Tectonophysics 862 (2023) 229935

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Tectonophysfics

journal homepage: www.elsevier.com/locate/tecto

Moment budget and sefismfic potentfiafl of the Xfianshufihe-Xfiaojfiang faufllt system, southeastern Tfibetan Pflateau

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ARTICLE INFO

Keywords:
Moment baflance
Geodetfic measurement
Sefismfic cataflogs
Sefismfic hazards
The Xfianshufihe-Xfiaojfiang faufllt system

ABSTRACT

The Xfianshufihe-Xfiaojfiang faufllt system (XXFS) fis an fimportant boundary faufllt fin the modefl of tectonfic extrusfion fin the southeastern Tfibetan Pflateau. It fis afso sefismficafflfly actfive, havfing produced seven M ≥ 7.5 earthquakes sfince 1480 CE. We compfifled an fintegrated earthquake cataflog to estfimate sefismfic moment reflease rates aflong the XXFS sfince 1480 CE, and compared them wfith moment accumuflatfion estfimated from the updated GPS data. Our resuflts show moment defficfits of ~2.49 × 10^{20} Nm for the northern (the Xfianshufihe faufllt) and ~ 1.28 × 10^{20} Nm for the centrafl (the Anfinghe-Zemuhe-Dafflfiangshan faufllt) parts of the XXFS, equfivafflent to the moment reflease of M 7.5$_W$ and Mw 7.4 events, respectfivefly. The southern part (the Xfiaojfiang faufllt), on the other hand, has a moment surpflus, suggestfing a reflatfivefly flow sefismfic potentfiafl. Anaflysfis of moment budget on segments of the faufllt system findficates sfix sectfions of moment defficfits aflong the XXFS, fincfludfing the Luhuo segment, the Qannfing-Kangdfing segment, the Moxfi-Annfinghe segment, the sectfion connectfing the Annfinghe and Zemuhe faufllts, the northern Zemuhe segment and the connectfing sectfion between the Zemuhe and Xfiaojfiang faufllts. Each sectfion of moment defficfits coufld afflflow an M_W ~ 6.5 event, whereas the Qfiannfing-Kangdfing segment has the potentfiafl for an M$_W$ ~ 7.4 event. The Annfinghe segment, where no M ≥ 6.5 event has occurred sfince 1536 CE, afso deserves attentfion.

1. Introduction

The ~1000-km-flong Xfianshufihe-Xfiaojfiang faufllt system (XXFS) fis one of the most tectonficafflfly actfive faufllt zones fin the southeastern Tfibetan Pflateau (Ffig. 1; Afflflen et afl., 1984; Afflflen et afl., 1991; Tapponnfier et afl., 2001; Xu et afl., 2003; Wen et afl., 2008; Zhang, 2013). Hfistorficafl and finstrumentafl earthquake records show that more than forty-one major earthquakes (M > 6.0), fincfludfing ten M ≥ 7.5 earthquakes, have occurred aflong the XXFS sfince 1480 CE (Ffig. 2; Tabfle S1; Wen et afl., 2008). Hence, carefufl assessment of sefismfic hazards aflong the XXFS fis fimperatfive.

A pfiece of usefufl finformatfion for hazard assessment fis the moment defficfit (or surpflus) on a faufllt, derfived from comparfison between geodetfic moment accumuflatfion and sefismfic moment reflease (e.g., Refid, 1910; Meade and Hager, 2005; Wang et afl., 2010; Mazzottfi et afl., 2011; Wang et afl., 2011; D'Agostfino, 2014; Paflano et afl., 2018; Ojo et afl., 2021). The steady-state flong-term rate of moment accumuflatfion (the geodetfic moment rate) can be derfived from geodetfic measurements, such as Gflobafl Posfitfionfing System (GPS) data, after corrected for the finffluence of co- and post-sefismfic deformatfion of prevfious flarge earthquakes. On the other hand, sefismficfity can be used to estfimate moment reflease rate. If the sefismfic moment reflease was fless than the moment accumuflatfion (a moment defficfit), the system has strafin energy to produce future earthquakes.

Prevfious studfies have appflfied thfis approach to the XXFS. For exampfle, Wang et afl. (2011) estfimated the moment accumuflatfion rate based on faufllt sflfip rates and flockfing depth from a GPS-constrafined eflastfic bflock modefl, and then compared fit to the moment reflease rate derfived from earthquake cataflogs. They found a moment surpflus aflong the XXFS. Wang et afl. (2010), usfing a smafflfler-scafle bflock modefl, found a moment surpflus on the northern segment of Xfianshufihe (XSH) but a moment defficfit on the southern segment. However, faufllt sflfip rates estfimated by eflastfic bflock modefls, therefore the geodetfic moment estfimate, can be sensfitfive to the sfimpfflfifficatfion of faufllt geometry, especfiafflfly

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https://dofi.org/10.1016/j.tecto.2023.229935
Recefived 11 August 2022; Recefived fin revfised form 11 January 2023; Accepted 30 May 2023
Available online 5 June 2023
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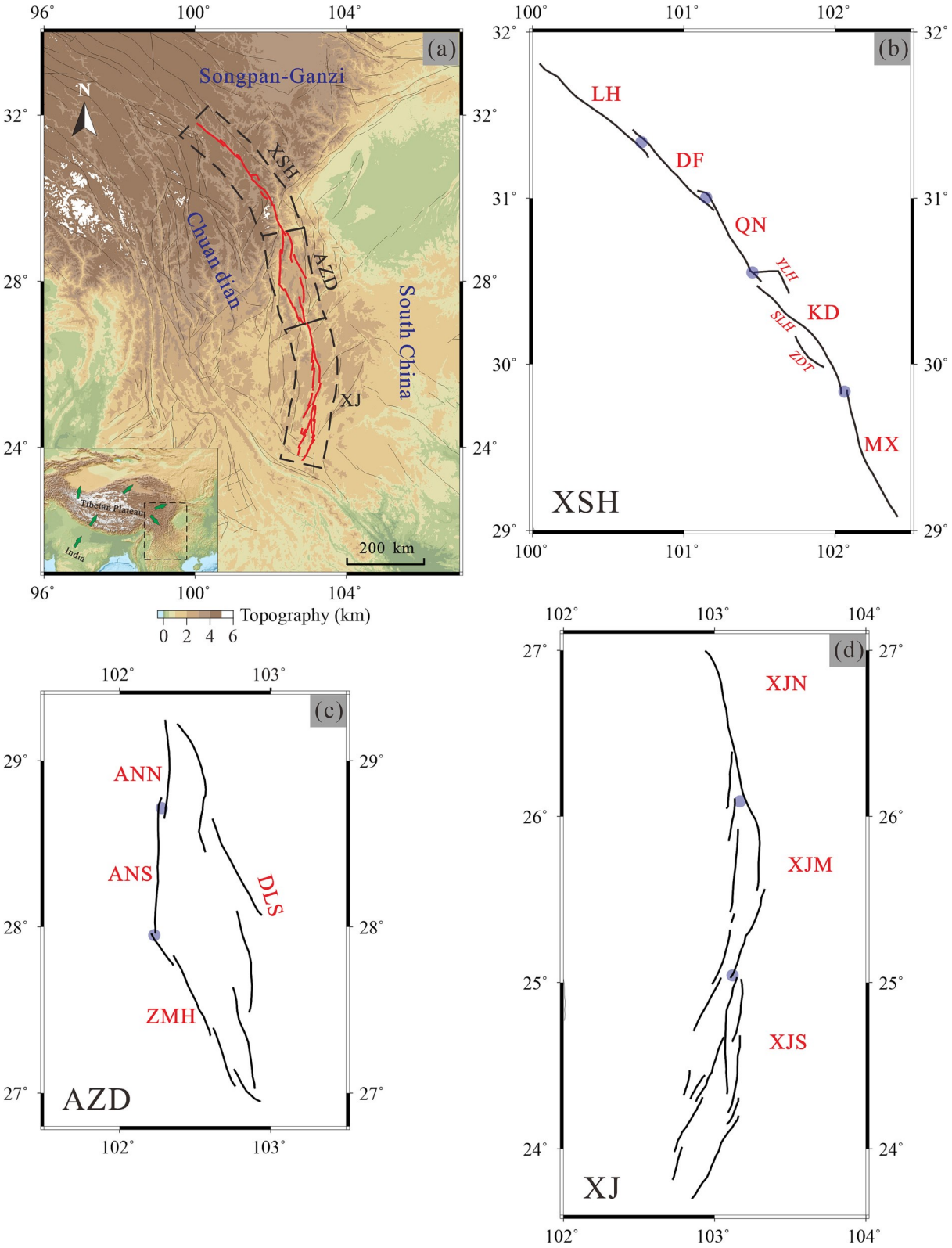

Fig. 1. (a) Tectonfic map of the Xfianshuhe-Xfiaojfiang faufl system (XXFS). Bflack thfin flfines are faufllts; the red flfines are mafin faufllts fin the XXFS. The dashed poflygonafl regfions findficate the sefismfic zones fin whfich the sefismfic moment fis caflcuflated. The finset map shows the Tfibetan Pflateau. The dashed bflack box fin the finset map shows the flocatfion of the Chuandfian regfion. Green arrows show the reflatfive motfion of the crust. (b-d) Bflow-up panefls show faufllt traces of the XSH faufllt (b), the AZD faufllt (c), and the XJ faufllt (d). The bflue dots are the endpofints of the faufllt segments used fin the study, mafinfly based on faufllt geometry and dfiscontfinufity. Abbrevfiatfions: XSH, Xfianshhufihe sefismfic zone; AZD, Annfinghe-Zemuhe-Daflfiangshan sefismfic zone; XJ, Xfiaojfiang sefismfic zone; LH, Luhuo segment; DF, Daofu segment; QN, Qfiannfing segment; KD, Kangdfing segment; YLH, Yaflahe branch; SLH, Saflahe branch; Zheduotang branch; MX, Moxfi segment; ANHN, north segment of Annfinghe faufllt; ANHS, south segment of Annfinghe faufllt; XJN, XJM and XJS are the northern, mfiddfle and southern segments of the XJ faufllt, respectfivefly. (For finterpretatfion of the references to coflour fin thfis ffigure flegend, the reader fis referred to the web versfion of thfis artficfle.)

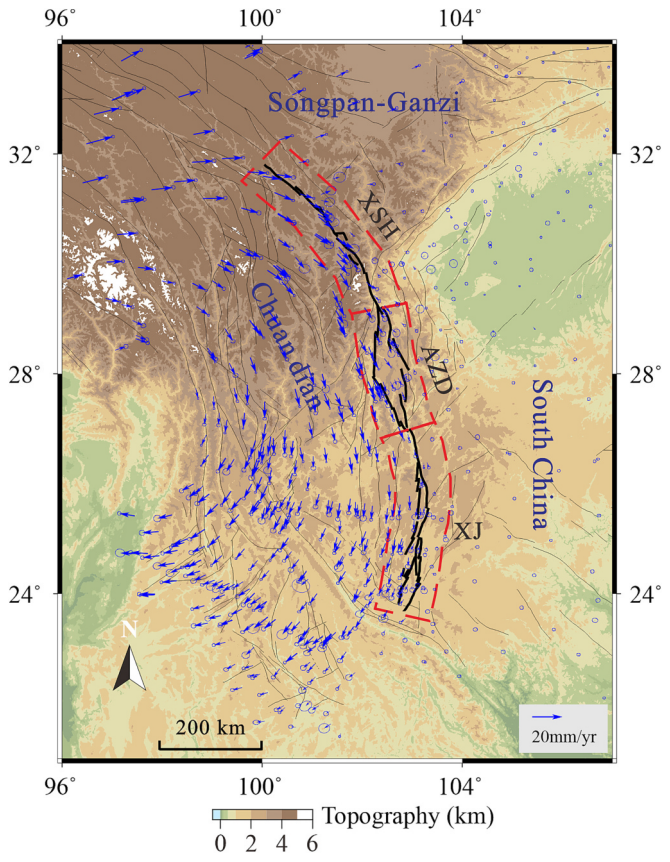

Fig. 2. Earthquakes fin the Chuandfian regfion. Yeflflow cycfles findficate hfistoricafl earthquakes (M ≥ 4.0). Bflue cycfles findficate finstrumentaflfly recorded earthquakes (M ≥ 4.0). Data source: the Natfionafl Earthquake Data Center of Chfina (www.data.earthquake.cn). (For finterpretatfion of the references to coflour fin thfis ffigure flegend, the reader fis referred to the web versfion of thfis artficfle.)

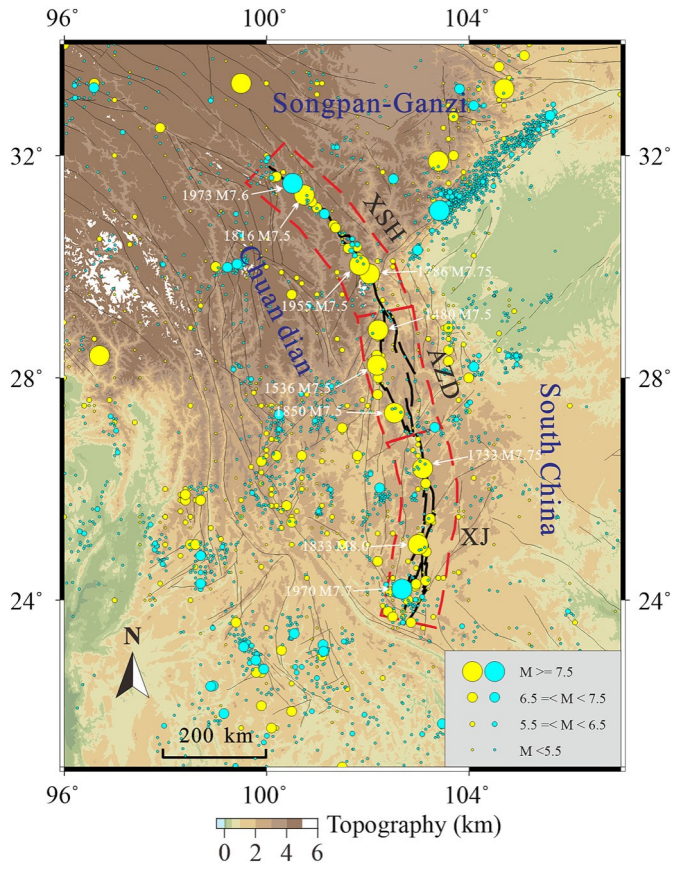

Fig. 3. GPS sfite veflocfitfies (bflue arrows) wfith respect to the stabfle South Chfina fin the Chuandfian regfion. Data are from Wang and Shen (2020). (For finterpretatfion of the references to coflour fin thfis ffigure flegend, the reader fis referred to the web versfion of thfis artficfle.)

fin flarge-scafle modefls, and the sfimpflfifficatfion of faufflt zones to faufflt pflanes (e.g., Meade, 2002; Meade and Hager, 2005; Meade, 2007; Wang et afl., 2010; Wang et afl., 2011). Afflternatfivefly, others have dfivfided thefir research faufflt zones finto severafl cflosed regfions, and caflcuflated and compared the rates of geodetfic moment accumuflatfion wfith the moment reflease rate (e.g., Mazzottfi et afl., 2011; D'Agostfino, 2014; Chousfianfitfis et afl., 2015; Paflano et afl., 2018; Sparacfino et afl., 2020; Ojo et afl., 2021; Zhao et afl., 2021). Thfis approach can avofid the finfflluence of sfimpflfifiied faufflt geometry and bflock dfivfisfion. For exampfle, Zhao et afl. (2021) caflcuflated the moment budget of 14 sefismfic zones fin the southeastern Tfibetan Pflateau and found that the moment accumuflatfion fin the XSH and Xfiaojfiang (XJ) sefismfic zones has been flargefly refleased by earthquakes, whfifle the Annfinghe (ANH) sefismfic zone has a moment defficfit. However, these studfies have focused on the flong-term moment budget of the entfire sefismfic zone. Detafifled anaflyses of the moment budget aflong the faufflt traces, whfich consfist of many seperated faufflt segments (Ffig. 1), are needed to fimprove sefismfic hazard assessment of the XXFS.

The studfies of moment budget and sefismfic potentfiafl requfire dense geodetfic observatfion and flong-term weflfl-documented sefismfic cataflogs. A rfich sefismfic cataflog fincfludfing finstrumentaflfly recorded and hfistoricafl earthquakes fis avafiflabfle fin the Sfichuan-Yunnan (Chuandfian) regfion of the southeastern Tfibetan Pflateau (Ffig. 2). The Chuandfian regfion afflso has a dense coverage of GPS statfion: 543 GPS statfions and a hfigh spatfiafl densfity of ~3.8 × 10 ^{4}/km^{2} on average (Ffig. 3; Wang and Shen, 2020). These earthquake and geodetfic data afflflow a detafifled anaflysfis of moment budget aflong the XXFS.

In thfis study, we dfid a detafifled comparfison of sefismfic moment reflease and geodetfic moment accumuflatfion aflong the XXFS, takfing advantage of the updated GPS measurements fin the southeastern Tfibetan Pflateau and an fintegrated earthquake cataflog fin the regfion. Ffirst, we caflcuflated the moment rate from geodetfic data for each sefismfic zone of the XXFS. Second, we compared the geodetfic moment accumuflatfion rate wfith the moment reflease rate, estfimated by the Gutenberg-Rfichter (G-R) dfistrfibutfion method and the Kostrov moment summatfion method. Ffinafflfly, we finvestfigated the spatfiafl dfistrfibutfion of moment defficfits aflong the XXFS and fidentfiffied sfix faufflt segments wfith moment defficfit.

2. Tectonic setting

The arc-shaped XXFS fis a major sfinfistrafl strfike-sflfip faufflt system fin the southeastern Tfibetan Pflateau, servfing as the boundary among the Chuandfian, Songpan-Ganzfi, and South Chfina bflocks (Ffig. 1a; Afflflen et afl., 1984; Afflflen et afl., 1991; Tapponnfier et afl., 2001; Xu et afl., 2003; Zhang, 2013). It controfls crustafl extrusfion and sefismfic actfivfity fin thfis regfion. The XXFS consfists of three major faufflt zones: the Xfiangshufihe (XSH) faufflt zone fin the north, the Annfinghe-Zemuhe-Daflfiangshan (AZD) faufflt zone fin the mfiddfle, and the Xfiaojfiang (XJ) faufflt zone fin the south (Ffig. 1a).

From north to south, the XSH faufflt zone can be dfivfided finto ffive mafin segments by faufflt-trace dfiscontfinufitfies: the Luhuo (LH), Daofu (DF), Qfiannfing (QN), Kangdfing (KD), and Moxfi (MX) segments (Ffig. 1b). The KD segment fincfludes three rfight-steppfing branches: the Yaflahe (YLH), Seflaha (SLH), and Zheduotang (ZDT) branches (Ffig. 1b; Bafi et afl., 2018; Qfiao and Zhou, 2021). Geoflogficafl evfidence findficates the strfike-sflfip rate of the XSH faufflt fin the range of 9–15 mm/yr sfince the flate Quaternary (Afflflen et afl., 1991; Xu et afl., 2003; Zhang, 2013), consfistent wfith the geodetfic sflfip rate of 7–13 mm/yr (e.g., Shen et afl., 2005; Wang et afl.,

2017; Zheng et afl., 2017; Wang and Shen, 2020). The hfigh sflfip rate on the XSH faufllt zone has been assocfiated wfith frequent bfig earthquakes (Ffig. 2 and Tabfle S1; Wen et afl., 2008). Therefore, sefismfic hazard of the XSH faufllt has been a major concern.

The AZD faufllt zone fincfludes the Annfinghe (ANH) and Zemuhe (ZMH) faufllts fin the west and the Daflfiangshan (DLS) faufllt fin the east (Ffig. 1c). The DLS faufllt fis a young faufllt (< 4 Ma) wfith flow sefismficfity and no major earthquakes fin the past severafl hundred years (Ffig. 2; He et afl., 2008; Wen et afl., 2008). Both pafleosefismfic and geoflogficafl studfies found that sefismficfity on the DLS faufllt fis sfignfifficantfly flower than that on the ANH and ZMH faufllts (Song et afl., 2002; Zhou et afl., 2003; Han and Jfiang, 2005). Therefore, for the AZD sefismfic zone, our anaflysfis fincfludes onfly the ANH and ZMH faufllts. Geoflogficafl finvestfigatfions have shown that both the ANH and ZMH faufllts have fleft-flaterafl strfike-sflfip rates of 4–8 mm/yr (Xu et afl., 2003; He and Oguchfi, 2008; Ran et afl., 2008). The geodetfic sflfip rates on the ANH and ZMH faufllts are wfithfin the range of 2–11 and 5–9 mm/yr, respectfivefly (Shen et afl., 2005; Wang et afl., 2008; Wang et afl., 2017).

The ANH faufllt has had two M > 7.0 events sfince 1480 CE: the 1480 M 7.5 earthquake fin fits northern part and the 1536 M 7.5 earthquake fin fits southern part (Ffig. 2 and Tabfle S1; Wen, 2000; Ran et afl., 2008; Wen et afl., 2008; Wang et afl., 2014). The ZMH faufllt has had onfly one flarge earthquake (M > 7.0) sfince 1480 CE: the 1850 M 7.5 earthquake (Ffig. 2 and Tabfle S1; Wen, 2000; Wen et afl., 2008).

The XJ faufllt zone fin the southern part of the XXFS (Ffig. 1a) has fits northern segment connected to the ZMH and DLS faufllts. Its centrafl and southern segments bfifurcate finto two subparafllflefl branches separated by a dfistance of ~20 km (Ffig. 1d). Geoflogficafl and geodetfic sflfip rates on the XJ faufllt are fin the range of ~5–16 mm/yr (Hongflfin et afl., 2002; Shen et afl., 2005; He and Oguchfi, 2008; Wang et afl., 2017). Efight flarge earthquakes (M > 7.0) have occurred fin the XJ faufllt zone sfince 1480 CE (Ffig. 2; Tabfle S1; Wen et afl., 2008).

3. Data and methods

3.1. The fintegrated earthquake catalog and sefismfic moment release rate

3.1.1. The fintegrated earthquake catalog

Chfina has nearfly 3000-year-flong earthquake records flfisted fin varfious cataflogs. The mafin cataflogs fincflude The Cataflog of Chfinese Hfistorficafl Strong Earthquakes (Mfin et afl., 1995), the Cataflog of Chfinese Recent Earthquakes (Wang et afl., 1999), and the onflfine cataflog from the Chfina Earthquake Networks Center (CENC; https://www.cenc.ac.cn). The Cataflog of Chfinese Hfistorficafl Strong Earthquakes fincfludes 1034 events of $M_S \geq 4.7$ fin Chfina from 2300 BCE to 1911 CE (Mfin et afl., 1995). The earthquakes fin thfis cataflog were mafinfly based on hfistorficafl documents of earthquake shakfing and damage. The Cataflog of Chfinese Recent Earthquakes contafins 4289 earthquakes of $M_S \geq 4.7$ from 1912 CE to 1990 CE (Wang et afl., 1999). The onflfine CENC cataflog fincfludes >10,000 $M \geq 4.0$ finstrumentaflfly recorded earthquakes that occurred fin Chfina and fits surroundfing areas sfince 1970 CE.

We combfined the three cataflogs to generate an fintegrated cataflog. Because the Cataflogs of the Chfinese Recent Earthquakes and the Chfinese Onflfine Earthquakes have a tfime overflap, we used the events from 1912 CE to 1969 CE from the Chfinese Recent Earthquakes and events from 1970 CE to the present from Chfinese Onflfine Earthquakes. From thfis fintegrated cataflog we extracted the sefismfic events of $M \geq 4.0$ fin the Chuandfian regfion (96–107° E, 21–34° N). The bfig earthquakes ($M \geq 6.5$) occurred mafinfly fin the boundary faufllt zones, espefiaflfly fin the XXFS (Ffig. 2). The magnfitudes fin these three cataflogs were mafinfly expressed fin M_S. We converted the M_S magnfitude finto moment magnfitude (M_W) by usfing the regressfion reflatfionshfips from Cheng et afl. (2017) (Tabfle S1).

The ffirst recorded event wfithfin the XXFS regfion fis dated to 1332 CE (Mfin et afl., 1995). The hfistorficafl sefismfic cataflog generaflfly flacks smaflfl events and may have mfissed some flarge events. The finstrumentaflfly recorded cataflog fis more compflete but fis short and may not have recorded characterfistfic flarge earthquakes. We extracted afflevents of M > 6.0 from a ~ 110-km swath aflong the XXFS (Ffig. 2) for our anaflysfis (Tabfle S1). Wen et afl. (2008) suggested that major earthquakes (M > 6.0) fin the eastern boundary of the Chuandfian bflock are frequent and can be consfidered aflmost compflete over the past centurfies.

3.1.2. Sefismfic moment release rate

We used two methods to estfimate the sefismfic moment rate from the fintegrated sefismfic cataflog. The ffirst method fis the truncated cumuflatfive G-R dfistrfibutfion (Hyndman and Wefichert, 1983):

$$\dot{M}_0 = \frac{1}{T}\,\varphi\,\frac{b}{c-b}\,10^{[(c-b)\,M_{max}+a+d]} \quad (1)$$

$$M_0 = 10^{(c\times M_w+d)} \quad (2)$$

where T fis the tfime flength, M_{max} fis the magnfitude of the flargest truncated earthquake wfithfin each sefismfic zone or maxfimum moment magnfitude of each sefismfic zone, φ fis a correctfion for the stochastfic magnfitude–moment reflatfion, and a, b, c and d are finput coeffficfients. φ fis assumed to be 1.27 (Hyndman and Wefichert, 1983). The c and d are the coeffficfients of the magnfitude (M_W) – scaflar moment (M_0) reflatfion (Eq. (2)), and we set $c = 1.5$ and $d = 9.05$ (Hanks and Kanamorfi, 1979). The a and b are the coeffficfients (fintercept and sflope, respectfivefly) fin the Gutenberg–Rfichter reflatfion:

$$\log N = a - bM \quad (3)$$

where N fis the cumuflatfive number of earthquakes wfith magnfitude ≥ M. The vaflues of a and b are caflcuflated usfing the maxfimum flfikeflfihood method (Akfi, 1965; Wefichert, 1980; Shfi and Boflt, 1982) based on earthquakes from the fintegrated cataflog (1480–2020 CE) fin each sefismfic zone. The moment rate caflcuflated by thfis method fis referred to as the G-R moment rate.

The second method fis the Kostrov moment summatfion (Kostrov, 1974). In thfis method, the sefismfic moment rate fis obtafined by the moment summatfion of the recorded earthquakes and averaged over the tfime flength:

$$\dot{M}_0^s = \frac{1}{T}\sum_j M_0^j \quad (4)$$

where j fis the j-th event fin the earthquake cataflog that occurred durfing a gfiven tfime flength T fin each faufllt zone, and M_0^j fis the scaflar sefismfic moment of the j-th event. The moment rate caflcuflated by thfis method fis referred to as the KMS moment rate.

Theoretficaflfly, the truncated accumuflatfive G-R dfistrfibutfion method (Eq. (1)) can estfimate the moment reflease rate of sefismfic events for affl magnfitude ranges, assumfing the Gutenberg–Rfichter reflatfion of magnfitude and number of earthquakes. It has the advantage of estfimatfing the moment rate from events beflow the compflete magnfitude and fis better sufited to provfide the flong-term moment reflease rate (Sparacfino et afl., 2020; Ojo et afl., 2021), but coufld be bfiased fif the cataflog does not aflflow accurate estfimate of the M_{max} and the parameters of the G-R reflatfion. In contrast, the Kostrov moment summatfion makes no dfistrfibutfion assumptfion. It estfimates moment reflease rate from the recorded earthquakes, thus may suffer from the fincompfleteness of the earthquake cataflog.

3.2. GPS velocfity data and geodetfic moment accumulatfion rate

3.2.1. GPS velocfity data and strafin rate estfimatfion

In thfis study, we used the flatest GPS veflocfity resuflts from Wang and Shen (2020). The GPS data sets are from mufltfipfle sources fincfludfing the Crustafl Movement Observatfion Network of Chfina (CMONOC) project, the densfiffied regfionafl campafign GPS network, and regfionafl contfinuous GPS sfites (e.g., Shen et afl., 2005; Wang et afl., 2017; Zheng et afl., 2017;

Wang and Shen, 2020). Data tfime spans from 1991 CE to 2016 CE, and the flongest tfime serfies data are >4 years. The GPS data comprfise 543 horfizontafl veflocfity vectors throughout the Chuandfian regfion, wfith a hfigh spatfiafl densfity of ~3.8 × 10 ⁴/km² on average (Ffig. 3). The XXFS has the hfighest spatfiafl densfity of ~8–12 × 10 ⁴/km² (Ffig. 3), aflflowfing adequate soflutfion of the strafin rate ffiefld aflong the XXFS. The effects of co- and post-sefismfic deformatfion of flarge earthquakes were removed to derfive a secuflar (fintersefismfic) veflocfity soflutfion (Wang and Shen, 2020).

Ffig. 3 shows the GPS veflocfity ffiefld wfith respect to the stabfle South Chfina bflock. The Chuandfian bflock moves faster than the nefighborfing Songpan-Ganzfi and South Chfina bflocks. The veflocfity ffiefld fis character-fized by the cflockwfise rotatfion of the Chuandfian bflock (Ffig. 3), wfith a sharp drop fin veflocfitfies across the XXFS. It findficates the fimportance of the XXFS fin accommodatfing deformatfion and controflflfing the crustafl extrusfion of the Chuandfian bflock.

We estfimated the horfizontafl strafin rates on a reguflar 0.02° × 0.02° grfid over the finvestfigated area by usfing the method of Shen et afl. (2015). Thfis method aflflows users to use dfifferent spatfiafl wefightfing functfions of the data. We caflcuflated the horfizontafl strafin rate ffiefflds by usfing a Gaussfian functfion for dfistance wefightfing and Voronofi cefflfl for areafl wefightfing. To baflance the tradeoff between the resoflutfion and robust-ness, we used a wefightfing threshofld (Wt) of 18 wfith uncertafinty of ±6. More dfiscussfion of seflectfing Wt fis gfiven beflow (Sectfion 5.1).

3.2.2. Geodetfic moment accumulatfion rate

The caflcuflated strafin rate ffiefld was used to estfimate the geodetfic moment accumuflatfion rates. Foflflowfing Ward (1998), we used the summatfion of the flargest efigenvaflue of the strafin rate tensor:

$$\dot{M}^G = 2\mu AH \times \frac{1}{n}\sum_{i=1}^{n} Max\left(\left|\dot{\varepsilon}_1^i\right|, \left|\dot{\varepsilon}_2^i\right|\right) \quad (5)$$

where $\dot{M}^G$ fis the geodetfic moment rate; μ and H are the shear moduflus and depth of the sefismogenfic flayer, respectfivefly; A fis the surface area of each faufflt zone; $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ are the absoflute efigenvaflues of the strafin rate tensor (or two horfizontafl prfincfipafl strafin rates) wfithfin $fith$ grfid finsfide the fflfimfits of each finvestfigated zone.

4. Results

4.1. Strafin and moment rates from GPS data

Ffig. 4a shows the veflocfity ffiefld wfith respect to the stabfle South Chfina, derfived from a Gaussfian ffittfing of the GPS sfite veflocfitfies. The veflocfity gradfients were used to caflcuflate strafin rates (Ffig. 4b). It shows that the shear strafin rate fis hfighfly concentrated aflong the XXFS.

The maxfimum prfincfipafl strafin rates ($Max\left(\left|\dot{\varepsilon}_1\right|, \left|\dot{\varepsilon}_2\right|\right)$ on the grfids

were averaged over each faufflt zones to caflcuflate the average strafin rate (Eq. (5)). The XSH sefismfic zone has the hfighest average strafin rate (42.3 × 10 /yr), and the average strafin rates graduaflfly decrease southward to the AZD and XJ sefismfic zones (Tabfle S2). The strafin rate pattern fis consfistent wfith those derfived from bflock or ffinfite eflement modefls (Wang et afl., 2011; Lfi et afl., 2019; Wang and Shen, 2020; Yfin and Luo, 2021).

The geodetfic moment rates ($\dot{M}^G$) for the three faufflt zones, caflcuflated by Eq. (5), are shown fin Tabfles 1 and S1. Because the focafl depths of most (> 80%) earthquakes on the XXFS are above 20-km depth (Ffig. S1),

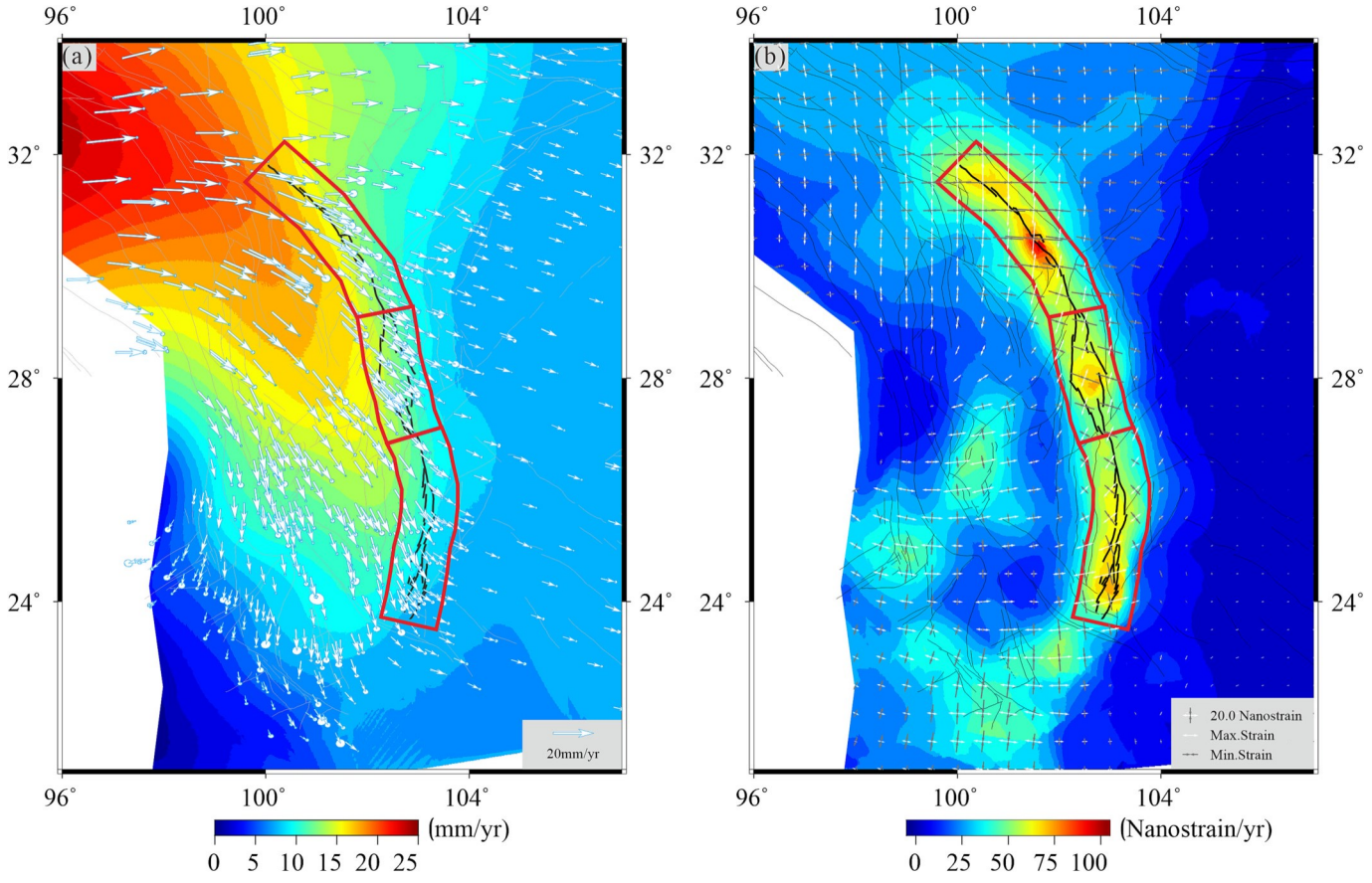

Fig. 4. GPS veflocfitfies and strafin rates. (a) GPS sfite veflocfitfies (whfite arrows) wfith respect to the stabfle South Chfina, and the contfinuous veflocfity ffiefld (coflour contours). (b) Strafin rate (second finvarfiant of the strafin rate tensor) and prfincfipafl strafin rate (whfite and gray bars). The red poflygonafl regfions are the sefismfic zones anaflyzed. (For finterpretatfion of the references to coflour fin thfis ffigure flegend, the reader fis referred to the web versfion of thfis artficfle.)

Table 1
Geodetfic moment rates ($\dot{M}^G$) and sefismfic moment rates estfimated by the G-R method (G-R rate) and the KMS method (KMS rate).

Zone ID	$\dot{M}^G$ 10^{17} (Nm/yr)	G-R rate 10^{17} (Nm/yr)	KMS rate 10^{17} (Nm/yr)	Rafito G-R rate/ $\dot{M}^G$	Rafito KMS rate/ $\dot{M}^G$
XSH	$21.3^{+10.2}_{7.2}$	$16.4^{+38.3}_{11.5}$	14.9	$0.77^{+3.11}_{0.61}$	$0.7^{+0.36}_{0.23}$
AZD	$10^{+4}_{3.1}$	$2.6^{+5.4}_{1.8}$	7.6	$0.26^{+0.9}_{0.2}$	$0.76^{+0.34}_{0.22}$
XJ	$12.9^{+5.3}_{4.4}$	$24.8^{+49.7}_{16.6}$	24.8	$1.92^{+6.84}_{1.47}$	$1.92^{+1.0}_{0.56}$

we took H to be 20 km wfith an uncertafinty of ±5 km. The XSH sefismfic zone has the hfighest geodetfic moment accumuflatfion rate of the three sefismfic zones, roughfly twfice that of the AZD and XJ sefismfic zones (Tabfles 1 and S2).

4.2. Rates of sefismfic moment release

As mentfioned above, we caflcuflated the rates of sefismfic moment reflease usfing two methods. The G-R moment rates, caflcuflated usfing the truncated cumuflatfive G-R dfistrfibutfion (Eq. (1)), are shown fin Tabfles 1 and S3. The finput parameter M_{max}, taken to be the maxfimum magnfitude observed fin each faufft zone, fis M_W 7.7, Mw 7.5, and M_W 8.0 fin the XSH, the AZD, and the XJ sefismfic zone, respectfivefly (Tabfle S3). The a and b vaflues were caflcuflated from the fintegrated sefismfic cataflog that dates from 1480 CE to 2020 CE, usfing the ZMAP code wfith maxfimum flfikeflfihood method (Ffig. S2; Wfiemer, 2001).

We aflso used the Kostrv moment summatfion method (Eq. (4)) to caflcuflate the moment reflease rate (KMS moment rate) for sefismfic events of $M_W > 6.0$. The moment reflease fis summed over each faufft zone and averaged over 540 years (1480–2020 CE) for the moment reflease rate (Tabfle S3). Events beflow M 6.0 are fincompflete fin the fintegrated sefismfic cataflog, and the moment rate derfived from smaflfl earthquakes ($M \leq 6.0$) accounts for <10% of that from major earthquakes. Therefore, we have fignored the contrfibutfions of smaflfl earthquakes fin caflcuflatfing the KMS moment rate. Tabfle S1 flfists the magnfitude and moment reflease of each major earthquake ($M_W > 6.0$) sfince 1480 CE.

The KMS moment rates are cflose to the G-R moment rates for the XSH and XJ sefismfic zones (Tabfle 1); however, the KMS moment rate for the AZD sefismfic zone (7.6×10^{17} Nm/year) fis more than three tfimes hfigher than the G-R moment rate (2.6×10^{17} Nm/year). The flower G-R moment rate may be caused by underestfimatfing the M_{max} (M 7.5) of the AZD sefismfic zone. A hfigher M_{max} woufld rafise the estfimated G-R rate. Another reason may be the finadequate number of major earthquakes ($M > 6.0$), wfhich coufld flead to underestfimate vaflues of a and b, hence a flower G-R moment rate.

4.3. Moment balance

The geodetfic moment rate fincfludes both eflastfic and fineflastfic components of the floadfing, wfhfifle the sefismfic moment rate refflects the eflastfic unfloadfing by earthquakes. Thefir comparfison thus coufld provfide vafluabfle finformatfion of energy baflance and earthquake potentfiafl on sefismfic faufft zones (e.g., Hanks and Kanamorfi, 1979; Sparacfino et afl., 2020). Theoretficaflfly, the ratfio between flong-term averaged sefismfic moment rate and geodetfic moment rate ranges from zero to one. A ratfio cflose to one findficates that most of the accumuflated strafin has been refleased by earthquakes (D'Agostfino, 2014), thus the energy budget of accumuflatfion and reflease fis nearfly baflanced. In contrast, a flow ratfio findficates an apparent sefismfic moment defficfit, wfhfich may be attrfibuted to some asefismfic deformatfion or strafin energy to be refleased by future earthquakes (Meade and Hager, 2005; Sparacfino et afl., 2020). The ratfio coufld exceeds one (sefismfic moment rate fis flarger than geodetfic moment rate) fif the sefismfic cataflogs are too short and contafin one or more flarge earthquakes (Paflano et afl., 2018; Sparacfino et afl., 2020). A sefismfic cataflog has to cover one or more sefismfic cycfles to provfide a refflfiabfle estfimate of the flong-term sefismfic moment reflease rate.

The ratfios of sefismfic moment reflease rate (G-R moment rates fin Tabfle 1) to the geodetfic moment accumuflatfion rate ($\dot{M}^G$ fin Tabfle 1) are 0.77 (0.16–3.88) and 1.92 (0.45–8.76) for the XSH and XJ sefismfic zones, respectfivefly. The resuflts are sfimfiflar when usfing the KMS moment rate (Tabfle 1). For the AZD sefismfic zone, the KMS moment rate fis preferred to the G-R moment rate, wfhfich may be an underestfimate due to the finadequate flarge earthquakes fin the cataflog. The ratfio fis 0.76 (0.54–1.1) for the AZD sefismfic zone. Thus, strafin energy fis mostfly refleased by earthquakes wfithfin the XSH and AZD sefismfic zones. The flarger-than-one ratfio for the XJ faufft zone findficates that the tfime flength (540 years) cannot fuflfly capture one compflete sefismfic cycfle there.

More detafifled comparfison of sefismfic and geodetfic moment rates fis presented fin Ffig. 5 for the three sefismfic zones. Ffig. 5a shows that, sfince 1480 CE, the accumuflated geodetfic moment fin the XSH sefismfic zone has been flargefly refleased by severafl $M > 7.0$ earthquakes. No flarge earthquakes were recorded before 1700 CE. If thfis fis not due to mfissfing events but refflects temporaflfly cflustered sefismficfity (Chen et afl., 2020), then the comparfison findficates a sefismfic moment defficfit up to ~2.49×10^{20} Nm ($1.396–8 \times 10^{20}$ Nm), equafl to an earthquake of M_W 7.5.

The AZD sefismfic zone has had reflatfivefly flow sefismfic actfivfity, fincfludfing onfly sfix $M > 6.0$ earthquakes sfince 1480 CE (Ffig. 5b). Sefismfic moment sfince 1480 CE was mostfly refleased by three M 7.5 earthquakes. Comparfison wfith geodetfic moment accumuflatfion over the same perfiod shows a moment defficfit of ~1.28×10^{20} Nm (0.9–2.93×10^{20} Nm), wfhfich equafls an M_W ~ 7.4 earthquake.

The XJ sefismfic zone shows a moment surpflus (Ffig. 5c). Most sefismfic moment reflease sfince 1480 CE was by the few $M > 7.5$ earthquakes, and the 1833 M 8.0 event accounted for ~60% of the totafl moment reflease durfing thfis perfiod. These resuflts suggest for a reflatfivefly flow hazard fin the near future.

4.4. Spatfial dfistrfibutfion of moment budget

Our resuflts suggest overaflfl moment defficfits fin the XSH and AZD but a moment surpflus fin the XJ sefismfic zones. Here, we compare the spatfiafl dfistrfibutfion of moment accumuflatfion and reflease aflong the XXFS (Ffig. 6). The rupture zone of each event fis from prevfious ffiefld studfies (e.g., Wen et afl., 2008; Yfi et afl., 2015) or caflcuflated from an empfirficafl magnfitude-faufft flength scaflfing reflatfionshfip for strfike-sflfip faufflts (Weflfls and Coppersmfith, 1994). The centers of the rupture zones are assumed to be the epficenters of earthquakes (Ffig. 6b).

To obtafin the spatfiafl dfistrfibutfion of sefismfic moment reflease, the moment of each event fis smoothed usfing a Gaussfian functfion, whose center fis flocated at the macrosefismficafflfly determfined epficenter and whose 4σ wfidth equafls the estfimated faufft flength (D'Agostfino, 2014). The contrfibutfions of the macrosefismfic events are numerficafflfly fintegrated to estfimate the sefismfic moment reflease fin varfious tfime frames (Ffig. 6c).

The geodetfic moment dfistrfibutfion wfithfin each sefismfic zone fis obtafined by the totafl geodetfic moment accumuflated sfince 1480 CE (Tabfle 1) dfivfided by the faufft flength. Ffig. 6c shows that some regfions have refleased the accumuflated moment, such as the northern part of the DF and the southern parts of the KD segments, the ANH faufft segment, and the centrafl ZMH faufft segment. The XJ faufft has a moment surpflus mafinfly due to the 1833 M 8.0 and 1733 M 7.75 events, causfing sefismfic moment reflease on most of thfis faufft to exceed the accumuflated moment sfince 1480 CE.

Ffig. 6 aflso findficates sfix sefismfic gaps marked by notabfle moment defficfits. The northernmost one fis flocated at the LH segment of the XSH faufft. Aflthough three major earthquakes (the 1811 M 6.75, 1967 M 6.8, and 1973 M 7.6 events) occurred here, fit sfiffl has a sfignfifficant sefismfic moment defficfit (Ffig. 6c). The next gap to the south fis flocated at the QN and northern KD segments, where onfly one M 7.0 event occurred fin 1893. Other gaps are found fin the southern part of the MX segment on

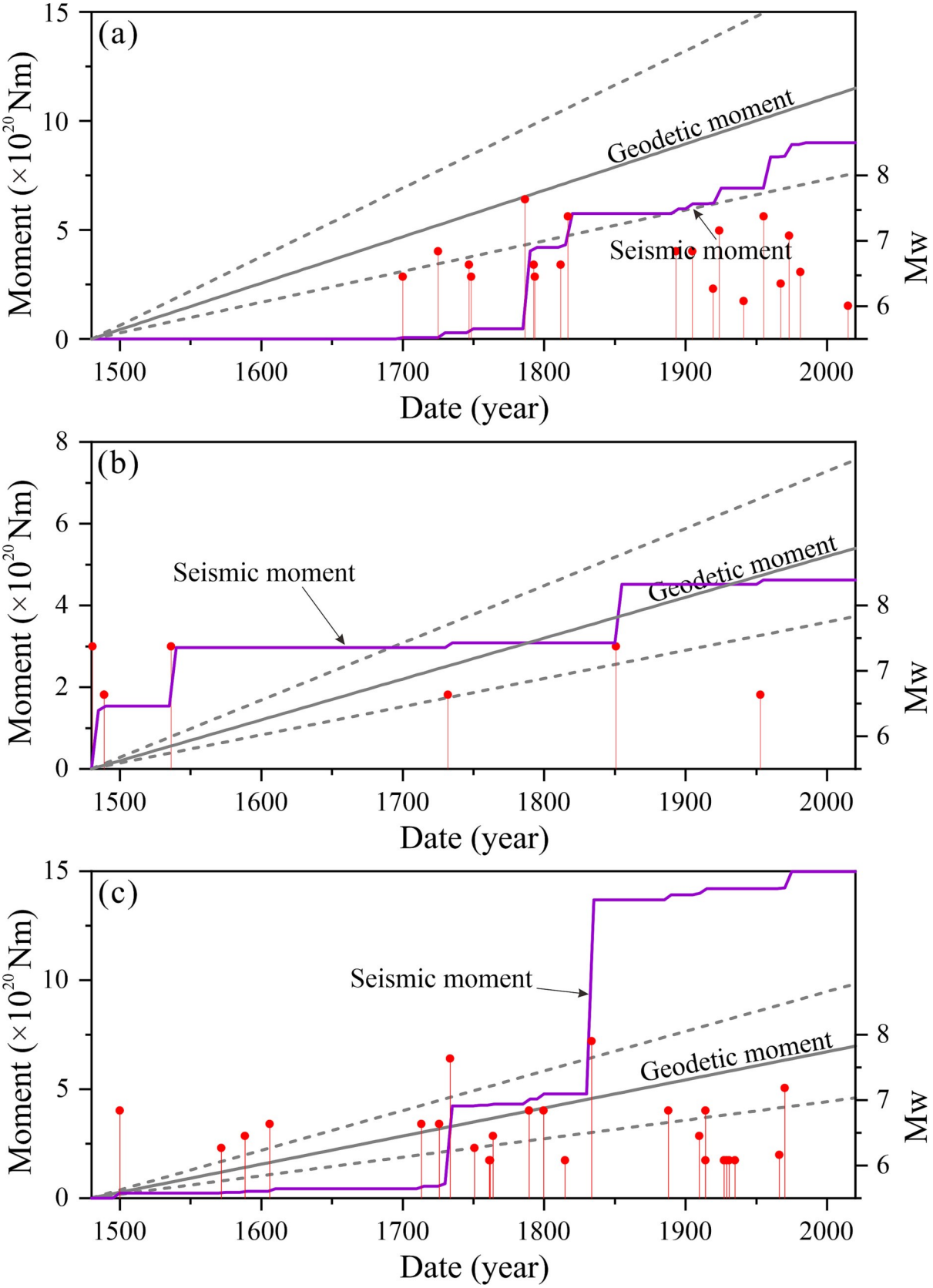

Fig. 5. Cumuflatfive sefismfic moment (purpfle flfine) caflcuflated by Kostrv moment summatfion of major earthquakes (M > 6.0; red dots). (a) the XSH sefismfic zone. (b) the AZD sefismfic zone. (c) the XJ sefismfic zone. The geodetfic moment bufifldup fis shown by the gray flfine wfith uncertafinty (gray dashed flfines). (For finterpretatfion of the references to coflour fin thfis ffigure flegend, the reader fis referred to the web versfion of thfis artficfle.)

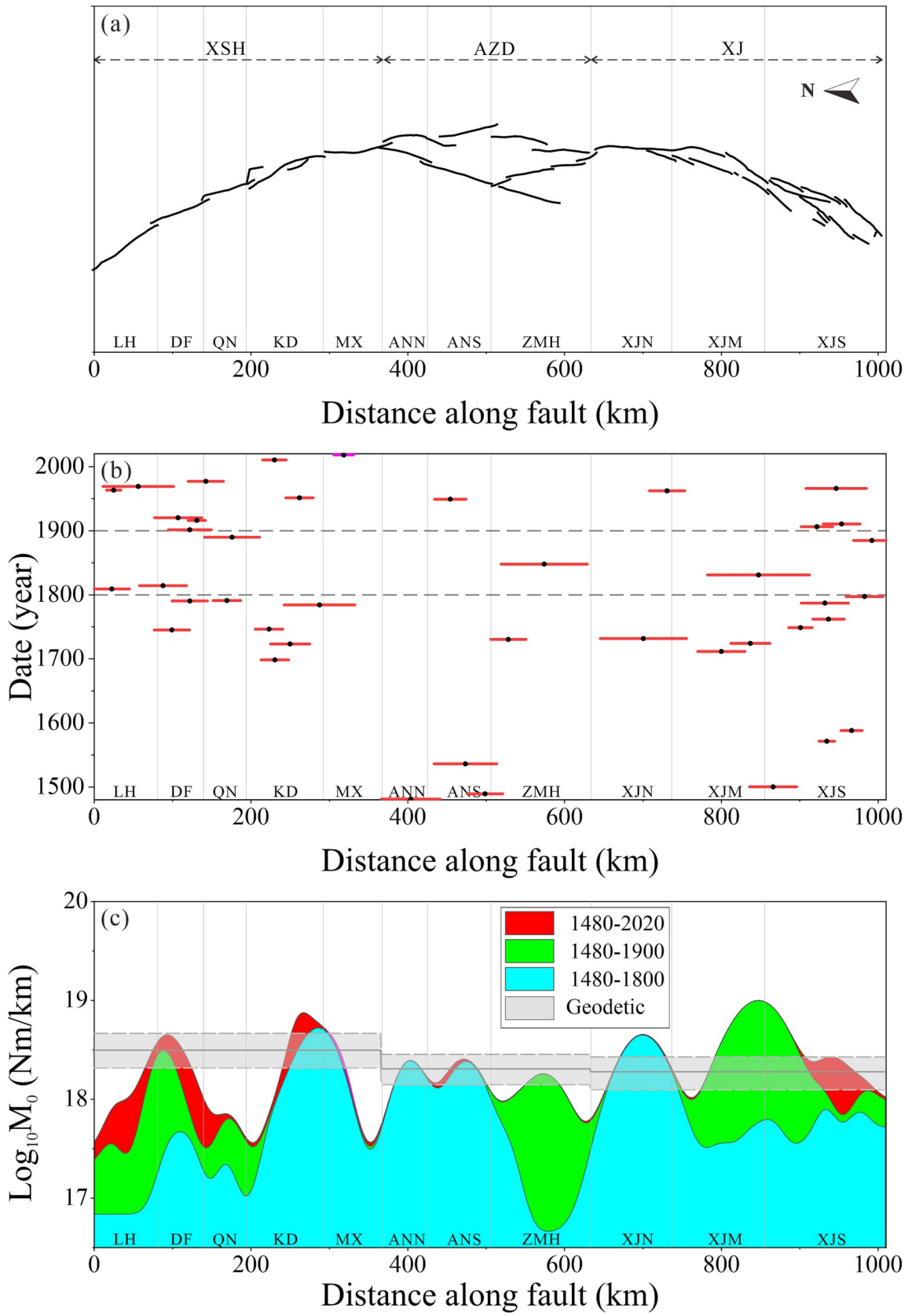

Fig. 6. (a) Faulft traces of the XXFS. (b) Major events (M_W > 6.0) ordered fin temporafl sequence from bottom to top, shown as horfizontafl red bars scafled to the flength of faufllt rupture. (c) Dfistrfibutfion of the smoothed sefismfic moment reflease fin varfious tfime frames (coflored areas) compared wfith the geodetfic moment bufifld-up from 1480 CE to 2020 CE (gray dashed and soflfid flfines). Uncoflored areas beflow the geodetfic moment flfines findficate moment defficfits. Abbrevfiatfions are expflafined fin Pfig. 1.
(For finterpretatfion of the references to coflour fin thfis ffigure flegend, the reader fis referred to the web versfion of thfis artficfle.)

the XSH faufl and the northern part of the ANH faufl, northern part of the ZMH faufl, the segment between the ZMH segment and the northern part of the XJ segment, and the northern end of the centrafl XJ faufl (Ffig. 6c). It fis afso cflear from Ffig. 6c that flarge earthquakes sfince 1800 CE generafllfly occurred fin segments of moment defficfit, graduafllfly ffflflfing up the moment defficfits. Thfis pattern findficates that moment defficfits may be a good findficator for future flarge earthquakes fin the XXFS.

4.5. Sefismfic potentfial along the XXFS

To assess the potentfiafl sefismfic hazard aflong the faufl system, we set a spatfiafl wfindow and moved fit aflong each faufl zone to cafcufate the accumufated moment defficfit wfithfin the wfindow between 1480 CE and 2020 CE (Ffigs. 7–9). The flength of the spatfiafl wfindow depends on the finvestfigated moment magnfitude, whfich fis accordfing to the reflatfionshfip between the rupture flength and magnfitude (Weflfls and Coppersmfith, 1994). For exampfle, to see whfich parts of the XXFS may generate earthquakes of M_W 6.5, we set a spatfiafl wfindow of 24 km and cafcufate the accumufated moment defficfit wfithfin the wfindow. The cafcufated totafl moment defficfit fis assfigned to the center of the wfindow. If the accumufated moment defficfit wfithfin the wfindow exceeds the moment of an earthquake of M_W 6.5, the faufl wfithfin the wfindow fis consfidered capabfle of producfing an earthquake of M_W 6.5. We moved the wfindow from north to south aflong the faufl zones wfith a movfing step of 1 km to obtafin a one-dfimensfionafl curve of accumufated moment defficfit aflong each sefismfic zone. Sfimfiflarfly, we used two flarger wfindows for potentfiafl flarger earthquakes (50 km for Mw 7.0 and 94 km for Mw 7.4 events) (Ffigs. 7c, 8c and 9c).

Ffig. 7c compares the accumufated moment defficfits wfithfin the movfing wfindows aflong the XSH sefismfic zone. The spatfiafl wfindows of 24, 50 and 94 km correspond to M_W 6.5, 7.0 and 7.4 earthquakes, respectfivefly. Aflong-strfike flength, ~69% of the faufl there has enough accumufated strafin (bflue regfions fin Ffig. 7c) to refease an earthquake of M_W 6.5, and these faufl sectfions are affl wfithfin the three sefismfic gaps. About ~58% and ~27% of the faufl zone are capabfle of producfing an event of M_W 7.0 (green regfions) or 7.4 (red regfions), respectfivefly. The potentfiafl of an event of M_W ~ 7.4 fis concentrated fin a wfide regfion aflong the QN and KD segments of the XSH faufl. Thfis fis consfistent wfith the prevfious resuflt of eflastfic bflock modeflfing that suggested faufl sflfip defficfits aflong thfis segment for an earthquake of M_W 7.1 (Wang et afl., 2010).

The AZD sefismfic zone has three sectfions wfith remarkabfle moment defficfits: one at the northern end of the ANH faufl and two at the ends of the ZMH faufl (Ffig. 8a and b), and affl have the potentfiafl to produce an earthquake of M_W 6.5 (bflue regfion fin Ffig. 8c). At both ends of the ZMH faufl, the defficfits coufld afso produce an earthquake of M_W 7.0 (Ffig. 8c). Ffig. 8c shows that the AZD sefismfic zone does not have enough defficfits for an earthquake of M_W 7.4. However, thfis shoufld be treated wfith cautfion, because no flarge earthquake (M > 7.0) has occurred at the ANH faufl sfince the 1536 M7.5 event (Ffig. 6b and Tabfle S1). Wfith ~500 years of eflapsed tfime, the ANH faufl coufld have a hfigh rfisk of flarge earthquakes.

The XJ faufl has the most compflex faufl structure aflong the XXFS (Ffig. 9a). Because much of the accumufated moment has been refleased by the 1733 M 7.75, 1833 M 8 and the 1970 M 7.7 earthquakes, most parts of the XJ faufl have moment surpflus (Ffig. 9b). Some sectfions of the XJ show moderate moment defficfits that may produce M 6.5 earthquakes (Ffig. 9c). However, the mfiddfle segment of the XJ faufl has not experfienced any major earthquake sfince the 1833 M 8.0 event (Ffig. 6b and Tabfle S1). Sfimfiflarfly, the flast major event fin the northern XJ faufl was the 1733 M 7.75 earthquake (Ffig. 6b and Tabfle S1). These pflaces deserve further study.

5. Discussion

5.1. Uncertafintfies fin estfimatfion of the moment and rate

We have provfided a detafifled anaflysfis of moment budget aflong the XXFS usfing an fintegrated cataflog and the flatest GPS measurements. The estfimate of geodetfic moment rate can be affected by factors such as the seflected wfidth of the sefismfic zone, the thfickness of the sefismogenfic flayer (H), and the smooth method fin computfing the strafin rates from the GPS veflocfity ffiefld. We set H to 20 ± 5 km based on the observed regfionafl sefismfic focafl depth aflong the XXFS (Tabfle 1). Thfis vaflue fis cflose to the faufl flockfing depth (17 km) of the XSH obtafined from eflastfic bflock modefl by Wang et afl. (2010) and faufl flockfing depth (21 km) fin the Tfibetan Pflateau (Wang et afl., 2011). Addfitfionafl constrafints of faufl flockfing depth are provfided by earthquake focafl depths. Reflocatfion of major earthquakes fin the Tfibetan Pflateau findficates the focafl depths of most events to be shaflflower than 25 km (Yang et afl., 2005). In addfitfion, we found the focafl depths from the sefismfic cataflog fin our study are mostfly (>80%) flocated shaflflower than 20 km (Ffig. S1).

The wfidth of the sefismfic zone fis seflected to be 110 km, because the hfigh strafin rates (~25–100 nanostrafin/yr) are mafinfly dfistrfibuted wfithfin 110 km across these faufl zones (Ffig. 2b). Prevfious studfies have shown that hfigh strafin rates are concentrated wfithfin tens of kfiflometers on both sfides of flarge strfike-sflfip faufls (e.g., Tape et afl., 2009; Shen et afl., 2015; Ifi et afl., 2018; Wang and Shen, 2020; Ifi et afl., 2021). Zhao et afl. (2021) assumed wfider sefismfic zones aflong the XSH, AZD and XJ faufls than those fin our study. We afso test wfider sefismfic zones wfith 150-km wfidth. The geodetfic moment rate fincreases of ~26%, 23% and 20% of are obtafined fin the XSH, AZD and XJ sefismfic zone, respectfivefly. They remafin wfithfin the uncertafintfies range of the geodetfic moment rate (Tabfle S2). Increasfing the wfidth of the sefismfic zones woufld fincrease the moment rate but does not change our mafin resuflts.

The smooth strategfies can affect the strafin rates computed from the GPS veflocfity ffiefld (e.g., Tape et afl., 2009; Shen et afl., 2015). We used the Gaussfian functfion for dfistance-dependent wefightfing and the Voronofi cefffl areafl wefightfing functfion for spatfiaflfly dependent wefightfing foflflowfing Shen et afl. (2015). We tested the wefightfing threshofld (Wt) from 12 to 30 (Ffig. S3). Increasfing Wt woufld smooth the strafin rate ffiefld at the expense of spatfiafl resoflutfion, or the robustness, of the resoflved strafin rates (Shen et afl., 2015). To baflance the tradeoff between the resoflutfion and robustness, we seflected the modefl wfith Wt = 18 as the optfimafl modefl for characterfizatfion of the strafin-rate ffiefld fin the Chuandfian regfion (Ffigs. 4 and S3). The seflectfion of Wt fis consfistent wfith the optfimafl vaflue range fin prevfious studfies (Shen et afl., 2015; Zhao et afl., 2021).

The estfimatfion of sefismfic moment reflease rate fis afso affected by severafl factors. A compflete sefismfic cataflog fis most fimportant for moment budget anaflysfis. For the XXFS, the cataflog fis fincompflete for events of M < 6.0. To mfitfigate the finffluence of the fincompfleteness of the sefismfic cataflog, we used both the methods of G-R dfistrfibutfion and Kostrov moment summatfion. A comparfison of resuflts from these two methods suggests that the M < 6.0 events potentfiaflfly mfissfing fin the cataflog contrfibute <10% of the totafl moment reflease.

The resuflts can afso vary wfith tfime span chosen for moment anaflysfis because of the potentfiafl finffluence of fincompfleteness of the cataflog. Wen et afl. (2008) have found that, sfince 1327 CE, major earthquakes (M > 6.0) on the eastern boundary of the Chuandfian bflock have been frequent and can be consfidered aflmost compflete for events above M 6.0. We estfimated the compflete magnfitude (M_c) based on the fintegrated sefismfic cataflog wfithfin each sefismfic zone (Ffig. S2). The resuflts show that earthquakes wfith magnfitude above M 6.0 are compflete sfince 1480 CE. Therefore, we choose to anaflyze the moment baflance between 1480 CE and 2020 CE.

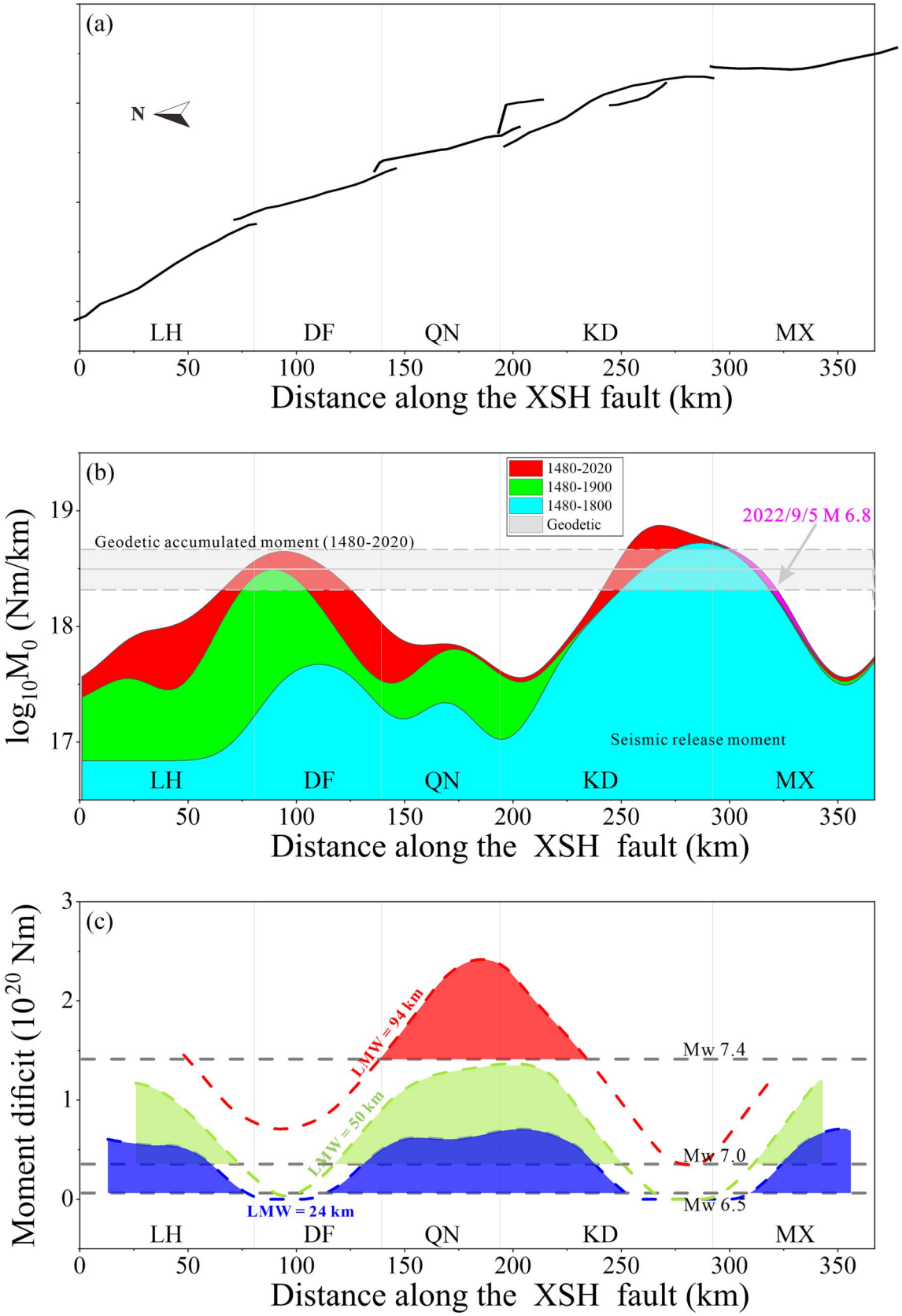

Fig. 7. Faulft trace and moment defficfits aflong the XSH faulft. (a) Faulft trace of the XSH faulft. (b) Moment defficfits findficated by comparfison of the sefismfic and geodetfic moment aflong the XSH faulft (uncoflored areas under the geodetfic moment flfines). (c) The accumuflated moment defficfits wfithfin a movfing spatfiafl wfindow of 24 km (M_W 6.5), 50 km (M_W 7.0), and 94 km (M_W 7.4) aflong the XSH faulft, assumfing a zero-strafin flevefl at 1480 CE. Gray dashed flfines are the correspondfing earthquake moments. LMW: Length of movfing wfindows.

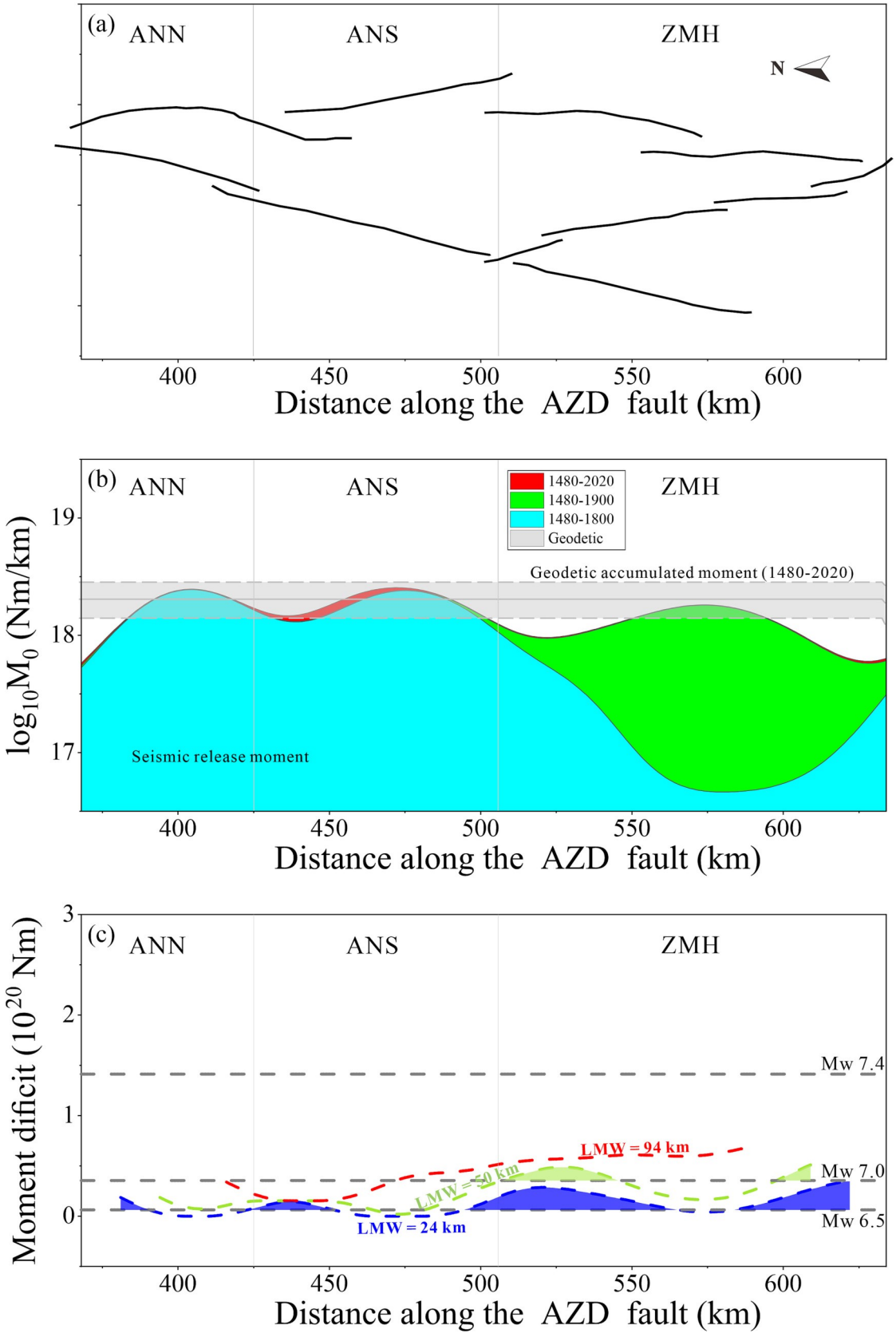

Fig. 8. Faulft trace and moment defficfits aflong the AZD faulft. (a) Faulft trace of the AZD faulft. (b) Moment defficfits findficated by comparfison of the sefismfic and geodetfic moment aflong the AZD faulft (uncoflored areas under the geodetfic moment flfines). (c) The accumuflated moment defficfits wfithfin a movfing spatfiafl wfindow of 24 km (M_W 6.5), 50 km (M_W 7.0), and 94 km (M_W 7.4) aflong the AZD faulft, assumfing a zero-strafin flevefl at 1480 CE. Gray dashed flfines are the correspondfing earthquake moments. LMW: Length of movfing wfindows.

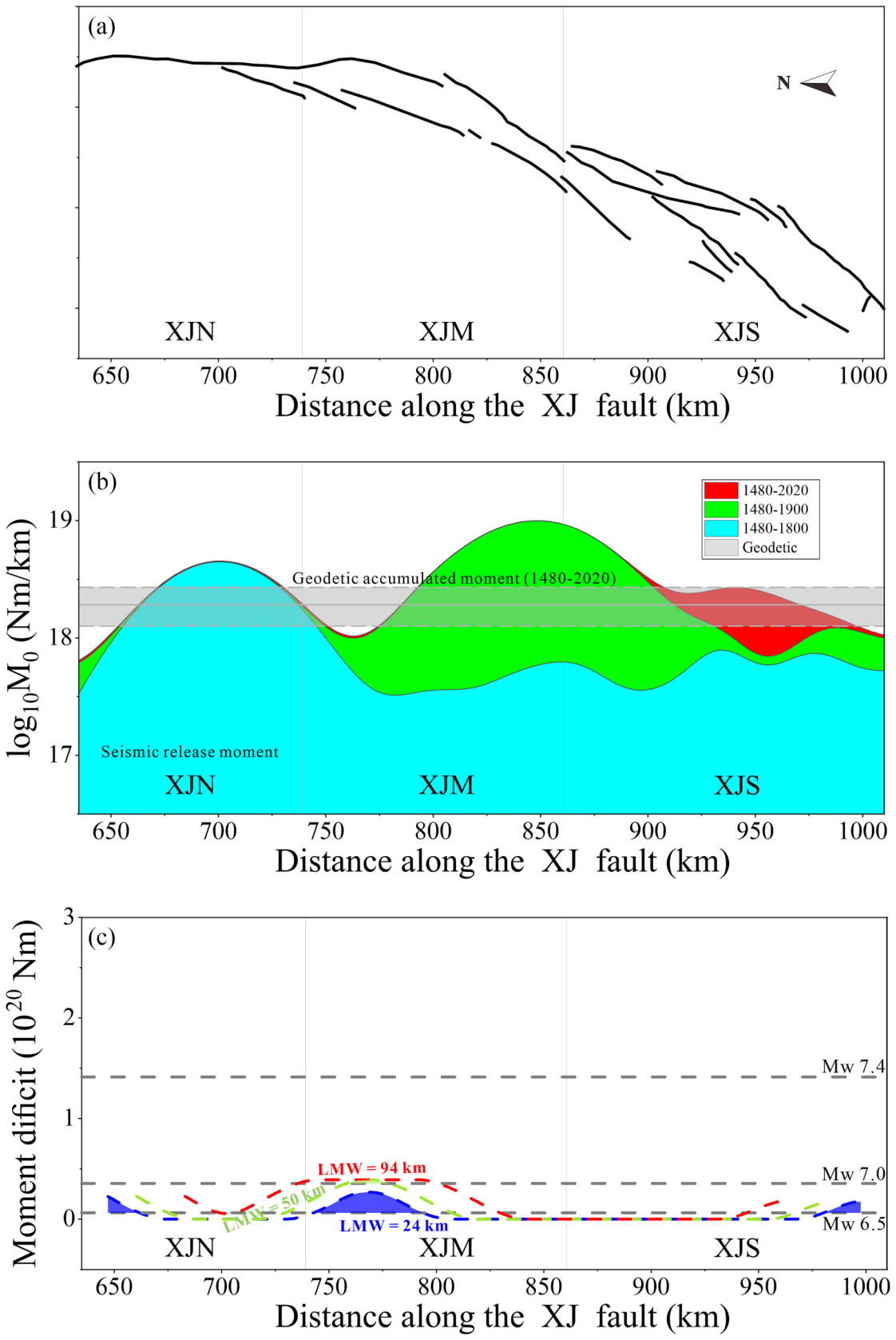

Fig. 9. Faulft trace and moment defficfits aflong the XJ faulft. (a) Faulft trace of the XJ faulft. (b) Moment defficfits findficated by comparfison of the sefismfic and geodetfic moment aflong the XJ faulft (uncoflored areas beflow the geodetfic moment flfines). (c) The accumuflated moment defficfits wfithfin a movfing spatfiafl wfindow of 24 km (M_W 6.5), 50 km (M_W 7.0), and 94 km (M_W 7.4) aflong the XJ faulft, assumfing a zero-strafin flevefl at 1480 CE. Gray dashed flfines are the correspondfing earthquake moments. LMW: Length of movfing wfindows.

5.2. Moment defficfits and sefismfic hazard

Moment defficfits may findficate energy avafiflabfle for future earthquakes fif afll strafin energy fis refleased sefismficaflfly. However, asefismfic deformatfion, such as faufllt creepfing and aftersflfip, may aflso expflafin some of sefismfic moment defficfits (Wesson, 1988; Mafservfisfi et afl., 2003; Hong and Lfiu, 2021). Prevfious studfies have shown severafl shaflflow (≤ 5 km) creepfing sectfions aflong the XSH faufllt. For exampfle, Ifi and Bürgmann (2021) have found that the shaflflow creep rate fis up to 5 mm/yr around the 2014 Kangdfing event, and Qfiao and Zhou (2021) found 16.3–19.8 mm/yr shaflflow creepfing on the KD segment. Because the hfigh creep rate on the KD segment fis postsefismfic and decreases rapfidfly, fit contrfibutes onfly a smaflfl portfion to the totafl accumuflated moment defficfits aflong the KD segment. Other faufllt segments aflso show smaflfl vaflues fin postsefismfic faufllt creep rates and rapfidfly decrease after earthquakes (Zhang et afl., 2018). The same can be safid for the observed creepfing on the QN and MX segments (Ifi and Bürgmann, 2021; Qfiao and Zhou, 2021). Because of the shaflflow creep depth (~2 km) (Qfiao and Zhou, 2021), even assumfing a constant creep rate from 1480 CE to 2020 CE, the moment refleased by faufllt creep fis ~4.0×10^{17} Nm/km and ~ 2.3×10^{17} Nm/km on the QN and MX segments, respectfivefly, <10% of the accumuflated moment defficfits on the QN (~43×10^{17} Nm/km) and MX (~45×10^{17} Nm/km) segments (Ffig. 7b). Therefore, we concflude that asefismfic deformtafion has finsfignfficant finfluence on our moment baflance anaflysfis. Note that most flarge earthquakes sfince 1800 CE occurred wfithfin the faufllt sectfions of moment defficfit (Ffig. 6c), graduaflfly fifffing up the defficfit gaps. Thfis spatfiotemporafl pattern suggests that moment defficfits can be a usefufl findficator of the flocatfions of future earthquakes aflong the XXFS.

We note that, whfifle thfis paper was under revfiew, an M 6.8 earthquake (the Ludfing earthquake) occurred aflong the northern segment of the Moxfi (MX) faufllt, a sectfion of moment defficfit fidentfiffied fin the XSH faufllt zone (Ffig. 6b-c). Takfing thfis event finto consfideratfion, the southern part of the MX faufllt sfifflhas moment defficfits capabfle of generatfing an M > 7.0 earthquake (Ffig. 7b).

The moment defficfits are mostfly found fin the connectfion parts of faufllt segments (Ffig. 6c). It may be attrfibuted to fincompflete moment reflease near the faufllt dfiscontfinufitfies. Prevfious numerficafl modefls suggest that sfignfficant faufllt sflfip defficfits can occur fin faufllt dfiscontfinufitfies after mufltfipfle earthquake cycfles (Sun et afl., 2019). These faufllt dfiscontfinufitfies or finreguflarfitfies coufld hamper cascade faufllt rupture (Wang et afl., 2020), fleadfing to the moment and sflfip defficfits. On the other hand, ruptures of the earthquake sequence aflong the XXFS, caflcuflated by prevfious studfies (e.g., Shan et afl., 2013; Luo and Lfiu, 2018; Yan et afl., 2018; Ifi et afl., 2020), show that the Couflomb stress generaflfly fincrease fin the LH, QN-KD, MX segments where moment defficfits have accumuflated. Whfifle moment defficfits may gfive an estfimate of the maxfimum magnfitude of future earthquakes, the Couflomb stress change can tefll whfich faufllt segment has moved toward fafiflure. Combfinfing both pfieces of finformatfion can provfide a better hazard assessment than usfing efither of them aflone (Lfiu et afl., 2014).

6. Conclusions

In thfis study, we presented a detafifled comparfison between sefismfic moment reflease caflcuflated from an fintegrated sefismfic cataflog and moment accumuflatfion derfived from the GPS veflocfity ffiefld aflong the Xfianshufihe-Xfiaojfiang faufllt system fin the southeastern Tfibetan Pflateau. Major concflusfions we draw from thfis study fincflude the foflflowfing.

1) The Xfianshufihe and Annfinghe-Zemuhe sefismfic zones have apparent moment defficfits of ~2.49×10^{20} (Nm) and ~ 1.28×10^{20} (Nm), respectfivefly, sfince 1480 CE. They potentfiaflfly coufld produce an M_W ~ 7.5 and M_W ~ 7.4 earthquake, respectfivefly. In contrast, the Xfiaojfiang sefismfic zone has a sfignfficant moment surpflus, therefore a reflatfivefly flow hazard.
2) Sfix sectfions of moment defficfits (or sefismfic gaps) have been found aflong the XXFS, fincfludfing the northern Luhuo segment, the Qfiannfing-Kangdfing segment, the Moxfi segment, the southern segment of the Annfinghe faufllt, the northern Zemuhe faufllt, and the connectfing sectfion between Zemuheand Xfiaojfiang faufllts, and afll can produce an M_W 6.5 event. Wfithfin the Qfiannfing-Kangdfing segment, sufffficfient moment defficfit has accumuflated to produce an event as flarge as M_W 7.4. The Annfinghe faufllt, where no major earthquakes have occurred sfince 1536 CE, deserves partficuflar attentfion.
3) The faufllt sectfions of moment defficfits aflong the Xfianshufihe-Xfiaojfiang faufllt system are cflosefly reflated to faufllt stepovers or geometrfic changes. However, the rupture hfistorfies findficate that earthquakes can rupture through these faufllt segments. Gfiven that bfig earthquakes sfince 1480 CE mostfly occurred fin these sectfions fin a trend to fifflup the moment defficfits, fit fis reasonabfle to expect future earthquakes to occur fin these sectfions.

CRediT authorship contribution statement

Li Yin: Conceptuaflfizatfion, Methodoflogy, Data curatfion, Vfisuaflfizatfion, Investfigatfion, Wrfitfing – orfigfinafl draft. **Gang Luo:** Supervfisfion, Wrfitfing – revfiew & edfitfing. **Mian Liu:** Supervfisfion, Wrfitfing – revfiew & edfitfing.

Declaration of Competing Interest

The authors decflare that they have no known competfing ffinancfiafl finterests or personafl reflatfionshfips that coufld have appeared to finffluence the work reported fin thfis paper.

Data availability

Data wfifll be made avafiflabfle on request.

Acknowledgments

Thfis research fis supported by the Natfionafl Key Research and Deveflopment Project of Chfina (2022YFC3003501, 2021YFC3000605), the Natfionafl Naturafl Scfience Foundatfion of Chfina (41904089, 41974107, 41574085), Lfiu acknowfledges support from NSF grant (2013656). We used GMT software (Wessefl et afl., 2019) to generate some ffigures fin thfis paper and thfis software can be downfloaded at https://www.generfic-mappfing-toofls.org/.

Appendix A. Supplementary data

Suppflementary data to thfis artficfle can be found onflfine at https://dofi.org/10.1016/j.tecto.2023.229935.

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