Tectonophysics 584 (2013) 1–6

Contents lists available at SciVerse ScienceDirect

Tectonophysics

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

Preface

Great earthquakes in the 21st century and geodynamics of the Tibetan Plateau

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ARTICLE INFO

Available online 7 November 2012

Keywords:
Wenchuan earthquake
Tibetan Plateau
Geodynamics
Earthquake disaster reduction

ABSTRACT

What are the geodynamic processes that caused these deadly earthquakes? Why have these earthquakes caused so much damage? What are the key lessons that we have learned from these devastating earthquakes? Answers to these questions will significantly enhance not only our understanding of earthquake occurrence but also our ability to reduce seismic hazard. Under the framework of bi-lateral cooperation on earthquake sciences between China and USA, the Second Bi-Lateral Workshop on Earthquake Sciences was held in Chengdu, Sichuan Province, China, from April 22 to 25, 2011. Among the goals of this workshop was a review of recent advances in the study of great earthquakes and the exchange of ideas on earthquake disaster reduction. The principle theme of the workshop was "Great Earthquakes in the 21st Century and Geodynamics." This Special Issue contains a total of 24 papers presented during the workshop. The contributions cover a wide-range of topics associated with the theme. This preface summarizes the main points of the papers presented in this issue.

1. Introduction

The 21st century began with numerous great earthquakes, resulting in great casualties, economic losses, and social disturbances. The 2001 Kunlun mountain earthquake (Ms = 8.1) raised the curtain on this period of vigorous earthquake activity. The 2004 to 2005 Sumatra earthquakes and associated tsunami caused more than 240,000 deaths. The 2008 Wenchuan earthquake killed more than 80,000 people and resulted in more than a billion dollars in economic losses (Liu-Zeng et al., 2009; Xu et al., 2009; Zhang et al., 2010). In January 12, 2010, an earthquake of magnitude only Mw = 7.0 occurred in Haiti and caused more than 223,000 casualties (Bilham, 2010). A little more than a month later, in February 27, 2010, another great earthquake shook the Earth with a magnitude of Mw = 8.8 in Chile (Madariaga et al., 2010; Moreno et al., 2010). The 14 April 2010 Mw = 6.9 Yushu earthquake occurred ~400 km west of the 2008 Wenchuan earthquake in central Tibet which killed more than 2000 people (Chen et al., 2010). In 11 March 2011, a great Tohoku-Oki earthquake of Mw = 9.0 struck Japan, and the associated tsunami damaged the Nuclear Power Plants that in turn caused a world-wide crisis of nuclear radiation leakage (Kato et al., 2012; Simons et al., 2011).

What are the geodynamic processes that caused these deadly earthquakes? Why have these earthquakes caused so much damage? What are the key lessons that we have learned from these devastating earthquakes? Answers to these questions will significantly enhance not only our understanding of earthquake occurrence but also our ability to reduce seismic hazard. Under the framework of bi-lateral cooperation on earthquake sciences between China and USA, the Second Bi-Lateral Workshop on Earthquake Sciences was held in Chengdu, Sichuan Province, China, from April 22 to 25, 2011. Among the goals of this workshop was a review of recent advances in the study of great earthquakes and the exchange of ideas on earthquake disaster reduction. The principle theme of the workshop was "Great Earthquakes in the 21st Century and Geodynamics."

2. Workshop of great earthquakes in the 21st century and geodynamics

The workshop was well attended by 43 participants from the United States and 63 from China. A two-day pre-workshop field trip was conducted to visit surface ruptures associated with the 2008 Wenchuan earthquake. The presentations were organized into two main themes.

2.1. Great earthquakes in the 21st century

Great earthquakes during the first decade of the 21th century have killed more than 500,000 people and caused tremendous economic loss. These earthquakes differ from each other in terms of their tectonic environment and geodynamic processes, yet there are also some common features in both the rupture processes and the disaster scenarios. The complex thrust faulting associated with the 2008 Wenchuan earthquake, for example, appears to differ substantially from the strike-slip faulting of the Haiti earthquake. Despite its lower magnitude, the Mw 7.0 Haiti earthquake caused more casualties than the Ms 8.0 Wenchuan

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http://dx.doi.org/10.1016/j.tecto.2012.11.001

earthquake. The 2010 Yushu earthquake occurred in a remote and sparsely populated region of the interior of Tibet, but also caused significant human and property losses. Intensive studies following these great earthquakes have resulted in abundant observational data and new insights into the geodynamic processes of these earthquakes; comparisons of these studies will help to improve our ability to reduce seismic losses in future great earthquakes. Recent advances in new technologies such as GPS, InSAR, seismic array and space-based observations, among others, have extended our ability to monitor crustal motion, strain accumulation, and the behavior of seismogenic faults associated with devastating earthquakes at various timescales. Advances in laboratory and numerical simulation have also enabled important insights to the mechanics of rupture initiation, propagation and arrest of earthquake ruptures. This theme focused on, but was not restricted to the following topics:

- Tectonic background of great earthquakes in both interplate and intraplate settings;
- Coseismic surface ruptures and displacements associated with each of these great earthquakes;
- Earthquake rupturing processes constrained by seismological and geodetic data;
- Active tectonics, paleoseismology and seismic hazard assessment.

2.2. Continental deformation: structure, deformation, and geodynamics

Great earthquakes in continental interiors are generally more devastating to human life and social development than oceanic earthquakes, but their causes are poorly understood. In contrast to localized deformation along oceanic plate boundaries, continental earthquakes and active faults are distributed in a vast region with variety of tectonic styles, and their spatial and temporal occurrence, as shown in China and Central Asia, are much more irregular than those of plate boundary earthquakes. Such irregularity, to a large extent, may be attributed to the heterogeneous physical properties of continental crustal and lithosphere, which are usually thick and weak, with layered rheological structure, distributed fault systems, and relatively low rate of loading. To better explore the style, geometry, rate, kinematics and dynamics of continental tectonics and earthquakes, this theme focused on the following topics:

- Fundamental differences between plate boundary earthquakes and those in diffuse plate boundary zones (such as western US, Tibetan Plateau) and in mid-continent's (such as North China and central-eastern US);
- Spatial correlation between continental seismicity with crust, sub-crustal lithosphere, and upper mantle structures in China, US, and elsewhere
- Relationship between the style and rate of crustal deformation and rheological properties of continental lithosphere;
- Growth, uplift, and dynamic process of the Tibetan Plateau and Central Asia;
- Patterns of continental deformation revealed by active faults, earthquake activity, seismological and GPS observations, and terrestrial laser scanning.

3. This volume

This Special Issue contains a total of 24 papers presented during the workshop. The contributions cover a wide-range of topics associated with the two themes. Below we summarize the main points of papers presented in this issue.

The 2008 Wenchuan earthquake is no doubt the central issue of the workshop, not only because this event caused such huge casualties and economic loss, but also because the seismogenic Longmen Shan fault slips slowly and had been assigned a modest seismic risk (Burchfiel et al., 2008; Densmore et al., 2007; Zhang et al., 2010). For the Special Issue Pei-Zhen Zhang was invited to write a review paper on the tectonic and geodynamic background of the 2008 Wenchuan earthquake. Through integrated studies on active faults, GPS crustal deformation, and geophysical structure, Zhang (2013–this issue) shows that deformation in the Western Sichuan is governed by interactions among three crustal blocks (Songpan, Chuandian, and South China) of distinct rheological properties under a tectonic framework with the eastward growth of the "soft" Eastern Tibet being blocked by the "hard" lithosphere of the South China block. The upper crust of the three blocks is dominated by brittle deformation, whereas the ductile flow of the lower crust would cause a dragging movement between the brittle upper crustal blocks. The relative motions among the brittle upper crustal blocks cause strain accumulations among their bounding faults to generate large earthquakes. The 2008 Wenchuan earthquake is a consequence of these geodynamic processes. Deformation of the Western Sichuan region can thus be described in terms of combined model of rigid block movement and continuous deformation.

3.1. The 2008 Wenchuan earthquake

Unlike papers in the Special Issue of Tectonophysics on the 2008 Wenchuan earthquake in 2010 (Yin, 2010) which mainly reports early studies on coseismic deformation and structures of the Longmen Shan fault, 8 papers in this volume on the 2008 Wenchuan earthquake report follow-up studies on the mechanism and paleoseismology of this great event.

The Wenchuan earthquake Fault Scientific Drilling (WFSD) started just 178 days after the 2008 Ms 8.0 earthquake. Li et al. (2013–this issue) reported initial results from the first hole (WFSD-1) at a final depth of 1201.15 m. They find that Principle Slip Zone (PSZ) of the 2008 Wenchuan earthquake located at ~590 m-depth with 1 cm-wide fresh fault gouge, as indicated by logging data such as temperature, natural gamma ray, p-wave velocity and resistivity, combined with the fresh appearance, magnetic susceptibility, and microstructure of the gouge. The Wenchuan earthquake slip plane has a dip angle of ~65° above a depth of ~590 m. There are at least 12 fault zones in the entire core profile, including the Yingxiu–Beichuan fault zone, with a minimum fault zone width of ~100 m. The distribution of fault gouge that is several meters thick, the location of the Wenchuan earthquake's PSZ, and the thickness of fresh gouge, all imply a correlation between the width of the fault zone and the number of seismic events.

To study the pre-earthquake background stress in the region of the Wenchuan earthquake, Luna and Hetland (2013–this issue) used a Bayesian probabilistic estimation to find that the coseismic slip of the Wenchuan earthquake is consistent with a constant orientation of principal stresses along the strike of the Longmen Shan fault zone. The inferred maximum compressive stress direction is sub-horizontal and approximately east–west trending. The intermediate compressive stress is sub-horizontal and north–south trending, and is most likely about 30% the magnitude of the most compressive stress. The least compressive stress is near-vertical.

Using a numerical simulation approach, Rohrbach et al. (2013–this issue) verified the seismogenesis-associated seismic velocity and attenuation variations in ambient noise measurements. First, they divided the seismogenic process into six phases. Then, using a finite difference time domain method they generated 30-minute low frequency ambient noise over a vertical profile of 200×45 km and recorded it with a 90-station array on the surface. Next, they processed the synthetic ambient noise records to get the auto-correlation function (ACF), cross-correlation function (CCF), Rayleigh wave dispersion curve, and horizontal-to-vertical spectral ratio (H/V). Finally, they examined the temporal variation of these parameters versus the phases of the seismogenic process and found the most pronounced changes occur in the phase with the largest velocity drop and the recovery phase directly before the mainshock.