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The China Seismological Reference Model project

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Key Points:

- The China Seismological Reference Model is being constructed using seismic data from 4511 seismic stations deployed in continental China.
- An associated product center has been created to archive and distribute seismic reference models, original seismic data, and seismic constraints.
- The Reference Model will offer insights into tectonics, enhance hazard mitigation programs, and provide guidance for future research directions.

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Abstract: The importance of developing high-resolution seismic models to improve understanding of tectonic processes and enhance seismic hazard mitigation programs, along with the rapid expansion of seismic coverage in China, called for a seismological reference model to be established in China. The China Seismological Reference Model (CSRM) project was initiated by the National Natural Science Foundation of China with two primary goals: (1) the CSRM would serve as a primary source for the current state of seismological research in China, and (2) the seismic data and constraints used to construct the CSRM would be used as a backbone open-access cyberinfrastructure for future research in seismology. The CSRM project was also intended to promote data exchange and scientific collaboration in seismology in China. Accordingly, two parallel efforts of the project are being pursued: (1) construction of the CSRM, and (2) development of a CSRM product center. The CSRM is jointly constrained by various types of seismic constraints extracted from the seismic data recorded at 4511 seismic stations in continental China following a top-down approach, with the seismic structures in the shallower part of the Earth constrained first. Construction of the CSRM involves three preparation steps: (1) building datasets of various seismic constraints from the seismic data, (2) developing a method to incorporate the constraints of surface wave observations from regional earthquakes into the inversion of the seismic structure, and (3) constructing high-resolution pre-CSRM seismic models of the velocity structure in the shallow crust and the *Pn*-velocity structure in the uppermost mantle. In the final process, the CSRM will be constructed by jointly inverting all the seismic constraints using the pre-CSRM models as starting models or *a priori* structures. The CSRM product center (http://chinageorefmodel.org) archives and distributes three types of products: CSRM models, the Level 1 original seismic data used to extract seismic constraints in the construction of the CSRM, and Level 2 data on the seismic constraints derived from the Level 1 data and the inferred earthquake parameters in the construction of the CSRM. The CSRM product center has archived 141 TB of Level 1 data from 1120 permanent broadband stations in the China Seismic Network Center and 3391 temporary stations from various institutions and data centers around the world, as well as 140 GB of Level 2 data on various seismic constraints and inferred event parameters from the construction of the CSRM. The CSRM is expected to provide significant insights into the composition and tectonic dynamics in continental China and to enhance the capability of various seismic hazard mitigation programs in China from near real-time rapid determination of earthquake parameters to an earthquake early warning system. The CSRM could also provide guidance for focuses in future seismological research and the design of future active and passive seismic experiments in China. Several focuses are suggested for future seismological research in China, along with the building of a national cyberinfrastructure to sustain and expand the operations of the CSRM project.

Keywords: China Seismological Reference Model; seismic structure; seismic hazard; tectonics; continental China

1. Introduction

Continental China is an assemblage of many tectonic blocks formed in various geological time periods, including the North China Craton and the Tarim Craton in the Archean, the South China Block in the Precambrian, and microcontinental blocks of the Junggar, Qiangtang, Lhasa, Qilian, Alxa, and Qaidam Blocks formed in the Archean or Precambrian (Zhai MG, 2013; Zhao GC et al., 2018; Figure 1a). In the first order, the assemblage was

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accomplished by the subduction of the Pacific Plate in the east and by the closure of the Tethys Ocean and the continental collision between the Indian and Eurasian Plates in the west (Jia CZ et al., 2013). These large-scale tectonic processes also promoted strong interactions between the tectonic blocks and generated several orogenic belts between the blocks, such as the Qinling Range between the North China Craton and the South China Block, and the Taihang Range between the North China Plain and the Ordos Craton (Meng QR and Zhang GW, 2000; Wang Y and Li HM, 2008; Figure 1a). The strong interactions of the tectonic blocks have also resulted in many moderate to large earthquakes between the tectonic blocks inside China, which is the primary source of seismic hazards occurring in China (Figure 1b).

Key to deciphering these tectonic processes and the origin of the interblock earthquakes is high-resolution imaging of the seismic structure beneath continental China. The formation of these distinct tectonic blocks and the tectonic processes occurring in continental China have left significant seismic imprints in the crust and mantle. In the east, the subduction and rollback of the Paleo-Pacific Plate may have caused regional extension and a corresponding crustal thinning in the North China Craton and eastern Yangtze Craton (Wang YH et al., 2005; Wilde, 2015; Liu L et al. 2016) and may have induced upwelling in the mantle and extensive magmatism in the region (Lei JS and Zhao DP, 2005; Zhou XM et al., 2006; Pirajno et al., 2009; Zhu RX et al., 2011, 2012; Li XY et al., 2015; Deng J et al., 2017), which may have modified the thermochemical structure of the lithosphere. In the west, the India–Eurasia collision thickened the crust, which may have resulted in partial melting in the middle of the crust (Molnar and Tapponnier, 1975; Nelson et al., 1996; Owens and Zandt, 1997; Royden et al., 1997; Yin A and Harrison, 2000; Tapponnier et al., 2001; Li XQ and Yuan XH, 2003; Royden et al., 2008) and underthrusting of the Indian lithosphere beneath the Tibetan Plateau (Zhao WJ et al., 1993; Ceylan et al., 2012; Replumaz et al., 2014; Chen M et al., 2017; He P et al., 2018; Bao XY and Shen Y, 2020). These complex tectonic activities have also produced many large sedimentary basins in continental China, with the Songliao and Bohaiwan Basins in eastern China having evolved from a series of rift and subsidence events related to the western subduction of the Pacific Plate (Ye H et al., 1985; Ren JY et al., 2002; Feng ZQ et al., 2010) and the Sichuan, Ordos, Tarim, and Qaidam Basins in the Circum-Tibetan Plateau Basin-Range System influenced by the collision between the Indian and Eurasian landmasses (Ye H et al., 1985; Xia WC et al., 2001; Ren JY et al., 2002; Yang YT et al., 2005; Wang CY et al., 2007; Feng ZQ et al., 2010; Jia CZ et al., 2013; Zhai MG, 2013; Wang MM et al., 2016).

High-resolution seismic models beneath continental China would also play a key role in the seismic mitigation program in China in other two aspects: (1) they could assist in better relocation of earthquakes occurring in continental China and better inference of the earthquake source rupture process, and (2) they could provide a more accurate estimation of ground motion during earthquakes, especially in the basin regions with high populations.

In the last two decades, we have witnessed an explosion of seismic coverage in continental China (Figure 2), with the China Earthquake Administration (CEA) leading the effort. The CEA operates the China National Seismic Network (CNSN), the nation's backbone seismic network for daily earthquake monitoring. The CNSN consists of 1120 permanent seismic stations deployed across the country, and it has provided continuous seismic data over the decades. From 2006 to 2016, the CEA also led the China Seismic Array (ChinArray) project, which covered 1770 seismic observational sites with an average station spacing of 35 km. Besides the CEA, various research institutions deployed 2451 temporary stations between 1990 and 2017, and the data from 973 seismic stations are available from the Incorporated Research Institutions for Seismology (IRIS).

The importance of high-resolution seismic models in understanding the tectonic processes and enhancing the seismic hazard mitigation programs, along with the rapid expansion of seismic cover-

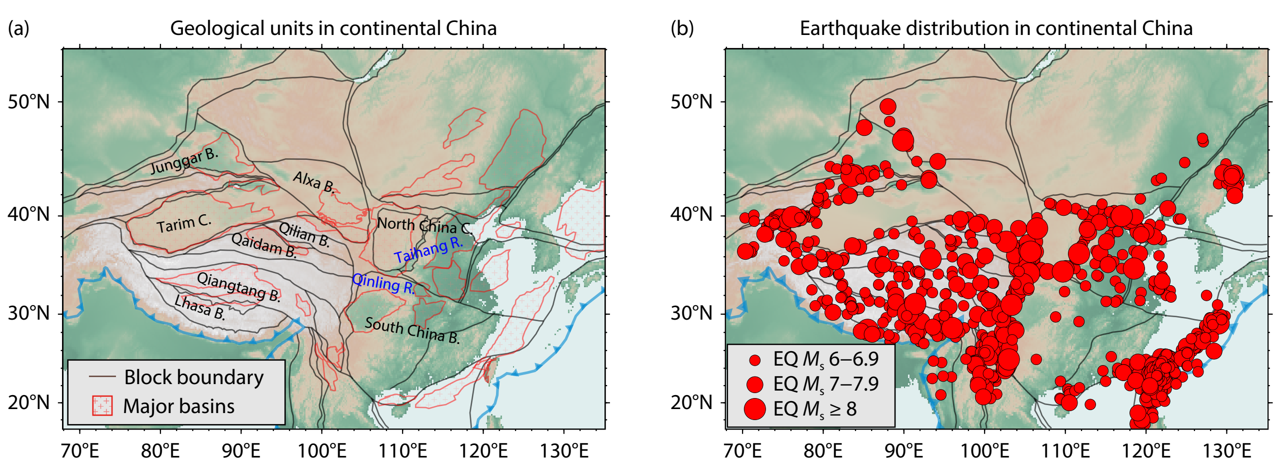

Figure 1. Major tectonic blocks, orogenic belts, sedimentary basins, and distribution of moderate to large earthquakes in continental China. (a) Major tectonic blocks (regions enclosed by black lines, with B. standing for Block and C. for Craton), orogenic belts (marked by blue text, with R. standing for Range), and major sedimentary basins (red-crossed regions) in continental China, along with plate boundaries (solid blue lines). (b) Location of moderate and large earthquakes (EQ; magnitude >6), based on the catalog from the Global Centroid Moment Tensor project (Ekström et al., 2012).

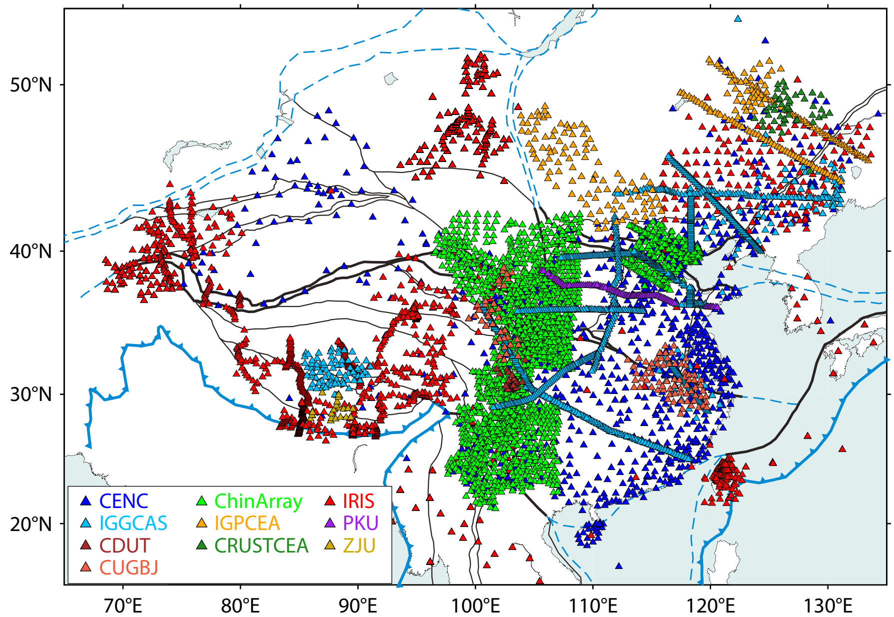

Figure 2. Seismic stations deployed in China. The different-colored triangles indicate stations operated by various networks or research institutions: CENC, China Earthquake Networks Center, China Earthquake Administration; ChinArray, China Seismic Array; IRIS, Incorporated Research Institutions for Seismology; IGGCAS, Institute of Geology and Geophysics, Chinese Academy of Sciences; IGPCEA, Institute of Geophysics, China Earthquake Administration; PKU, Peking University; CDUT, Chengdu University of Technology; CRUSTCEA, Institute of Crustal Dynamics, China Earthquake Administration; ZJU, Zhejiang University; CUGBJ, the China University of Geosciences (Beijing).

age in China, called for the establishment of a seismological reference model in China. A reference model would provide a scientific database of reference for the current state of seismology in China and a guidance for future focuses in seismological research. It would also promote data exchange and scientific collaboration in seismology in China.

2. Initiation of the China Seismological Reference Model Project

In 2016, a working group was formed by the Division of Solid Earth Geophysics and Space Science, Department of Earth Sciences, National Natural Science Foundation of China (NSFC), to explore a possible project of establishing a seismological reference model in China. The working group was composed of seismologists from major institutions of seismological research across the country, seismic network managers, and NSFC staff. In June 2016, the working group organized a scientific meeting in Beijing, hosted by the Institute of Geology and Geophysics, Chinese Academy of Sciences. The meeting attracted more than 300 people from around the world. During a business meeting after the scientific meeting, the working group summarized the status of seismology in China and proposed establishing a China Seismological Reference Model (CSRM) project.

The working group commented that the seismic coverage in China was rather dense and had surpassed that of the United States of America in many regions, such as in the North–South Seismic Belt and north China. Chinese seismologists had also carried out important research on the seismic structures in various regions of China and had gained significant insights into the tectonic processes in continental China. However, the working group also commented that several challenges still remained:

(1) Seismic coverage needed improvement in the areas of northwestern China, the Tibetan Plateau region, north central China, and the oceans.
(2) There were differences in the existing seismic models, and various types of seismic data constraints had yet to be integrated into seismic model construction.
(3) Seismic data sharing needed to be strengthened among scientific researchers.

To facilitate a national effort to overcome these challenges, the working group believed that there was a need to establish a seismological reference model in China and that the time was ripe.

The working group established basic rules for model construction and data sharing. The CSRM should be established by a construction group. Researchers who made important contributions to the model construction, provided original seismic data, or developed new seismic methods would be members of the construction group. The seismic data and seismic results would be shared with scientific researchers once the CSRM was established. Researchers could use the shared data only for their own research, while ensuring compliance with the confidentiality requirements of the source of the original data. Data users should consult with the original data provider regarding how to share the research results obtained by using the shared data, with the minimum requirement being the citation of the article that published the original data. Recently, the working group has also approved an official CSRM logo (Figure 3) as a form of citation for any data or product distributed from the CSRM project.

3. The CSRM Project

The CSRM was established with two primary goals in mind:

Figure 3. Official logo of the China Seismological Reference Model.

(1) The CSRM would serve as a primary source for the current state of seismological research in China.
(2) The seismic data and constraints used to construct the CSRM would be archived and shared as a backbone open-access cyber-infrastructure for future research in seismology.

Because the seismic data would continue to accumulate rapidly and new seismic methods are constantly being developed, the CSRM and its construction method would also need to be updated continuously. The updating of the model had to be a process of reintegrating those seismic constraints with the new observations and reincorporating all available constraints by the new methods. To accomplish these goals, the construction of the reference model needed to retain all the original data and seismic constraints that were used in the model construction. Accordingly, two parallel efforts of the project were pursued: (1) construction of the CSRM, and (2) development of a CSRM product center as the cyberinfrastructure to ensure the long-term sustainability of the CSRM goals.

3.1 Construction of the CSRM

The CSRM was not to be constructed as a patchwork of existing models. The CSRM had to be jointly constrained by various types of seismic data. In other words, the model would need to be established by simultaneously integrating all types of seismic data into the constraining of the seismic structure. The final establishment of the model would also follow a top-down process, with the seismic structures in the shallower part of the Earth constrained first, given that the structures in the shallow part of the Earth would affect the accuracy of the inverted seismic structures in the deep part of the Earth.

The actual construction of the CSRM would involve three preparation steps: (1) building datasets of various seismic constraints from the seismic data, (2) developing a method to incorporate the constraints of surface wave observations from regional earthquakes into the inversion of the seismic structure, and (3) constructing high-resolution pre-CSRM seismic models of the velocity structure in the shallow crust and the *Pn*-velocity structure in the uppermost mantle. The purpose of incorporating regional surface wave waveforms would be to increase the seismic sampling in the regions of sparse station deployment and areas in the deep mantle that are beyond the seismic sampling of seismic ambient noise. Pre-CSRM models would be constructed to establish models that could be independently constrained with certain seismic datasets and that would provide good references as starting or *a priori* information in constructing the CSRM. In the final process, the CSRM would be constructed by jointly inverting all the seismic constraints using the pre-CSRM models as starting models or *a priori* structures.

Seismic constraints were derived from the continuous seismic ambient noise data and waveforms of regional and teleseismic events recorded at 4511 seismic stations deployed in continental China (Figure 4). The number of seismic stations used in constructing the CSRM was approximately 85% of all the seismic stations deployed in continental China (cf. Figures 4 and 2). The extracted seismic constraints included the *P*-wave polarization angle from teleseismic events, Rayleigh wave ellipticity, receiver function, *Pn*-wave travel time, interstation phase and group velocity dispersions, and event–station phase and group velocity dispersions. These seismic constraints provided excellent sampling of the seismic structure throughout the crust and in the uppermost mantle. In particular, the *P*-wave polarization angle and short-period Rayleigh wave ellipticity were sensitive to the seismic structure in the top 10 km of the crust, the receiver function was sensitive to the existence and seismic property contrasts of the seismic discontinuities inside the Earth, the *Pn*-wave travel time was sensitive to the seismic structure of the top 15–245 km of the uppermost mantle, the interstation phase and group velocity dispersions were sensitive to the seismic structure of the crust, and the event–station phase and group velocity dispersions and long-period Rayleigh wave ellipticity were sensitive to the seismic structures in the crust and the mantle.

The *P*-wave polarization angles and receiver functions were obtained from three-component waveforms of 9361 teleseismic events, the *Pn*-wave travel times were handpicked from the recordings of 3446 seismic stations from 6787 regional earthquakes, the short-period Rayleigh wave ellipticity was estimated from seismic ambient noise waveforms from 3649 seismic stations, the interstation Rayleigh wave phase and group velocity dispersions were extracted from 639,171 empirical Green's functions obtained by cross-correlating the seismic ambient noise waveforms from 4424 seismic stations, the event–station Rayleigh wave phase and group velocity dispersions were estimated from surface wave waveforms of 226 intermediate to large ($4.5 \le M_W \le 7.0$) regional earthquakes, and the long-period Rayleigh wave ellipticity was calculated with waveforms from 9361 teleseismic events. Significant effort was also devoted to quantifying the uncertainties of those seismic constraints. An example of the estimated long-period Rayleigh wave ellipticities (represented by the ZH ratio, the amplitude ratio between the vertical and radial components of Rayleigh wave waveforms) is shown in Figure 5, along with their estimated uncertainties.

The regional surface wave observations were incorporated into the seismic inversion by developing an inversion scheme to simultaneously determine the surface wave phase velocity and the earthquake centroid parameter, jointly using the earthquake and

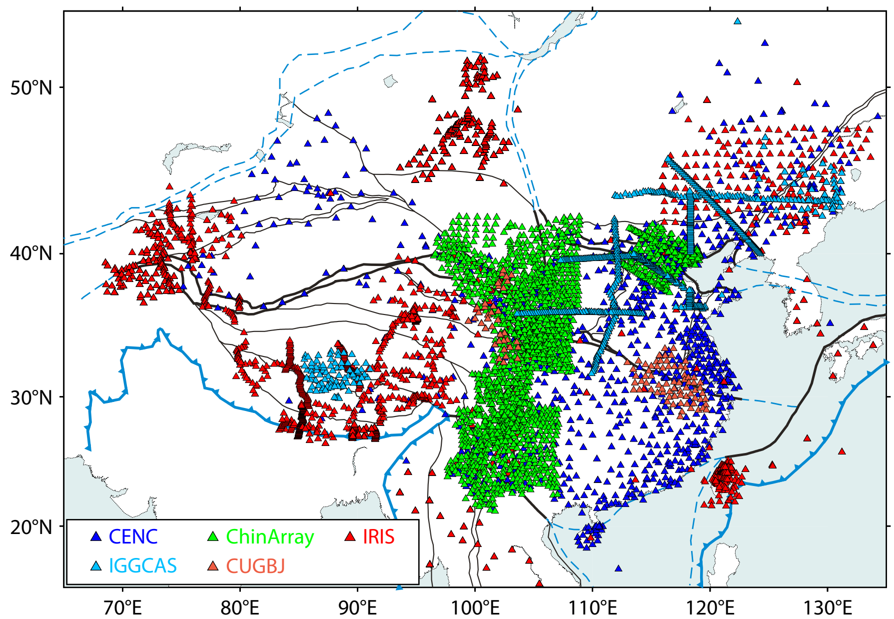

Figure 4. Seismic stations used in the construction of the China Seismological Reference Model. Different-colored triangles indicate stations operated by different networks or research institutions: CENC, China Earthquake Networks Center, China Earthquake Administration; ChinArray, China Seismic Array; IRIS, Incorporated Research Institutions for Seismology; IGGCAS, Institute of Geology and Geophysics, Chinese Academy of Sciences; IGPCEA, Institute of Geophysics, China Earthquake Administration; CUGBJ, the China University of Geosciences (Beijing).

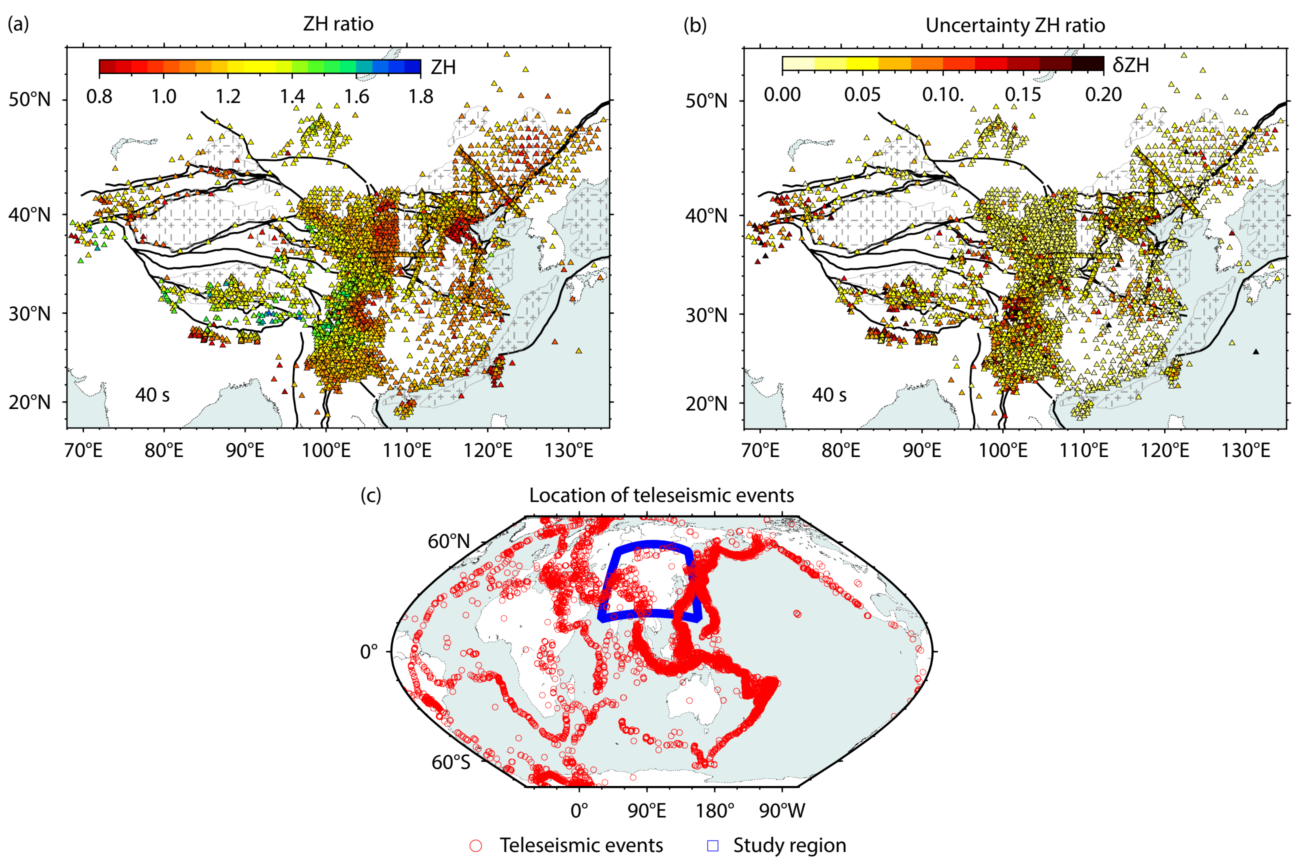

Figure 5. Estimated ZH ratios and their uncertainties in continental China in an example period of 40 s. (a) ZH ratios and (b) their uncertainties plotted at the locations of the seismic stations. Major sedimentary basins are indicated by the gray-crossed regions. (c) The locations (red circles) of 9361 teleseismic events whose data were used to estimate the ZH ratios and their uncertainties, with the study region (a, b) marked by the blue contour.

ambient noise data. This inversion scheme overcame the difficulty of using regional surface wave observations in which the uncertainty of the earthquake source parameters strongly influenced the accuracy of the surface wave phase velocity measurements. The incorporation of regional surface wave data improved the construction of the CSRM in two major ways:

(1) It significantly improved the seismic sampling in the western part of continental China, especially in the Tibetan Plateau (cf. the left and right panels in Figure 6a). Those are the regions of significant importance to our understanding of the continental tectonics and seismic hazards, but with a sparse coverage of seismic stations.

(2) It expanded the seismic sampling to the deep mantle, which was beyond the sampling limit of the empirical Green's functions extracted from the seismic ambient noise (Figure 6b).

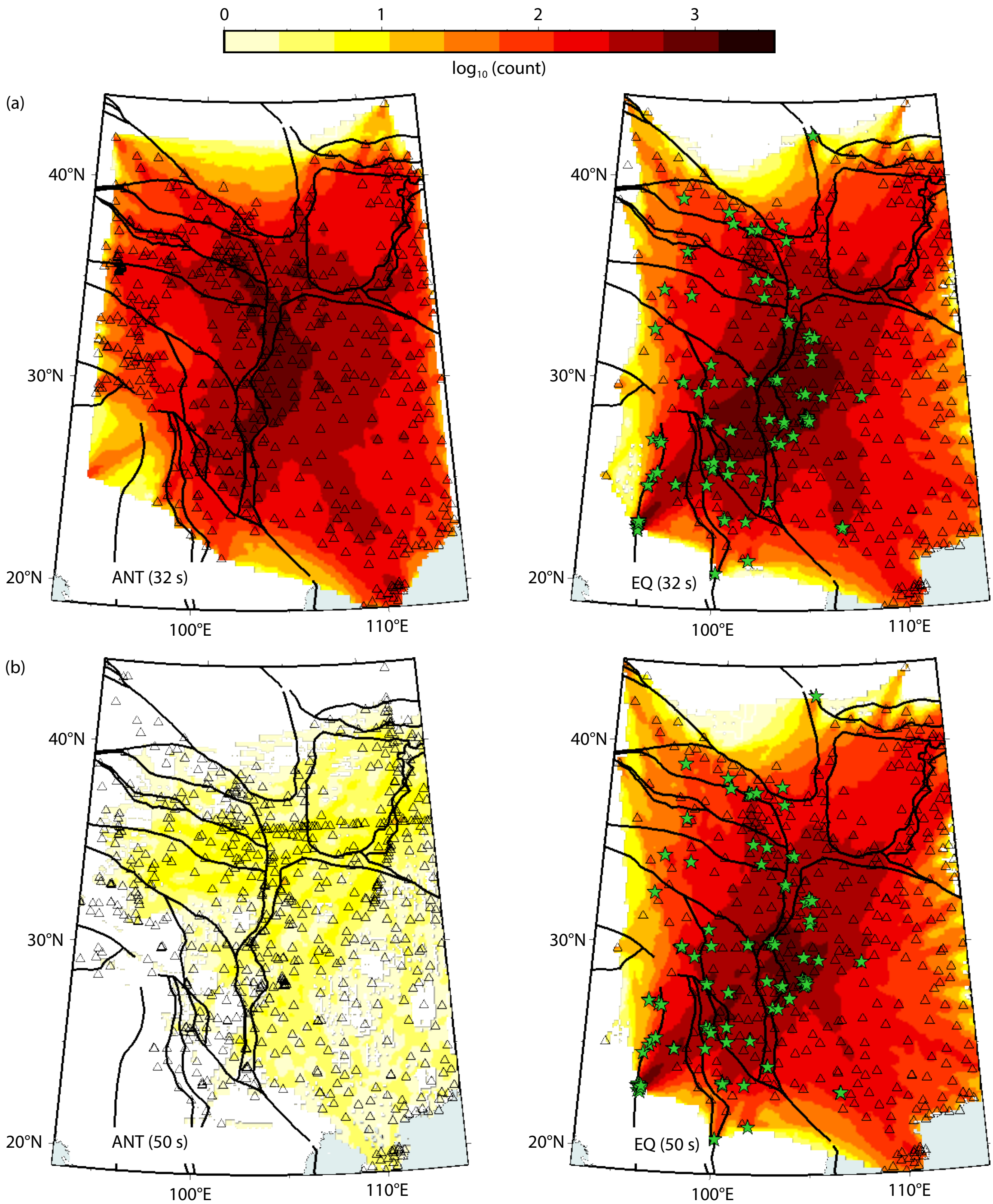

Figure 6. Improved seismic sampling from surface wave observations of regional earthquakes in two example periods. The left and right panels show the path densities (colored background) of interstation empirical Green's functions obtained from the seismic ambient noise (ANT) and surface wave waveforms from regional earthquakes (EQ), respectively, whereas the top (a) and bottom (b) panels are for the example periods of 32 s and 50 s. The black triangles and green stars mark the locations of seismic stations and earthquakes, respectively.

The pre-CSRM models included high-resolution three-dimensional models of shear wave velocity and sedimentary layer thickness in the shallow 10 km of the crust, the *Pn*-velocity in the uppermost mantle, and the averaged V_p/V_s (κ) (seismic compressional and shear velocity ratio) in the crust and in the sedimentary layers. The shallow seismic model was constrained by the *P* polarization, Rayleigh wave ellipticity, and receiver function obtained from the records of 3848 seismic stations. It had a spatial resolution of 0.6°–1.2° in the North–South Seismic Belt and the Trans-North China Orogen, and 1°–2° in the rest of continental China (except the Tarim Basin and southwest Tibet, where no seismic coverage was present). The *Pn*-velocity model was constructed through a new tomographic scheme by simultaneously inverting the event epicenter location and *Pn*-velocity while accurately accounting for the *Pn* propagation effects of varying crustal thicknesses. The inversion integrated a combined dataset of 32,427 absolute *Pn* travel times and 62,431 interstation *Pn* differential travel times, manually picked from the recordings of 2989 stations in and around continental China, yielding a model of spatial resolutions ranging from 0.75° × 0.75° to 3° × 3°. And, the average V_p/V_s (κ) model was constrained by 1,150,543 receiver functions obtained from the seismic data recorded at 3837 seismic stations deployed in or around continental China. It had a spatial resolution of 0.25° × 0.25° in the North–South Seismic Belt and parts of the North China Craton and a spatial resolution of 0.5° × 0.5° in other regions.

The CSRM model is being constructed by a joint inversion of the observed receiver function, Rayleigh wave ellipticity, and phase and group velocity dispersion, with incorporation of prior seismic constraints for three pre-CSRM models of the shallow seismic structure (Xiao X et al., 2021), the average V_p/V_s in the crust (Cheng SH et al., 2022), and the *Pn*-velocity structure (Ma JY et al., 2023; Figure 7).

3.2 Development of the CSRM Product Center

The CSRM product center was created when the CSRM project was initiated and is accessible through the CSRM webpage (http://chinageorefmodel.org/). The primary goal of the CSRM product center is to serve as a centralized location that archives and distributes the CSRM and the seismic data used to construct the CSRM, and as a venue for seismologists to share and collaborate. The product center also hosts seismic models contributed by various research groups and many geophysical databases that are relevant to studies of the seismic structure, composition, geodynamics, and seismic hazards in continental China.

The CSRM product center archives and distributes three types of products: CSRM models, Level 1 seismic data, and Level 2 seismic data. The CSRM models contain model parameters and their associated uncertainties. Level 1 data are the original seismic data used to extract the seismic constraints in the construction of the CSRM, whereas Level 2 data are the seismic constraints derived from the Level 1 data and the earthquake parameters inferred in the construction of the CSRM.

Up to 2023, the CSRM product center had archived 141 TB of Level 1 data, which included continuous waveform data, seismic event waveform data, and the instrument responses of 1120 permanent broadband stations from the China Seismic Networks Center, 1726 temporary broadband stations of ChinArray, 120 temporary stations from the NorthEast China Seismic Array to Investigate Deep Subduction (NECsaids), 81 temporary stations from the Seismic Array iNtegrated Detection for a Window of Indian Continental Head (SANDWICH) of the Institute of Geology and Geophysics, Chinese Academy of Sciences, 71 temporary broadband stations from the Middle-Lower Yangtze broadband seismic Network (MLYN) of the China University of Geosciences in Beijing, and 1393 temporary stations downloaded from the Public seismic Data Management Centers (PDMC) of the IRIS, the GFZ German Research Centre for Geosciences (GEOFON), the Swiss Seismological Service (SED), and the French seismological and geodetic network Resif-Epos (RESIF).

The CSRM product center has also archived 140 GB of Level 2 data, which includes datasets of seismic constraints and some seismic results inferred in the construction of the pre-CSRM models and the CSRM. The archived seismic constraints include the teleseismic *P*-wave receiver function, short-period Rayleigh wave ellipticity from ambient noise, long-period Rayleigh wave ellipticity from earthquake data, *P*-wave polarization angle, *Pn* travel time, empirical Green's function from ambient noise, surface wave dispersion curves from regional earthquakes, and *SKS* shear-wave splitting parameters (Table 1). The archived inferred seismic results include the earthquake hypocenter horizontal location, *P*-wave travel time beneath an earthquake, *P*-wave travel time beneath a seismic station, earthquake centroid parameter, earthquake hypocenter depth, explosion source parameter, and landslide source parameter (Table 2).

The CSRM product center also hosts 22 seismic models, contributed by 11 research groups, that are available for public download. Those models include seismological parameters of crustal velocity, crustal thickness, mantle *P*- and *S*-wave velocities, depth of the upper mantle discontinuities, and a seismic *Lg*/*Pn* phase attenuation factor, covering regions of northeast China, north China, south China, and the Tibetan Plateau.

The CSRM product center has released some pre-CSRM models and the Level 1 and 2 data. The released pre-CSRM models include models of the shallow seismic structure (Xiao X et al., 2021) and *Pn*-velocity structure (Ma JY et al., 2023). The Level 1 data released include 20 TB of waveform data of the CNSN stations from 2012 to 2018 on global earthquake events with a magnitude above 5.5 and the corresponding instrument response files. The Level 2 data released include 320 MB of *P*-wave polarization, 14 MB of short-period Rayleigh wave ellipticity, and 6 MB of *Pn* travel time.

4. Future Perspectives

The CSRM project will result in the construction of seismic models of the highest resolution at the continental scale in China. Multidisciplinary efforts to explore the implications of the seismic structures revealed by those models could provide significant insights into the composition and dynamics of tectonic processes in continental China. The CSRM could also be integrated into seismic hazard mitigation programs in China and provide high-resolution background velocity models for high-precision determination of earthquake location and accurate prediction of strong ground

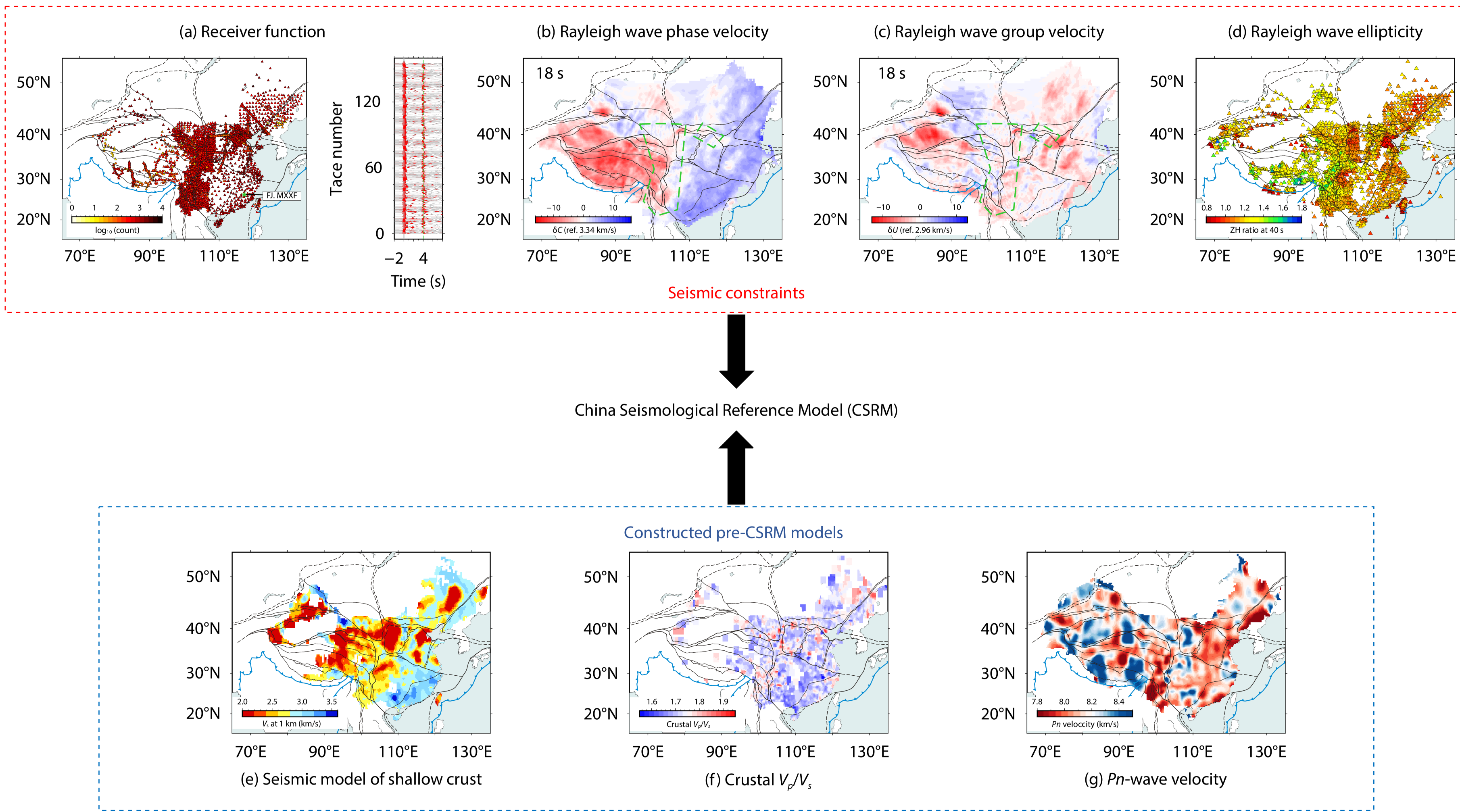

Figure 7. Construction of the China Seismological Reference Model (CSRM). The CSRM will be constructed by joint inversion of (a–d) seismic constraints using (e–g) pre-CSRM models as starting models or *a priori* structures. The seismic constraints include the (a) receiver function, (b) Rayleigh wave phase velocity (in an example period of 18 s), (c) Rayleigh wave group velocity (in an example period of 18 s), and (d) long-period Rayleigh wave ellipticity. The pre-CSRM models include (e) the seismic structure of the shallow crust, (f) the crustal V_p/V_s, and (g) the *Pn*-velocity.

Table 1. CSRM Level-2 data — seismic constraints.

Seismic constraint	Data count	Data source	Reference
P-wave polarization angle	5,439,702	Teleseismic *P*-wave waveform	Xiao X et al. (2021)
Short-period Rayleigh wave ellipticity from ambient noise	4193	Continuous seismic ambient noise waveform	Xiao X et al. (2021)
Teleseismic *P*-wave receiver function	2,235,462	Teleseismic *P*-wave waveform	Cheng SH et al. (2022)
Pn- travel time	95,878	Regional earthquake waveform	Ma JY et al. (2023)
Empirical Green's function from ambient noise	639,171	Continuous seismic ambient noise waveform	Unpublished
Long-period Rayleigh wave ellipticity from earthquake data	2,528,341	Teleseismic surface wave waveform	Unpublished
Surface wave dispersion curves from regional earthquakes	54,792	Regional earthquake surface wave waveform	Unpublished
SKS shear-wave splitting parameters	11,719	Teleseismic *SKS*-wave waveform	Unpublished

Table 2. CSRM Level-2 data — inferred seismic results.

Seismic result	Data count	Reference
Earthquake hypocenter horizontal location	433	Ma JY et al. (2023)
P-wave travel time beneath an earthquake	433	Ma JY et al. (2023)
P-wave travel time beneath a seismic station	281	Ma JY et al. (2023)
Earthquake centroid parameter	226	Xiao X et al. (2022)
Earthquake hypocenter depth	220	Unpublished
Explosion source parameter	74	Unpublished
Landslide source parameter	224	Unpublished

motion. The high-precision locations of earthquakes inferred in the construction of the CSRM could also provide good reference event parameters for a more accurate determination of earthquake parameters in the seismic hazard mitigation programs. The CSRM will reveal shortcomings in current seismic coverage and new important seismic features that warrant further detailed exploration, thereby providing guidance for the focuses of future seismological research and the design of future active and passive seismic experiments in China.

The CSRM will also need to evolve with the new seismic observations as they become available in China and the new innovative methods as they are being developed in seismology. On the observational front, the seismic coverage is being significantly densified in continental China, with the launch of the earthquake early warning project by the CEA and ongoing seismic experiments across China. The earthquake early warning project will deploy 10, 349 new regular stations across the country, expand the number of reference stations by approximately 80%, reaching 1987, and expand the number of base stations by 60%, reaching 3269 (Figure 8). All these stations will provide continuous data recording; altogether, the project will deliver a seismic coverage up to a station spacing of approximately 12.5 km in many regions of the country. At the same time, several ongoing field experiments by different institutions in China have seismic deployments in the western part of China and will expand the seismic coverage in those tectonically important regions. This increase in seismic coverage will require the CSRM to refine along with the new seismic observations and integrate them into its refinement. On the theoretical front, we expect the development of many new seismic imaging methods using seismic data from the dense array, possibly with waveform inversion and three-dimensional migration methods leading the way in delineating sharp features of the seismic anomalies in the crust and mantle. The CSRM project will need to be proactive in developing and adapting these new methods in its construction of next-generation reference models.

On the basis of our experience from the current construction of the CSRM, we suggest the following focuses for future seismological research in China:

(1) More resources may need to be devoted to improving seismic station coverage in the regions of significant importance to enhance our understanding of the tectonics in continental China, in particular, the Tibetan Plateau and the South China Sea.
(2) Efforts could be made to promote the development of new methods of seismic imaging, especially methods that could delineate the geometric and structural features of the seismic anomalies inside the Earth. In this regard, collaboration could be promoted between earthquake seismology and exploration seismology.
(3) Efforts could be made to integrate the latest CSRM results into near real-time earthquake monitoring, the earthquake early warning system, and other national seismic hazard mitigation programs.
(4) Multidisciplinary research could be encouraged to explore the implications of the latest seismic results to enhance our understanding of the composition and dynamics of tectonic processes in continental China.
(5) A national cyberinfrastructure could be built to sustain and expand the operations of the CSRM project.

5. Conclusions

The CSRM project was initiated by the NSFC with two primary goals: (1) the CSRM would serve as a primary source for the

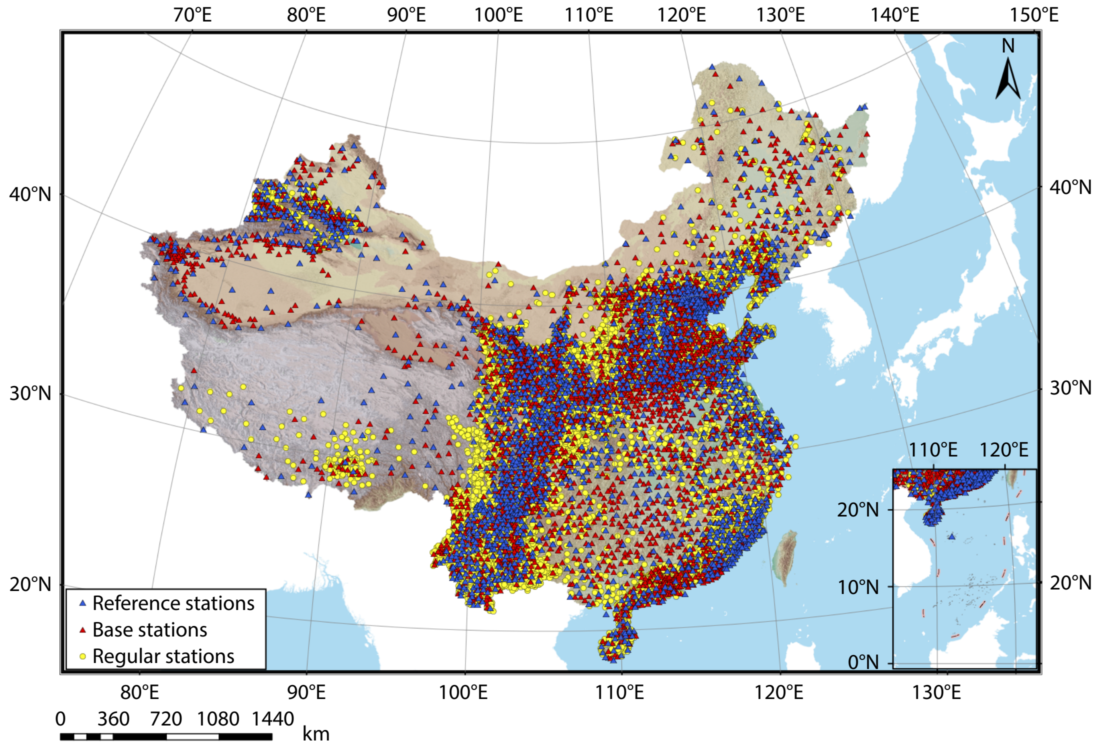

Figure 8. Seismic stations operated by the China Earthquake Administration with the launch of the earthquake early warning project. Reference stations (blue triangles) are equipped with broadband and accelerometer sensors, base stations (red triangles) are equipped with accelerometer sensors, and regular stations (yellow dots, some are covered by triangles) are equipped with simple accelerometer sensors.

current state of seismological research in China, and (2) the seismic data and constraints used to construct the CSRM would be used as a backbone open-access cyberinfrastructure for future research in seismology. The CSRM project was also intended to promote data exchange and scientific collaboration in seismology in China. Accordingly, two parallel efforts of the project are being pursued: (1) construction of the CSRM, and (2) development of the CSRM product center.

The CSRM will be jointly constrained by various types of seismic constraints extracted from the seismic data recorded in 4511 seismic stations in continental China following a top-down approach, with the seismic structures in the shallower part of the Earth constrained first. Construction of the CSRM involves three preparation steps: (1) building datasets of various seismic constraints from the seismic data, (2) developing a method to incorporate the constraints of surface wave observations from regional earthquakes into the inversion of the seismic structure, and (3) constructing high-resolution pre-CSRM seismic models of the velocity structure in the shallow crust and the *Pn*-velocity structure in the uppermost mantle. In the final process, the CSRM will be constructed by jointly inverting all the seismic constraints using pre-CSRM models as starting models or *a priori* structures.

The CSRM product center was created when the CSRM project was initiated and is accessible through the CSRM webpage (http://chinageorefmodel.org/). The primary goal of the CSRM product center is to serve as a centralized location that archives and distributes the CSRM and the seismic data used to construct the CSRM, and as a venue for seismologists to share and collaborate.

The CSRM product center archives and distributes three types of products: (1) CSRM models, (2) Level 1 seismic data, and (3) Level 2 seismic data. The CSRM models contain model parameters and their associated uncertainties. Level 1 data are the original seismic data used to extract seismic constraints in the construction of the CSRM, whereas Level 2 data are the seismic constraints derived from the Level 1 data and the earthquake parameters inferred in the construction of the CSRM. The CSRM product center has archived 141 TB of Level 1 data from 1120 permanent broadband stations from the China Seismic Network Center and 3391 temporary stations from various institutions and data centers around the world, and 140 GB of Level 2 data on various seismic constraints extracted from the Level 1 data and various seismic results inferred from the construction of the CSRM.

The CSRM is expected to provide significant insights into the composition and dynamics of tectonic processes in continental China and enhance the capability of various seismic hazard mitigation programs in China, from the near real-time earthquake monitoring system to the earthquake early warning system. The CSRM could also provide guidance for focuses of future seismological research and the design of future active and passive seismic experiments in China. Several focuses are suggested for future seismological research in China, along with the building of a national cyberinfrastructure to sustain and expand the operations of the CSRM project.

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References

Bao, X. Y., and Shen, Y. (2020). Early-stage lithospheric foundering beneath the eastern Tibetan Plateau revealed by full-wave P_n tomography. *Geophys. Res. Lett.*, *47*(8), e2019GL086469. https://doi.org/10.1029/2019gl086469

Ceylan, S., Ni, J., Chen, J. Y., Zhang, Q., Tilmann, F., and Sandvol, E. (2012). Fragmented Indian plate and vertically coherent deformation beneath eastern Tibet. *J. Geophys. Res.: Solid Earth*, *117*(B11), B11303. https://doi.org/10.1029/2012JB009210

Chen, M., Niu, F. L., Tromp, J., Lenardic, A., Lee, C. T. A., Cao, W. R., and Ribeiro, J. (2017). Lithospheric foundering and underthrusting imaged beneath Tibet. *Nat. Commun.*, *8*, 15659. https://doi.org/10.1038/ncomms15659

Cheng, S. H., Xiao, X., Wu, J. P., Wang, W. L., Sun, L., Wang, X. X., and Wen, L. X. (2022). Crustal thickness and *Vp*/*Vs* variation beneath continental China revealed by receiver function analysis. *Geophys. J. Int.*, *228*(3), 1731–1749. https://doi.org/10.1093/gji/ggab433

Deng, J., Wang, Q. F., and Li, G. J. (2017). Tectonic evolution, superimposed orogeny, and composite metallogenic system in China. *Gondwana Res.*, *50*, 216–266. https://doi.org/10.1016/j.gr.2017.02.005

Ekström, G., Nettles, M., and Dziewoński, A. M. (2012). The global CMT project 2004-2010: centroid-moment tensors for 13,017 earthquakes. *Phys. Earth Planet. Inter.*, *200-201*, 1-9. https://doi.org/10.1016/j.pepi.2012.04.002

Feng, Z. Q., Jia, C. Z., Xie, X. N., Zhang, S., Feng, Z. H., and Cross, T. A. (2010). Tectonostratigraphic units and stratigraphic sequences of the nonmarine Songliao Basin, Northeast China. *Basin Res.*, *22*(1), 79–95. https://doi.org/10.1111/j.1365-2117.2009.00445.x

He, P., Lei, J. S., Yuan, X. H., Xu, X. W., Xu, Q., Liu, Z. K., Mi, Q., and Zhou, L. Q. (2018). Lateral Moho variations and the geometry of the main Himalayan thrust beneath the Nepal Himalayan orogen revealed by teleseismic receiver functions. *Geophys. J. Int.*, *214*(2), 1004–1017. https://doi.org/10.1093/gji/ggy192

Jia, C. Z., Li, B. L., Lei, Y. L., and Chen, Z. X. (2013). The structure of circum-Tibetan Plateau Basin-range system and the large gas provinces. *Sci. China Earth Sci.*, *56*(11), 1853–1863. https://doi.org/10.1007/s11430-013-4649-7

Lei, J. S., and Zhao, D. P. (2005). P-wave tomography and origin of the Changbai intraplate volcano in northeast Asia. *Tectonophysics*, *397*(3-4), 281–295. https://doi.org/10.1016/j.tecto.2004.12.009

Li, X. Q., and Yuan, X. H. (2003). Receiver functions in Northeast China – implications for slab penetration into the lower mantle in northwest Pacific subduction zone. *Earth Planet. Sci. Lett.*, *216*(4), 679–691. https://doi.org/10.1016/S0012-821X(03)00555-7

Li, X. Y., Zhu, P. M., Kusky, T. M., Gu, Y., Peng, S. B., Yuan, Y. F., and Fu, J. M. (2015). Has the Yangtze craton lost its root? A comparison between the North China and Yangtze cratons. *Tectonophysics*, *655*, 1–14. https://doi.org/10.1016/j.tecto.2015.04.008

Liu, L., Xu, X. S., and Xia, Y. (2016). Asynchronizing paleo-Pacific slab rollback beneath SE China: insights from the episodic Late Mesozoic volcanism. *Gondwana Res.*, *37*, 397–407. https://doi.org/10.1016/j.gr.2015.09.009

Ma, J. Y., Sun, L., Wang, W. L., Wu, J. P., Wang, X. X., and Wen, L. X. (2023). Uppermost mantle seismic *Pn*-velocity in continental China and its tectonic implications. *J. Geophys. Res.: Solid Earth*, *128*(3), e2022JB025667. https://doi.org/10.1029/2022jb025667

Meng, Q. R., and Zhang, G. W. (2000). Geologic framework and tectonic evolution of the Qinling orogen, central China. *Tectonophysics*, *323*(3-4), 183–196. https://doi.org/10.1016/S0040-1951(00)00106-2

Molnar, P., and Tapponnier, P. (1975). Cenozoic tectonics of Asia: effects of a continental collision. *Science*, *189*(4201), 419–426. https://doi.org/10.1126/science.189.4201.419

Nelson, K. D., Zhao, W. J., Brown, L. D., Kuo, J., Che, J. K., Liu, X. W., Klemperer, S. L., Makovsky, Y., Meissner, R., … Edwards, M. (1996). Partially molten middle crust beneath southern Tibet: synthesis of project INDEPTH results. *Science*, *274*(5293), 1684–1688. https://doi.org/10.1126/science.274.5293.1684

Owens, T. J., and Zandt, G. (1997). Implications of crustal property variations for models of Tibetan Plateau evolution. *Nature*, *387*(6628), 37–43. https://doi.org/10.1038/387037a0

Pirajno, F., Ernst, R. E., Borisenko, A. S., Fedoseev, G., and Naumov, E. A. (2009). Intraplate magmatism in central Asia and China and associated metallogeny. *Ore Geol. Rev.*, *35*(2), 114–136. https://doi.org/10.1016/j.oregeorev.2008.10.003

Ren, J. Y., Tamaki, K., Li, S. T., and Zhang, J. X. (2002). Late Mesozoic and Cenozoic rifting and its dynamic setting in Eastern China and adjacent areas. *Tectonophysics*, *344*(3-4), 175–205. https://doi.org/10.1016/s0040-1951(01)00271-2

Replumaz, A., Capitanio, F. A., Guillot, S., Negredo, A. M., and Villaseñor, A. (2014). The coupling of Indian subduction and Asian continental tectonics. *Gondwana Res.*, *26*(2), 608–626. https://doi.org/10.1016/j.gr.2014.04.003

Royden, L. H., Burchfiel, B. C., King, R. W., Wang, E., Chen, Z. L., Shen, F., and Liu, Y. P. (1997). Surface deformation and lower crustal flow in eastern Tibet. *Science*, *276*(5313), 788–790. https://doi.org/10.1126/science.276.5313.788

Royden, L. H., Burchfiel, B. C., and van der Hilst, R. D. (2008). The geological evolution of the Tibetan Plateau. *Science*, *321*(5892), 1054–1058. https://doi.org/10.1126/science.1155371

Tapponnier, P., Xu, Z. Q., Roger, F., Meyer, B., Arnaud, N., Wittlinger, G., and Yang, J. S. (2001). Oblique stepwise rise and growth of the Tibet Plateau. *Science*, *294*(5547), 1671–1677. https://doi.org/10.1126/science.105978

Wang, C. Y., Han, W. B., Wu, J. P., Lou, H., and Chan, W. W. (2007). Crustal structure beneath the eastern margin of the Tibetan Plateau and its tectonic implications. *J. Geophys. Res.: Solid Earth*, *112*(B7), B07307. https://doi.org/10.1029/2005jb003873

Wang, M. M., Hubbard, J., Plesch, A., Shaw, J. H., and Wang, L. N. (2016). Three-dimensional seismic velocity structure in the Sichuan Basin, China. *J. Geophys. Res.: Solid Earth*, *121*(2), 1007–1022. https://doi.org/10.1002/2015jb012644

Wang, Y., and Li, H. M. (2008). Initial formation and Mesozoic tectonic exhumation of an intracontinental tectonic belt of the northern part of the Taihang Mountain Belt, eastern Asia. *J. Geol.*, *116*(2), 155–172. https://doi.org/10.1086/529153

Wang, Y. H., Houseman, G. A., Lin, G., Guo, F., Wang, Y. J., Fan, W. M., and Chang, X. (2005). Mesozoic lithospheric deformation in the North China block: numerical simulation of evolution from orogenic belt to extensional basin system. *Tectonophysics*, *405*(1-4), 47–63. https://doi.org/10.1016/j.tecto.2005.05.012

Wilde, S. A. (2015). Final amalgamation of the central Asian Orogenic Belt in NE China: paleo-Asian ocean closure versus paleo-Pacific plate subduction—a review of the evidence. *Tectonophysics*, *662*, 345–362. https://doi.org/10.1016/j.tecto.2015.05.006

Xia, W. C., Zhang, N., Yuan, X. P., Fan, L. S., and Zhang, B. S. (2001). Cenozoic Qaidam Basin, China: a stronger tectonic inversed, extensional rifted basin. *AAPG Bull.*, *85*(4), 715–736. https://doi.org/10.1306/8626c98d-173b-11d7-8645000102c1865d

Xiao, X., Cheng, S. H., Wu, J. P., Wang, W. L., Sun, L., Wang, X. X., and Wen, L. X. (2021). Shallow seismic structure beneath the continental China revealed by *P*-wave polarization, Rayleigh wave ellipticity and receiver function. *Geophys. J. Int.*, *225*(2), 998–1019. https://doi.org/10.1093/gji/ggab022

Xiao, X., Sun, L., Wang, X. X., and Wen, L. X. (2022). Simultaneous inversion for surface wave phase velocity and earthquake centroid parameters: methodology and application. *J. Geophys. Res.: Solid Earth*, *127*(9), e2022JB024018. https://doi.org/10.1029/2022JB024018

Yang, Y. T., Li, W., and Ma, L. (2005). Tectonic and stratigraphic controls of hydrocarbon systems in the Ordos Basin: a multicycle cratonic basin in central China. *AAPG Bull.*, *89*(2), 255–269. https://doi.org/10.1306/10070404027

Ye, H., Shedlock, K. M., Hellinger, S. J., and Sclater, J. G. (1985). The North China basin: an example of a Cenozoic rifted intraplate basin. *Tectonics*, *4*(2), 153–169. https://doi.org/10.1029/TC004i002p00153

Yin, A., and Harrison, T. M. (2000). Geologic evolution of the Himalayan-Tibetan orogen. *Annu. Rev. Earth Planet. Sci.*, *28*(1), 211–280. https://doi.org/10.1146/annurev.earth.28.1.211

Zhai, M. G. (2013). The main old lands in China and assembly of Chinese unified continent. *Sci. China Earth Sci.*, *56*(11), 1829–1852. https://doi.org/10.1007/s11430-013-4665-7

Zhao, G. C., Wang, Y. J., Huang, B. C., Dong, Y. P., Li, S. Z., Zhang, G. W., and Yu, S. (2018). Geological reconstructions of the east Asian blocks: from the breakup of rodinia to the assembly of Pangea. *Earth-Sci. Rev.*, *186*, 262–286. https://doi.org/10.1016/j.earscirev.2018.10.003

Zhao, W. J., Nelson, K. D., Che, J., Quo, J., Lu, D., Wu, C., and Liu, X. (1993). Deep seismic reflection evidence for continental underthrusting beneath southern Tibet. *Nature*, *366*(6455), 557–559. https://doi.org/10.1038/366557a0

Zhou, X. M., Sun, T., Shen, W. Z., Shu, L. S., and Niu, Y. L. (2006). Petrogenesis of Mesozoic granitoids and volcanic rocks in South China: a response to tectonic evolution. *Episodes*, *29*(1), 26–33. https://doi.org/10.18814/epiiugs/2006/v29i1/004

Zhu, R. X., Chen, L., Wu, F. Y., and Liu, J. L. (2011). Timing, scale and mechanism of the destruction of the North China Craton. *Sci. China Earth Sci.*, *54*(6), 789–797. https://doi.org/10.1007/s11430-011-4203-4

Zhu, R. X., Xu, Y. G., Zhu, G., Zhang, H. F., Xia, Q. K., and Zheng, T. Y. (2012). Destruction of the North China Craton. *Sci. China Earth Sci.*, *55*(10), 1565–1587. https://doi.org/10.1007/s11430-012-4516-y