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Global large deep-focus earthquakes: Source process and cascading failure of shear instability as a unified physical mechanism

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ABSTRACT

We apply a multiple source inversion method to systematically study the source processes of 25 large deep-focus (depth >400 km) earthquakes with Mw > 7.0 from 1994 to 2012, based on waveform modeling of P, pP, SH and sSH wave data. The earthquakes are classified into three categories based on spatial distributions and focal mechanisms of the inferred sub-events: 1) category one, with non-planar distribution and variable focal mechanisms of sub-events, represented by the 1994 Mw 8.2 Bolivia earthquake and the 2013 Mw 8.3 Okhotsk earthquake; 2) category two, with planar distribution but focal mechanisms inconsistent with the plane, including eighteen earthquakes; and 3) category three, with planar distribution and focal mechanisms consistent with the plane, including six earthquakes. We discuss possible physical mechanisms for earthquakes in each category in the context of plane rupture, transformational faulting and shear thermal instability. We suggest that the inferred source processes of large deep-focus earthquakes can be best interpreted by cascading failure of shear thermal instabilities in pre-existing weak zones, with the perturbation of stress generated by a shear instability triggering another and focal mechanisms of the sub-events controlled by orientations of the pre-existing weak zones. The proposed mechanism can also explain the observed great variability of focal mechanisms, the presence of large values of CLVD (Compensated Linear Vector Dipole) and the super-shear rupture of deep-focus earthquakes in the previous studies. In addition, our studies suggest existence of relationships of seismic moment $\sim$ (source duration)^3 and moment $\sim$ (source dimension)^3 in large deep-focus earthquakes.

1. Introduction

Physics of deep-focus earthquakes remains enigmatic, since deep-focus earthquakes occur at the depth below 400 km where the pressure would strongly inhibit brittle failure and the temperature would result in ductile deformation (Scholz, 2002). Various models have been proposed to explain the unexpected occurrence of deep-focus earthquakes, including dehydration embrittlement, transformational faulting and shear thermal instability. Dehydration embrittlement suggests that deep earthquakes may be triggered by embrittlement accompanying dehydration of hydrous minerals (such as serpentine) (Jung et al., 2004; Meade and Jeanloz, 1991), although it is unclear if the water content below the 400 km depth can support this mechanism. Transformational faulting mechanism hypothesizes that a meta-stable olivine wedge exists in the mantle transition zone and the phase transformation can lead to catastrophic earthquake failure (Green, 2007; Green and Burnley, 1989; Green and Houston, 1995; Kirby, 1987; Wiens et al., 1993). And, shear thermal instability suggests that rapid deformation can be achieved (especially, in pre-existing rheological weak zones), when a stress or temperature perturbation promotes a positive feedback between shear heating and temperature-dependent rheology (Hobbs and Ord, 1988; Karato et al., 2001; Kelemen and Hirth, 2007; Ogawa, 1987).

Studies of source processes of large deep-focus earthquakes provided important constraints on deep-focus earthquake mechanisms. During the past 20 yr, various methods have been applied to study source processes of deep-focus earthquakes. Rupture directivity is analyzed to determine fault plane orientations of deep-focus earthquakes occurring in the Tonga–Kermadec subduction zone (Warren et al., 2007). Both sub-horizontal and sub-vertical fault planes are detected, corresponding to a complex rupture system with either a reactivated or new generated fault system (Warren et al., 2007). Super-shear rupture was also reported for an Mw 6.7 aftershock of the Okhotsk earthquake (Zhan et al., 2014b). A number of large deep earthquakes, especially

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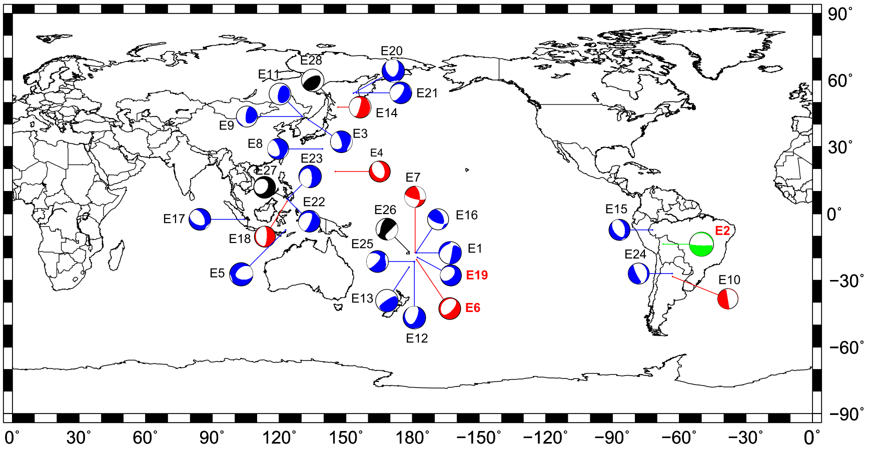

Fig. 1. Distribution of the global large deep-focus earthquakes (Mw > 7 and depth > 400 km) from 1994 to 2012, and their GCMT focal mechanisms, labeled with event numbers in Table S0. The earthquakes labeled with green, blue and red represent those in categories one to three as classified in Section 4. The events labeled with red numbers are the example events presented in the main text. Three earthquakes with black beach balls are not studied (see text for the reasons).

the 1994 Mw 8.2 Bolivia and 2013 Mw 8.3 Okhotsk deep earthquakes, have also been studied by multiple source inversion (Chen et al., 2014; Silver et al., 1995; Zhan et al., 2014a) and finite fault inversion (Antolik et al., 1996, 1999; Estabrook, 1999; Wei et al., 2013; Ye et al., 2013). The source processes of these two largest ever-recorded deep earthquakes provided particularly important insights on the physical mechanisms of deep earthquakes. Both the Bolivia earthquake (Silver et al., 1995; Zhan et al., 2014a) and the Okhotsk earthquake (Wei et al., 2013; Ye et al., 2013) were determined to have a large source region that totally cuts out of the assumed meta-stable olivine zone, seemingly excluding the transformation faulting as a possible mechanism. In a recent study, we showed that the Okhotsk earthquake consists of six sub-events that cannot spatially be fit into plane rupture and have variable focal mechanisms; we further suggested that the source process can be best explained by a cascading failure of shear thermal instabilities distributed at different depths, with one shear instability triggering another (Chen et al., 2014).

Though the past studies have provided important constraints on deep earthquake physics, several issues remain to be resolved. 1. Do deep-focus earthquakes rupture in a single fault plane? 2. Do deep-focus earthquakes behave the same between hot and cold subducted slabs? 3. Is there a unified mechanism to explain all the seismic results? In this study, we perform a systematical study of source processes of the global large deep-focus earthquakes with a moment magnitude greater than 7 and depth larger than 400 km, based on waveform modeling of direct P and SH waves and near-surface reflected pP and sSH waves through multiple source inversion. Combining the direct and near-surface reflected phases places a tight constraint on the depth distribution of the seismic energy release during these earthquakes (Chen et al., 2014). The multiple source inversion also makes no *a prior* assumption on the focal mechanism of the sub-events in waveform modeling and is able to resolve varying focal mechanisms in the source process. In the following sections, we present event information and seismic data in Section 2, multiple source inversion method in Section 3, multiple source inversion results in Section 4, a unified physical mechanism of shear thermal instability for explaining the seismic results in Section 5, and implications to the observed focal mechanism variation and super-shear rupture of deep earthquakes in Section 6.

2. Seismic data

We search the events with Mw > 7.0 and depth > 400 km from 1994 to 2012. There are a total of 28 earthquakes matching the criterion (Fig. 1 and Table S0). The studied events are well recorded by the Global Seismographic Network (GSN). The data consist of broadband compressional waves (P), near-surface reflected compressional waves (pP), transversally polarized shear waves (SH) and near-surface reflected transversally polarized shear waves (sSH) recorded at tele-seismic distances between 30° and 90°. The selected data constitute good azimuthal coverage for all the events (Figs. S1a–S25a). As we will mention later, the combination of direct P and SH waves with the near-surface reflected pP and sSH waves places a tight constraint on depth extent of seismic source. The displacement seismograms are deconvolved with their respective instrument responses and bandpass filtered between 0.01 and 4 Hz. Our source models are constrained mostly by the seismic energy in a lower frequency band, but the use of the high-frequency data provides better arrival time reading of the P wave onsets while producing little artifacts in the inversions (supplementary information).

3. Multiple source inversion method

3.1. Method procedure

We apply a multiple point source inversion procedure to infer the source processes based on waveform fitting of direct phases P/SH and near-surface reflected phases pP/sSH (Chen et al., 2014). The method treats a large earthquake as a combination of multiple double couple point sources (sub-events) separated in space and time, and resolves the spatio-temporal separation and focal mechanism of each sub-event by modeling the seismic data. Each sub-event is represented by nine parameters: seismic moment, seismic duration (the width of the source time function represented by a half sine function), strike, dip and slip for focal mechanism, dt for time separation of origin time from the initiation time, and de, dn and dz for distance separations from the initiation point in east-, north- and vertical-direction, respectively. Seismic Green's functions are computed by the Generalized Ray Theory method (Helmberg, 1968), based on the velocity and attenuation structures of PREM (Preliminary Reference Earth Model, downloaded from IRIS EMC-PREM) (Dziewonski and Anderson, 1981). The seismic response of each sub-event is obtained by convolving Green's function with source time function (Ji et al., 2002). The $9 \times N$ (N, number of sub-events) model parameters are searched by the simulated heat annealing algorithm for the best-fitting solution that generates the least root mean square (RMS) residual between the seismic data and synthetic waveforms (Chen et al., 2014).