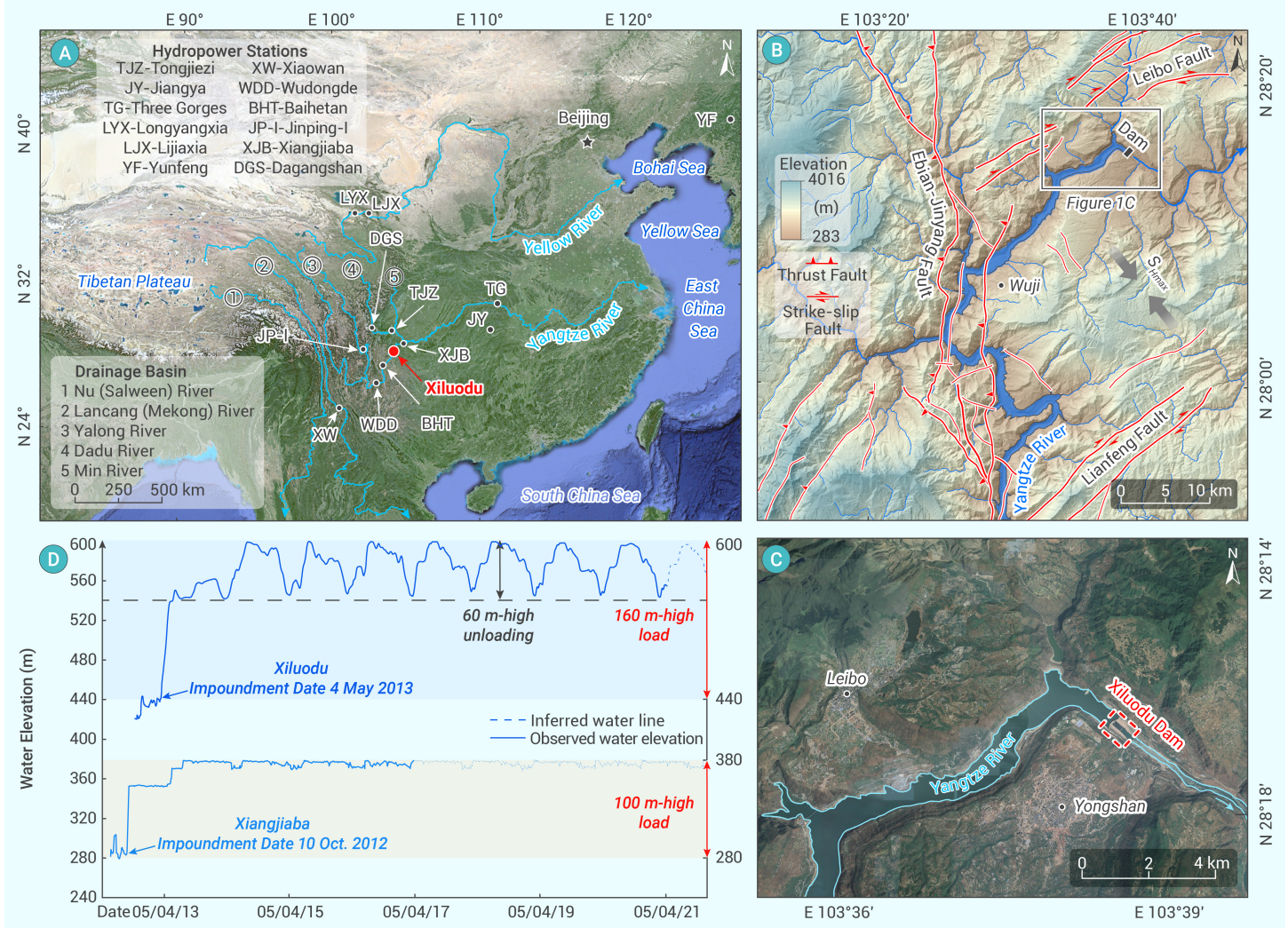


Figure 1. The geographical setting and water level history for the Xiluodu and Xiangjiaba Reservoirs on the upper Yangtze River (A) Locations of large hydropower stations in southwestern China. (B) Close-up view of the Xiluodu Reservoir area with fault lines following Su et al. (2020).²⁰ The blue polygon denotes the reservoir extent at the normal impoundment level of 600 m a.s.l. Grey arrows show the orientation of regional maximum horizontal compression (S_{Hmax}) based on Xu et al. (2016).²² (C) Map of the head area of the Xiluodu Reservoir. (D) Impoundment and operational history of the Xiluodu and Xiangjiaba Reservoirs used to compute water loads in the modeling.

than that calculated from the layered half-space model, with subsidence magnitude increasing with decreasing T_e (Figure S8). The *EPM* represents the contribution of lower-crustal and upper-mantle relaxation to the deformation. The flexural *EPM* deformation is much broader, and its subsidence center lies ~8.5–9.5 km to the southeast of that under the *LEM* (Figure S11), which reflects the initial response of crustal deformation. The total vertical displacement due to both initial elastic deformation and full plate flexure is as much as 460 mm assuming $T_e = 20$ km, with 80% of the large displacement (>370 mm) located in the Xiluodu area (Figure S11).

To test the reliability of the modeled deformation and associated subsidence centers of the *LEM* and *EPM*, we also estimate the displacements due to hydrologic loading at the Xiluodu Reservoir using Interferometry Synthetic Aperture Radar (InSAR) time-series data (Figure 2H–I; Figure S12). By fitting the time-series data with sinusoidal functions, the distribution of peak-to-peak amplitudes ($2c$, see descriptions in Methods) is consistent with the modeled deformation caused by the seasonally varying, 60 m-high hydrologic load (Figures 2F and 2H); and the maximum amplitude, ~12 mm (~20 km southwest of the Xiluodu dam), is located near the modeled subsidence center of the *LEM* (Figure 2H). The time-series data at point *P* show the amplitude changes with fluctuation of the water levels, with corresponding subsidence peak lagging behind the water loading for approximately half a cycle, and its magnitude is small during the initial impoundment and increased up to 12–17 mm (comparable to the maximum vertical displacement in Figure 2F) since 2017 (Figure 2J). In addition, the maximum of the

cumulative vertical displacement, ~55 mm (~25 km southwest of the Xiluodu dam), is shown near the modeled subsidence center of the *EPM* (Figure 2I), which is comparable to the long-wavelength deformation pattern simulated by the *EPM* model (Figure 2G). Because the beginning time of our InSAR data is later than the initial impoundment time, there exists a difference between modeled and observed displacement magnitudes. In general, a consistency in pattern between the geodetic observation and the simulation result confirms the reliability of the modeled deformation pattern.

We must emphasize that mechanisms for the observed seasonal deformation are complex, and elastic loading due to water level changes is only one of them. Other factors include the development of slope failures,²⁷ poroelastic deformation,¹³ and the evolution of thermal and seepage fields²⁸ due to local groundwater level variations. Thus, we may have underestimated the seasonal deformation in our analysis. For instance, an abnormal high-displacement feature in southwestern Yongshan county (Figure 2I; Figure S12) is also seen in the time-series of two-dimensional displacements obtained from multi-orbit SAR datasets (Sept. 2014–Apr. 2019),²⁷ and has been interpreted to reflect a resurgence of paleolandslides due to water-level fluctuation, seismicity, and surface water seepage.²⁹ We note the potential challenge associated with separating the vertical rate of deformation due to reservoir loading from the background tectonic vertical displacements in this region,³⁰ and the seasonal elastic response due to water management dominates the InSAR time-series near the reservoir (Figure 2J). However, the long-wavelength tectonic deformation and uncorrected tropospheric delays

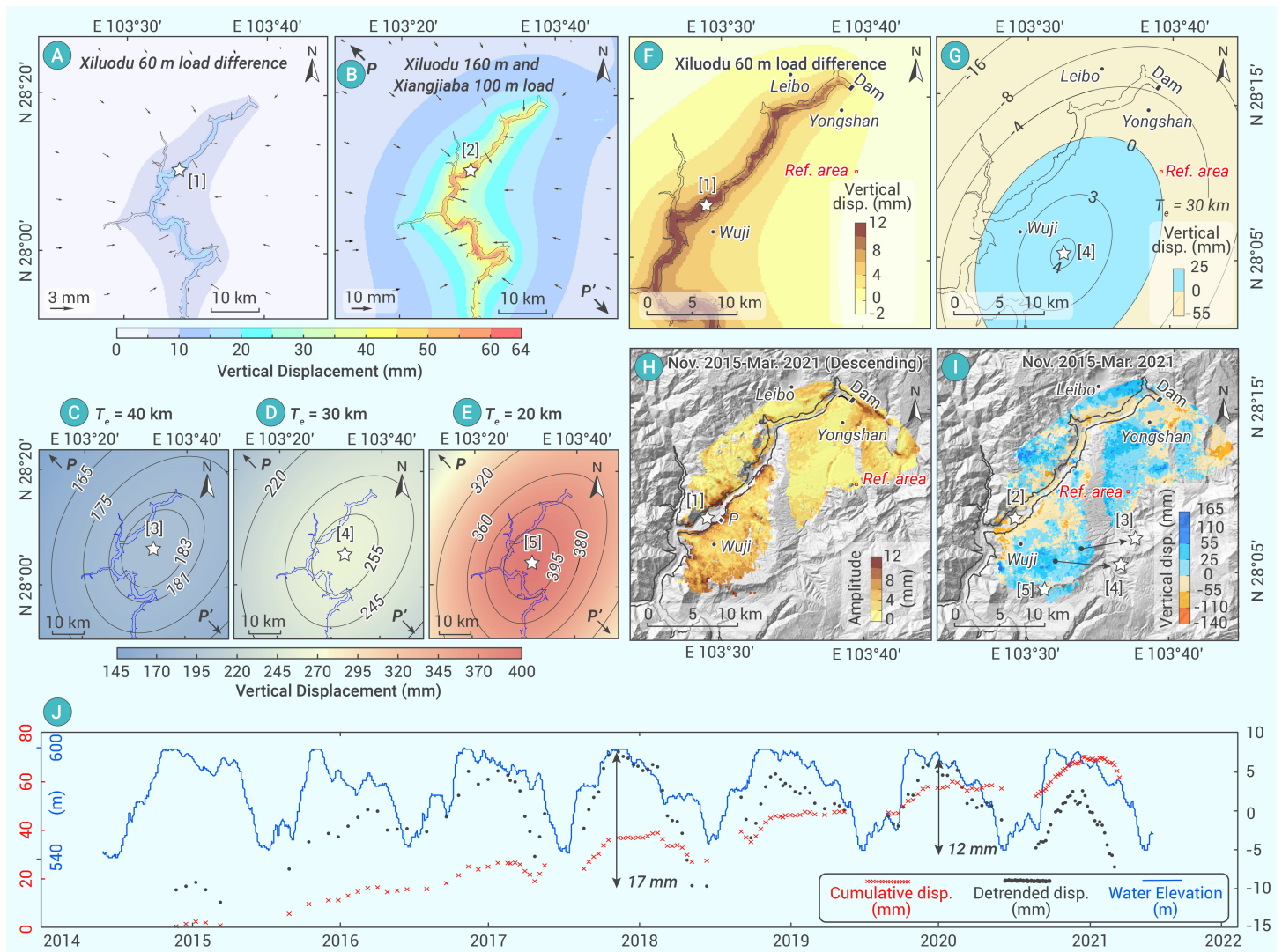


Figure 2. Modeled and observed crustal deformation in the Xiluodu area (A-B) Vertical (colored contours, positive for subsidence) and horizontal (arrows) displacements in elastic response to hydrologic load difference of the Xiluodu (60 m), and total loads of the Xiluodu (160 m) and Xiangjiaba (100 m), respectively, using a layered elastic Earth structure (Figure S1). Black lines mark the hydrologic load geometry and white stars numbered as 1-2 show locations of subsidence centers under these two different types of loads. (C-E) Modeled fully relaxed flexural isostatic deformation (positive for subsidence) with T_e of 40, 30, and 20 km, respectively. Blue lines mark the hydrologic load geometry and white stars numbered as 3-5 show locations of subsidence centers given different T_e . Black isolines and numbers show contours of calculated deflection and their corresponding values. (F-G) Results (positive for subsidence) of seasonal load model from Figure 2A (F) and the EPM model from Figure 2D (G), with the same dimension as panels (H-I). Black isolines and numbers show contours of calculated deflection and corresponding values. (H) Peak-to-peak amplitude ($2c_1$) of sinusoidal functions fitting the time-series deformation obtained from the InSAR descending track. The white star (number 1) marks position of the subsidence center in (A) and the red open box denotes the reference area relative to which the amplitudes are calculated. (I) InSAR time-series measurements of the cumulative vertical displacement (positive for subsidence). White stars numbered as 2-5 mark positions of subsidence centers in (B-E), respectively; and the red open box denotes the reference area relative to which the velocity field is shown. (J) The relationship between the time-series deformation (in line-of-sight direction) and water levels at point P in (H).

may only shift but not change the pattern or amplitudes of the seasonal deformation. Therefore, it has very little effect on what we care most about here, which is how the pattern of the deformation due to reservoir impoundment correlates with the short-term and evolving distribution of seismicity around the reservoir area.

Spatiotemporal patterns of seismicity around the Xiluodu Reservoir

Notable earthquakes in the Xiluodu area were rare before the initial impoundment. However, a significant increase in seismicity was recorded after the impoundment, including two magnitude 5+ earthquakes in 2014 (Figures 3-4). The earthquakes around the Xiluodu Reservoir show an obvious spatial distribution and are clustered near the LEM subsidence center of the rapid crustal response to water loading (Figure 4B; Movie S1). These events are convincingly attributed to the reservoir impoundment, and thus considered as likely reservoir-triggered earthquakes. A high-precision seismicity relocation analysis shows that of all magnitude 1.2-5.2 earthquakes (1266 events) within 30 km of the subsidence center during May 2013-Sept. 2021, approximately 81% (1023 events) were clustered within a 15-km radius

from the subsidence center of the LEM, including all magnitude 4+ events (Figure 5A). The remainder are mainly located around the dam or ~20-25 km to the southwest of the subsidence center (near the Ebian-Jinyang fault zone; Figure 4B). Moreover, almost all events near the subsidence center are shallower than 10 km (Figure 5A; Figure S13), which may be explained by the fact that, the topmost 10-15 km is most sensitive to loading (see results of the ΔCFS below), and therefore, the deformation concentrated there can trigger earthquakes.

An examination of the temporal evolution shows a high event rate at the beginning of the reservoir impoundment during Jun.-Jul. 2013 near the dam, followed by a clustered burst of seismicity (mainly near the subsidence center the LEM) during the first water level rise (540 to 600 m a.s.l.) during Apr.-Dec. 2014 (Figures 4B and 5B). Additional accelerations of seismicity occurred during the following five seasonal reservoir filling-drawdown cycles, i.e. May-Oct. 2015, May 2018, Oct. 2018-Jun. 2019, Jan.-May 2020, and Jan.-Mar. 2021 (Figure 5B). Note that the largest events (magnitude 4-5.2) occurred during these seasonal loading/unloading periods. This can be demonstrated more clearly in the month-of-the-year seismicity counts based

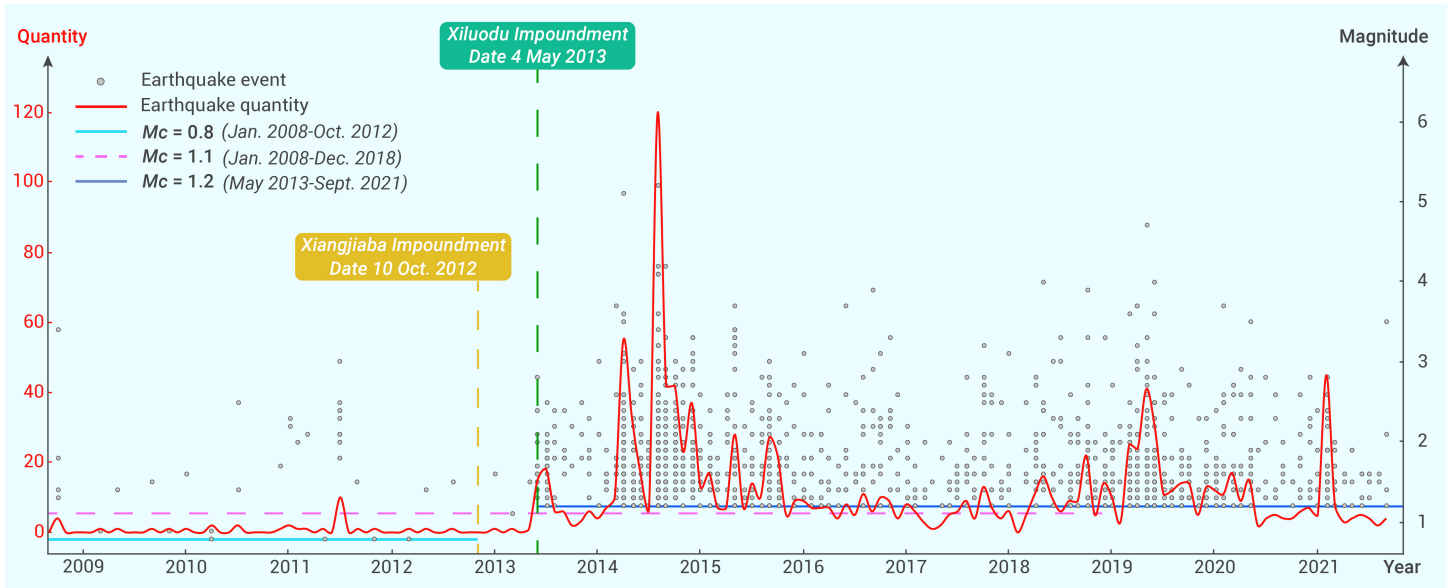


Figure 3. Comparison of earthquake number and magnitude before and after impoundment of the Xiluodu Reservoir All magnitude 1.2+ events (from a relocated and declustered catalog) were selected for analysis (see Methods and Figure S6 for calculation of the magnitude of completeness [M_c]). Red line represents the number of earthquake events per month. Dashed black and green lines show the impoundment date of the Xiangjiaba and Xiluodu Reservoirs, respectively. A significant increase in seismicity is evident at the time immediately after the reservoir impoundment. The area for statistics of the earthquake catalog is the same as the dimension of Figure 1B.

on the earthquake catalog spanning Oct. 2014–Sept. 2021 (period spanning seasonal water level cycles; Figure 5C). The abnormal high number of earthquakes in Aug. (184 events in total, 120 of which in 2014) corresponds to the period of rapid water loading when the water level first rose to the normal level (Jun. 2014–Oct. 2014; Table S2), and thus, we set aside events during this period. The results show a tendency for high seismicity in May (period of rapid water unloading) and Oct. (period with the highest (600 m a.s.l.) and relatively stable water levels; Figure 5C), and these earthquakes are concentrated around the subsidence center of the LEM (Figure S14A). The presence of two annual peaks in earthquake occurrence in May and Oct. is likely due to a combination of both elastic loading and pore pressure diffusion.^{31,32} However, the relatively small total number of events and remaining clustering effects in the data may challenge our ability to resolve seasonal modulation of earthquakes around the Xiluodu Reservoir.

Analysis of distribution of half-year-summed focal depths with low (Apr.–Sept.) and high (Oct.–Mar.) water levels since the reservoir impoundment show a decline in both seismicity frequency and focal depths during Mar. 2014 to Mar. 2017. Later on, this is followed by a general increase in seismicity frequency and focal depths (Figure 5D). The former (before Mar. 2017) may be caused by the elastic stress changes after impoundment, while the latter (after Mar. 2017) may also be influenced by an increasing degree of pore pressure diffusion. Events occurred during low water levels are mainly concentrated around the subsidence center of the LEM, while events occurred during high water levels are not only distributed near the subsidence center, but also around the Ebian–Jinyang fault zone (Figure S14B).

A further spatiotemporal analysis of the earthquake distribution shows that the location of peak event density in 2019 has migrated southeastward by ~10 km from that in 2013 (Figure 6B–C; Movie S2). This pattern is similar to the expected migration of the modeled subsidence center as the deformation transitions from the immediate and localized elastic response to the flexure following relaxation of the lower crust and upper mantle (Figure 6A). Note, that events that occurred in 2021 are mostly near the Ebian–Jinyang fault zone (Figure 4B), thus they are not considered in the analysis.

Coulomb stress changes around the Xiluodu Reservoir

To further test whether the reservoir loading/unloading may trigger seismicity, we resolve Coulomb failure stress changes (ΔCFS), considering the focal mechanisms of the M_s 5.2 earthquake²⁰ and geometries of the Ebian–Jinyang, Leibo and Lianfeng faults as receiver faults. For the latter, the rake angles are set to be 90° for thrust faulting (the Ebian–Jinyang fault) and 180° for right-lateral strike-slip faulting (the Leibo and Lianfeng faults). Our results

suggest that ΔCFS induced by the 160 m water loading of the Xiluodu Reservoir reaches up to 0.08 MPa, much higher than the threshold value of 0.01 MPa inferred for triggering earthquakes.^{33,34} Thus, such ΔCFS tends to promote the thrust-slip motion (positive ΔCFS ; Figure 7A–B; Figures S15–16). In comparison, ΔCFS induced by the seasonal 60 m water unloading of the Xiluodu Reservoir can promote both thrust-slip and strike-slip motions, with ΔCFS up to 0.07 and 0.1 MPa, respectively. (Figure 7C–D; Figures S17–18). The two largest earthquakes, M_s 5.1 (in Apr. 2014 with reverse faulting mechanism) and M_s 5.2 (in Aug. 2014 with strike-slip faulting mechanism) are triggered during rapid water unloading and loading, respectively (Table S2). Focal mechanisms of almost all magnitude 4.0+ triggered earthquakes are of strike-slip (Figure 5B),³⁵ and they all occurred during rapid water loading and unloading. The simulation results of ΔCFS are consistent with the pattern of seismicity.

DISCUSSION

The distribution and expansion of triggered seismicity in the Xiluodu area

Our results show that the deformation induced by hydrologic loading at the Xiluodu and Xiangjiaba Reservoirs can explain the overall spatiotemporal evolution of the seismicity around the Xiluodu Reservoir. Approximately 81% of earthquakes (including all magnitude 4+ events) are located within 15 km of the subsidence center of the instantaneous crustal response to water loading (Figure 5A). Furthermore, the distribution of earthquake clusters in the region display a temporal outward migration from near the subsidence center of the initial crustal response to water loading captured by the LEM, to that of the eventual flexural response represented by the EPM (except for a cluster of earthquakes located along the Ebian–Jinyang reverse fault system; Figure 6). While lacking a detailed temporal evolution of the deformation center migration, our study shows a clear correlation between the migration of these centers (caused by the post-loading viscous relaxation of the lower crust and upper mantle) and the outward expansion of triggered earthquakes. Low effective lower-crustal viscosities in the region estimated from postseismic deformation of the Wenchuan earthquake suggest that this time-dependent evolution of deformation and stress would indeed occur over the course of a few years.^{26,36} This nicely explains why earthquakes migrated temporally for a relatively long distance (>20 km) from the subsidence center to the Ebian–Jinyang fault (Figure 4B; Movie S2), which is difficult to be explained by pore pressure diffusion in this region.¹³

Taken together, we suggest that the hydrologic loading/unloading and associated flexural deformation play a significant role in controlling the

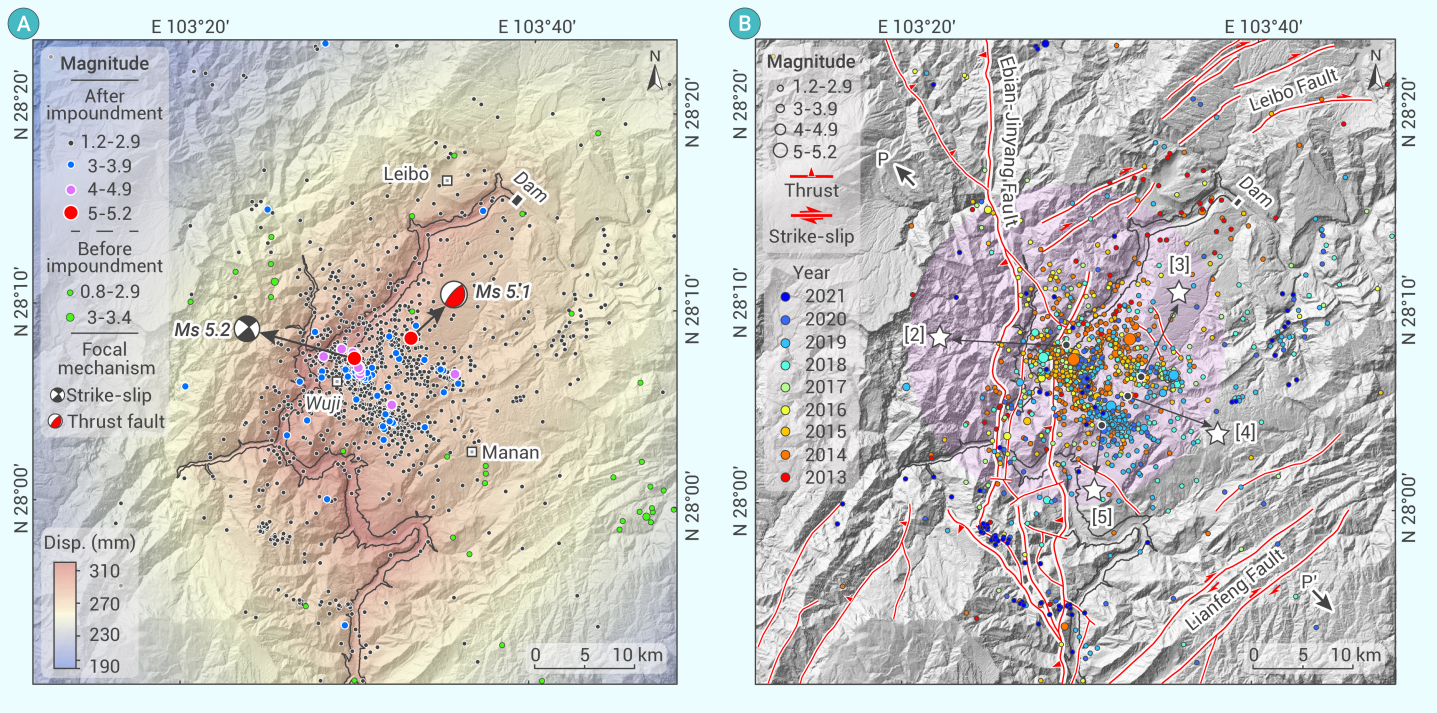


Figure 4. Spatiotemporal distribution of earthquakes in the Xiluodu area (A) The map shows correlation between the total deformation following flexural response ($T_e = 30$ km) and distribution of earthquakes. (B) Spatiotemporal evolution of the earthquakes since initial impoundment of the Xiluodu Reservoir. Solid blue circles show locations of the most recent events. White stars numbered as 2-4 mark positions of subsidence centers in Figure 2B-E, respectively. The circle shaded in magenta shows the area ~ 15 km in radial distance from the subsidence center of the LEM.

spatiotemporal distribution of earthquakes around the Xiluodu Reservoir. Thus, our results highlight that a more extensive region around the post-impoundment maximum deformation represents a zone of potential seismic hazard around large hydropower stations.

Correlation between elastic stress changes and triggered seismicity

Subsurface stress changes due to the initial elastic load and eventual flexural deformation, along with pore pressure changes and the existence of pre-existing structures (such as fractures, cracks, joints and faults within the reservoir area), collectively contribute to the subsidence center acting as a seismicity hotspot. The elastic stress changes associated with the initial elastic load and eventual flexural deformation can explain the overall distribution and expansion of seismicity. While additional triggering mechanisms, if exist, might affect the spatiotemporal distribution of the seismicity, these are not the primary focus of this study. For instance, the best-fit seismic triggering front to the earthquake events in the Xiluodu area (Figure S19) does not closely align with data that conform to 1D pressure-diffusion curves in typical cases.³⁷⁻³⁹ This suggests that pressure diffusion may not be predominant factor triggering earthquakes in the Xiluodu area. Therefore, we attempt to reveal the pattern of seismicity mainly from the perspective of elastic stress changes. Because earthquakes were rare in the area before the reservoir impoundment, we think that prior to reservoir impoundment, the regional stresses were likely near critical (Figure 8A) with relatively low deformation rates,²¹ as reflected in moderate background seismicity rates. However, upon the initiation of impoundment, the loading and subsequent flexural deformation increase the maximum (σ_1) and the minimum (σ_3) principal stresses (σ_1 and σ_3 are horizontal and vertical, respectively in contractional regimes), and led to a decrease in the differential stress ($\Delta\sigma = \sigma_1 - \sigma_3$). This is because the change of the vertical stresses caused by the water loading is more pronounced than that of the horizontal stresses in the uppermost crust caused by flexure of the lithosphere.^{40,41} The increase of σ_1 and σ_3 , and the decrease of $\Delta\sigma$ would lead to a rightward shift and reduced size of the Mohr circle (Figure 8B). In addition, the rapid water loading from the initial impoundment generates an instantaneous undrained response, which could increase pore pressures (P_1) and subsequently decrease the strength of the underlying rock.^{11,13,42} Further, the clay minerals in the strata will saturate and

could become soft/weak under continuous chemical effect of water. These processes result in a reduced friction coefficient (μ_1) and shear strength on the fault plane.^{12,43} Relevant studies show that friction coefficient for pure clays may be <0.2 under water action if the fractures were initially dry.^{44,45} This increased pore pressure (P_1) and decreased friction coefficient (μ_1) causes a clockwise rotation of the Mohr-Coulomb criterion line. The final result during reservoir filling is that the Mohr circle intersects the Mohr-Coulomb criterion line, and therefore result in additional earthquakes (Figures 5B & 8B).

The frequency of earthquakes during the drawdown phase increased after several filling/drawdown cycles (Figure 5B-C). During the drawdown phases (unloading), σ_1 and σ_3 decrease due to the reduction of gravitational loading and the isostatic rebound of the lithosphere. The vertical stress changes typically exceed the horizontal stresses, which results in a net increase of $\Delta\sigma$.^{40,41} In this case, the Mohr circle becomes larger and shifts to the left (Figure 8C). In addition, hydrologic unloading and the subsequent crustal relaxation could produce mass tensile fractures within the shallow surface (especially within 10 km of the subsidence center). These microcracks are notable regions for increased water infiltration and subsequent pore pressure diffusion (P_2).^{12,46} This diffusion of pore pressure (P_2) along with the decreased friction coefficient (μ_2) causes a further clockwise rotation of the Mohr-Coulomb criterion line. Similar to the filling scenario, the reservoir drawdown process also forces the Mohr circle and the Mohr-Coulomb criterion line to intersect, thereby leading to seismicity (Figures 5C & 8C).

The migration of subsidence centers of eventual flexural isostatic deformation, following the relaxation of the viscous lower crust and upper mantle, relative to those after the immediate and localized elastic response, likely contributes to the spatiotemporally outward migration of triggered earthquakes (Figure 8D). This significant magnitude of deformation may also result in an increase in focal depths over time (Figure 5D).

Numerous studies show that ΔCFS up to the order of 0.01 MPa can trigger seismicity on critically stressed faults.^{33,34} The results of modeled ΔCFS support the conclusion that the bursts of clustered earthquakes temporally relate to rapid hydrologic loading/unloading periods. However, note that ΔCFS around hypocenters of some earthquakes are <0.01 MPa (Figures S15-18), and these earthquakes cannot be explained solely by the ΔCFS induced

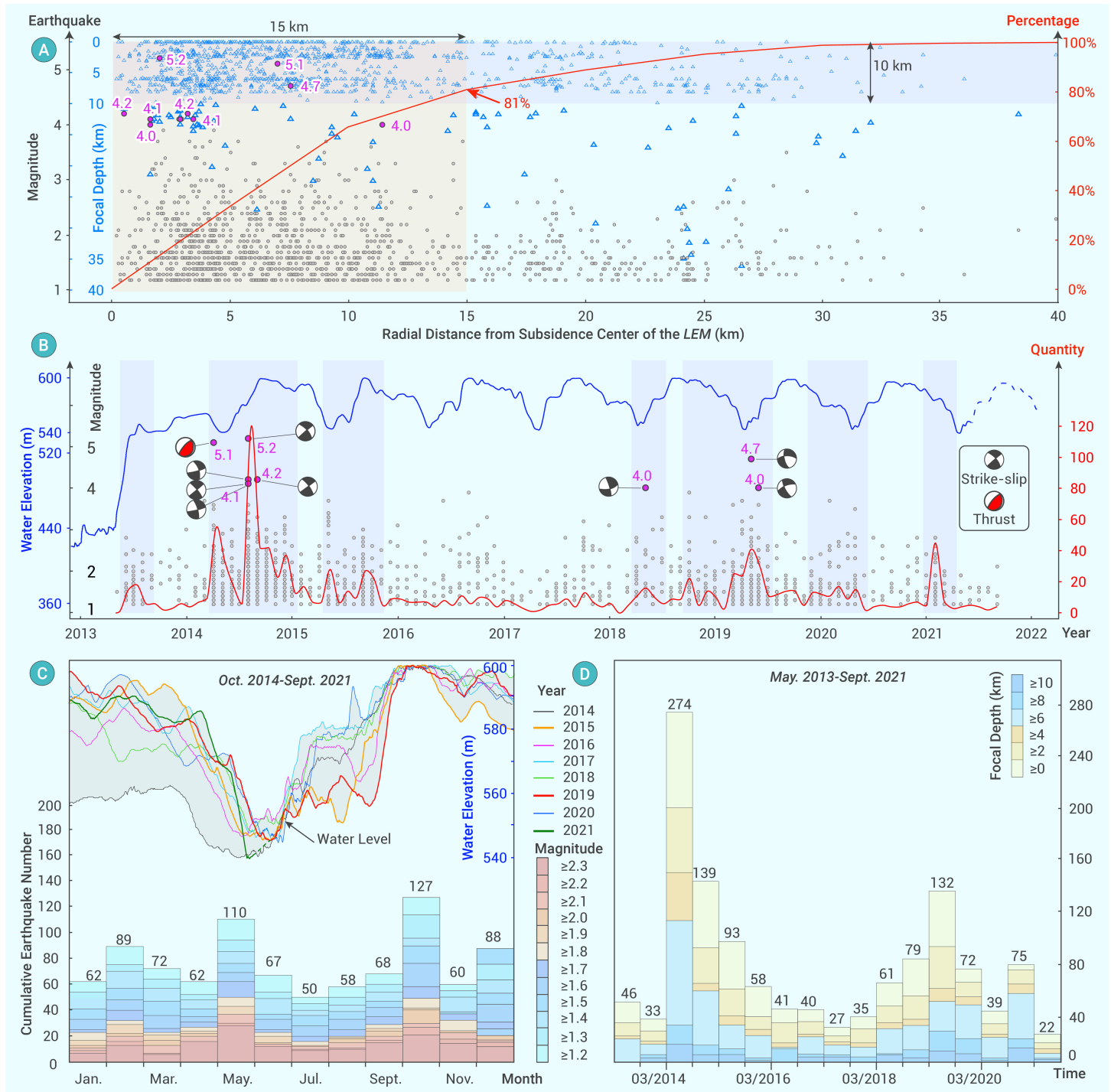


Figure 5. Spatiotemporal correlation between the impoundment of Xiluodu Reservoir and seismicity (A) Distribution of earthquake source parameters along the radial distance from the subsidence center of the LEM and the normalized (in % of the total) cumulative number of events. (B) Temporal evolution of earthquakes relative to the reservoir impoundment history. Periods with high earthquake frequency and magnitude that occur during rapid water filling and discharge are shaded in light blue, with focal mechanisms of almost all magnitude 4.0+ triggered earthquakes are of strike-slip. (C) Comparison between month-of-the-year seismicity frequency (during Oct. 2014–Sept. 2021) and water level variations in specific years (colored curves). Shaded colors show earthquake magnitudes and numbers above each column represent the cumulative earthquake number per month. (D) Distribution of focal depths during May 2013–Sept. 2021. Shaded colors show focal depths. Numbers above each column represent the cumulative earthquake number per half a year with low (Apr.–Sept.) and high (Oct.–Mar.) water levels.

by hydrologic loading.

Pore pressure diffusion complicates the mechanism of triggered seismicity

We acknowledge the complexity in mechanisms for triggering earthquakes around the Xiluodu area. In addition to elastic load stresses, other processes, such as pore pressure diffusion, may also contribute to the instability of nearby faults. In fact, when superimposing the effect of pore pressure diffusion, ΔCFS can be markedly increased, which is considered to be of nonneg-

ligible impact in triggered seismicity under critical stress state.¹³ The infiltration of water into pre-existing joints and fractures after the impoundment could increase pore pressures within fault zones, leading to weakened fault strength, increased seismicity frequency and focal depths (e.g., those after Mar. 2017, Figure 5C). Previous studies have attributed increased earthquake frequency to the strength reduction on the faults of the Koyana-Warna seismic zones, due to seasonal deformation induced by reservoir impoundment.¹⁶ In the Xiluodu area, our results show that 1) deformation peaks revealed by InSAR time-series data exhibit a half-cycle lagging effect with respect to

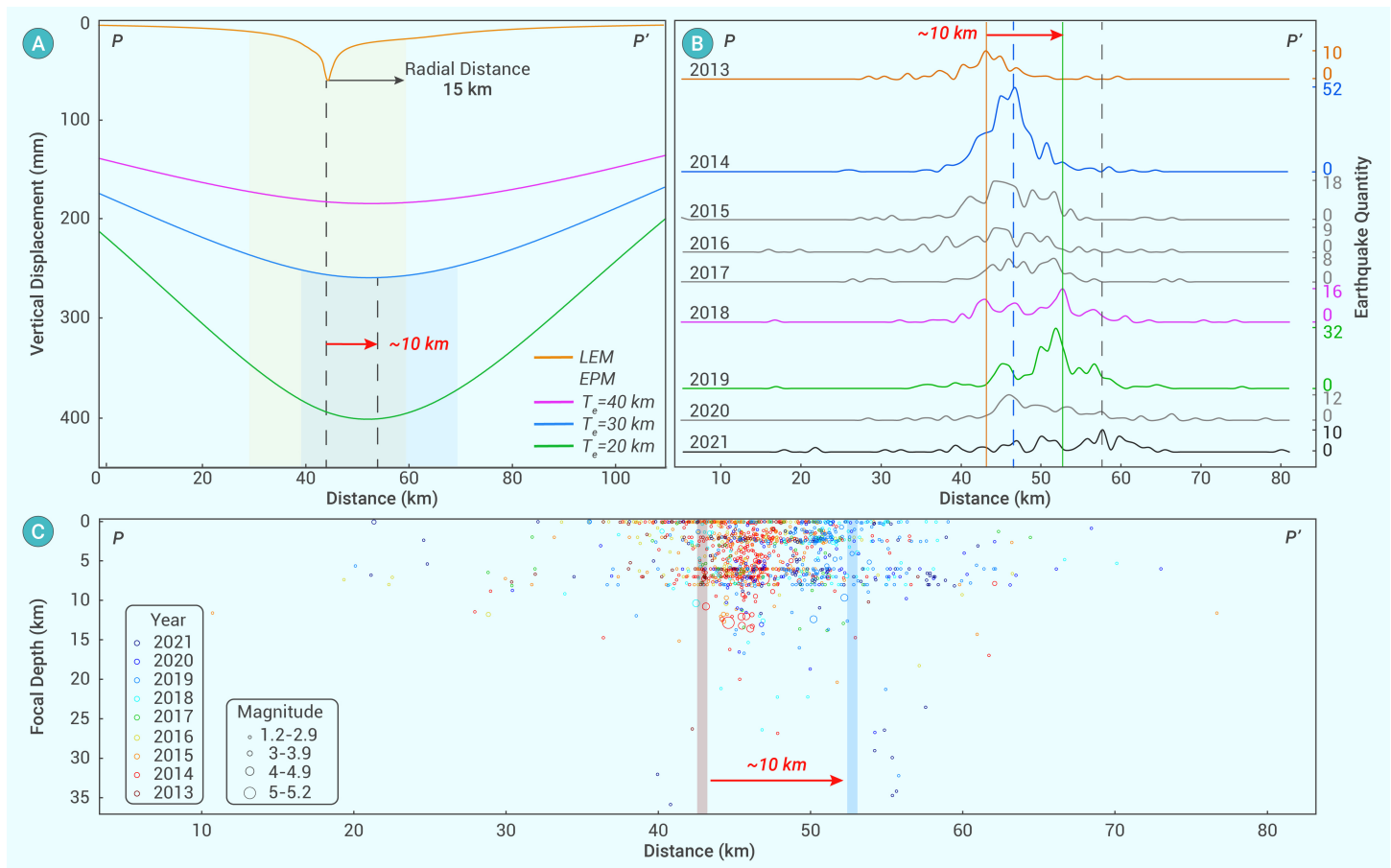


Figure 6. The migration of modeled subsidence centers calculated by the LEM and EPM models (A) and seismic clusters (B-C), inferred to be caused by the viscous relaxation effect. Red arrows and numbers indicate the migration direction and distance, respectively. See profile locations of (A) in Figure 2B-E and (B-C) in Figure 4B.

water levels (Figure 2J); 2) the peak of month-of-the-year seismicity occurred during the rapid water unloading and stable water levels (Figure 5C), indicating that despite efforts to rule out clustering effects and assurance of equal sampling of each year, the seasonal distribution is not very clear; and 3) a deepening of triggered seismicity is evident after Mar. 2017 (Figure 5D). Thus, elastic stress changes and additional effects from pore pressure diffusion^{31,32} and other processes may together contribute to the deformation and seismicity in this area. That said, the above analysis may explain why earthquakes occur at high rates during rapid reservoir filling and drawdown periods, and why a seismicity hotspot exists at the subsidence center.

Insights for seismic monitoring and construction of large reservoirs

Accurate and efficient monitoring and prediction of reservoir-triggered seismicity is crucial for the safe operation of hydroelectric facilities and the protection of surrounding residents' lives and properties. It has been a hotspot area of research since the discovery of artificial water reservoir-triggered earthquakes at Lake Mead in 1945,⁴⁷ due to its significance social and economic development. The occurrence of triggered earthquakes with magnitudes 6+ has been documented in four reservoirs after their impoundment, including Xinfengjiang, China (1962), Kariba, Zambia-Zimbabwe Border (1963), Kremasta, Greece (1966), and Koyna, India (1967).⁹ The varying effective lower-crustal viscosities in these large reservoirs emphasize the need for long-term observation of deformation and stress evolution. Evidence of both a linear elastic response to the hydrologic loading and a transition towards a relaxed, flexural response from the Xiluodu Reservoir area advances our understanding of complexity in mechanisms for triggering earthquakes. Further interdisciplinary research is necessary to uncover the spatiotemporal patterns of triggered seismicity, particularly for the world's largest cascade reservoir system, the Wudongde, Baihetan, Xiluodu, and Xiangjiaba Reservoirs, upstream of the Yangtze River (Figure 1A). This holds significant influence for the earthquake monitoring of operational reservoirs, and site selec-

tion of large reservoirs that are currently planned both in stable continental regions and tectonically active areas with low-viscosity lower crust.

CONCLUSION

Utilizing interdisciplinary methods involving numerical simulations of crustal deformation, InSAR time-series analysis, and earthquake relocation, we investigated the spatiotemporal patterns of seismicity around the Xiluodu Reservoir in China. The subsidence center induced by hydrologic loading appears to control the distribution of triggered earthquakes. This underscores the crucial necessity of monitoring seismicity within the extended deformation zone of large reservoirs, considering both immediate elastic-load and longer-term flexural deformation. Pre-existing faults, whether nearby or far away from the subsidence center, exhibit a likelihood of reactivation after several periods of rapid filling and drawdown. An illustrative example is the Ebian-Jinyang fault, where seismicity can be triggered under hydrologic loading, associated viscous relaxation, and pore pressure diffusion, particularly after a relatively prolonged period of water impoundment. These processes could potentially lead to triggering of large and hazardous earthquakes around large reservoirs. Thus, our findings also serve as a critical reference for guiding the construction of large reservoirs to mitigate potential seismic risks.

MATERIALS AND METHODS

We use a layered elastic model (LEM; Figure S1)⁴⁸⁻⁵⁰ to quantify the instantaneous crustal response to 1) the seasonal hydrologic loading (600-540 m a.s.l.) of the Xiluodu Reservoir (Figure S2) and 2) the total hydrologic load of the Xiluodu (600-440 m a.s.l.) and Xiangjiaba (380-280 m a.s.l.) Reservoirs (Figure S3) and examine the effects on the distribution of nearby seismicity. The elastic Earth structure is inferred from seismologic data (Figure S1).⁵¹ To calculate the eventual flexural isostatic deformation following the relaxation of the viscoelastic lower crust and upper mantle, we also consider elastic

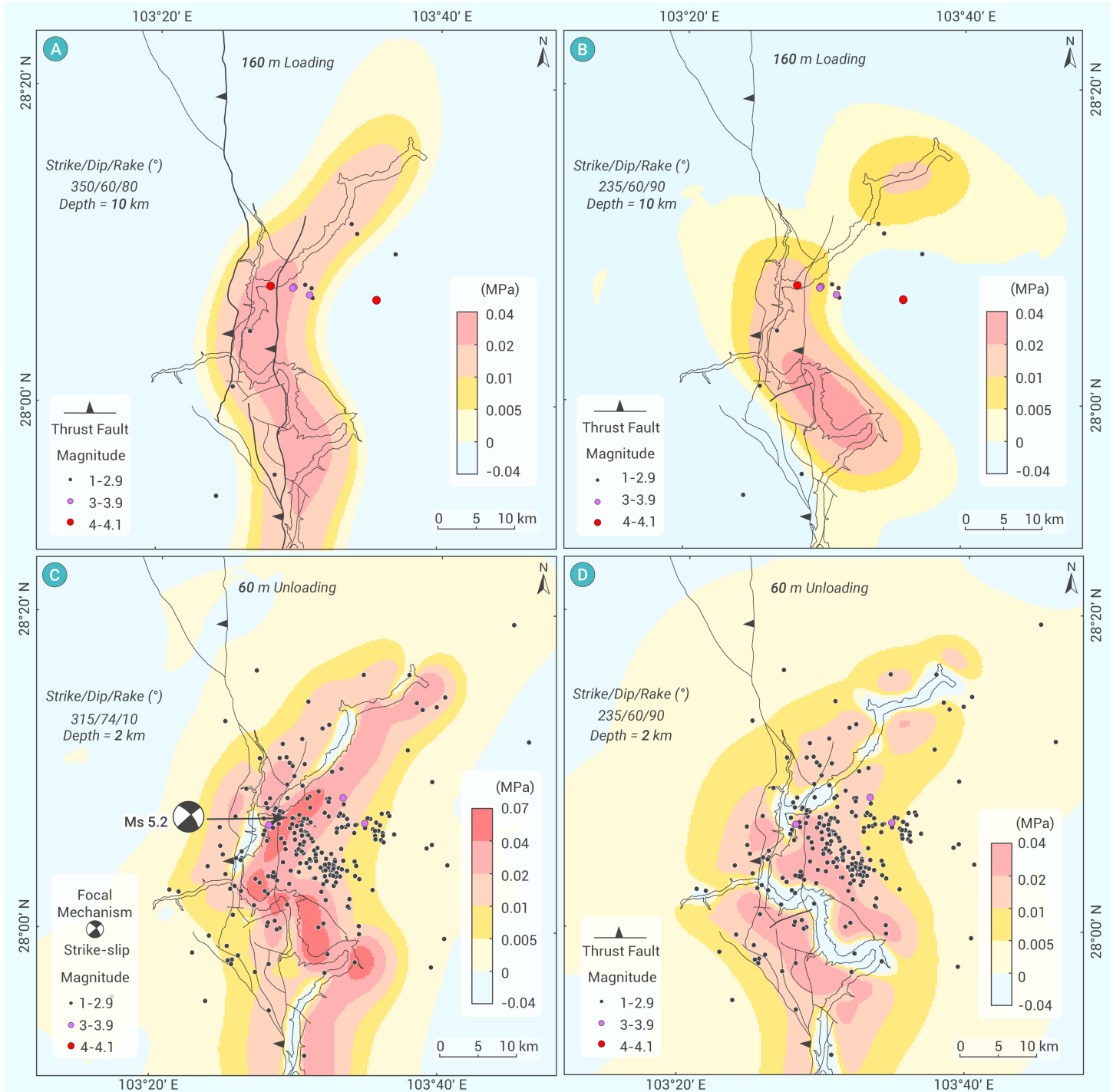


Figure 7. Spatial distribution of modeled Coulomb failure stress changes in the head area of the Xiluodu Reservoir (A-B) ΔCFS induced by the 160 m water loading at 10 km depth. The simulation refers to the receiver geometry of the Ebian-Jinyang fault. (C-D) ΔCFS induced by the 60 m water unloading at 2 km depth. The simulation refers to the E-dipping nodal plane of the M_s 5.2 earthquake (C) and geometry of the Ebian-Jinyang fault (D). The seismicity shown includes events that occurred within the considered depth range of ± 600 m (depth uncertainty in earthquake relocation) at 2 km and 10 km, respectively. See Figures S15–18 for more details.

plate models (EPM)⁵² and follow methods of Shi *et al.*^{53,54} to compute the pattern of deformation assuming different crustal effective plate thicknesses (T_e). The EPM allows us to analyze the deformation induced by the viscous relaxation component. Postseismic deformation studies of the nearby 2008 M_w 7.9 Wenchuan earthquake rupture inferred transient and steady-state lower-crustal viscosities of $\sim 5 \times 10^{17}$ Pa s and $\sim 5 \times 10^{18}$ Pa s, respectively, suggesting relaxation times on the order of a few years.²⁶ Thus, we expect that a significant portion of the relaxation in response to the impoundment of the two reservoirs should have occurred during the last decade. The total load deformation is the sum of the LEM and EPM models with full impoundment.

To measure the surface displacement caused by hydrologic loading around the Xiluodu Reservoir, we employ Interferometry Synthetic Aperture Radar (InSAR) time-series analysis, with 155 ascending and 171 descending Sentinel-1 SAR scenes (Figure S4), from Nov. 2015 to Mar. 2021. We process the SAR images on our burst-based Sentinel-1 processor,⁵⁵ and employ the LiCSBAS software for the time-series analysis.⁵⁶

For earthquake relocation, we apply a double-difference algorithm to the event arrival times⁵⁷ and adopt Hypo2000⁵⁸ to relocate the selected seismic events. We obtain 1302 earthquake events (Oct. 2008–Sept. 2021; Data S2) after declustering the seismicity (Figure S5)⁵⁹ and setting aside events below the magnitude of completeness (M_c ; Figure S6)^{60,61} within the Xiluodu area

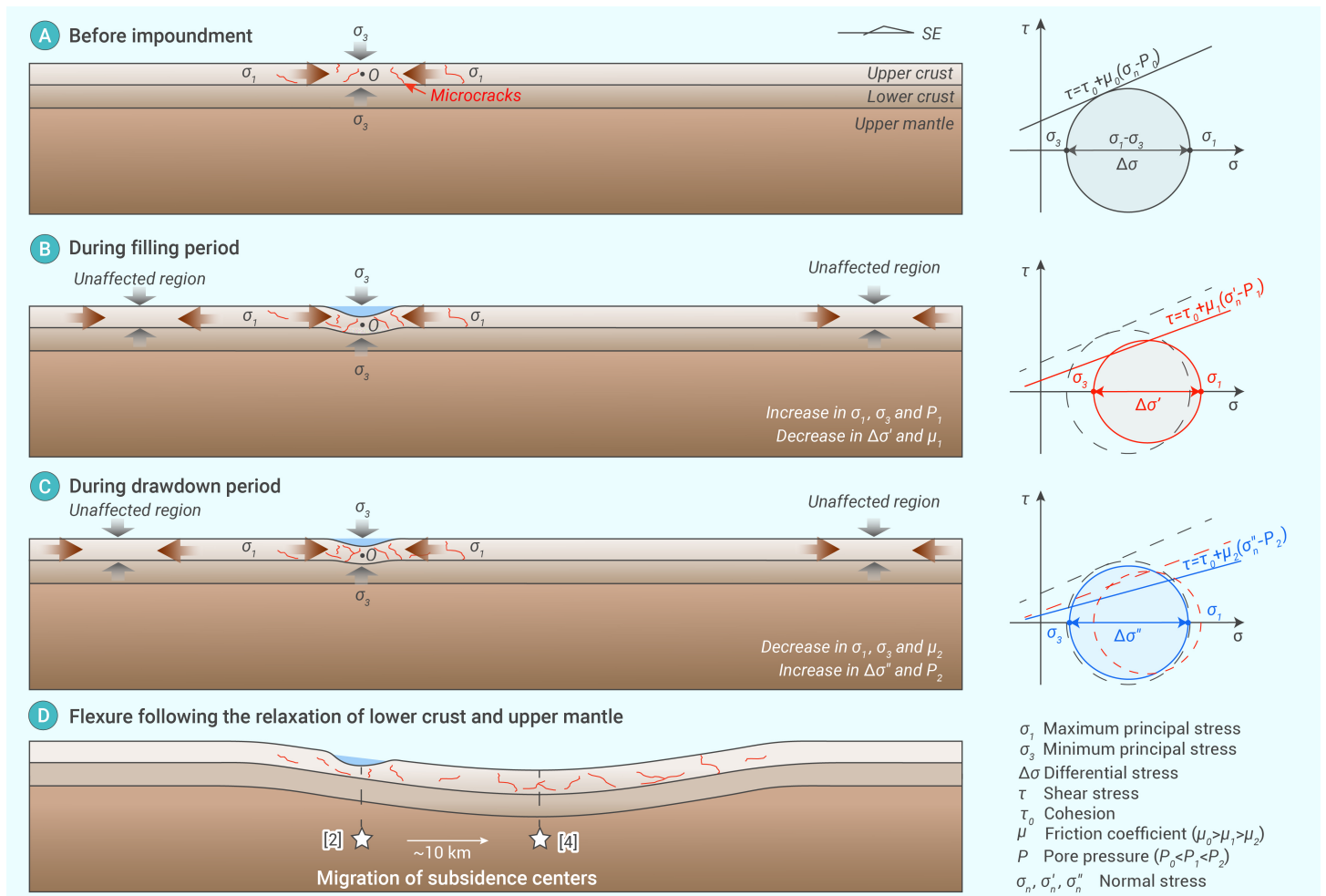


Figure 8. A simple schematic illustration and Mohr diagrams highlighting changes in the crustal stress field around the Xiluodu Reservoir, without considering the pore pressure diffusion effect (A) Regional stress were considered near critical with relatively low deformation rates before the impoundment. (B) Stress state during rapid water loading and crustal deformation in the Xiluodu area. This process leads to the increase of σ_1 , σ_3 (see parameter explanation below) and P_1 , and the decrease of $\Delta\sigma'$ and μ_1 , which make the Mohr circle intersect the Mohr-Coulomb criterion line, and therefore result in triggered earthquakes. (C) Stress state during rapid water unloading and rebound in the Xiluodu area. This process results in the decrease of σ_1 , σ_3 and μ_2 , and the increase of $\Delta\sigma''$ and P_2 , which leads to similar results as (B). Mohr circles are for stress at point O close to microcracks. Here we only discuss relative changes in each parameter before and after the impoundment in contractional regimes existing in the Xiluodu area. Figure 8A-C is modified partially after Zhang et al. (2018)¹² and Turpeinen et al. (2008).⁴¹ (D) Eventual flexural isostatic deformation following the relaxation of lower crust and upper mantle. White stars numbered as 2 and 4 mark positions of subsidence centers in Figure 2B and 2D, respectively. Red arrows and numbers indicate the migration direction and distance of subsidence centers, respectively.

(map area in Figure 1B) for further discussion.

Finally, we use the Boussinesq solution⁶² for an elastic half-space to explore the related Coulomb failure stress changes (ΔCFS) to reveal the influence of impoundment on earthquake triggering. This analysis is based on integration of the loading and unloading from the reservoir impoundment history and receiver fault geometry based on fault orientations and focal mechanisms of moderate earthquakes in this region (see Supplemental Information for detailed information about Methods).

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AUTHOR CONTRIBUTIONS

X.S., H.C., Y.S. and R.B. conceived the study. L.X. and W.X. completed the layered elastic and Coulomb failure stress changes simulation. X.S. and Y.S. ran the flexural isostatic

simulation. L.H. conducted the relocation analysis of the earthquakes. T.W. and Z.C. contributed to the InSAR time-series analysis. X.S., Y.S. and H.C. wrote the manuscript. All authors discussed, commented and edited the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

It can be found online at <https://doi.org/10.59717/j.xinn-geo.2024.100047>