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The Present Status and Prospect of Earthquake Focal Depth Locating[1]

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Locating an earthquake's focal depth is always a key project in seismology. Precise focal depth is of critical importance for evaluating seismic hazards, deciphering dynamic mechanisms of earthquake generating, estimating aftershock evolutions and risk, as well as monitoring nuclear tests. However, how we determine an accurate focal depth is always a challenge in seismological studies. Aiming to solve these problems, we analyzed and summarized the present status and the future development of earthquake focal depth locating. In this paper we first reviewed the present status of focal depth locating in the world, and summarized the frequently-used relocating methods and ideas at present, and introduced two types of focal depth relocating ideas: arrival time relocating and waveform modeling methods. For these ideas, we systematically described the S-P and the Pn-Pg methods that belong to arrival time method, and polarization focal depth locating and amplitude focal depth locating that belongs to waveform modeling, and further analyzed the advantages and limitations of these methods. Since the depth phase methods are highly sensitive to focal depth, and are relatively free from the uncertainties of crustal models, we mainly reviewed the depth phases of sPmP, sPL, sPn, and sSn, and quantitatively evaluated their availabilities and characteristics. Second, we also discussed the effects of crustal velocity models on the reliability of focal depth locating, and reviewed the advancements of seismic tomography techniques over recent years. Finally, based on the present status of the progress on the focal depth locating, and studies of seismic velocity structures, we proposed an idea of combining multiple datasets and relocating methods, jointly utilizing seismologic and geodetic techniques to relocate focal depth, which should be the major research field in investigating focal depth and source parameters in the near future.

Key words: Focal depth relocating; Arrival time locating; Waveform modeling; Depth phase; Joint inversion

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INTRODUCTION

Seismic depth is one of the core issues in seismological research. Accurately determining the focal depth of an earthquake has extremely important scientific significance in the following areas:

(1) Accurate determination of seismic depth is an important basis for seismic hazard assessments. Earthquake disasters are closely related to the depth of the earthquake source. Generally speaking, the shallow source earthquake disaster is relatively large, and the deep source earthquake disaster is relatively small. This is why the Lushan earthquake is not too large in magnitude, but it is one of the most important factors causing damage (Liu Chengli et al., 2013; Xie Zujun et al., 2013). Relatively speaking, the destruction of deep earthquakes is much smaller. For example, the deep-source earthquake in the northeast China region, although causing a large area of quake, is less destructive.

(2) The depth of the earthquake source is the key basis for the cause of the earthquake. Statistical studies have shown that the vast majority of continental earthquakes occur in the crust of more than 15km. This is because the strength of the crust varies greatly at different depths, presenting patterns such as sandwiches, Crème brûlée or banana slices (Bürgmann et al., 2008). Different models correspond to different rock compositions and dynamic environments. Earthquakes usually occur in areas from brittle areas to brittle-creeping transformations. Therefore, by determining the depth of earthquakes, the depth of seismogenicity and the composition of the crustal materials can be understood to a certain extent. Environmental and earthquake causes give quantitative basis.

(3) Accurate seismic depth information plays an important role in determining the development of strong aftershocks. Usually the aftershock of an earthquake has a clear corresponding relationship with the break point of the main shock. The strong aftershock is mainly distributed around the rupture area of the main shock. If the depth of the main shock is accurately determined, it is possible to speculate the possible aftershock area to some extent. In addition, through the change trend of the depths of aftershocks, it is also important to judge the future development process of strong aftershocks (Zheng Yong et al., 2009, 2013).

(4) Accurate seismic source depth is also the key criterion for nuclear blast monitoring. Since most natural earthquakes occur underground, especially in rock formations, the depth of the earthquake is not particularly shallow. On the contrary, nuclear explosions generally occur at or close to the ground surface. Therefore, their depth is often 0km or very shallow. At this time, in combination with the earthquake source mechanism and other waveform information, nuclear explosions can be more accurately determined in terms of the location and nature. Therefore, the location of earthquake depth has important application value in military security.

In addition, accurate in-depth positioning can also play an important role in earthquake warning, determination of the source process of large earthquakes, exploration of underground mineral resources, and exploitation of shale gas. Therefore, how to accurately determine the depth of earthquake source not only has scientific applications, but also has important application value in the national economy.

However, the magnitude determination has been a difficult issue in seismological research. In general, in the three elements of the earthquake (earthquake moment, source location and magnitude), the location of the source and the moment of origin are relatively easy to determine and can now be accurately determined. The accuracy of the magnitude determination is also relatively high. The main problems at the moment are focused on determining the magnitude of large earthquakes. In contrast, the determination of the focal depth has always been a problem in seismic positioning. Since the distance between earthquake stations is usually larger than the depth of the earthquake, under the condition that the station is relatively sparse, the impact of a small amount of earthquake level change will be greater than the error caused by the depth of the earthquake. Therefore, the error of seismic depth location of the earthquake is still a very challenging issue in the field of seismology. Therefore, it has been listed as one of the most important research challenges in the United States in the past decade.

At the same time, the depth positioning of earthquakes is also an old problem. The idea is to use a variety of depth positioning methods to obtain the depth of the source under a given velocity model. Since Geiger's (1912) earthquake location method was proposed, the study of seismic depth has been carried out for more than 100 years and has made considerable progress. It mainly includes two aspects: one is the method of earthquake depth positioning, and the other is the acquisition or update of the velocity model. Therefore, this article begins with the positioning method of earthquakes, summarizes the current status of seismic depth positioning, and expounds the research on the speed model, and to a certain degree, looks forward to the next development direction of seismic depth positioning.

1 RESEARCH STATUS OF EARTHQUAKE DEPTH LOCATION

In general, the current international and domestic methods for seismic depth location can be roughly divided into two categories. One is the arrival time location method and the other is the waveform inversion method. Next we will elaborate and analyze these two aspects.

1.1 Arrival Time Location Method

Depth positioning based on time has been widely used in the positioning software at home and abroad. Its advantage is that the phase is simple and easy to pick up, and for the dense distribution of regional stations near the earthquake, the accuracy can meet the needs. However, such methods require small intervals between seismic stations. Studies have shown that only when the minimum epicentral distance is less than 1.4 times the focal depth, the focal depth determined by the arrival time method has a higher accuracy (Mori, 1991). However, usually there are not many opportunities for earthquakes to occur within 20km of a station. Therefore, the positioning error of seismic source depths shallower than 15km is generally larger. The use of regional data for absolute seismic location has a trade-off between the depth of the source and the moment of the origin. Seismic time-dependent changes caused by different depths of earthquakes can be compensated within a certain range by changing the moment of the origin, making it difficult to determine the exact depth and the moment of the shock. For the Chinese mainland, the focal depth of the eastern region averages at (13 ± 6) km (Zhang Guomin et al., 2002). Based on this, only when the distance between the stations is about 18km can we provide a more accurate source depth. At present, the average spacing of seismic stations in the eastern part of China is generally greater than 20km. Under existing observation conditions, it is difficult to give the depth of the source with higher accuracy based on the arrival information.

In recent years, some scholars have developed new methods based on arrival time in response to the shortcomings of the traditional approach. Liu Chun et al. (2009) proposed a method for determining the depth of earthquakes by visually judging whether the earthquake was "just right" under the "positive" station and located directly below the station. In the earthquake, the P-wave and S-wave seismic phases were identified in a three-component seismic record, and the seismic depth was calculated from the time difference between P-wave and S-wave. This method has made it relatively easy for some earthquakes just below the station to determine its depth. However, under the current situation that the Chinese seismological network is sparse, there are not many earthquakes just below the station. Therefore, the scope of application is very limited.

In addition, the method of seismic positioning using S-P arrival time difference (Earthquake Research Institute, 1950) has also been widely used in the determination of earthquake locations. However, the accurate S-P time-delay also depends on the crustal velocity model of P-wave and S-wave. Due to the low reliability of the S-wave velocity model, the constraints on the seismic location, especially the seismic depth, are insufficient. Greensfelder (1965) proposed using a Pg-Pn wave arrival time difference recorded at the same station to determine the seismic depth and applied it to the seismic depth measurement study in the Nevada area of the United States. Due to the large differences in the exit angles of Pg and Pn waves, more constraints are provided for the determination of seismic depth. However, in using the Pg and Pn wave phases of the same station, the Pn wave is continued to the seismic phase, making it difficult to identify and pick up the Pn wave arrival time. Not only that, Greensfelder (1965) also showed that the Pg-Pn wave arrival time difference is very sensitive to the crust and upper mantle velocity models used. Zhu Yuanqing et al. (1990) proposed using the Pn wave at a remote station and the Pg wave arrival time difference Pn-Pg at a nearby station to determine the depth of the source. It was found that at a different speed structure, the 5km focal depth would cause a 0.7 second difference in Pn-Pg arrival time. Considering that the Pg wave at the near station and the Pn wave at the remote station are both the initial arrival phase, the accuracy of seismic phase recognition and pick-up time will be significantly improved, and it will also help improve the accuracy of the seismic depth measurement results.

1.2 Waveform Inversion

Compared with the earthquake phase, the seismic waveform contains more abundant information. If the waveform recording quality is high and the seismic phase is clear, using the seismic waveform to determine the depth of the source can produce a more accurate source depth result (Wu Changjiang et al., 2004). Commonly used waveform depth methods include polarization information method, amplitude information method, and depth phase method. Different methods can be selected for different seismic features, different epicentral distance ranges, and different waveform qualities.

(1) Polarization Information Method

P-wave polarization (ratio of radial to vertical amplitudes) can constrain the depth of the earthquake to some extent. In general, the ratio of epicentral distance and depth is closely related to the ratio of vertical amplitude and radial amplitude of the P-wave: the epicenter distance is constant, and the deeper the earthquake, the greater the ratio of the P-wave vertical amplitude to the radial amplitude. The disadvantage of this method is that only when the epicentral distance is much smaller than the focal depth can the P-wave polarization effectively constrain the ratio of epicentral distance and depth. Moreover, due to the influence of the shallow velocity structure, when the velocity model is not very accurate, using the P-wave polarization to determine the focal depth has some uncertainty, so this method is only valid under certain conditions and can be used as a kind of supplement to other depth determination methods.

(2) Amplitude Information Method

The amplitude of the seismic wave has a direct relationship with the focal depth. Therefore, based on the information of the amplitude, we can obtain important parameters for seismic depth. At present, the use of amplitude information to study the depth of the earthquake mainly lies in the following ways, including Rayleigh wave amplitude spectrum method, ratio method of surface wave and body wave, and Coda intensity method.

The excitation of Rayleigh surface waves can be expressed as (Aki & Richards., 1980):

$$E(\omega,\phi,h) = \frac{\mathrm{d}r_2}{\mathrm{d}z}\mid_h M_{zz} + K(\omega)r_1(h)\left[M_{xx}\cos^2\phi + 2M_{xy}\sin\phi\cos\phi + M_{yy}\sin^2\phi\right]$$
$$+ i\left[\frac{\mathrm{d}r_1}{\mathrm{d}z}\mid_h - K(\omega)r_2(h)\right]\left[M_{xz}\cos\phi + M_{yz}\sin\phi\right] \tag{1}$$

where ω is the frequency, k is the corresponding wave number, ϕ is the azimuth angle, and h is the focal depth. Therefore, in the case of accurate mechanism solutions, the spectrum of surface waves is only related to depth. Tsai et al. (1970) pointed out that among the many factors affecting the spectrum of seismic surface waves, the crust thickness, source parameters, and inelasticity attenuation have smaller influence in contrast with depth. Therefore, when the accurate fault parameters are obtained and the fracture length is less than 10km, the focal depth can be obtained through the spectrum. This method computes the Rayleigh wave amplitude spectrum corresponding to different focal depths through the solution of the normal mode, and fits the Rayleigh wave amplitude spectrum of the actual observation according to the characteristics that the Rayleigh wave amplitude spectrum varies greatly with the focal depth, and comparing it with the theoretical map we can determine the focal depth.

The development distance of the short-period Rayleigh wave is related to the focal depth. The typical development distance is about 5 times the focal depth. The development of Rayleigh waves can be used as a reference for the ratio of the Rayleigh wave to the S-wave. The S-wave amplitude ratio between Rayleigh wave and S-wave at the same station decreases with the increase of the source depth. Luo Yan et al. (2010) determined the source depth of an aftershock sequence at the northern end of the Wenchuan earthquake by comparing the theoretical seismogram and the actual recorded ratio of Rayleigh and S waves on the basis of the focal mechanism solution.

In addition, seismic wakes can also be used to study seismic depth. It is generally believed that the seismic wake is generated by multiple reflections or refractions during the propagation of seismic waves. Due to the strong heterogeneity of the shallow crust and the fact that the free surface is a strong reflection surface, the seismic waves are scattered more in the shallow part. Pitarka et al. (2007) showed through numerical calculations that the S waves and Lg waves excited by the explosion source and scattering in the shallow part are the major cause of the coda, and the intensity of the Lg coda is inversely proportional to the focal depth. Based on these characteristics, the coda wave can be used in the depth study of shallow earthquakes.

(3) Depth Phase Method

Depth phase is a type of seismic phase that is particularly sensitive to changes in focal depth and can significantly improve the accuracy of focal depth measurements (Langston et al., 1987, 1996; Saikia C. K. et al., 2001; Fang Mingshan et al., 1995; Zhang Ruiqing et al., 2008). For earthquakes with $M \geqslant 5.0$, the source depth can be calculated by using pP and sP. For earthquakes with $M < 5.0$, the focal depth can be determined by using the seismic depth phases sPL, sPg, sPmP, and sPn, and their reference seismic phases PL, Pg, PmP, and Pn. A schematic diagram of these seismic phases is shown in Fig. 1. Because different depth seismic phases generally have their superior epicentral distance range and applicable conditions, and the amplitude of the deep seismic phase is weak, the initial motion is more vague and difficult to identify. Therefore, in the routine earthquake location, there is still some difficulty in using the depth of the phase to quickly determine the focal depth. At present, relevant studies at home and abroad focus on the following types of in-depth phases:

① The sPL Phase

The sPL seismic phase is a wave train formed by horizontally propagating P waves and multiple reflections and refracted waves formed by an S-wave incident on a free surface at a small epicenter distance (30km – 50km). Synthetic seismogram studies show that sPL has typical

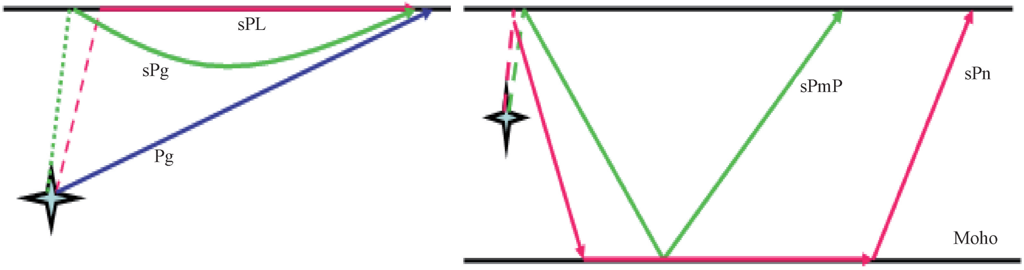

Fig. 1

Schematic diagram of several deep seismic phases using the depth phase method
(a) Three types of phases of Pg, sPg and sPL;
(b) sPmP, sPn phases reflected and slipped from the Moho surface

characteristics of depth-seismic phase, and its arrival time difference with direct P-waves increases almost linearly with the depth of the source, and is insensitive to the epicentral distance, so it can well constrain the focal depth (Chong Jiajun et al., 2010). The sPL is formed by reflection on a free surface, and the reflection efficiency is greatly affected by topographic relief and shallow structures. When the topography fluctuates greatly, the proportion of multiple scattering components in the sPL is relatively large, so the wave packet is relatively wide, and it is easy to be mixed with subsequent earthquakes. For sedimentary basins, shallow seismic wave speeds are relatively low. At this time, sPL is formed by combining multiple seismic phases, which can also lead to a wider sPL wave packet. At the same time, the wave packet of direct P-wave also becomes wider, and interference is likely to form. Therefore, for complex topography and internal structural regions, the characteristics of sPL phases and development distances need further study. Li Zhiwei et al. (2015) used this phase, as well as short-period surface wave and CAP methods, to analyze the reliability of the focal depths of the $M4.0-5.0$ earthquakes in the UGGS catalogue, and achieved good results.

② The sPmP Phase

In the tangential component of the seismic wave, because there is no P-SV wave coupling, the waveform is relatively simple, and the SmS and sSmS earthquakes are relatively easy to identify and is suitable for determining the depth of the source. However, few studies have used the tangential components of the SmS and sSmS seismic phases to determine the focal depth. Only a few researchers have used sSmS to do some research (Zhao Lianshe et al., 1993; Helmberger et al., 1993). Some studies have found that only at high frequencies can SmS and sSmS have clear seismic phases, and long-period seismic waves of more than 2s are mainly direct S-wave and surface-wave components, especially the intensity ratio of SmS and sSmS over long-period seismograms over 5s is much weaker that those of the S-wave or S multiple waves. In broad-spectrum seismograms, clear SmS can be observed in short-period (1s or so) seismograms in a relatively simple structure (Xie Zujun et al., 2012), but it is difficult to identify in areas with complex structures. Therefore, sSmS can only be used as an auxiliary depth seismic phase, and it is applicable in the case of a simple structure and a deep source depth

③ The sPn and sSn Phases

As early as the 1960s, earthquake scientists in the former Soviet Union began to use the sPn phase to calculate the focal depth, and European and American countries often use this phase. The seismic phase sPn is a relatively useful seismic phase parameter for the determination of focal depth of near-field shallow earthquakes, and it is more adaptable to earthquakes above $M4.0$ earthquakes.

In China, we have also used sPn and sSn to conduct some researches on the depth of earthquakes (Fang Mingshan et al., 1995; Ren Kexin et al., 2004; Zhang Ruiqing et al., 2008). The observation range of sPn is generally within the epicenter distance less than 1,000km. In some stations in northwest, southwest, east China, north China and northeast China, the sPn phase can be clearly recorded. According to the travel time equations of Pn and sPn, it can be known that for a particular earthquake, the arrival time difference between sPn and Pn is a constant and has nothing to do with the epicentral distance. If the data comes from multiple stations, Pn can be aligned and then the sPn phase can be measured. However, because sPn and Pn both belong to the initial wave, the initial motion amplitude is weak, and the resolution is not as good as those of the various direct waves such as Pg and Sg, and it is easily affected by noise and wake waves, and the reliability of a single selection is not high. Manual identification is more difficult.

④ The P + pP/sP Seismic Phases of Teleseismic

In the moderate-strong earthquakes with $M \geqslant 5.0$, relatively clear depth-seismic phases pP and sP can often be observed on the teleseismic maps with an epicenter distance of 30° to 90°. By calculating the teleseismic seismograms of different depths and comparing them with actual observations, the best depth fit for the depth-phase pP and sP and direct P-wave arrival time difference is the focal depth sought. When the epicentral distance is between 30° and 90°, the seismic wave is almost a perpendicular incident at the station, and the arrival time difference between P-wave and pP and sP is mainly affected by the focal depth, but the epicenter distance has little effect. With a focal depth of about 2km, it can cause significant changes in the time difference between pP, sP, and P waves. If the depth of phase records is clear, the depth accuracy determined by this method can reach 2km (Engdahl E. R. et al., 1998; Stein S. et al., 1986). For a stronger earthquake (M6.0+), the source duration may be greater than the depth phase time. In this case, the depth needs to be measured by waveform fitting. At present, CAPtel and CAP joint methods have been developed to invert teleseismic waveforms and determine the mass depth of the focal center (Xie Zujun et al., 2013).

At present, these positioning methods have made great progress, and many methods have been applied to conventional seismic positioning. However, it is worth noting that these methods have their own advantages, but different methods also have their own limitations. Therefore, only by taking into account the different positioning needs and integrating different methods for depth positioning can we get better results.

2 RESEARCH STATUS OF SPEED STRUCTURE

Seismic positioning is essentially the use of seismic waves in the propagation of subsurface media to generate response signals. Therefore, there are constraints on the speed model, whether it is the positioning of seismic waves or the fitting of waveforms. How to obtain an accurate velocity model is another major task in seismic depth research. Obtaining accurate crust and upper mantle velocity models is of great significance for studying the focal depth.

Common methods for obtaining crustal velocity models include artificial seismic sounding (Li Songlin et al., 2006) and body wave tomography (Huang Jinli et al., 2006; Zhao Dapeng, 2009; Tian You et al., 2009; Li Chang et al., 2010), surface wave velocity imaging (Tang Qunshu et al., 2008; He Zhengqin et al., 2009; Yao Huajian et al., 2008) and receiver function methods (Chen Ling et al., 2009; Ge Can et al., 2011; Zhou R. M. et al., 2009;) etc. Artificial seismic sounding can obtain high-precision crustal layered models, but the profile location is sparse and the observation cost is relatively high. The main acquisition is P-wave velocity. Seismic body wave and surface wave tomography can obtain the velocity structure at the depth of the regional scale, but the sensitivity to the shallow layer, especially the crust, is low, and the resolution is limited by the distribution of the earthquake.

With the rapid development of China's Broadband Digital Seismic Network in recent years, noise imaging technology (Barmin M. P. et al., 2001; Lin Fanchi et al., 2009) has played an increasingly important role in the study of the velocity structure of the crust and mantle in China. Compared with traditional seismic tomography, the noise imaging method has prominent advantages in determining the velocity structure of the crust and upper mantle. First, the main frequency of background noise is concentrated in a period of 3s to 40s. The period is relatively short, and is just in the sensitive cycle of the crust. The results of noise imaging are more sensitive and accurate to the structure of the crust than the signal of the seismic surface wave. Secondly, noise imaging uses the correlation function between the two stations as the empirical Green's function. Since the station's position is accurately known, the error due to the inaccurate position of the source is fundamentally excluded. Thirdly, since the station's distribution can be artificially laid out, for areas where the earthquake distribution is sparse and the azimuth distribution is uneven, it can be considered that the accurate speed structure of these areas can be obtained by considering the continuous observation of stations. Based on these advantages, at present, noise imaging methods have played an important role in the study of the velocity structure of the upper mantle and mantle in the Chinese mainland (Fang Lihua et al., 2010; Zheng Yong et al., 2010a, 2010b, 2011; Yang Yingjie et al., 2010, 2012; Zhou et al., 2012; Shen Weisen et al., 2016; Lü Jian et al., 2016; Jiang Chengxin et al., 2016).

However, similar to conventional surface wave tomography, the noise imaging method is not very sensitive to the crustal internal interface and the Moho surface undulations, and there is a tradeoff between the Moho surface undulation and the crustal velocity in the surface wave inversion. The thickness of the crust and the internal interface information are of great significance for obtaining an accurate crustal velocity structure and thus determining an accurate depth of earthquake. Different from surface wave inversion, the teleseismic receiver function is sensitive to the interface and relatively insensitive to the velocity of the crust. Therefore, using the receiver function can obtain reliable crust thickness information. Some scholars used the receiver function method to obtain information on the Moho interface fluctuations in North China (Chen Ling et al., 2009; Ge Can et al., 2011; Zhou R. M. et al., 2009) and the Qinghai-Tibetan Plateau (Zhao Junmeng et al., 2010).

3 FUTURE DIRECTIONS

As mentioned above, earthquake location is a very challenging problem. It is very difficult to accurately locate all earthquakes with a single method. Therefore, the direction of future development will not only require further research from the perspective of the seismological technology itself, but also require the introduction of techniques and methods from other disciplines, especially geodetic methods, such as InSAR, multi-directional and multi-data positioning and depth research.

3.1 Research on Seismic Depth by Using Geodesy

Geodetic techniques such as InSAR and GPS have made revolutionary progress in the past two decades and have been widely used in seismological research. Especially in seismic source research, combined with seismological methods, it has been possible to obtain various features of earthquake source ruptures (Liu Chengli et al, 2015a, 2015b, 2016, 2017; Bürgmann et al., 2002) which has also succeeded in the study of the source properties of small and medium earthquakes (Zheng Yong et al., 2015; Zheng Yong et al., 2016). The method can invert the seismic parameters alone (Wright et al., 1999, 2004; Massonner D. et al., 1993). It can also combine the inversion of seismic waveforms and field observations to accurately invert seismic source parameters (Delouis B. et al., 2002). Due to the large deformation field generated by the shallow source earthquake at the surface and the surface displacement decreases rapidly with the increase of seismic depth and epicentral distance (Dawson J. et al., 2008), the depth of the source can be accurately inverted by the change of surface displacement. Therefore, this method is particularly suitable for shallow earthquakes. Dawson J. et al. (2008) used InSAR data to study two shallow-shock earthquakes (approximately 1km depth) occurring in Australia, with a reorientation accuracy of 100m, and calculated the corresponding focal depth and mechanistic solution. The smallest shallow source seismic model obtained by inversion using InSAR method so far has a magnitude of $M_W 4.4$. Therefore, the InSAR method can calibrate shallow earthquakes with a magnitude of about $M5.0$, so as to match the source depth of the reference earthquake with other methods.

3.2 Study on the Relationship between Seismic Intensity and Depth

The focal depth is an important factor influencing seismic intensity. Yan Zhide et al. (1985) used the data of 57 large earthquakes before 1979 to establish the relationship between magnitude and epicentral intensity and focal depth by using binary linear regression. It was found that the focal depth had a significant impact on seismic intensity. Due to the absence or inaccuracy of historical seismic source depth data, it is often impossible to accurately consider the influence of focal depth parameters in the process of intensity attenuation and the relationship between epicenter intensity and source parameters (Xiao Liang et al., 2011; Lü Jian et al., 2009; Sun Jihao et al., 2011).

Zhang Jianfu et al. (2005) used 75 seismic cases with source depth data before 2000 to establish the relationship between epicenter intensity and magnitude and focal depth, and the relationship between intensity area and magnitude with consideration of the influence of focal depth. No satisfactory results have been obtained due to the low accuracy of the depth data. It has become a trend to develop a more reasonable seismic intensity attenuation relationship by using seismic source depth parameters with higher accuracy to conduct related research. In recent years, with the increasing application of broadband digital seismographs and the development of different positioning methods, the accuracy of seismic source depth measurements has been greatly improved, and the attenuation law of seismic intensity can be studied in terms of focal depth. The progress provides highly accurate statistical data for inferring the depth of the historical earthquake source from historical macroscopic intensity data (Zhou Zhonghong et al., 2010).

3.3 Seismic Phase Identification of Mantle Earthquakes

Study finds that there is also a small number of earthquakes in the mantle. Zhu Lupei et al. (1996) discovered three earthquakes below the crust by means of waveform fitting using the observations of eleven broad-band seismometers distributed in the Qinghai-Tibetan plateau. Compared with ordinary earthquakes, earthquakes under the earth's crust have distinct features. There is no existence of Pn and Sn. Therefore, the waveforms of Sd and Pd are sharp at long distances. In addition, Sd + SmS waveform on the SH component of general seismic waves is very clear, but the Sd + SmS phase in the seismic waveform of the mantle is missing. Therefore, using these two features, we can more accurately determine whether the earthquake occurred below the crust. Although the earthquake inside the mantle is relatively small, its significance is very important. It can help us to understand the structural and dynamic nature of the continental collision zone and other regions. Therefore, it is worth studying and analyzing.

3.4 Combining Multiple Data and Multiple Technologies

The development of deep seismic positioning in recent years has not only been limited to the earthquake itself, but also has made great progress in the direction of geodetic survey. However, in the past, these studies have mainly focused on a single field. For example, geodetic surveys only focus on geodetic surveys, and seismology only focuses on seismology. This has a certain influence and restrictions on depth positioning. In addition, the study of the velocity structure itself cannot be separated from the development of the nature of seismic sources. Therefore, more and more technologies combine velocity models with seismic locations and simultaneously invert earthquake location and velocity structures (Zhang Haijiang et al., 2003; Fang Hongjian et al., 2014) in order to achieve self-consistent results. The future development will inevitably be the joint positioning of various materials and technologies. Simultaneous study of the earthquake location and velocity model should be carried out to combine the geodetic data such as InSAR as constraints to jointly determine the location and nature of the earthquake.

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