Dear Topical Editor (se-2017-17),

We appreciate the time and effort you have spent in reviewing this manuscript. The comments and suggestions helped us improve the manuscript significantly. Our point-by-point replies to the comments are shown below. Some of the language comments and suggested revisions will be referred in the revised manuscript.

1. Editor's comment:

The paper is interesting, its structure is sound, but the grammar and wording are rather poor.

Concerning the content, I struggle to understand the purpose of the modeling. Since you have access to detailed GPS data, the measured velocity field (Fig.4) can be interpolated onto each fault plane to produce your fig.6 to fig.9. Why do you need to model the velocity field, why can't you use the GPS data?

If you are after fault properties, then these properties could be determined by minimizing the mismatch between the GPS data (Fig.4) and the modeled velocity field (Fig.5). But this would be a different paper.

Authors' reply:

First of all we need to correct a critical wording error in the title of the original manuscript. The modeled velocities in this paper refer to long-term velocities over several seismic cycles. We mistakenly used the word "present-day" in the title of the original manuscript and we have changed it to "contemporary".

The faults in this model are described by a pair of slidable contact surfaces. The mesh division of the contact surfaces is the same, so there are two nodes at any position of the fault, which belong to the two contact surfaces respectively. Driven by boundary conditions, the paired contact surfaces of each fault in the model undergo relative motion. According to the velocity of the fault nodes output by the model, the velocity difference of the paired nodes on the paired contact surfaces of the fault can be calculated one by one, so as to obtain the lateral slip rate of the fault. Take Fig. 6 as an example. Shown in the Fig.6 is the relative slip rate of the two contact surfaces of the fault, which cannot be obtained by GPS interpolation.

Moreover, the internal deformation of the blocks cannot be deducted by GPS interpolation to the fault plane, resulting in a high velocity on the fault plane. In addition, the small number of GPS stations may exacerbate the inaccuracy of the interpolation results.

It is also noted that we have used the services of a professional English editing company to improve the language of the manuscript. Hopefully, our fully revised version can meet the journal publication requirements.

2. Editor's comment:

Line2: Your title is not very informative. It states what you have been doing (numerical simulation of kinematics) but says nothing about the outcome of your work, which should be the focus of your title.

Authors' reply:

Thank you for this suggestion.

We changed the title to "Numerical Simulation of Contemporary Kinematics at the Northeastern Tibetan Plateau and its implications for seismic hazard assessment". It better reflects the work we have done and the corresponding outcomes.

3. Editor's comment:

Line 25–35: Odd sentence, rephrase; Vague, be more specific; Useless sentence…

Authors' reply:

Line 25-35 have been rephrased as follows:

The northeastern margin of the Tibetan Plateau (NETP) is the growth front of the Tibetan Plateau (TP). Modern geomorphology and tectonic features of the NETP are inferred to be formed due to the expansion of the TP toward its periphery, which has been ongoing since the Indian and Eurasian plates collided (P. Zhang et al., 2013, 2014). Having experienced the strong Cenozoic deformation, crust of this area develops a complex fault system with several large and deep faults, such as the generalized Haiyuan fault (F1), West Ordos fault (F2), West Qinling fault (F3), East Kunlun fault (F4), that divide the NETP into the Alxa, Ordos, Qilian, Qaidam, and Bayan Har blocks (Zhang et al., 2003; Fig.1). These faults are characterized by extremely intense tectonic movements and seismic activities (Zhang, 1999; Zheng et al., 2016b). At least 5 earthquakes with magnitudes of ≥ 8, such as the 1654 M8.0 Tianshui, 1739 M8.0 Pingluo, 1879 M8.0 Wudu, 1920 M8.0 Haiyuan, and 1927 M8.0 Gulang earthquakes, occurred in this area and caused huge loss of life and property in history (Fig. 1).

4. Editor's comment:

Line 38: "Accurate fault slip rates can calculate seismic cycles (Shen et al., 2009) and assess the seismogenic potential ... ". Fault slip rates, accurate or not, can't calculate anything. Please re-write.

Authors' reply:

We have rephrased the sentences as follows.

Since the generation and magnitude of an earthquake is closely related to fault activity, long-term fault slip rate plays a key role in medium- and long-term seismic hazard assessment (Ding et al., 1993; Xu et al., 2018). For example, combined with coseismic displacements, long-term fault slip rates can be used to calculate earthquake recurrence interval (Shen et al., 2009) and assess the magnitudes of potential earthquakes (Bai et al., 2018; Hergert and Heidbach, 2010).

5. Editor's comment:
All approaches have limitations and advantages. By combining several approaches, one can mitigate their respective limitation. What are the limitations and advantages of numerical simulations?
Authors' reply:
In this paper, one of the advantages of the numerical simulation is that we can obtain the 3D continuous slip rate of the faults. However, the modeled results strongly depend on the accuracy of the model input parameters. If we want to get reliable conclusions, we must set detailed parameters for the model, including model geometry, petrophysical properties, fault friction coefficient, initial crustal stress, and boundary conditions driving the model. Previous work on the NETP did not take these factors into account comprehensively, resulting in questionable results. The relevant text is in line 52–60 of the revised manuscript. The excerpt is as follows.

Numerical modeling provides a powerful tool to study the large-scale crustal kinematics (Hergert and Heidbach, 2010; Hergert et al., 2011) as well as the comprehensive 3D view of fault activities with spatially continuous distribution. High efficiency and accuracy have made the numerical modeling a widespread technology in the field of geosciences, especially for the study of kinematics and dynamics of the NETP (Pang et al., 2019a, b; Sun et al., 2018, 2019; Zhu et al., 2018; Xiao and He, 2015). However, all these previous numerical models are either two-dimensional (2D) or three-dimensional (3D) with extremely simplified fault planes. To our knowledge, so far there is no 3D geomechanical model that take into the complex 3D fault system in the NETP. Therefore, detailed kinematics of the crust and faults in the NETP still remains unclear.

6. Editor's comment:
Line 52: "as they provide a comprehensive view of current fault activities"
Not sure about this, can you please elaborate?
Authors' reply:
The results obtained by the geological method only represent the slip rate at one measurement point of the fault. Through numerical simulation, we can obtain the 3D motion state of any point of the entire fault plane from the model, as shown in Fig.6 to Fig.8. Line 52 have been rephrased as follows.

Numerical modeling provides a powerful tool to study the large-scale crustal kinematics (Hergert and Heidbach, 2010; Hergert et al., 2011) as well as the comprehensive 3D view of fault activities with spatially continuous distribution.

7. Editor's comment:
A proper Introduction should mention the main results.
Authors' reply:
Thanks for your suggestions. We have updated the last paragraph of Introduction as follows.

In this study, instead of a simple conceptual model, a comprehensive 3D geomechanical model of the NETP with detailed complex 3D fault geometries, heterogeneous rock properties and reasonable initial crustal stress is constructed. After calibrated by model-independent observations, the results of the geomechannical model, such as the horizontal crustal velocities, spatially continuous slip rates of major faults, are presented. Based on these results, we summarized the long-term crustal deformation characteristics in the NETP. Finally, we assessed the seismic hazards of major faults in the study area, and suggested that the Jinqiangshan–Maomaoshan fault has the potential for a M_S 7.1~7.3 earthquake in the coming decades.

8. Editor's comment:

Line 79: "30 arcseconds". Give an indication in meter.

Authors' reply:

Thanks for your suggestion. We have added an indication in meter as follows.

The topography of the model's surface is based on GTOPO30 elevation data, which has a resolution of 30 arcseconds (about 900m).

9. Editor's comment:

Line 83–84: "... they cut through the Moho and reach the bottom of the model ..." How do you know? Any references to support this claim?

Authors' reply:

We have updated the relevant text as follows.

Based on their depth, the faults of the model can be categorized into lithospheric and crustal faults. Lithospheric faults (i.e., F1, F2, F3, and F4) cut through the Moho and reach the bottom of the model (Zhan et al., 2005; B. Liu et al., 2017; Zhao et al., 2015; Fig. 2a, b; Table 1). All other faults are crustal faults that terminate in the upper, middle, or lower crust (Yuan et al., 2002b, 2003; Lease et al., 2012; Meng et al., 2012; B. Liu et al., 2017; Wu et al., 2020).

10. Editor's comment:

Line 125: "The frictional relations of the fault surface are critically important for the kinematics of a fault." What do you mean by "frictional relations"?

Authors' reply:

We have rephrased the sentence as follows.

The friction coefficient of the fault surface is important for the kinematics of a fault.

11. Editor's comment:
Line 142: "which predicts that all deformations due to gravitational loading occur in the vertical direction and that no expansion or contraction occurs in the lateral direction." Does this means that there is no horizontal gravitational forces due to lateral variation of gravitational potential energy?

"Loading" suggests "stress", but "expansion" and "contraction" suggest strain. This is a bit confusing. Can you rephrase this by saying that vertical stress, leads to horizontal stress via the Poisson's ratio...

Authors' reply:
Yes, you are quite right form a global perspective of the model. However, in the local part of the model, there will be a horizontal gravitational force caused by the lateral variation of gravitational potential energy, so that the material is force-balanced.

The sentence has been phrased as follows.

The initial stress state that is most commonly employed in previous numerical modeling studies of the NETP is the uniaxial strain reference state (Zhu et al., 2016), which based on the boundary condition that no elongation occurs in the horizontal direction, and the strain only occurs in the vertical direction.

12. Editor's comment:
Line 149: "Furthermore, k-values obtained globally from in situ measurements always greatly exceed 1/3 (Hergert and Heidbach, 2011)."
Shouldn't it exceed 1? i.e. horizontal stress > vertical stress?
Authors' reply:
Global stress magnitude measurements show that the horizontal stress is generally greater than the vertical stress in the shallow crust, but this is not the case for all measured data, as shown in the Fig. R1. Therefore, "always greatly exceed 1/3" might be a more reasonable description.

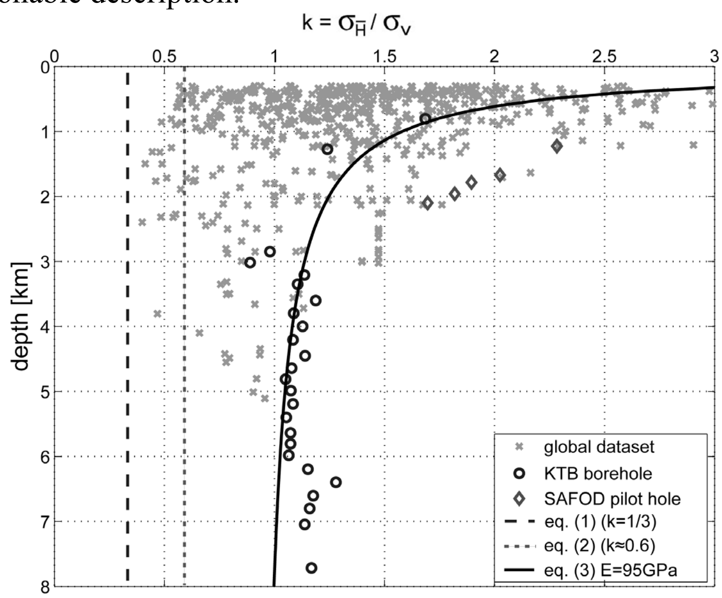

Figure R1. Global compilation of stress magnitude measurements (Hergert and Heidbach, 2011).

13. Editor’s comment:

Line 165: “it was assumed that the lateral velocities of the 3D model do not vary with depth”. Why is this a reasonable assumption? and what would be the consequences if velocity were depth-dependent?

Authors’ reply:

The observed vertically coherent deformation imply that the crust and lithospheric mantle are mechanically coupled (Wang et al., 2008). Thus it was assumed that the lateral velocities of the 3D model do not vary with depth. This assumption is also widely used in previous numerical simulation studies (Xiao and He, 2015; Li, Hergert et al., 2021; Sun and Luo, 2018).

14. Editor’s comment:

Figure 4: Please add faults' id. The integration of the velocity field along the boundary should give the amount of material entering (overall thickenning) or leaving (overall thinning) the cartesian model.

Authors’ reply:

The boundary condition we impose on the model is displacement, and the total amount of material in the model is constant. Therefore, there is no need to emphasize the material entering or leaving. The faults’ id of Fig. 4 has been added as follows.

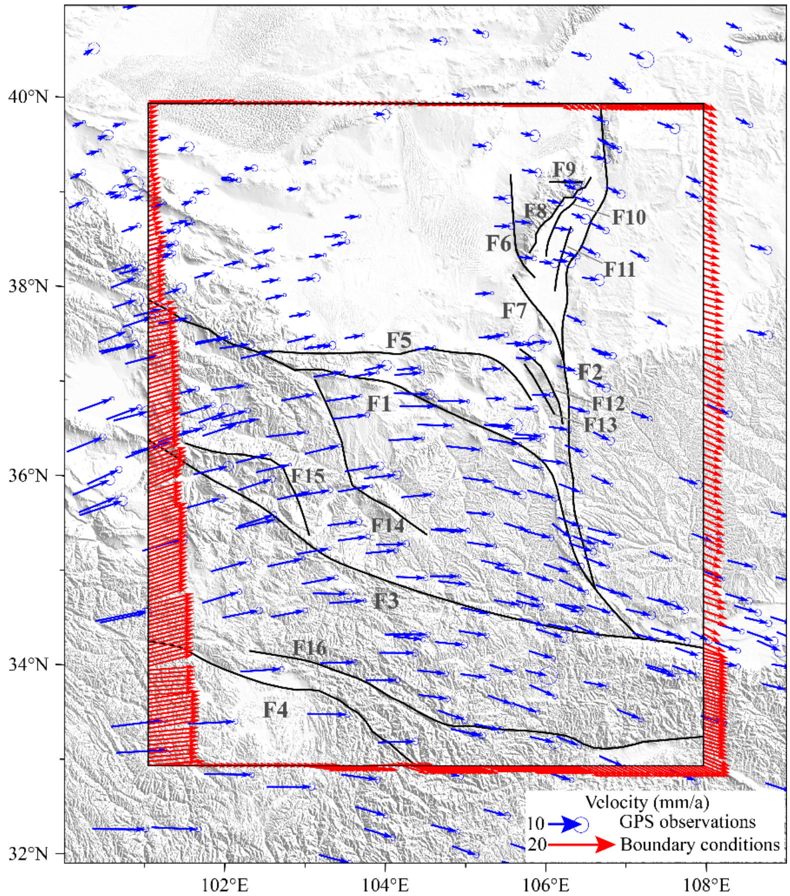

Figure 4 The faults’ id has been added.

15. Editor’s comment:
Line 180: “indicating that their internal deformation is low”. I don't understand the logic of this statement. The velocity high or low says nothing about internal strain (i.e., a rigid block could move very fast without internal deformation). Gradients of velocity in the other hand indicates internal strain.
Authors’ reply:

Thanks for your comment. The statement is indeed incorrect. We have removed the sentence in the revised manuscript.

16. Editor’s comment:
Figure 5: Can you plot the mismatch between figure 4 (observed velocity) and figure 5 (calculated velocity)?
Authors’ reply:

Thanks for your suggestion. Actually, the comparison between observed velocity and calculated velocity has been plotted in Fig. 12 of the original manuscript.

17. Editor’s comment:
Figure6: Only panel a/ is useful.
Authors’ reply:

We believe that these subgraphs can reflect the motion state of the fault more concretely.

Although subgraphs of (b), (c) and (d) can be considered subsets of subgraph (a), the specific information contained in them may also be of interest to some readers.

18. Editor's comment:

Line 206–208: "Can you please locate these earthquakes on Figure 4?"

Authors' reply:

Thanks for your suggestion.

Figure 4 integrates less information and is only used to show the boundary conditions of the model. We have labeled strong earthquakes with magnitudes M ≥ 8.0 in Figure 1 as follows.

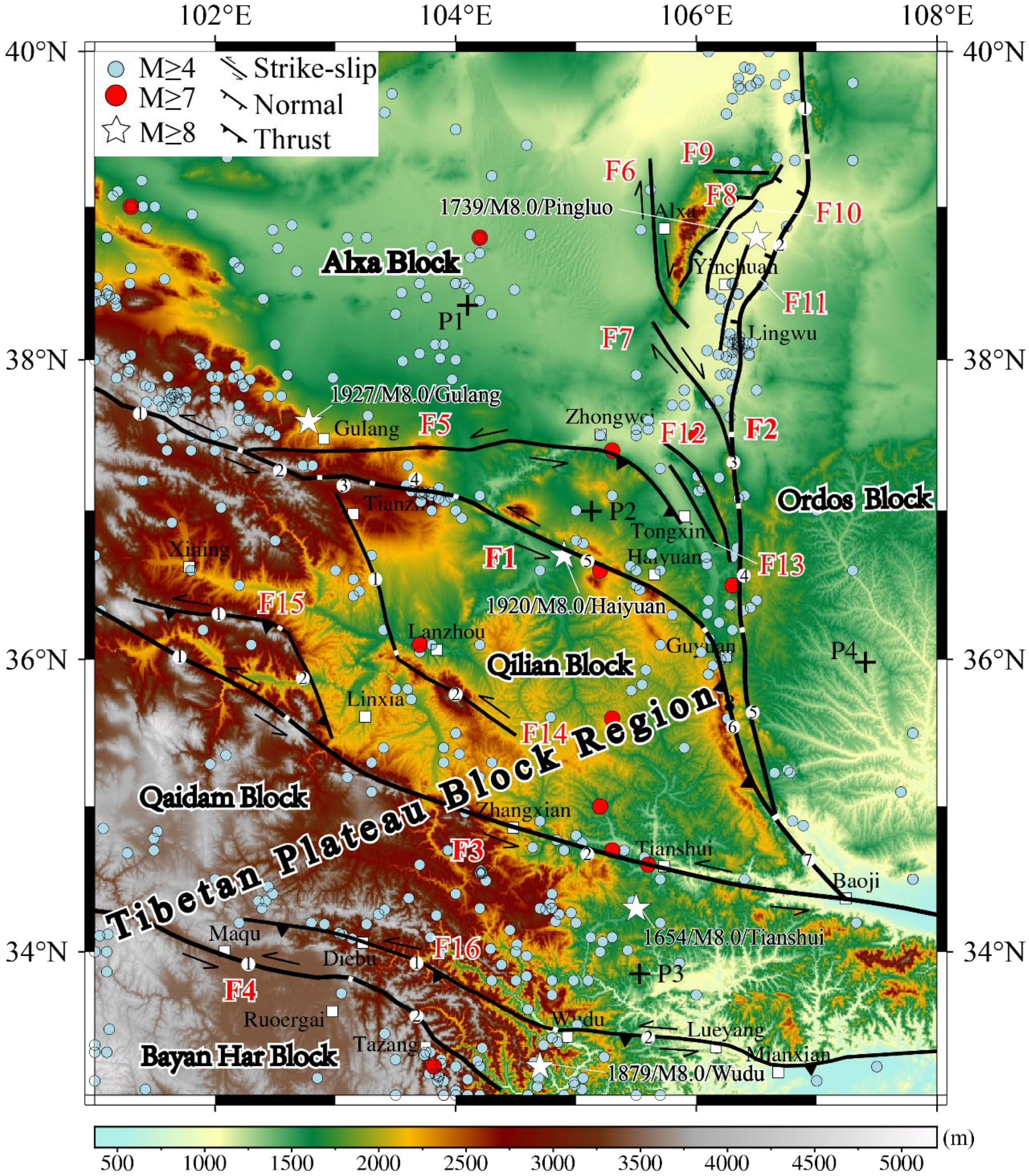

Figure 1. Earthquakes with magnitude M≥ 8.0 are labeled.

19. Editor's comment:

Line 219, Line221: "Liupanshan faults have the rake ranging from 10° to 20°"

A fault plane has no rake. A striae on a fault plane has a rake (rake = 90 - the striae pitch). It looks like your rake is in fact the pitch.

Authors' reply:

As we replied in the comment 1, the faults in this model are described by a pair of slidable contact surfaces. Driven by boundary conditions, the paired contact surfaces of each fault in the model undergo relative motion. The slip rakes in line 219 and 221 mean the slip directions on the surfaces. We used GeoStress to calculate it (Stromeyer et al., 2020).

20. Editor's comment:

Figure 10: Can you compare and contrast with the observed slip rates and slip senses?

Authors' reply:

We believe that there has been a misunderstanding about the slip rates in Fig. 10.

Plotted in Fig.10 are the long-term slip rates of the faults over several seismic cycles which are totally different from the GPS observations obtained during the interseismic periods. There is no comparability between them.

21. Editor's comment:

Line 270: "Given the zero vertical velocity imposed at the base of the model, is the calculated vertical velocity field of any significance?"

Authors' reply:

The modeled vertical motion at the surface is hardly affected by the motion state of the bottom of the model. On the contrary, it is generated by the horizontal motion on a complex model that includes factors such as fault geometry, topography, crustal interfaces, etc.

Actually, there is a high consistency between the modeled vertical velocities at the surface and the basin subsidence rates obtained by geological means (Wang et al., 2011; Ma et al., 20221).

22. Editor's comment:

Figure 13: Can you do the same thing but along the faults planes? So you can compare observed and calculaled velocity on faults?

Authors' reply:

Thank you for bringing this to our attention.

However, the slip rate of a fault is obtained by calculating the relative motion of the paired contact surfaces. It is different from the GPS observations interpolated to the fault plane. Therefore, there is no comparability between them.

23. Editor's comment:

Table 3: Can you please explain the purpose of the modeling? It looks to me that the GPS data is sufficient to extrapolate the velocity field from which the velocity field on each fault can be determined. One could simply use the velocity field to constraint faults properties via a mismatch minimization procedure.

Authors' reply:

Please see the reply to the comment 1.

24. Editor's comment:

Line 298: "we selected a SW–NE profile that covers the study area (Figure 12, C–C') and projected all GPS-observed values within 50 km onto the profile".
Please do this on faults and compare with 6, 7 and 8.

Authors' reply:

As we reply to comment 22, the slip rate of a fault is obtained by calculating the relative motion of the paired contact surfaces. It is different from the GPS observations interpolated to the fault plane. Therefore, there is no comparability between them.

25. Editor's comment:

Line 307: The slip rates (2.6–3.0 mm/a) simulated for the F2-2 Luoshan Fault are similar to the measured slip rate (2.2 mm/a) and the slip rates simulated for the West Qinling Fault in the Zhangxian and Tianshui region (2.4–3.0 mm/a, Figure 10) are consistent with the slip rates obtained using geological methods (2.5–2.9 mm/a; Chen et al., 2019).
Can you quantify this a bit better. "Similar" is a bit vague.

Authors' reply:

The sentence has been rephrased as follows.

The modeled slip rates on the F2-3 Luoshan Fault (2.6–3.0 mm/a) are in line with the geological slip rate (2.2 mm/a). A good agreement between these two kinds of slip rates also exists on the West Qinling Fault in the Zhangxian and Tianshui region (Table 3).

26. Editor's comment:

Line 312: "The M8.0 Gulang earthquake occurred in 1927 in the northwestern part of the F1 fault, whereas the M8.0 Haiyuan earthquake occurred in 1920 on the Haiyuan Fault". Can you show these earthquakes on a figure?

Authors' reply:

We have labeled these earthquakes in Fig. 1 of the revised manuscript, as shown in reply to comment 18.

27. Editor's comment:

Line 317-321: "Based on the slip rates and other fault data, we estimated the earthquake magnitude based on the energy accumulated during elapsed time (Purcaru et al., 1978) and recurrence intervals (Shen et al., 2009), as shown in Table 4. The Jinqianghe, Maomaoshan, and Laohushan faults can generate M_S6.9, M_S7.2, and M_S6.8 earthquakes, with recurrence intervals of 320 707, 890, and 1132 years, respectively."

This seems an important result, can you detail the procedure?

Authors' reply:

We have updated the calculation according to the RC1's comment. The updated results are shown as follows.

Table 4. Earthquake magnitude and recurrence interval of each fault based on the energy accumulated during the elapsed time since the last remarkable earthquake

Fault name	V_1(mm/a)	V_2(mm/a)	L_1 (km)	L_2 (km)	μ (Gpa)	t	S (m)	M_S	T (a)
JQHF	3.5	/	34	20	34.5	675	1.5	7.1	424
MMSF	3.9	/	51	20	34.5	952	2.2	7.3	571
LHSF	4.1	2.5	70	20	34.5	133	3.1	6.6	1910
MSLPSF, SSLPSF	2.5	/	80	23	34.5	570	3.5	7.2	1397
GG-BJF	0.7	/	70	23	34.5	1400	3.1	7.1	4365

V_1 is the modeled average slip rate of the fault in this study; V_2 is the aseismic creep rate of the fault (Y. Li, et al., 2021); L_1 is the length of the fault (Xu et al., 2016); L_2 is the depth of the seismogenic, which refers to the locking depth(Y. Li, et al., 2017, 2021); μ is the shear modulus of the rocks (Aki et al., 2002); t is the time that has elapsed since the most recent remarkable earthquake (Gan et al., 2002; Shi et al., 2013, 2014; Wang et al., 2001); S is the largest maximum coseismic displacement, calculated using the method of Gan et al. (2002); M_S is the earthquake magnitude corresponding to the energy accumulated by the fault between recurrences (Purcaru et al., 1978); T is the recurrence interval of the earthquake, where T = S/(V_1-V_2) (Shen et al., 2009). The fault names are defined in Fig. 1 and Fig. 14.

The magnitude of the earthquake (M_S) corresponding to the energy accumulated during the elapsed time can be estimated by the following formula (Purcaru et al., 1978):

$$M_0 = \mu AD$$

$$\log M_0 = 1.5M_s + 9.1$$

where M_0 is the seismic moment (N.m), μ is the shear modulus of the rock, and A is the rupture area of the fault (A = L_1 * L_2), D is the average displacement of fault during the elapsed time (D = (V_1 – V_2) * t). S is calculated by empirical formula in the TP ($lgS = -1.36 + lgL1$; Gan et al., 2002). T is the recurrence interval of the fault, where T = S/(V_1-V_2) (Shen et al., 2009).

28. Editor's comment:

Figure 14: There figures are confusing, please add an arrow to clearly show the north direction.

Authors' reply:

Thanks for your suggestion, we have updated the figures as follows.

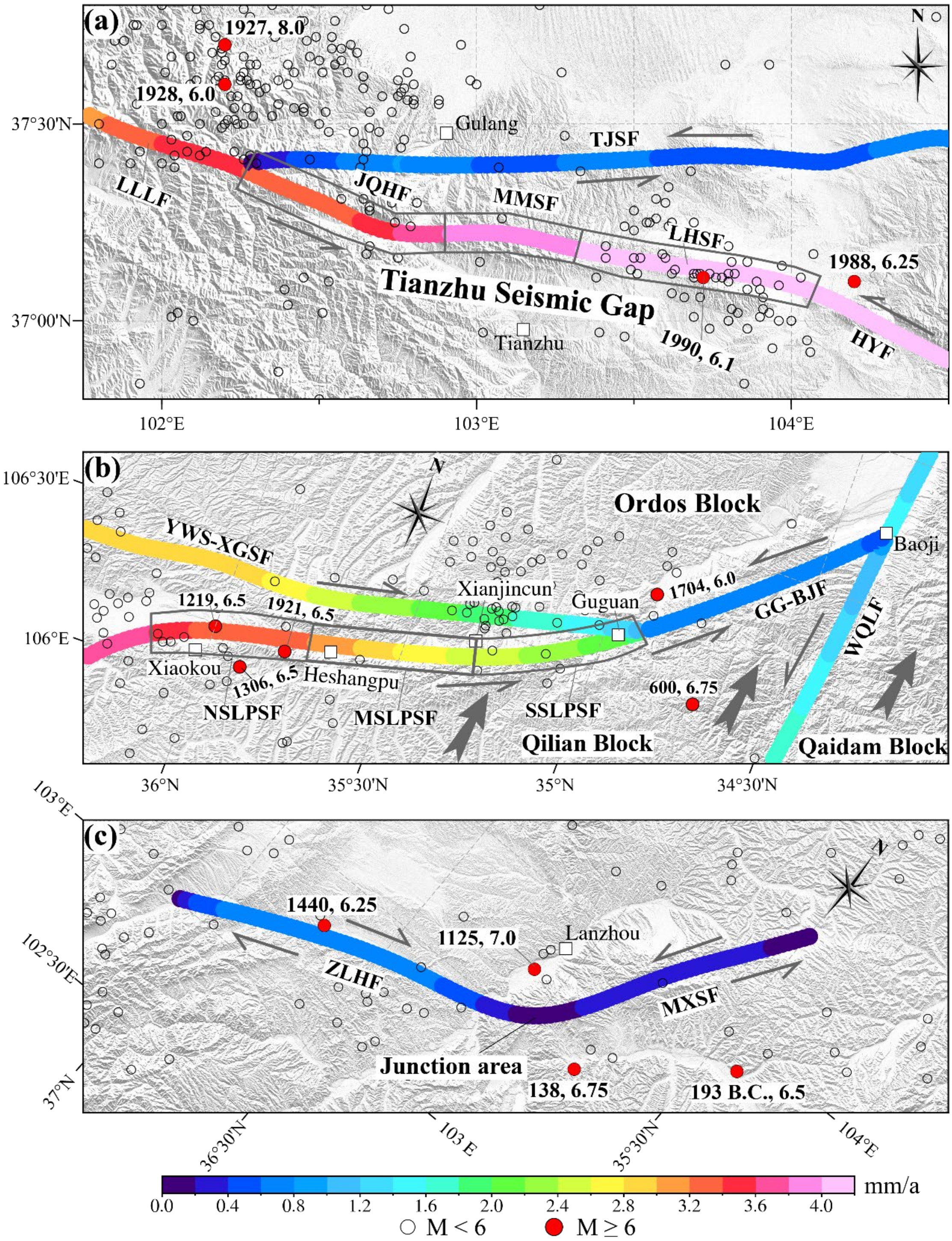

Figure14 Arrows were added to show the north direction.

29. Editor’s comment:
Line 340: “by three sources of tectonic stress”.
Very poor working. There are three interacting blocks, separated by fault zones, each with contrasting velocity fields.
Authors’ reply:
We have rephrased the sentence as follows.

The Liupanshan and Guguan–Baoji faults are jointly affected by three interacting blocks with contrasting velocity fields (Fig. 14b)

30. Editor’s comment:
Line 344-345: “Third, our simulations show that the Yunwushan–Xiaoguanshan Fault has a significant right-lateral strike-slip component”.
I am pretty sure that this can be seen in the field. Why rely on numerical modeling, when field geology can provide observables?
Authors’ reply:
The continuous slip rates of the fault can be obtained by numerical simulation, which is almost impossible in field work. Actually, few literatures are devoted to the study of the Yunwushan-Xiaoguanshan fault, whether through field work or other means.

31. Editor’s comment:
Line 364: “we estimated that the energy accumulated…”
How was this estimation made? Or is it just a speculation?
Authors’ reply:
Please see the reply to the comment 27.

32. Editor’s comment:
Line 366: “Because the next event is not likely to occur for a long time, the…”
This is a rather bold statement to make. What if a Ms7 earthquake happens in the next few years? Could the authors' responsibility be engaged, and could they be liable?
Authors’ reply:
Thanks for your suggestion. We have rephrased the sentences as follows.

Therefore, we infer that the middle-southern Liupanshan fault and the Guguan-Baoji fault are most likely in a state of stress accumulation, and the likelihood of a large earthquake on these fault segments in the next few decades is thought to be low.

32. Editor’s comment:
Line 377: “the left-lateral strike-slip motions of the Maxianshan Fault may not be as intense as previously thought”.
What does "intense motion" mean?
Authors’ reply:
We have rephrased the sentence as follows.

the left-lateral strike-slip rates of the Maxianshan Fault may not be as large as previously thought.

33. Editor's comment:

Line 395: "This implies that the deformations of the TP should display "aggregated" 395 characteristics."

Not sure what this means "aggregated characteristics"? Can you please rephrase?

Authors' reply:

Based on the comments of the RC1, we have rewritten Section 4.3. This sentence has been removed in the revised manuscript.

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