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Origin and significance of deep earthquake clusters surrounding a pronounced seismic gap in northeast China

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ABSTRACT

From analysis of earthquakes in the Global centroid moment tensor (GCMT) catalog, we identify an intermediate depth (~250–350 km) seismic gap having dimensions of ~300 km × 500 km within the subducting northwestern Pacific plate (NPP), and surrounded by several groups of isolated earthquakes near northeast China. Normally, groups of unusual deep earthquakes may represent a detached slab segment, as in Tonga–Vanuatu; and a deep seismic gap maybe either be the aseismic continuation of a subducting slab or a possible gap in the subducting plate. We evaluate the characteristics of deep earthquakes in the NPP and focus on three isolated clusters, particularly one directly beneath the seismic gap and northeast China. This sub-gap cluster has a peak in the number of quakes near depth ~580 km, unlike seismicity in the NPP as a whole. Its *b*-value (~0.60) is significantly smaller than *b*-values in two other nearby clusters (~0.81 and ~0.86) in the NPP. Focal mechanisms in this sub-gap cluster also show a variation with depth, and projections of their *T*, *P*, and *B* axes differ from what is observed for the other isolated clusters. We speculate why these sub-gap earthquakes are isolated and suggest two possible models explaining the presence of the gap and the characteristics of the underlying cluster beneath northeast China. In the first model, the seismic gap is attributable to aseismic deformation caused by abnormally high temperatures in the subducting lithosphere. And, the characteristics of the sub-gap clusters and its related slab structures are attributed to slab buckling caused by resistance to subduction. In the second model, the seismic gap represents absent subducting lithosphere and the missing material has migrated to the bottom of subducting slab. Although we favor the second model, both models are consistent with our knowledge of deep earthquakes and the results of recent studies near northeast China.

1. Introduction

The subducting northwestern Pacific plate (NPP) has a relatively high thermal parameter, and many deep earthquakes that define its location within the mantle. Seismic observations (Frohlich, 2006) and laboratory experiments (Green, 2007; Karato et al., 2001) confirm that most earthquakes with depths exceeding 60–70 km only occur within relatively cold subducting slabs and their characteristics are mostly controlled by the stress and thermal conditions within slabs. Meanwhile, these constraining factors are related to characteristics of subduction, such as the age of subducting lithosphere, convergence velocity, etc. Therefore, the widely distributed deep earthquakes within the NPP provide an opportunity to investigate the historical and dynamic state of subduction lithosphere there.

Beneath northeast China, various methods, including tomographic inversion, receiver function analysis, and waveform modeling utilize seismic waves from deep earthquakes to investigate the structure of the slab and the discontinuities in the mantle transition zone in the NPP (Ai et al., 2003; Bagley et al., 2013; Gu et al., 2012; Huang and Zhao, 2006; Li et al., 2013; Tajima et al., 2009; Zhao et al., 2011). Furthermore, various models have been proposed to explain regional structure and dynamic processes, including complex structure in velocity discontinuities in the mantle transition zone, and the intraplate volcanism on the surface (Tang et al., 2014; Zhao and Tian, 2013; Zhao et al., 2009, 2011).

Instead of analyzing seismic waves, the present study will analyze regional seismicity; i.e., the locations and characteristics of the deep earthquake themselves. We analyze their frequency, *b*-values and location within the NPP, and identify a significant seismic gap

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within the subducting plate surrounded by several isolated clusters. We then focus on three isolated clusters, and particularly on one unique isolated cluster situated directly beneath this distinct seismic gap beneath northeast China. We relocate earthquakes and interpret focal mechanisms within this sub-gap cluster, and compare it with other isolated clusters in the NPP. Finally, we explore possible models consistent with these observations and the complex structures indicated by previous studies near northeast China.

2. Data and methods

In this study earthquakes and focal mechanisms are mostly from the Global centroid moment tensor catalog (GCMT), occurring between January 1977 and September 2013; we also include data from two other catalogs: deep-focus (greater than 300 km) events occurring between 1962–1976 (Huang et al., 1997) and intermediate-depth (70–300 km) events 1962–1975 (Chen et al., 2001). In the NPP region (Fig. 1), there are 1056 deep events (depth greater than 70 km) in total, including 37 before 1977. Among these earthquakes, the smallest magnitude is 4.7 Mw; the largest is 8.3 Mw with a depth of 609 km (Ye et al., 2013).

To evaluate the spatial properties of these earthquakes, we used single-link cluster analysis (Frohlich and Davis, 1990). For a group of N earthquakes, this method links all earthquakes to their nearest neighbors to form event sub-groups; then sub-groups are linked to neighboring subgroups recursively, until N-1 links are found. Considering inter-event distances reported by other investigations of isolated deep earthquakes (Boddington et al., 2004; Lundgren and Giardini, 1994) and the properties of isolated groups we observe in the NPP, we chose 150 km as the critical link size defining "isolation" in this study, i.e., we consider a cluster to be isolated if it is further than 150 away from the neighboring events or clusters. Using this method and criteria, we identify seven groups of isolated clusters (Table 1) for more detailed investigation.

One isolated cluster of deep earthquakes (group G1 in Table 1), separated by 170.5 km from neighboring seismicity, is relocated in this research. The G1 cluster is chosen because: (1) The cluster is located near the hinge zone of the subducting slab and directly beneath the seismic gap; (2) Its characteristics differ from those of the other isolated clusters; and (3) It contains a workable number of quakes for accurate relocation. We thus relocated all G1 earthquakes in latitude range 40–45°N, longitude range 125–137°E and compared these relocations to locations reported in other catalogs, including the International Seismological Centre (ISC) bulletin and the EHB catalog (Engdahl et al., 1998).

To relocate these earthquakes, we retrieved three-component broadband seismograms from seven stations in northeast China that surround cluster G1 (Fig. 1a and Table 1). Station MDJ (Mudanjiang, PRC) is situated directly above cluster G1 and the other stations are about 8° away. Data are available for all these stations from November 1996 to the present, except TSK (Tsukuba, Japan) which closed in May 2012. We obtained records for 85 events from the Incorporated Research Institutions for Seismology Data

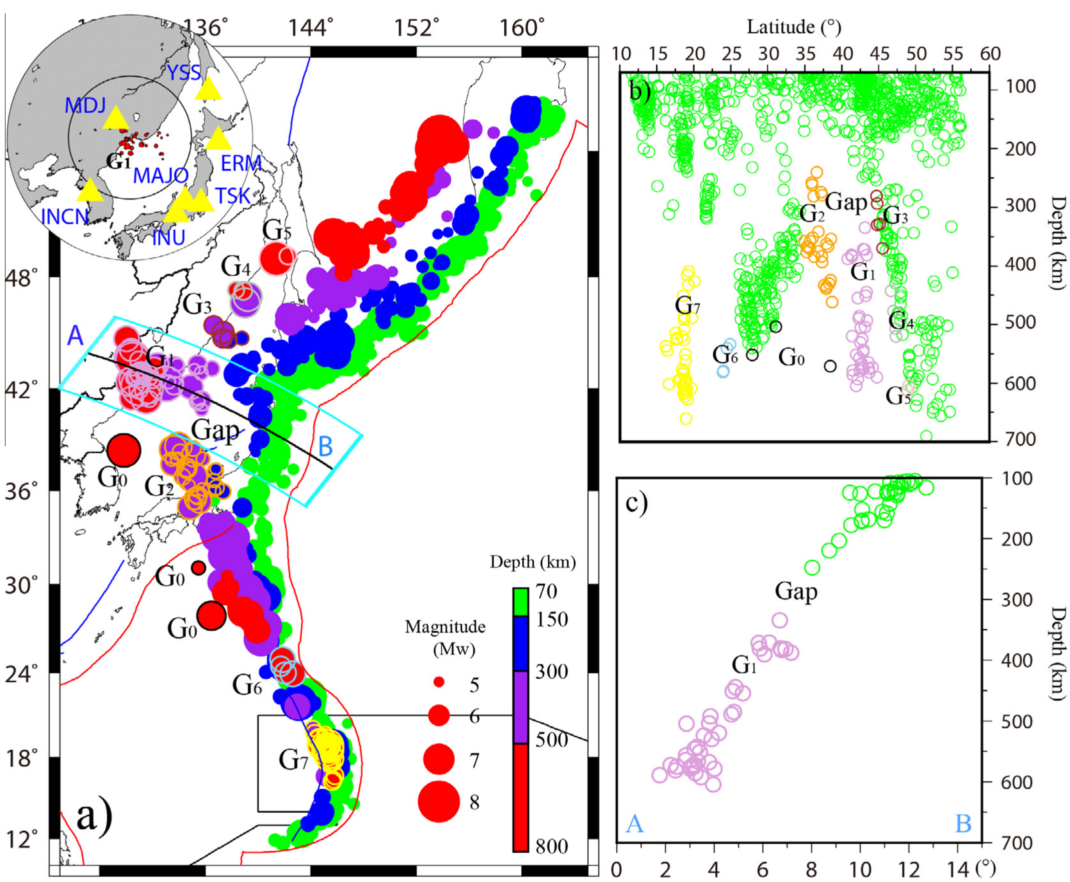

Fig. 1. Map showing the distribution of deep earthquakes (circles) in the NPP; all data are earthquakes occurring between 1962 and 2013 from the GCMT catalog, augmented by events from two other catalogs (Huang et al., 1997; Chen et al., 2001). Solid circles with different colors indicate earthquakes of different depths; the different colors of the edges of solid circles in (a) correspond to the open circles with different colors in (b) and (c), and indicate labeled groups of earthquakes. The green open circles in (b) and (c) represent earthquakes not labeled. Line AB and the area surrounded by cyan lines in (a) indicate the earthquakes plotted in cross-section (c); in this paper we call the earthquakes within the cyan lines the Japan–China subduction (JCS) group. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)