Supraslab earthquake clusters above the subduction plate boundary offshore Sanriku, northeastern Japan: Seismogenesis in a graveyard of detached seamounts?

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[1] Thousands of offshore repeating earthquakes with low-angle thrust focal mechanisms occur along the subduction plate boundary of NE Japan. Double-difference relocation methods using *P*- and *S*-wave arrivals reveal clusters of events *above* these repeating events. To assure good depth control we restrict our study to events that are close to seismic stations. These "supraslab" earthquake clusters are regional features at depths of 25 to 50 km, and most of these clusters are below the depth of the forearc Moho, which we determined from converted waves. Seismicity over this depth range does not occur under the inland area of NE Japan except just below the vicinity of the arc volcanoes. Re-entrants in the inner trench slope indicate that repeated collisions of seamounts have occurred in the past. Our preliminary interpretation of supraslab clusters is that they represent seismicity in seamounts detached from the Pacific plate during slab descent, driven by the resistance of seamounts to subduction. Detachment during slab descent probably occurs on the sedimented and hydrothermally altered seafloor on which seamounts were originally constructed since these are known as zones of weakness during active island growth. High fluid pressure produced during dehydration of clay minerals and other low-temperature hydrous minerals could enable detachment at depths. Seamount crust is thus accreted to forearcs, possibly leading to a long-term component of near-coastal uplift. Supraslab earthquake clusters may be our most direct evidence of the fates of seamounts and suggest that tectonic underplating is actively occurring in this subduction system.

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1. Introduction

[2] Over the last decade a number of methods have been developed to improve the spatial resolution of earthquake hypocenter determination in subduction zones based on phase data collected by regional high-sensitivity land stations, teleseismic stations with good azimuthal coverage, and deployments of ocean bottom seismometers (OBSs) in offshore regions. We have applied the double-difference relocation method [*Waldhauser and Ellsworth*, 2000] to these data from the regional high-sensitivity network to investigate the fine structure of the near-shore region of the northern Tohoku subduction system. A particular challenge in the interpretations of the seismicity in cross sections of subduction systems is to establish the three-dimensional (3-D) location of the subduction plate boundary and the forearc Moho. Accurate hypocenter determinations of interplate thrust events based on well-determined focal mechanisms is the most straightforward approach to constraining plate-boundary geometry that is deforming in depth, but such events are sometimes sparse in subduction zones. Estimation of the 3-D positions of velocity discontinuities is also a powerful method for locating the plate boundary. Body-wave conversions (including those inferred from receiver-function analysis) from local and teleseismic sources may be identified with the top of the subducted crust [*Matsuzawa et al.*, 1990; *Shiomi et al.*, 2004; *Heit et al.*, 2007]. Multichannel seismic reflection imaging has also been useful in establishing the subducting plate boundary along many observation lines [*Tsuru et al.*, 2000, 2002; *Ito et al.*, 2004, 2005; *Fujie et al.*, 2006].

[3] Over the last decade, thousands of repeating earthquakes have been documented offshore of the Tohoku district of NE Japan (Figure 1a), including the famous Kamaishi sequence [*Matsuzawa et al.*, 2002, *Okada et al.*, 2003; *Uchida et al.*, 2005, 2007]. Focal mechanism studies have shown that these remarkable events represent repeated slip on small asperity patches of the subduction

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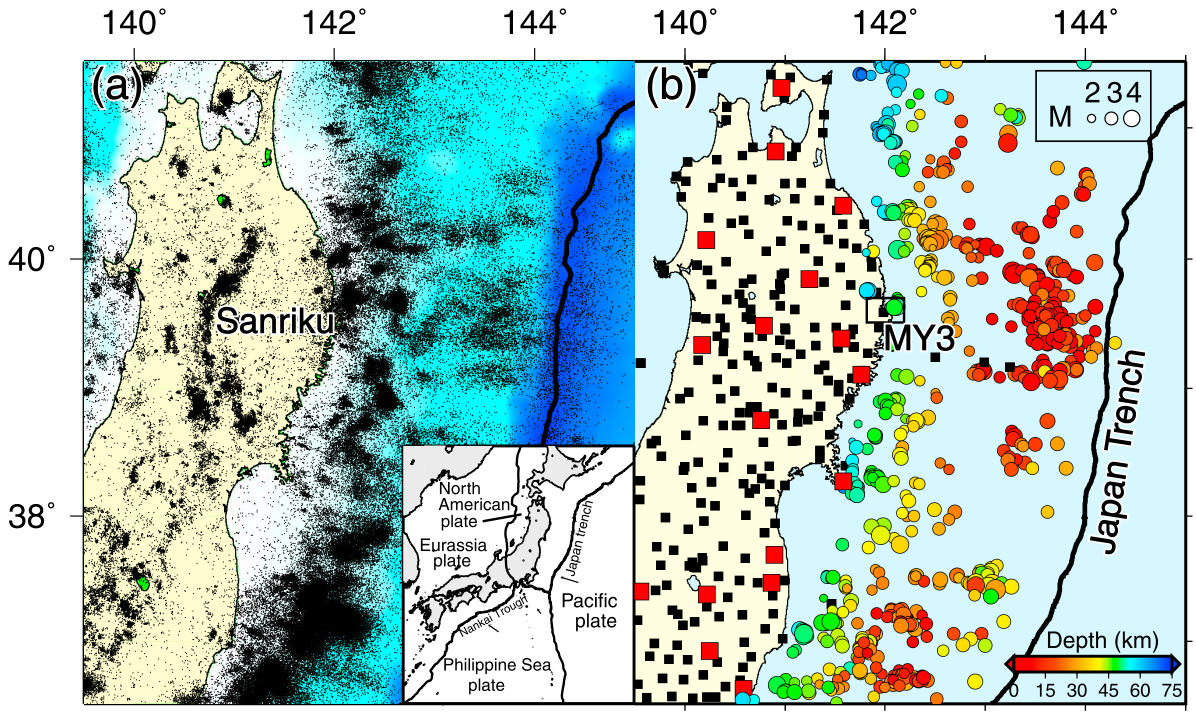

Figure 1. (a) Regional map showing the distribution of shallow (depth, ≤60 km) earthquakes (filled circles) recorded and located during the period 1980 to 2001 by Tohoku University. Inset map shows the plate-tectonic setting of our study area. (b) Map showing the distribution of well-recorded repeating earthquake groups (circles) off the Pacific coast of NE Japan that are color coded according to depth. The hypocenter locations are derived from the Japan Meteorological Agency (JMA) and Tohoku University's catalog. Also shown are the locations of permanent seismic stations maintained by the National Institute for Earth Sciences and Disaster Prevention (NIED) and universities and three permanent cabled ocean bottom seismograph (OBS) stations off Sanriku, installed and maintained by the Earthquake Research Institute of the University of Tokyo (filled black squares). Filled red squares shows seismic stations used for the identification of repeating earthquakes. Seismograms for events near station MY3 and recorded by that instrument (rectangle) are shown in Figure 3.

boundary [*Matsuzawa et al.*, 2002; *Igarashi et al.*, 2003; *Okada et al.*, 2003]. If the hypocenters of repeating earthquakes can be accurately determined and are distributed broadly enough, then such events could be useful constraints on the geometry of subduction plate boundaries in relation to the seismicity of other classes of earthquakes. Namely, hypocenters of repeating earthquakes give us a reference that tells us whether an earthquake is located above or below the plate boundary. This approach is superior to others because repeating earthquakes and other earthquakes are located using the same method and hence the resulting hypocenters should have small mislocation errors in terms of relative location if we have good seismic station coverage. Well-located repeating earthquakes on the plate boundary are also useful in constraining the location of the Moho above the repeaters: upgoing waves from the repeater sources can partially convert to other phases at the Moho, enabling us to determine the spatial distribution of the forearc Moho depth.

[4] In the course of an investigation of the seismicity of the near-coastal part of the northern Tohoku district in NE Japan (also known as the Sanriku area), we documented clusters of earthquakes that occur just above the subduction boundary determined by these methods [*Kirby et al.*, 2005]. Similar clusters were previously found by *Okada et al.* [2004] using double-difference (DD) methods and phase data obtained from cabled OBS stations, but their existence and significance were not discussed. Such "supraslab" earthquake clusters are significant in that the material in which they occur is apparently related to the subduction motion of the Pacific plate since they form an inclined zone that is roughly parallel to the underlying Pacific-Plate slab. However, the material in which they are occurring is no longer moving at the same subduction rate as the Pacific-plate slab since they are above the megathrust plate boundary defined by the repeaters. We discuss the significance of these findings in the context of a number of alternative models, including the possibility that these supraslab earthquake clusters occur in seamounts detached from the subducting Pacific plate.

2. Repeating Earthquake Analysis

[5] Small repeating earthquakes are useful in identifying subduction plate boundaries since they have almost exclusively low-angle thrust mechanisms that line up along curviplanar zones. Their spatial distribution corresponds to other independent indicators of the 3-D position of the plate

boundary, such as the precise hypocenters of conventional low-angle interplate thrust earthquakes and body-wave conversion points indicating abrupt changes in seismic wave speed [e.g., *Uchida et al.*, 2003; *Kimura et al.*, 2006]. Their high level of activity indicates that relatively fast aseismic slip (creep) occurs around the repeater because a fast loading process is required to explain their short earthquake recurrence intervals (typically within 2–5 years) and high average seismic moment release rates. Hypocenters of repeaters are thus numerous direct indicators of the local position of the plate boundary.

[6] Small repeating earthquakes are identified based on the similarities of seismograms recorded by the microearthquake observation network of Tohoku University (red squares in Figure 1b) for the observation period from July 1984 to December 2007. We calculated the coherence of waveforms for events whose standard catalog epicentral separations are less than 30 km. The time windows for the seismogram analysis were set at 0–40 s from the *P*-wave arrivals. This time window always contains the S phase, allowing us to check that the events have essentially the same *S*-*P* time (i.e., the same location). We considered a given earthquake pair as repeating earthquakes when the averaged coherence at 1 to 8 Hz was larger than 0.95 at two or more stations. Then a pair (group) of repeaters was linked with another pair (group) if the two pairs (groups) shared the same earthquake. In total, we searched about 37,000 shallow (depth, <70 km) earthquakes with Japan Meteorological Agency (JMA) magnitudes of ≥2.5 and obtained 2831 repeating earthquakes that satisfied these criteria. Small repeating earthquakes are distributed mainly between the Japan Trench and the eastern coast of Honshu. The average depth of repeaters (Figure 1b) deepens from east to west, following the position of the upper surface of the subducting Pacific plate. Note that the relatively scattered catalog depths of repeaters that are located far from the land seismic stations and outside of our study area are due to increasing errors in hypocenter determination caused by unfavorable station distribution.

3. Earthquake Relocation

[7] We relocated events with magnitudes of ≥1 at depths of 0–200 km for the period from April 2002 to January 2007 by using the DD method [*Waldhauser and Ellsworth*, 2000]. We used arrival time data provided by the JMA. The seismic stations include the dense nationwide seismic network (Hi-net) by the National Institute for Earth Sciences and Disaster Prevention (NIED), and the seismic networks of the JMA, Tohoku University, Hirosaki University, Hokkaido University, and the University of Tokyo (Figure 1b). We use a model of *P*- and *S*-wave velocity structure that is used in the routine procedure for hypocenter locations at Tohoku University [*Hasegawa et al.*, 1978]. This velocity structure is one dimensional and hence we cannot discuss absolute locations in detail. However, we can obtain good relative locations by the DD method, which minimizes travel-time difference residuals [*Waldhauser and Ellsworth*, 2000].

[8] For relocation by the DD method we selected event pairs with apparent epicentral separations of less than 15 km, epicentral distances between the recording station and the pair of events of less than 300 km, and west of 142.5 E. We also selected events having more than eight arrival-time differences from neighbors. A total of 2,905,336 arrival time differences obtained for *P* waves and 2,572,809 arrival time differences obtained for *S* waves were used to determine the hypocenters of 35,253 events. Relocation was performed in three subregions owing to computer memory limitations. The averaged root mean square variance for observed versus calculated travel-time differences was reduced by this procedure from 0.13 to 0.08 s.

[9] We use additional information on hypocenters to delineate the offshore seismicity in the NE Japan subduction zone. One source is the offshore hypocenter distribution with depth constrained by the *sP* depth phase recorded by the local seismic network [*Umino et al.*, 1995; *Gamage et al.*, 2009]. With event depths of these earthquakes determined from *S*-*P* times and arrival times of the *sP* converted phase, *Gamage et al.* [2009] obtained the hypocenters of the earthquakes by redetermining epicenters using these new focal depths. Another hypocenter data source is the Engdahl, van der Hilst, and Buland (EHB) catalog [*Engdahl et al.*, 1998], which also uses depth phases, but those recorded at global stations. We use EHB hypocenters for the period from 1964 to 2002. Focal mechanisms estimated by *P*-wave first motion (JMA catalog) and moment tensor determination (Full Range Seismograph Network of Japan, NIED) were also used to characterize deformation patterns caused by earthquakes.

[10] The resultant distribution of earthquakes is shown in Figure 2a (circles). We selected events that are west of 142.5°E and that fall within 45° from vertical below any station to ensure their depth accuracy. This excludes earthquakes that are far from the land stations that have poor depth constraints. The selected events have typical relative hypocentral errors of 0.3 to 1.6 km, which are estimated from the residuals of DD data. Comparison with repeating earthquake locations with ~20 m accuracy by waveform cross-spectrum analysis [*Uchida et al.*, 2007] also shows a similar hypocenter uncertainty of 0.2 to 1.2 km. As an example of the relocated earthquakes, we show in Figure 3 seismograms of some of the events with epicenters near station MY3 (Figure 1b). The earthquakes are classified by the delay between the *S* arrivals relative to the *P* arrivals, indicating systematic differences in source depth. Repeating earthquakes have *S*-*P* delays that are intermediate between intraslab events and events above the plate boundary under station MY3. We also note that the members of each repeating earthquake group (the first three events in Figure 3b belong to one group and the last two events belong to another group) have very similar waveforms. Intraslab earthquakes of the upper (first two events in Figure 3c) and lower (last three events in Figure 3c) planes of the double seismic zone are apparent.

4. Depth of the Forearc Moho

[11] As it is desirable to establish the position of the forearc Moho relative to the hypocenters of repeaters and possible supraslab events, we used previously established methods to extend determination of Moho depths seaward of the Pacific coastline. Phases identified as body waves converted at the Moho and other velocity boundaries have often been detected in seismograms of local earthquakes,

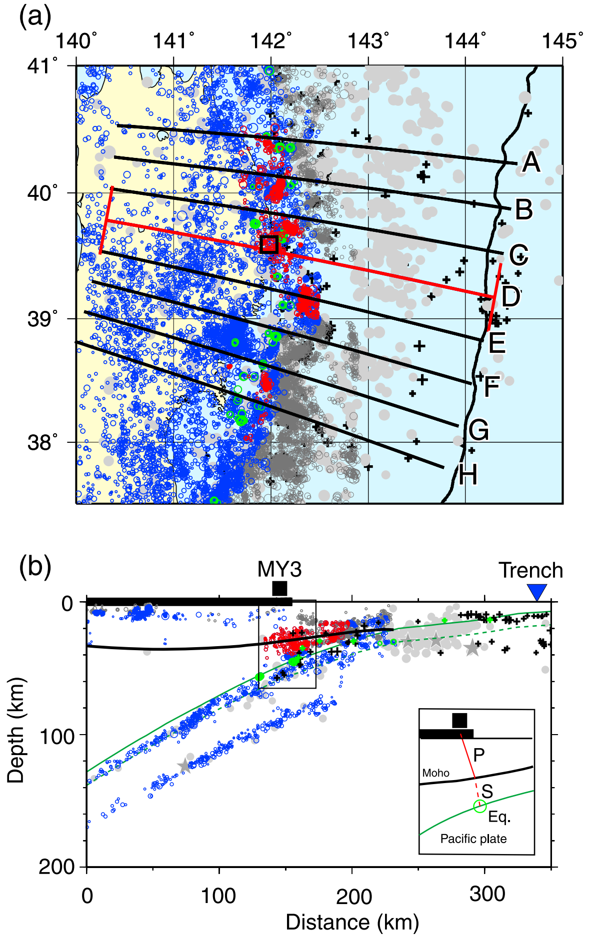

Figure 2. Epicenter map and cross section of the Sanriku region of NE Japan for events relocated by the double-difference method. Events are color coded as repeating earthquakes at the subduction boundary (green circles), supraslab events 5–25 km above that boundary (red circles), and other well-located earthquakes (blue circles). Offshore events with depths determined from the *sP* depth phase (crosses); Engdahl, van der Hilst, and Buland (EHB; *Engdahl et al.* [1998]) events (filled gray circles and stars (for magnitudes greater than 6) determined from phase data recorded by global and regional stations) are also shown. Open gray circles are earthquakes outside the 45° window below stations (see text for more explanation). (a) Epicenter map also shows the position of the Japan Trench and the location of the cross sections shown in Figures 2b and 5. (b) Cross section showing the events described in the preceding figure caption and the position of the subduction plate boundary (solid green line), the Moho in the subducted Pacific plate (dashed green line), and the Moho in the overlying plate (black line; described in section 3).

and their travel times are used to estimate the location of such boundaries [e.g., *Snoke et al.*, 1977; *Horiuchi et al.*, 1982; *Matsuzawa et al.*, 1990; *Zhao et al.*, 1990; *Nakajima et al.*, 2002]. Converted phases are also seen in the waveforms of small repeating earthquakes, which are shown in Figure 3b. The high-amplitude phase that arrives between *P* and *S* can be interpreted as an *S* wave converted to a *P* wave at the Moho, a major velocity boundary crossed by waves from most offshore earthquakes and received by land stations (see Figure 2b for the ray path). These *SP* converted waves arrive at land stations as a *P* wave whose high amplitude suggests that it is generated at a sharp seismic velocity boundary. We found that the seismograms of most of the relocated small repeating earthquakes have prominent *SP* converted phases. The use of small repeating earthquakes on the plate boundary as sources for the *SP* phase used in estimating the locations of the Moho reduces the possibility of phase misidentification because there is no possibility of wave conversion or reflection at the plate boundary, which is the other major velocity boundary in subduction zones.

[12] We visually identified 132 *SP* converted phases from 30 repeating earthquakes and read *S*-*SP* times from three component waveforms from the Hi-net and Tohoku University's seismic stations (Figure 4a). In addition to the offshore converted phases, we included results from phases converted and reflected at the Moho beneath the land area studied by *Nakajima et al.* [2002]. The number of data points is 223 for *PP* reflected waves, 269 for *SS* reflected waves, 61 for *PS* converted waves, and 140 for *SP* converted waves.

[13] Then we expressed the depth distribution of the Moho as a function of latitude (ϕ) and longitude (λ) following *Horiuchi et al.* [1982] and *Nakajima et al.* [2002]:

$$H_m(\phi', \lambda') = C_0 + C_1\phi' + C_2\lambda' + C_3\phi'^2 + C_4\phi'\lambda' + \cdots + C_{20}\lambda'^5, \quad (1)$$

where $\phi' = \phi - 39.0$ and $\lambda' = \lambda - 141.5$.

[14] The unknown C_i coefficients were determined by an inversion of all travel-time differences. The forearc velocity structure used for travel-time calculation consists of three layers, which correspond to the upper crust, lower crust, and uppermost mantle. We assigned the *P*-wave velocity to be 5.9 km/s in the upper crust, 6.6 km/s in the lower crust, and 8.0 km/s in the uppermost mantle based on the results of previous studies [*Hasegawa et al.*, 1978; *Horiuchi et al.*, 1982; *Zhao et al.*, 1990]. *S*-wave velocity is obtained by assuming V_p/V_s to be 1.71 in the crust and 1.78 in the uppermost mantle [*Hasegawa et al.*, 1978; *Horiuchi et al.*, 1982; *Zhao et al.*, 1990]. Depth to the Conrad discontinuity is fixed at 15 km.

[15] The Moho depth variations determined at the conversion/reflection points (Figure 4b) are shown in Figure 4c. We also show the approximate eastern limit of the mantle wedge (i.e., the contact point of the forearc Moho and the Pacific plate), which has been previously determined along three profiles in reflection/refraction surveys [*Ito et al.*, 2004, 2005; *Fujie et al.*, 2006] (filled circles in Figure 4c). The Moho depths along these profiles are compatible with our new results from converted and reflected phases. The conversion and reflection points from the data of *Nakajima et al.* [2002] (small diamonds and circles) are distributed under the inland area, and those from our study (large circles) are distributed mainly in the offshore (Figure 4b). Most of the travel-time residuals are less than 1 s and there is no regional pattern to the signs or magnitudes of the residuals. The Moho depths in the forearc area become shallower from near the coastline (~30 km) to the approximate eastern limit of the mantle wedge (~20 km; dashed line

in Figure 4c), whereas the Moho depth beneath the land area is very similar to that of *Nakajima et al.* [2002].

5. Supraslab Earthquakes

[16] In Figure 2b we show relocated earthquakes within 30 km from line D (Figure 2a) with the Moho discontinuity (black line) and the upper surface of the Pacific plate (green line [*Zhao et al.*, 1997]). Among these earthquakes, events that are within 5–25 km above the plate boundary were designated "supraslab" events and are plotted as open red circles. Small repeating earthquakes that were selected and relocated by the same procedure are shown by green circles (Figure 2). Relocated hypocenters of offshore events using the regional *sP* depth phase from *Gamage et al.* [2009] are plotted by crosses. Earthquake hypocenters from the EHB catalog [*Engdahl et al.*, 1998], based largely on teleseismic phase data, are shown by filled gray circles ($M < 6.0$) and filled gray stars ($M \geq 6.0$), respectively.

[17] There are many supraslabearthquakes above the Pacific plate boundary, especially near the Sanriku coast. Small repeating earthquakes are also distributed in the same geographic area, demonstrating that these supraslab clusters are truly *above* the Pacific-plate subduction boundary. Their distribution is not uniform and consists of a number of earthquake clusters whose dimensions are as large as 15 to 30 km. Some of these clusters are continuous with clusters of events seaward of our near-coastal study region that do not have the same station coverage and good depth constraints. Presumably these clusters just outside our selection area are also supraslab. Farther south, many earthquake clusters also appear to be supraslab, but this hypothesis cannot be proven since they occur too far east of the coastline of Sendai Bay for us to be confident of their relative depths.

[18] The cross sections along lines A to H (Figure 5) show the depth distributions of earthquakes within 10 km from each section using the same symbols as in Figure 2b. We also show the location of the Moho in all sections. The double seismic zone beneath the land area and the hypocenters using the regional *sP* depth phase and EHB catalog between the coast and the Japan Trench (Figure 5; triangle) clearly delineate the Pacific plate (Figure 5; solid green line). Supraslab earthquakes are evident in cross sections A-H. They are distributed mostly at depths of between 20 and 50 km and at 0 to 25 km above the plate boundary (solid green line). Small repeating earthquakes (green symbols) are distributed along the subduction plate boundary (solid green line), and their existence beneath

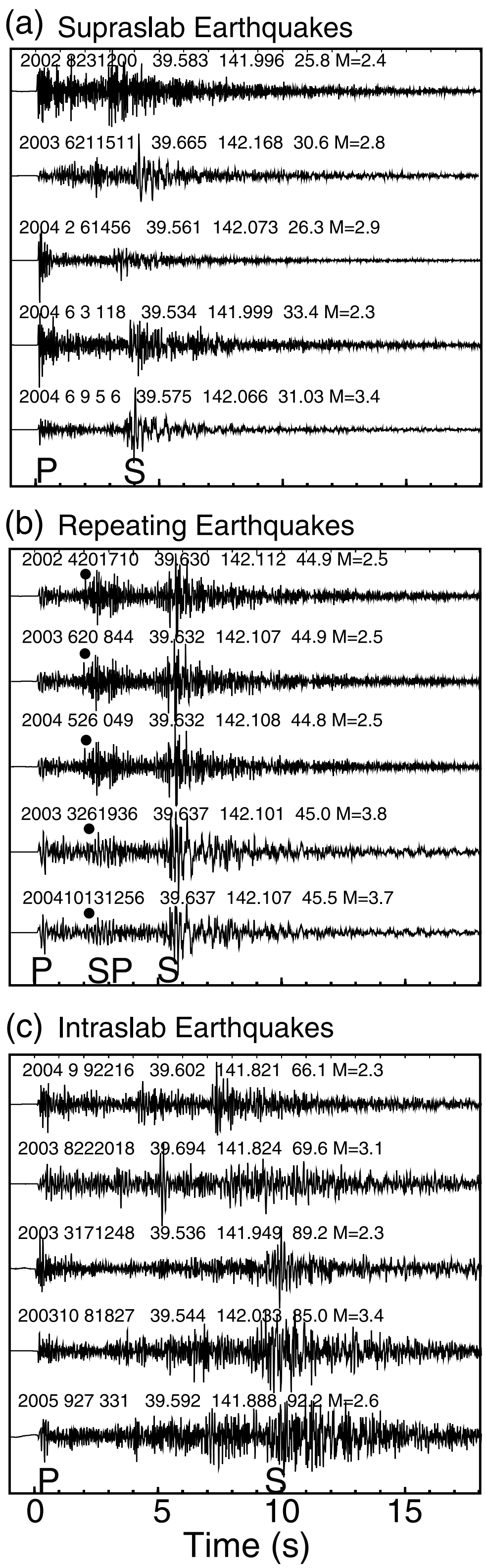

Figure 3. Velocity seismograms of the up-down component recorded by the Tohoku University station MY3 for events within the rectangle shown in Figure1b. Tic marks on the time coordinate are at 1 s intervals. Labels in each plot show the origin time, hypocenter location, and magnitude. These records are aligned with the *P* arrivals and classified according to the delay between *S* and *P* arrivals as an indicator of differences in depths. (b) Records from repeating earthquakes that are along the subduction boundary. (a) Records with shorter *S*-*P* delays and, hence, from supraslab events. (c) Records of events with longer *S*-*P* delays, which are intraslab earthquakes. Some of these seismograms record phases between *P* and *S* that represent body-wave conversions at wave-speed discontinuities, such as the slab Moho, the plate boundary, and the forearc Moho. Filled circles in Figure 3b show the arrival time of converted waves that were interpreted as SP converted waves at forearc Moho.

these supraslab cluster earthquakes ensures that the locations of these earthquakes are indeed above the plate boundary. All of the focal mechanisms for the small repeating earthquakes (Figure 6a; green "beachballs") are low-angle thrust type, whereas the focal mechanisms for supraslab events (red "beachballs") show a wide variation in the orientations of nodal planes and *P* and *T* axes. These focal mechanisms are in contrast not only to those of the repeating earthquakes, but also to those of the intraslab earthquakes in the subducting Pacific plate [*Kita et al.*, 2006].

[19] Cross sections of earthquake hypocenters determined from phase data acquired during short-term OBS deployments above the forearc of NE Japan also show supraslab events above plate-boundary earthquakes [*Yamamoto et al.*, 2008]. Those cross sections show fewer supraslab earthquakes because they represent deployments of months rather than years of monitoring by land stations. Several groups of supraslab clusters are evident among these well-located events.

[20] In an effort to illustrate the regional pattern of seismicity we collapsed cross sections A-H by projecting the earthquake hypocenters, volcano positions, and Moho surfaces along the strike of the trench by plotting their distance from the Japan Trench (Figure 7). Although some supraslab events are clearly in the forearc crust, most are located within or near the trenchward corner of the forearc mantle. As discussed in section 6, this is a finding that has significance in interpreting supraslab earthquake clusters.

6. Discussion

[21] By using the methods just described, the dense onshore stations in Tohoku and the cabled and conventional OBS stations deployed at times on the inner slope of the Japan Trench have permitted exceptional earthquake depth resolution in this subduction system. Moreover, the identification and relative locations of numerous repeating earthquakes that are known to represent seismogenic slip on the interplate boundary put accurate controls on the position of the plate boundary, in addition to the other constraints already discussed. The existence of numerous well-located earthquakes clusters just above this plate boundary poses a fundamental question: What is the nature of the source region where such clusters occur? A perhaps significant observation is that many of the supraslab clusters occur just below the forearc Moho, just west of its intersection with the upper surface of the Pacific-plate slab. Thermal models indicate that this is the coldest part of the forearc mantle and is an environment where serpentine is stable and may be formed, provided that water released from the descending

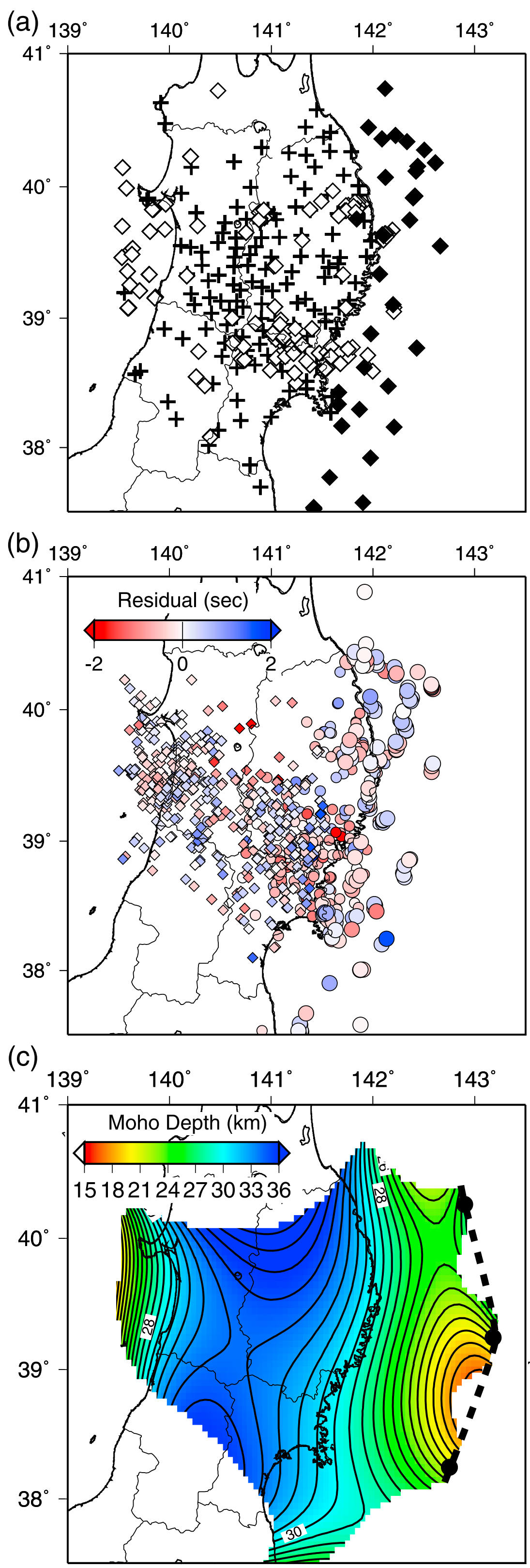

Figure 4. Moho depth variations in the central part of NE Japan. (a) Stations (crosses), earthquake sources from *Nakajima et al.* [2002] (white diamonds), and earthquake sources of offshore repeating earthquakes (black diamonds). (b) Distribution of conversion points (circles) and reflection points (diamonds) at the Moho are color coded according to travel-time residual between the observed and the theoretical travel-time differences. Large symbols are the conversion points from small repeating earthquakes and small points are conversion or reflection points from the data of *Nakajima et al.* [2002]. (c) The depth of the Moho, contoured and color coded according to depth. The contour interval is 1 km. Filled circles and bold dashed lines show the observed [*Ito et al.*, 2004, 2005; *Fujie et al.*, 2006] and interpolated locations of the eastern limit of the mantle wedge, respectively.

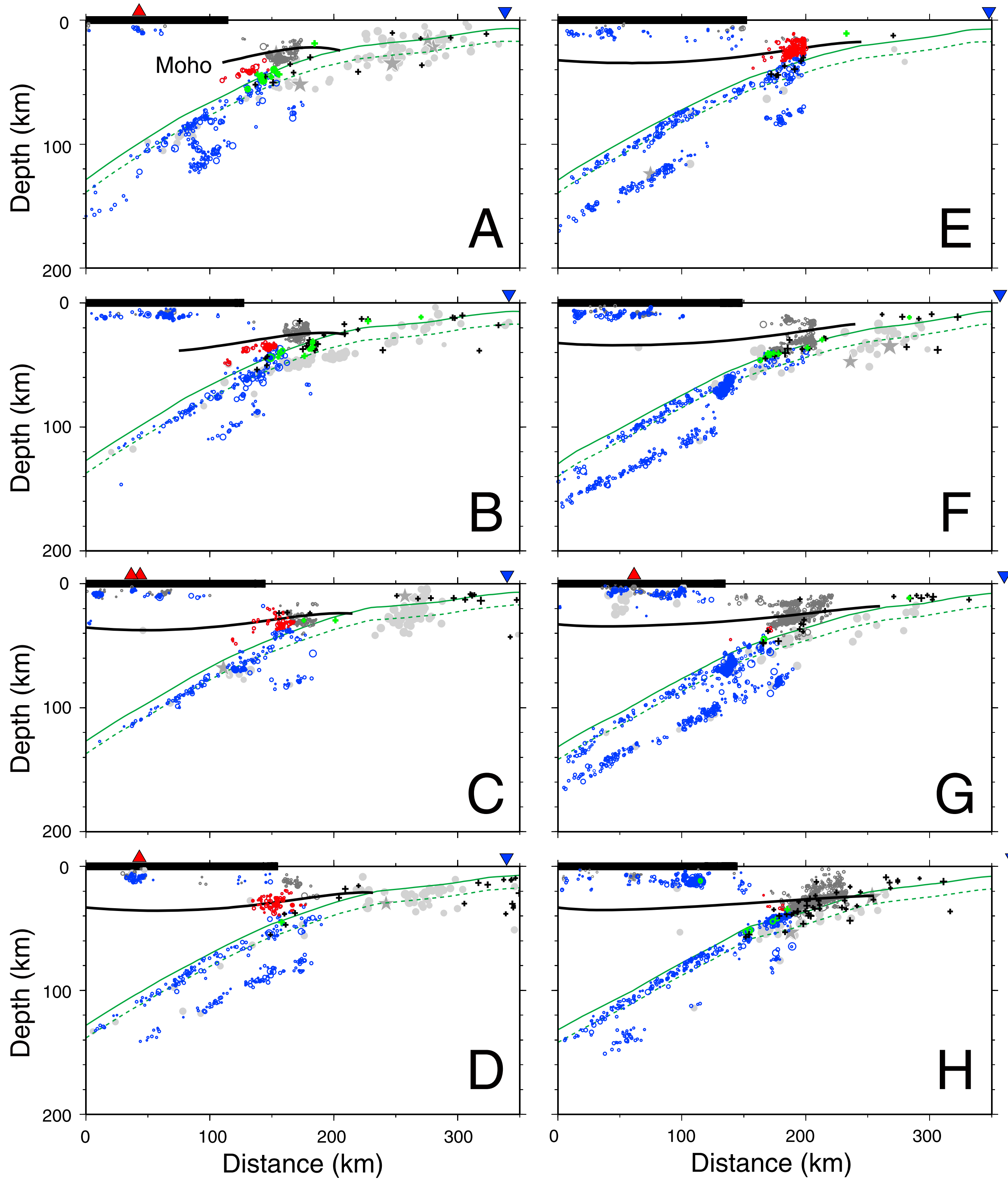

Figure 5. Trench-perpendicular cross sections A through H of the seismicity shown in Figure 2 using the same symbols as in that figure. Filled red triangles are the positions of Quaternary volcanoes. Note the numerous supraslab earthquakes above the subduction plate boundary in sections A through E but absent in section F.

Pacific plate actually migrates into this cold region. Actually, *Yamamoto et al.* [2006, 2008] suggest that the mantle wedge in the southern part of our study area is partially serpentinized based on 3-D seismic tomography using both onshore and offshore seismic station data. Seismological and other geophysical evidence indicates that such a partially serpentinized wedge probably also exists in the forearc mantle in the Cascadia [*Bostock et al.*, 2002; *Brocher et al.*,

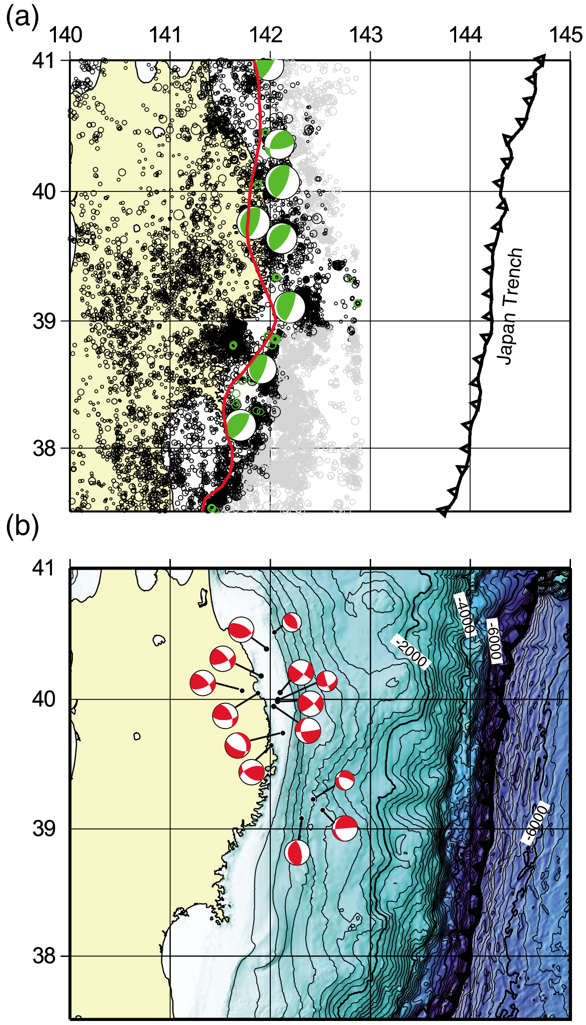

Figure 6. Focal mechanisms (lower-hemisphere projection) of relevant earthquakes estimated by *P*-wave first motions (JMA catalog) and moment tensor determination (Full Range Seismograph Network of Japan, NIED). (a) Repeating earthquakes showing low-angle thrust mechanisms with nodal planes generally parallel to the trench. The red line shows the approximate position of the downdip limit of interplate thrust earthquakes on the subduction boundary [*Igarashi et al.*, 2001]. (b) Focal mechanisms of supraslab earthquakes showing very diverse mechanism types, including strike-slip faulting. Bathymetric map base is courtesy of Azusa Nishizawa (Hydrographic and Oceanographic Department, Japan Coast Guard). Note the complex scalloped morphology of the inner trench slope, which is thought to represent the effects of prior seamount collisions with the forearc.

2003; *Blakely et al.*, 2005] and SW Japan subduction zones [*Seno*, 2005].

[22] In this study we observed supraslab clusters down to a depth of about 50 km. However, environments where earthquakes occur deeper than about 20-25 km worldwide are usually restricted to collision zones or subduction zones where the thermal structure is cold in the downgoing plate and hydrous minerals may be carried to depths and temperatures where they dehydrate and liberate water, which can facilitate brittle fracture and frictional sliding [*Raleigh*, 1967; *Kirby et al.*, 1996; *Peacock and Wang*, 1999; *Hacker et al.*, 2003]. Exceptions include deep-crustal or deep-mantle earthquakes under arc volcanoes [*Hasegawa et al.*, 1991; *Hasegawa and Yamamoto*, 1994] and intraplate volcanoes, such as Hawaii [*Eaton and Murata*, 1960; *Wilshire and Kirby*, 1989], oceanic lithosphere subjected to plume magmatism, and bending near trenches [*Seno and Yamanaka*, 1996]. These exceptions all potentially relate to settings where deep magmatic fluids may be involved [*Wilshire and Kirby*, 1989; *Kirby*, 1995].

[23] Subducting slabs are especially fertile environments for such dehydration enbrittlement. Thermal models [e.g., *Furukawa*, 1993; *Peacock and Wang*, 1999; *Hacker et al.*, 2003; *Yamasaki and Seno*, 2003] show that as initially cold and hydrated oceanic lithosphere descends into the mantle, the slab heats up, and pressurizes and slab rocks are expected to sweep through the equilibrium dehydration metamorphic boundaries [e.g., *Hacker et al.*, 2003] and liberate their water of hydration. Pore pressures in the granular material along the plate boundary (the subduction channel) are also expected to be high, as both compaction and sediment mineral dehydration occur. A little-discussed feature of such models is that, assuming that heat transfer is largely by conduction, thermal models also show that the thermal structure of slabs and forearc regions becomes stable after only a few tens of millions of years of subduction, provided that the thermal inputs (convergence rates, slab dip, and thermal structure of the incoming plate) do not change (unpublished results from thermal modeling reported by *Kirby et al.* [1996]). If such thermal models are applicable, then forearcs above slabs are not expected to be an environment of rapid prograde (dehydration) metamorphism. This situation is reasonable for the NE Japan subduction zone because it is a mature subduction system where subduction has persisted for much of the Cenozoic onward, and the seafloor age and rate of convergence of the Pacific plate entering the Japan Trench have not changed greatly during this period [*Richards and Engebretson*, 1992]. Therefore, for simple thermal models the forearc source region of the supraslab clusters would be thermally stable and in contrast with subducting slabs, where conductive heating, dehydration, and intraslab earthquakes occur. Why should earthquakes occur in this forearc region if the base of the forearc is expected to be thermally stable?

[24] The properties of supraslab earthquakes and the foregoing discussion allow us to evaluate several alternative interpretations of their origin. (1) These earthquakes occur along faults that splay off the subduction boundary. Such structures are known to occur at shallower depths in some subduction systems [*Plafker*, 1965; *Park et al.*, 2002]. However the DD relocated supraslab hypocenters in the present study do not resolve obvious fault-like structures as they often do in investigations of fine-scale seismicity using the DD method, and hence there is no apparent spatial coherence as thrust focal mechanisms that would support such a hypothesis. (2) Supraslab events and clusters represent fluid-pressure effects of water migration from the Pacific-plate slab into the cold forearc mantle, reducing the effective normal stresses and promoting brittle fracture and unstable frictional sliding at depth. However, free water as a fluid phase is expected to be unstable in the presence of

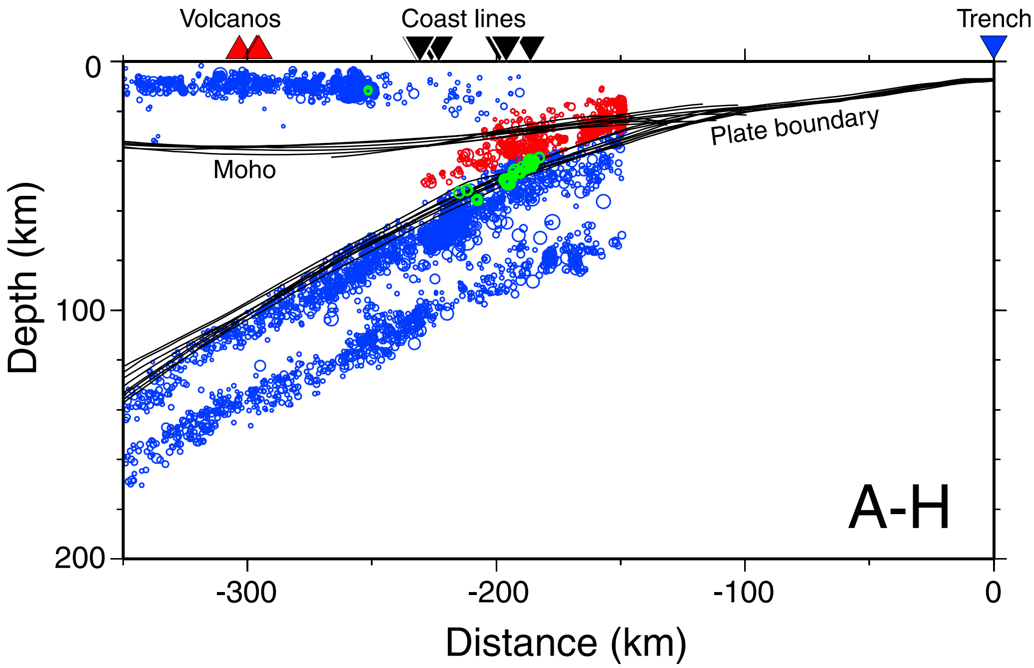

Figure 7. Composite of cross sections A through H in Figure 4 collapsed along the coordinate normal to the sections showing the regional seismicity patterns for the Sanriku sector of the Japan-Trench subduction system. Supraslab earthquakes are shown in red above the plate boundary defined by repeating earthquakes in green. Thin black lines are the subduction plate boundary and the Moho in the overlying plate for each cross section. Note that most of the stations are distributed to the west of the coast lines (inverted triangles) and the earthquakes that do not fall within 45° from vertical below any station and to the east of 142.5°E are not plotted here. Many of the deeper supraslab events occur within the forearc mantle.

peridotite at such low temperatures, producing serpentine and its accessory minerals [*O'Hanley*, 1996]. Also, antigorite, the high-pressure form of serpentine, exhibits velocity strengthening behavior in the laboratory and hence exhibits stable frictional sliding [*Reinen et al.*, 1994]. Earthquakes are therefore not expected in serpentinized mantle or along serpentinized faults zones in forearc mantle. These inferences would seem to rule out upward migration of pressurized water into the cold forearc mantle closest to the trench as an explanation of supraslab seismogenesis. However, such a process could operate at shallower depths within the forearc crust. Some of the shallow supraslab seismicity seen in the crust of the overlying plate (above the forearc Moho) could be occurring by this process. (3) The thermal models discussed above assume that no mass transfer occurs across the subduction boundary. If cold, hydrated material in a slab somehow accretes to the forearc *from* the slab, then seismogenic faulting would be enabled *above* the interplate boundary, since such materials would start out colder than the base of the forearc, carry hydrated material, and then heat up and dehydrate with time. Seamount crust might be such a material. There is abundant bathymetric and seismic evidence that seamounts survive their initial descent under forearcs [e.g., *von Huene and Lallemand*, 1990; *von Huene et al.*, 1997, 2000; *Mochizuki et al.*, 2008]. This shallow seamount collision environment involves the frontal prism of the forearc, where seismic velocities are low, migrating fluids are abundant, and, by inference, forearc rocks are weak. At deeper levels geological investigations suggest that tectonic underplating of mafic crust may occur in subduction systems [*Cloos*, 1993], including volcanic ridges and seamounts, and the detachment process might be seismogenic [*Cloos*, 1992]. The supraslab earthquake clusters described in this paper may represent a seismological expression of underplating occurring by seamount detachment.

[25] By what process does tectonic underplating occur? Insight into how and why detachment should occur during subduction should draw on the geological histories of the development of volcanic seamounts and islands in the ocean basins. There are many large volcanic seamounts exposed on the Pacific seafloor off the Japan Trench. Many are guyots, having flat tops and, hence, evidently large enough to have been islands earlier in their histories [*Winterer et al.*, 1993; *Koppers et al.*, 2003; *Hirano et al.*, 2006]. Some of these guyots have been dated from 94 to 120 Ma B.P., compared with the seafloor ages of 128 to 145 Ma (anomalies M8 to M16 [*Koppers et al.*, 2003; *Hirano et al.*, 2006]). These guyots were therefore emplaced on young, thin lithosphere at shallow seafloor depths, and they are likely to have flexurally subsided under their own weight [*Watts*, 2001] to near-equilibrium plate deflection. They have also thermally subsided with the cooling of the Pacific plate, explaining their wave-cut tops and their present-day abyssal depths. There is widespread bathymetric evidence of prior seamount subduction at the Japan Trench in the form of collisional re-entrants or furrows in the inner trench slope produced by seamount plowing [*von Huene and Lallemand*,

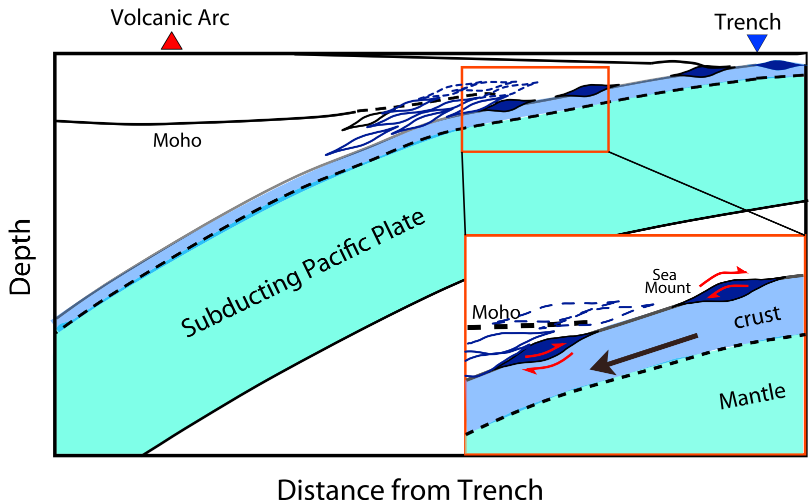

Figure 8. Schematic diagram illustrating the proposed conceptual model proposed for supraslab earthquakes involving seamount subduction and detachment in NE Japan. Not to scale. Seamount crust off the Japan Trench (light blue lens shapes) subducts with the Pacific-Plate slab (dark blue lenses), at first plowing the forearc and piling up eroded material ahead of the seamount. According to this model, where the forces resisting the relief of the seamount motion with the Pacific plate exceed the strength of the base of the seamount, the seamount detaches (white lenses), accretes to the forearc, and fragments along internal sources of weakness, such as former volcanic rifts, slump block boundaries, and normal faults created near the trench. Repetition of such processes over geologic time leads to subduction erosion near the trench and stacking (underplating) of seamount crust at greater depths nearer the coastliner and, perhaps, flexural uplift of the near-coastal region. See text for additional explanation. These hypothetical detachment and fragmentation processes could lead to a seamount graveyard where earthquakes continue to occur as these seamount fagments heat up, dehydrate, and fault under subduction-related stresses as enabled by dehydration embrittlement.

1990; *von Huene et al.*, 2000; *von Huene*, 2009] and, also, "bumps" on the inner trench slope, some of which have been imaged as seamounts by seismic reflection and magnetic surveys [*Mochizuki et al.*, 2008]. Such features may be seen in the bathymetry off Sanriku (Figure 6b).

[26] The structure and kinematics of intraplate volcanic islands and seamounts in the ocean basins give us clues as to how underplating by seamount detachment might occur. The active volcanic island of Hawaii has been shown to grow by voluminous volcanic lava flows, by dike injection along volcanic rifts, by seaward thrusting of sectors of the volcanic edifices along the sedimented seafloor on which the volcano was laid down [*Wyss*, 1988], and by seaward slumping of blocks of the island edifice. The $M = 7.1$ Kalapana earthquake of 1975 has been interpreted as a seismic expression of this sector spreading [*Ma et al.*, 1999]. Detailed bathymetry and the seismic structures of seamounts often show the morphology of volcanic rifts (expressed as radiating ridges) and flank sector development by slip on the original seafloor [*Watts*, 2001].

[27] We argue that these same basal zones under volcanic seamounts and islands could, at depths greater than about 10–15 km, lead to detachment during subduction by the following mechanism (see schematic in Figure 8). Volcaniclastic rocks surrounding islands and seamounts, pillow basalts laid down on the seafloor at sites of intraplate volcanism, and shallow basalts at midocean ridges are known to be altered by interaction with seawater to form clay minerals, zeolites, and other minerals stable at low temperatures. At depths of approximately 10 to 30 km and 100° to 200°C, such minerals should dehydrate [*Peacock*, 1990; *Oleskevich et al.*, 1999] and hence have the potential to create a high fluid pressure at the bases of seamounts, which could consequently detach more easily than at shallow depths. Internal structures, such as volcanic rifts, slump and landslide block boundaries, and normal fault zones produced by seamount bending at trenches, should also be altered by such minerals, and subsequent release of water by dehydration could lead to tectonic dismemberment of seamounts into fragments that could be internally seismogenic since they are cold and are altered when they enter trenches.

[28] Some supraslab clusters have map dimensions of the order of 10 to 30 km (Figure 2a). This dimensional range is broadly consistent with the range of dimensions of large seamounts exposed on the ocean floor off the Japan Trench [*Nishizawa*, 1999; *Tsuru et al.*, 2000; *Nishizawa et al.*, 2009] and subducted seamounts revealed by seismic reflection surveys just west of the Japan and Izu trenches [*Tsuru et al.*, 2002]. However, many supraslab clusters are much smaller than this dimensional range and are broadly dispersed (Figure 2). These smaller clusters could represent fragments of seamounts that have been mechanically dismembered during subduction along internal planes of weakness developed earlier when they were active volcanoes. That the deformation environment represented by these earthquakes is complex is shown by their extremely diverse focal mechanisms (Figure 6b).

[29] It is also noteworthy that the supraslab clusters in the Sanriku region are just landward of the downdip limits of

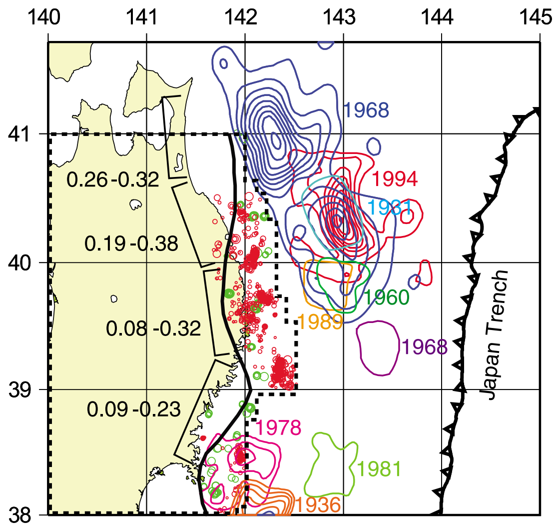

Figure 9. Map of the supraslab earthquake epicenters of this study (red circles) in relation to the rupture areas of $M \geq 7$ interplate earthquakes from 1930 to 2004 (contours) inferred from inversions of seismic waveforms by *Yamanaka and Kikuchi* [2004]. Note that the earthquakes that are apparently shallower than the plate boundary, and inside of the region shown by the dashed line, are considered in this study (see text and caption to Figure 7). Green circles are small repeating earthquakes and the bold black line shows the downdip limit of interplate earthquakes [*Igarashi et al.*, 2001]. Coastal uplift rates (m/kyr) estimated from Quaternary marine terrace uplift data [*Koike and Machida*, 2001] in four sections of the Sanriku coast are also indicated by numbers to the left of the square brackets. Supraslab earthquake clusters generally are downdip of the asperities of large subduction earthquakes.

the largest interplate earthquakes that have occurred since the 1930s (Figure 9) [*Yamanaka and Kikuchi*, 2004]. Most of the interplate repeating earthquakes beneath the supraslab clusters are small (<0.5 km in their rupture dimensions). This downdip limit of the largest interplate thrust earthquakes is presumably governed by the depth at which large-scale mechanical decoupling takes place between the Pacific plate and the Tohoku forearc. A transitional plate-boundary slip region may be defined between the downdip limit of the largest plate-boundary events and the downdip limit of all plate boundary earthquakes (at roughly 45 to 55 km in depth; black line in Figure 9), including repeaters. We have found most of the supraslab earthquake clusters above this transitional region of the plate boundary. The normal sedimented and altered seafloor base on which seamounts are laid down is thermally shielded temporarily from conductive heating by seamount crust and probably dehydrates and detaches by fluid-pressure-assisted basal slip at greater depths than for interplate slip on normal oceanic crust. Normal seismic interplate decoupling on ordinary sedimented and altered seafloor may therefore have some kinship with processes that lead to seamount detachment.

[30] If seamount subduction does tend to occur over a specific depth interval, then this process would be cumulative, with seamounts sequentially detaching, dismembering, and stacking up under the forearc (Figure 8). We infer that the continental crust in the forearc region is partially constructed by the detached seamounts (Figure 8; dashed lenses). This possible accretive process is also in the context of subduction erosion that tectonically removes material from the base of the forearc at shallower depths nearer to the Japan Trench. The Quaternary marine terrace data show a coastal uplift rate of 0.08–0.38 m/kyr (Figure 9) [*Koike and Machida*, 2001]. Although the contraction deformation in plate conversion direction in the Tohoku forearc region since 3.5 Ma [e.g., *Sato*, 1994] may have contributed to the uplift, it could also be explained by the accretion of seamounts.

[31] A recent paper by *Tsuji et al.* [2008] describes the results of a DD tomographic study of the same area of NE Japan, with a focus exclusively on the seismic velocity structure of the Pacific-plate slab and mantle wedge at depths greater than 70 km under the land. However, their tomography and relocated hypocenters also cover the shallower structure and seismicity of the offshore forearc mantle that includes our study area. Although their study does not include discussion of this shallower region of the slab and forearc, it reveals a low-wave-speed region of the forearc mantle nearest the Japan Trench, lower than typical mantle wave speeds. A calculated V_p/V_s tomographic image of theirs also shows that this coldest part of the forearc mantle is heterogeneous. Our study was able to trace the forearc Moho above this region, suggesting that although the average wave speed is lower than for normal mantle, a sufficiently large velocity contrast exists with the lower forearc crust to reflect and convert body waves that impinge on it. These combined findings suggest to us that the forearc mantle region under study where supraslab earthquakes occur is composed of lithologies mixed with peridotite mantle. The most likely lithologies mixed with peridotite are serpentinite and mafic rocks, such as gabbro or metagabbro and metabasalts, consistent with accreted seamount crust. At this point, we cannot discriminate between these two possible models (reduced mantle seismic velocities caused by forearc mantle serpentinization or by accretion of seamount crust into the forearc mantle) for mixed lithologies in the cold seaward limit of forearc mantle in the Japan Trench system. It is noteworthy that in the best case for serpentinized forearc mantle, the Cascadia subduction system, the serpentinized forearc mantle is aseismic [*Bostock et al.*, 2002]. The possible presence of serpentinized forearc mantle caused by release of water from the slab therefore cannot explain seismic activity above the slab because serpentinization under stress does not lead to fracture or unstable sliding.

[32] Clearly more detailed information is needed to test this seamount hypothesis. Marine seismic refraction and reflection surveys are needed to investigate the fine structures of the guyots off the Izu and Japan Trenches in order to interpret how seamount structure might influence mechanical fragmentation during slab descent. OBS deployments above supraslab clusters could provide fine-scale details of hypocenter distribution and focal mechanisms and how such information might relate to the kinematics among possible seamount fragments.

7. Summary

[33] A class of earthquakes and earthquake clusters has been described that are located above a suite of repeating

earthquakes that accurately mark the subduction plate boundary of NE Japan. Most of these supraslab earthquakes are within about 25 km above the plate boundary and many occur below the forearc Moho. A number of hypotheses were considered in attempting to interpret these observations, but we argue that supraslab earthquakes can be best explained by seismogenesis that occurs within detached seamounts and seamount fragments. These cold and hydrated materials are expected to warm up, dehydrate, and enable brittle fracture and frictional sliding after detachment and fragmentation during subduction. If this hypothesis is correct, then the recognition of supraslab earthquakes represents the first direct evidence of crustal underplating of ocean-island-basalt materials as an active, ongoing process in a subduction zone.

[34] **Acknowledgments.** This paper evolved from "brainstorming" sessions at the Research Center for Prediction of Earthquakes and Volcanic Eruptions, Tohoku University (RCPEV). We acknowledge the value of discussions with those participants who are not coauthors. The authors thank an anonymous associate editor, two anonymous reviewers, and Editor Robert Nowack for their thoughtful reviews of the manuscript. We used seismic waveform data obtained by the off-Sanriku cabled ocean bottom seismic observation system operated by the University of Tokyo Earthquake Research Institute and arrival time data provided by the Japan Meteorological Agency. We also acknowledge the supply of EHB hypocenters from E. Robert Engdahl at the University of Colorado, Boulder, the offshore hypocenter catalog from S. S. N. Gamage, phase data on the Moho reflected and converted waves from J. Nakajima, and the first version of a data set of DD-relocated hypocenters from S. Kita. We are grateful for all these contributions.

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