The Pennsylvania State University
College of Earth and Mineral Sciences
Department of Geosciences

Historical Seismicity and Earthquake Dynamics along the Kuril-Kamchatka, Tonga-Kermadec and Solomon Islands Subduction Zones

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by

Kara A. Cahoon

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We approve this thesis:

Charles J. Ammon, Professor of Geosciences

Mark Patzkowsky, Associate Professor of Geosciences
Associate Head of the Undergraduate Program

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Date
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Abstract

Earthquake processes are dynamic and the style and mechanism of earthquake rupture varies greatly from one subduction zone to the next, and often within a single subduction zone. The development of the asperity model (Scholz, 1974; Lay and Kanamori, 1982) was an important conceptual advance in earthquake seismology at the time. The idea that faults include both regions that slip aseismically as well as strongly coupled regions of relatively high stress, termed asperities, which can differ in size and location to one another, seemed to explain the first-order variation in seismic behavior observed along many subduction zones. For the most part, this conceptual model remains valuable, but the lack of large earthquakes in the several decades following its introduction meant that these ideas remained mostly untested. In the last two decades, however, an increase in large earthquake activity has not only allowed us to test this hypothesis, but introduced further complications—evidence that subduction zone earthquake processes are more complex and more dynamic than originally thought.

The addition of two-to-three decades of seismic observations is a very short interval compared to the cycle of large subduction zone earthquakes. However, since the early 1980s, the development of an earthquake catalog that includes faulting geometry and accurate seismic moment estimates (Dziewonski et al., 1981) has produced information on tens of thousands of small earthquakes with which to explore the earthquake processes along subduction plate boundaries. The central question of this thesis is to determine whether the substantial increase in reliable information on the faulting geometry, size, and depth of moderate-to-large earthquakes along with the new information gleaned from recent major and great earthquakes provides
additional insight into large-earthquake rupture processes since they were developed in the 1970s.

In the following, I try to answer this question by investigating seismicity in three of the most active regions in the world. While the asperity model still seems to explain the first-order characteristic rupture style seen in these regions, recent observations demonstrate that earthquake interaction (triggering) and the impact of slow-deformation processes are more dynamic and perhaps have a broader impact than originally thought. Release of stress following an earthquake can result in the redistribution of stress not only along the same structure but at other locations along and adjacent to the plate boundary. The presence of slow-deformation on major faults may help explain the patterns associated with earthquake doublets and large earthquakes, however further work is needed to better identify the affects of slow-slip events on the nucleation of large earthquakes (Kato et al., 2012). In the scope of an undergraduate thesis, not all avenues can be investigated; the most robust observations may also be those that are most obvious in the data, and these are the patterns I explore.
**Introduction**

The generation of large (Mw > 7.0) earthquakes has been a focus within the scientific community since the establishment of the field of seismology (e.g. Milne, 1886; Gutenberg and Richter, 1954; Lay & Kanamori, 1980; Pacheco and Sykes, 1992). In the 1950s and 1960s, the world experienced a number of very large (megathrust) events, propelling the scientific community to investigate the causes and to categorize the behavior of different subduction zones. Lay and Kanamori (1982) published a review of the historical seismicity of all circum-pacific subduction zones, including a description of the rupture style for each region viewed in the light of the asperity model of plate-boundary friction. The asperity model states that along the plate-interface there are regions of high stress accumulation, termed *asperities*, and large earthquakes occur when a large asperity or a series of large asperities ruptures. There has been debate on this issue, and some argue that the occurrence of large earthquakes may not be an issue of subduction zone characteristics, but of recurrence intervals or limited sampling history (McCaffrey, 1994; Stein and Okal, 2007). Despite wide acceptance that fast subduction of young, hot lithosphere is associated with large seismic rates and the generation of great (Mw > 8.0) earthquakes (e.g. Bird et al., 2009; Heuret et al., 2011; Gutscher and Westbrook, 2009), more events were needed to test the varying hypotheses on where and why large and great earthquakes can occur.

For more than three decades, there was a worldwide period of relative quiescence (in terms of large earthquakes), without a single earthquake greater than Mw = 8.5. Then the 2004 great Sumatra-Andaman event occurred. As the first earthquake of its size in 40 years, the event generated much focus within the seismological community. The 2004 Mw = 9.2 event ruptured a 1,300 km section along the Sunda Trench, and produced a devastating tsunami that killed more than 283,000 people (Lay et al., 2005). The megathrust event did not only rupture in the expected...
region of convergence along the Sunda Trench, but propagated more than 1,000 km to the north into a region with plate motion parallel to strike. Additionally, this event and events in 2005, 2007 and 2010 ruptured and re-ruptured regions of the plate boundary that had failed previously and therefore were thought not to be capable of harboring a great earthquake. The earthquake was not only the first of its size in several decades and unusual, but it occurred along a boundary where such a large event was unexpected. The oceanic lithosphere at the plate boundary is not young, the rate of subduction is not fast (57 mm yr\(^{-1}\)) and the region is active with back-arc spreading (Ruff and Kanamori, 1980)—all characteristics previous thought to indicate that a region was not capable (or at least, likely) of rupturing in a great megathrust earthquake. Debate continues within the scientific community, many arguing that this event was further evidence that the regional lack of large and great earthquakes is an issue of recurrence time (McCaffrey, 1994) and limited sampling history (Stein and Okal, 2007), and not simply a consequence of subduction zone characteristics; some have suggested that large and great earthquakes could happen anywhere (Gutscher and Westbrook, 2009).

The Sumatra-Andaman event not only questioned what we thought we knew about how subduction zones behave and where large and great earthquakes can occur, but it occurred at the onset of a period of increased large seismic activity, with continued large events occurring worldwide (e.g. Kuril Islands, Solomon Islands, Northern Tonga, Chile, Tōhoku). A focus developed on determining whether the frequency of earthquakes, particularly large and great earthquakes has increased in the last decade (Kerr, 2011). As the scientific community re-examines worldwide subduction zone earthquake processes, there is hope that in the light of recent seismic events and with technological advances in the past half-century, we can better constrain and possibly better forecast seismic behavior along subduction zones.
To examine whether the new observations provide more insight into the old ideas of how subduction zones are seismically classified, in this investigation, I focus on the Kuril-Kamchatka, Tonga-Kermadec and Solomon Islands subduction zones (Fig. 1), regions with three of the fastest convergence rates worldwide, as determined from the MORVEL 2010 database (DeMets et al., 2010). We are still limited by short observing intervals, but these regions of rapid plate convergence should have advanced more than slower converging boundaries in the time since the earlier summary studies. In the last several years, there has been an overwhelming focus on the seismic behavior along the Sumatra and Japan subduction zones because of the very large earthquakes that occurred there. As a result, they are not addressed in detail in this report. A detailed analysis of the events and the seismicity of the regions in which they occurred can be found in Lay et al. (2005); Ammon et al. (2005) and Sato et al. (2011); Ozawa et al. (2011); Lay et al. (2011), respectively.
For each of the three focus regions, a literature review of the seismic history, along with data on the seismic activity from the recently constructed PAGER-CAT (Allen et al., 2009), the USGS's NEIC Search database and the Global Centroid Moment Tensor Project (Global CMT Project, 2012) is provided. To begin, I updated historical reviews of the seismicity of these three subduction zone regions with a focus on large and great earthquakes in order to reexamine ideas on seismic behavior in these regions, and to identify any implications that can be made for subduction zones worldwide as a result.

**Completeness of Seismic Catalogs**

As in any investigation of seismic activity, it is first necessary to examine the earthquake catalog characteristics. Historic earthquake magnitudes and moment tensor solutions for the
regions analyzed in this report were obtained from three seismic catalogs: the NEIC PDE database, the Global CMT database, and the PAGER-CAT database. In order to analyze the completeness and homogeneity of each catalog, the well-established Gutenberg-Richter empirical relationship between the common logarithm of earthquake frequency and magnitude:

\[ \log(N) = a - bM \]

where \( N \) is the number of earthquakes with magnitude greater than \( M \), and \( a \) and \( b \) are constants, was used. The expected relationship is one where \( \log(N) \propto -M \), where a \( b \)-value of one indicates that the frequency of earthquakes of a given magnitude is ten times greater than that of the magnitude one unit smaller. A non-constant \( b \)-value deviating from one can indicate an incomplete seismic catalog or reflect the seismic characteristics of a particular region where the frequency of events in not proportional to \( 10^{-M} \).

**NEIC Preliminary Determination of Epicenters Database**

The USGS's National Earth Information Center (NEIC) constructs and manages the NEIC PDE catalog, an online database of worldwide earthquakes updated roughly each month as a part of its publication, Preliminary Determination of Epicenters (PDE). Hypocenter information in this catalog proceeds through several stages, starting with daily hypocenter estimates (earthquakes with magnitude greater than 5.0 are routinely updated in near-real time), then followed by more refining weekly and monthly, to produce a final estimate as more data are examined. The catalog includes data for US earthquakes with magnitude \( \geq 2.5 \) and worldwide earthquakes with magnitude \( \geq 4.5 \) since 1973 (Sipkin et al., 2000). The completeness of the catalog is affected by variation in the density of seismic networks throughout the world that report their data to the NEIC as well as the uniformity of the station locations. The magnitude in
this catalog may be a preferred value selected from mb, Ms, or several estimates of Mw, depending on the source size and location. Thus the generic catalog magnitude is called a summary magnitude.

A Log(frequency) versus magnitude curve was created using all available NEIC PDE events, from 1973 through the 2011. The graph in Figure 2 shows a linear relationship between frequency and magnitude (above magnitude \( \sim 4.5 \)), an expected outcome given the catalog completeness mentioned. The b-value is close to unity when considering events greater than \( M = 4.5 \).

![Figure 2. The Gutenberg-Richter relationship for the NEIC Preliminary Determination of Epicenters Database. For events \( M > 4.5 \), the b-value is unity.](image)
Global Centroid Moment Tensor Database

The Global Centroid Moment Tensor (GCMT) database (Dziewonski et al., 1981; Global CMT Project, 2012) was started in 1976 as the Harvard CMT catalog. The database is updated regularly and contains centroid moment tensor solutions for earthquakes with magnitudes ≥ 5.0 starting in 1976. Because long-period seismic waves are used in moment-tensor estimation, these catalogs saturate for earthquakes with magnitude ≥ 9.0 (USGS, 2009). Figure 3 illustrates the Gutenberg-Richter relationship for the entire Earth, which indicates a b-value of unity for the events with magnitude ≥ 5.0.

Figure 3. The Gutenberg-Richter relationship for the Global Centroid Moment Tensor Database. For events M > 5, the b-value is unity.
PAGER-CAT

The USGS’s Prompt Assessment of Global Earthquakes for Response Catalog (PAGER-CAT) system contains earthquake source data merged from several published catalogs (including Gutenberg and Richter (1954), Abe (1981), Pacheco and Sykes (1992) and the NEIC PDE and GCMT (for more recent events)) for earthquakes with magnitude ≥ 5.5 from 1900 – June 2008 (Allen et al., 2009). GCMT is the primary source for magnitude data within the catalog for events after 1976. For events prior to this, earthquake information in PAGER-CAT is obtained from the Centennial Catalog (Engdahl and Villasenor, 2002), which contains data for earthquakes with M ≥ 6.5 for 1900 – 1963 and M ≥ 5.5 post-1963. For this reason, PAGER-CAT serves as the primary source for earthquake data prior to 1976, and is used as such in this report. The catalog is complete for recent events greater than 5.5, but probably only complete to a magnitude of 6.5 for events pre-dating the NEIC and GCMT catalogs. Again, the slope of the Gutenberg-Richter relationship for the entire planet is roughly unity (Fig. 4).
Figure 4. The Gutenberg-Richter relationship for the PAGER-CAT earthquake database. For events $M > 5.5$, the $b$-value is unity.

Having reviewed the global patterns, I now investigate the seismicity patterns and descriptive statistics of the three focus areas.

Kuril Islands and Kamchatka

The Kuril-Kamchatka plate boundary is comprised of an approximately 2,200 km segment extending from the island of Hokkaido, Japan in the southwest to the northeast along the coast of Kamchatka, ending where it intersects the Aleutian Trench at the Bering Sea. Along the trench, old continental crust of the Pacific Plate subducts beneath the North American Plate to the northwest at an average rate of 80 mm yr$^{-1}$ (MORVEL, 2010). A line of active volcanic islands comprising the Kuril Islands parallels the associated deep-sea trench. The Kuril-Kamchatka subduction zone is a very seismically active margin (Fig. 5), regularly generating
large earthquakes. In the last 40 years alone, roughly 30 large events have occurred. Historically, several great earthquakes have occurred in this region, including ones that generated destructive tsunamis.

One interesting characteristic of the Kuril-Kamchatka subduction system is the existence of a double Benioff zone, in which two parallel regions of seismicity exist. Down-dip compressional events occur along the top layer, while the lower layer is generally characterized by down-dip extension. The top layer of seismicity, beginning at a depth of 50 – 60 km, dips at 30° – 40° and the bottom layer, which begins at a depth of 70 – 80 km has an average dip of 20° – 35° (Kao and Liu, 1995). The two layers of seismicity are separated by approximately 25 – 40

Figure 5. Historic seismicity along the Kuril-Kamchatka Trench. Events are scaled logarithmically to magnitude and rupture area. All events from 1973 through 2011 are shown in gray; historic large earthquakes (M > 7) from 1900 – 1972 are shown in red.
km at depth and merge into a single layer at a depth of approximately 200 km (Kao and Chen, 1994). In 1994, Kao and Chen identified the geometry of the double seismic zone as two layers of seismicity that overlap in the central portion of the arc. This overlapping region is located approximately between 46° – 53°N. North of this region, it is thought that the upper layer of compressional events extends as a single seismic zone, while to the south, a single seismic zone of extensional events occurs.

The Gutenberg-Richter characteristics for events located in this region, as determined by the three catalogs used in this report, are shown in Figure 6. The PAGER-CAT record shows a slight shift in the frequency data, indicating a change in b-value between events of $M = 5.5 – 6.3$ and those larger. The b-value for the PAGER-CAT is .9. The b-values for the NEIC catalog data and the GCMT data for the Kuril and Kamchatka region are one or slightly lower, 1.0 and .9, respectively. The combination of a b-value for all three catalogs of one or less than one indicates a very slight preference in this region for larger earthquakes, which has continued recently given the continued low b-values of the NEIC and GCMT catalogs. However, statistics on the small number of large earthquakes are uncertain given the brevity of the available catalogs.
On November 4, 1952 one of the largest magnitude earthquakes ever recorded occurred in Kamchatka (Fig. 7). This $M_w = 9.0$ event occurred along the southeast coast of Kamchatka (52.3°N, 161°E), with the rupture propagating to the southeast for approximately 700 km. The event generated a tsunami with wave heights up to 12 meters (Ruppert et al., 2007). The average slip was estimated to be 3 meters and maximum slip was 11 meters (Johnson and Satake, 1999). A lack of aftershocks in the region of the greatest slip is thought to reflect the presence of a large asperity, which ruptured entirely during this event.

Other notable Kamchatka events occurred in 1904 and 1923, both of which also generated tsunamis. An $M_s = 8.3$ event occurred on June 25, 1904, rupturing a section of the plate boundary located down-dip from the central portion of the 1952 rupture, that did not
rupture at the time of the 1952 event. On February 2 and 3, 1923 a doublet occurred along the northeast edge of Kamchatka (Mw = 8.5), but also did not extend into the 1952 rupture region (Ruppert et al., 2007; Johnson and Satake, 1999). (By doublet we mean two similar-sized earthquakes that occur within a few months of one another—and in some cases, a few hours to days.) Aside from these two events, other large (M > 7) events have occurred over the last century along the Kamchatkan coast, surrounding, but not completely re-rupturing the area of the 1952 event.

Along the Kuril Trench, there have been several notable great earthquakes (Fig. 7), including shallow thrust events that occurred along the plate boundary and at shallow depths in the outer rise within the subducting slab. The largest event recorded on seismic instruments in this region occurred on October 13, 1963. The Mw = 8.6 event occurred in the south-central region of the arc propagating to the northeast with a rupture length of about 250 km (Fig. 7). The event triggered a tsunami with a run-up height of up to 5 meters along the Kuril Island Arc (Ruppert et al., 2007). It occurred north of an Mw = 8.4 earthquake that occurred on November 6, 1958; there was overlap of the rupture region for these events. More than 40 years after the 1963 event, a great shallow thrust earthquake occurred in the central Kuril plate boundary. The Mw = 8.3 event occurred on November 15, 2006 rupturing a 300 km segment and filling a previously noted seismic gap located between events that nucleated in 1915 and 1918 (Fig. 7) (Ruppert et al., 2007). In the two months leading up to the rupture, a sequence of foreshocks occurred in the region and the main shock was followed by a typical aftershock sequence. The 2006 event occurred in what could be considered a seismic gap that had remained quiet since at least 1915 (Lay and Kanamori, 1980).
Two months after the 2006 event, on January 13, 2007, an unusual and unexpected event occurred. An Mw = 8.1 normal faulting intraplate earthquake ruptured less than 50 km from the November epicenter. The event was the third largest normal faulting event ever recorded; it occurred in the trench-wall/outer rise area, and the aftershocks coincided with the activity of the 2006 earthquake. While the occurrence of outer rise events following great earthquakes along the Kuril-Kamchatka Trench is not uncommon, the magnitude of this earthquake was quite unusual. Raeesi and Atakan (2009) have suggested that a combination of strong coupling along the plate interface in this region, and slab pull forces following the November event caused extension in the outer rise which led to the January 13, 2007 normal faulting event. This dynamic triggering
of earthquakes and evolution of deformation styles, from shallow thrusting compressional events to normal faulting extensional events between 1963 and 2007, provides new insight into earthquake triggering and how and where large and great earthquakes can occur. Figure 8 shows the focal mechanisms of events from 1976 through 2011, including the January 13, 2007 event. Additional large events along the Kuril Trench include an Ms = 8.3 that occurred on October 4, 1994 along the trench just south of the 1958 event.

![Figure 8: Focal mechanisms for events along the Kuril-Kamchatka Trench from 1973 through 2011. Earthquakes are color-coded by depth: red $\leq$ 100 km, blue: 100 – 500 km, green: 500 – 800 km.](image)

The occurrence of a large megathrust earthquake along the Kuril-Kamchatka Trench in 1952 indicates that this region is certainly capable of rupturing large segments of a fault in a
single event (Fig. 7). In terms of the asperity model, major earthquakes occurring in the area surrounding the rupture zone of the 1952 event represent stress adjustments or deformation to the locked zone, but not a complete re-rupturing of this asperity, meaning more great earthquakes can certainly be expected in this region in the future—particularly along the region between the 1963 and 2006 Kurile Island events, and the 2006 and 1952 Kamchatka events. Given that re-rupturing of the same region has occurred along the adjacent Kuril Trench (Fig. 7), it is not unreasonable to expect that this may occur within these two regions of relatively little recent seismic activity, which if the areas are locked, would certainly indicate the possibility of producing great earthquakes.

**Tonga and Kermadec**

The Tonga Trench has the greatest rates of subduction and back arc extension of anywhere on Earth. Located just south of the island of Samoa in the South Pacific, the Tonga Trench trends N15°E, running parallel to the volcanic arc containing the island of Tonga (Bonnardot et al., 2007). It transitions into the Kermadec Trench prior to terminating at North Island, New Zealand (where subduction continues along the North Island). To the west of the Tonga Trench, between Tonga and the island of Fiji is the Lau Basin, a V-shaped basin that marks the eastern extent of the Australian Plate and in which active seafloor spreading is occurring. To the east of the Tonga Trench is the Pacific Plate. It is thought that the Lau Basin formed when the Tonga Ridge rifted, separating from the Lau Ridge. The Lau Basin is unique in that it is very seismically active and opening at a rate of 160 mm yr\(^{-1}\), the fastest rate of back-arc spreading worldwide, a significant contribution to the overall rate of convergence along the Tonga Trench (Bevis et al., 1995). Similar to regions of the Kuril-Kamchatka Trench, a double
Benioff zone also exists along the Tonga Trench north of 25°S that extends to a depth of 300 km—much greater than that of its Kamchatka counterpart (Bonnardot et al., 2009). Bonnardot et al. (2009) suggests that slab detachment may explain an observed seismic gap at depth along the trench in this region, however the focus of this investigation is on shallow trench seismicity.

Figure 9 illustrates the Gutenberg-Richter relationship between the frequency and magnitude of events along the Tonga-Kermadec Trench, as determined from the three catalogs used in this investigation. For this region, the b-value for the NEIC catalog is 1.1, as evidenced by the lack of events above M = 8 and dominance by events as low as M = 4.5. The b-value for PAGER-CAT is also 1.1, with a pronounced shift in slope around M = 6, a reflection of the disproportionately low number of large and great earthquakes in this region, and also a shift in the completeness of the seismic catalog. The b-value obtained from the GCMT catalog is 1.0. The trend for all three catalogs of b-values ≥ 1.0 reflects the lack of great earthquakes (M > 8) and that seismicity along the Tonga-Kermadec Trench is dominated by frequent, small earthquakes.
Since 1981, several short seismic campaigns have been carried out which characterize the background seismicity of the Tonga region, the majority of which is occurring in the Lau Basin as deep (>500 km) earthquake swarms. GPS campaigns carried out from 1990 – 1992 record spreading rates within the basin of 90 – 160 mm yr\(^{-1}\) (Bevis et al., 1995). Rates of subduction along the Tonga-Kermadec Trench range from 164 – 240 mm yr\(^{-1}\), the highest on Earth.

As already mentioned, this region is characterized seismically by frequent small events and many moderately-sized events, with a 90-year coupling factor of .4—that is, over a period of 90 years, thirty percent of the observed slip rate was accounted for seismically (Pacheco and Sykes, 1993). The lack of strong regions of seismic coupling may be due to the combination of fast convergence and very old subducting crust (Okal et al., 2004). But the important question of
whether we have been observing long enough to witness great events in this region, remains. The region is difficult to monitor geodetically and so estimating the area of the plate boundary that may be locked is a challenge. Historically, several tsunamis have occurred as a result of events along the Tonga-Kermadec Trench. Figure 10 shows the seismicity of the region from 1900 through 2011, including the location of large historic events. Figure 11 is a map of focal mechanisms for events from 1976 through the 2011.
Figure 10. Historic seismicity along the Tonga-Kermadec Trench. Events are scaled logarithmically to magnitude and rupture area. All events from 1973 through 2011 are shown in gray; historic large earthquakes (M > 7) from 1900 – 1972 are shown in red.
Figure 11. Focal mechanisms for events along the Tonga-Kermadec Trench from 1973 through 2011. Earthquakes are color-coded by depth: red $\leq 100$ km, blue: 100 – 500 km, green: 500 – 800 km.
Since 1981, four Mw = 8.0+ underthrust earthquakes have occurred along the Tonga-Kermadec Trench. The most notable great earthquake to occur in recent decades in this region was a series of three events, the first of which was an Mw = 8.1 normal faulting event on September 29, 2009 that occurred on the northern end of the Tonga subduction zone (Lay et al., 2010). Two minutes later, a doublet occurred consisting of two Mw = 7.8 thrust events. The events triggered a deadly tsunami with run-ups of 2 – 12 meters along the coast of American Samoa (USGS, 2009). Not only was the first event rare—a large extensional event occurring in the shallow trench slope—but it is also unusual in that it triggered these two large thrust earthquakes; it is more common to see extensional events triggered by thrust faulting. Lay et al (2010) suggests the region of the megathrust that ruptured in this incident was a region that typically experiences slow-slip; the sudden high rates of strain from the rupturing of the Mw = 8.1 extensional event triggered the megathrust to fail.

Prior to this event, four other large historic earthquakes that occurred along the Tonga-Kermadec Trench are known to have triggered tsunamis. Events on May 1, 1917 (Mw = 8.1), June 26, 1917 (Mw = 8.0) and April 30, 1919 (Mw = 8.2) each caused local tsunamis. Okal et al. (2004) cites an event on November 16, 1865 (Mw = 8.4) as the earliest record of a tsunami event in this region. The moment release for the 1865 event as determined by Okal et al. (2004) indicates that it was likely significantly larger than the 1919 event, which would also make it the largest event recorded along the Tonga-Kermadec Trench. However, PAGER-CAT lists the June 26, 1917 event as a Mw = 8.5 (from Pacheco and Sykes, 1992), making it larger than the 1865 event, although PAGER-CAT does not include the 1865 event, so it is difficult to make a direct comparison. In general, estimating the size of these old events is a challenge, but understanding
the capability of the subduction system to produce large tsunamigenic earthquakes is a critical aspect of global hazard assessment.

A seismic gap exists along the Tonga-Kermadec Trench; there has been a lack of any events with magnitude greater than 7.2 between 21 – 25.5°S, excluding a single Ms = 7.7 event on December 19, 1982 (24.1°S). This, combined with the fact that no earthquake above ~ M = 8.6 has been recorded in this particular region may indicate that this portion of the plate boundary is dominated by slow-slip deformation that extends across much of the subduction boundary. The occurrence of tsunami-generating earthquakes in the past supports the argument that the Tonga-Kermadec Trench may be a slow-slip region quite capable of generating tsunami earthquakes (as defined by Kanamori, 1972) (Okal et al., 2004). The lack of many great earthquakes despite the fastest convergence rates in the world may be indicative of the plate boundary characteristics (size and number of asperities) in this region, the age of subducting lithosphere, or simply indicate that the recurrence interval is too large, and more great earthquakes have yet to occur—though it appears unlikely that we have missed a particularly large event given the extremely high rates of subduction. Still, the historical activity from 1865 suggests caution in any pronouncements.

**Solomon Islands**

The focus here is on the New Britain and Solomon Island Trenches in the region surrounding the Solomon Islands (Fig. 12). The Solomon Sea Plate subducts beneath the Bismarck Sea Plate along the New Britain Trench at 104 mm yr\(^{-1}\) (MORVEL, 2010) to the northwest. There is a sharp bend where the New Britain Trench meets the Solomon Island Trench about 150 km south of the island of New Ireland (In some places, both legs are referred to as the New Britain Trench, for clarity, they are distinguished here); along this opposing leg,
the Solomon Sea, Woodlark and Australian Plates subduct beneath the Pacific Plate (Ontong-Java Plateau). On the opposite side of the Solomon Islands, the Pacific Plate is subducting to the southwest beneath the Solomon Islands, however the primarily deep seismicity related to this subduction is not the focus of this investigation. The Solomon Island Trench extends through the Woodlark Basin. Just south of the island of Bougainville, the Woodlark Rise, a transform fault, intersects the Solomon Island Trench perpendicularly, forming a triple junction that separates the Solomon Sea Plate subducting at a rate of 92 – 125 mm yr$^{-1}$ from the Woodlark Plate, subducting at 108 mm yr$^{-1}$ (Taylor et al., 2008; Miyagi et al., 2009; Tregoning et al., 1998; Weissel and Taylor, 1982). Further to the southeast, at the end of the islands that make up the Western Province, the Simbo Ridge transform boundary intersects the Solomon Island Trench forming a second triple junction, which serves as the boundary between the Woodlark Plate and the Australian Plate, subducting beneath the Pacific Plate at 97 mm yr$^{-1}$ (Taylor et al., 2008; Miyagi et al., 2009). Beyond this triple junction, the Solomon Island Trench continues as the San Cristobal Trench. This investigation focuses on the seismicity along this region until the island of Makira-Ulawa.
Figure 12. Plate boundaries and geography for the Solomon Islands region. Italics denotes island names. Arrows show the general plate motion of subduction, but are not meant to illustrate the precise direction of convergence.

Figure 13 shows the Gutenberg-Richter relationship for all events within the Solomon Islands. The region is very seismically active and the b-values for all three catalogs are very close to unity. The b-value for the PAGER-CAT is .93, for the NEIC catalog .98 and for the GCMT catalog is .99. The region lacks any seismicity with a magnitude larger than 8.4. Figure 14 illustrates the historical seismicity and Figure 15 displays focal mechanisms for this region for all events from 1976 through 2011.
Figure 13. The Gutenberg-Richter relationship for events along the Tonga-Kermadec Trench for all three catalogs. The b-values are as follows: PAGER-CAT .93; NEIC .98; GCMT .99.
Figure 14. Historic seismicity along the Solomon Island subduction zone. Events are scaled logarithmically to magnitude and rupture area. All events from 1973 through 2011 are shown in gray; historic large earthquakes (M > 7) from 1900 – 1972 are shown in red.
The Solomon Islands subduction zone is characterized by large shallow thrusting events that occur in doublets, a few hours to several days and less than 100 km apart, making this region distinct from all other subduction zones. My focus here is on pairs of events with magnitude \( \geq 7.0 \), often occurring with a few hours to a couple days of one another. This behavior has been attributed to the presence of closely spaced asperities along the plate boundary that trigger slip on one another when they fail (Lay and Kanamori, 1980). The trend of large shallow thrust events was initially apparent following doublet events in 1971, 1974 and 1975. The location, magnitude and rupture time for all large (\( M > 7.0 \)) doublet events determined between 1900 – 2011 are listed in Table 1.
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* NI = New Ireland, NB = New Britain Trench, SI = Solomon Island Trench, SCT = San Cristobal Trench.
† GCMT = Global Centroid Moment Tensor project (Global CMT Project, 2012); PAGER = PAGER-CAT (Allen et al., 2009)

In July of 1971, the largest and most unique doublet occurred in the Solomon Islands. The first event, on July 14 occurred along the northwest end of the Solomon Island Trench; body wave analysis performed by Schwartz et al. (1989) suggest that during the rupture process the faulting geometry changed. They indentify two distinct periods of moment release, which are attributed to the rupturing of adjacent asperities. This Ms = 7.9 event triggered a second earthquake of the same magnitude twelve days later, unique in that it occurred on the New Britain Trench rather than on a linear section along strike with the first event, which may indicate that the subducting lithosphere is intact across the junction between these two trenches (Schwartz et al., 1989). Doublet events also occurred in 1974 and 1975 in the southeast end of
the Solomon Island Trench near the island of Bougainville. The 1974 Ms = 7.0 and Ms = 7.1 events occurred approximately four hours apart, the 1975 events were five hours apart. Through their investigation of these three doublet events, Lay and Kanamori (1980) identified a P-wave pattern for the Solomon Islands characterized by high stress drops and a pattern of only one or two distinct ruptures.

Following the 1975 doublet events, there appeared to be a clear seismic gap along a 120 km segment of the Solomon Island Trench between the locations of the 1971 doublet events. Xu and Schwartz (1993) speculated that due to strong coupling on either end of this region, parts of this segment were locked and therefore large events might nucleate here. Just as they predicted, an August 1995 doublet sequence ruptured the fault segment between the two events. The Mw = 7.7 and Mw = 7.2 events occurred 50 km southeast of the July 14, 1971 event. Schwartz (1999) performed body wave inversions on the 1995 event, determining that the rupture from this event was not the same as the 1971 event, but filled a gap between two asperities identified in the 1971 event. This indicates that the 1995 event was not a repeat event and cannot be used to identify a recurrence interval for this region, but may qualitatively support the seismic gap ideas.

Additionally, a year later, an Mw = 7.2 thrust event occurred approximately 100 km southeast of the 1995 event, and just north of the 1975 event, further confirming the presence of a seismic gap and strong coupling in this region. For several decades there also appeared to be a large seismic gap along the San Cristobal Trench between the 1974 and April 1939 events. Despite events in 2007 and 1991 both occurring within this region, there is still a trench segment more than 100 km in length along the island of New Georgia which is noticeably absent of Mw > 7 events, indicating a possible region for a large earthquake in the future.
In reviewing large earthquakes which occurred in this region prior to the 1970s events (Abe, 1981), a few notable ones that may indicate a recurrence interval within the region are noted here. Lay and Kanamori (1980) suggested that pairs of events in 1945/1946 and 1919/1920 along the nearby Vanuatu Trench indicate an approximately 25 year recurrence interval within the region. Several other events also appear to fit this trend. Two events in 1943 (Ms = 7.3) and 1949 (Ms = 7.9) occurred at the northwest end of the Solomon Island Trench, very close to where the 1971 doublet events later occurred, and may have ruptured the same asperity (Xu and Schwartz, 1993). Events in 1932 (Ms =7.1) and January of 1939 (Ms = 7.8) may also coincide with the 1975 events, indicating a possible recurrence interval in this region of a few decades, and the possibility of a major event in this region in the near future, given the lack of recent major or great events here. Events in 1936 (Ms = 7.4), 1952 (Ms = 7.2) and 1959 (Ms = 7.1) ruptured near the Woodlark Rise, near the location where the 1974 event would later occur.

Along the Solomon Island Trench between the islands of Makira and Guadalcanal, several major events have occurred since 1900, including two doublets in 1931 (Mw = 7.7; 7.8) and 1977 (Mw = 7.2; 7.1) as well as a July 1939 Mw = 7.9 event. This region later experienced other large thrust events including an Mw = 7.5 on February 7, 1984 and a second Mw = 7.5 event on August 10, 1988.

Since the 1975 doublet event, there have been a few large (Mw > 7) earthquakes in this region of the Solomon Islands. In 1991, an Mw = 7.2 underthrusting event occurred 350 km southeast of the 1974 event, along the San Cristobal Trench. In November of 2000, a sequence of three major events (Mw = 8.0; 7.8; 7.8) occurred within two days of one another at the northwest end of the Solomon Island Trench, where it intersects the New Britain Trench. The first event, an Mw = 8.0 occurred on the transform boundary running roughly north-south along New Ireland.
The second two events occurred in the same region as, and approximately 30 years after, the 1971 doublet event.

The most notable recent event in the Solomon Islands region occurred on April 1, 2007. The epicenter of this Mw = 8.1 event is located 150 km southeast of the 1974 doublet epicenter along the Solomon Island Trench. The absence of any large events in the region surrounding this event from the period of 1900 – 2006 suggested initially that this region may be slipping aseismically. However, the 2007 event demonstrates that the plates subducting along the Solomon Island and New Britain Trenches are strongly coupled, releasing strain in large, infrequent events (Taylor et al., 2008). The rupture from the 2007 event extended to the northwest across the triple junction between the Woodlark, Pacific and Australian Plates; the Woodlark Plate was underthrust with different slip directions, due to the varying rates and directions of convergence (relative to the Pacific Plate) across the triple junction (Furlong et al., 2009). The rupturing of adjacent subducting plates during one event is not previously known to have occurred prior to this event. As a result, this event (along with the 1971 doublet) has led to questions about the role of structural boundaries in limiting the rupture length of thrust events in subduction zones and challenged conventional ideas on where great earthquakes can occur. The extent of the 2007 rupture did, however, reach the 1974 rupture; there is no seismic gap between the two events (Miyagi et al., 2009).

The Solomon Islands is notably lacking many great earthquakes. Events in 1943, 1929, 1971 and 2000 all ruptured in approximately the same region, indicating that the same asperity may have ruptured in each case, and further supporting the idea of a recurrence interval two-to-three decades in length. Along the Solomon Island Trench, there is strong coupling between plates and based on past events, asperities present appear not to be large enough to rupture in an
event much greater than M = 8.2, though the dynamic triggering of doublets observed in this region indicates they are likely closely spaced.

Discussion

If we are able to accurately characterize the stress regime of subduction zones, it follows that we will be better able to predict seismic behavior. However, major earthquakes in the last two decades have illustrated that this is not a simple task. The Sunda Trench along Sumatra was thought not to be capable of nucleating in a great earthquake; the 2007 Solomon Island event ruptured across a plate boundary, something never seen before; in 2009 a large extension event off Tonga triggered a large underthrusting doublet and in the reverse case, a large thrust event triggered a normal faulting event along the Kuril-Kamchatka Trench in 2007. For the three subduction zones examined here, the interactions between earthquakes in each region are the greatest area of interest.

A recent publication by Kato et al. (2012) investigating the rupture dynamics of the 2011 Tōhoku, Japan earthquake shows a previously unnoticed propagation of slip leading up to the M = 9.0 rupture, leading to questions about whether this may be the case in other subduction zones as well. The Tonga-Kermadec region is characterized by frequent small events and several large tsunami generating earthquakes despite an extreme amount of plate convergence, which may indicate that this area is experiencing substantial slow-slip. Deeper investigation into the patterns of smaller-magnitude seismicity surrounding this region could help to fully explore this idea. A continued pattern of loading, slip, and loading, likely visible as earthquake swarms along the plate boundary may indicate that this region is slowly slipping and that the large earthquakes observed here are slow-slip events. The 2009 extensional event which triggered a doublet event
is certainly unique. Because the timing of rupture for the events overlaps, it is assumed that the extensional event triggered the weakly coupled megathrust region to fail, resulting in the doublet event. In terms of slow-slip, it may be that this region, which normally experiences aseismic creep, underwent unusual loading following the extensional event, causing it to fail. How the subduction of young lithosphere at a high convergence rate affects the seismic behavior here is not entirely known, however it would appear that the argument that the length of recurrence intervals explains the lack of great earthquakes in this region is not valid.

The Tonga subduction zone experiences the highest rate of convergence of anywhere else in the world; it seems unlikely that we have not yet had time to load the fault enough to rupture in a great earthquake. If slip deficit accumulates at such a high rate, one would expect to have seen at least one great (megathrust) event in the region if that was its natural mode of operation. However, the recent surprises in great earthquake activity should give us caution when expecting simple patterns to be easily extrapolated to the future. In Tonga, for example, there is a section of the fault long enough to rupture in a great earthquake. One hopes that the lack of large events in this region is not simply an issue of limited seismic history and recurrence intervals. Ocean-bottom GPS and perhaps careful study of the plentiful small earthquake activity could lead to more clues to assess this important question.

Along the Solomon Islands, earthquake triggering is frequent and the result of large doublets. As suggested by earlier researchers, the lack of great earthquakes and occurrence of large doublet events in this region suggests that the fault interface is composed of similar-sized, strongly coupled and closely spaced asperities. As subduction occurs the asperities are loaded and when they fail, the sudden change in stress distribution triggers adjacent asperities, which fail shortly thereafter. In 2007, we saw the first instance of an earthquake rupturing across a plate
boundary, one in which plate motion on the two plates was not only different in rates, but also
direction. This event was the first of its kind, and countered what the scientific community
believed about how structural boundaries limit the rupture length of earthquakes on plate
interfaces. Some notable seismic gaps remain along the Solomon Island Trench. Based on past
seismicity it seems likely that these regions are strongly coupled and will rupture as large events,
possibly as one or more events on the same fault section.

Of the three regions investigated in this report, the Kuril-Kamchatka Trench is most
heterogeneous is terms of stress distribution. The plate interface is comprised of asperities of
various sizes, some of which are quite large, as we see from the nucleation of the 1952
Kamchatka event, one of the largest earthquakes ever recorded. The recent increase in large
events in the past several decades indicates that a number of these larger asperities have
accumulated stress since the last great event and have been failing periodically, possibly
indicating a recurrence interval of around a half a century. We see the ability for unusual
triggering in the 2006/2007 events, where a large thrust event on the plate interface near the
Kuril Islands preceded a normal faulting event in the backarc two months later. The areas of
great historic ruptures (Fig. 7) show the presence of seismic gaps along the Kuril-Kamchatka
Trench, where great earthquakes have not occurred in recent times. Based on the characteristics
of earthquakes nucleated here, it is not unreasonable to expect more large and great earthquakes
to occur in the future, filling these gaps.

Conclusion

The increase in seismic activity in the past several years has allowed for better
characterization of subduction zone behavior and earthquake dynamics. The mechanics of
rupturing can still be explained in terms of the asperity model, where some regions appear to hold to a particular style of rupturing. For Tonga-Kermadec and the Solomon Island regions, that is the absence of great earthquakes and frequent doublets; along the Kuril-Kamchatka Trench, great earthquakes are not unexpected. In the light of recent events, however, such as the 2004 Mw = 9.2 Sumatra-Andaman, it is understood that our knowledge of many subduction plate boundary zones remains incomplete. Further investigation of slow-slip events, tsunami earthquakes, and detailed analyses of moderate-sized earthquakes may shed additional light on strain accumulation in subduction systems. Part of this involves active work to develop and install off-shore GPS technologies, so that a better measure of creep and slip along the fault can be determined. The recent seismic activity in the three regions investigated here illustrates the complexities of earthquake triggering, adding more understanding to how stress changes during an earthquake. The release of stress on a fault during an earthquake results in a redistribution of stress not only along that same fault, but also elsewhere on the plate. This occasionally (and often in the Solomon Island region) results in the nucleation of earthquake doublets; the additional stress is just enough to overload a fault or stress a plate to the point of breaking.

A full understanding of earthquake processes is still yet to come and theories explaining subduction zone behavior are evolving. Even the capability of a single earthquake to trigger other events was not fully recognized until recent years. Closer investigations into historical seismicity, the advancement of technology and density of instrumentation, and with time, the occurrence of more earthquakes, will continue to add to the understanding of subduction zone dynamics.
Acknowledgments

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Additional Research Tools

Earthquake Catalogs


EQ Search


The Generic Mapping Tools (GMT)


UNAVCO Plate Motion Calculator


Plate Motion Model: