An examination of the presence and topography of the D'' discontinuity under the Russia–Kazakhstan border region using seismic waveform data from a deep earthquake in Spain

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Abstract The D'' layer, which is located atop the core–mantle boundary, has long been an area of focus for global seismology studies. A widely used approach to study the discontinuities in the D'' layer involves the use of the SdS phases between the S and ScS phases, which requires that certain stringent conditions be satisfied with respect to an epicentral distance and earthquake depth. Therefore, this approach is only practical for investigating the presence and topography of velocity interfaces in certain local regions around the world. The Russia–Kazakhstan border region has been a “blind spot” with respect to this detection method. The seismic network deployed in the north-eastern margin of the Tibetan Plateau has recorded relatively clear SdS phases for the M_S 6.3 earthquake that occurred in Spain on April 11, 2010, allowing this blind spot to be studied. This paper compares the observed waveforms and synthetics and uses the travel times of the relevant phases to obtain a D'' discontinuity depth between 2,610 and 2,740 km in the examined area. This study provides the first results regarding the depth of the D'' layer discontinuity for this region and represents an important addition to the global studies of the D'' layer.

Keywords D'' · Russia-Kazakhstan border · Spain deep earthquake · North eastern margin of Tibet

1 Introduction

The core–mantle boundary (CMB) is an important thermo-chemical interface in the deep Earth. A separate layer, the D'' layer, lies atop this boundary; in the D'' layer, the density, seismic velocity, viscosity, and other physical parameters change rapidly with depth (Lay 2007; Lay and Garnero 2007). The D'' layer has recently become a focus of studies examining the physics within Earth's interior due to its significance in understanding a variety of phenomena such as the phase change and migration of deep Earth materials, plume origins, subduction processes, and the dynamics of mantle convection (Garnero and McNamara 2008). The D'' layer exhibits lateral heterogeneity, anisotropy, and velocity discontinuities (e.g., Gaherty and Lay 1992; Rost and Revenaugh 2003, 2004; Wookey et al. 2005; He et al. 2006; He and Wen 2009; Huang et al. 2009). The global mantle tomography and PKIKP precursor studies suggest that the D'' layer may be the final location for certain subducting slabs (Grand 2002; Shen and Zhou 2009).

Many global seismic observations have indicated that a distinct phase exists between the SH and ScS phases at an epicentral distance between 70° and 80°; the sign of this phase is consistent with the sign of SH (ScS): either both signs are positive, or both are negative (Lay 2007). Theoretical calculations have revealed that this phase should derive from the D'' discontinuities; therefore, the phase in question is generally referred to as the SdS phase. Analyses of long-period shear wave (S-wave) data from seismic wave records have demonstrated that the D'' layer is located approximately 200–300 km above the CMB interface with

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an increase of the S-wave velocity by approximately 2.5 %–3.0 % (Kendall and Shearer 1994; Wyss et al. 1998).

The use of the SdS phase in D'' discontinuity studies is significantly limited by data distribution. In principle, certain epicentral distances greater than 70° and focal depths greater than 50 km are required to ensure the identification of clear SdS. The epicentral distance greater than 70° is the domain of near- and post-critical angles of incidence. Even small velocity gradients or discontinuities can then produce relatively large secondary arrivals (Lay and Garnero 2011). The source time functions of deep earthquakes are relatively simple. Furthermore, in an epicentral distance range of 70°–80°, one can more easily identify and analyze the SdS phases given the absence of interference from depth phase sS. However, deep earthquakes frequently occur only in specific regions, significantly restricting the spatial feasibility of using SdS of deep earthquakes to study the D'' layer. Therefore, the previous studies utilizing this method have focused only on specific regions. Nevertheless, by analyzing the SdS phases, researchers have revealed the presence of seismic discontinuities in the D'' layer under many regions of the world. In particular, velocity discontinuities have been clearly observed under (among other regions) north-central Asia, the Indian Ocean, the Arctic, certain areas of the Pacific Ocean, portions of South America, Central America, and Alaska that lie along the Pacific Rim (e.g., Lay 2007; He and Wen 2009; Lay and Garnero 2011). Seismologists are currently attempting to expand the study areas in which the presence and topography of the D'' discontinuity may be examined and outline the global characteristics of this discontinuity.

On April 11, 2010, a rare M_S 6.3 deep earthquake occurred in Granada, Spain. Findings from the Global Centroid-Moment-Tensor (GCMT) project¹ (Dziewonski et al. 1981; Ekström et al. 2012) indicated that the focal depth of this earthquake was 616.5 km. The seismic records from this deep earthquake provide ideal waveform data for examining the D'' discontinuity under the Russia–Kazakhstan border region, an area in which this discontinuity could not previously be investigated. In this study, the presence and topography of the D'' discontinuity under the Russia–Kazakhstan border region were examined by analyzing the relevant seismic phases between the S and ScS phases in these waveform records. The deep geodynamic processes associated with this D'' discontinuity were then discussed.

2 Data processing

The data used in this study were acquired from the seismic network of Gansu Province, which obtained three-

component velocity waveform records from broadband CTS-1 seismographs at 23 permanent stations (Fig. 1). The CTS-1 seismographs were made by the Institute of Seismology, China Earthquake Administration. The black curves in Fig. 1 indicate the great-circle paths from the earthquake source to the 23 stations, whereas the gray squares in this figure mark the reflection points of the ScS phases at the CMB interface. The earthquake focal mechanism is provided by the CMT moment tensor solution.

The SdS phases associated with D'' discontinuities are relatively weak. To increase the clarity with which these phases were obtained, the waveform records were processed as follows: (1) The ENZ (east/west-north/south-vertical) three-component velocity records were integrated to displacement at first, then rotated to RTZ (radial-transverse-vertical) coordinates based on the back-azimuth of the source relative to each station. Because the T-component of the recorded data primarily includes SH waves without P-SV converted waves, the T-components of the examined waveforms were relatively simple and therefore helpful in extracting the phases relevant to the D'' discontinuity. (2) Because the response parameters of the some seismometers are not given correctly, we could not remove the response of seismometers from the observed waveforms, but filtered the T-component waveforms to enhance the signal-to-noise ratios by using the Butterworth band-pass filter with the frequency window of 0.05–0.2 Hz among the 120 s–20 Hz in which all CTS-1² seismographs exhibited flattened amplitude-frequency characteristics. (3) The preliminary reference Earth model (PREM) (Dziewonski and Anderson 1981) was utilized to calculate the S and ScS arrival times. The S-phase peak positions were then determined manually, and all records were aligned in accordance with the S-wave peaks and the epicentral distances.

The waveforms obtained from the aforementioned processing procedures are illustrated in Fig. 2. The differential travel times in the ScS phases relative to the S phases, as calculated using the PREM model, are also indicated in this figure. Figure 2 demonstrates that the observed differential arrival times in the ScS phases relative to the S phases were consistent with the theoretical values. In addition, another phase clearly exists between S and ScS. The abnormal phase has the same polarity and comparable amplitude as S and ScS phase. Besides, this additional phase exhibits clear move out similar to the ScS phase. These characteristics rule out the contributions of complicated earthquake source or heterogeneities of the crust and upper mantle structures of source or receiver sides (Lay and Garnero 2011). So this phase should be the SdS phase associated with discontinuities in the D'' layer. We manually determined the peak

¹ <http://www.globalcmt.org>.

² http://data.earthquake.cn/datashare/network/csn48_stations.jsp.

Fig. 2 T-components of seismograms aligned by the direct S phases. The dashed lines show the theoretical travel times related to the direct S phases. The asterisks show the SdS arrivals. The station codes are labeled at the right side

SdS phases, which differ significantly at certain stations. This phenomenon suggests that the observations cannot be simply interpreted using a one-dimensional model; in other words, the D'' discontinuity fluctuates within the examined region.

To determine the topography of the D'' discontinuity in the study area using the observed waveforms, we first constructed models based on the PREM model but with different discontinuity depths. The following model construction principles were employed: discontinuity depths were examined every 10 km from 2,540 to 2,740 km; the velocity above the discontinuity was identical to that obtained from the PREM model, whereas a 3 % jump in velocity was noted across the discontinuity; and the velocity decreased steadily from the discontinuity to the CMB with the same average velocity in both the PREM model and the constructed model. Figure 5a depicts the 21 S-wave velocity structure models constructed according to the aforementioned principles. Based on the depth of the earthquake examined in this study, arrival time differences between the SdS and S phases at various epicentral distances were calculated for each model. The constructed travel-time curves are illustrated in Fig. 5b. The diagram

Table 1 The locations of the ScS reflected points, the related differential travel times (dt) of SdS to S, and the depths (H) of D'' discontinuity

Sta	Distance (°)	Lon (°)	Lat (°)	dt (s)	H (km)
AXX	73.12	42.60	51.12	14.19	2,610
DAW	79.54	47.68	49.52	5.64	2,680
DHT	72.78	42.40	50.62	14.81	2,610
GTA	76.28	45.03	51.79	13.60	2,720
HUL	79.84	47.92	50.95	6.75	2,710
HXP	78.32	46.65	52.03	10.48	2,730
HYS	78.76	46.98	52.27	6.32	2,660
JYG	75.04	44.07	51.50	14.81	2,700
LEH	72.55	42.33	49.64	16.63	2,630
LYT	72.61	42.17	51.31	18.94	2,680
MEY	78.44	46.79	51.36	10.38	2,740
MIH	79.99	48.03	51.27	8.06	2,740
MIQ	78.60	46.80	52.72	10.58	2,740
QIL	77.26	45.85	51.31	11.49	2,720
QTS	74.81	43.91	51.30	12.59	2,650
SBC	73.78	43.18	50.67	13.00	2,610
SDT	77.42	45.93	51.87	11.79	2,730
SGT	79.20	47.37	51.87	5.77	2,670
SNT	76.49	45.23	51.46	10.98	2,680
YJZ	74.97	43.96	51.90	12.90	2,660
YMS	71.21	41.05	51.28	18.64	2,610
YWX	73.49	42.80	51.71	12.80	2,600
ZHY	76.91	45.53	51.87	12.19	2,720

In the table, Sta abbreviates the station code, and Lon and Lat abbreviate the longitude and latitude of the ScS reflected point, respectively

of Fig. 5b just looks like a dictionary in which the depth of discontinuity in D'' can be determined by the value of the time difference of SdS-S and epicenter distance. The points corresponding to the epicentral distance and the arrival time difference between the SdS and S phases for each station listed in Table 1 are plotted in Fig. 5b. For each point, the depth corresponding to the closest travel-time curve is that the D'' discontinuity associated with this SdS phase. Using this approach, the D'' discontinuity depths corresponding to each SdS phase in Fig. 2 were determined, and the results are listed in Table 1. The depth differences between the reflection points of the individual D'' discontinuities and the CMB are plotted in Fig. 6 in which the values of these depth differences are represented by different square sizes. Figure 6 demonstrates that, within the study region, the D'' discontinuity is located between 150 and 280 km above the CMB. Generally, the results can be divided into two portions by longitude of 44° . The thickness of D'' discontinuity of southwestern and northeastern portions is ~ 260 km and ~ 180 km, respectively.

Fig. 3 The ray paths (a) and the travel times (b and c) of the S, Sab, Scd, and ScS phases. **b** Shows the theoretical times of S and ScS with PREM earth model and **c** shows the travel times calculated with the modified PREM model

4 Discussion and conclusions

To analyze the characteristics of the D'' discontinuity, one must integrate the findings of this investigation with the results of other studies. The results of high-temperature, high-pressure experiments have indicated that at a depth of approximately 2,700 km below the Earth's surface (where

Fig. 4 The observed seismograms (in black) and the synthetic seismograms (in red) with modified PREM model

the pressure is approximately 125 GPa and the temperature is approximately 2,500 K), $(\text{Mg,Fe})\text{SiO}_3$ perovskite (Pv), the primary component of the Earth's lower mantle, undergoes a phase transition to post-perovskite (pPv). This Pv–pPv phase transition may increase the S-wave velocity by 2 %–4 % and the little changes in P-wave velocity (Lay et al. 2006). These changes in seismic wave velocities are consistent with many observations (Lay and Garnero 2004; Russell et al. 1999). If the D'' discontinuity is generated solely by this mineral phase transition, then it should be present around the globe. However, although observations have revealed a significant D'' discontinuity under certain aforementioned areas—portions of north-central Asia, the Indian Ocean, the Arctic, the Pacific Ocean, and the Pacific Rim—little evidence of a D'' discontinuity has been found under other regions, such as the western central Pacific Ocean. Thus, the observed phenomenon of seismic wave velocity changes cannot be fully explained by the Pv mineral phase transitions alone.

Accumulated remnants of ancient subducting oceanic plates may cause changes in the mineral composition of the D'' regions (Wyssession et al. 1998) that could contribute to the D'' discontinuity. This rationale may also partially explain the observed differences in the presence of D'' discontinuity around the world. The seismic tomography

Fig. 5 The differential travel times of ScS to S in different models. **a** In different models based on the PREM (*in red*), only the discontinuity depths change from 2,540 to 2,740 km stepped with 10 km. **b** The differential travel times of ScS to S are calculated for different models and the *black lines* from bottom to top relate to the different discontinuity depths from 2,540 to 2,740 km. The observed differential times from seismic stations are also labeled

Fig. 6 The thickness of the discontinuity in D'' . The *squares* indicate the location of reflected points of ScS. The size of square represents the thickness of the discontinuity in D'' . The background is the S tomography between the depth of 2,650–2,890 km (Grand 2002)

results support this theory (Grand 2002). Thus, a reasonable model for the D'' discontinuity should incorporate the combined effects of the mineral phase transition, accumulated remnants of ancient subducting plates, and thermal and chemical reactions.

The study area for this investigation is located in the Russia-Kazakhstan border region. Global S-wave tomography results (Grand 2002) indicated the presence of a low-velocity anomaly at a depth of 2,650–2,890 km to the north of this study area and significant lateral heterogeneity of the S-wave velocities across the entire region. In general,

significant anomalies involving high S-wave velocities occur in regions in which the remnants of ancient subducting plates have accumulated; thus, the aforementioned tomography results suggest that no such accumulation has occurred in the given study area. Therefore, we believe that the D'' discontinuity under this region is primarily caused by the Pv–pPv phase transition. The distribution of the depths of the SdS reflection points in the D'' layer indicates a relatively shallow average depth of the D'' discontinuity in this region. The S-wave velocities are sensitive to temperature changes, with lower S-wave velocities associated with higher temperatures. The occurrence of the Pv–pPv phase transitions requires higher pressures in locations with higher temperatures (Lay et al. 2006). Locations of the same depth within the Earth will experience the same pressure. Thus, the Pv–pPv phase transition will first be completed in the low-temperature regions of a given depth, forming the D'' discontinuity in these regions. In contrast, in high-temperature regions, the Pv–pPv phase transition will require greater pressure and will therefore occur in regions of greater depth; as a result, the D'' discontinuity will form closer to the CMB. In this study, the calculated differences in depth between the D'' discontinuity and the CMB were approximately coherent with the previously obtained S-wave tomography results. The averaged value of the thickness of D'' discontinuities is ~ 260 km in the southwest area with higher S-wave velocities and ~ 180 km in the northeast area with lower S-wave velocities.

This study used broadband waveforms from a relatively rare deep earthquake in Spain recorded in the northeastern margins of the Tibetan Plateau to detect a significant D'' discontinuity involving a high-seismic wave velocity jump

under the Russia–Kazakhstan border region. To examine this discontinuity, travel-time curves and synthetic seismograms of the seismic phases were calculated to create theoretical models. The results indicate that a D'' discontinuity with a large topography was present under this region, approximately 150–280 km above the CMB. The D'' discontinuity is deeper in regions with lower S-wave velocities. Based on the temperature characteristics of the phase transitions, the most plausible origin of the D'' discontinuity under the study area is the P_v – pP_v phase transitions.

In this study, we just considered the most likely model for explaining the observed data and the SdS phase arrival time variations were completely attributed to the effects of the discontinuity depths. The information of amplitude and arrivals of SdS and ScS are perfect to constrain the velocity model. There are also large variations in the SdS amplitude in our observations. The results of amplitude in our study are not so robust because of the data limitation and the instrument response, while the arrivals are relatively stable and reliable. So we just use the arrival information of SdS to constrain the depth of discontinuity in D'' . However, the presence of a 130-km topography in a local D'' discontinuity is relatively unusual and the strong heterogeneities may also affect the SdS arrival times, so more work still needs to be done for the discontinuity according to the increasing observations.

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