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Studies on the Source Parameters of the 23 June 2014 Rat Islands, Alaska, $M_W$ 7.9 Earthquake Sequence

Dariush Motazedian and Shutian Ma

Abstract

On 23 June 2014, an $M_W$ 7.9 earthquake occurred in the Rat Islands region, Alaska, United States. We inverted the full moment tensor for the mainshock, and found the shallow-dip nodal plane (P1) is: strike 207.4°, dip 27.1°, slip –12.7°; the steep-dip plane (P2) is: strike 308.7°, dip 84.2°, slip –116.5°. The larger aftershocks that have depth phase records were relocated and found the majority were distributed along a moderate dipping trend. The steep-dip plane was selected as the causative plane. Using the steep-dip plane as the rupture plane, source rupture process inversions were performed. The obtained maximum slip was about 3.5 m. The optimal rupture velocity $V_R$ was about 2.0 km/s. The shallow-dip plane was also used as a rupture plane to perform rupture inversion trials. Curiously the overall waveform fit between the observed and the synthetic seismograms is slightly better than that when the steep-dip plane was used. The catalogue hypocenters of the aftershocks with magnitude ≥ 4.0 were used to simulate a spatial plane. The simulated plane is moderate dipping towards north-west. When the simulated plane was used as the rupture plane, the overall waveform fit was poor. The moderate dipping plane was not the causative plane.

Keywords: the 23 June 2014 Rat Islands $M_W$ 7.9 earthquake, source rupture model, aftershocks, master-event relocation, depth phase

1. Introduction

On June 23, 2014, an $M_W$ 7.9 earthquake occurred in the central Aleutians near the Rat Islands, Alaska (Figure 1). This earthquake was one of the largest seismic events along the boundary between the Pacific and the North American plates in a century. The focal depth of this earthquake was about 100 km; it is an intermediate-depth event. In most cases, intermediate-depth events are not followed by many aftershocks [1]. However, this mainshock was followed by a large number of aftershocks. The Alaska Earthquake Centre (AEC) located more than 1800 aftershocks within 1 month after the mainshock, and more than 40 of them were larger than magnitude 4 [2].
Intermediate-depth earthquakes with $M_W \geq 7.5$ are rare. The Global Centroid Moment Tensor (G-CMT) catalog lists only 14 with magnitude $M_W \geq 7.5$, which occurred between depths of 70–200 km [2]. The occurrence of this large earthquake with many aftershocks is a very rare case.

The mainshock caused an intention to the seismological society. Some seismologists studied it and published papers on or related to this Rat Islands earthquake sequence.

Ye et al. [3] modeled the source ruptures using both nodal planes. They found the shallow-dip fault plane with strike azimuth Az 205.9° and dip angle 23.6° toward the northwest provides better matches to $P$ waveforms at azimuths from 300° to 340° than does the steep-dip fault plane (strike azimuth Az 308° and dip angle 84°). However, the overall waveform mismatch is comparable between the two models, and some signals are better fit using the steep-dip fault plane, so their preference for selecting the shallow-dip plane as the rupture plane is mild. In another word, for this $M_W 7.9$ earthquake, its causative plane cannot be 100% determined using the fit.
between the observed and the synthetic waveforms. The maximum slip they obtained is 10.3 m; the average slip is 3.9 m. The rupture velocity they used is 1.5 km/s.

Macpherson and Ruppert [2] relocated the aftershocks. To attempt to determine the correct rupture plane, they plotted cross-sections parallel to the dipping directions of the nodal planes as determined by the Global Centroid Moment Tensor (gCMT) project. The gCMT solutions found one nodal plane with subvertical dip (84°) and a strike of 308° and the other with a moderate dip of 26° and strike of 207°. They found that the seismicity is dipping at a moderate angle to the northwest and does not align well with the dips from either of the gCMT nodal planes. They also found the shallow-dip plane does align well with the mainshock hypocenter and a group of unusual oceanic mantle seismicity to the south of the mainshock. They interpret that alignment as delineating the mainshock fault plane, and thus, they prefer the moderately dipping nodal plane as the rupture plane of the \(M_W 7.9\) mainshock. They used the double-difference relocation method [4], and the catalog travel time picks from 29 Broadband and short-period stations to relocate over 2500 earthquakes, which occurred from June 23, 2014, to the end of the year in the mainshock epicenter region (50°N–53°N; 176°E–178°W). As those smaller aftershocks were included; the catalog travel time picks for smaller earthquakes may not be accurate, and the relocation results may or may not be reliable.

Twardzik and Ji [5] first performed a set of finite-fault inversions to invert the slip history of the \(M_W 7.9\) earthquake. They found they cannot identify the causative fault plane by comparing the misfits between observed and the synthetic seismograms. As such, they relocated aftershocks and used the relocated hypocenters to determine the causative plane. They used the Joint hypocenter determination (JHD) method and the arrival times of seismic phases (P, S, pP, sP, PcP, and ScP) reported by the International Seismological Centre (ISC). They selected a dataset, including 19 earthquakes with \(m_b \geq 4\); 17 earthquakes with \((3 \leq m_b \leq 4)\), occurred from June 23 to September 23, 2014, within 60 km from the epicenter of the mainshock. The mean horizontal error of those JHD locations is 6.2 km; the mean vertical error is 19.8 km. They found that most relocated aftershocks distribute along a 40 km long linear segment orienting northeast and that coincides with the width of the surface projection of the steep-dip fault plane. Vertically, the relocated aftershocks span a depth range from 70 km to 150 km. It is noteworthy that the depth extension of the relocated aftershock distribution is nearly double of its horizontal extension. They concluded that the relocated aftershocks tend to align preferentially along with the fault plane that has a dip of 87° and a strike of 308°. Since the mean vertical error is 19.8 km in the relocated aftershocks, the hypocenter distribution may have some uncertainties. The maximum slip they obtained is about 3.5 m; the rupture velocity \(V_R\) is about 2.0 km/s.

Miyazawa [6] studied the remote and dynamic earthquake triggering phenomena caused by global transient stress changes generated from seismic waves’ propagation of other large earthquakes at a great distance. The author calculated the dynamic changes beneath station ADK and AMKA in the Coulomb Failure Function (\(\Delta CFF\)) for the \(M_W 7.9\) mainshock. The focal mechanism from the Global CMT (strike 207°, dip 26°, and rake/slip \(-13°\)) and focal depth 109 km were used. It was found that the \(\Delta CFF\) varies within roughly 10 Pa when the Lame’s parameters, \(\lambda\) and \(\mu\), are 66 GPa and the effective friction coefficient \(\mu_0\) is assumed to be 0.4 at the depth. The stress changes varying within at most 10 Pa at the hypocenter region probably caused a reduction in the fault’s strength by cyclic fatigue and eventually triggered the fault failure and released energy in the form of an \(M_W 7.9\) earthquake. Unfortunately, the author did not provide the results from the steep-dip plane.
Florez and Prieto [7] introduced a relative earthquake depth determination algorithm using depth phases. They applied their method to determine focal depths for 17 larger aftershocks of the $M_{\text{W}} 7.9$ earthquake. They projected their relocated hypocenters onto two vertical planes. One is parallel to the steep-dipping direction; the other to the shallow-dipping direction. They found that their results are not consistent with a shallow-dip nodal plane. Therefore, they can confidently assign the causative fault plane to the steep-dip plane. It seems that the catalog epicenters were used when projections of the hypocenters were plotted. It is noticed that their hypocenter projections on the vertical plane that is parallel to the steep-dipping direction did not form a linear trend along with the $84^\circ$ dipping. The majority are along with about $60^\circ$ dipping (their Figure 2c).

The above authors made contributions to the studies of this $M_{\text{W}} 7.9$ sequence. For example, they found that the causative plane of the mainshock cannot be determined using the misfit between observed and synthetic waveforms. Some phenomena related to the mainshock are still not very well emphasized. Such as, the majority of the aftershocks were distributed along with a moderate-dipping trend neither along with the shallow dip nor the steep-dip nodal plane. We have been studying this very rare event from its occurrence; we want to present our results and confirm some phenomena we found. We organized a chapter, which covers parts of our results.

1. The seismic activity features obtained using catalog data for earthquakes with magnitude $\geq 4.0$, occurred before and after seven and half years from the mainshock;

2. introduction to some of the methods used in our studies;

3. full moment tensor solution for the mainshock; the double-couple solution retrieved is:

   - nodal plane 1, $P_1$: strike $207.4^\circ$, dip $27.1^\circ$, rake/slip $-12.7^\circ$, dipping at Az $297.4^\circ$ (shallow-dip);

   - nodal plane 2, $P_2$: strike $308.7^\circ$, dip $84.2^\circ$, rake/slip $-116.5^\circ$, dipping at Az $38.7^\circ$ (steep-dip).

4. hypocenter relocations for larger aftershocks which have depths obtained using a depth phase method;

5. source rupture process modeling results;

6. discussions of some issues.

2. Several types of data used in our work

The catalog data: We retrieved the catalog of earthquakes with magnitude $\geq 4$, which occurred between 2007-0101 and 2022-0220 in the $M_{\text{W}} 7.9$ source region and its vicinity from IRIS (the Incorporated Research Institutions for Seismology), and made up a computer program to process the catalog for plotting various hypocenter distribution figures. The data duration covers about seven and a half years before and after the occurrence of the mainshock.
Seismogram data: When we perform a moment tensor inversion, and model source rupture process for an earthquake, we need waveform records. Usually, we retrieve waveform records from IRIS. For this \( M_{W} 7.9 \) earthquake:

1. the Broadband records at tele-stations (some seismic arrays) were retrieved for measuring the time differences between the tele-depth phase pP and the direct P phase to calculate focal depths.

2. the Broadband records at regional stations were retrieved for measuring the arrival times of P and S phases to relocate those larger aftershocks that have focal depth solutions obtained using a tele-depth phase.

3. the Broadband records at tele-stations around the epicenter of the mainshock were retrieved for modeling source rupture processes.

4. the long period mantle wave records at tele-stations globally were retrieved for moment tensor inversion.

An earth velocity model is required for relocations of the aftershocks. We used the velocity model provided by Macpherson and Ruppert [2], to replace the crustal part in the Preliminary Reference Earth Model (PREM; [8]). This revised model was used for aftershock relocations and the source rupture modeling.

3. The geological background and seismic activities in the source region and its vicinity

The \( M_{W} 7.9 \) Rat Islands earthquake ruptured beneath the Rat Islands in the western Aleutians Islands, Alaska. Figure 2 shows its geographic location and the seismicity in the epicenter region and its vicinity. This Mw 7.9 event happened within the subducting Pacific slab in a region where the Bowers Ridge and the Aleutian Trench (subduction zone) meet. The Aleutian Trench is the boundary between the Pacific Plate and the America Plate. In the Aleutian Trench region, the Pacific Plate is moving relative to the North American plate, which is relatively stationary, at a rate of about 7.5 cm/year [e.g., [9]].

The Aleutian trench is, along the Alaska-Aleutian arc, one of the largest active tectonic margins in the world, spanning nearly 4000 km from the Gulf of Alaska to the Kamchatka Peninsula, Russia. The arc is formed by a convergent plate boundary where the Pacific plate is subducted beneath the North American plate at a rate that varies between 5.4 cm/yr in the east to 7.8 cm/yr in the far west [9]. The Aleutian trench zone is very seismically active. In the Rat Islands region, there are 10 earthquakes with a magnitude ≥ 7 occurred since 1960 (IRIS earthquake catalog). The June 23, 2014 \( M_{W} 7.9 \) earthquake occurred at a depth of about 100 km. It is often called an intermediate-depth event. In the following paragraphs, we analyze the seismicity that occurred about seven and a half years before and after the \( M_{W} 7.9 \) earthquake in the source region and its vicinity.

Figure 3 shows the epicenter distribution of earthquakes with magnitudes ≥ 4.0, which occurred about seven and half years before and after the Mw 7.9 mainshock in the mainshock region and its vicinity. A solid circle shows the epicenter of an earthquake. It was color-coded with focal depth; its size is proportional to the magnitude.
The left panel (a) shows the earthquakes that occurred seven and half years before the occurrence of the Mw 7.9. The events within the rectangular area are those that occurred in the source region. The right panel (b) shows the earthquakes that occurred after the occurrence of Mw 7.9. The aftershocks formed a trend in the northwest direction.

To analyze the seismicity along the vertical direction, we simulated a spatial plane using the hypocenters of 90 earthquakes with magnitudes \( \geq 4.0 \), which occurred below the depth of 80 km from 2007-0101 to 2014-0622. The simulated strike is Az 276.8°; the dip angle is 47.7°. The plane dips at Az 6.8°. Then we projected the hypocenters of earthquakes onto a vertical plane that is parallel to the dipping direction. Figure 4 shows the hypocenter projection comparison for the same earthquakes in Figure 3. The left panel (a) shows that the hypocenter projections beneath about 90 km are aligned with a dipping of 47.7° direction. Coincidently the hypocenter distribution trend of the aftershocks in the right panel (b) is also approximately along this dipping direction. The trend is neither in the dipping direction of the steep-dip plane nor in the dipping direction of the shallow-dip plane.

To observe the spatial distribution features of the aftershocks of the Mw 7.9, we simulated a spatial plane using the hypocenters of 184 aftershocks, of which the magnitudes \( \geq 4.0 \). The simulated strike is 201.7°; the dip angle is 39.4°. The plane dips at Az 291.7° (from north to west 68.3°). These parameter values are close to those of the nodal plane P1 (strike Az 207.4°, dip angle 27.1°, dips at 297.4°; Table 1). Figure 5 shows the hypocenter projections onto a vertical plane, which is perpendicular to the strike of the simulated plane. It is found that the hypocenters of the aftershocks were distributed approximately along the simulated dipping direction (39.4°).
To further observe the spatial distribution trend of the aftershocks, we projected the hypocenters onto two vertical planes. The left panel of Figure 6a shows the hypocenters projected onto a vertical plane at a steep-dipping direction. The tilted Figure 3.

The epicenter comparison for earthquakes with magnitudes ≥ 4.0, occurred about 7 and half years before and after the Mw 7.9 mainshock, in the mainshock region and its vicinity. (a) the earthquakes occurred 7 and half years before the occurrence of the Mw 7.9 (between 2007-0101 and 2014-0622). (b) the earthquakes occurred after the occurrence of the Mw 7.9 (between 2014-0623 and 2022-0220). The earthquakes in the rectangle of the left panel are in the source region of the mainshocks. The star with the number 7.9 shows the initial location of the Mw 7.9 mainshock. The catalog was retrieved from IRIS.

Figure 4. The hypocenter projection comparison for the same earthquakes in Figure 3. (a) The hypocenter projections show the seismic activity along the dipping direction of a simulated spatial plane. The simulation was performed using the hypocenters of 90 earthquakes with magnitudes ≥ 4.0, which occurred below the depth of 80 km from 2007-0101 to 2014-0622. The simulated strike is Az 276.8°; the dip angle is 47.7°. The plane dips at Az 6.8°. The relatively narrow seismicity belt below the red star may be assumed to be close to the boundary between the Pacific Plate and the North American plate beneath the Rat Islands region. The red star shows the initial location of the mainshock. (b) The hypocenter projections of earthquakes occurred between 2014-0623 and 2022-0220.

To further observe the spatial distribution trend of the aftershocks, we projected the hypocenters onto two vertical planes. The left panel of Figure 6a shows the hypocenters projected onto a vertical plane at a steep-dipping direction. The tilted...
Dashed line indicated with the P2 projection shows the projection of the steep-dip plane (P2). Generally, those aftershocks should form a linear trend around that tilted line, if the plane P2 is the real rupture plane. The right panel (b) shows the hypocenters on a vertical plane in a shallow-dipping direction. In the same sense, those aftershocks should form a linear trend around that tilted line indicated with P1.

### Table 1
A full moment tensor solution for the Rat Islands Mw 7.9 mainshock.

<table>
<thead>
<tr>
<th>Major double couple: moment = 9.16</th>
<th>Prin. val.</th>
<th>Dev. part</th>
<th>Azimuth</th>
<th>Plunge</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1: strike 207.4 dip 27.1 slip -12.7 dipping at 297.4 (shallow-dip)</td>
<td>P –8.895</td>
<td>–9.159</td>
<td>192.50</td>
<td>44.47</td>
</tr>
<tr>
<td>P2: strike 308.7 dip 84.2 slip -116.5 dipping at 38.7 (steep-dip)</td>
<td>T 9.088</td>
<td>8.825</td>
<td>61.10</td>
<td>33.97</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Minor double couple: moment = 0.33</th>
<th>N 0.597</th>
<th>0.334</th>
<th>311.60</th>
<th>26.36</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1: strike 93.2 dip 44.8 slip</td>
<td>Isotropic part: moment = 0.26 (trace = 0.78)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P2: strike 187.9 dip 85.3 slip</td>
<td>134.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: prin. val. refers to the principal axis value (10^20 Nm); dev. part refers to the deviatoric part (10^20 Nm); P, T, and N mean the compressional, tensional, and null components. P1 and P2 mean nodal planes 1 and 2. The unit for the strike, dip, slip, and dipping is the degree (°), and for the moment is 10^20 Nm. Compared to the scalar moment of the major double couple, the isotropic part (ISO) is 2.88%, and the minor double couple is 3.64%. The inversion was performed using a depth of 105 km.

Figure 5.
Hypocenter projections onto a vertical plane, perpendicular to the simulated spatial plane using the hypocenters of 184 aftershocks, of which the magnitudes ≥ 4.0. The red star shows the initial location of the mainshock. The simulated strike is 201.7°; the dip angle is 39.4°. The plane dips at Az 291.7° (from north to west 68.3°). These parameter values are close to those of the nodal plane P1: strike Az 207.4°, dip angle 27.1°, dips at 297.4° (Table 1).
projection, if \( P_1 \) is the real rupture plane. The trend of the belt formed by the after-shocks in (a) or (b) is not consistent with the \( P_2 \) projection or \( P_1 \) projection.

4. Method introduction

To perform source parameters studies on the \( M_W \) 7.9 mainshock and its larger aftershocks we used several advanced methods. These methods are introduced briefly in this section.

4.1 Method used to obtain a full moment tensor

An earthquake source can be described using a seismic moment tensor. The moment tensor can be decomposed into three parts: an isotropic (ISO), double-couple (DC), and compensated linear vector dipole (CLVD) part (e.g., [10]). It can also be decomposed into an isotropic (ISO), a major double-couple, and a minor double-couple part (e.g., [11]). The seismic moment is a 3 \( \times \) 3 matrices. In linear algebra, a complex matrix can be expressed by the summation of several simple, independent matrices. Applying this principle, Kikuchi and Kanamori [12] expressed an arbitrary moment tensor by summing six different constant moment tensors. Given an earthquake hypocenter and earth model, each of the constant tensors is used to generate Green's functions and obtain three-component synthetic seismograms at a given seismic station.

There are several ways to generate Green's functions depending on the wave type used. As the \( M_W \) 7.9 Rat Islands earthquake was large, we used a long-period Rayleigh
wave fitting method to obtain its moment tensor. Green’s functions were generated using the normal modes summation method [13].

Once Green’s functions are obtained, synthetic seismograms are calculated using a set of coefficients. A moment tensor inversion is to search for a set of the coefficients used to generate synthetic seismograms, which should be as similar as possible to the observed seismograms in shapes and amplitudes. To do this, two functions are often separately used. One function is to calculate the correlation between the synthetic and the observed seismograms using:

$$ e_j = 1 - \frac{\sum_i X_j(t_i) \cdot O_j(t_i)}{\sqrt{\sum_i X_j^2(t_i) \cdot \sum_i O_j^2(t_i)}} $$

(1)

where the subscript $j$ is an ordinal number of the digital recording; $i$ is the data time point index in the observed or the synthetic seismograms. $O_j(t_i)$ is a segment of a digital record; $X_j(t_i)$ is a segment of a synthetic seismogram corresponding to $O_j(t_i)$.

The second function is to calculate the amplitude differences between the synthetic and the observed seismograms:

$$ e_j = \sqrt{\frac{\sum_i [X_j(t_i) \times a_0 - O_j(t_i)]^2}{N_j}} $$

(2)

The factor $a_0$ is a constant, determined using the following function:

$$ a_0 = \frac{1}{N} \sum_{j=1}^{N} \frac{O_j(t_i)_{max}}{X_j(t_i)_{max}} \times 10^{20} \text{dyne} \cdot \text{cm} $$

(3)

where $N$ is the number of records used in the inversion.

We, first, use function (1) to obtain a preliminary moment tensor solution, then use (3) to obtain $a_0$, and use (2) to obtain a solution. The procedure is repeated many times to find a target set of coefficients when function (2) is at its minimum. Then the moment tensor is calculated using the target set of coefficients. We used the procedures developed by Ma and Adams [14] for simultaneous waveform shape and amplitude inversion.

4.2 The method to determine focal depth using arrival time difference pP-P

Crotwell, et al. [15] developed a Taup Toolkit, called “Flexible Seismic Travel-Time and Raypath Utilities.” Using this tool, the travel times for many seismic phases can be calculated.

We developed a procedure [16] using the relationship that the time duration between the tele-depth phase pP and its reference phase P is roughly positively proportional to the focal depth, to determine focal depths for the larger aftershocks of the Rat Islands, $M_{W} 7.9$ earthquake.

1. For a given station, we pick out the station distance from the SAC record at the station;

2. We select a possible depth range;

3. Using the station distance and a range of depth, with the Taup tool we calculate several time durations between the tele-depth phase pP and its reference P;
4. Using Matlab, we plot a line determined by the focal depths and the corresponding calculated time durations pP-P, and obtain a linear formula;

5. Put the measured time duration pP-P at the selected station in the formula, the calculated focal depth for the aftershock is obtained;

6. For several stations at which the time durations pP-P are measured, several focal depth solutions are obtained, and the average is used as the final solution for the earthquake.

4.3 Earthquake locating method

Earthquake hypocenter parameters are fundamental information for studying earthquakes, as such many people have contributed to earthquake locating methods and computer programs. The hypocenter locating program that we used is a part of a computer program package called SEISAN. The SEISAN (seismic analysis system) is a complete set of programs for analyzing earthquakes. With SEISAN it is possible to locate events, determine spectral parameters, seismic moments, and so on. The hypocenter locating program used in this article in the SEISAN package is a modified version of HYPOCENTER [17–19].

4.4 The method to set up a source rupture model

The commonly used procedure to set up an earthquake rupture model is described below. One of the nodal planes obtained from a seismic moment tensor is used as the earthquake rupture plane. Usually, the x-axis is along the strike direction, and the y-axis is along the dip direction. The selected rupture plane is divided into \( M \times N \) sub-faults with lengths of \( dx \) and \( dy \). Each sub-fault is treated as a point source and the synthetic seismogram at each seismic station is the summation of the synthetic seismograms generated by all of the sub-faults. The source time function of a sub-fault is usually depicted as overlapped triangles. The layout of the source rupture model can be found in Hartzell and Heaton [20].

A unit constant rupture slip vector for each sub-fault is divided into two orthogonal vector components (one aligned along the strike and the other aligned along the dipping direction). Any slip vector on the sub-fault is obtained by multiplying the two constant vector components with appropriate coefficients. The goal of the inversion method is to obtain the coefficients of all of the sub-faults. The slip function (source time function) of each sub-fault is depicted by overlapped \( L \) triangles with a rise time \( \tau \), which is half the length of the bottom side of the triangle. The initial constant unit slip direction \((\text{slip}0)\) of each sub-fault is the slip of the selected nodal plane. The initial slip is separated into two components in the directions of \((\text{slip}0 + 45^\circ)\) and \((\text{slip}0 - 45^\circ)\). This breakdown is convenient for Green's functions calculations.

If we assume that on a sub-fault \( mn \) \((m = 1, \cdots, M; n = 1, \cdots, N)\) at the \( k \)th component direction \((k = 1, 2)\), the slip corresponding to the \( l \)th triangle is \( X_{mnk} \) and the vertical component of the Green's functions generated at station \( j \) is \( g_{mnkj} \), at the same station the vertical component of the synthetic seismogram, \( W_j \), generated by all sub-faults at the time point \( t_i \), is expressed as:

\[
W_j(t_i) = \sum_{mnk} X_{mnk} g_{mnkj}(t_i - (l - 1)\tau - T_{mn} - d t_{mn})
\]
where $T_{mn}$ is the rupture start time at the $mn$th sub-fault and $dl_{mn}$ is a time delay generated by the different travel path lengths between the $P$-waves generated by the $mn$th sub-fault and the rupture start sub-fault $m_0n_0$ (hypocenter). The set of $X_{mnjk}$ that can generate a $W_j$, which is most similar to the observed seismogram at station $j$, is the best fitting rupture model for the earthquake.

In this study, two methods were used to determine the rupture slip distribution—the non-negative least squares (NNLS) method [21] and the simulated annealing (SA) method [22]. For most trial inversions, we used the NNLS method, while the SA method was used at the final step to confirm the solution obtained with NNLS.

The smoothness constraint of the total spatial slip distribution was implemented by a Laplacian differential operator to stabilize the slip solution [23]. To calculate the time delay $dl_{mn}$ in function (5), a rupture velocity is required. To calculate Green's functions, we need an initial focal depth, which is also required to obtain a reasonable slip distribution.

5. The source parameters obtained using the methods introduced above

Using the methods introduced above we studied the source parameters for the mainshock and relocated its larger aftershocks that occurred about 20 days following the mainshock. In this section, we present those results.

5.1 Full moment tensor inversion for the $M_W 7.9$ Earthquake

Using the method outlined above, we performed the full moment tensor inversions for the Rat Islands earthquake using a range of focal depths and provided the moment tensor solution obtained using a focal depth of 105 km.

5.1.1 Rayleigh wave records

Since the Rat Islands $M_W 7.9$ earthquake was very large, it generated very strong Rayleigh waves, recorded at stations throughout the world. Hundreds of these waveform records were on the LHZ (long period, high gain, and vertical component) channel. We selected vertical records from 57 stations, filtered those records with a band-pass filter of 135 s to 500 s, and decimated the sampling interval from 1 s to 10 s. When the velocity of the mantle waves is assumed to be on the order of 3 km/s, the shortest wavelength is on the order of 400 km, which was approximately seven times of the rupture length of this $M_W 7.9$ earthquake. For such long-period mantle waves, the earthquake source can be treated as a point source.

5.1.2 Full moment tensor inversions

We conducted the following tests using a depth range from 80 km to 120 km with a depth increment of 5 km. For each focal depth, (1) we calculated the Green’s functions, (2) took the same length for the observed Rayleigh wave record aligned with the synthetic seismogram, calculated at the focal depth, and (3) performed a full moment tensor inversion. The used source time function was three overlapping triangles. The time length of each bottom side was 20 s. Table 1 lists the obtained
parameters for the full moment tensor solution using our preferred focal depth of 105 km. Compared to the scalar moment of the major DC in Table 1, the isotropic (ISO) is 2.88%. At all other depths from 80 km to 120 km (not listed), the ISO as a percentage of the total seismic moment was less than 6%. The smallest ISO occurred at the depth of 95 km.

The trace (trace = 3 × ISO; e.g., [11]) obtained in our inversions was small. As the trace quantifies a volume change in the source region (e.g., [11]), the small trace implied that the change of the earth’s material volume in the source region was small. Compared to the major DC moment in Table 1, the minor DC moment was only 3.64%. The small minor DC and small ISO moments imply that the Rat Islands mainshock was dominated by a major DC event.

To evaluate the credibility of the solutions we need to compare the synthetic seismograms with those of the observed ones. Figure 7 shows the moment tensor projection and the waveform comparison for the first four pairs of seismograms. The similarities between the synthetic and observed seismograms in both the waveform shapes and the maximum amplitude ratios were good. Other pairs at the remaining 53 stations had a similar quality. The good waveform fit implies that the moment tensor solution obtained is reasonable.

Figure 7. (a) The lower hemispherical projection of the moment tensor solution obtained using a depth of 105 km. (b) Comparison between the first 4 observed and synthetic seismograms used in the inversion. For each pair, the upper trace is the observed (solid line), and the lower trace is the synthetic (dashed line), generated with the solution displayed in panel (a). Both the observed and synthetic waveforms were filtered with a band-pass filter in the range of 135 s to 500 s. The symbols and numbers on the left side of each pair from the top to the bottom indicate the station name, vertical component, station distance in degree, station azimuth in degree, and the ratio between the observed and synthetic maximum amplitudes. The waveform shape similarity and the small bias of the ratios from an ideal case (ratio = 1) show that the fit is good.
5.2 Relocation of aftershocks with magnitude $\geq 4.5$

There are two nodal plane solutions in Table 1. One nodal plane is close to the rupture plane of the $M_{W} 7.9$ mainshock. The hypocentral distribution of the aftershocks could help us to identify which nodal plane is close to the rupture plane. The requirement is that the errors in the hypocenters should be small. To obtain a distribution of hypocenters with small error, the aftershocks with magnitude $\geq 4.5$ were relocated.

The error in the focal depth obtained using a conventional method may be large. The reason is that the travel times of the P and S phases are dominated by the station distance, not the focal depth. We used a combined procedure to relocate the aftershocks.

We searched tele-depth phase pP from the vertical component (BHZ) of teleseismic P-wave records retrieved from IRIS for 23 aftershocks that occurred in the specified date range.

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Note: lat. means latitude (°); lon., longitude (°); depth in km; m, magnitude; t-err, error in the origin time (s); lat-err, error in latitude (km); lon-err, error in longitude (km). The magnitude values are from the IRIS database. The bold text shows the 5 larger aftershocks.

Table 2. Catalog of the 23 relocated aftershocks.
between June 23 and July 11, 2014, with magnitude ≥ 4.5, and determined focal depths for these 23 aftershocks using depth phase pP [16]. Then the arrival times of the recorded P and S phases at the same four regional stations for these 23 aftershocks were carefully measured, and the SEISAN [24, 25] was used to locate the epicenters at the focal depth obtained using the depth phase pP. The re-located 23 aftershocks were listed in Table 2.

The bird-view distribution of the obtained 23 hypocenters in Figure 8 shows that the hypocenters are separated into two groups. Group 1 was formed by the hypocenters with the lighter color, while group 2 was formed by the hypocenters with the deeper color. Figure 9a shows the hypocenter projection onto a vertical plane perpendicular to the steep-dip plane (nodal plane 2). Eleven (11) aftershocks in group 2 formed a linear trend in the steep-dipping direction. The other hypocenters are scattered. Figure 9b shows the hypocenter projection onto a vertical plane, perpendicular to the shallow-dip plane, indicated with P1 projection (nodal plane 1). No linear trend was formed by the hypocenters at the dipping (27.1°) direction of the shallow-dip plane.

In order to observe a spatial trend, we simulated a plane using the hypocenters of the 23 well relocated aftershocks. Figure 10 shows the simulated spatial plane. Its strike is at Az 258.2°; its dip angle is 44.8°. To clearly observe the dipping of the simulated plane we projected the hypocenters of the mainshock and the 23 aftershocks onto a vertical plane which is along the simulated dipping direction. Figure 11 shows that most hypocenters were distributed along the tilted line, the projection of the simulated plane, at dip angle 44.8°. This angle is close to the one (47.7° in Figure 4a)
Figure 9.
Hypocenter projections. (a) The hypocenters of the mainshock and the 23 relocated aftershocks projected onto a vertical plane that is perpendicular to the steep-dip nodal plane (P2). The tilted dashed line indicated with 84.2° is the projection of the steep-dip plane. The number 84.2 is the dip angle. Eleven (11) aftershocks in group 2 formed an about 15 km linear trend along the steep-dip plane. (b) The hypocenters of the mainshock and the 23 relocated aftershocks are projected onto a vertical plane that is perpendicular to the shallow-dip plane (P1). The tilted dashed line indicated with 27.1° is the projection of the shallow-dip plane. It was found that no linear trend was formed along a nodal plane (P1).

Figure 10.
The simulated spatial plane uses the hypocenters of the 23 well-relocated aftershocks (Table 2). The simulated strike is Az 258.2°; the dip angle is 44.8°. The plane dips at Az 348.2° (from north to west 11.8°). The red star shows the initial location of the mainshock.
obtained by simulating hypocenters of the earthquakes occurred before the mainshock. They are neither close to the steep-dip angle 84.2° nor the shallow-dip angle 27.1°. The trend may be close to the boundary between the Pacific Plate and the north America plate beneath the Rat Islands region.

5.3 Source rupture inversions for the Rat Islands Mw 7.9 earthquake

We performed the source rupture inversions for the Rat Islands earthquake using the procedure outlined above and the inversion code developed by Kikuchi and Kanamori, provided by Lingling Ye (personal communication) with a subroutine we revised to speed up the calculations of the Green’s functions.

5.3.1 Initial depth selection for the rupture model

For the Rat Islands mainshock, the focal depth published online by ISC is 102.1 km; the centroid depth calculated by the G-CMT group is 104.3 km. The shallowest focal depth for the 23 aftershocks we relocated is 92.3 km. From the consideration that 104.3 km is the centroid depth, the mainshock is a large one with normal faulting, the rupture initial point may be shallower than the centroid depth by tens of kilometers; therefore, we took 92 km as the initial rupture depth. This value is close to that (95 km) used by Ye et al. [3].
5.3.2 Source rupture inversion results using the steep-dip nodal plane

In the rupture inversion procedure, the nodal plane 2 of the full moment tensor solution obtained using a depth of 105 km, was used as the rupture plane (Table 1; strike 308.7°, dip 84.2° and slip -116.5°). The epicenter (51.7028°N; 178.6428°E) used in the inversion was retrieved from the IRIS website. The fault model dimensions are 270 km × 210 km, while the size of each sub-fault is 15 km × 15 km. The total number of sub-faults is 252.

To perform the source rupture inversion, we needed a rupture propagation velocity (V_R). The rupture velocity (V_R) is often assumed to be a fraction of the shear wave velocity (β). For example, Stein and Wysession [26] assumed a formula \( V_R = 0.7 \beta \). To obtain a proper rupture velocity, we performed trial inversion tests using a \( V_R \) from 1.3 km/s to 2.6 km/s with an increment of 0.1 km/s. Figure 12 shows the variance (the misfit between the observed and the synthetic waveforms) change with rupture velocity when the initial rupture depth was taken 92 km. The minimum variance (0.1570) occurred at a \( V_R = 2.0 \) km/s.

Figure 13 shows the source time function and the final slip distribution obtained using an initial depth of 92 km and a \( V_R = 2.0 \) km/s. The initial point is indicated by a star sign *. The largest slip (3.52 m) occurred at a depth of about 120 km. The rupture area is about 60 × 60 km². Figure 14 shows a waveform comparison between the observed and synthetic seismograms. The fit in each pair between the observed (upper) and synthetic (bottom) traces was generally good, except that at station AAK. This station is in the strike direction of the steep-dip nodal plane.

5.3.3 Source rupture inversion results using the shallow-dip nodal plane

Based on the well-relocated hypocenter trend, we used the steep-dip plane as the rupture plane. This was the same as that by Twardzik and Ji [5]. However, Ye et al. [3]
found that the back-projection images were more straightforwardly reconciled with the shallow-dip plane. They also found their waveform misfits were comparable when the steep-dip plane or the shallow-dip plane was used as the causative plane, and some signals were better fitted using the steep-dip plane. As a result, their preference for the shallow-dip plane was mild. We also performed trial inversion with the key parameters used by Ye et al. [3], $V_R = 1.5$ km/s, and the initial depth = 95 km. Figure 15 shows the rupture distribution we obtained. The largest slip (3.33 m) occurred at a depth of about 115 km within the largest patch. Figure 16 shows a waveform comparison between the observed and synthetic seismograms. The fit in each pair between the observed (upper) and synthetic (bottom) traces was also good.

Figure 13. (a) Lower hemispherical projection of the double couple focal mechanism (Table 1). (b) Source time function. (c) Distribution of the slip on the steep-dip nodal plane (Table 1). The star sign “start point” shows the location of the initial rupture. The arrow at a sub-fault shows the direction and the amount of the slip. The maximum slip was about 3.52 m and occurred at a depth of about 120 km. The used rupture velocity $V_R = 2.0$ km/s, at which the variance reached the minimum (Figure 12). The dashed circles show the rupture propagation.

Figure 15 shows the rupture distribution we obtained. The largest slip (3.33 m) occurred at a depth of about 115 km within the largest patch. Figure 16 shows a waveform comparison between the observed and synthetic seismograms. The fit in each pair between the observed (upper) and synthetic (bottom) traces was also good.
To observe the misfit between the observed and the synthetic seismograms, we found the fit at station AAK (Az 308°) was better in Figure 16 than that in Figure 14.

Ye et al. [3] found that the shallow-dip fault plane toward the northwest provides better matches to P waveforms at azimuths from 300° to 340° (their Figure S2) than does the steep-dip fault plane solution (their Figures S3 and S4). This result is exactly the same as that we obtained.

To confirm that the record at AAK does not have a problem, we retrieved the records in the station AAK region, plotted the seismograms, and found the waveform shapes are similar (Figure 17). This implies that the recording quality at AAK does not
have a problem, so the better waveform fit at AAK support to select the shallow-dip plane as the rupture plane.

5.3.4 Source rupture inversion results using the simulated plane

Based on the simulated spatial plane obtained using the well-relocated hypocenters, we found the majority of the hypocenters distributed around a mild dipping plane (Figure 11; dip 44.8°). We may assume that the mainshock ruptured on that plane. We performed trial inversions with the values of input parameters, rupture velocity \( V_R = 1.5 \text{ km/s} \), and the initial depth = 95 km. Figure 18 shows the rupture distribution obtained. Figure 19 shows a waveform comparison between the observed
and synthetic seismograms. The observed waveforms are exactly the same as those in Figure 16. The fits at stations AAK, KIP, and MIDW are not good; the ratio of the maximum amplitudes at several stations is not close to 1 (the ideal ratio is 1). The average variance (0.2720) is larger than those in Figures 14 and 16. The obtained maximum slip is about 3.36 m, which occurred at about a depth of 70 km within a smaller patch. Logically the maximum slip should occur at a depth below the initial depth (95 km), owing to the normal faulting. Since the misfit at several stations is not good, the ratio between the observed and synthetic maximum amplitudes at several stations is far from the ideal value, and the maximum slip occurred at a too shallow depth, the simulated plane is not acceptable to be the rupture plane.

Figure 16. Comparison between the 27 observed and synthetic seismograms. For each pair of waveforms, the upper trace is the observed (solid-line); the lower trace is the synthetic (dashed-line), generated with the slip distribution in Figure 15c. The observed waveforms are exactly the same as those in Figure 14. The overall fit between the observed and the synthetic seismograms is also good. The fit at station AAK is better than that, and the average variance (0.1545) is slightly smaller than that, in Figure 14.
6. Discussion and conclusion

This $M_W$ 7.9 event intrigued scientific interests and generated issues. In this section, we discuss some issues and provide some conclusions.

Beneath the Rat Islands at a depth of 100 km, the shear wave velocity is about 4.5 km/s. Using the PREM earth model and the assumed rupture velocity formula $V_R = 0.7\beta$, $V_R = 0.7 \times 4.5 \approx 3.1$ km/s. This value is much larger than what was obtained using the back-projection method (1.5 km/s) by Ye et al. [3]. The average rupture velocity obtained by Twardzik and Ji [5] was 2.4 km/s from modeling the steep-dip plane and 2.3 km/s from the shallow-dip plane. The optimal rupture velocity we obtained from trial inversion tests at the initial depth of 92 km was 2.0 km/s. For the trial tests with an initial depth of 84 km, the optimal rupture velocity was 1.8 km/s, and 2.1 km/s at the initial depth of 105 km. Therefore, the rupture velocities of around 2.0 km/s may be reasonable for the Rat Islands $M_W$ 7.9 earthquake.

**Figure 17.**
Vertical P-wave displacement records in station AAK region (63°N–66°N; 50°W–54°W). It is clear that the shapes of these waveform records are similar, showing that the record at AAK does not have a problem. Along the bottom trace, UCH/BHZ three ruptures are indicated. The first one is small, the second one is larger, and the third is a combination of at least two large ruptures. The station (UCH) distance is 7300 km.
Two nodal planes can be retrieved from an earthquake moment tensor solution. One of them is assumed to be close to the rupture plane and used for establishing a rupture slip model. Ye et al. [3] preferred the shallow-dip plane for rupture modeling. Twardzik and Ji [5] relocated larger aftershocks. Based on the relocated hypocenters they selected the steep-dip plane as the rupture plane. When Miyazawa [6] calculated the dynamic changes in the Coulomb Failure Function for the $M_w$ 7.9 mainshock, the shallow-dip plane of the G-CMT was used. Macpherson and Ruppert [2] relocated the aftershocks. They found that the seismicity is dipping at a moderate angle to the northwest and does not align well with any dip. They also found the shallow-dip plane

![Figure 18](image.png)

(a) Lower hemispherical projection of the simulated focal mechanism. (b) Source time function. (c) Distribution of the slip on the simulated plane. The star sign * with “start point” shows the assigned location of the initial rupture. The arrow at a sub-fault shows the direction and the amount of the slip. The obtained maximum slip is about 3.36 m, occurred at about a depth of 70 km. The used rupture velocity $V_R = 1.5$ km/s. The dashed circles show the rupture propagation.
does align well with the mainshock hypocenter, so they preferred the moderately dipping nodal plane as the rupture plane of the \( M_W 7.9 \) mainshock. Florez and Prieto [7] recalculated the focal depths for a subset of 17 \( M_W > 4.9 \) aftershocks using the time difference between a tele-depth phase pP and direct P phase. Based on their results they confidently assigned the causative fault plane to the steep one. To identify which nodal plane is close to the rupture plane we also relocated the larger aftershocks. We carefully recalculated the focal depths using pP-P times and relocated the epicenters at the recalculated depths for 23 aftershocks with mb > 4.5, which occurred within 20 days after the mainshock. We found a linear segment about 15 km long formed by 11 aftershocks in the deeper group (Figure 9a) is approximately parallel to the dipping of

![Figure 9c](http://dx.doi.org/10.5772/intechopen.104600)

Comparison between the 27 observed and synthetic seismograms. For each pair of waveforms, the upper trace is the observed (solid-line); the lower trace is the synthetic (dashed-line), generated with the slip distribution in Figure 18c. The fits at stations AAK, KIP, and MIDW are not good; the maximum amplitudes ratio at several stations is not close to 1 (AAK 2.58; BFO 0.37; KBS 0.47; MIDW 0.46; TARA 0.46). All these numbers are far from the ideal ratio (1). The average variance (0.2720) is also larger than those in Figure 14 (0.1570) and Figure 16 (0.1545).
the steep-dip plane, but no linear segment along the dipping of the shallow-dip plane was formed (Figure 9b). Based on the above features we deduced that the steep-dip nodal plane is close to the rupture plane of the mainshock.

When the steep-dip plane was used as the rupture plane, the major rupture patch we retrieved was distributed in a depth range from about 80 km to 140 km (Figure 13, the largest patch). The maximum slip we obtained was about 3.5 m, which was well consistent with that (3.7 m) obtained by Twardzik and Ji [5].

We also performed trial inversion using the shallow-dip plane as the rupture plane and found the average variance (0.1545) is almost the same as that (0.1570) obtained using the steep-dip plane. This implies that the rupture plane indeed cannot be identified using the mismatch between the observed and synthetic seismograms.

Since the majority of aftershocks are distributed along a moderate-dipping plane, it may be thought that the mainshock ruptured along the moderate-dipping plane. Test inversions using the simulated plane as the rupture plane were performed. It was found that the waveform fits at stations AAK, KIP, and MIDW are not good; and the ratio of the maximum amplitudes at several stations is far from the ideal ratio. The average variance (0.2720) is much larger than those in Figures 14 and 16; so, the simulated moderate-dipping plane was denied to be the rupture plane of the mainshock.

Based on the assumption that the immediate aftershocks occurred on the rupture plane of the mainshock or near the edges of the rupture [27], aftershock distributions are often used to select the rupture plane from the two nodal planes. When Kikuchi and Kanamori [28] studied the 1994 Shikotan $M_W$ 8.2 earthquake, they found the aftershocks seem to favor the steep nodal plane as the fault plane. The steep-fault model resulted in a better waveform match than the shallow-dip fault model. Delouis and Legrand [29] found that the aftershocks of an intermediate-depth large earthquake delineate a low angle plane, and the low angle fault model provides a much better fit for the strong-motion waveforms. However, for this $M_W$ 7.9 earthquake, the majority of aftershocks were distributed neither along the steep-dip, nor the shallow-dip nodal plane. The waveform fits for both nodal planes are almost the same.

A hypothesis may be able to explain that the majority of aftershocks occurred along a moderate-dipping plane, which may be close to the boundary between the Pacific plate and North American plate beneath the Rat Islands region—most parts of the huge rupture fault were immediately locked under a tremendous pressure blow about 80 km of the depth after the occurrence of the mainshock, the stress in the source region was re-distributed, and migrated to the boundary region beneath the Rat Islands region, so most aftershocks distributed along that boundary, rather than the rupture plane of the mainshock.

This huge earthquake is very unique. For example, it had a vigorous aftershock sequence; other intermediate-depth earthquakes were usually followed by few or no aftershocks [1]. Solve the mysteries behind the observed phenomena requires more studies.

Acknowledgements

This research was supported by the Natural Sciences and Engineering Research Council of Canada under the Discovery Grant programs. We gratefully acknowledge the constructive comments and suggestions from the academic editor Gaurav Chauhan for INTECHOPEN LIMITED. The waveform records were processed using SAC2000, redseed and geotool programs. Some of the figures were prepared using MATLAB and Generic Mapping Tools. Dr. Lingling Ye at the Department of Earth and
Planetary Sciences, University of California, Santa Cruz, California provided a version of the source rupture modeling program. We are grateful for her help.

Data sources

The seismograms, the earthquake catalog, and G-CMT solution used in this study were collected from the Incorporated Research Institutions for Seismology (IRIS) database at http://www.iris.edu (last accessed the 20 February 2022).

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