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Review

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Review

Seismological challenges in earthquake hazard reductions: reflections on the 2008 Wenchuan earthquake

Yong Chen [1, *], Jiupeng Hu [2], Fei Peng[3]

[1.] The School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China;
[2.] The Institute of Geophysics, China Earthquake Administration Seismic Observation and Geophysical Imaging Laboratory, Beijing 100081, China;
[3.] The Institute of Earthquake Forecasting, China Earthquake Administration, Beijing 100036, China.

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Email address: yongchen@seis.ac.cn

Abstract

The Wenchuan earthquake is a natural disaster. Its occurrence and aftermath have demonstrated the critical roles of seismology and earthquake engineering in reducing seismic hazards and damages. However, their existing limitations should also be underscored. This article summarized and reviewed the current scientific understanding of earthquake ruptures, and new insights gained since the Wenchuan event. This study focused on the related challenges to seismology and earthquake engineering as follows: (1) The under-estimation of earthquake risks before occurrences; (2) The current limited data regarding large earthquakes in continental thrust fault systems; (3) The causal relationship between the Wenchuan earthquake and the reservoir impoundment in its vicinity; (4) The identification of low-velocity zone in the crust and its seismogenical role; and (5) The casualties and economic losses from a cascade of diverse natural hazards triggered by the ruptures, and the excellent earthquake resistance associated with tunnels in mountainous terrain.

Introduction

At 14:27:59 local time, on May 12, 2008, an M_S 8.0 earthquake struck Wenchuan County in Sichuan Province of southwestern China [1, 2]. The Wenchuan earthquake was noted as being one of the most destructive earthquake events to occur in China since 1949, due to its widest recorded region of influence and greatest disaster- triggered losses.

The Wenchuan earthquake also caused major casualties. Estimates from August 25, 2008 show that 69,226 people had been killed, along with 374,643 reported injured, and 17,923 lost. The earthquake caused a total direct economic loss of 845.1 billion yuan. During the earthquake event, numerous urban and rural buildings were devastated. The Ministry of Civil Affairs (June 25, 2008) states that approximately 23 million housing units were broken down duo to the earthquake (one house being equivalent to four housing units on average), with as many as 6,525,000 left completely destroyed. Also, a vast number of villages in the vicinity of the earthquake were razed to the ground.

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The Wenchuan earthquake affected all aspects of local society completely. The infrastructures of the area were severely damaged by the earthquake event, and systems providing transport, logistics and daily-life service were paralyzed over a large area. Since all of the facilities were out of operation for at least one week following the earthquake event, there were no landline communication connections available. A large number of hospitals and schools suffered severe damage, as did many historical sites and natural heritage. Moreover, many important industries and corporations were destroyed by the event resulting in severe impediment of industrial progress. The earthquake also effectively destroyed a lot of forested land and wildlife habitats to break down the eco-environment and degrade the area's ecological functions.

These enormous losses left seismologists and engineers many questions to consider. First of all, they needed a clear scientific understanding of the earthquake rupture, including the nature and size of the seismic waves and the ground accelerations they produced. Also, the secondary post-earthquake hazards which had been generated by the main earthquake event required examination, so that the seismic hazards could be better assessed and guarded against in the future. In this research study, the previous research study results which had been made available regarding this particular earthquake during recent years were summarized and reviewed in an attempt to obtain new insights into the disaster. Also, this study focused on the current related challenges to seismology and earthquake engineering following major earthquake events.

1. Destructive earthquake events

As previously mentioned, the Wenchuan earthquake was an extremely devastating earthquake event. The first challenge it presented to seismologists and engineers was the accurate assessments of the risks of mega earthquakes. The losses which had occurred during this earthquake were far beyond imagination. At least the following factors jointly caused the unprecedented intensity of the earthquake's destruction.

Firstly, the ground motions caused by the Wenchuan earthquake were extremely powerful. The recorded maximum peak ground acceleration (PGA) was determined to be greater than 1 g in the epicenter region [3]. The earthquake wave produced by the event propagated through the Earth, while the surface wave generated went around the Earth several full times, as shown in Fig. 1 [4]. The surface waves (Rayleigh waves) dominated the ground motions, which produced peak-to-peak amplitudes exceeding 1 mm, even at the side of the Earth on the surface away from epicenter. The Rayleigh waves generated drastic ground motions, with peak-to-peak amplitudes larger than 1mm even in the farthest places of the Earth away from the epicenter. Generally, the energy released from an earthquake E is calculated bias the seismic magnitude M from which they originated, as follows:

$$\log E = 11.8 + 1.5\,M$$

Therefore, with a magnitude of M_S 8.0, the Wenchuan earthquake was determined to release about $10^{23.8}$ ergs energy, which was equivalent of 10 megatons of TNT, or one thousand Hiroshima A-bombs.

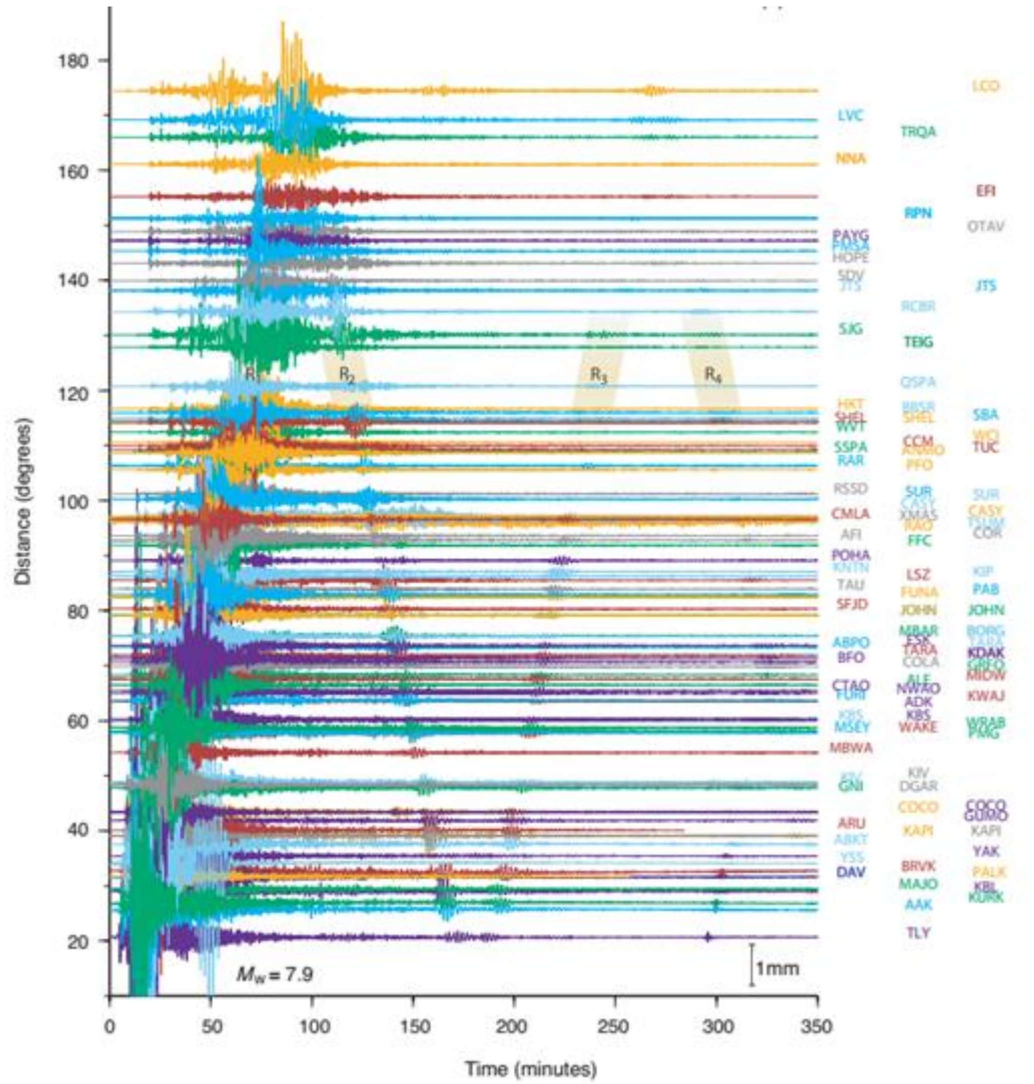

Fig. 1 Vertical seismic profile of the Wenchuan earthquake recorded by global seismographs of GSN and NDSN across the Earth. Vertical axes are the distance from the epicenter in degrees and horizontal axes are time in minutes. It can be found that the surface waves (Rayleigh waves) dominated the ground motions, with drastic motion amplitudes all over the world. A 1 mm scale is located at lower-right corner. The major seismic phases R1 and R2 are marked in the figure, which denote the Rayleigh wave traveling along minor and major great circle path respectively, as well as R3 and R4, which denote the same pulses as R1 and R2 respectively but having traveled an extra circle around the Earth.

The Wenchuan earthquake was felt in countries neighboring southern China, even in remote Beijing and Shanghai (more than 1500 km away). People in high-rise buildings in both cities felt the sway from the tremors. The ground motion data recorded at Beijing earthquake observation station (BJT) is given in Fig. 2. The peak displacement amplitude on ground surface was approximately 7 cm actually, which in result make tall building in Beijing shake significantly several minutes after the original time of mainshock event. This earthquake resulted in the cities

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of many provinces of western China classified as disaster zones, and approximately 450,000 km^2 of land was designated as disaster areas.

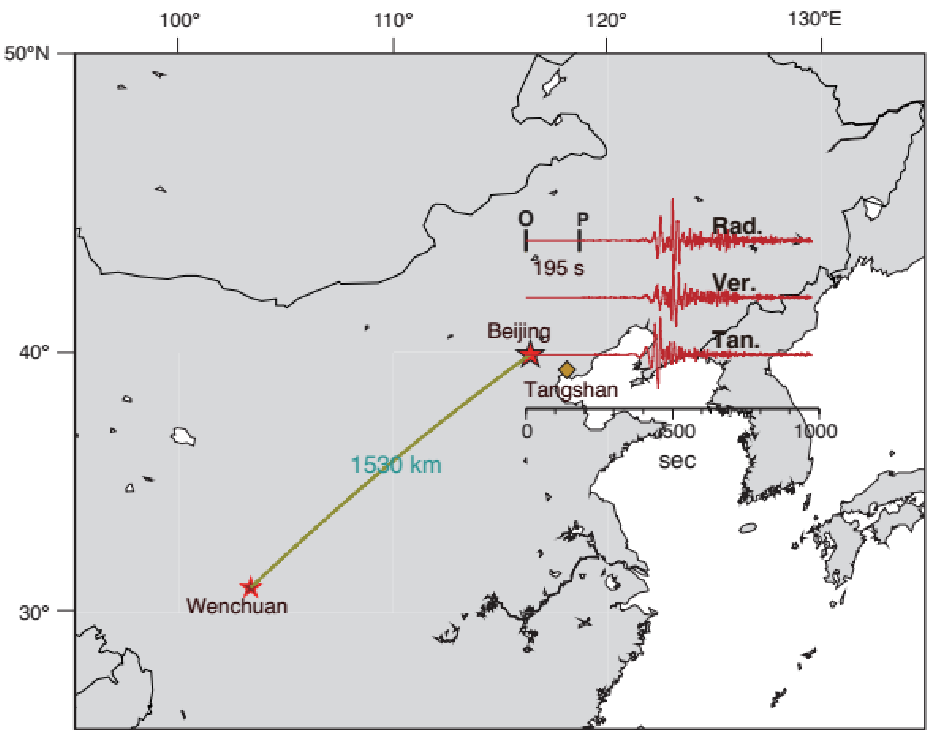

Fig. 2 Seismic Rayleigh waves recorded at the Beijing seismic station (located 1,530 km from Wenchuan). The ground displacement at this station was approximately 7 cm, with a five second wave period.

The second factor of the destructive effects was the underestimation of the hazard risks of the Wenchuan earthquake event. Fig. 3 shows the historical earthquake distribution map during the 2,000 years prior to the Wenchuan earthquake, so as to explain the seismicity background against which the M_S 8.0 Wenchuan earthquake occurred. In this map all the recorded earthquakes in the last 2800 years with a magnitude of $M \geq 5.0$ are shown. From the distribution of the historical earthquakes, we observed that none $M > 7.0$ event had previously took place in the midsection of the north-south seismic belt (Longmenshan Section) in a substantial period of time (prior to 2008). These findings indicated that, compared to other vigorous segments of the north-south seismic belt, a seismic gap was present along the central segment of the Longmenshan fault zone in history.

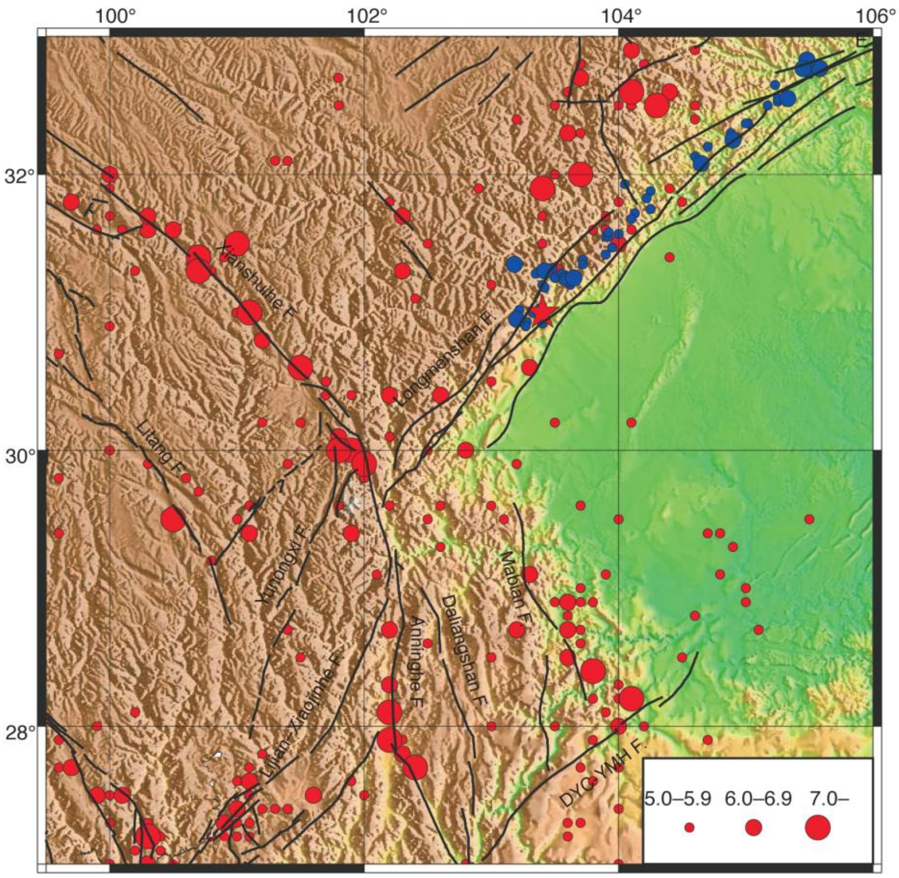

Fig. 3 The distribution of recorded earthquakes with a magnitude $M \geq 5.0$ in history near the Wenchuan event. The location of the study area is shown in lower left corner. The red dots denote the historical earthquakes and the red star denotes the Wenchuan mainshock (May 12, 2008). The blue dots represent the aftershocks of Wenchuan earthquake (up to June 12, 2008). Note: It was determined that no-one $M > 7.0$ event had previously took place in the midsection of the north-south seismic belt (Longmenshan Section) over the past two millennia (prior to 2008) [5].

The most recent zonation map was issued in China in 2001 [6]. Prior to 2008, relatively low intensity earthquake zoning rates were assigned to a number of Chinese counties located within the Wenchuan earthquake fault belt, e.g. VI or VII intensities with a maximum intensity of XII by the China standard. Accordingly, earthquake resistance was rarely considered in the area's building codes in this area. As a consequence of this oversight, the majority of the public-service architecture and dwelling houses were extremely vulnerable to earthquake damages. However, the reference earthquake intensity rates in this region and its surrounding areas were significantly changed after a 5.12 earthquake event occurred [7]. The majority of the previous researchers had considered that the Wenchuan area was a relatively weak earthquake zone. However, they then reconsidered their understanding of the Longmen Mountain Fault System (LMFS).

Many lessons have been learned from the occurrence of the Wenchuan earthquake in 2008. For example, it was confirmed that the seismic hazard assessment processes needed to be formulated using a broader context, which included a deeper understanding of the continental dynamics in the region. The seismic hazards in the region had been significantly underestimated

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prior to the major earthquake event of 2008. This had been mainly due to the fact that the current hazard assessments were based on historical seismicity and geodetic data. The occurrence of the Wenchuan earthquake indicated that future hazard assessments needed to consider the continental dynamics of the Tibetan Plateau, along with the deformation mechanism of the region.

The third factor which affected the destructive effects of the aforementioned 2008 major earthquake event was the numerous secondary post-earthquake hazards. Following the main Wenchuan earthquake, the secondary hazards included landslides, falling rocks and debris flow. It was determined that these secondary hazards accounted for more than one third of the total losses. These results were found to be extremely rare throughout the world's history of earthquake disasters.

2. Thrust fault systems of continents

A special feature of the Wenchuan earthquake was that it had occurred within a known thrust fault system on the Asian continent, and had provided a valuable window for the examination of continental thrust fault movements.

It is known that earthquakes result from sudden motions of the Earth's faults. These are typically dipping motions, of which the upper part is referred to as the hanging wall, and the low part is referred to as the heading wall (or footwall). During an earthquake event, there are three different modes of possible movement in the fault plane, which are used to divided faults into strike-slip fault, thrust fault and normal fault, respectively [8]. The Angle between the fault plane and the horizontal plane is called the dip, which can assist in classifying the type of a fault. The dip of a strike-slip fault is roughly 90°where the two rock parts move horizontally. There are many methods to address the fault parameters of earthquakes [9]. Though lager earthquakes have complex rupture process [10, 11], in most cases the dip of a thrust fault is a minor angle (as shown in Fig. 4). Normal and thrust faulting both belong to dip-slip movements, in which the displacement travel along the direction of the dip, while vertical motion is also present. The majority of continental earthquake events have resulted due to the movements of the faults composed of both dip and strike slip motions, which are referred to as oblique-slip movements. However, this was not found to be the case for the Wenchuan earthquake of 2008.

The focal mechanism solution indicated that the fault in which the Wenchuan mainshock event had occurred was a thrust fault. The China Earthquake Network Center (CENC) determined the principal source parameters of the mainshock event as follows:

The Original time of Wenchuan earthquake is May 12, 2008, 14:28:04; epicenter is located in 30°57' N, 103°24' E and the magnitude is M_S 8.0. In addition, focal depth is 16 km [12].

Fig. 4 shows the focal mechanism solution of the Wenchuan earthquake event. The focal mechanism solutions for the mainshock event of the Wenchuan earthquake were achieved by numerous research teams working with the data from China Seismic Network and the remote seismic data recorded by various global network [13]. Minor discrepancies were found to exist among the different studies. However, the overall solutions were determined to be in reasonable agreement. As noted in Fig. 4, the Longmenshan Fault was located on a thrust fault in the Longmen Mountain region, located in Sichuan Province, southwestern China [13, 14]. The strike

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of the fault plane was in an approximate NE direction. It was determined that the motions of this fault zone were responsible for an uplift in the western mountainous areas compared to the Sichuan Basin.

It has been confirmed that the Wenchuan earthquake took place within a thrust fault circumstance, making it unusual in the continental areas of the world. Thrust faults most usually appear in subduction zones in ocean, in which it has been observed that earthquakes frequently occur within oceanic inter-plates. All large oceanic earthquakes have been confirmed to exhibit thrust fault movements. In contrast, it has been observed that the majority of earthquakes display strike-slip characteristics in continent. Nevertheless, the majority of earthquake events which previously occurred within the margins of the Tibetan Plateau have displayed thrust fault mechanisms (Fig. 5).

The Longmenshan Fault, which is part of the Longmen Mountain Fault System (LMFS), produced 300-km-long surface rupture during the Wenchuan earthquake [15]. The LMFS contains numerous faults of northeast-southwest trend, which divide the eastern Tibetan Plateau and of the western Yangtze Block [16]. The LMFS is intersected by the North-South seismic belt, which is an important seismic belt in China, as well as a dividing boundary of both geography and geophysics features [17]. In subsurface, the LMFS cuts the crust into two parts. Within the LMFS there are high mountains and deep valleys located in the LMFS. Throughout a 50 km region of the system from east to west, the average elevation has been observed to sharply change from 2500 m to 5500 m, and the maximum reaches 7500 m. In addition, the depth of the Moho in the core of the system increases dramatically from 40 km to 60 km.

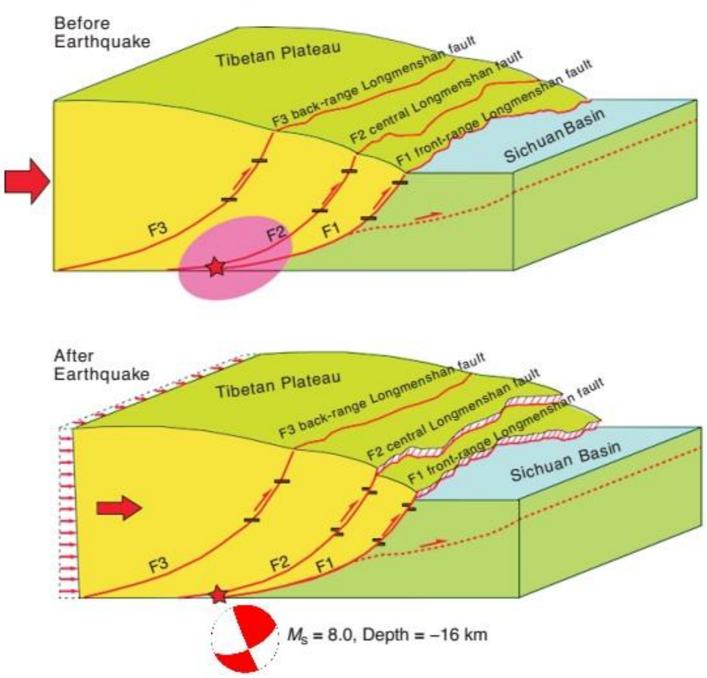

Fig. 4 A schematic map of the source area of the Wenchuan earthquake. The condition of the regional stress and the direction of the faults movement indicate that the Wenchuan earthquake occurred in a thrust fault circumstance. The earthquake source area and focal mechanism are given in this figure, as

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well as the geomorphology. The sudden motions had occurred on three segments of Longmenshan fault zone that are F1(the front-range fault), F2 (the central fault) and F3 (the back-range fault) [18].

The seismic activities of the LMFS and East Asia are caused by the collision caused by the northward movement of the Indian Plate onto Eurasia Plate. This movement has resulted in uplifts in the entire Tibetan Plateau and related seismic activities. These deformations have also resulted in extrusions of crustal material from the plateau in a western direction toward the Sichuan Basin and the rest of southeastern China. The area bordering the Tibetan Plateau and Sichuan Basin is known to be very prone to destructive earthquakes. However, the kippe structure which had been discovered in the 1920s was believed to dominate the area. As a result, shortening or convergent characteristics were obvious. Moreover, although thrust fault movements had previously occurred in the LMFS area prior to the Wenchuan earthquake in 2008, the area was observed to exhibit a number of geological features atypical to active convergent mountainous belts. However, no large-magnitude low-angle thrust faults were present, nor was a young high topography (post ca. 15 Ma) [17], and a thickened Earth's crust was observed in the region. The low shortening rates were found to be in accordance with the GPS observations (i.e. < 3 mm/year), and it was concluded that no coeval foreland subsidence was observed [16].

Depending on its specific features, the Wenchuan earthquake was very important due to the rare opportunity it provided to observe the movements of a thrust fault within a continent. As a result, scientists obtained a better understanding of continental dynamics.

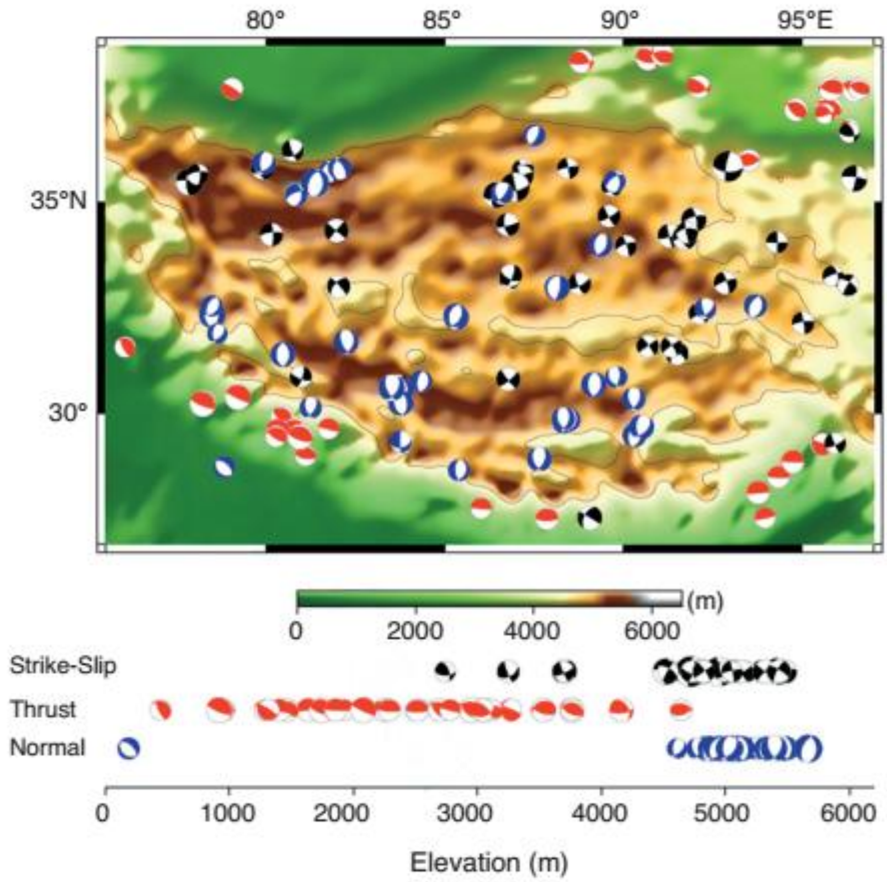

Fig. 5 The earthquakes spread all over the Tibetan Plateau and their focal mechanism solutions. The black beach balls indicate strike-slip mechanisms, the red ones denote thrust mechanisms and blue ones

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represents normal mechanisms. The majority of the previous earthquakes which occurred within the Tibetan Plateau have displayed normal or strike-slip faulting. In contrast, the earthquakes on margin region of the plateau have displayed thrust characteristics [19].

3. Determination of whether or not the reservoir impoundment triggered the Wenchuan earthquake event

Following the Wenchuan earthquake, a debate occurred among researchers and residents of the area as to whether or not the Wenchuan earthquake was in fact a reservoir earthquake triggered by the Zipingpu Dam and its reservoir. Zipingpu Dam make up an integrated water conservancy facility mainly used for irrigation and water supply, combined with power generation, flood control and tourism. The Zipingpu Dam is a rock-fill dam located in Minjiang River in Sichuan Province, and the maximum dam height is 156 meters with a total capacity of 1.112 billion m^3, which makes it one of the biggest dams in China. Though completed in 2006, the Zipingpu Dam began to store water in the fall of 2005, about 3 years ahead the time when the Wenchuan earthquake occurred 20 km west [20]. During the Wenchuan earthquake, this rock-filled dam was damaged but remained structurally safe according to a post-earthquake investigation.

Reservoir earthquakes is a type of induced seismicity, typically refers to the emergence of minor earthquakes or increased seismicity in the vicinity of a reservoir following impoundment [21]. However, the majority of the previous reservoir earthquakes have been moderate or weak events, which presented no major damage risks to the dams. Only 18 reservoir dams have suffered damages from reservoir-triggered earthquakes, the strongest of which registered at a magnitude of *M* 6.4. The observational results of Marathon Earthquake in 1931, considered as the first recorded reservoir earthquake, give us a hint that human activities such as water impoundment can change the stresses and strains of subsurface, which in turn can potentially induces earthquakes. Though the majority of the reported reservoir earthquakes are of a low magnitude and have presented little damage to related facilities, there have been 18 dams damaged by reservoir earthquake till 2008. The biggest reservoir earthquake in hostory happened in India in 1967 even reached a magnitude of *M* 6.3.

Reservoir earthquake has always received the attention of seismologist. Xu et al. did a statistic of the focal mechanism of all registered reservoir earthquake [22]. They found that the majority had been strike-slip or normal events. Furthermore, none of the mainshocks of reservoir earthquake events were found to show thrust mechanisms, although some of the aftershock earthquakes had. These facts provide us with a clue to identify a reservoir earthquake by the focal mechanism. It has been confirmed that the Wenchuan earthquake was a result of the collision of the Tibetan Plateau onto the South China Block, which caused a sudden dislocation in LMFS along Yingxiu-Beichuan. According to the local geological features and other mechanism research, it's obvious the Wenchuan earthquake occurred in a thrust fault, which doesn't agree with the reservoir earthquake statistics mentioned above. Actually, in reservoir earthquake case, the water acted as a load above the fault and had created tensile stress in the subground, which facilitated strike-slip or normal fault but not thrust fault. That was believed to be the reason that the majority of reservoir earthquakes occurred on strike-slip and normal faults. Differently in the Wenchuan

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earthquake case, the main fault of the earthquake was a thrust fault, which was the result of the strong horizontal pressure (not tensile) which had pushed motion of the fault, where the loading effect of storage water would go against the slide between the hanging wall and foot wall. To some extent, having a thrust mechanism, the Wenchuan earthquake was more similar to the earthquake in oceanic subduction zone rather than a terrestrial reservoir earthquake.

Currently, despite many published research results, there is no absolute convincing model that explains how the reservoir impoundment trigger seismic activities. A lot of study still needs to be done to further understanding the relevant theories of reservoir earthquakes [23]. However, expounding the detailed analyses of causal relationship between reservoir impoundments and triggered earthquakes is not the point of this article. We just want to find a simple and effective way to confirm whether or not the Wenchuan event is a reservoir earthquake. In this research study, only the special case of this event was discussed, along with the Zipingpu reservoir's possible triggering role. And our conclusion was that, at least from the aspect of phenomenology and source mechanics, the 2008 Wenchuan event differed a lot from classic reservoir seismicity, consequently we can safely deduce that the Wenchuan earthquake is not triggered by reservoir impoundment.

4. Low-velocity zones (LVZ) in the Earth's crust

The Wenchuan earthquake event had occurred against the backdrop of the long-term uplift and eastward enlargement which had occurred in the Tibetan Plateau. In the region involved in this research study, scientists found thicken crust and uplifted surface, but there was no obvious evidence of the existence of shortened late Cenozoic crust around the eastern edge of Tibetan Plateau. One credible reason for the explanation of the preceding phenomenon is that a lower crustal flow exists there.

Previously, the concept of LVZ was introduced in the study of partial melting in the earth's upper mantle, where about 1% melting existed. In partial melting layers, water accumulates to reduce the material's melting point and may further affect the composition of the mantle sunstance. Under the conditions of the rapid uplifting of the Tibetan Plateau, an S-wave LVZ covered a large area. Su et al. determined that the S-wave low velocity was at a depth of 40 km beneath the plateau, and this LVZ was the largest S-wave LVZ in China [24].

After the 2008 Wenchuan earthquake, scientists carried out many image researches on the region of southeastern Tibetan Plateau. For example, Wei et al. made a three-dimension tomography deep to the top mantle at preceding area [25]. They used data from National Seismic Network (Sichuan and Yunnan) composed of 71,670 P-wave travel times of 3594 earthquakes. The results of their study (Fig. 6) showed that outstanding slow P-wave velocity (low-V_P) anomalies had filled the lower part of the crust in the western area of Longmenshan Mountain [25]. On the contrary, fast crustal velocity (high-V_P) anomalies had existed under the Sichuan Basin. With Longmenshan Mountain as a boundary, the Tibetan Plateau invaded towards the Sichuan Basin which in turn resulted in stain accumulating at the boundary where Wenchuan earthquake occurred. These tomography results and related geological process present the dynamic scenario of the lower crustal flow in this area. Moreover, Li et al. also discovered the obvious low velocity zone in the middle crust using ambient noise data [26].

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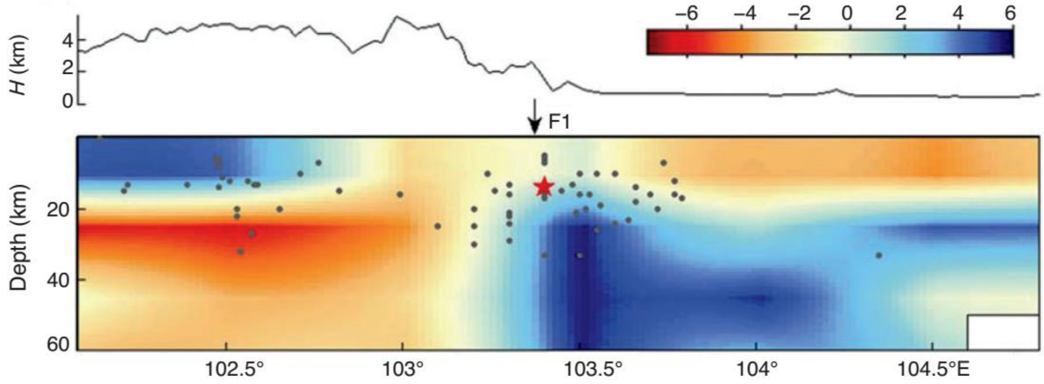

Fig. 6 P-wave tomography results of a profile from Wei et al. [25]. The surface topography is given at the top with the Tibetan Plateau on the left and Sichuan Basin on the right. The arrow at F1 denotes Longmenshan fault where the Wenchuan mainshock (red star) occurred. The grey dots represent epicenters near the profile (with a perpendicular distance< 15 km). We can find that a lower velocity perturbations zone lies beneath Tibetan Plateau while a higher velocity perturbation zone lies under Sichuan Basin at the same depth. We also find that the transitional region of slow and fast velocity zone is a significant seismogenic area for big earthquakes [25].

Lei and Zhao also determined that a significant low-velocity zone lay beneath the hypocentral region of the Wenchuan earthquake [27]. They suggested that the LVZ contained fluids that may have played an important role in the formation process of this great earthquake. Moreover, Wei et al.'s aforementioned work provided another geophysical description of geological structure and activities under the LMFS area, where lower crustal flow invaded upward.

A subcrustal low-velocity zone is known to have occurred near the boundary between the lithosphere and asthenosphere, at a depth of 220 ± 30 km. A significant feature of subcrustal zone is that the S-wave velocity of this zone is abnormal lower than outside's. Beno Gutenberg first found the subcrustal LVZ in 1959. However, in contrast with Gutenberg’s subcrustal LVZs, LVZs in the Earth's crust (at depths of 20 to 40 km) were observed along the Longmenshan Fault Zone[27-29]. Therefore, the dynamic processes of the LVZ formation, along with its impact on the seismicity of this area, still require further study.

5. Losses from earthquake-triggered disasters accounting for more than one third of the total losses following the Wenchuan earthquake even t

The hazard assessment model which had been used prior the Wenchuan earthquake event had only focused on the possible hazards related to the main event and its aftershocks. However, it did not take the post-earthquake hazards into account. This practice resulted in major problems in the subsequent disaster assessments of the Wenchuan earthquake. The Wenchuan earthquake was followed by numerous secondary post-earthquake hazards which were caused by landslides, rock falls, and debris flow. Most of these disasters appeared in the transitional areas along the Longmen

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Mountains, which is the diving line of Tibetan Plateau and Sichuan Basin. In this region, the respective geological and topographical conditions of the western and eastern partition varied a lot, as did their socio-economic development levels. The deaths which were associated with the earthquake-triggered geological disasters exceeded one third of the total casualties due to the Wenchuan earthquake. These findings were determined to be extremely rare in the history of earthquake disasters. Therefore, the future disaster assessment and hazard reduction processes should revisit the effects of these devastating secondary disasters.

It has been found that the environments of global mountainous regions are fragile. The slope instability caused by the Wenchuan event then led to landslides. Landslides are considered to be major geological hazards. According to estimations, tens of thousands of earthquakes were determined to be the inducement to subsequent landslides and avalanches. The number of massive landslides with volumes exceeding 10 million m^3 reached 30. The Anxian County landslide triggered by Wenchuan earthquake was the biggest one in history, which formed a rackfall dam 550 m in height and was equivalent to 750 million m^3 in volume. Substantial numbers of landslides not only have caused many death - a landslide which occurred in Beichuan County entombed more than 1,600 people, but also have damaged residential and basic public facilities. Moreover, these landslides even changed the appearance of the mountain regions in which they occurred. Not only do landslides often cause direct damages to occupants and infrastructures, they also have been known to be responsible for tremendous difficulties which have hampered the successful operation of post-disaster relief and reconstruction activities. These difficulties have been the direct results of the persistence of landslide dangers while emergency personnel have attempted rescue operations.

In the Wenchuan area, flooding had become a major hazard within a short period of time after the Wenchuan event. Many nearby rivers were blocked by large landslides triggered by Wenchuan event and accessory powerful aftershocks, and the blockages formed "earthquake lakes" in turn. Next, the water level of these earthquake lakes rose rapidly as time went by. Many people worried about that the ever-increasing water pressure would break these nature-formed dams, thereby threatening the millions of inhabitants of the lower reaches. According to the estimations, there were 21 earthquake lakes existing in the disaster area till late May 2008 and at least 10 of these lakes presented potential dangers to the local inhabitants.

The traffic conditions serve as the lifeblood of the rescue procedures following disaster events. Roads were the most critical way of transportation due to the mountainous feature where the Wenchuan event occurred. However, almost all of the roads in the disaster areas were broke down to some degree following the earthquake. It was found that many of the main roads were entirely cut off for a long time, which slowed down the progress of the rescue activities in the core earthquake stricken areas. The traffic disruptions were mainly caused by the subsequent landslide hazards following the earthquake. The roads which had been constructed on the mountain slopes suffered major damages due to the large and numerous landslide disasters, and widespread severe traffic disruptions were common.

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Fig. 7 Longdongzi Tunnel after the Wenchuan earthquake. This tunnel located near Dujiangyan City. It was damaged but didn't collapse in Wenchuan earthquake. Actually none of the tunnels in the area were found to have collapsed during the Wenchuan earthquake's powerful shaking motions. Since few fault lines dissected a tunnel in this earthquake, almost all of the tunnels in the area (even in the intensity X degree areas) had suffered no or only slight damages during the earthquake event (Lu Ming).

It should be noted that, a lot of tunnels and road bridges on the national and provincial roads had recently been constructed in Wenchuan area prior to the 2008 earthquake event. During these constructions, strict building codes and high technology processes had been applied. According to statistics collected from 1,657 road bridges in the zones with seismic intensities equal to or greater than an earthquake intensity of VII, most of the them displayed good earthquake resistance capabilities [30]. These capabilities were made apparent as only 1.09% of these bridges were destroyed. Along with the road bridges, road tunnels had been constructed during the recent years prior to the 2008 event, and these also displayed good earthquake resistance capabilities. Although the shaking effects of the Wenchuan earthquake were very strong, it was observed that the damages to the majority of the tunnels were very minor (Fig. 7). During the destructive earthquake, none of the tunnels and only a small number of bridges were broken down, although not a few bridge columns crumbled. These results demonstrated the advantages of traverse mountainous terrain via bridges and tunnels.

However, the severe earthquake-triggered disasters following the Wenchuan earthquake event served as reminders that reasonable hazard assessments and land-use regulations become the most urgent issues involved in disaster mitigation for mountain regions in China. Therefore, it is necessary to adopt impactful building codes and set up feasible land-use regulations based on an area's earthquake engineering research results.

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6. Conclusions

In observance of its 10-year anniversary, there are many lessons which can be learned from the Wenchuan earthquake event of 2008. A broader context of understanding of continental dynamics is still required in order to gain correct assessment results of earthquake risks, as well as to effectively mitigate seismic hazards. The existing huge earthquake-related fault structures and underground low-velocity zones need to be revisited for the purpose of recognizing their roles in seismic activities. A new reasonable hazard assessment model which focuses on both direct and secondary hazards should also be established. Moreover, the relationships between human activities and earthquake events still require effective resolutions. Also, the generalizations of better building codes and transportation methods in the mountainous terrain need to be given sufficient attention. These all definitely will present scientific challenges for seismology and earthquake engineering in the future.

Conflict of interest

The authors declare that they have no conflict of interest.

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Chen Yong

Geophysicist, who was elected academician of Chinese Academy of Sciences in 1993, was elected academician of the Third World Academy of Sciences in 2000. He has been engaged in geophysics and petrophysics. He mainly does research about artificial sources recent years. He served as deputy director of China Earthquake Administration and chairman of the China Geophysical Society. He is currently Professor of School of Earth Sciences and Engineering, Nanjing University.

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