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Zhongliang Wu · Ying Li ·
Xiaodong Zhang *Editors*

Scientific Investigation of Continental Earthquakes and Relevant Studies

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Editors
Yong-Gang Li
Department of Earth Sciences
University of Southern California
Los Angeles, CA, USA

Yongxian Zhang
Institute of Earthquake Forecasting
China Earthquake Administration
Beijing, China

Zhongliang Wu
Institute of Earthquake Forecasting
China Earthquake Administration
Beijing, China

Ying Li
Institute of Earthquake Forecasting
China Earthquake Administration
Beijing, China

Xiaodong Zhang
Institute of Earthquake Forecasting
China Earthquake Administration
Beijing, China

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Preface

The present book is with dual missions: firstly to commemorate the 50th anniversary of the successful prediction of the Haicheng $M_S7.3$ earthquake (occurred on February 4, 1975) and secondly to illustrate the part of recent practical results from the regional and international collaboration in earthquake research and disaster mitigation fostered by the China Seismic Experimental Site (CSES). The CSES is carried out by geoscientists from Chinese scientific community with colleagues abroad and international organizations. The CSES provides a principal natural laboratory to support core researches in earthquake geology, tectonic geodesy, seismology, earthquake engineering, and computational science. Researchers from different schools, different "paradigms" and different technical routes, carrying out comparative studies and collaborative experiments by the CSES and other international experimental sites help promote standardization work, including the data products, planning, quality assurance, sharing, and upgrades in the design of earthquake science and technology. Reflecting the ongoing practices of the CSES, this book highlights the scientific investigation of earthquakes, that is, the close-in contact with earthquakes shortly after their occurrence, focusing on seismogenic and tectonic environments, seismogenic structures, seismogenic fault structures, source physics, focal mechanism, rupture dynamic process, induced earthquake by hydraulic fracturing, gas emission linked to earthquake activities, earthquake anomalies monitoring and risk assessment, exploration of prediction methods, earthquake disaster characteristics and disaster-causing mechanisms, ground motion prediction, as well as state-of-the-art techniques. The readers of this book will broaden their horizons about observational, computational, and applied seismology, and earthquake physics and prediction via learning from the CSES' practice to aid in preparedness, mitigation, and management of seismic risk.

Los Angeles, USA — Yong-Gang Li
Beijing, China — Yongxian Zhang
Beijing, China — Zhongliang Wu
Beijing, China — Ying Li
Beijing, China — Xiaodong Zhang

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Chapter 1
Scientific Investigation of Continental Earthquakes and Relevant Studies: An Overview

Yong-Gang Li, Yongxian Zhang, Zhongliang Wu, Ying Li, and Xiaodong Zhang

Abstract Scientific investigation of earthquakes, characterized by its timing and multidisciplinary features, plays an important role in deepening the understanding of the nature of earthquakes and the reduction of the risk of seismic disasters. With new techniques emerging, the scientific investigation of earthquakes has had significant advancements. As reviewed in this introductory chapter, all the chapters in the book are aligned along this direction. The book itself is hoped to initiate the endeavor of systemization and the establishment of the practice-oriented theoretical framework.

Keywords Scientific investigation of earthquakes · Multidisciplinary feature · Continental earthquakes · Scientific expedition of Wenchuan · Maduo, Luxian, and Luding earthquakes

On May 21, 2021, Beijing time, a strong earthquake occurred in Yangbi, Yunnan Province, China. Hours later, a bigger earthquake happened in Maduo, Qinghai Province, China. Scientific expeditions for these two earthquakes were promptly organized by the Department of Science and Technology and International Cooperation of China Earthquake Administration (CEA), in association with the emergency response. The scientific expeditions were coordinated by the Institute of Earthquake Forecasting of CEA and the Qinghai Earthquake Agency. The Institute of Geophysics, Institute of Geology, Institute of Engineering Mechanics, the First Monitoring and Application Center, the Second Monitoring and Application Center, of CEA, and China Earthquake Networks Center, China Earthquake Disaster Prevention

Y.-G. Li (✉)
Department of Earth Sciences, University of Southern California, Los Angeles, California 90089, USA
e-mail: ygli@usc.edu

Y. Zhang · Z. Wu · Y. Li · X. Zhang
Institute of Earthquake Forecasting, China Earthquake Administration, No. 63 Fuxing Avenue, Beijing, China

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Center Jiangsu Earthquake Agency, Hubei Earthquake Agency, and Tongji University participated in the scientific investigation. The scientific investigation obtained fruitful results related to the seismotectonics, the seismogenesis, the source process, the seismic disaster and disaster chain, and so on (Institute of Earthquake Forecasting, CEA, 2022). Such results with multiple scientific disciplines were obtained based on the updated technologies of geodesy, seismology, remote sensing, geochemistry, and so on.

From May 12, 2008, when the great Wenchuan earthquake stroke, and the scientific expedition was organized in a hurry, to May 21, 2021, when the pre-planned comprehensive scientific expeditions of the two earthquakes were conducted in parallel, there have been significant advances in both earthquake science and technology and the systems engineering of the planning and organization of the scientific investigation of earthquakes. These advancements facilitate the enhancement of the capabilities of earthquake emergency response and scientific investigation. Modernization of the scientific investigation of earthquakes has shown its potential for promoting the development of earthquake science and technology and for seismic disaster risk reduction.

This book is to summarize the ongoing practice and theoretical framework along the direction of the scientific investigation of earthquakes, or the close-in contact with earthquakes for investigating the seismogenesis, the preparation process, the rupture process, and the disasters of the earthquakes. For seismic disaster risk reduction, retrospective investigation of the potential earthquake precursors, the seismic hazard assessment, and the preparedness for earthquake disasters played an important role in getting the lessons and experiences for the future. Related to this, new technologies and methods of earthquake science are the important components. Specifically, this book highlights continental earthquakes which have had more serious threats to sustainability.

The eleven chapters are all in the direction of the scientific investigation of earthquakes. In such investigation, the deformation before and after the earthquake is one of the important issues to study. Su and Meng (Chap. 2) utilized the long-term accumulated Global Navigation Satellite System (GNSS) observations of the epicenter and its surrounding areas to investigate the regional seismogenic environment, co-seismic displacements, and early post-seismic deformation evolution after the M_W7.3 Maduo earthquake occurred in Golog Tibetan Autonomous Prefecture, Qinghai Province in China. They observed that the horizontal GNSS velocity field, which indicates the seismogenic environment of the epicenter and its surrounding areas, showed mainly sinistral shear mechanism of this strong earthquake. They found that the relative crustal deformation of the main boundary fault accounts for 60% of the relative movement of the whole Bayan Har block, while the internal one accounts for 40%. The calculated GNSS strain rate field by using multi-scale spherical wavelet method shows that the significant strain accumulation areas are distributed along the main boundary fault of the block, and the epicenter is located on the high-to-low strain rate transition zone. Through continuous GNSS observations and calculations of the co-seismic and early post-seismic deformations, they found that the significant post-seismic deformation in the first 5 days accounts for 72% of the first 20 days, and its direction is consistent with the co-seismic one.

Seismological observation plays an essential role in characterizing the earthquake sequence and the tectonic environment of large earthquakes. Chang et al. (Chap. 3) deployed a dense seismic array to record aftershocks after the 2021 Maduo $M_W7.3$ earthquake to investigate the deep seismogenic environment in the source area, in terms of earthquake locations, three-dimensional high-resolution seismic imaging, focal mechanism solutions, and shear wave splitting. The results show obvious velocity in-heterogeneities around the main rupture. The delay times in the intensive area of aftershocks along the main rupture are significantly greater than those on the north and south sides outside the intense aftershock zone. The distribution of aftershock sequences, fast wave polarization, and surface rupture alignment around the main rupture zone exhibit strong consistency and segmentation characteristics. The aftershocks are mainly distributed on the north side of the main rupture, with larger delay times observed on the north side compared to the south side. The shape of seismogenic fault, as revealed by a high-resolution catalog, indicates a northward dip. The eastern segment for the main rupture is characterized by the most intensive distribution of aftershocks and the mainshock with the largest scale of high-velocity anomaly and the larger delay times in the source region. These characteristics suggest that the stress accumulation during the seismogenic process of the Maduo $M_W7.3$ earthquake is mainly concentrated in the eastern segment due to blockage of the high-speed anomaly in the east.

In recent years, some earthquakes induced or triggered by human activities have occurred, being a challenge to industry, while providing a good opportunity to study the mechanics of earthquakes. On September 16, 2021, $M_S6.0$ ($M_W5.4$) Luxian earthquake occurred in the Luxian shale gas field. This is the second $M_S \geq 6$ earthquake to hit the Sichuan Basin since 2014, following the $M_S6.0$ Changning earthquake on June 17, 2019. Since 2014, a number of hydraulic fracturing wells for shale gas exploitation has increased rapidly, probably resulting in a sharp increase in the seismicity in the southern Sichuan Basin. Ye and Lu (Chap. 4) investigate the seismotectonic settings in the Sichuan Basin, eastern Tibetan Plateau, the largest shale gas-producing region in China, and the seismogenic mechanism of the 2021 $M_S6.0$ Luxian earthquake which might be induced by hydraulic fracturing in the Luxian shale gas field located in the southern Sichuan Basin. Sophisticated methods and techniques (software) were used in various data analyses, including the normal-mode summation code Mineos to compute Green's function and waveform inversion to obtain the source mechanism solution, the machine learning code PhaseNet to detectseismic phases, the REAL, Hyposat and HypoDD to obtain accurate locations of aftershocks, the generalized Cut and Paste (gCAP) code to obtain the ambient stress field, the Sentinel-1 Synthetic Aperture Radar images and GNSS observations to determine the seismogenic fault and slip distribution, the maximum curvature and likelihood methods to calculate b-value and its spatiotemporal variations, ambient noise tomography and the 3D seismic reflection profiling to construct a high-resolution 3-D S-wave velocity regional model and seismogenic fault structure. The results show that the underlying active fault structures and tectonic stress state control the rupture model of induced earthquakes in southern Sichuan. The seismicity in the southern Sichuan Basin in recent years is closely related to the tectonic activity by the eastern extension of the southeastward of Tibetan Plateau, and those induced strong earthquakes took place on the pre-existing basement faults. The seismogenic fault is located in the Precambrian basement, suggesting that the mainshock is most likely caused by the poroelastic effects due to fluid injection. Hydraulic fracturing could have reactivated a large-scale basement fault and triggered the strong earthquakes under relatively high geo-stress conditions in the study area.

Due to seismic and tectonic activities, underground gases were released into the atmosphere from the fault zones through the earth's degassing, leading to the variations in gases such as CH_4 and CO in the atmosphere. Cui et al. (Chap. 5) examined gas emissions from the Kangding area associated with strong earthquakes, where the Longmenshan, Xianshuihe, and Anninghe faults characterized by intense degassing are important active faults in the eastern part of the Tibetan Plateau. They found that the variations of CH_4 and CO in the Kangding area were closely related to earthquakes and tectonic activities, evident in their spatial alignment with tectonic distributions and their responsive patterns to nearby seismic events over time, thereby reflecting changes in tectonic stress. Degassing from faults provides a new approach for monitoring seismic activities in this region.

Characterizing and monitoring of earthquake sequence has been one of the important missions of the scientific investigation of earthquakes. Zhang and Zhang (Chap. 6) reviewed several strong or large earthquakes occurred in Western China, over the past four years in terms of operational aftershock forecasting research for investigation of recent seismic activities in China. These attractive earthquakes include the Yutian, Xingjiang $M_S6.4$ earthquake in 2020, the Maduo, Qinghai $M_W7.3$ earthquake in 2021, the Luding, Sichuan $M_S6.8$ earthquake in 2022 and the Linxia, Gansu $M_S6.2$ earthquake in 2023. The comprehension of the potential for strong aftershocks, as gleaned from the analysis of operational aftershock forecasting models, assumes a crucial role in facilitating prompt emergency responses and informed scientific decision-making. They used the 2021 Maduo $M_W7.3$ earthquake and the 2022 Luding $M_S6.8$ earthquake as examples, and employed a range of forecasting models, including the Epidemic Type Aftershock Sequence (ETAS) model, to describe the temporal features of the sequence attenuation and the potential for triggering subsequent offsprings. This involved a short-term forecasting for the next three days, in a tracking manner and provided the probability and occurrence rate of aftershocks with different target magnitudes. Then, the Receiver Operating Characteristic (ROC) method and a straightforward approach were employed to compare the performance of the two models with that of a random guess and relative consistency, respectively. These statistical methods in practice demonstrate their effectiveness in providing scientific and technological support for earthquake prediction.

Predictability of an earthquake has been a challenging issue in earthquake science. The scientific investigation of earthquakes, although usually in retrospective perspectives, provides earthquake forecast study with heuristic clues. Liu et al. (Chap. 7) revisited the instrumental and historical earthquake catalogues of the 2008 $M8$ Wenchuan earthquake, and discussed its predictability from the perspective of the

'Dragon King' theory and the 'nowcasting' approach by inspecting the frequency-magnitude relation of earthquakes. Using the century-scale earthquake catalogue, this earthquake cannot be regarded as a 'Dragon King' event. However, on the decade to the annual time scale, this earthquake may be regarded as a 'Dragon King' events. In the framework of 'nowcasting earthquakes', the hazard of such a devastating earthquake can be described by the 'earthquake potential score' (EPS, up to 94%) and 'potential magnitude' (M_{P}, up to 7.4) just prior to the occurrence of this event.

Focusing on the scientific investigation of earthquakes in China, this book also pays attention to the state-of-the-art methods developed and applied in relevant investigations of earthquakes around the world. Rundle et al. (Chap. 8) developed the earthquake generative pretrained transformer model, "QuakeGPT", a deep learning technology to nowcasting earthquake disaster characteristics and disaster-causing mechanisms based on science transformers. It is a type of model that underpins the new AI technologies like ChatGPT, to tag important sequences of data and to identify relationships between those tagged data. Typically, the data used to train the model is in the billions or larger when applied to earthquake problems. This transformer might be able to learn the sequence of events leading up to a major earthquake. In this research, authors simulated catalogs from the physics-based model Virtual Quake and from stochastic seismicity models. In the current work, they are using a new type of stochastic seismicity model "ERAMS" (Earthquake Rescaled Aftershock Model for Seismicity) to find emergent properties of the underlying scaling parameters by mining the USGS online catalog of California for the time rescaling and the spatial migration of aftershocks.

In the scientific investigation of an earthquake, the most straightforward investigation of evaluating the prescribed seismic hazard (or ground motion level) is of no doubt through the comparison of real strong ground motion records with the assessed results. On the other hand, however, as discussed by Zhang et al. (Chap. 9) in the framework of neo-deterministic seismic hazard assessment (NDSHA), such an evaluation can be implemented directly through a comparison between the magnitude of the earthquake and the M_{design}, which seems not fully discussed in the agenda of the scientific investigations of earthquakes. The contribution of this chapter lies in that at the present time there have been results related to probabilistic SHA (PSHA) and deterministic SHA (DSHA), and the evaluation of SHAs based on scientific investigations of earthquakes, albeit without a 'standard' procedure.

Because actual fault zones are composed of multiple layers of varying lithology at depths, they usually form a depth-dependent multi-layer low-velocity waveguide (LVWG). Li (Chap. 10) discussed fault-zone waveguide effects from numerical tests and field observations that aid in rock failure estimation at depth and ground motion prediction. 3-D finite-difference synthetic fault-zone trapped waves (FZTWs) in terms of a multi-layer LVWG show that the early portion of FZTWs with larger amplitude peak at lower frequency is mainly produced within the top layer of the LVWG having the slower velocity, while the late portion of FZTWs with smaller amplitude peaks at higher frequencies arises from deeper layers of the LVWG having faster velocities. Even if the seismic source is located out of the multi-layer LVWG, as long as it is lower than the bottom of the upper layer of LVWG, FZTWs with large amplitudes could be produced when waves enter the upper layer, but they show shorter post-S durations with smaller PSSP ratios than those for the source located at the same depth within the LVWG. These FZTWs from off-fault events might lead us to extract the shallow portion of the fault damage zone, but miss its deep portion. Therefore, we should carefully identify the FZTWs from these deep on-fault events when we analyze the recorded waveform data to accurately extract the depth extension of a realistic fault damage zone. Our numerical investigations are consistent with the observed FZTWs at rupture zones of the Landers, Hector Mine, and Parkfield earthquakes in California. The fine structure of fault damage zone around the earthquake source at depth will influence rupture propagation and may offer a basis for "asperities", "barriers" and the upper bound frequency "fmax" of seismic waves that can be radiated from a fault zone in sake for the strong ground motion prediction.

Scientific investigation of earthquakes is by its nature a systems engineering. It is especially challenging in the planning stage for an earthquake which is not predicted. More challenges in the organization lie in the interdisciplinary feature of the comprehensive investigation. Dealing with these challenges, Hu et al. (Chap. 11) summarize the detailed investigation of earthquake hazardous areas and comprehensive scientific investigation of earthquakes in China by proposing a comprehensive project. The experiences of practice call for the establishment of the theoretical framework of the scientific investigation of earthquakes, in such development there is apparently much to be done. In this regard, this book is just a starting of the research and reflection. In cooperation with the general guidances to the scientific investigation of earthquakes (Institute of Earthquake Forecasting, CEA, 2024), this book provides the scientific investigation of earthquakes with case examples of the application of the general guidances, although it is still neither systematic nor optimized.

In recent years the present book series has focused on the development of earthquake science in China with implications for the development of global seismology, including the decade retrospective of the 2008 Wenchuan earthquake (Li, 2019) and the China Seismic Experimental Site (Li et al., 2021). As a continuation of this series, the present book, focusing on the scientific investigation of earthquakes, covers the disciplines of seismology, geodesy, geology, geochemistry, engineering seismology, earthquake engineering, etc., and faces a wide range of readers from scientists in the field of natural science and disaster risk reduction to graduate students in geosciences, covering multi-disciplinary topics to allow readers grasp the various methods and skills used in data processing, analysis and numerical modeling for geological, geophysical, and mechanical interpretation of earthquake phenomena and physics. This book is a self-contained volume and explores each topic with in-depth detail. Reference lists and cross-references with other volumes facilitate further research to aid the understanding of earthquake processes and hazards globally.

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Chapter 2
Crustal Deformation and Regional Seismogenic Environment Associated with the 2021 Maduo M_W7.3 Earthquake

Xiaoning Su and Guojie Meng

Abstract The Maduo M_W 7.3 earthquake occurred at 2:04 local standard time on May 22, 2021, in Maduo County, Golog Tibetan Autonomous Prefecture, Qinghai Province, China. In this chapter, the regional seismogenic environment, co-seismic displacements, and evolution of early post-seismic deformation are studied by using the long-term accumulated GNSS observations of the epicenter and its surrounding areas. Firstly, we obtained the horizontal GNSS velocity field, which indicated the seismogenic environment of the epicenter and its surrounding areas is mainly sinistral shear. The relative crustal deformation of the main boundary fault accounts for 60% of the relative movement of the whole Bayan Har block, while the internal one accounts for 40%. Secondly, we calculated the GNSS strain rate field by using a multi-scale spherical wavelet method considering robustness. The result shows that the significant strain accumulation areas are distributed along the main boundary fault of the block, and the epicenter is located in the transition zone from the great strain rate values to the low one. Finally, the co-seismic and early post-seismic deformation were calculated by continuous GNSS observations. Two strategies were adopted to calculate the co-seismic displacements, the difference between them indicated the co-seismic displacements can be obtained more accurately by using the strategy of 4 h observations after the mainshock, and the results of a single day strategy have included the early post-seismic deformation. The significant post-seismic deformation was obtained at station QHMD, and its direction is consistent with the co-seismic one. The logarithmic attenuation model which characterizes mainly after-slip deformation can accurately model the observed values. The post-seismic deformation in the first 5 days accounts for 72% of the first 20 days.

Keywords 2021 Maduo M_W 7.3 earthquake · Crustal deformation · Seismogenic environment · Co-seismic displacements · Post-seismic deformation

X. Su (✉)
Faculty of Geomatics, Lanzhou Jiaotong University, Lanzhou 730070, China
e-mail: suxiaoning_666@126.com

G. Meng
Institute of Earthquake Forecasting, China Earthquake Administration, Beijing 100036, China

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2.1 Introduction

According to the China Earthquake Network Center, at 2: 04 Beijing time on May 22, 2021, an earthquake of M_W 7.3 occurred in Maduo, Qinghai Province, China with the epicenter at (98.34° E, 34.59° N) and the focal depth at 17 km (provided by China Earthquake Networks Center). The epicenter of this earthquake is located close to the Maduo-Gande fault and the Kunlunshankou-Jiangcuo fault (Xu et al., 2016), approximately 70 km away from the East Kunlun fault zone, which forms the northern boundary of Bayan Har block. Wang et al. (2021) initially identified the Kunlunshankou-Jiangcuo fault as the main seismogenic fault for this earthquake. Xu et al. (2016) suggested that the seismogenic structure was a high-angle, left-lateral strike-slip fault within the Bayan Har block oriented in an NWW direction. Zhu et al. (2021) speculated that the seismogenic fault was parallel to the Kunlun Mountain fault on the main boundary by integrating the distribution of post-seismic slips and the displacement discontinuities in InSAR interferogram. Li et al. (2021), through extensive field geological surveys combined with source parameters, aftershock distribution, and InSAR co-seismic deformation results, confirmed that the seismogenic fault is an NW-trending and sinistral strike-slip Kunlunshankou-Jiangcuo fault, and the rupture segment is Jiangcuo section (Fig. 2.1). The focal mechanism solution (GCMT) and the characteristics of earthquake surface rupture consistently indicated that this was a typical sinistral strike-slip event (Li et al., 2021). It is the second major earthquake closely related to the activity of the Bayan Har block with a magnitude greater than M 7.0, following the M 7.0 Jiuzhaigou earthquake in September 2017, occurring after a gap of 3 years and 8 months. Precise aftershock relocations revealed that over 1241 aftershocks were recorded within ten days after the main shock, forming a belt 170 km in length (Wang et al., 2021). Analysis of the spatiotemporal distribution characteristics of aftershocks showed that a belt of aftershock distribution had already formed within one day after the mainshock, with subsequent aftershocks merely superimposing on the existing spatial layout. The mainshock was positioned in the middle of the aftershock belt, with rupture lengths of about 85 km on both the eastern and western sides of the mainshock, exhibiting a bilateral rupture feature.

The Bayan Har block is a strip-shaped active tectonic block in the central-eastern part of the Tibetan Plateau. Owing to the continuous northward push of the Indian plate, the block undergoes a general southeastward lateral extrusion movement, which has also led to a series of major earthquakes along its periphery and within it (Gao & Deng, 2013; Wen et al., 2011; Xu et al., 2008a). Besides the large left-lateral strike-slip Garze-Yushu-Xianshuihe fault zone and the East Kunlun fault zone at the southern and the northern boundaries of the block, a series of late Quaternary active faults with NW-trending and left-lateral strike-slip movement are also developed in the block, showing the complex and unique characteristics of tectonic movement and strain accumulation in the block boundary and its interior (He et al., 2018; Jiang et al., 2006; Li et al., 2011; Meng et al., 2016; Xu et al., 2008b; Zhou et al., 1996).