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Editorial

Resolving Quaternary Tectonic Activity with High-Resolution Data in Space and Time

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Large earthquakes are among the most dangerous natural disasters with potentially devastating effects on society and infrastructure across the globe. In order to better understand earthquakes, research in active tectonics aims at quantifying crustal deformation throughout the active fault's earthquake cycles by studying geomorphic and stratigraphic evidence of recent and past earthquakes. The underlying assumption in this approach is that a fault's current and previous seismic behavior is representative of its future behavior. Constraining a fault's seismic behavior in such a manner requires high-resolution geomorphic and stratigraphic records that enable us to resolve the spatial and temporal characteristics of co-, post-, and interseismic phases, ideally over multiple earthquake cycles. Recent technological developments have dramatically increased not only the amount and resolution of topographic and geophysical survey data sets but also our ability to date stratigraphic units and geomorphic surfaces. These technological advances have enabled us to better understand the interplay between crustal deformation, earthquake ruptures, and their signature in geomorphic and stratigraphic records. In particular, the availability of high-resolution data sets from LiDAR, SfM, or geophysical surveys and the use of accurate dating methods such as cosmogenic or OSL dating allow us to quantitatively study surface deformation at high spatial resolution over large areas and at multiple time scales—from a few years to millions of years. In this special issue, we focus on the tectonic activity of active faults and the geomorphic processes in various tectonic regimes worldwide. It covers active tectonics, earthquake geology, remote sensing, tectonic geomorphology, Quaternary geochronology, geohazard, and seismology.

1. Introduction

The pioneer active tectonic studies are often rising from regions having suffered from earthquake disasters, such as the 1891 M 8.0 Nobi earthquake (Japan), the 1906 M 8.3 San Francisco (USA), and the 1920 Haiyuan M 8.5 earthquake (China). Professor B. Koto is one of the pioneer researchers that noticed the relationship between earthquake and fault through studies of the 1891 Nobi earthquake [1]. Professors Weng Wenyi and Xie Jiarong studied the 1920 Haiyuan earthquake, one of the first earthquake studies in China. However, the above studies were mostly qualitative. The investigation on the 1906 Great San Francisco earthquake might have been the first systematical study that deciphered the occurrence of earthquakes by correlating them to seismogenic structures—underlying active faults [2]. H. F. Reid formulated the elastic-rebound theory of the earthquake source, which remains the main model for understanding earthquake cycles and seismic hazard analyses [3]. Since then, the field of geology per se opened up new disciplines to link geologists and seismologists—active tectonics.

One century after the 1906 Great San Francisco earthquake, the amount and resolution of topographic and geophysical survey data sets, as well as our ability to date stratigraphic units and geomorphic surfaces have dramatically increased. Therefore, resolving Quaternary tectonic activity with high-resolution data in space and time is more timely than ever, hence this special issue carried by Dr. Z. K.

Ren et al., O. Zielke et al., M. L. Chevalier et al., E. Nissen et al., and H. Zhang et al. All of us have been leaders in active tectonic studies for many years (e.g., [4–10]). In 2016, we held sessions at AOGS and AGU meetings entitled "Active Tectonics and Paleoseismology from High Resolution Topography and Chronology" and "High-Resolution Topography and Dating in Active Tectonics," respectively. In 2018, we were invited to write a review article "Active Tectonics in 4D High-Resolution" for the Journal of Structural Geology for the 40th Anniversary Special issue: "Back to the future: 40 years of structural geology and beyond" [10]. That session continued at the 2019 AGU meeting, entitled "Resolving Tectonic Activity with High-Resolution Data in Space and Time." During those meetings, the participants urged us to organize a special issue in a highly ranked scientific journal to gather recent advances in active tectonics to better understand the interplay between crustal deformation, earthquake ruptures, and their signature in geomorphic and stratigraphic records.

This special issue compiles 12 manuscripts advancing our understanding of active tectonics, linked to strike-slip, normal, and thrust faults worldwide (Figure 1). These articles cover a wide range of topics from active tectonics, seismology, geological evolution, coseismic landslides, using high-resolution data sets from Light Detection and Ranging (LiDAR), Structure from Motion (SfM), geophysical surveys, and seismic tomography, as well as precise dating methods such as cosmogenic or OSL dating (Figure 2). Such high-resolution topographic data are key for mapping of active faults, offset measurements, geohazard assessment, and seismogenic structure detection for moderate earthquake.

The published papers may be classified into the following three groups.

2. Active Tectonic Studies Using High-Resolution Topographic Data Sets

2.1. Surface Rupture Mapping. The 1931 M 8.0 Fuyun earthquake produced distinct coseismic surface rupture along the Fuyun fault. Liang et al. [11] remapped the coseismic surface ruptures of the 1931 M 8.0 Fuyun earthquake based on 1 m resolution DEM from Unmanned Aerial Vehicles (UAV) based on SfM photogrammetry. They obtained the along-strike-slip distribution of the rupture by identifying and measuring offset gullies. By analyzing the offset cluster characteristics, they identified four paleoearthquakes including the latest 1931 Fuyun earthquake. The coseismic surface rupture zone was segmented into four segments, with high offset gradient in the step area. They propose that the 1931 Fuyun earthquake was a cascade rupture formed by four rupture segments.

The Xianshuihe fault zone is one of the most active left-lateral strike-slip fault in China. The Zheduotang fault is located in the Kangding segment within the Xianshuihe fault zone. Based on high-resolution DEMs from stereo pair of satellite and UAV images, Ma et al. [12] mapped in detail the trace of the active Zheduotang fault segment and measured the total length of the 1955 M 7.5 Kangding earthquake as 46 km. That earthquake ruptured the entire ~30 km long SE segment. By analyzing the slip distribution and cumulative offset probability density (COPD), they proposed that the earthquake pattern is a uniform slip model along the SE segment. They also analyzed the seismic hazard potential to be higher on the NW segment than the SE segment of the Zheduotang fault.

Active tectonic studies in the Loess Plateau are more challenging than those in Fuyun, for example, due to the difficulty in preserving surface ruptures. One historical M 8.0 earthquake occurred in Tianshui, Gansu, China, in 1654. The seismogenic fault of this event remains controversial due to the lack of geologic and geomorphologic evidence and precise chronologic constraints. Based on high-resolution UAV DEM, ^{14}C dating, and field investigations, Xie et al. [13] determined the age of the latest slip on the Lixian-Luojiapu fault and the corresponding surface rupture range. They suggested that the seismogenic structure of the Tianshui M 8.0 earthquake both include the Lixian-Luojiapu and the West Qinling faults. They also suggested that strain accumulation on the Lixian-Luojiapu fault poses a high seismic risk in this region, which should be given more attention.

2.2. Fault Slip Rates and Paleoseismology Studies. Fault slip rates are key quantitative parameters to evaluate fault activity and seismic hazard [6, 10]. In this special issue, based on high-resolution UAV DEM and ^{10}Be cosmogenic dating, Chen et al. [14] obtained the slip rate along the central segment of the dextral Elashan fault near Qinghai Lake, NE Tibetan Plateau, as 2.6 ± 1.2 mm/yr. They suggest that slip rates of the major strike-slip faults around Qinghai Lake have remained approximately constant since the late Pleistocene and that the kinematic deformation of the NE Tibet interior behaves as a nonrigid bookshelf model that consists of counterclockwise rotation (~0.8° Myr-1) and distributed thrusting.

The Tancheng-Lujiang fault has been the most active fault zone in eastern China. The Anqiu–Juxian fault represents the most recently active fault and has the clearest surface traces and the highest seismic risk. Zhang et al. [15] comprehensively analyze the kinematic characteristics of the Jiangsu segment of the Anqiu–Juxian fault using field geological surveys, trenches, shallow seismic reflection surveys, combined borehole section exploration, and middepth seismic reflection surveys. They suggested the two-stage evolution of the fault activity of the western and eastern branches within the fault zone. They also reported the vertical slip rates of the Anqiu–Juxian fault.

Paleoseismology has been one of the main research fields in active tectonics, being a joint research field involving tectonic geomorphology, sedimentology, and stratigraphy. Trench excavation has been the main technique in paleoseismology since the 1970s. In this special issue, Gao et al. [16] study the paleoseismicty of the Litang fault, which is the seismogenic fault of the 1948 M 7.3 Litang earthquake, located in SE Tibet. They found 15 paleoearthquake events on the Litang fault, based on detailed field work, paleoseismic trenching, and radiocarbon dating. They suggested that the rupture pattern along the Litang fault is a "rupture cycle model" and divided the Holocene events into 3 rupture

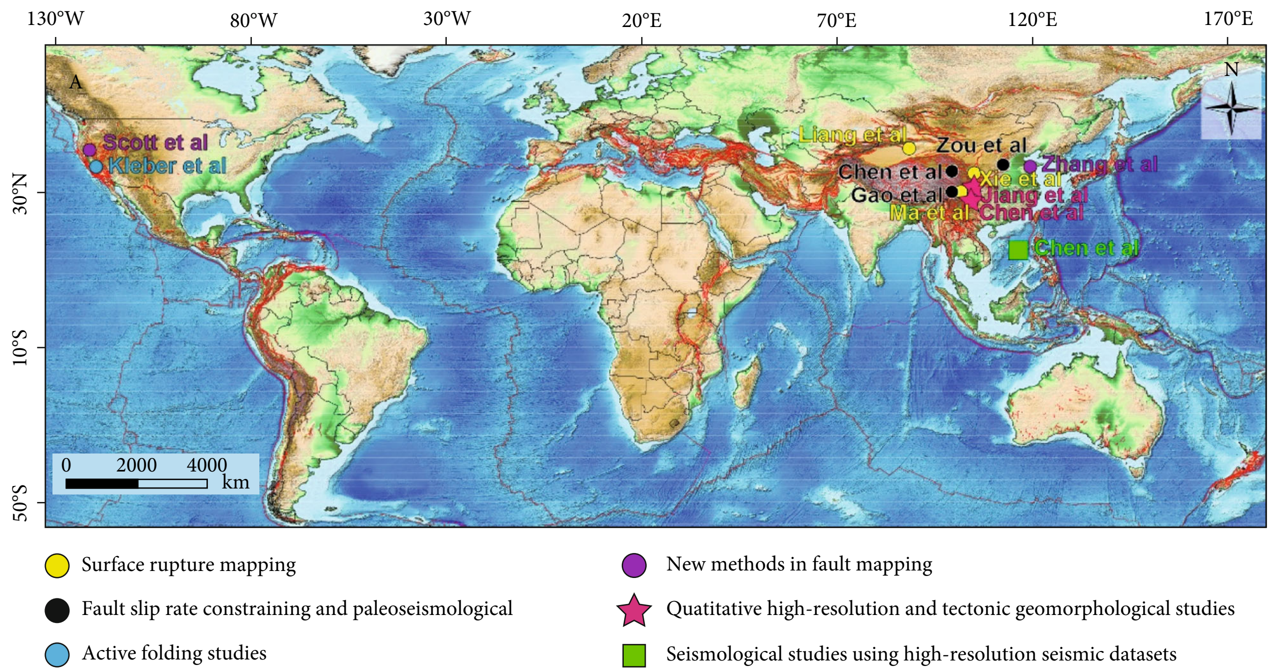

Figure 1: The distribution and classification of the manuscripts in this special issue.

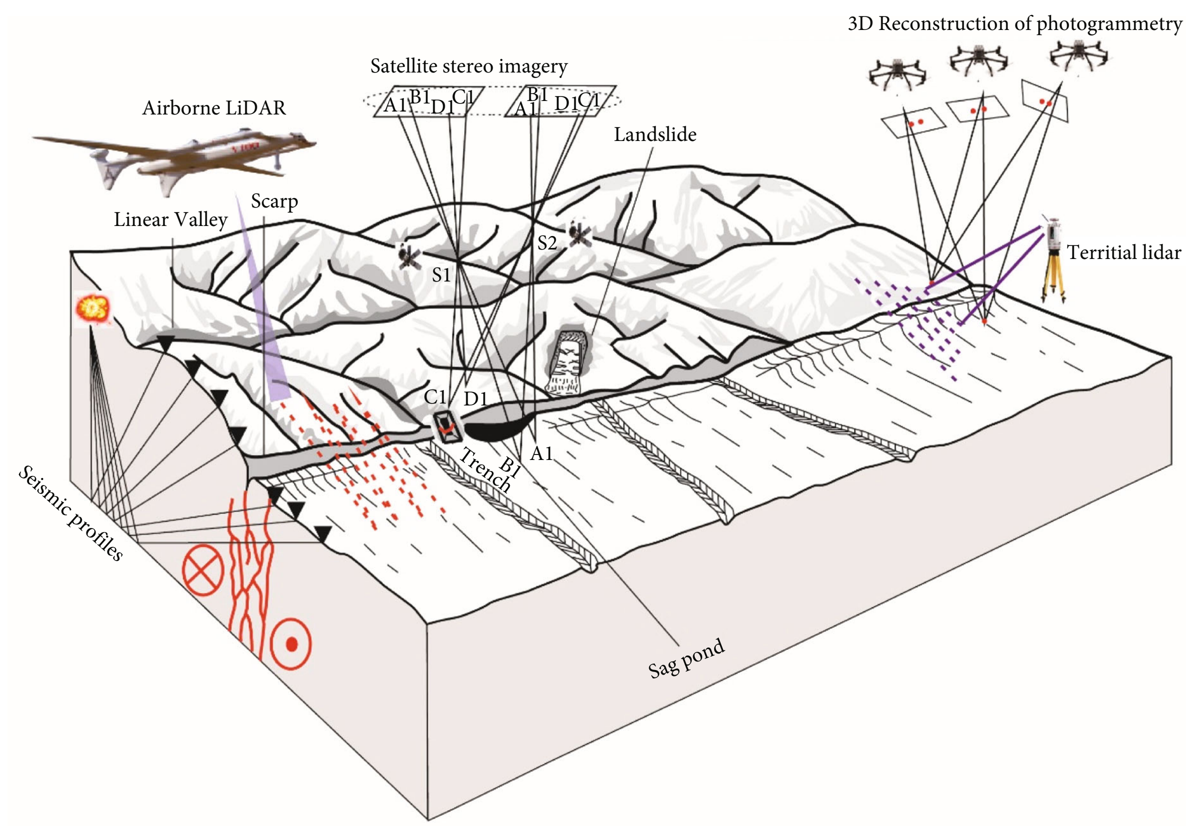

Figure 2: The diagram showing the widely used methods in tectonic activity studies.

cycles based on fault geometry and dating results. The rupture pattern migrated southeastward and the earthquake recurrence interval shortened dramatically from 8000 to 500 years since the Holocene, which might indicate enhanced activity along the Litang fault, emphasizing the role of the Litang fault in accommodating SE Tibet deformation.

In recent years, researchers have used micromorphology of bedrock fault surfaces to identify paleoearthquakes, because trenching methods are not applicable to bedrock. In this issue, Zou et al. study the Jiaocheng fault in the Shanxi rift, dominated by extension [17]. Two bedrock fault surfaces are investigated in detail, at SXC and SLZ along the northern and central segments of the fault. Based on isotropic empirical variogram and moving window, they conducted quantitative fractal analysis, which showed that both bedrock fault surfaces are characterized by vertical segmentation, which might be due to repeated earthquakes. The coseismic slip of each event could thus be determined by the height of each segment. By summarizing previous studies, the three events may have occurred during the Holocene, with a recurrence interval of ~2.6 kyr. They suggested that the seismic hazard potential of the Jiaocheng fault is high and should be studied in detail immediately.

2.3. Active Folding Studies. The formation and development of active fault propagation folds and the associated wind and river gaps are key challenges for tectonic geomorphic analysis of active folding. In this issue, Kleber et al. [18] quantify the rate of surface uplift and lateral propagation of the Wheeler Ridge anticline, based on high-resolution LiDAR data and infrared optically stimulated luminescence (IRSL) ages. It was discovered that the rate of surface uplift and lateral propagation has not been constant along the fold, showing a systematic, although punctuated, decrease in rates across structural barriers (tear faults) from west to east. They proposed a geomorphic evolution model, which predicts the timing of formation of wind and river gaps, which suggests its development during late Pleistocene dry climatic intervals.

2.4. New Methods for Fault Mapping. Fault geometry and cumulative slip distribution are key issues in active tectonic studies, which are essential for constraining fault behavior over temporal scales from single earthquakes to fault's history. In this issue, Scott et al. [19] developed a MATLAB algorithm to semiautomatically map active faults and measure scarp heights from high-resolution topographic data including small unscrewed aerial system (sUAS, sometimes also called UAV), airborne LiDAR, Pléiades stereo satellite imagery, and SRTM digital elevation model. By applying the semiautomatic algorithm to the Volcanic Tablelands of eastern California and Hurricane fault in Arizona and Utah, they showed that the algorithm mapped faults and other prominent topographic feature well and could be applied in a variety of geomorphic and tectonic settings. It will substantially decrease the time required to analyze such fault systems, expanding its applications to other active tectonic studies.

3. Quantitative High-Resolution Geomorphology Studies

The eastern boundary of the Tibetan Plateau is its steepest topographic boundary. This region serves as a natural laboratory to reveal the role of geological deformation in topographic evolution due to its typical steep topography boundary and lack of typical foreland basin, which has been the focus of geomorphologic studies for decades. In this issue, Jiang et al. [20] focused on the deformation pattern and shortening rates of the southern Longmen Shan, consisting of the Xiongpo, Sansuchang, and Longquanshan anticlines. They measured and dated the six-level terraces of the Qingyi River, which flows across the Longmen Shan. Their results indicate that the late Quaternary shortening rate of the foreland is 2.04 mm/yr, among which the Xiongpo anticline accounts for 48% (0.99 mm/yr), that of Longquan Shan for 43% (0.88 mm/yr), and that of Sansuchang for 9%. They suggested a kinematic model in which the southern Longmen Shan is an actively expanding edge of the plateau and that shortening is distributed to the three anticlines. They concluded that crustal shortening is the dominating force in the Longmen Shan deformation at present. By analyzing the along-strike variation of the Longmen Shan, they proposed that the southern Longmen Shan is in a state of compression, while the northern Longmen Shan accommodates transpressional strain into dextral strike-slip movement.

Landslides play an important role in geomorphic evolution, which is one of the driving mechanisms of slope material migration, i.e., one of the key researches in disaster prevention and mitigation. In this issue, Chen et al. [21] developed a new approach to predict the potential landslide areas. They analyzed the distribution of the coseismic landslides produced by the 2014 Ludian M 6.5 earthquake. A new parameter, the expected slope (ES) angle, is defined to describe the terrain features. They found that large landslides may occur in regions where the expected and average slope angle are clearly different. The potential landslide areas derived from this new approach are consistent with actual coseismic landslides. The occurrence of coseismic landslides corresponds to simultaneous adjustment of excess geomorphic hillslopes to a steady state.

4. Seismological Studies Using High-Resolution Seismic Data Sets

Seismic tomographic inversions have commonly been used to reveal structural discontinuities at depth in earthquake seismology studies. In this issue, Chen et al. [22] present high-resolution seismic tomography images from the Hainan mantle plume combined with geochemical analyses of volcanic glasses from an International Ocean Drilling Program core (Site U1434) in the South China Sea. The geochemical features of the samples are consistent with those of the late Cenozoic volcanic rocks on Hainan Island and surrounding areas associated with a mantle plume. The tomography results are obtained by inverting local and teleseismic travel time data recorded by seismic networks in SE Asia. Positive velocity anomaly is observed near the mantle transition zone beneath the South China Sea while negative velocity anomaly is observed beneath Hainan Island and the northern margin of the South China Sea. The existence of a Hainan mantle plume and stagnant subducted slab is further supported by geophysical evidence from a recent 3D P-wave seismic tomographic model.

5. Perspective: Active Tectonics towards High-Resolution in 4D

The development of active tectonics during the past century has paved the way towards high-resolution in 4D. Studies changed from qualitative to high-resolution quantitative. Although lots of knowledge about Quaternary tectonic activity and seismic behavior have been acquired, many unsolved problems remain in the field of active tectonics: what controls the strain accumulation and releasing process? What governs earthquake frequency and locations? Is there a quantitative relationship between fault slip rate and earthquake magnitude and recurrence interval? How to judge whether a trench exposure records a complete event sequence? Are there real characteristic earthquake models observed in nature? High-resolution data sets in space and time are essential to address these pressing questions. Scientific collaboration between geologists, exploration geophysicist, seismologists, and geochronologists is also needed to resolve Quaternary tectonic activity with high-resolution data in space and time. Researchers from different backgrounds and countries, i.e., "space," and from multigenerations, i.e., "time," thus need to work hand in hand to resolve the remaining key Quaternary tectonic activity issues with high-resolution data.

The 12 high-quality, original research articles compiled in this special issue are just one small step, and we hope that it will help motivate more researchers to get involved in active tectonic research using higher resolution in 4D.

Conflicts of Interest

The authors declare no conflicts of interest.

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