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Potential pollen evidence for the 1933 M 7.5 Diexi earthquake and implications for post-seismic landscape recovery

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Abstract

The relationships between strong earthquakes, landslides, and vegetation destruction and the process of post-seismic recovery in tectonically active alpine valley areas have not been adequately documented. Here we show detailed pollen study results from a swamp located near the epicenter of the 1933 M 7.5 Diexi earthquake in eastern Qinghai-Tibetan Plateau (QTP) to reveal the impact of earthquake on vegetation, and the post-seismic recovery process. Based on 210Pb, 137Cs age model, the seismic event layer is well constrained. The earthquake event corresponds stratigraphically to a zone with the lowest pollen concentrations, the lowest pollen diversity, and a high frequency of non-arboreal pollen. Elaeagnaceae scrubs rapidly developed in post-seismic landscape recovery processes, which is important for reducing soil erosion and landslide activities. Natural ecological recovery is slow due to increasing human activities and historical climatic fluctuations.

1. Introduction

Strong earthquakes that occur in tectonically active areas of high mountains and steep valleys often trigger large landslides, strip the mountains, and cause vegetation destruction and ecosystem degradation, consequently affecting earth biogeochemical cycles (e.g. Jin et al 2016, Wang et al 2016, Frith et al 2018). Post-seismic natural revegetation on the exposed landslide is helpful to reduce landslide activities and soil erosion. For example, the M 8.0 Wenchuan Earthquake on May 12, 2008, caused vegetation destruction up to 1249.5 km², of which shrubs comprised the largest proportional area (Cui et al 2012). Post-seismic vegetation restoration in the disaster area is a dynamic process, and the recovery is not complete even now (e.g. Chen et al 2012, Cui et al 2012, Wang et al 2014, Jiang et al 2015). Thus, the process and degree of vegetation restoration needs to be monitored. However, there is a lack of effective and continuous monitoring method in the long time scales. Palynology provides an important proxy when studying vegetation succession.

Palynological analysis is traditionally used as a palaeoecological tool (e.g. Chen et al 2015, Huang et al 2018). Strong earthquakes may change vegetation, which in turn may be registered in changes in pollen assemblages, pollen concentrations, and the occurrence of pioneer pollen taxa within sediments (e.g. Cowan and Mcglone 1991, Mathewes and Clague 1994, Hughes et al 2002, Leroy et al 2009, 2010). Furthermore, little attention was paid to the post-seismic landscape recovery when palynology was used in paleoseismology.

The 1933 M 7.5 Diexi Earthquake is a catastrophic event with the loss of over 10 000 lives in eastern Tibet (figure 1) (e.g. Chai et al 1995, Chang et al 1938, Tang et al 1983, China Earthquake Administration 1999, Ren et al 2018). In this earthquake, Diexi Old Town totally fell into the Minjiang River, and huge landslides blocked the Minjiang River and formed twelve dammed lakes (Chai et al 1995). Two months after the earthquake, flooding triggered by dam failure caused more than 2500 deaths along the Minjiang River, and this secondary disaster shocked the world (e.g. Chai et al 1995, Tang et al 1983, Shen...
The earthquake cracked the bedrocks and generated a large amount of loose sediments, which provided favorable conditions for the occurrence of landslides and debris flows. Eighty-four years later, a huge landslide-debris avalanche occurred on the morning of June 24, 2017 (e.g. Fan et al 2017, Su et al 2017). The secondary disasters caused by the original strong earthquakes are far-reaching (Su et al 2017). The seismogenic fault for the Diexi earthquake has been a controversial subject for many years. Numerous researchers attributed it to the southern part of the Minjiang fault (Chen et al 1994), but recent detailed studies of surface rupture show the Songpinggou normal fault to be the seismogenic fault (Ren et al 2018).

Here we conducted detailed pollen analysis of a 27-cm-thick sediment monolith in the Yangwan section, Songpinggou River, about 3 km away from the epicenter of the Diexi earthquake. A robust chronology was established from short-lived radioisotopes (210Pb and 137Cs) dating. The palynological records of the past 150 years provide a new perspective for exploring the impact of the strong earthquakes on vegetation degradation and ecosystem deterioration. The post-seismic revegetation and landscape recovery processes are also discussed, in order to provide a theoretical basis for enhancing artificial intervention and reducing secondary disasters in the study region.

2. Study area

The upper reaches of the Minjiang River (31°26′-33°16′N, 102°59′-104°14′E, ca. 337 km in length) are located in the transition zone from eastern QTP to Sichuan Basin (He et al 2006). There are two major mountain ranges: the Min Shan and Longmen Shan. The geomorphology is characterized by alpine valleys, ranging in elevation from 870 to 6253 m with an incision depth of 800 to 3000 m. The mountainous topography results in a large degree of vertical variation in precipitation and air temperature (Li et al 2006). Its northern area is extremely cold, with an altitude of more than 2000 m a.s.l. and annual precipitation of 730–840 mm; the southern area is arid valley with an altitude of 1200–2000 m a.s.l. and annual precipitation of 420–566 mm. More than 80%–90% of annual precipitation falls from May to October.

The upper reaches of Minjiang River are a typical and key mountainous region with an upland ecosystem vulnerable to alpine and tectonic processes (Li et al 2006). The regional vegetation belongs to the Abies faxoniana, Picea asperata, Pinus densata, and Tsuga chinensis forest district according to the Vegetation Map of China (Zhang et al 2007). The vertical zonation of vegetation changes distinctly with increasing elevation, mainly consists of small-leaf, arid shrubs (1300–2200 m a.s.l.), coniferous and broad-leaved mixed forests, evergreen and deciduous broad-leaved mixed forests (2000–2800 m a.s.l.), Picea and Abies forests (2800–3600 m a.s.l.), and alpine shrubs and meadows (> 3600 m a.s.l.) (Ma et al 2004, Zhang et al 2007). Strong earthquakes in this area often induce frequent landslides, which significantly destroy the natural vegetation (Fang et al 2008, Yang et al 2018).

Eastern Tibet is also in the middle segment of the ‘north-south seismic zone’ in China, including Longmen Shan, Minjiangiang and Huya faults (e.g. Zhang et al 2010, Zhang 2013). Strong earthquakes are frequent, such as the 2017 M 7.0 Jiuzhaigou, 2013 M 7.0 Lushan, 2008 M 8.0 Wenchuan, 1976 Songpan–Pingwu (M = 7.2, 6.7 and 7.2), and 1933 M 7.5 Diexi earthquakes (figure 1). The bedrock in the study area is shallow metamorphic clastic rocks, such as Silurian carbonaceous phyllite, sericite quartz schist, and carbonatite. Phyllite is often strongly weathered and broken (Dai et al 2011, Xu et al 2015).

3. Materials and methods

Songpinggou River is a tributary of Minjiang River, which is nearly parallel to Songpinggou Fault (Ren et al 2018). It flows from northwest to southeast with a drainage area of 669 km² (Su et al 2017, figure 2). The Yangwan section (32°4′26.8″N, 103°38′48.7″E, 2264 m a.s.l) is located in a small intermontane basin. It is now in a relatively stable marsh environment. Considering frequent landslides and earthquakes in the study area, it is an ideal place to study earthquakes using palynology and sedimentology. The main species at the coring site are Kobresia and Typha. The upper ~27 cm of a sediment monolith were excavated, photographed, and stored in a cold room (4 °C) at the Institute of Geology, China Earthquake Administration (IGCEA) in 2016. The sediments are silt, and silty sand with occasional small gravels. The sediments were sub-sampled at 1-cm interval for pollen and total organic carbon (TOC) analysis. Moss samples were also collected for pollen analysis in order to explore the relationships between modern vegetation and pollen assemblages (table 1, figure 3).

Approximately 5–18 g of each subsample was processed following palynological procedures (Xu et al 2013), including treatments with 15% HCl and 3% NaOH, heavy liquid flotation with KI solution, treatments with 40% HF and 15% HCl, and sieving (7 µm) if necessary. For the moss samples, no acetylation treatment was done because, the pollen grains were clean and contained no protoplasm when viewed under a microscope. One tablet of Lycopodium spores was added to each sample in order to estimate the pollen concentration. The prepared specimens were mounted in glycerol for pollen identification. For moss samples, approximately 450 pollen grains (excluding spores) per sample were counted and were used as the pollen sum for pollen percentage calculation. Percentages of spores were calculated based on the total sporepollen count. For Yangwan section, the number...
Figure 1. Map showing the study area and isoseismal data of the 1933 Diexi earthquake (dashed lines, Tang et al. 1983). Major active faults and seismicity are also displayed (adapted after Ren et al. 2018). Abbreviations for active faults: HYF, Huya fault; LMSF, Longmen Shan fault; LRBF, Longriba fault; MJF, Minjiang fault.

Table 1. Detailed information of 11 modern pollen sites collected along the Songpinggou River. The sample number is the same as in figure 3(b).

| Sample No. | Lat. (N) | Long. (E) | Alt. (m) | Type       | Main vegetation types          |
|------------|----------|-----------|----------|------------|-------------------------------|
| B31        | 32°12.61' | 103°28.94' | 2936     | moss       | Mixed broadleaf-conifer forest|
| B30        | 32°07.64' | 103°36.22' | 2436     | moss       | Mixed broadleaf-conifer forest|
| B15        | 32°02.91' | 103°41.10' | 2303     | moss       | Arid valley shrubs            |
| B29-3      |          | 2315      |          | moss       | Arid valley shrubs            |
| B29-2      |          | 2256      |          | moss       | Arid valley shrubs            |
| B29-1      | 32°02.64' | 103°40.42' | 2191     | moss       | Arid valley shrubs            |
| B18-1      | 32°02.69' | 103°40.01' | 2230     | moss       | Arid valley shrubs            |
| B18-2      |          | 2201      |          | moss       | Arid valley shrubs            |
| B18-3      |          | 2170      |          | moss       | Arid valley shrubs            |
| B16        | 32°04.56' | 103°43.08' | 2203     | moss       | Arid valley shrubs            |
| B17        | 32°03.04' | 103°39.97' | 2149     | moss       | Arid valley shrubs            |

Lat. = Latitude, Long. = Longitude, Alt. = Altitude.

is about 150 grains due to the low pollen concentrations. Pollen diagrams were plotted using Grapher software, and all samples were grouped by cluster analysis (CONISS). TOC contents were measured with an Elementar Rapid CS analyzer following procedures described in (Xiao et al. 2006). All samples were processed at the State Key Laboratory of Earthquake Dynamics, IGCEA.

The age model is based on a combination of $^{210}$Pb and $^{137}$Cs dating methods (figure 3(a)). The bulk-weighted, dry samples were sealed in plastic test tubes with caps for $^{210}$Pb dating by gamma spectrometry with well-type coaxial low background intrinsic germanium detectors (Ortec HP Ge GWL series) at the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences. The $^{210}$Pb activity was determined via gamma emissions at 46.5 keV. The emissions of $^{226}$Ra with the 295 keV and 352 keV γ-rays emitted by its daughter nuclide $^{214}$Pb were determined after 3 weeks of storage in sealed containers to allow for radioactive equilibrium. The radioactivity of $^{137}$Cs was measured with the 662 keV photo peak. The counting time of $^{137}$Cs and $^{210}$Pb is typically in the range of 14 to 24 h, providing a measurement precision of 5% to 10% at the 95% level of confidence. The supported $^{210}$Pb in each sample was assumed to be in equilibrium with the in-situ $^{226}$Ra, and unsupported $^{210}$Pb activities ($^{210}$Pb$_{ex}$) was determined from the difference between the total $^{210}$Pb and the supported $^{210}$Pb activity (Pratte et al. 2019).
Figure 2. (a) Distribution map of modern vegetation along the Songpinggou River (Zhang et al. 2007), locations of the surface pollen sites, and photos of b-g. (b-c) Photos showing the landscape of the upper part of Songpinggou River (site location 32°12′36.4″N, 103°28′56.0″E, 2936 m a.s.l.), note mixed coniferous and broad-leaved forests mainly *Picea*, *Abies* and *Betula* etc. (d-e) Photos showing the landscape of the middle part of Songpinggou River (site location 32°09′07.1″N, 103°34′24.2″E, 2620 m a.s.l.), note mixed coniferous and broad-leaved forests mainly *Picea*, *Abies* and *Hippophae* etc. In the middle of the photo (e) is the sea buckthorn with small orange berries. (f) Coring sites in Yanwan (core location 32°4′26.8″N, 103°38′48.7″E, 2264 m a.s.l.). (g) Xinmo landslide on June 24, 2017 (landslide location 32°4′47″N, 103°39′46″E, range from 3431–2280 m a.s.l, Fan et al. 2017).

4. Results

4.1. Age model

Unsupported $^{210}$Pb$_{ex}$ activities display an exponential decrease with depth ($R^2 = 0.93$) making it possible to apply the Constant Initial $^{210}$Pb Concentration (CIC) model for dating of the sediment layers. It gives a constant sedimentation rate of 1.84 mm yr$^{-1}$ (5.48 yr cm$^{-1}$) (figure 3(a)). The bottom age is estimated to be ca. A.D. 1870.

The value of $^{137}$Cs increases rapidly at 7–6 cm (figure 3(a)), which very likely represents A.D. 1963, the year of maximum fallout from the testing of nuclear weapons (Appleby 2001). The $^{137}$Cs peaks at 4–3 cm, which probably represents A.D. 1986, the year of the Chernobyl accident (Chen et al. 2006).
Figure 3. (a) Lithology of Yanwan section and $^{210}$Pb/$^{137}$Cs dating model. (b) Pollen percentage diagram of moss samples along the Songpinggou River.

The corresponding deposition rate was 1.33 mm yr$^{-1}$ (7.54 yr cm$^{-1}$). The peak value of $^{137}$Cs was significantly higher in A.D. 1986 than in A.D. 1963, probably due to high content of organic matters for the upper layer and the special alpine topography. The eastern QTP is featured by alpine valleys. Similar $^{137}$Cs dating results have also been documented in other geological records in China, e.g. Bosten Lake, Xinjiang (1048 m a.s.l., Chen et al. 2006), Gonghai Lake, Shanxi (1860 m a.s.l., Chen et al. 2015), and Lake Qinghai (3194 m a.s.l., Jin et al. 2010).

Combing the $^{210}$Pb and $^{137}$Cs dating results, we determined that the stratigraphic position of the 1933 Diexi earthquake was limited to 10–15 cm for Yanwan.

4.2. Modern pollen assemblages along the Songpinggou River

Two pollen assemblage zones can be identified based on the variations in percentages of the main pollen taxa and modern vegetation type (figure 3(b)):

Zone I (2 samples, altitude > 2300 m): This zone is dominated by arboreal pollen taxa, such as Abies (38.8–40.5%), Picea (10.7–21.5%), Pinus (5.9–18.5%), Tsuga (1.3–2.9%), Quercus evergreen (Quercus E., 3.0–10.7%), and Betula (3.0–8.8%). Pollen of shrubs and herbs are present at low frequencies, including Artemisia (1.0–7.6%), Hippophae (4.4–11.0%), and Dipsacaceae (0–7.6%).

Zone II (9 samples, altitude between 2100 and 2300 m): This zone is dominated by shrubs and herbs, such as Artemisia (17.7–61.5%), with the presence of Asteraceae (0–10.4%), Amaranthaceae (0.8–5.5%), Hippophae (0–5.1%), and Elaeagnus (0–6.3%). Arboreal pollen taxa are significantly lower than those in zone I, such as Abies (3.3–19.3%), Picea (0.4–3.5%), Pinus (5.9–22.2%), Tsuga (1.1–9.1%), Quercus E. (2.1–12.2%), Betula (2.2–21.1%), and Juglans (0–3.3%). The contents of fern spores increase, such as Polypodiaceae (1.8–47.8%) and Selaginella (0.3–4.7%).

Apparently, herbaceous pollen taxa such as Artemisia dominate in the area below 2300 m in elevation. Mixed coniferous and broad-leaved forests develop above 2300 m (figure 3(b)). Modern pollen assemblages well reflect the relationship between vegetation and altitude, although it could be influenced by human activities to some extent. Shrubs mainly Elaeagnaceae (up to 11.0%) distribute on slopes, with an altitude of 2300–2900 m, and the percentage is much lower than that in Yanwan section,
which may be ascribed to special topography. The distribution and transportation of modern pollen in high mountain and steep valley areas are greatly affected by steep slopes (Zhang et al. 2017).

4.3. Pollen results in the Yanwan section

Sixty pollen taxa were identified. Pollen assemblages are dominated by shrub and herb pollen taxa (such as Elaeagnus, Hippophae, Artemisia, Asteraceae, and Amaranthaceae), whereas arboreal pollen taxa (such as Pinus, Picea, Abies, Quercus E. and Betula) are less abundant (figure 4, table 2). Some fern spores and algae are also commonly found (such as Polypodiaceae, Selaginella, and Spirogyra). Three pollen assemblage zones are distinguished based on the variations in percentages of the main pollen taxa and cluster analysis (figure 4, table 2):

Zone I (27–15 cm): Pollen concentrations vary between 74 and 234 grains · g⁻¹. The TOC content varies between 0.42% and 0.53%, mean 0.47%. Herb and shrub pollen occupied the largest proportion. Commonly found taxa include Artemisia (9.5–25.8%, average 15.6%), Hippophae (4.8–19.5%, average 9.7%), Asteraceae (4.1–12.3%, average 7.5%), Amaranthaceae (3.1–11.5%, average 7.8%), Elaeagnus (0–13.3%, average 4.8%), Cyperaceae (0–11.0%, average 4.2%), and Polygonaceae (1.0–9.5%, average 3.9%). The arboreal pollen are less abundant, mainly Abies (1.5–16.3%, average 6.1%), Picea (0.7–9.8%, average 5.7%), Pinus (4.0–8.5%, average 6.4%), Tsuga (0–4.0%, average 1.2%), Quercus E (0.8–11.0%, average 7.2%), and Betula (0.8–6.0%, average 3.0%). Fern spores are frequently found, including Polypodiaceae (9.7–21.6%, average 14.9%) and Selaginella (0.6–6.0%, average 3.2%).

Zone II (15–10 cm): This zone is characterized by the lowest pollen concentrations ranging from 59 to 97 grains · g⁻¹ and the lowest pollen diversity. The TOC content varies between 0.52% and 0.70%, mean 0.61%. The herb pollen are also the most abundant. Amaranthaceae, Asteraceae and Hippophae pollen increase; Artemisia pollen decrease. The broad-leaved tree pollen decrease. Fern spores (20.8–34.7%, average 25.1%) increase to the highest value of the section.

Zone III (10–0 cm): Pollen concentrations vary from 177 to 6567 grains · g⁻¹, which are the highest in the whole section. However, the pollen concentrations decrease exponentially with depth. The TOC content (0.93–14.36%) also shows a downward exponential decrease with depth. The topmost sample of this zone is characterized by high content of Cyperaceae (55.6%), which is consistent with the surrounding marsh vegetation. The arboreal pollen (e.g. Picea and Betula) decrease to the lowest value in the section. Shrubs become the most abundant. Elaeagnus percentages (4.2–41.7%, mean 22.2%) follow a bell shape curve towards the top, but Hippophae (3.7–53.7%, mean 21.8%) shows a decreasing trend upward in this zone. Herbs and ferns decrease to the lowest value in the section. The vegetation changed into shrubs at the expense of herbs.

5. Discussion

The pollen data of the Yanwan section reflect regional vegetation in pollen zone I: mixed coniferous and broad-leaved forests grew at higher elevations; shrubs and herbs distributed at lower elevations. Zone II is abnormal for the lowest pollen concentrations and lowest pollen diversity. Shrubs, mainly Elaeagnaceae, dominate pollen zone III, suggesting significant vegetation change during the past decades. Here we try to interpret the pollen data from two aspects.

5.1. Pollen assemblages record the 1933 M 7.5 Diexi earthquake

Previous studies on modern pollen preservation in soil profiles from northeastern QTP indicate that pollen concentrations in a stratigraphic profile decrease from top to bottom, which is attributed to high soil pH values, strong oxidation, and biodegradation by fungi and bacteria (Li et al. 2005). In the Yanwan section, the pollen concentrations and TOC content also decrease exponentially with depth except in zone II that is characterized by the lowest pollen concentrations and lowest pollen diversity (figure 4). This may possibly be attributed to climate change, human activities, or sudden catastrophic events, which will be discussed below.

Global temperatures are currently rising (Moberg et al. 2005, Ge et al. 2013), and the global warming trend is about 0.07 °C per decade over the past one hundred years (Jones and Moberg 2003, figure 5(a)). There are temporal and spatial differences in terms of precipitation patterns during the past two hundred years (figure 5). The northeastern QTP and northern China showed a trend of increasing rainfall, especially in the past 50 years (Shao et al. 2005, Yang et al. 2014, Chen et al. 2015, figures 5(b) and (c)). There are several dry and pluvial periods in the southeastern QTP and southwestern China (Gou et al. 2013, Xu et al. 2019). However, the eastern QTP is getting drier, with several obvious drought periods occurring in the 1820s, 1860s, 1920s, 1960s and 1990s (Liang et al. 2006, Linderholm and Brauning 2006, figure 5(d)). The pollen of shrubs and herbs increase and arboreal pollen and fern spores decrease from bottom to top in the Yanwan section (figure 4), which is consistent with a drying trend as suggested by tree ring records (Linderholm and Brauning 2006). However, climate change cannot fully explain the abrupt change in pollen zone II.

Vegetation destruction in the upper reaches of Minjiang River occurred at least one thousand years ago (Zhang 1992). According to Marco Polo Travel Notes, approximately 600 years ago, the valleys of the main stream and tributaries of Minjiang River were
Table 2. Summary of the vegetation history and pollen zones of Yanwan section.

| Pollen zone (depth cm) | Age (AD)   | Total number of pollen taxa | Description                                                                                     | Inferred local vegetation                                      |
|------------------------|------------|-----------------------------|-------------------------------------------------------------------------------------------------|------------------------------------------------------------------|
| I (27–15 cm)           | 1870–1930  | 41                          | Herb and shrub pollen occupy the largest proportion, including Artemisia, Hippophae, Asteraceae, Amaranthaceae, Elaeagnus, Cyperaceae, and Polygonaceae. The arboreal pollen are less abundant with the presence of Abies, Picea, Pinus, Tsuga, Quercus E, and Betula. Fern spores are frequently found. | Regional vegetation: mixed coniferous and broad-leaved forests grew at higher elevations; shrubs and herbs distributed at lower elevations. Elaeagnus decreased upwards. |
| II (15–10 cm)          | 1930–1965  | 32                          | Amaranthaceae, Asteraceae and Hippophae increase; Artemisia decrease. The broad-leaved tree pollen decrease. Fern spores increase to the highest value of the section. This zone is marked by the lowest pollen concentrations and the lowest pollen diversity. | Broad-leaved forests increasingly opens. Hippophae increased. Conifers on higher elevations were less affected by the earthquake. |
| III (10–0 cm)          | 1965–2016  | 49                          | Herbs and ferns decrease to the lowest value. The topmost sample with the highest content of Cyperaceae reflect the surrounding marsh vegetation. The arboreal pollen (e.g. Picea and Betula) decrease to the lowest value. Shrubs become the most abundant. Elaeagnus follow a bell shape curve towards the top, but Hippophae show a decreasing trend upward in this zone. | The vegetation changed into shrubs mainly Elaeagnaceae, at the expense of herbs. Spruce and fir decline may be related to human deforestation since 1960s. |

Figure 4. Synthetic pollen diagram of Yanwan section with selected pollen taxa, total pollen concentrations, and TOC contents plotted against age (AD). Note the total pollen concentrations and TOC contents showed a downward exponential decrease with depth.
Figure 5. Diagram of changes in temperature and precipitation since AD 1800. (a) Temperature anomaly, note its rising trend, pink = China temperature anomaly (Ge et al 2013); black = Northern Hemisphere temperature anomaly (Moberg et al 2005), and red = the instrumental record of global air temperature anomaly updated to 2018 (Jones and Moberg 2003). (b) Annual precipitation reconstructed from high resolution pollen data in North China (Chen et al 2015). (c) Reconstructed annual precipitation for the northeastern Qinghai-Tibetan Plateau (QTP) from tree-ring records (blue, Yang et al 2014; green, Shao et al 2005). (d) Drought index reconstructed from tree-ring width records in eastern QTP (Linderholm and Bräuning 2006). (e) Previous September to current June precipitation reconstructed from tree ring records in southeastern QTP (blue line = 11 points moving average) (Gou et al 2013). (f) Rainy season (May–October) precipitation reconstructed from tree ring cellulose oxygen isotope ($\delta^{18}$O) data in southwestern China (Xu et al 2019).

covered by boundless forests with a coverage of 50%; however, in the early 1950s, the forest coverage was reduced to about 30% (Guo and Tang 1995), suggesting a general trend of ecological degradation in this region. Moreover, in the 1960s, with the large-scale steelmaking activities associated with the Great Leap Forward movement, the forest was severely destroyed, resulting in the rapid decline of forest coverage to 18.8% in 1980 (Expedition of Minjiang River 1980, Guo and Tang 1995). In the late 1990s, the execution of two ecological protection policies of Natural Forest Protection and Grain for Green were beneficial
to the forest restoration in the upper reaches of Minjiang River (Li et al. 2006). On the other hand, the population in Maoxian County increased from 37300 in 1950 to 79208 in 1963, the fastest growth in history. In general, human activities and national policies have become the most important factors affecting the ecological environment in the upper reaches of Minjiang River since the 1950s (Li et al. 2006, Fang et al. 2018). The 137Cs peak value for A.D. 1963 occurred in the depth of 7–6 cm (figure 3(a)). Accordingly, the pollen changes recorded in zone II predate the periods of intense human activities. Therefore, human activities cannot be the main cause of this event.

The most likely cause of the abrupt changes in pollen zone II is the 1933 Diexi earthquake, a sudden catastrophic event. In this earthquake, many landslides occurred on the left bank of Songpingou River (Ren et al. 2018), causing severe vegetation destruction and ecological degradation. Consequently, sediments with scarce pollen grains were deposited in the Yanwan section, resulting in pollen assemblages characterized by low pollen concentrations, low pollen diversity, and high content of fern spores. Broad-leaved forests increasingly opens. Coniferous forests were less affected by the earthquake, which may be due to higher altitude distribution and deep roots. Herbs recovered more quickly after the earthquake. As reported in studies from the North Anatolian Fault, recent earthquakes are often associated with turbidite deposits and soil inwash and characterized by low overall palynomorph concentrations but high values of thick-exined pollen, fern spores, and fungal spores (Leroy et al. 2009). In other studies, meadows recovered fast and mixed coniferous and broad-leaved forests recovered most slowly after five years following the 2008 Wenchuan earthquake (Jiang et al. 2015).

5.2. Implications for post-seismic landscape recovery
In the Yanwan section, Elaeagnaceae (including Hippophae and Elaeagnus) pollen increase rapidly in pollen zone III, suggesting that Elaeagnaceae grew abundantly on denuded grounds caused by landslides in the Diexi earthquake (figure 4). Post-seismic natural revegetation on the exposed landslide scars is helpful to reduce further landslide activities (Huang and Fan 2013, Yang et al. 2018). The Elaeagnaceae shrubs recovered quickly after the Diexi earthquake, which plays an important role in ecological restoration and reducing soil erosion in major disaster areas.

Hippophae is a mesic deciduous shrub, an ideal plant for soil erosion control, land reclamation, wildlife habitat enhancement and farmstead protection (Rousi 1971, Li and Shroeder 1996, figure 2(e)). Elaeagnus mainly occurs in the Yangtze River valley to the south, but also in Northwest China. It can grow in diverse habitats at elevations of 50–3100 m, such as lakeshores, stream sides, rocky slopes, forests and scrublands (Sun and Lin 2010), Elaeagnus and Hippophae often grow on floodplains and barren land as pioneer plants (Schlütz and Lehmkuhl 2009), while tree species such as birch will develop and replace them in natural succession. These strong adaptabilities are mainly due to the deep root system, nitrogen-fixing functions, and wide ecological amplitude that these genera develop (Rousi 1971, Enescu 2014). Hippophae and Elaeagnus also have an appreciable nutritional and medicinal value (Bal et al. 2011).

Remarkably, Elaeagnus harbor nitrogen-fixing bacteria in their roots and can grow vigorously in low-nitrogen soils. This ability makes them extremely successful pioneer and invasive plants. It has been reported that they can become so dominant and self-perpetuating that they can even hinder the restoration of natural vegetation and limit the biodiversity in an area (Daehler 1998).

As discussed above, the dramatic increase in population occurred in the 1950s in Maoxian County. Human activities and national policies are the most important factors affecting the ecological environment in the upper reaches of Minjiang River (Li et al. 2006, Fang et al. 2018). The fragile ecological environment, intensifying human activities, and climatic fluctuations could lead to the slow recovery of natural vegetation in the earthquake-prone upper reaches of Minjiang River.

6. Conclusions
Detailed pollen data from the Yanwan section showed that the 1933 Diexi earthquake corresponded to the lowest pollen concentrations, the lowest pollen diversity, and high contents of non-arboreal pollen, indicating that the earthquake significantly damaged the local vegetation. The Elaeagnaceae pollen increased rapidly in post-seismic sediments, reflecting vigorous growth of this pioneer shrub on the denuded landslide scars or deposits. The documentation of this pattern of vegetation succession is important for the management of ecological restoration and controlling soil erosion in major disaster areas. Nevertheless, ecological monitoring should be strengthened due to the self-perpetuating Elaeagnaceae communities that may hinder complete vegetation recovery under certain conditions. With increasing human activities and climatic fluctuations, ecological recovery may be a slow and long-term process.

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Data availability statement

The data that support the findings of this study are available online at: https://doi.pangaea.de/10.1594/PANGAEA.910735.

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