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Key Points:
• Over 35 million arrival times of seismic phases reported to the ISC for well-recorded global earthquakes have been reprocessed
• The data set, called ISC-EHB, contains refined locations and depths for 170,550 globally distributed seismic events between 1964 and 2016
• The ISC-EHB data set is used to highlight features of subduction zones globally

Supporting Information:
• Supporting Information S1

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ISC-EHB 1964–2016, an Improved Data Set for Studies of Earth Structure and Global Seismicity

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Abstract A data set of earthquake hypocenters and associated traveltime residuals for seismic phases recorded by seismograph stations globally is an essential starting point for most studies of global seismicity and Earth structure. Such data sets have been produced in various forms by national and international agencies since the beginning of instrumental seismology at the turn of the twentieth century. We have reprocessed the comprehensive data used to produce the routinely distributed bulletins of the International Seismological Centre (ISC) since 1964 to construct a new refined data set of hypocenters with improved focal depths and phase residuals. This data set, called ISC-EHB, is used to reveal features of the seismotectonic zones in downgoing slabs in greater detail than previously routinely available.

1. Introduction

Earthquake catalogs and arrival times are foundational to seismic studies. The original EHB (Engdahl, van der Hilst, and Buland) global data set (Engdahl et al., 1998), a groomed subset of well-recorded hypocenters and associated station residuals sourced from the bulletin of the International Seismological Centre (ISC, www.isc.ac.uk) (International Seismological Centre, 2019a), has seen wide use in Earth science studies, including global and regional tomography (e.g., Huang & Zhao, 2006; Li et al., 2008; Montelli et al., 2004; Schmid et al., 2008) and regional tectonic studies (e.g., Duarte & Schellart, 2016; Engdahl et al., 2006; Hayes et al., 2012; Pesicek et al., 2012; Waldaus er et al., 2012). It was introduced at a time when global compilations of earthquake hypocenters and associated phase arrival times and residuals were often too inhomogeneous to be confidently applied, for example, to problems such as Earth structure determination. The main issue was the varying level of mislocation, particularly focal depth, introduced largely by errors in the reference Earth model, unaccounted for the effects of lateral heterogeneity, and seismic phase misidentification, resulting in the loss of structural signal in the traveltime residuals (time difference between observed and theoretical arrival times of a seismic phase). With the EHB approach the bias in hypocenter determination was significantly reduced and at least part of the lost structural signal recovered by using a modern one-dimensional (1-D) reference Earth model (Kennett et al., 1995); limiting the events of interest only to those that were well constrained by stations at teleseismic distances (> 28°); using direct and later arriving phases in the relocation procedure; and solving for location and depth that included a probabilistic reidentification of the depth phases pP, sP, and pwP at each iteration (Engdahl et al., 1998). In particular, the use of these later phases avoids the depth to origin time tradeoff and in the absence of nearby stations (e.g., within few tens of km from the source) results in the strongest possible constraints on the depth of earthquakes. Traveitimes for the water phase pwP were estimated from its bounce point bathymetry using an averaged NOAA ETOPO1 global relief file (Amante & Eakins, 2009). This was a unique feature that had not been previously implemented in the routine depth determination of suboceanic earthquakes. An inspection of the reported depth phase residuals was used to roughly characterize the reliability of the focal depth estimate for each event. However, a feature that was lacking was any kind of review of the focal depths in subduction zones globally using arc centric detailed cross sections. This important feature was addressed in the approach used to construct the ISC-EHB (Weston et al., 2018), in addition to carrying forward and improving on what was achieved by the original EHB. As one of the main motivations behind the ISC-EHB data set is to provide a broad community in the geosciences with a reliable input for research, here we briefly recall the main features of the ISC-EHB processing, summarize the content of the data set, and, finally, show the new ISC-EHB data set in different tectonic settings to demonstrate its potential for further research.
2. Main Features of the ISC-EHB

An increase in the volume and quality of data reported to the ISC and the development of updated procedures for processing these data were among some of the motivating factors for reconstructing and extending the original EHB to produce the ISC-EHB. These updated procedures have been described in detail in Weston et al. (2018) for the period 2000–2013. A brief description of the more important changes

Figure 1. Subduction zone regions for which sectors have been constructed. Plate boundaries (Bird, 2003) are shown in orange.

Figure 2. ISC-EHB locations color coded by depth (top) and number of events per year (bottom). Topography/bathymetry from ETOPO1 (Amante & Eakins, 2009).
Table 1  
Number of Events in Each Depth Category

| Depth category | Count (percentage) |
|----------------|--------------------|
| L1             | 58,420 (34.25%)    |
| L2             | 49,597 (29.08%)    |
| L3             | 62,533 (36.67%)    |

Note. The total number of events in the ISC-EHB for 1964–2016 is 170,550.

3. Content of the ISC-EHB Data Set, 1964–2016

The ISC-EHB procedure uses arrival times of first arriving \( P \) and \( S \) phases (which include the crustal phase \( P_g/S_g, P_b/S_b, \) and \( P_n/S_n \) and mantle propagation at teleseismic distances for \( P \) and \( S \) waves), branches of PKP (core phases PKPab, PKPbc, and PKPdf), and arrivals of near source surface reflections (depth phases \( pP, pwP, \) and \( sP \)). More detailed descriptions of these phases and corresponding propagation path examples are available in Storchak et al. (2003). The arrival time data of such phases are extracted from the ISC Bulletin (International Seismological Centre, 2019a) for the seismic events that fulfill the selection criteria described in detail in Weston et al. (2018). Currently, the ISC-EHB lists 170,550 seismic events globally distributed (Figure 2) between 1964 and 2016. Table 1 lists the number of events in each depth category (Figures S1–S2 in the supporting information show the event distribution for free and fixed solutions, respectively).
Of great importance for tomographic studies are also the traveltime residuals. For the ISC-EHB events over 35 M seismic phases have been used to constrain the locations. The summary of these phases (P, S, PKP branches, and depth phases) and residuals for phase arrival times (time defining) that were used to locate events is shown in Figure 3 and Table 2. The arrival times come from over 16,000 seismic stations globally distributed, with an evident increase in recent years (Figure 4). To highlight the refined picture of Earth’s seismicity provided by the ISC-EHB, Figures S3–S5 compare the original ISC Bulletin solutions with the ISC-EHB in different areas of the world. For most of the events the change in location and depth is within a few tens of kilometers (Figure S6).

Figure 3. (top) Number of seismic phases used in the ISC-EHB in bins of 10°. Red, blue, brown, and magenta bars represent time-defining (i.e., used to constrain the location) arrival times of P, S, PKP, and depth phases, respectively. Table 2 reports the overall counts for each seismic phase (bottom) Time residual histograms (bin size = 0.5 s) for the seismic phases used in the ISC-EHB. The residual cutoff for phase identification is ±15 s (with the exception of PKP phases where, because of multibranching, the cutoff is set to ±3.5 s).
Figure 4. (bottom) Annual number of time-defining phases (all types) in the ISC-EHB 1964–2016. The increase over the years is nearly constant and more pronounced in recent years. Maps showing the seismic stations (triangles) with time-defining phases for 1964–1999 (top) and 2000–2016 (middle). The stations are color coded by the logarithm of the number of time-defining phases. The choice of year 2000 for splitting the maps in two different time periods is arbitrary, and its only purpose is to emphasize the increase in stations reporting to the ISC in more recent years. The total number of stations for the periods 1964–1999 and 2000–2016 is 7,235 and 12,879, respectively.
4. Examples of Major Seismicity Features Using the ISC-EHB

The ISC-EHB may be used as a reference data set for seismological and multidisciplinary geoscience studies. Here we briefly show some features highlighted by the ISC-EHB in different tectonic settings.

4.1. Flat Subduction

Improved resolution of flat slab subduction is seen in several areas in our data set (Peru, Northern Chile, and Guerrero, Mexico). The Peruvian flat slab has been widely studied regarding the change in dip along-strike and downdip (e.g., Barazangi & Isacks, 1976; Cahill & Isacks, 1992; Gutscher et al., 2000). A selected cross section of seismicity in the Peru sector (Figures 5a and 5b) shows a well-defined flat slab with a gradual downturn in depth at the eastern end. Not shown is a continuation of the flat slab to the northeast where there is a change in strike and a slight change in dip of the subduction zone. The deeper seismicity shown in Figures 5a and 5b appears unconnected to the seismicity defining the flat slab and also has a different orientation.

4.2. Stagnant Slabs

Between the Vanuatu and Fiji-Tonga subduction zones an active region of deep seismicity (450–650 km) is well documented, sometimes referred to as the Vityaz earthquakes (e.g., Chen & Brudzinski, 2001; Giardini, 1992; Okal & Kirby, 1998; Sykes, 1966). It has been suggested that this seismicity could be due to a mobile stagnant slab (Okal, 2001; Wu et al., 2017) that may have moved into the upper mantle millions of years ago. A cross section for this region (Figures 6a and 6b) reveals a clear isolated flat structure at depth about 100-km thick that supports the hypothesis of a flat stagnant slab. It is a unique feature found here and perhaps other places globally (e.g., east Asia) that calls for a reassessment of the conventional idea of subducting plates being assimilated into the deeper mantle as they descend. Note that the deep slab seismicity shown in Figures 6a and 6b appears to be unconnected to seismicity in the steeply dipping Vanuatu slab and has also a different orientation.
4.3. Slab Segmentation

The structure of the Tonga subduction zone is the focus of much research in part due to its rapid rate of subduction (~200 mm/year, e.g., Bevis et al., 1995). Numerous earthquake hypocenter and regional tomographic studies in this region have reported that the cold slab sinks steeply and at depth there is a remnant slab (e.g., Brudzinski & Chen, 2003; Chen & Brudzinski, 2001; Hanuš & Vaněk, 1979). A map of ISC-EHB events in the region (Figure 7a) reveals two separate linear earthquake groups over 4–5° along strike at depths greater than 300 km. In cross section (Figure 7b) these two groups appear as separate steeply dipping clusters at depths greater than about 500 km, suggesting a potential slab break off.

4.4. Complex Subduction

Figure 8b reveals two opposite dipping seismic zones in the Sulawesi region of Indonesia. More narrowly defined cross sections across the region suggests that there are two slabs passing by one another with the slab to the west dipping to the south and the slab to the east dipping to the north. Some separation in location at about 123° can also be seen in the earthquake clusters related to these slabs (Figure 8a). A tectonic map published by Bellier et al. (2006) suggests a boundary there between the North Sulawesi subduction zone on the west side and a western limb of the more active Molucca plate subduction zone on the east side. The distribution of deeper earthquakes in this cross section is distorted in this projection but is probably related to the Molucca slab. Refer to the ISC-EHB webpages for other examples of where the details of complex subduction can be better resolved by using maps and cross sections of ISC-EHB hypocenters.

4.5. Anomalous Events

The M7.9 deep earthquake of 30 May 2015 at a depth of about 680 km was surprising in that it occurred more than 120-km deeper than any well-recorded event in the Bonin Islands subduction system.
locations from the ISC-EHB data set for the Izu-Bonin region are plotted according to focal depth interval in Figure 9a. The cross section of seismicity in the sector A-A’ is shown in Figure 7b. (b) Cross section of the seismicity in sector A-A’ of Figure 7a. Plot parameters and symbol definitions are the same as in Figure 5b. Thickness of dipping slab is a result of along strike changes in the location of the seismotectonic zone in the slab that are not reflected in more narrowly defined cross sections across the sector.

Some published papers have claimed that the 2015 deep Bonin earthquake occurred in a steeply dipping sector of the Bonin slab based largely on seismic tomography (e.g., Zhao et al., 2017), but none of these studies have demonstrated sufficient resolution to provide convincing evidence of high-wave speed slab material clearly linking the 2015 hypocenter with the main Bonin WBZ. Kirby et al. (2019) interpret the 2015 event as occurring in a slab fragment separated from the main Bonin WBZ. They suggest a possible fragmentation scenario involving an oceanic plateau collision, a consequent slab detachment, and an eastward trench retreat. This event also presents an opportunity to show how ISC-EHB hypocenters can be used in combination with Global Centroid Moment Tensor (GCMT) data (Dziewonski et al., 1981; Ekström et al., 2012) to display related source mechanisms. The cross section shown in Figure 10 contains all events with GCMT solutions that are included in Figure 9b, except they are plotted at ISC-EHB hypocenters. These mechanisms are primarily of the normal faulting type indicating downdip tension in the deeper part of the subducting plate. Figure 11 is a plot of the ray coverage by reported P and S waves for the 2015 event. The residuals for these rays and from other events in the region from 1964 to 2016 demonstrate the potential of the ISC-EHB data set as a primary source of data for regional seismic tomography in the region.

4.6. Other Tectonic Settings

In addition to subduction zones the ISC-EHB data set can be a valuable resource for studies of mid-ocean ridge and continental earthquakes. Shallow earthquakes at mid-ocean ridges and nearby transform faults reflect the creation of lithosphere as the plates move apart creating a rift valley. Maps of ISC-EHB
seismicity (Figures 2 and S7 for global and Arctic seismicity maps, respectively) show that the locations of these events are consistent with known plate boundaries (Bird, 2003). The depth of these events is normally set at a default depth of 10 km unless there is a sufficient number of depth phases, in particular pwP, that suggest otherwise. Those ISC-EHB mid-ocean ridge events for which we have sufficient depth constraints are all found to be less than 35 km in depth. ISC-EHB seismicity in continental regions reveals improved details of areas where there are linear trends, possibly related to preexisting faults, or clustering of events. Most continental earthquakes are shallow depth, but there are exceptions of deeper events in areas of thickened lithosphere or previous subduction.

4.7. Aftershock Zones

Finally, the ISC-EHB data set provides improved details of aftershock zones of large events globally. For example, ISC-EHB hypocenters during the first year of the 2011 Tohoku aftershock sequence confirm previously reported observations (Lay et al., 2011; Lay & Kanamori, 2011; Ye et al., 2011). The aftershock zone extends ~300 km from near the trench to near the Honshu coastline with a mixture of seismic and aseismic patches (Figure 12a). A cross section of the entire aftershock zone indicates a westward downturn in aftershock depth (Figure 12b). A cross section near the mainshock, where an $M_w$ 7.1 aftershock is located...
**Figure 9.** (a) ISC-EHB earthquakes in the Bonin Islands (1964–2016). Symbol definitions and plate boundaries are plotted as in Figure 5a. Star is the location of the 2015 event. A cross section of seismicity in the sector A–A’ is shown in Figure 9b. (b) Cross section of ISC-EHB events within the box shown in Figure 9a. Plot parameters and symbol definitions are the same as in Figure 5b. The star symbol is the 2015 event (L1 depth category).

**Figure 10.** Cross section of GCMT source mechanisms (Dziewonski et al., 1981; Ekström et al., 2012) within the sector shown in Figure 9a plotted at ISC-EHB hypocenters.
5. Conclusions

A robust data set (ISC-EHB) for tectonic, structural, and tomographic studies globally has been developed for the period 1964–2016. It provides improved resolution of clusters of seismicity, sharper definition of the seismotectonic zone in subducting slabs and slab geometry, and an improved view of global seismicity relative to other routinely produced catalogs. Examples have been shown that can lead to a better understanding of Earth processes related to flat subduction, the fate of subducting slabs, slab segmentation, complex subduction, and the occurrence of anomalous events. These examples also make it possible to better understand the interactions between slab structures and Earth processes. In particular, detailed cross sections of subduction zone sectors globally can provide new information about the role seismogenic width plays in the maximum size of earthquakes in subduction zones. The website http://www.isc.ac.uk/isc-ehb/ provides user-friendly means to access and download all ISC-EHB-related products, including maps and cross sections of subduction zones globally. Among the most important of these products are improved phase residual data for crust, mantle, and core phases (Figure 3) that have been carefully culled and expanded beyond the original EHB data set. The potential for higher-resolution tomographic inversions, both regional and global, makes this residual database a primary source of data for these types of studies. In addition, we expect the ISC-EHB to become a benchmark data set for different purposes, from the description of the seismicity of a region to education and outreach. In future ISC-EHB procedures will be applied to events beyond 2016 after the
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**Figure 12.** (a) ISC-EHB aftershock locations during the first year following the 2011 Tohoku mainshock. Symbol definitions and plate boundaries are plotted as in Figure 5a. A cross section of seismicity for the entire sector A-A′ is shown in Figure 12b, and a cross section immediate to the mainshock along the line near the center of the sector is shown in Figure 12c. The large orange star is the location of the mainshock, and the smaller orange stars are the locations of Mw 7 or greater aftershocks. (b) Cross section of the aftershock zone shown in sector A-A′ of Figure 12a. Plot parameters and symbol definitions are the same as in Figure 5b. The thickness of the dipping Honshu slab is a result of along strike changes in the location of the seismo-tectonic zone in the slab that, along with trench and volcano offsets, are not reflected in more narrowly defined cross sections across the sector. The large orange star is the location of the mainshock, and the smaller orange stars are the locations of Mw 7 or greater aftershocks. (c) Similar to Figure 12b except only aftershocks in the immediate vicinity of the mainshock are plotted in cross section.

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