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The PKP Caustic at the Trinity College Seismograph Station (TCCT) from the Sumbawa-Indonesia Earthquake on November 8th, 2009

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TRINITY COLLEGE

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BY

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TABLE OF CONTENTS

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ABSTRACT

On November 8th, 2009 the Trinity College Seismograph Station (TCCT) recorded an earthquake of magnitude Mw = 6.7 with body wave amplitudes that were larger than expected. This earthquake, located in Sumbawa-Indonesia, generated similar body wave amplitudes as earthquakes of the same magnitude (Mw = 6.7) and comparable depth (shallow focus: $0<h<70$km) that occurred closer to TCCT, such as the Vancouver earthquake on September 9th, 2010 and the Alaska earthquake on July 18th, 2010. The large body wave amplitudes were caused by a set of consecutive PKP waves that constructively interfered. The distance from the Sumbawa-Indonesia earthquake to TCCT of 144.96° falls between the lower and higher estimates for the PKP caustic point. The observations at TCCT helped establish a theoretical region, in which future seismic events could create a caustic at or in the proximity of TCCT. It is suggested to use the IRIS network to better estimate the distance to the caustic point for future events occurring in the theoretical region.

INTRODUCTION

On November 8th, 2009 the Trinity College Seismograph Station (TCCT) recorded an earthquake of magnitude Mw = 6.7 with body wave amplitudes that were larger than expected. The large amplitudes were generated by PKP body waves, which are waves that enter the mantle as a P-wave, pass through the Earth's core and then reemerge as a P-wave to continue to travel through the mantle (Macelwane, 1932; Bastings, 1934; Storchak *et. al*, 2012).

Earthquakes produce different types of seismic waves that can be classified under two main categories, body waves and surface waves. Surface waves cause the strongest ground shaking after an earthquake and cause the most damage on infrastructure. Body waves travel through the Earth's interior and therefore the study of body wave propagation is fundamental to the understanding of the planet's internal structure. Most of the knowledge about the internal structure and physical properties of the Earth, from the core to the crust, is derived from the study of seismic waves generated both naturally and artificially. The study of these seismic waves has enabled scientists to map the interior of the Earth. However the internal structure of the Earth (e.g. thickness of layers) varies depending on location (Robertson, 1966; Yockstick, 1987).

As seismic body waves propagate through the Earth, they interact with its various layers. Some waves may be reflected or diffracted at discontinuities, while others may travel from source to receiver without any major reflection or diffraction caused by the inner or outer core (Fig.1) (Lillie, 1999). Along each unique travel path, seismic waves may change

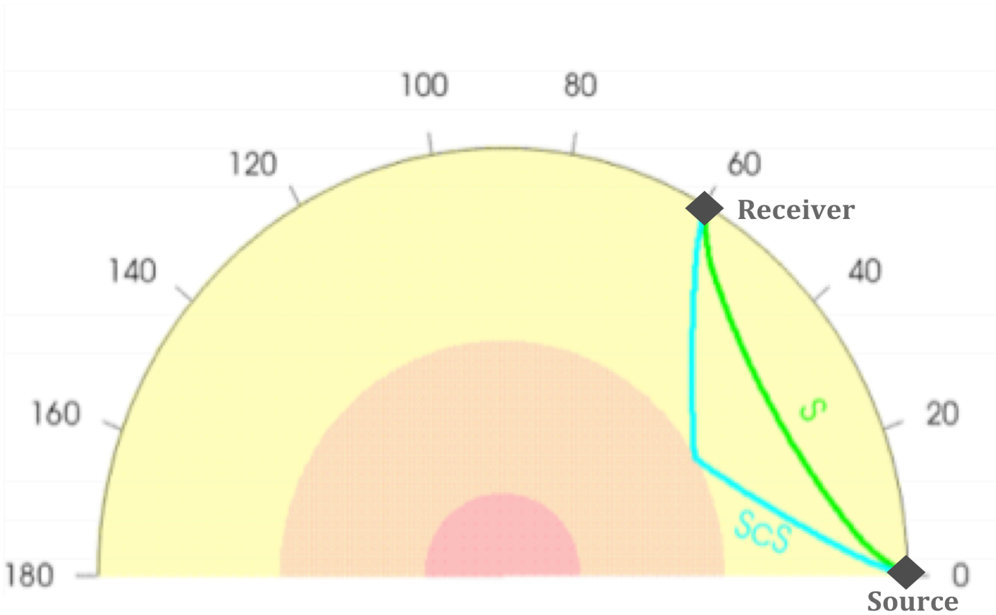


Figure 1. Cross section of the Earth showing two different travel paths of seismic waves between source and receiver. The green line (S), shows the path of a direct wave that was not reflected or diffracted during its propagation from source to receiver. The blue line (ScS) shows the travel path of a seismic wave that was reflected by the core mantle boundary (CBM). The direct wave covers a shorter distance and will therefore arrive at the receiver in less time and with more energy than the reflected wave (Adapted from Boremann *et. al,* 2009b).

their phase and/or speed after interacting with the different structures of the Earth's interior. As a result, the body waves generated after an earthquake arrive at the receiver at different times and have different phases and intensities (Shearer, 1999).

A specific type of body wave, called PKP can provide information on a discontinuity at the base of the mantle as well as on the depth of the core mantle boundary (CMB) (Houard *et. al,* 1993). This type of body wave was recorded at the Trinity College Seismograph Station (TCCT) in Harford, Connecticut on November 8th, 2009 from an earthquake in Sumbawa, Indonesia. The analysis of the data collected at TCCT is compared with previous studies that examine the implications of this type of body wave.

Seismic Wave Attenuation and Amplitude

As seismic waves propagate through the Earth they undergo attenuation, which is a gradual loss in energy. The seismic wave energy is reduced due to inelastic material behavior or internal friction during wave propagation. In addition, energy is lost through the scattering of energy at heterogeneities along the travel path (Ben-Menahem and Singh, 1981; Boremann and Müller, 2012). For this reason, seismic waves lose energy as they travel longer distances within the Earth's interior.

The energy of a seismic wave is recorded in a seismogram and can be derived from the amplitude of the waveform. The amplitude is the maximum value of the vertical displacement of the seismogram within a specified time frame (Fig. 2). Therefore, seismic waves with higher energy cause larger amplitudes than seismic waves with low energy. According to this principle, a low magnitude earthquake close to a seismograph station could generate the same amplitude as a distant earthquake of higher magnitude. Similarly, a nearby

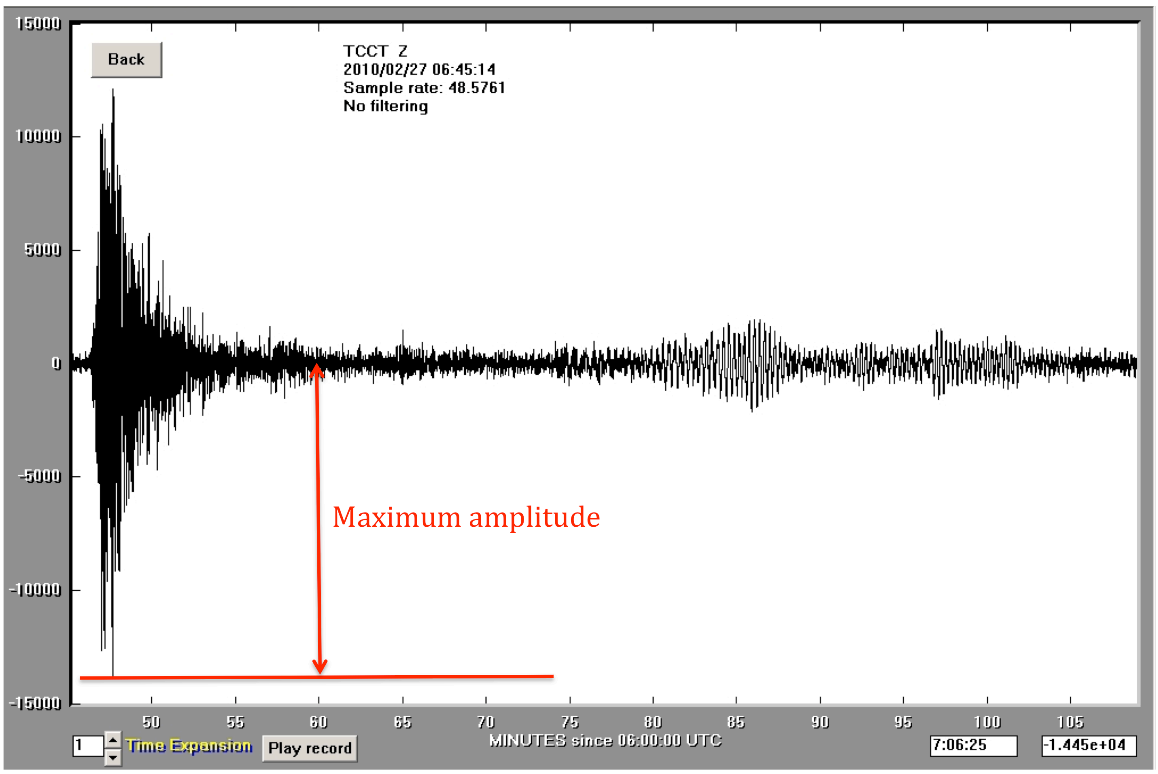


Figure 2. Seismogram of the 2010 Chile earthquake as recorded in the Trinity College Seismograph Station (TCCT). The red arrow indicates the maximum vertical displacement during the Chile earthquake, which corresponds to the first body wave arrival.

earthquake generates larger wave amplitudes than a distant earthquake of the same magnitude.

SHADOW ZONE

The P-waves (or compressional waves) compress and expand the medium where they travel, which allows P-waves to travel through solid, gas and liquid. The S-waves (or transversal waves) shake the ground transverse to the direction the wave is traveling and therefore cannot travel through liquid or gas. When waves travel beyond 104° away from the source, they must interact with the liquid core, where S-waves are stopped and the density change slows down and refracts the P-waves. The refracted P-waves then reemerge at distances beyond 140° away from the source after interacting with the inner and/or outer core. This creates a shadow zone that occurs between 104° and 140° away from the source, where no direct seismic waves are received (Fig. 3) (Lehmann, 1953; Bullen, 1956; Boremann and Müller 2012). The extent of the shadow zone has been found to vary depending on location (Lehmann, 1958). The lowest estimate however is 140° (Boremann *et. al,* 2009a).

THE PKP CAUSTIC

Global spherical Earth models such as PREM, IASP1 or 1066B provide essential tools for travel-time calculations, as well as for waveform and amplitude analysis, but they are sometimes inaccurate, especially near discontinuities (Houard *et. al*, 1993). Several studies support the existence of a discontinuity in the D'' layer between the mantle and the outer core (Fig. 4) (Bullen, 1942; Lay and Helmberger, 1983; Baumgardt, 1989; Young and Lay, 1990; Houard and Nataf, 1992). The existence of this discontinuity, as well as the depth

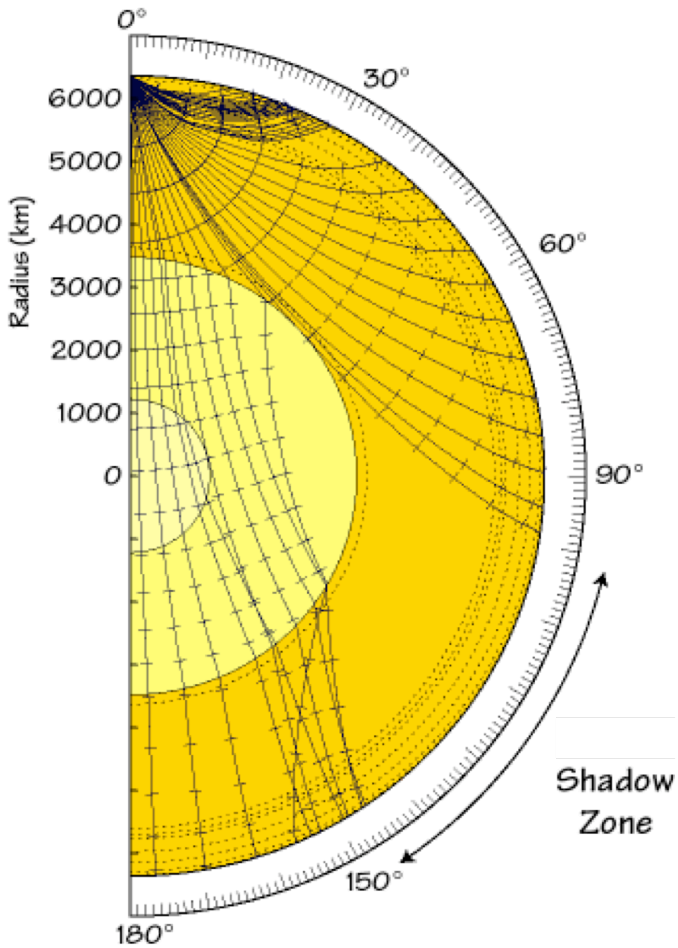


Figure 3. Cross-section of the Earth showing the shadow zone phenomenon. As the distance from the source approaches 100°, the P-waves are diffracted by the CMB up to 104°. After 104° however, the P-waves are refracted by the core and do not resurface until the distance approaches 140° ("Earthquake Glossary – Shadow Zone").

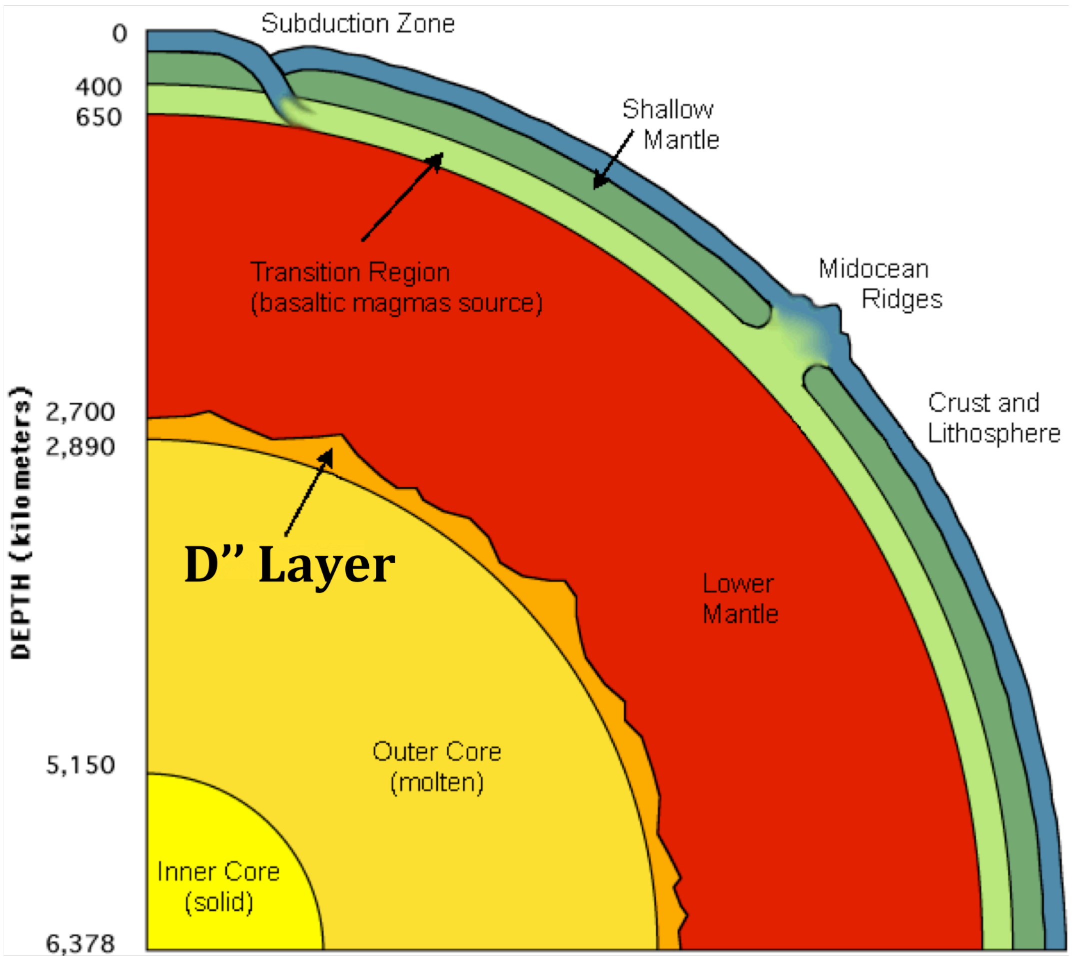


Figure 4. Cross-section of the earth showing the D'' layer at the base of the core mantle boundary. The D'' layer is represented in orange and it is located between the mantle (red) and the outer core (light yellow) (Adapted from Beatty, 1990).

of the core-mantle boundary affects the distance at which large body wave amplitudes are recorded (Houard *et. al*, 1993).

At a distance beyond 140°, which marks the shadow zone boundary, there is a point where large wave amplitudes can be recorded (Červený and Janský, 1994). At approximately 145° away from the source, the PKP waves interfere constructively to form a caustic. The caustic is the point at which a large concentration of simultaneously arriving seismic energy is observed (Boremann and Müller, 2012). At the caustic, three branches of a seismic wave of the form PKP arrive at the receiver at the same time (Fig. 5). These three branches constructively interfere or "stack" to create wave amplitudes similar to earthquakes of the same magnitude occurring at shorter distances from the seismograph station (Massot and Rocard, 1982; Houard *et. al,* 1993; Boremann *et. al,* 2009b). The three branches are named PKPab, PKPbc and PKPdf. The lower case letters specify in which part of the Earth the PKP wave is bottoming (i.e., having its turning point). The PKPab is a wave bottoming in the upper outer core, the PKPbc is a wave bottoming in lower outer core and the PKPdf is a wave bottoming in the inner core (Storchak *et. al,* 2012).

The distance from source to receiver where the caustic point is found, was estimated by Gilbert and Dziewonski (1975) and Dziewonski and Anderson (1981) to be 144.9° and Kenneth and Engdahl (1991) calculated the distance to be 144.2°. Their measurements were tested by several authors such as Massot and Rocard (1982), who estimated the distance at 145.6° and Houard *et. al,* (1993) who calculated the distance to be 144.5°. Previous studies such as the ones by Massot and Rocard (1982) and Houard *et. al,* (1993) recorded PKP waves in France from nuclear explosions in Mururoa in the south Pacific. Young and Lay (1990) detected PKP waves in Alaska from earthquakes in the western Pacific. The critical

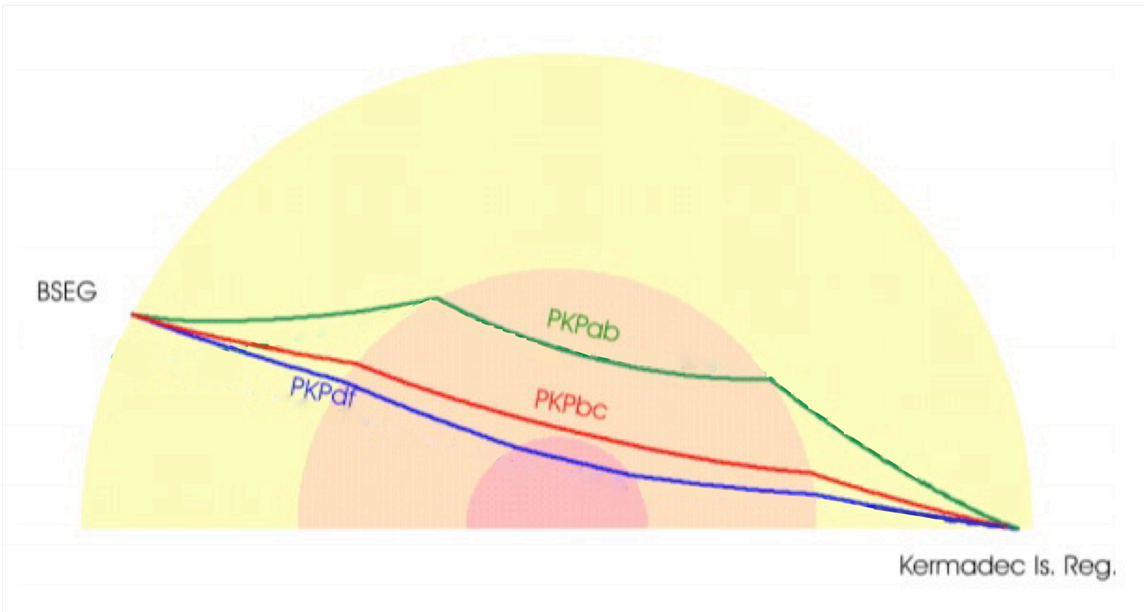


Figure 5. Cross-section of the Earth showing the travel paths of the three branches of a PKP wave. The caption on the right denotes the name of the location where the earthquake occurred. The captions on the left refer to the names of the seismograph stations that recorded the waves. The focusing event is clearly seen in the station named BSEG, where the three branches represented by the solid lines meet at the same spot (Adapted from Boremann *et. al,* 2009b).

distance at which the caustic point for PKP waves is found seems to vary depending on the location of the earthquake as well as the location of the seismograph station (from 144.2° to 145.6° away from seismic source)

Studies such as the one carried out by Massot and Rocard (1982) used nuclear blasts in Mururoa to record seismic waves in the Labratoire De Detection Et Geophysique (LDG) network in France. The LDG network contains numerous seismic stations with the same type of seismograph that can record seismic signals at different distances from an epicenter. For the LDG network, it was possible to plot epicentral distance circles centered in Mururoa every 1° (Fig. 6). With this tool, Massot and Rocard (1982) were able to estimate the caustic point at 145.6° after plotting the seismic wave amplitude vs. distance for PKP waves near the caustic point (Fig. 7). Using the same technique, Houard *et. al,* (1993) used more recent blasts in Mururoa and estimated the distance of the PKP caustic point at 144.5°.

PKP WAVES RECORDED AT TCCT

TCCT is equipped with an EQ-1 seismograph, which detects only the vertical ground motion. It has recorded several earthquakes with the same magnitude and similar depths that occurred at different distances from the seismograph station. These earthquakes have occurred both beyond the shadow zone boundary at 140° and at distances less than 104°, which marks the theoretical boundary of the shadow zone (Fig. 8). On November 8th 2009 TCCT recorded an earthquake of magnitude Mw = 6.7 with body wave amplitudes that were larger than expected. The earthquake in the Sumbawa Region in Indonesia was positioned at nearly 145° away from TCCT in Hartford, Connecticut. The earthquake in Sumbawa had similar body wave amplitudes as earthquakes occurring at distances less than 104°.

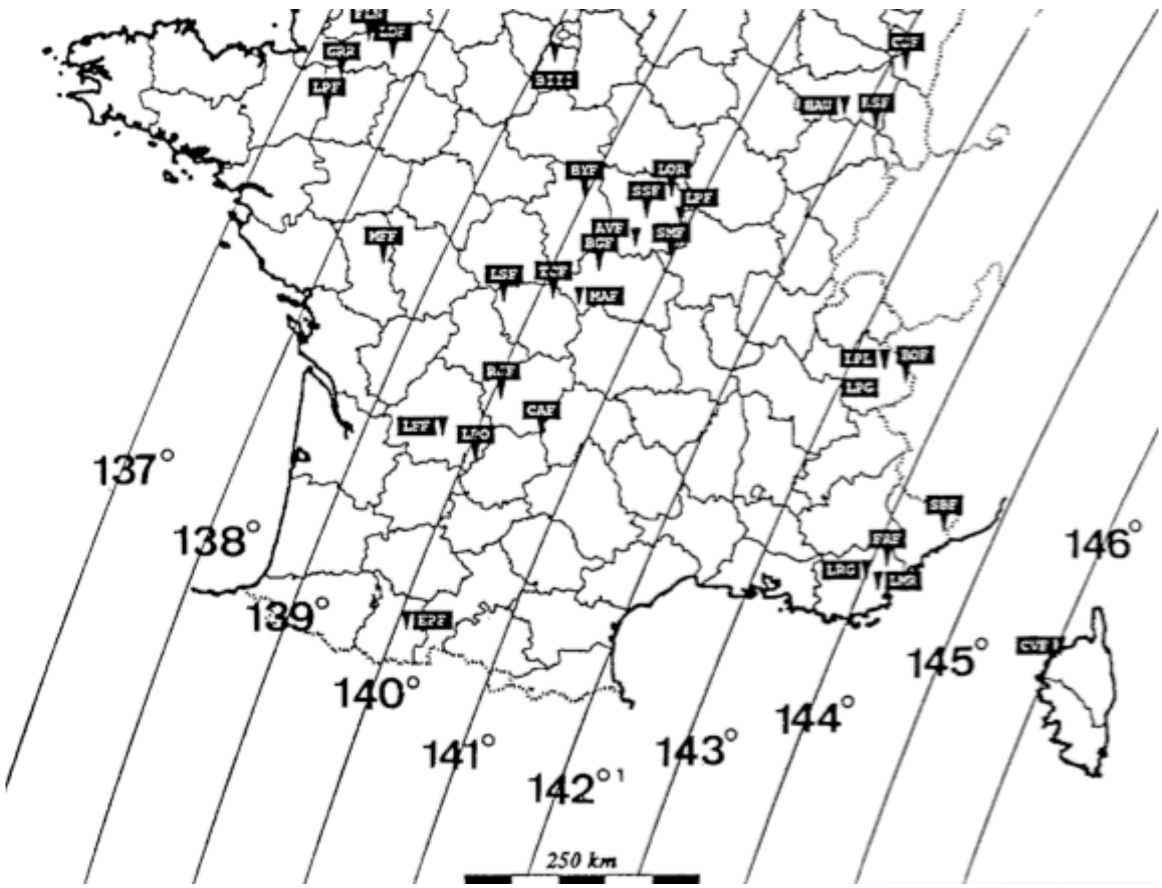


Figure 6. Map of the Labratoire De Detection Et Geophysique (LDG) network in France. Epicentral distance circles centered in Mururoa were plotted every 1° in order to identify where the largest amplitude occurs (From Houard *et. al,* 1993).

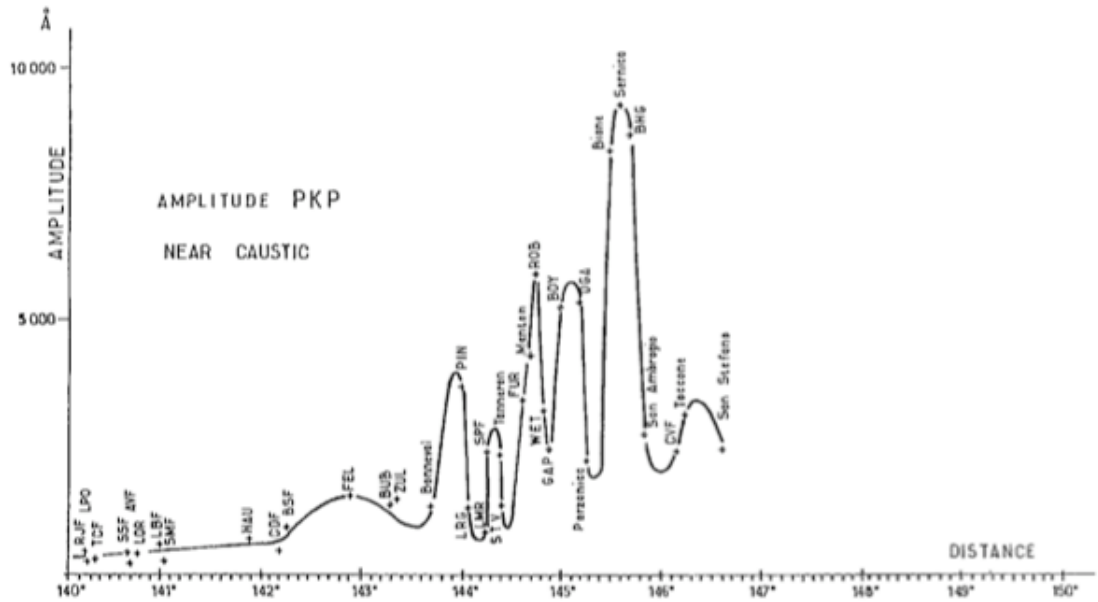


Figure 7. Plot of the PKP amplitude vs. distance from nuclear blasts in Munruroa. The largest wave amplitude was found at 145.6° (From Massot and Rocard 1982).

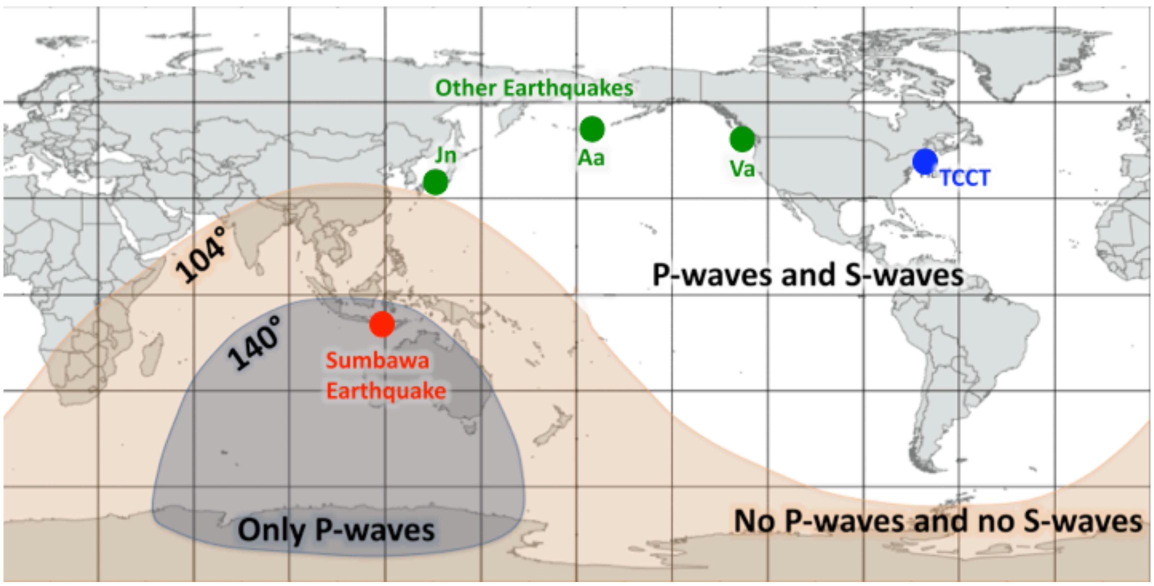


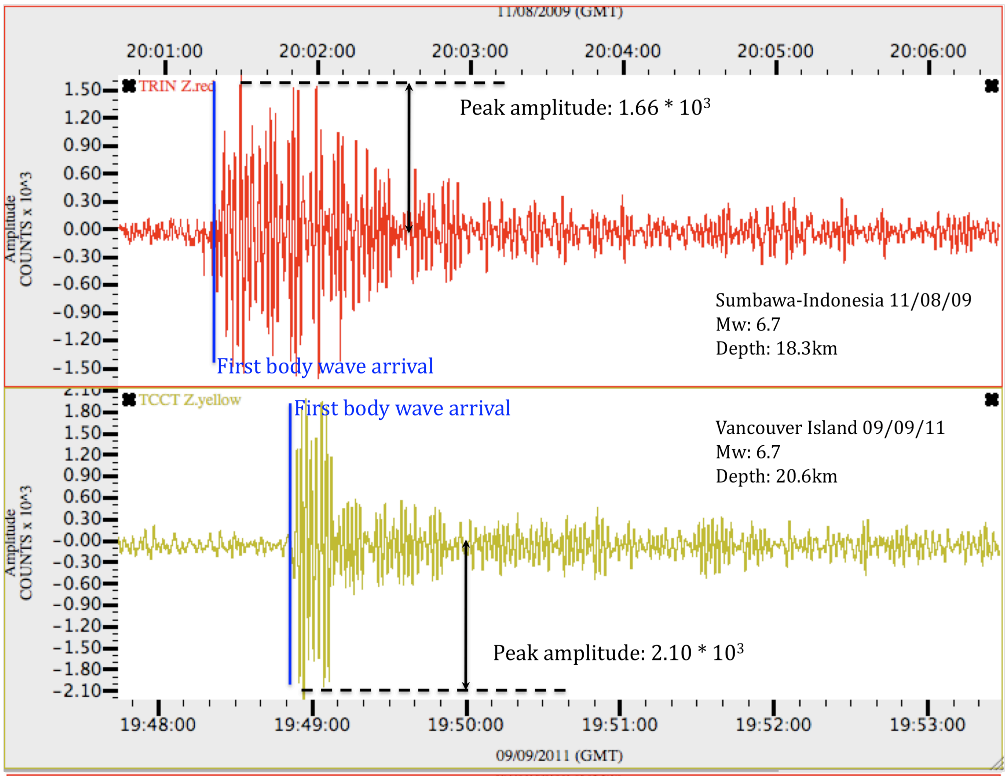
Figure 8. Map showing the location of TCCT relative to the earthquakes included in this study. The theoretical shadow zone for TCCT was included in the map in the light orange polygon. The red marker indicates the location of the Sumbawa earthquake, which had body wave amplitudes comparable to earthquakes (green markers) of similar magnitude and depth that occurred closer to TCCT. The body wave amplitude of the Sumbawa earthquake exceeded the body wave amplitude of two of the three earthquakes shown in green. The green captions indicate the specific location of the Japan (Jn), Alaska (Aa) and Vancouver (Va) earthquakes, which were used to compare the body wave amplitudes.

The distance between the Sumbawa earthquake (8°18'59.04"S/118°41'47.76"E) and TCCT (41°44'45.38"N/ 72°41'27.77"W) was calculated using the measurement tool in Google Earth to be 144.96°. This earthquake generated similar body wave amplitudes as earthquakes of the same magnitude (Mw = 6.7) and comparable depth (shallow focus: 0<h<70km) that occurred closer to TCCT, such as the Vancouver earthquake on September 9th, 2010 and the Alaska earthquake on July 18th, 2010. In addition, the Sumbawa earthquake generated larger wave amplitudes than the Japan earthquake of higher magnitude (Mw = 7.2) on March 9th, 2011 (Fig. 9). The location of the earthquakes relative to TCCT is shown in Figure 8. An essential difference between the earthquakes mentioned above is the seismic phase in which the body waves arrived at TCCT. The Alaska, Japan and Vancouver earthquakes occurred at an angle less than 104°, while the Sumbawa earthquake occurred beyond the shadow zone limit at 140°. For this reason, the first waves recorded from Alaska, Japan and Vancouver are direct P-waves that did not travel through the Earth's core. On the other hand, the first body waves recorded from Sumbawa are diffracted and refracted P-waves that traveled through the Earth's core, changing their phase and arriving to TCCT as PKP waves. The phase identification and arrival times for the earthquakes recorded at TCCT are shown in Figures 10 and 11.

LARGE WAVE AMPLITUDE FROM SUMBAWA CAUSED BY PKP CAUSTIC

As it is shown in the seismogram analysis (Fig. 11), the first body wave arrival from Sumbawa is a set of consecutive PKP waves arriving 19 minutes and 27 seconds after the earthquake. The location of the Sumbawa earthquake at 144.96° falls between the lowest

Figure 9. Seismogram of the Sumbawa earthquake compared to the Vancouver, Alaska and Japan earthquakes. The blue line indicates the first body wave arrival and the dashed black lines indicate the peak amplitude of the body wave. The earthquake in Vancouver occurred 37.95° from Hartford and had a peak amplitude of $2.10 * 10^3$ counts, while the Sumbawa earthquake occurred 144.96° from Hartford and its peak amplitude was $1.66 * 10^3$ counts. This represents a difference of only $0.44 * 10^3$ counts. The body wave amplitude of the Sumbawa earthquake is larger than the Alaska earthquake which occurred 61.53° from Hartford. In addition, the Sumbawa earthquake had larger amplitude than the Japan earthquake of greater magnitude and lesser distance.



Sumbawa

Mw = 6.7

Distance: 144.96°

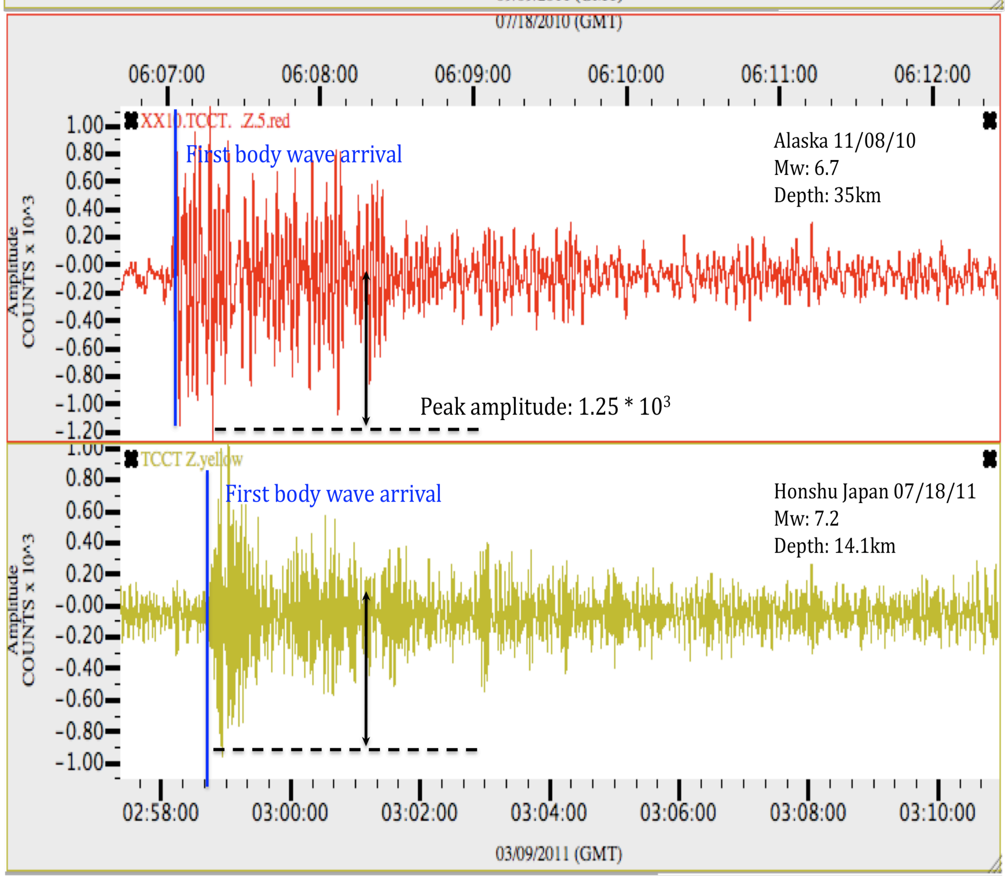
Peak amplitude: $1.66*10^3$

Vancouver

Mw = 6.7

Distance: 37.95°

Peak amplitude: $2.10*10^3$



Alaska

Mw = 6.7

Distance: 61.53°

Peak amplitude: $1.25*10^3$

Japan

Mw = 7.2

Distance: 93.96°

Peak amplitude: $1.09*10^3$

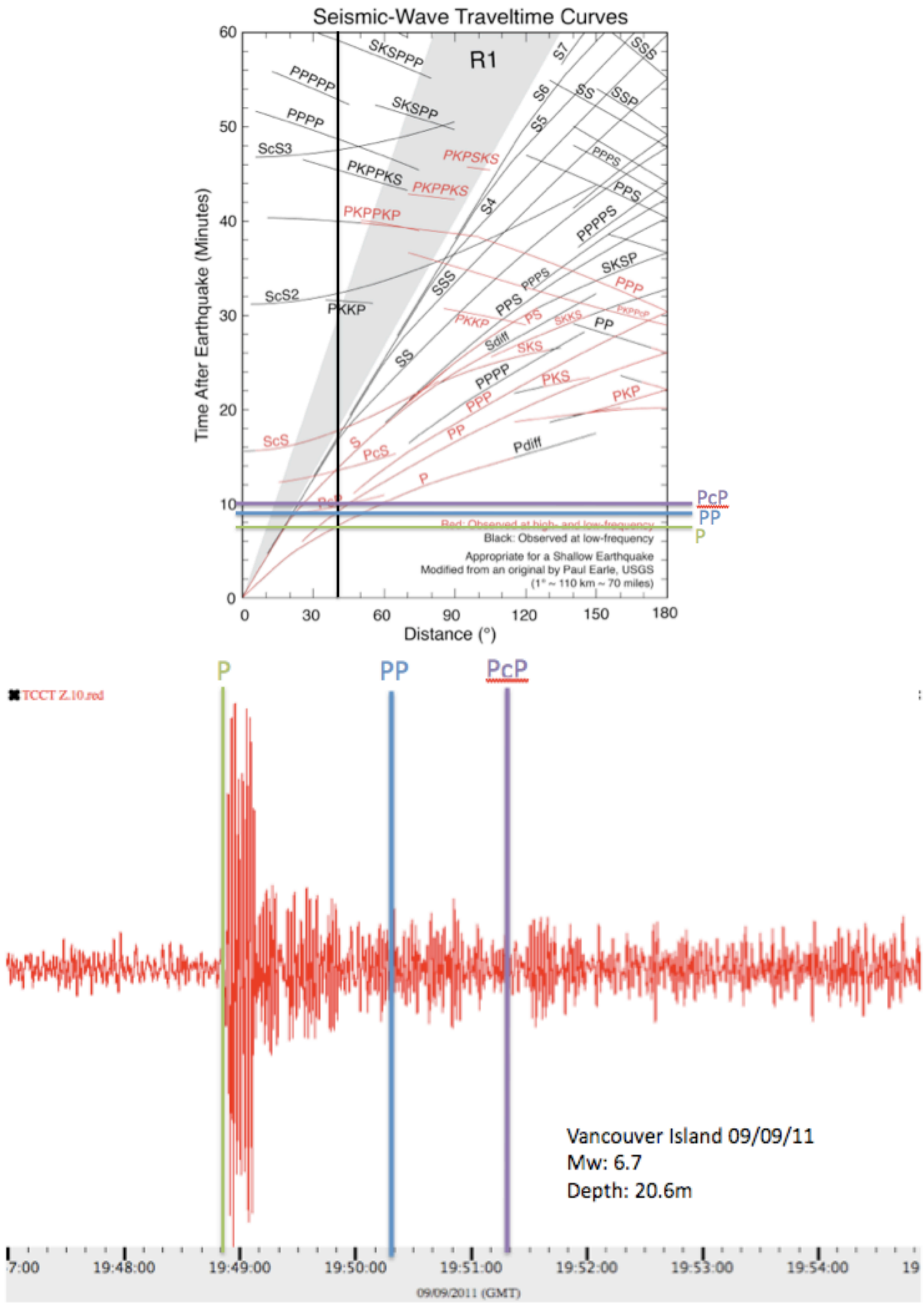


Figure 10. The seismic-wave travel time curves are shown above. The black vertical line indicates the distance from the Vancouver earthquake epicenter to TCCT. The green, blue and purple horizontal lines indicate the first possible body waves and their respective arrival times. In this case, the first body wave arrival occurs 7m and 2s after the earthquake and it is a direct P wave (below).

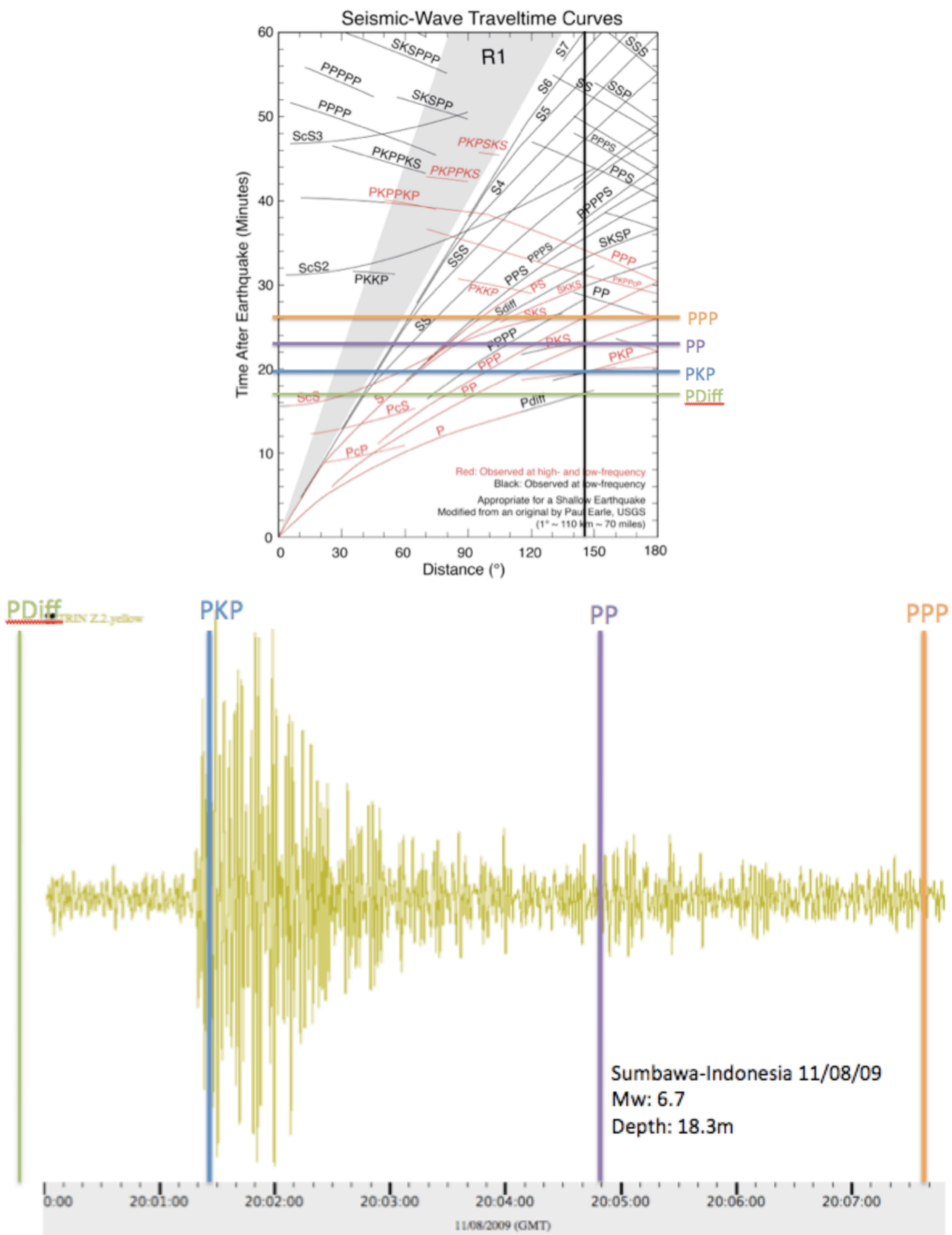


Figure 11. The seismic-wave travel time curves are shown above. The black vertical line indicates the distance from the Sumbawa earthquake epicenter to TCCT. The green, blue, purple and orange horizontal lines indicate the first possible body waves and their respective arrival times. In this case, the first body wave arrival occurs 19m and 27s after the earthquake and it is a PKP wave (below).

estimate of 144.2° (Kenneth and Engdahl, 1991) and the highest estimate of 145.6° (Massot and Rocard, 1982).

The observation of large amplitudes at TCCT from the Sumbawa earthquake at 144.96° suggests that the seismograph is at or nearby the caustic point. The set of waves observed at TCCT contains the energy of the three different branches, which are arriving at the same time. As a result, constructive interference generated large amplitudes comparable to amplitudes of earthquakes of same magnitude and similar depth occurring closer to TCCT (Fig. 12).

DISCUSSION

Using the Trinity College Seismograph Station, it was possible to record PKP waves from an earthquake located at a teleseismic distance. The favorable position of the Sumbawa earthquake and TCCT allowed the examination of the Sumbawa-Hartford caustic point. The data from a single earthquake does not provide sufficient evidence to calculate a more accurate distance. However, the large amplitude recorded does suggest that TCCT is located at or in the proximity of the caustic point for the Sumbawa-TCCT azimuth.

Because TCCT belongs to a network of seismograph stations (Incorporated Research Institutions for Seismology network or IRIS), such as the LDG network, it could be possible to estimate with greater accuracy, the distance at which the caustic point occurs. When the earthquake in Sumbawa-Indonesia occurred, only three other stations in the IRIS network recorded the earthquake. Two of the stations are located at distances less than 142°, which is less than the lowest estimate of 144.2° (Kenneth and Engdahl, 1991). The third station, located at 145.4° used an AS-1 seismograph instead of an EQ-1 seismograph, like the one at

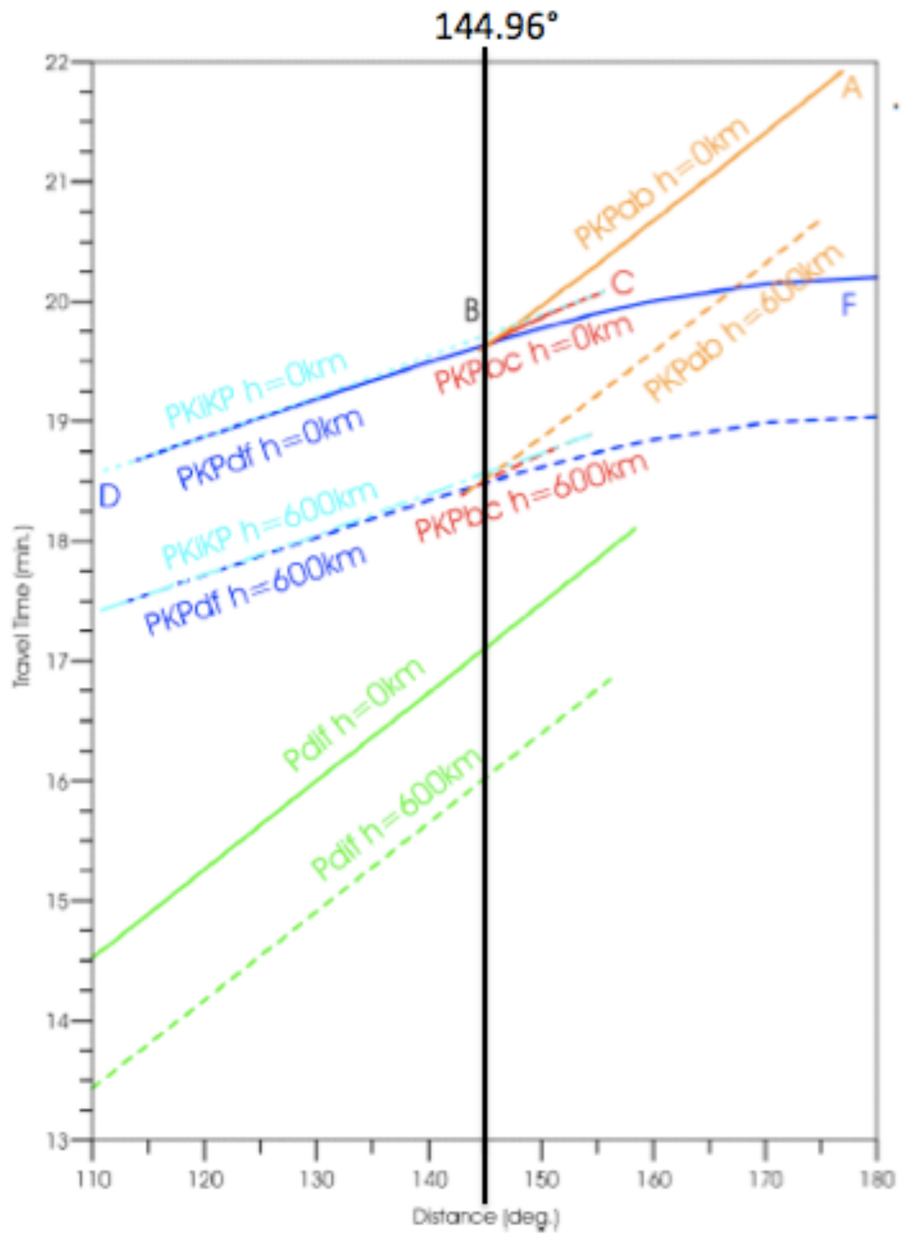


Figure 12. Travel time curves for PKPab, PKPbc, PKPdf, Pdif and PKiKP for surface focus and deep focus events. The vertical black line indicates the distance of the Sumbawa earthquake from TCCT. The caustic point at which the three travel time curves intersect is labeled as B. This intersection occurs between 19 and 20 minutes for a shallow focus earthquake at around 145°. At this distance, three branches namely PKPab (orange), PKPbc (red) and PKPdf (blue) arrive at the same time (From Boremann *et. al,* 2009b modified from Gilbert and Dziewonski, 1975).

TCCT. With only one additional seismograph of a different model, it was not possible to create an amplitude vs. distance plot.

The observations at TCCT helped establish a theoretical region, in which future seismic events could create a caustic at or in the proximity of TCCT. This region is beyond the shadow zone boundary at 140° and covers the north coast of the Java Island in Indonesia as well as parts of North and West Australia (Fig. 13). Future earthquakes occurring in this area could generate body wave amplitudes larger than expected.

CONCLUSION

-The large amplitudes from the Sumbawa-Indonesia earthquake on November 8th, 2009 were caused by a set of consecutive PKP waves.

-The distance from Sumbawa to TCCT of 144.96° falls between the lower and higher estimates for the caustic point.

-The large amplitudes recorded from Sumbawa suggest that TCCT is at or in the proximity of the caustic point.

-With a larger set of data, it would be possible to better estimate the distance between the theoretical region (Fig. 13) and the caustic point in the proximity of TCCT.

Figure 13. Theoretical region, in which earthquakes could produce amplitudes larger than expected at TCCT. The region is designated by the two green lines between 144.2° and 145.6. The red line is located at 144.9° away from TCCT. The location of the Sumbawa earthquake on November 8th, 2009 is labeled with an S.

Literature Cited

Bastings, L., 1934. Shear waves through the Earth's core. *Nature*, 134, 216-217.

Baumgardt, D. R., 1989. Evidence for a *P* wave velocity anomaly in D'', *Geophys. Res. Lett.,* 16, 657-661.

Beatty, J. Kelly. 1999, The New Solar System.*Cambridge UP*.

Ben-Menahem, Ari, and Sarva Jit Singh., 1981. Seismic Waves and Sources. *New York: Springer-Verlag.*

Bormann, P., Engdahl, B., & Kind, R., 2009a. Seismic Wave Propagation and Earth models. In P. Bormann (Ed.. *New Manual of Seismological Observatory Practice (NMSOP).* Potsdam: Deutsches GeoForschungsZentrum GF, 1-70.

Bormann, P., Klinge, K., & Wendt, S., 2009b. Data Analysis and Seismogram Interpretation. In P. Bormann (Ed.. *New Manual of Seismological Observatory Practice (NMSOP).* Potsdam: Deutsches GeoForschungsZentrum GFZ, 1-102.

Bormann, P., & Müller, H., 2012. Glossary. In P. Bormann (Ed.. *New Manual of Seismological Observatory Practice 2 (NMSOP 2).* Potsdam: Deutsches GeoForschungsZentrum GFZ, 1-196.

Bullen, K. E., 1942. The Density Variation of the Earth's Central Core. *Bull. Seism. Soc. Of Amer.,* Vol. 32, pp. 19-29.

Bullen, K. E., 1956. Seismology and the earth's deep interior, *Aust. J. Sci.* 19, 99- 100

Červený, V., and J. Janský, 1994. P and PKP Amplitude-distance Curves. *Acta Geophysica Polonica* 4th ser. 42: 242-72.

Dziewonski, A. M. and D. L. Anderson, 1981. Preliminary reference Earth model, physics. *Earth Planet. Interiors.* 25, 297-356.

"Earthquake Glossary – Shadow Zone." *Earthquake Hazards Program.* U.S. Geological Survey, 03 Nov. 2009. Web. 02 March 2012.

Gilbert, F and A. M. Dziewonski, 1975. An application of normal mode theory to the retrieval of structural parameters and source mechanisms for seismic structure, *Phil Trans Roy. Soc. London A,* 278, 187-269.

Houard, S., J. L. Plantet, J. P. Massot, and H. C. Nataf, 1993. Amplitudes of Core Waves near the PKP Caustic, from Nuclear Explosions in the South Pacific Recorded at the "Labratoire De Detection Et Geophysique" Network, in France. *Bulletin of the Seismological Society of America* 83.6: 1835-854.

Houard, S. and H.-C. Nataf, 1992. Further evidence for the 'Lay discontinuity' beneath northern Siberia and the North Atlantic from short-period P-waves recorded in France, *phys. Earth planet. inter*. 72, 264-275.

Kenneth, B. L. N. and E. R. Engdahl, 1991. Traveltimes for global earthquake location and phase identification, *Geophys. J. Int.* 105, 429-465.

Lay, T. and D. V. Helmberger, 1983. A lower mantle S wave triplication and the shear velocity structure of D'', *Geophys. J. R. Astr. Soc.* 75, 799-838.

Lillie, Robert J., 1999. Whole Earth Geophysics: An Introductory Textbook for Geologists and Geophysicists. *Upper Saddle River, NJ: Prentice Hall*.

Lehmann, I., 1953. On the shadow of the Earth's core, *Bull. Seismol. Amer.,* 43, 291-306.

Lehmann, I., 1958. On amplitudes of *P* near he shadow zone. *Annaldi di Geofisica,* 11, 13-15.

Macelwane, James B., and F. W. Sohon, 1932. Introduction to Theoretical Seismology. *New York: J. Wiley & Sons*.

Massot, J. P. and Y. Rocard, 1982. Variation of amplitude of *PKP* from underground explosions in South-central Pacific, *Geophys. Res. Lett.,* 9, 1211-1214.

Robertson, E.C., 1966. The interior of the Earth; an elementary description: *U.S. Geological Survey Circular* 532.

Shearer, Peter M., 1999. Introduction to Seismology. *Cambridge University Press*.

Storchak, D. A., Bormann, P., & Schweitzer, J., 2012. Standard nomenclature of seismic phases. In P. Bormann (Ed.. *New Manual of Seismological Observatory Practice (NMSOP)* Potsdam: Deutsches GeoForschungsZentrum GFZ, 1-18.

Yockstick, M.L., 1987. Earthbook -- Encyclopedia of the Earth: *Stockholm, Sweden, Esselte Map Service*.

Young, Christopher J., and Thorne Lay, 1990. Multiple Phase Analysis of the Shear Velocity Structure in the D″ Region Beneath Alaska. *Journal of Geophysical Research* 95.B11: 17385-7402.