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# Accurate focal depth determination of oceanic earthquakes using water-column reverberation and some implications for the shrinking plate hypothesis

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## ABSTRACT

Investigation of oceanic earthquakes is useful for constraining the lateral and depth variations of the stress and strain-rate fields in oceanic lithosphere, and the thickness of the seismogenic layer as a function of lithosphere age, thereby providing us with critical insight into thermal and dynamic processes associated with the cooling and evolution of oceanic lithosphere. With the goal of estimating hypocentral depths more accurately, we observe clear water reverberations after the direct P wave on teleseismic records of oceanic earthquakes and develop a technique to estimate earthquake depths by using these reverberations. The $Z$–$H$ grid search method allows the simultaneous determination of the sea floor depth ($H$) and earthquake depth ($Z$) with an uncertainty less than 1 km, which compares favorably with alternative approaches. We apply this method to two closely located earthquakes beneath the eastern Pacific. These earthquakes occurred in ∼25 Ma-old lithosphere and were previously estimated to have similar depths of ∼10–12 km. We find that the two events actually occurred at dissimilar depths of 2.5 km and 16.8 km beneath the seafloor, respectively, within the oceanic crust and lithospheric mantle. The shallow and deep events are determined to be a thrust and normal earthquake, respectively, indicating that the stress field within the oceanic lithosphere changes from horizontal deviatoric compression to horizontal deviatoric tension as depth increases, which is consistent with the prediction of lithospheric cooling models. Furthermore, we show that the P-axis of the newly investigated thrust-faulting earthquake is perpendicular to that of the previously studied thrust event, consistent with the predictions of the shrinking-plate hypothesis.

## 1. Introduction

Depth estimates of oceanic earthquakes have been useful in the investigation of many problems of tectonophysics: depth extent of the seismogenic layer in intraplate settings (Okal et al., 1980; Bergman and Solomon, 1980; Wiens and Stein, 1983) and the corresponding limiting temperature above which earthquakes do not nucleate (McKenzie et al., 2005), along mid-ocean ridges (Huang and Solomon, 1988), along transform faults (Engeln et al., 1986; Bergman and Solomon, 1988), and along the outer rise of trenches.

Source mechanisms of intraplate oceanic earthquakes have been used to infer the state of stress of the lithosphere (e.g., Sykes and Sbar, 1974; Stein and Okal, 1978; Wiens and Stein, 1983; Bergman and Solomon, 1984; Zoback et al., 1989). Sykes and Sbar (1974) studied focal mechanism solutions of earthquakes occurring off the mid-ocean ridge axis using P-wave first motion data, and found that most earthquakes occurring in oceanic lithosphere older than ∼15 Ma indicate thrust faulting while those observed in the younger oceanic lithosphere indicate normal faulting. This change in focal mechanism was interpreted as a stress state transition from ridge axis (horizontal deviatoric tensional) to intraplate stress (horizontal deviatoric compressional) regime. Wiens and Stein (1984), however, found mixed types of earthquake mechanisms occurring in oceanic lithosphere between 3 and 35 Ma and concluded that there is a no general tensional-to-compressive stress transition in the oceanic lithosphere. On the other hand, different types of earthquake mechanisms observed for the same lithospheric age have different focal depth (Bergman and Solomon, 1984; Wiens and Stein, 1984), indicating that there is a stress state change with depth. These are now interpreted as

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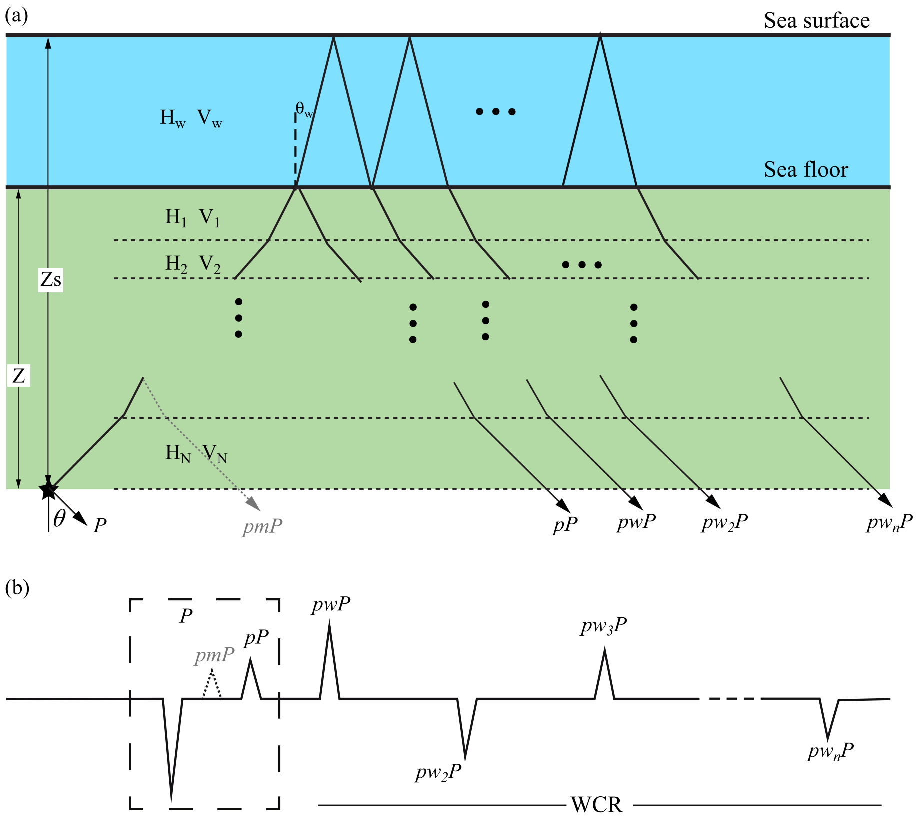

**Fig. 1.** (a) A schematic diagram showing the ray paths of the $P$, $pP$, $pwP$, and the water reverberations $pw_nP$. The upper and lower layers shaded with light blue and green indicate the seawater and oceanic lithosphere, respectively. The horizontal dashed lines represent the boundaries of constant velocity layers in the reference velocity model with a thickness of $H_i$ and velocity $V_i$. (b) A schematic seismogram showing the sequence of arrivals in a vertical record of an oceanic earthquake at teleseismic distances. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

being due to depth-dependent stress and strain. Numerical modeling also suggests that the stress field within the lithosphere varies systematically and significantly with depth. The upper and the lower competent lithosphere are in horizontal deviatoric compression and tension, respectively (Parmentier and Haxby, 1986; Wessel, 1992). These investigations have helped to establish the role of thermo-elastic stresses in the evolution of oceanic lithosphere (Parmentier and Haxby, 1986; Wessel, 1992)

Recently, source mechanisms of oceanic intraplate earthquakes and their depth dependence have come under renewed interest because of the hypothesis that horizontal thermal contraction of the lithosphere may lead to measurable non-rigidity of oceanic plates (Kumar and Gordon, 2009; Kreemer and Gordon, 2014; Mishra and Gordon, submitted for publication). Kumar and Gordon (2009) estimate that vertically averaged strain rates due to thermal contraction vary as $\sim t^{-1}$, where $t$ is the age of the lithosphere, with vertically averaged horizontal contraction rates ranging from $10^{-5}$ $\text{Ma}^{-1}$ ($3 \times 10^{-19}$ $\text{s}^{-1}$) to $2 \times 10^{-2}$ $\text{Ma}^{-1}$ ($5 \times 10^{-16}$ $\text{s}^{-1}$) (Kumar and Gordon, 2009; Mishra and Gordon, submitted for publication). Such strain rates accumulated across the Pacific plate may sum to significant displacement rates ($\sim$2 mm $\text{a}^{-1}$), which are non-negligible in estimating global plate velocity (Kumar and Gordon, 2009; Kreemer and Gordon, 2014). This has caused renewed interest in the deformation of oceanic lithosphere, including that manifested in earthquakes. Because of the expected depth dependence of earthquake mechanisms, one cannot simply look at the epicenters associated with focal mechanisms or centroid-moment tensors—one must also know the depth of the event. It is therefore appropriate to seek methods to obtain more accurate estimates of the depths of oceanic earthquakes, which are thought to have uncertainties of ±1 km or more (Bergman and Solomon, 1984; Wiens and Stein, 1984).

The tradeoff between earthquake origin time and focal depth is a well known problem in hypocentral inversion. One of the most reliable ways of constraining focal depths is to identify the depth phases ($pP$ and $sP$) and add their arrival times in the inversion. Many methods have been developed to improve the identification of depth phases in seismograms, from simple stacking technique using array data (e.g., Key, 1968) to more sophisticated techniques, such as the $F$-detector technique proposed by Heyburn and Browers (2008). The above routine depth-phase method, however, works only when the depth arrivals are located outside the source time window such that they can be robustly picked. Assuming a source time function of 5 s, the minimum source depth that can be constrained with the routine depth-phase method is $\sim$15 km. Chu et al. (2009) developed an iterative waveform fitting method to determine earthquake focal depths and source time functions using teleseismic P waves. This method, however, requires full knowledge of the moment tensor solutions of earthquakes, which could be difficult to obtain for intermediate-size earthquakes ($\sim$M5.0). It also becomes increasingly challenging to isolate the depth phases from the direct P wave since their ray parameters are nearly identical to the direct P wave when earthquakes occur at depths shallower than 5 km. The CAP (cut-and-paste) is another widely used method, which uses regional waveform data to search for the optimum focal mechanism and hypocentral depth (Zhao and Helmberger, 1994; Zhu and Helmberger, 1996). This method also requires a source time function, which is difficult to obtain when the direct P and the depth phases are mixed in the case of shallow earthquakes.