



## RESEARCH LETTER

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## Key Points:

- The 2014 Rat Islands  $M_w$  7.9 earthquake ruptured within the Pacific slab
- It is the largest intermediate depth earthquake in 100 years
- This category of event presents poorly recognized seismic hazard for some zones

## Supporting Information:

- Readme
- Movie S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6

## Correspondence to:

T. Lay,  
tlay@ucsc.edu

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The 23 June 2014  $M_w$  7.9 Rat Islands archipelago, Alaska, intermediate depth earthquake

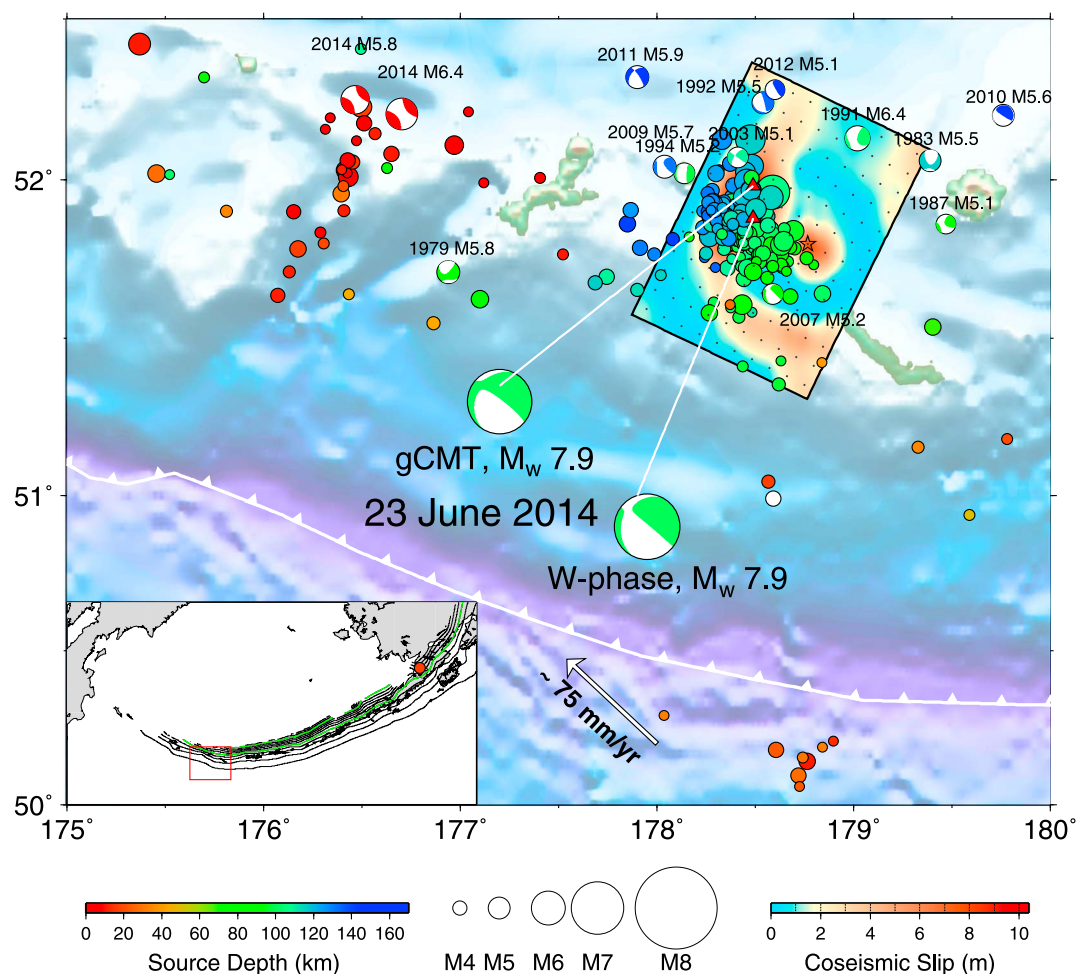
Lingling Ye<sup>1</sup>, Thorne Lay<sup>1</sup>, and Hiroo Kanamori<sup>2</sup>
<sup>1</sup>Department of Earth and Planetary Sciences, University of California, Santa Cruz, California, USA, <sup>2</sup>Seismological Laboratory, California Institute of Technology, Pasadena, California, USA

**Abstract** On 23 June 2014, the largest intermediate depth earthquake ( $M_w$  7.9) of the last 100 years ruptured within the subducting Pacific plate about 100 km below the Rat Islands archipelago of the Western Aleutian Islands, Alaska. The unusual faulting orientation, strike = 206°, dip = 24°, and rake = −14°, is possibly related to curvature of the underthrust slab and high obliquity of the relative plate motions. The first ~15 s of the rupture generated relatively weak seismic waves, followed by strong energy release for the next 25 s. The seismic moment is  $1.0 \times 10^{21}$  Nm, and slip of up to ~10 m is concentrated within a 50 km × 50 km region. The radiated energy is  $1.1$  to  $2.7 \times 10^{16}$  J, assuming attenuation  $t^*$  of 0.4 to 0.7 s. This type of intraplate faulting can be very damaging for populated regions above subduction zones such as Japan, Taiwan, Chile, and Indonesia.

## 1. Introduction

Large subduction zone earthquakes usually involve thrust faulting at shallow depths offshore on the plate boundary megathrust fault, producing both shaking and tsunami hazards for nearby regions. Large intraplate earthquakes also occur in subduction zones, including normal faulting events near the outer trench slope; the largest known example being the great ( $M_s$  ~8.3+) 1933 Sanriku-oki earthquake [e.g., Kanamori, 1971]. The shaking and tsunami hazard of these near-trench events are now broadly recognized [e.g., Lay et al., 2009, 2011], although it remains difficult to quantify. Less well recognized are the hazards presented by large intraslab earthquakes at depths of ~70 to 200 km, which places them between the coastline and volcanic arc. While not tsunamigenic, the relatively high stress drops commonly observed for intraplate events can result in strong ground shaking from these events. Recent examples include the 78 km deep 30 September 2009  $M_w$  7.6 Indonesia earthquake which struck near the city of Padang [e.g., McCloskey et al., 2010], taking more than 1100 lives, and the 95 km deep 13 June 2005  $M_w$  7.8 Tarapaca, Chile earthquake [e.g., Delouis and Legrand, 2007]. Comparable size events at these depths are infrequent but have struck beneath Fiji, the Philippines, Hokkaido, Peru, the Solomon Islands, and Romania in the past 35 years; and the largest magnitude intermediate depth events of this type appear to be  $M$  ~8.1 events in 1903 beneath Kythira, Greece [Papadopoulos and Vassilopoulos, 2001] and in 1911 under the Ryukyu Islands [Allen et al., 2009]. Large population centers such as Taipei, Taiwan, and Tokyo, Japan are exposed to risk from this type of intermediate depth faulting [e.g., Kanamori et al., 2012]. Complex internal slab deformation is involved in such events, and the seismic hazard framework of these events is not clearly defined.

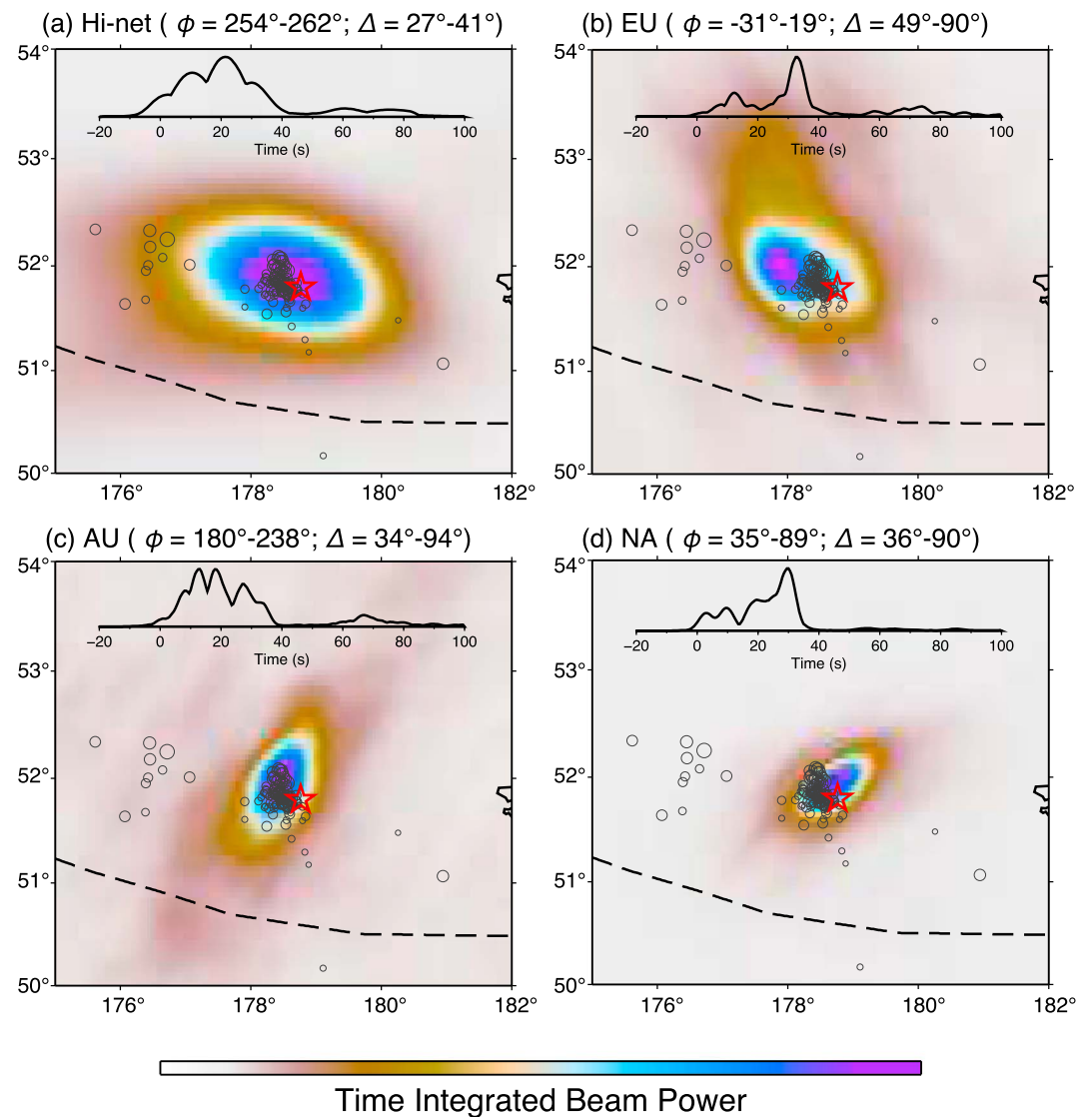
On 23 June 2014, the largest magnitude intermediate depth (70–300 km) earthquake to strike in 100 years ruptured within the subducting Pacific slab beneath the Rat Islands archipelago of the Western Aleutians, Alaska (Figure 1). The hypocenter (51.797°N, 178.760°E, 107.5 km deep, 20:53:09 UTC) (U.S. Geological Survey (USGS) National Earthquake Information Center (NEIC)): (<http://earthquake.usgs.gov/regional/neic/>) is downdip of the curving Aleutian trench in a region of highly oblique relative plate motion, with the Pacific plate underthrusting the North American plate at about 75 mm/yr [e.g., DeMets et al., 2010]. Aftershocks spread northwestward from the hypocenter with depths spanning 90 to 140 km and about 50 km horizontal extent. Two of the largest early aftershocks are shallow strike-slip events, apparently being triggered events in the North American crust. While fortunately in a low-population region, this event is representative of the intermediate depth ruptures that can pose hazards in some subduction zones.



**Figure 1.** Map showing the rupture model and aftershocks in the first 2 months for the 23 June 2014  $M_w$  7.9 Rat Islands archipelago intermediate depth earthquake. The inset locates the source region in the western Aleutian Islands, Alaska, with the trench location and 100 km depth contours indicating the position of the underthrusting Pacific plate. The global centroid moment tensor (gCMT) and W-phase moment tensor solutions for the main shock are shown along with their associated centroid locations (red triangles) relative to the hypocenter from the USGS NEIC (star). Moment tensor solutions for all 70–200 km deep events in the gCMT catalog from 1976 to 2014 preceding the earthquake are shown with corresponding year and  $M_w$  labeled. Aftershocks with  $M_w \geq 3$  are shown by circles, color coded with source depth and radius-scaled proportional to magnitude, including two shallow events with rapid gCMT solutions in the west. The preferred slip model is shown with total coseismic slip indicated by the color scale at bottom right. The barbed curve indicates the position of the Aleutian trench. The white arrow indicates the highly oblique motion of the Pacific plate relative to a fixed North America plate (model, MORVEL [DeMets et al., 2010]).

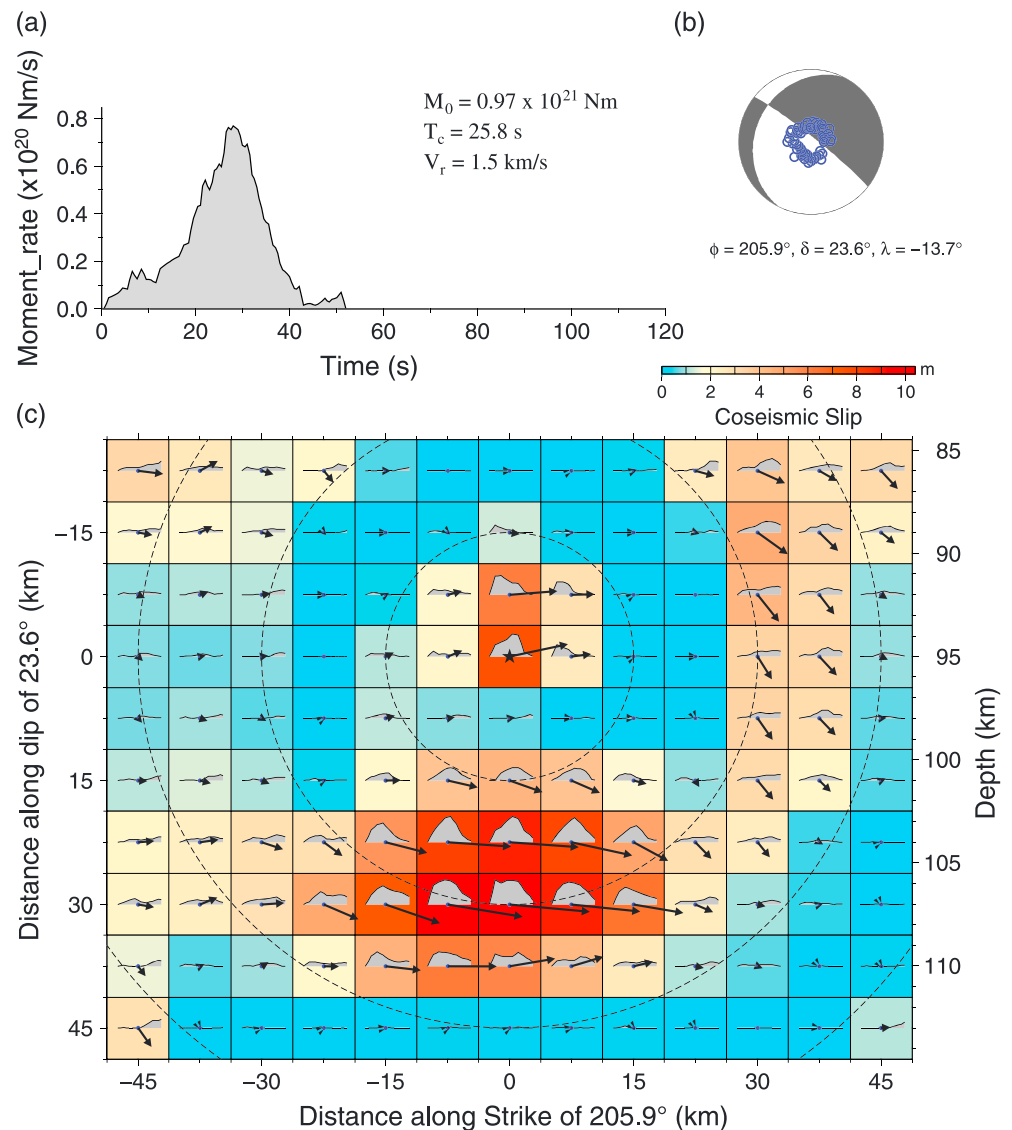
## 2. Rupture Analysis

Point-source focal mechanisms for the 2014 Rat Islands earthquake obtained from long-period seismic wave methods give consistent, predominantly double-couple, faulting geometries. The global centroid moment tensor (GCMT) solution (<http://www.globalcmt.org/CMTsearch.html>) has major double-couple nodal planes with strike  $\phi = 207^\circ$ , dip  $\delta = 26^\circ$ , and rake  $\lambda = -13^\circ$  and  $\phi = 308^\circ$ ,  $\delta = 84^\circ$ , and  $\lambda = -115^\circ$ , a centroid depth of 100.8 km, a centroid time shift of 22.9 s, and a seismic moment  $M_0 = 1.0 \times 10^{21}$  N m. We performed moment tensor inversions of 1–5 mHz passband W-phase signals [Kanamori and Rivera, 2008] using 132 ground motion recordings from 58 stations, obtaining a solution with best nodal planes with  $\phi = 205.9^\circ$ ,  $\delta = 23.6^\circ$ ,  $\lambda = -14.1^\circ$  and  $\phi = 308.8^\circ$ ,  $\delta = 84.4^\circ$ , and  $\lambda = -113.0^\circ$ , a centroid depth of 100.5 km, a centroid time shift of 22.9 s, and  $M_0 = 1.0 \times 10^{21}$  N m. These solutions give  $M_w$  7.9, and both have a null axis striking close to the relative plate motion direction (Figure 1), representing either subhorizontal or nearly vertical shearing of the slab.



**Figure 2.** Imaged locations of coherent short-period seismic energy release from the 23 June 2014  $M_w$  7.9 Rat Islands archipelago earthquake obtained by backprojection of teleseismic  $P$  wave recordings in the period range of 0.5 to 2.0 s from large networks of (a) Hi-net stations in Japan, (b) broadband stations in Europe (EU), (c) broadband stations in Australia and South Pacific (AU), and (d) broadband stations in North America (NA). The time-integrated normalized beam power for each backprojection is shown with the color scale ranging from zero (white) to 1.0 (purple). The peak beam amplitudes as a function of time are shown at the top of each panel. The stations used in each backprojection are shown in maps in Figure S1 in the supporting information. The azimuthal ( $\phi$ ) and distance ( $\Delta$ ) ranges of the stations in each network are shown. Animations of the time-varying sequence for each backprojection are also provided in the supporting information.

Backprojections of teleseismic  $P$  wave recordings from large networks of stations in Japan (short-period Hi-net stations), Europe (EU), Australia and the South Pacific (AU), and North America (NA) were performed using the method of Xu *et al.* [2009]. The four networks all indicate 50 to 100 km westward rupture propagation over an interval of about 40 s, as shown by time-integrated maps of the coherent short-period energy release in the passband 0.5–2.0 s (Figure 2). The associated station configurations are shown in supporting information Figure S1, and animations of the time-varying backprojections are shown in Movie S1. The slightly west-northwestward distribution of energy release corresponds with the distribution of aftershocks in the first 10 days after the event. Array response artifacts smear the images slightly along the great-circle directions to the networks, and there is no direct resolution of depth extent of the rupture from this method. However, indications of modest north-south broadening of the rupture are apparent in the animations,

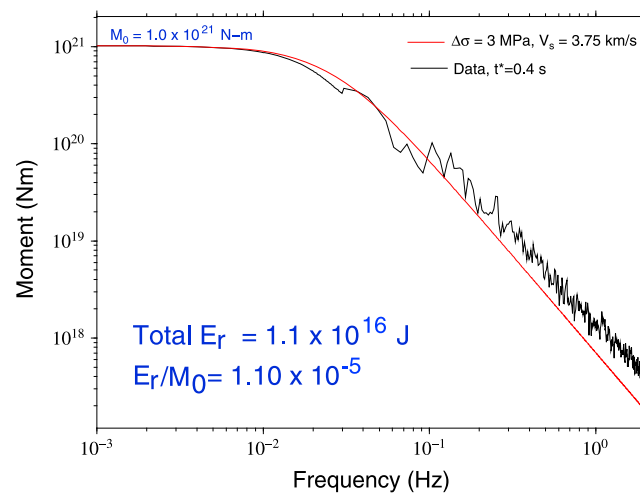


**Figure 3.** Rupture model for the preferred shallow-dipping rupture plane of the 23 June 2014  $M_w$  7.9 Rat Island archipelago earthquake obtained by linear waveform inversion of teleseismic  $P$  and  $SH$  ground displacements and ground velocities for the period band 1.1–200 s. Corresponding waveform fits are shown in Figure S2. (a) The moment rate function with the body wave inversion estimates of seismic moment,  $M_0$ , rupture centroid time  $T_c$ , and average rupture expansion velocity  $V_r$ . (b) The average fault geometry focal mechanism, with strike,  $\phi$ , dip,  $\delta$ , and rake,  $\lambda$  for the preferred fault plane. (c) Slip distribution on the model fault plane, which has 7.5 km grid spacing. The average slip for each subfault is color coded, and the vectors indicate the slip magnitude and direction of the hanging-wall plane relative to the footwall. The dashed circles are isochrones for the expanding rupture front in 10 s increments. The subfault source time functions are indicated by the polygons in each subfault, with the total rupture duration of each being 9 s. The star indicates the position of the hypocenter and corresponds to the star in Figure 1.

which slightly favor the shallow-dipping nodal plane. The limited spatial resolution does not tightly bound the rupture velocity, but all the images favor a modest horizontal extent of the rupture zone, which indicates a low apparent horizontal rupture expansion velocity of about  $\sim 1.5$  km/s.

The point-source solutions and backprojections guided the development of a finite-fault rupture model inverted from broadband teleseismic  $P$  and  $SH$  wave ground motions, with the favored model being shown in Figures 1 and 3. Ground displacement and ground velocity signals from 63  $P$  waves and 49  $SH$  recordings were inverted. A 13 column by 10 row grid of subfaults with 7.5 km grid spacing was used in a linear least



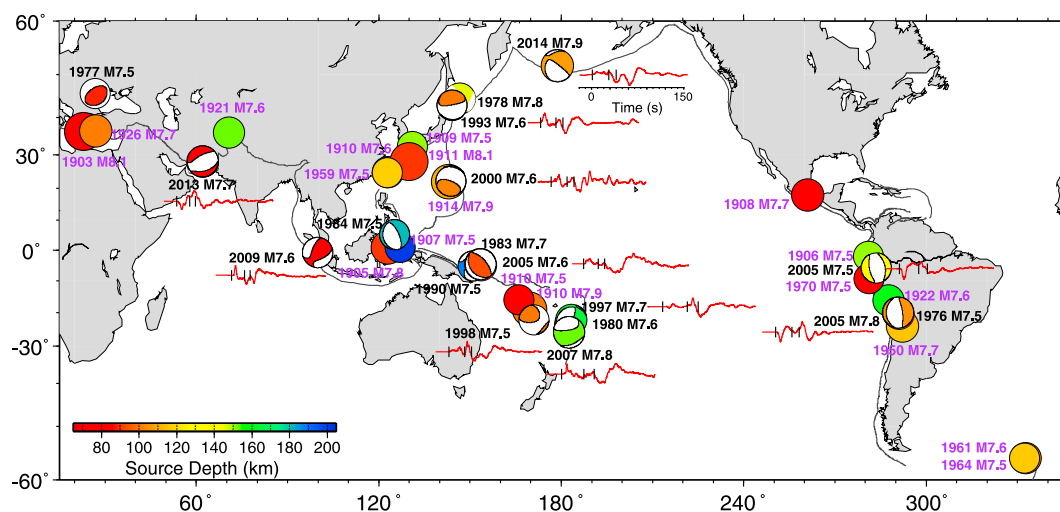


**Figure 4.** Average source spectrum for the 23 June 2014 Rat Islands archipelago  $M_w$  7.9 intermediate depth earthquake. The spectrum of the moment rate function (Figure 3) is used for spectral amplitudes for frequencies less than 0.05 Hz, whereas averaged spectra from teleseismic  $P$  wave ground displacements, corrected for an average  $t^* = 0.4$  s, are used for the higher-frequency spectrum. The radiated seismic energy,  $E_r$ , is estimated from the teleseismic  $P$  wave ground velocities and augmented for the proportion of energy in the average spectrum for frequencies below 0.05 Hz.

squares inversion with specified rupture expansion velocity [Kikuchi and Kanamori, 1991]. Each subfault was allowed to have variable rake, with the subfault source time function prescribed by eight overlapping triangles with 1 s rise times, giving subfault durations of up to 9 s. The hypocentral depth was designated as 95 km. The strike and dip of the fault plane were taken from the shallow-dipping nodal plane of the W-phase solution. Inversions were performed for a wide range of rupture velocities, grid dimensions, and subfault durations. Corresponding suites of models were computed for the steeply dipping nodal plane of the W-phase solution. We sought models that gave seismic moments consistent with the long-period moment tensor values and centroid time shifts within a few seconds of the point-source solutions.

The shallow-dipping fault plane with  $\phi = 205.9^\circ$  and  $\delta = 23.6^\circ$  toward the northwest provides better matches to  $P$  waveforms at azimuths from  $300^\circ$  to  $340^\circ$  (Figure S2) than does the steeply dipping fault plane solution (Figures S3 and S4). However, the overall waveform mismatch is comparable between the models, and some signals are better fit using the steeply dipping fault plane (notably for  $P$  arrivals at lapse times of 30 s for stations with azimuths around  $135^\circ$ – $180^\circ$ ), so our preference for the shallow-dipping plane is mild. The USGS-NEIC finite-fault model solution also adopts the shallow-dipping plane. Comparison of the catalog aftershock locations with the two possible fault planes does not provide compelling evidence to favor either plane (Figure S5), but the horizontal spread of the aftershocks and the backprojection images is more straightforward to reconcile with the horizontal plane. We cannot preclude rupture over a set of horizontally offset vertical faults. Aftershocks may also occur on separate structures, and this is clearly the case for shallow events in the upper plate located to the west of the epicenter (Figure 1).

The moment rate function has relatively low level for about the first 15 s of the rupture, and the waveforms show small short-period pulses during this interval that are hard to match in the finite-fault inversion. This interval is followed by a large triangular pulse with about 25 s duration (Figure 3). W-phase and body wave inversions of short-time windows of the first 25 s of the teleseismic signals do not resolve significantly different faulting geometry of the early radiation. Typical of teleseismic inversions, particularly for intraplate ruptures, the data have limited resolution of rupture velocity. However, using 1.5 km/s as suggested by the backprojections provides a solution that is slightly favored in terms of waveform fit and places the primary slip regions in the vicinity of the aftershock distribution (Figure 1). The rupture velocity and subfault source time function parameterization have significant trade-offs in controlling the spatial distribution of slip. The slip function for this model shows about 6 m of slip near the hypocenter followed by a  $30 \text{ km} \times 30 \text{ km}$  patch of large slip (up to 10.3 m) centered about 25 km downdip (toward the northwest) (Figure 3). Similar northwestward offset of the main pulse is found for the steeply dipping fault plane (Figure S3). The seismic moment is  $1.0 \times 10^{21} \text{ N m}$ , and the centroid time shift is 25.8 s, with the average depth of the slip distribution being 101 km, so the model in Figure 3 is compatible with long-period point-source constraints. Trimming off subfaults that have less than 15% of the peak subfault moment, the rupture area is found to be  $3487.5 \text{ km}^2$ , and the average slip is 3.9 m. Assuming a circular rupture area, the static stress drop is 11.8 MPa. These estimates have substantial uncertainties corresponding to the limited spatial resolution of the teleseismic inversion.



**Figure 5.** Map showing the global distribution of all 37 earthquakes in the depth range 70 to 200 km between 1900 and 2014 with  $M_w \geq 7.5$  from the PAGER-CAT [Allen *et al.*, 2009], with events since 1976 displayed as the GCMT moment tensor. For the recent large events, a broadband  $P$  wave ground displacement is shown with tick marks indicating the  $P$ ,  $pP$ , and  $sP$  arrival times (all have the same time scale with 20 s leader ahead of the  $P$  arrival and 150 s of signal after that). Figure S6 identifies the specific stations shown for each event. Some events may actually be shallower events with over-estimated depth in the catalog, and some events actually in this depth range may be missed because the catalog depths are incorrectly estimated as less than 70 km.

The average source spectrum is shown in Figure 4, along with the measured radiated energy,  $E_r$ . The source spectrum is obtained from the spectrum of the moment rate function for frequencies less than 0.05 Hz, and from the stack average of broadband  $P$  wave displacement spectra, corrected for radiation pattern and an attenuation operator with  $t^* = 0.4$  s, for higher frequencies. The specific choice of  $t^*$  is not well resolved. The intermediate depth of the event and the presence of the steeply dipping subducting slab traversed by the down-going signals below the source motivate a relatively low  $t^*$ . This source spectrum is slightly enriched in high-frequency spectral levels relative to a reference  $\omega$ -squared source spectrum with a stress parameter of 3 MPa. For the frequency band from 0.0 to 2.0 Hz the total radiated energy  $E_r = 1.1 \times 10^{16}$  J, for a  $t^* = 0.4$  s. This estimate is based on the methodology of Venkataraman and Kanamori [2004] applied to teleseismic  $P$  wave ground velocities, augmented by the relative proportion of energy in the spectrum for frequencies less than 0.05 Hz [e.g., Ye *et al.*, 2013]. The corresponding seismic moment-scaled energy ratio is  $E_r/M_0 = 1.1 \times 10^{-5}$ . Use of a higher  $t^* = 0.7$  s gives  $E_r = 2.7 \times 10^{16}$  J for the same passband.

### 3. Discussion and Conclusions

The 23 June 2014  $M_w$  7.9 Rat Islands archipelago earthquake ruptured within the subducting Pacific plate downdip from the megathrust fault that produced the great 4 February 1965  $M_w$  8.7 Rat Island earthquake [e.g., Wu and Kanamori, 1973; Beck and Christensen, 1991]. That event induced a large  $M_w$  7.6 trench slope normal faulting aftershock on 30 March 1965 [Abe, 1972], as commonly observed seaward of great interplate ruptures [e.g., Lay *et al.*, 1989; Craig *et al.*, 2014]. Such intraplate faulting may provide hydrated zones that can be reactivated as the slab sinks to intermediate depths and undergoes dehydration reactions that release fluids and reduce confining stresses on the fault zone. This general scenario is commonly invoked to account for intermediate depth earthquakes as fluid-assisted dehydration embrittlement faulting, although self-localizing thermal shear runaway mechanisms are also considered viable [Prieto *et al.*, 2013]. Even if correct in general, reactivation of prior fault systems does not provide a simple strain accumulation and release context like that for the relative plate motions driving megathrust faulting to provide guidance on the frequency of large intermediate depth events. The best approach that we have is to characterize the attributes of such events based on the limited number of recorded examples and to recognize their general potential in earthquake hazard assessments.

The faulting orientation for the 2014 Rat Islands event is not easily related to geometry of shallow plate bending faults, with the deeper slab either displacing northeastward on the favored shallow-dipping plane or almost vertically downward on the steeply dipping plane. Given the increasing obliquity of the relative plate motions along the curving Aleutian trench, contortion of the subducted Pacific plate is expected to affect the intraplate stresses in the slab beneath the Rat Islands archipelago [e.g., Creager and Boyd, 1991; Ruppert et al., 2007], but the faulting orientation may be influenced by inherited shallow intraplate fault zone structure.

The distribution of large earthquakes at depths from 70 to 200 km with  $M_w \geq 7.5$  from the seismological record is shown in Figure 5. Epicenters of events dating back to 1900 are shown by circles, and GCMT focal mechanisms are shown for the events since 1976. Comparisons of teleseismic  $P$  waveforms from several of the larger recent events are included, demonstrating the overall similarity of the 2014 event signals to events in other regions. The map indicates the global extent of this class of intraslab earthquakes relative to population centers. Slabs with varying thermal structures, convergence rates, and geometries experience large intermediate depth events, and detailed work is required to evaluate whether there are any tectonic controls on their occurrence that could guide hazard assessments. Each region likely has unique tectonic stresses and inherited faulting geometries from shallower plate bending, making it difficult to infer recurrence and total distribution of such events from the short seismological record along with the lack of geologic record; but at a minimum, recognition of this class of infrequent large ruptures should be incorporated into seismic hazard assessments in populated subduction zone environments.

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