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An Overview of the 28 October 2012 M_w 7.7 Earthquake in Haida Gwaii, Canada: A Tsunamigenic Thrust Event Along a Predominantly Strike-Slip Margin

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Abstract—The boundary between the Pacific and North America plates along Canada's west coast is one of the most seismically active regions of Canada, and is where Canada's two largest instrumentally recorded earthquakes have occurred. Although this is a predominantly strike-slip transform fault boundary, there is a component of oblique convergence between the Pacific and North America plates off Haida Gwaii. The 2012 M_w 7.7 Haida Gwaii earthquake was a thrust event that generated a tsunami with significant run up of over 7 m in several inlets on the west coast of Moresby Island (several over 6 m, with a maximum of 13 m). Damage from this earthquake and tsunami was minor due to the lack of population and vulnerable structures on this coast.

Key words: Thrust earthquake, Haida Gwaii, tsunamigenic, oblique convergence, strike-slip margin.

1. Introduction

The 03:04 28 October, 2012 (20:04 27 October local time) M_w 7.7 earthquake that occurred off the west coast of Haida Gwaii, Canada, (formerly the Queen Charlotte Islands) was the first major thrust event recorded along this predominantly strike-slip margin. The Pacific-North America boundary along the British Columbia and Southeast Alaska coast is mainly a transform fault plate boundary, with ocean crust seaward and continental crust landward. It is dominated by the right lateral Queen Charlotte Fault (QCF), an underwater seafloor feature that extends for more than 800 km from the triple junction region north of Vancouver Island to Cross Sound in the Alaska Panhandle, where it transitions into the continental Fairweather Fault (Fig. 1). The QCF is the northern equivalent of the San Andreas Fault (with the Cascadia subduction zone between these two major transform faults). This margin accommodates between 50 and 60 mm/year relative motion between the Pacific and North America plates (e.g., DEMETS *et al.* 2010; STOCK and MOLNAR 1988; DEMETS and DIXON 1999). Canada's two largest instrumentally recorded earthquakes have occurred here—the 1949 M 8.1 strike-slip event and the 2012 M 7.7 thrust event discussed herein. The northernmost portions of the QCF ruptured in a M 7.6 earthquake near Sitka in 1972 and a M 7.5 earthquake to the west of Ketchikan in 2013, both strike-slip with minimal tsunami generation. This article provides a summary of the tectonics and earthquake history of this region, and an overview of the results to date analysing the 2012 M 7.7 Haida Gwaii earthquake that generated the largest tsunami recorded in the world in 2012.

2. Tectonics

This region is dominated by strike-slip tectonics with an overprint of convergent tectonics. The near-vertical Queen Charlotte Fault accommodates about 52 mm/year of right-lateral motion in the direction N338 between the Pacific and North American plates (e.g., DEMETS *et al.* 2010; STOCK and MOLNAR 1988; DEMETS and DIXON 1999). Recent high-resolution seafloor imaging of the fault shows that the surface expression of the fault exhibits the characteristics of a nearly pure strike-slip fault trace (BARRIE *et al.* 2013). North of Graham Island, Haida Gwaii, the trace of the Queen Charlotte fault is almost aligned with the Pacific-North America relative plate motion (Fig. 1). Along the southern portion of this fault off Moresby Island, however, there is a change in margin orientation to a difference of 15°–20° compared to the direction of relative plate motion, thus requiring a

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component of convergence. This difference decreases gradually to the north, off Graham Island. As has been observed in other parts of the world, this type of oblique convergence is usually accommodated by a combination of thrusting nearly orthogonal to the margin and strike-slip faulting further landward, i.e., a forearc sliver (e.g., Fitch 1972; Jarrard 1986; McCaffrey 1992). The high, steep topography along the west coast of Haida Gwaii is probably the result of the initiation of oblique convergence and underthrusting initiating at ~6 Ma (Hyndman and Hamilton 1993). In the Haida Gwaii region, the component of convergence is interpreted to be accommodated mainly by oblique underthrusting of the seafloor beneath Moresby and Graham Island (e.g., Yorath and Hyndman 1983; Hyndman and Hamilton 1993). Especially important evidence comes from receiver function studies (Smith *et al.* 2003; Bustin *et al.* 2007; Cassidy *et al.* 2014) that show an eastward dipping 10-km-thick low-velocity zone interpreted as the subducted oceanic crust.

A series of structural and other geophysical studies have been used to develop three main models to explain how the oblique convergence is accommodated across the Haida Gwaii margin through a combination of thrust and strike-slip faulting or through crustal shortening (e.g., Dehler and Clowes 1988; Prims and Govers 1997; Rohr and Currie 1997; Rohr *et al.* 2000; Rohr and Dietrich 1992; Smith *et al.* 2003). These models include; (a) simple oblique subduction with the strike-slip QCF in the overlying continental plate, i.e., a forearc sliver; (b) oblique subduction with the nearly vertical strike-slip QCF cutting the subducting oceanic plate; and (c) much of the convergence accommodated by crustal shortening (see Fig. 3 of Smith *et al.* 2003). The 2012 thrust event has provided evidence that the first model is mostly correct. There are separate thrust and strike-slip faults accommodating the orthogonal and parallel components of relative plate motion (Fig. 1). The now preferred model is discussed below with the M_w 7.7 2012 event.

3. Seismicity

The Haida Gwaii region is one of Canada's most seismically active areas (Fig. 2a). There have been four large (M >7) earthquakes and 18 M >6 earthquakes during the past eight decades. The modern seismic recording history of this region began in 1898 when a seismograph was deployed in Victoria, British Columbia (~800 km to the south of Haida Gwaii) that could detect earthquakes of M >7 in the Haida Gwaii region. With the deployment of a seismic station at Sitka, Alaska in 1904 (~500 km to the north of Haida Gwaii), and improvements in the global earthquake monitoring network, earthquakes of M > 6 could be detected and roughly located along this plate boundary region. Since the 1950s, it has been possible to locate most M > 5 earthquakes in this region. Between 1982 and 1996, a temporary network of 12 analog seismographs was operated on Haida Gwaii and the adjacent mainland that allowed location of earthquakes as small as M 0.3 in some locations. Since the mid-1990s, a network of six digital stations has operated on Haida Gwaii, and since the 2012 earthquake, other temporary digital stations have been installed.

Several detailed studies of microseismicity have been conducted that located and examined earthquakes as small as M −0.5 in the Haida Gwaii region during limited time periods. Studies of composite earthquake mechanisms have provided important information on the regional stress and strain directions along the Haida Gwaii margin indicated by the earthquakes, as discussed below.

3.1. The Largest Earthquakes

The Haida Gwaii region is home to Canada's two largest instrumentally recorded earthquakes—the 1949 M 8.1 strike slip event that initiated off the northwest tip of Graham Island (e.g., Bostwick 1984; Rogers 1983), and the 2012 M 7.7 thrust earthquake that occurred off the west coast of Moresby Island (Fig. 1). There are very important differences between these two large earthquakes; the 1949 event was a nearly pure strike-slip mechanism that involved slip along the QCF [and generated a small tsunami (Soloviev and Go 1984)], whereas the 2012 earthquake was a thrust event, with no evidence uncovered so far that it involved any movement along the strike-slip QCF, and it

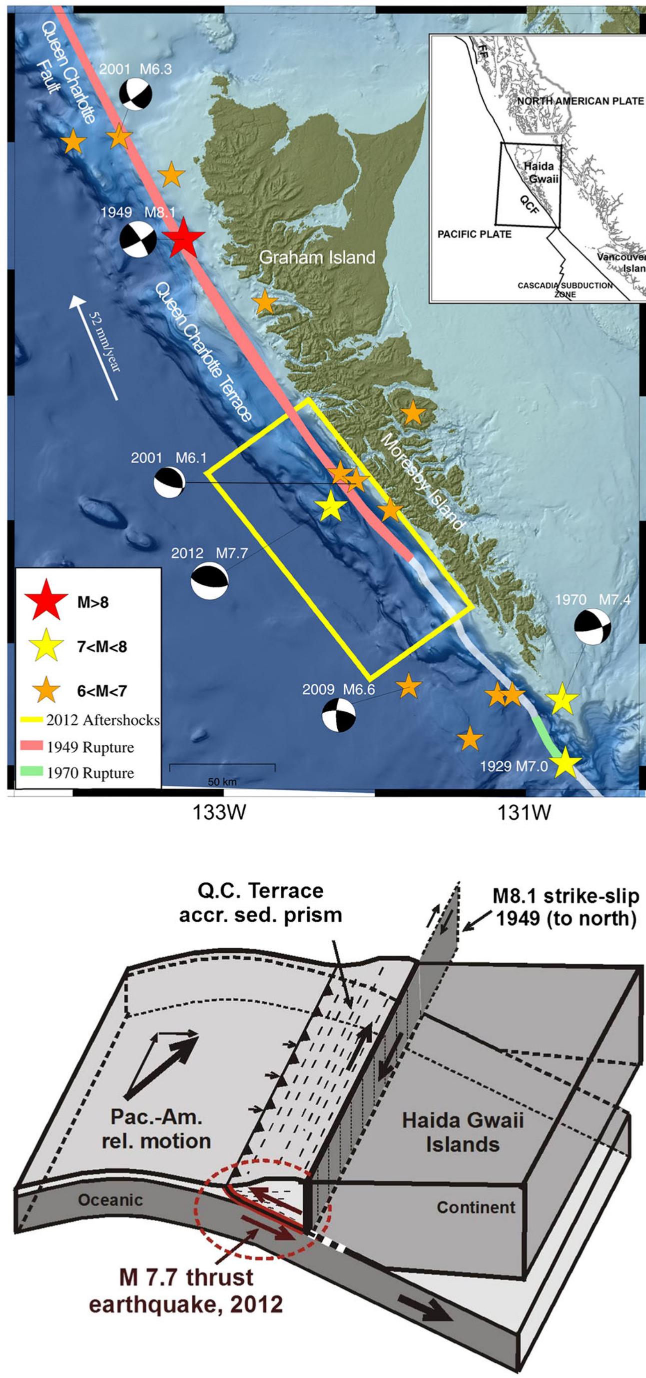

Figure 1

Tectonic setting in the Haida Gwaii region. *White arrow* indicates the direction of relative motion between the Pacific and North America plates. Locations and focal mechanisms (if available) of the largest historical earthquakes (*stars*) are shown, heavy *pink* and *green lines* indicate rupture zones of the two previous largest historical earthquakes (1949 and 1970). The section of the QCF between the southern end of the 1949 rupture (*pink line*) and the northern end of the 1970 rupture (*green line*) is the “seismic gap” identified by Rogers (1986). The approximate extent of the aftershock zone of the 2012 thrust event is shown as a *yellow box*. Inset shows the regional tectonics, *QCF* is the Queen Charlotte Fault and *FF* is the Fairweather Fault. Cartoon shows the location of the thrust fault beneath the Queen Charlotte Terrace along which the 2012 earthquake occurred, the relative plate motions in this area, and the location of the near-vertical Queen Charlotte fault

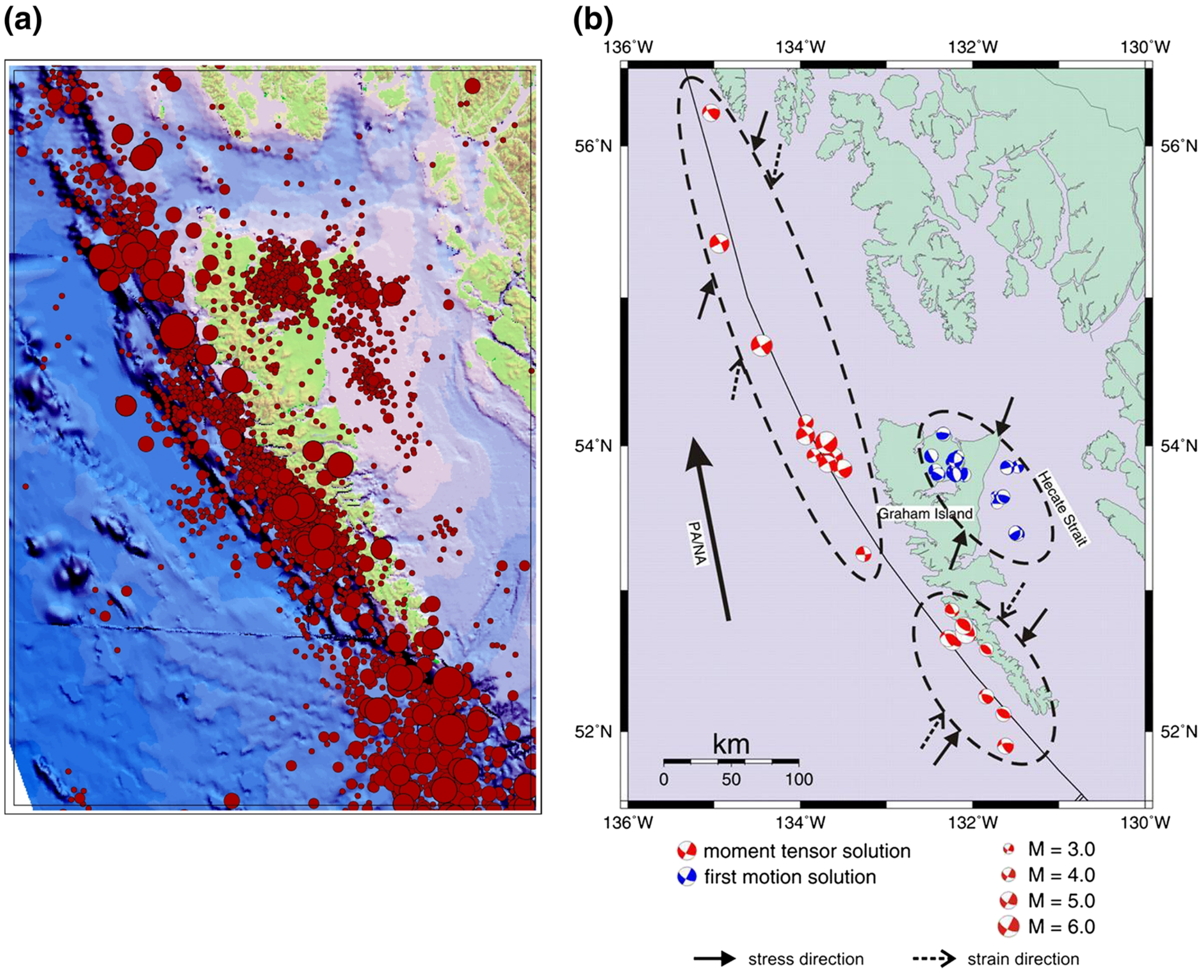

Figure 2

a Seismicity of the Haida Gwaii region (1900–2012). Earthquakes (red dots) are scaled according to magnitude and range from M < 1 to M 8. **b** Previous earthquake focal mechanisms (1982–2004), stress and strain directions in the vicinity of Haida Gwaii modified from Ristau *et al.* (2007). The southernmost ellipse shows the region of mainly high-angle thrust mechanisms with a nearly margin-normal maximum compressive stress direction. The northern ellipse shows the area of mainly strike-slip mechanisms (consistent with the strike of the QCF trace) and a more northerly (margin-oblique) maximum compressive stress direction

generated a significant tsunami. Other large earthquakes (Fig. 1) along this margin include two M ~7 earthquakes off the southern tip of Moresby Island in 1970 and in 1929 (Rogers 1986). The section of the QCF between those two earthquakes and the southern end of the 1949 rupture was identified as a potential seismic gap by Rogers (1986). Since 2001, there have been four M >6 earthquakes off Haida Gwaii. The 2001 M_w 6.1 thrust event generated a small tsunami recorded on tide gauges on the west coast of Vancouver Island to the south of Haida Gwaii (Rabinovich *et al.* 2008).

3.2. *Earthquake Focal Mechanisms and Stress and Strain Directions*

Ristau *et al.* (2007) determined the regional moment tensor solutions for 15 M >4 earthquakes along the Queen Charlotte Fault (Fig. 2b). Such studies provide average crustal strain directions as accommodated by the earthquakes, and the inferred average stress direction. Off the west coast of Graham Island and to the north, the mechanisms are mainly strike-slip (consistent with the strike of the QCF trace), often with a small thrust component. However, off the west coast of Moresby Island in the south, the solutions are mainly high-angle thrust mechanisms. Ristau *et al.* (2007) show a change in maximum compressive stress direction from nearly margin normal off Moresby Island to more northerly (margin oblique) off Graham Island. Although the thrust solutions off Moresby Island indicate convergence, they are mainly on high-angle faults and so not on the main thrust that generated the large 2012 earthquake. The focal mechanisms of the largest earthquakes and ongoing GPS survey results from Haida Gwaii (Mazzotti *et al.* 2003) also agree with the proposed tectonic models of convergence and underthrusting along the southern portion of the Haida Gwaii margin (e.g., Hyndman and Hamilton 1993; Ristau *et al.* 2007).

3.3. Microseismicity Studies

The first microseismicity study of the Haida Gwaii region was undertaken by Hyndman and Ellis (1981) who deployed a temporary array of on-land seismic stations on Moresby Island and three ocean bottom seismographs just to the west. They were able to accurately locate 11 earthquakes (M 0.4–2.1) during a 9-day period. Ten of those were located (within uncertainties) beneath the surface trace of the strike-slip Queen Charlotte Fault mostly at depths between 15 and 20 km. The rate of seismicity was consistent with the long-term average for larger earthquakes in the region.

During the summer of 1983 a total of 22 seismographs (19 on land and three ocean bottom seismographs) were deployed for a larger-scale microseismicity study of Haida Gwaii (Bérubé *et al.* 1989). During this 9-week survey, 317 earthquakes were recorded, of which 109 were well located. Key results from the Bérubé *et al.* (1989) study include:

1. Most of the microseismicity along the west coast occurs in the vicinity of the Queen Charlotte Fault, beneath the inner bathymetric slope (and about 15 km east of the main surface trace of the fault).
2. Seismicity is within the top 20 km, and composite focal mechanisms reveal a NE-oriented maximum horizontal compressive stress.
3. Microseismicity along the QCF is higher within the aftershock zone of the 1949 earthquake compared to adjacent areas. In contrast, only two earthquakes occurred in the "seismic gap" off southern Moresby Island.

Another detailed microseismicity study with a temporary array of seismographs between 1982 and 1996 (Bird 1997) examined more than 2,600 earthquakes and revealed a variation in intensity of seismicity in the vicinity of the Queen Charlotte Fault. A paucity of activity was identified along the QCF just to the south of the 1949 M 8.1 epicentre, and also in the "seismic gap" off southern Moresby Island. First motion focal mechanisms in the region show a mixture of strike-slip and high angle thrust faulting, and also reveal a north-northeast compressional stress regime (Bird 1997). Further focal mechanism solutions were subsequently obtained as noted above (Ristau *et al.* 2007).

3.4. Previous Tsunami Generating Earthquakes in the Haida Gwaii Region

Prior to 2012, only two earthquakes in the Haida Gwaii region are known to have generated a tsunami. The 1949 M 8.1 strike-slip earthquake generated a small tsunami recorded on tides gauges in Sitka, Alaska (7.5 cm) and Hawaii (10 cm) (Leonard and Hyndman 2010; Soloviev and Go 1975) and the 2001 M_w 6.1 thrust earthquake that produced a small tsunami (maximum 23 cm) recorded on Vancouver Island (Rabonovich *et al.* 2008). This lack of tsunami observations is, in part, due to the fact that the plate boundary in this region is predominantly strike-slip, and tsunami-generating earthquakes are relatively rare. Other factors are the short observing time, the lack of settlements along the west coast of Haida Gwaii, and the fact that there are no tide gauges on the outer coast of Haida Gwaii (with the exception of Henslung Cove, on the very northern tip of Moresby Island).

The nearest tide gauges have been on northern Vancouver Island more than 400 km to the south in a direction of expected low amplitude for thrusting orthogonal to the Haida Gwaii margin. There is one tide gauge station on the landward side of Haida Gwaii, again where little amplitude is expected for thrust earthquakes off the west coast.

4. The Oct 2012 M 7.7 Thrust Earthquake

On 28 October 2012 at 0304 UTC (8:04 p.m. October 27 local time), Canada's second largest instrumentally recorded earthquake occurred off the west coast of Moresby Island (James *et al.* 2013; Szeliga 2013; Lay *et al.* 2013). Strong shaking was experienced on Haida Gwaii, but fortunately no significant damage resulted, as the region adjacent to the fault rupture is an uninhabited National Park and the large tsunami was limited to the west coast of the islands where there are no settlements or significant coastal structures. The closest community, the village of Queen Charlotte, is about 50 km from the estimated rupture surface (James *et al.* 2013). This earthquake was felt as far away as 1,500 km in Alberta, Yukon, Washington State, and Montana.

For tsunami generation and modeling, the earthquake focal mechanism and slip distribution are key factors. The mechanism of the mainshock was thrust faulting (H. Kao, personal communication, 2013; http://earthquake.usgs.gov, http://globalcmt.org, Lay *et al.* 2013) along a shallow eastward dipping plane (Fig. 1). Estimates of dip in the various focal mechanism solutions vary from 17° to 25°. Finite fault analysis suggests a maximum slip of over 5 m (http://earthquake.usgs.gov, Lay *et al.* 2013). Lay *et al.* (2013) estimate a maximum slip of 7.7 m and an average slip of 3.3 m. The overall rupture zone is about 150 km long as defined by the aftershocks (Fig. 3), and about 30 km wide—which is the approximate width of the Queen Charlotte Terrace. It is noteworthy that there is no indication that this slip represents any movement along the strike-slip QCF, but rather represents movement on a shallow thrust fault beneath the Queen Charlotte Terrace (see Fig. 1), to the west of the QCF. The preferred (Geological Survey of Canada) epicenter (Fig. 1) that utilizes both local (Haida Gwaii) data and regional waveforms, is located offshore ($\sim$25 km SSW of the initial USGS epicenter). The exact landward limit of rupture is still under investigation, but is approximately to the location of the strike-slip fault near the coast at a depth of 15–20 km. Thermal models of the thrust zone also suggest this is about the landward limit of rupture (Smith *et al.* 2003). The recent slip model (Wang, personal communication; Nykolaishen *et al.* 2013) incorporates the latest GPS coseismic deformation data, improved hypocenter and fault geometry information, as well as the expected landward limit based on thermal modeling. It shows in the offshore region a vertical uplift of as much as 3 m, and a maximum horizontal slip of up to 6–8 m.

The October 2012 earthquake generated a large tsunami [with significant local run-ups exceeding 7 m in some of the small inlets along the west coast of Haida Gwaii (possible maximum of 13 m)—see papers by Leonard and Bednardski (2014), and Fine *et al.* (2014) in this volume]. The nearest tide-gauges on northern Haida Gwaii and Vancouver Island were not exposed to the main focus of the tsunami energy and recorded amplitudes up to 0.5 m. In Hawaii (more than 4,000 km to the southwest, but in the focus of the tsunami energy), the maximum amplitude recorded on a tide gauge was 0.8 m.

This earthquake has had a very rich aftershock sequence, with tens of thousands of recorded aftershocks. Figure 3 shows the best-located aftershocks ($M > 2$) as of 1 May 2013. There are two concentrations—one over 50 km offshore, west of the Queen Charlotte Terrace, and the other concentrated just offshore and east of the surface trace of the Queen Charlotte fault. Most of the largest aftershocks are located in the farthest offshore concentration in the Pacific plate and show normal faulting (Farahbod *et al.* 2013; Lay *et al.* 2013) (Fig. 3). These events are west of the thrust rupture surface of the mainshock. It is common to observe outer rise normal faulting aftershocks seaward of large megathrust earthquake in subduction zones. The concentration of aftershocks closest to land have a larger depth range and appear to be in both in the North American plate and Pacific, and have a variety of focal mechanisms. Thus far, no aftershocks with low angle thrusting mechanisms similar to the mainshock have been identified (Honn Kao, personal communication 2013, Farahbod *et al.* 2013; Lay *et al.* 2013). GPS data from Haida Gwaii reveal up to 1.2 m of co-seismic southwestward surface displacement on the west coast of Moresby Island (James *et al.* 2013; Nykolaishen *et al.* 2013). Vertical coseismic subsidence of up to 30 cm was measured at near-coastal GPS sites on Moresby Island. GPS observations reveal

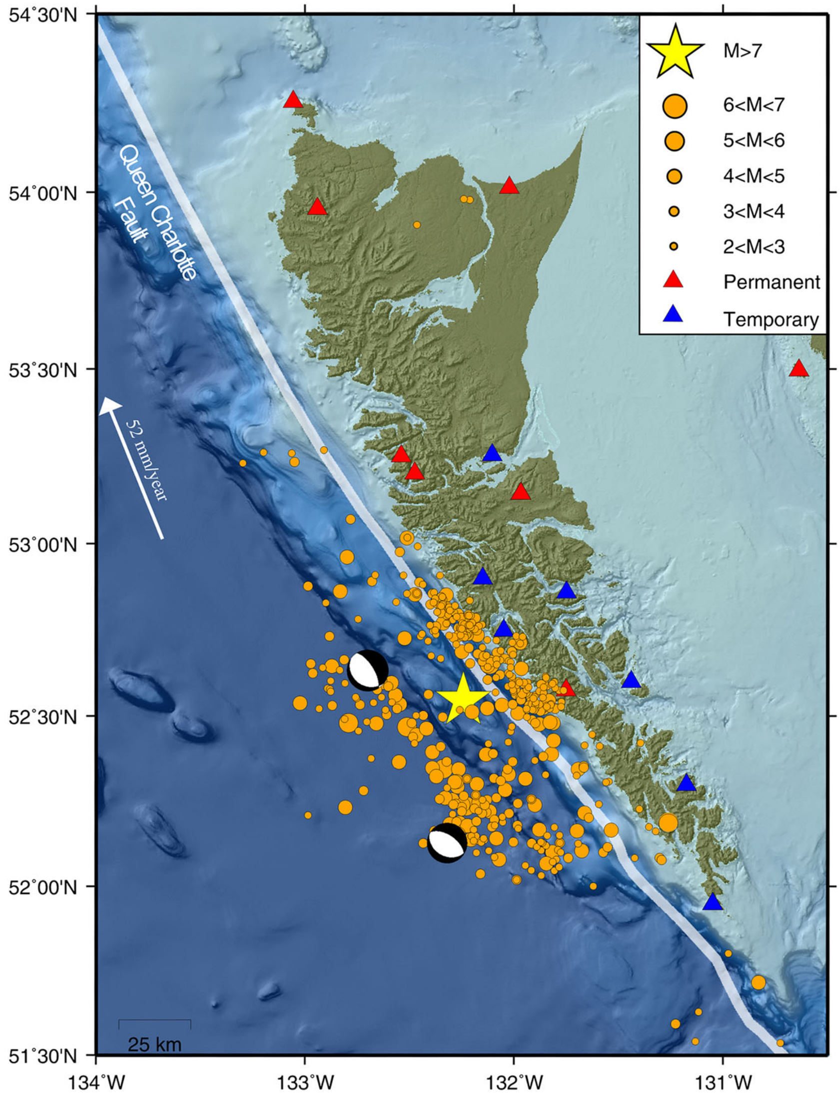

Figure 3

Haida Gwaii aftershocks (M >2) with the highest-quality solutions from October 2012 to 1 May 2013. The focal mechanisms (normal faulting) of the two largest aftershocks are shown. *Yellow star* denotes the epicentral location of the mainshock (note that the focal mechanism of the mainshock is shown on Fig. 1). *Grey line* is the trace of the near-vertical strike-slip Queen Charlotte Fault. Locations of seismic stations (both permanent stations of the Canadian National Network and temporary stations set up to monitor aftershocks) are indicated by *triangles*

postseismic motions that are still ongoing as of December 2013 (14 months after the earthquake).

A large thrust earthquake like this one at this location is a relatively rare event. If we use a margin normal convergence estimate for the southern Haida Gwaii region of 6–10 mm/year (Mazzotti *et al.* 2003) and the maximum slip (about 8 m) and average slip (about 3.5) resulting from finite fault slip modeling (http://earthquake.usgs.gov, Lay *et al.* 2013), repeat times ranging from 350 to 1,300 years result.

5. Summary

The M 7.7 2012 Haida Gwaii earthquake is the largest recorded thrust earthquake along the predominantly strike-slip Pacific-America plate boundary. It generated a substantial tsunami with run-ups of over 7 m (with a possible maximum of 13 m) in several inlets on the west coast of Moresby Island [see paper in this volume by Leonard and Bednarski (2014)]. An event of this nature was expected based on our understanding of the tectonics and previous small thrust earthquakes. Numerous geophysical and seismic studies over the past several decades, combined with analysis of recent small to moderate earthquakes and analysis of GPS derived velocity vectors, have clearly shown the compressional nature of the southern portion of the Queen Charlotte Fault and the potential for large thrust earthquakes and their accompanying tsunamis (e.g. LEONARD *et al.* 2012). The detailed studies of the M 7.7 2012 earthquake that are currently underway will provide valuable insight and understanding into the subduction earthquake and tsunami potential in both the Haida Gwaii and Vancouver Island regions.

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