Crustal structure and seismic activity at subduction zones

Struktura i seizmicka aktivnost subdukcione zone zemljine kore

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Kratak sadrzaj na Srpskom:

Vecina zemljotresa je generisana u zonama kontakta tektonskih ploca. Jedan vid ovakvog kontakta nastaje u podrucju suceljavanja okeaske i kontinentalne Zemljine ploce, gde dolazi do podvlacenja ili subdukcije okeanske ploce ispod kontinentalne. Zone podvlacenja su podrucja koja se odlikuju najraznovrsnijim i najsnaznijim zemljotresima na svetu. Prema mestu nastanka, zemljotresi u zonama podvlacenja se dele na kontinentalne, subdukcione i Wadati-Benioff. Ovaj rad ima za cilj da citaocu ukratko izlozi savremena saznanja o subdukcionim i Wadati-Benioff zemljotresima, cija je pojava iskljucivo vezana za zone podvlacenja. Posebna paznja je posvecena mogucnosti primene reflektivnih seizmickih istrazivanja pri proucavanju ovih dubokih zemljotresa. Prikazana istrazivanja su izvedena na podacima prikupljenim u subdukcionim zonama severoistocnog Tihog okeana. Pri interpretaciji korisceni su podaci reflektivnih seizmickih istrazivanja, seizmoloski podatci o hipocentrima zemljotresa, batimetrijske karte, geomagnetske izohrone, kao i rezultati tomografskih, geodetskih, gravitacionih i termalnih ispitivanja.

Key words: Subduction, seismicity, earthquake, megathrust, reflection, imaging, plate.

Abstract

The largest and the most diverse earthquakes on Earth occur in subduction zones. These are areas where oceanic and continental plates converge and where oceanic plates dip or subduct underneath the continental plates. The focus of this paper is on megathrust and Wadati-Benioff or intraslab earthquakes, both of which are specific to subduction zones. Much of what we today know about these earthquakes has been gathered through observational seismology, and more recently through laboratory P-T studies, thermal modeling of heat-flow data, and dislocation modeling of geodetic data. However, all of these investigation methods either have firm resolution limits, or rely on extrapolation of laboratory results, or require extremely long periods of observation thus restricting our ability to further our understanding about the nature of the subduction zone earthquakes. Here, I show that controlled source seismic investigations, which have traditionally been used for determining the structure of subduction zones, also have the potential to provide us with important complementary information about the megathrust and intraslab earthquakes. I first discuss the possibility of using seismic reflection data to extract information about the size and location of the magthrust rupture areas. Then, I argue that the distribution, frequency and maximum magnitude of intraslab seismicity for a particular area can potentially be predicted also using seismic reflection data. I base my arguments and conclusions on data from several subduction zones of the eastern Pacific Rim, north of equator.

1. Introduction

Vast majority of earthquakes are generated within the contact zone between tectonic plates. The largest of them occur in subduction zones, where oceanic and continental plates converge. These zones of underthrusting, where the oceanic plate dips or subducts underneath the continental plate are also known for their large diversity of earthquakes. Based on the spatial distribution, earthquakes generated in subduction zones can be sorted into three groups: continental, megathrust and intraslab. The topic of this paper are megathrust and intraslab earthquakes, which are known to occur only within subduction zones.

1.1 Megathrust earthquakes

Megathrust or subduction thrust earthquakes occur on subduction zone megathrusts and, having magnitudes greater than 8-9, are the largest earthquakes on Earth. Tsunamis generated by the magathrust earthquakes can exact a tremendous toll on human population. The M9.3 2004 Andaman and Nicobar Islands megathrust earthquake tsunami left over 300000 people dead or missing. Subsidence, liquefaction, other ground failure, and strong ground motions due to megathrust earthquakes also cause human loss, as well as extensive damage to the infrastructure. Megathrust earthquakes thus pose significant seismic hazard to many coastal urban centers and are of great interest and concern for both scientists and general public.

In Fig. 1, a schematic diagram of the subduction earthquake cycle is shown. Between two successive megathrust events, part of the subduction thrust becomes locked (strongly coupled) causing stress build-up and elastic deformation in the overlying continental crust (Fig. 1a). Stresses often build for hundreds of years until the locked part of the megathrust ruptures in a great or large earthquake (Fig. 1b). For the largest earthquakes, the rupture is recorded to propagate along the subduction zone for more than 1000 kilometers and to last up to about 10 minutes. After the rupture, the stress build-up resumes.

The updip limit of subduction earthquake rupture is defined either by the trench, or by the change from seismic to aseismic slip regime. The trench acts as a free boundary, while the change in slip regime within the shallow portion of the decollement can be caused by high fluid pressure that is known to dramatically reduce friction (e.g., *Bangs and Westbrook*, 1991; *Shipley et al.*, 1994). At its downdip or landward end, the subduction earthquake rupture is likely limited by the change in the mechanical behavior of rocks, from brittle to ductile (*Nedimovic et al.*, 2003). This change, caused by increasing temperatures and free water released by dehydration processes operating on the subducting plate, occurs within the limits of the area called the transition zone (Fig. 1). Farther downdip of the transition zone is the slow-slip zone that exhibits fully aseismic behavior (Fig. 1).

The amount of coupling along the “locked” portion of the megathrust can also vary laterally and, if so, it influences both seismic moment release distribution and sideways extent of rupture. Strongly coupled portions of the interplate interface, separated by areas exhibiting only partial coupling or even free slip, form asperities within which most of the seismic moment is released during subduction earthquakes. Lateral, or along strike changes in megathrust coupling appear to be mostly governed by the geometry of the subduction zone and the topography of the interplate interface.

The accuracy with which we can determine the interplate coupling along the subduction zones defines how well we can mitigate against future megathrust seismic hazards. The location of the updip limit of rupture is of particular importance for determining the megathrust tsunami hazards, while the single greatest uncertainty in probabilistic seismic hazards maps for megathrust events is the downdip limit of the region of maximum coseismic slip (*Peterson et al.*, 2002). Unravelling the lateral variations in coupling may help better constrain the width and location of the megathrust segments that repeatedly rupture.

Much of what we know today about the coupling on megathrusts we have inferred through earthquake studies, thermal modeling of heat-flow data, and dislocation modeling of geodetic data. Earthquake studies provide detailed information about great earthquake rupture areas and about their repeatability in space and time, but can require an extremely long period of observation. Recurrence rates for great earthquakes are often hundreds of years (e.g., *Atwater and Hemphill-Haley*, 1997; *Goldfinger et al.*, 2003) and modern instrumental recording is only about a century old. Deformation studies of post-seismic uplift from geodetic data have led to the most recent breakthroughs in our understanding of plate coupling at subduction zones but they are based on very short periods of observation and only provide information about the present interplate interface behavior. Furthermore, the resolution of the deformation studies is limited because most of the locked zones on the subduction thrusts are located offshore and accurate deep-sea geodesy is not available yet, despite promising recent developments (e.g., *Speiss et al.*, 1998). Numerical thermal modeling can at best provide accurate temperature estimates for the subduction thrust but megathrust slip behavior depends on a number of other factors such as rock composition and fluid-filled porosity (*Hyndman and Wang*, 1995). These limitations of earthquake, deformation and thermal studies provide motivation to test alternative approaches for short-term detailed characterization of the long-term slip behavior of the megathrusts. In this paper, I discuss the potential of using deep seismic reflection imaging to characterize at high resolution coupling along the subduction interfaces.

1.2 Intraslab earthquakes

Intraslab or Wadati-Benioff earthquakes occur within the subducting oceanic slab and are recorded to reach hypocentral depths of ~680 km and moment magnitudes of up to ~8.3 (e.g., *Silver et al.*, 1995). Although generally of smaller magnitude than the megathrust earthquakes, and occurring at greater depth, intraslab earthquakes still represent a formidable hazard to people and infrastructure of many coastal areas, most notably of the Pacific Rim.

Based on their hypocentral depth, intraslab earthquakes are grouped into: shallow- (<~40-60 km), intermediate- (~40-60 km to ~300 km) and deep-focus (~300-~680 km) earthquakes. The depth ranges for the three groups of intraslab earthquakes are still a matter of debate, as is the mechanical origin of the intermediate- and deep-focus earthquakes (*Meade and Jeanloz*, 1991). Mechanisms other than those responsible for the generation of the relatively well-understood shallow intraslab earthquakes are required to describe the deeper (>~40-60 km) events because they occur at depths at which unassisted brittle failure is inhibited by high pressures and temperatures (e.g., *Jung et al.*, 2004).

Despite the controversy about the origin of the intermediate- and deep-focus earthquakes, a growing body of evidence suggests that metamorphic reactions likely play the key role in triggering these events (*Peacock*, 2001). Deep-focus earthquakes may be caused by faulting associated with the metastable reaction of olivine to spinel (e.g., *Green and Burnley*, 1989; *Kirby et al.*, 1991). Intermediate-depth earthquakes may be triggered by dehydration embrittlement associated either with the transformation of metabasalt and metagabbro to eclogite within subducting oceanic crust (*Kirby et al.*, 1996) or with the dehydration of serpentine within the uppermost subducting mantle (*Meade and Jeanloz*, 1991). Shallow, trench–outer-rise events are generally characterized by horizontal tensional and compressional axes in the shallow and deep portions of the slab, respectively, consistent with stresses produced by bending of an oceanic plate prior to subduction (Seno and Yoshida, 2004).

Although they have a different trigger mechanism, shallow- and intermediate-depth intraslab earthquakes both appear to have ruptures that are generally localized along the pre-existing zones of weakness. For the shallow intraslab events, the pre-existing zones of weakness are fault planes formed at the mid-ocean ridges during crustal accretion. These, and any other faults formed in the trench–outer-rise area due to subduction bending represent pre-existing zones of weakness for the intermediate-depth intraslab earthquakes.

What we know today about the intraslab seismicity has mostly been gathered through observational seismology and laboratory P-T (pressure-temperature) studies. While these investigative methods provide invaluable information, they either have resolution limits, as is the case with earthquake tomography, or require extrapolation of small-scale laboratory results to large-scale natural settings. Such limitations of the currently available information restrict our ability to fully understand the nature of the intraslab seismicity. Here, I investigate the possibility of using reflection seismology to provide new constraints about the intraslab seismicity that are complementary to those already existing. I pay particular attention to the hydration processes that occur before the oceanic plate subducts, and investigate their effect on the most damaging of all intraslab seismicity, the intermediate-depth earthquakes.

3. Study Area, Data and Methods

The area covered in this work encompasses parts of several subduction zones of the eastern Pacific Rim, north of equator (Fig. 2). From north to south, these are Alaska subduction zone, Cascadia subduction zone, and Central or Middle America subduction zone. Crustal age and style of subduction both vary significantly along the investigated margins. The youngest (<~10 Ma old) and the warmest crust is subducted at the Cascadia margin, where much of the sediment is scraped off the incoming plate to form an accretionary prism. Colder and older (>~20 Ma old) crust is subducted along the studied parts of the Central America margin, where there is little sediment input and erosion of the overlying continental plate is taking place. Crust of similar age as at the Central America margin is subducted at the accretionarry Alaska subduction zone.

A variety of data and results have been analyzed for this study. First, a few thousand kilometers of 2D seismic reflection data were examined in detail and processed into reflection images. Interpretation of the results obtained via reflection seismology was then carried out using other available geophysical and geological information. Particularly useful for the interpretation were earthquake hypocentral locations, bathymetric maps, magnetic isocrons, tomography velocities, thermal profiles, geodetic results and gravity maps.

4. Megathrust reflection mapping

The change from aseismic to seismic slip is known to occur on both the shallow and deep portions of the megathrusts and to form the updip and downdip limits of the locked zones, respectively. MCS (multichannel seismic) data were first used to study the change in the slip nature at the shallow decollement. This is because the shallow portions of subduction thrusts are found offshore and are easily accessible for collecting relatively inexpensive marine MCS data. The change from seismic to aseismic slip at the deep, landward end of the locked zones is often located at or near the shore thus requiring very expensive combined marine and land investigations. Furthermore, the deep aseismic slip was only recently discovered (e.g., *Dragert et al.*, 2001), and the geologic structure is more challenging to image at the deep than at the shallow end of the locked zones using the reflection technique.

Some of the most notable seismic reflection studies done at the updip limit of the locked zones were carried out over the Barbados Ridge decollement (*Bangs and Westbrook,* 1991; *Shipley et al.*, 1994). There, it was discovered that the locked and aseismically slipping portions of the shallow megathrusts are characterized by distinct reflection signatures. The shallow, coupled and therefore seismogenic part of the decollement displays positive, normal polarity reflections. The shallow, decoupled and therefore aseismically-slipping decollement has a reflection signature with negative polarity (reversed polarity relative to the seafloor) that is likely caused by focused planes of high fluid pressure. This change in the reflection signature between the coupled and the decoupled shallow megathrust provides an important tool for high-resolution mapping of coupling at the updip limit of the locked zones.

Although a great wealth of MCS data collected over subduction zones exist, only a small fraction can be used to study geologic structure at the transition from a strongly coupled megathrust to deep aseismic sliding. Most of these data come from the northern Cascadia subduction zone, where inland waterways provide an opportunity to collect inexpensive marine data deep into the forearc (1998 SHIPS experiment, *Fisher et al.*, 1999). Together with the 1984 land data collected on Vancouver Island for the Lithoprobe project, and the 1985 and 1989 Geological Survey of Canada marine data collected offshore Vancouver Island, there exists a dense network of crustal-scale MCS profiles covering the subduction zone from the trench to the forearc mantle wedge (Fig 3a).

A recent detailed analysis of the existing northern Cascadia margin crustal-scale seismic reflection data (*Nedimovic et al.*, 2003) indicates that the reflection signature on the megathrust also appears to change at the downdip limit of the locked zones (Figs 3b and 3c). Moreover, this change in the megathrust reflection character appears to correlate well with the change in the slip nature on the megathrust as inferred by thermal and dislocation modeling (Figs 3a and 3d). The locked zone, generally used as a proxy for the seismogenic zone, correlates with the generally thin (<2 km thick) megathrust reflection package (reflection zone 1). 2) The transition zone, generally considered to produce little seismic moment during great megathrust events, correlates with the zone of gradual thickening of the megathrust reflections (reflection zone 2). 3) The fault area that moved in the well-defined 1999 and other slow slip events correlates with the fully developed (>4 km thick) megathrust reflection package (reflection zone 3).

The correlation of the thin and thick reflection zones with the locked and aseismically slipping portions of the northern Cascadia megathrust, respectively, can be explained via rock mechanics. The inherent property of brittle failure to localize along fault planes is the likely cause for the thin megathrust reflection package found along the locked portion of the northern Cascadia subduction thrust. The thick megathrust reflection package that correlates spatially with the zone where deep aseismic slip occurs is probably related to both shearing and fluids, with the bulk of reflections caused by shearing. Temperature (*Hyndman and Wang*, 1995) and fluid-filled porosity (*Kurtz et al.*, 1990) estimates, combined with laboratory and field studies (*Higgins*, 1971; *Jones and Nur*, 1984) indicate that plastic deformation (e.g., ductile banding), which is known to be distributed over a larger rock volume, prevails within the shear zone outlined by the thick reflection package found at the top of the megathrust (*Nedimovic et al.*, 2003).

The landward edge of the locked zone on the northern Cascadia megathrust inferred by reflection mapping (*Nedimovic et al.*, 2003) appears to lie some 30 km closer to the land than estimated from thermal and dislocation modeling, implying a wider zone of coupling than currently proposed (Figs 3a and 3d). If this wider zone is confirmed, a somewhat greater megathrust seismic hazard is suggested at local urban centers. More recent and independently obtained results based on gravity data (*Wells et al.,* 2003), show a strong spatial correlation between the location of the Pacific Rim forearc basins and the measured coseismic slip maxima of instrumentally recorded megathrust earthquakes. The location of the downdip limit of coseismic slip inferred by gravity work in northern Cascadia (*Wells et* *al.*, 2003) closely corresponds to that inferred by reflection mapping (*Nedimovic et al.*, 2003).

Causes for large-scale lateral variations in coupling along the megathrusts are not well understood, perhaps because they may be the most challenging to study. Many factors affect lateral coupling on the megathrust. These are, for example, changes in the roughness of the interplate interface, changes in the lithology on the megathrust, temperature changes, and the overall geometry of the subduction zone. At least a dense grid of high-quality 2D MCS data is necessary to study the lateral changes in megathrust coupling. Today, only portions of the Nankai subduction zone appear to be covered with the required data, so we may have to wait some time before such studies become truly feasible.

More accurate mapping of updip and down dip limits of the locked seismogenic zones requires calibration of the reflection method at a subduction zone that has experienced megathrust earthquakes with the rupture extent defined by aftershocks and geodetic data. Subduction zones of Alaska, Chile and SW Japan all satisfy these preconditions. Furthermore, existing deep seismic reflection images from Alaska (Fig. 4) (*Fisher et al.*, 1989), Chile (*Buske et al.*, 2002) and SW Japan (*Kodaira et al.*, 2002) show a megathrust reflection signature similar to that observed at the northern Cascadia subduction zone. Eastern Alaska-Aleutian subduction zone, a target of a 2006 study (Fig. 4a), is particularly attractive for the calibration tests because the transition from the locked to aseismically sliding megathrust is fully accessible for relatively inexpensive marine investigations, and the dislocation modeling shows significant lateral changes in megathrust coupling (Zweck et al., 2002).

5. Water, temperature and intraslab seismicity

Water stored in subducting oceanic plates and later released landward of the trenches through dehydration is believed to strongly affect a number of processes of importance to natural hazard studies. The released water promotes partial melting responsible for arc magmatism and leads to dehydration embrittlement that is often considered to be the most plausible earthquake mechanism for intraslab events at intermediate depths. Free water can also affect the physical properties of rocks at the megathrust by reducing the temperature at which transition from brittle to ductile deformation occurs, thus possibly having significant impact on the location of the downdip limit of seismogenic zones. Despite of its importance, little is known about how much free or chemically embedded water oceanic plates bring into subduction zones.

In Fig. 5, larger magnitude intraslab seismicity for both the Cascadia and the Central America subduction zones is shown. Only the part of Central America subduction zone for which there exist modern seismic reflection images and thermal profiles, offshore Nicaragua and Costa Rica, is shown. The two subduction zones have vastly different seismicity. At the Cascadia margin (Fig. 5a), most of the intraslab seismicity occurs offshore, along Blanco and Sovanco fracture zones connecting Gorda, Juan de Fuca and Explorer ridge segments. Intermediate-depth intraslab seismicity in the subducted slab is sparse, reaches depth of only ~70 km, and is focused around the bend in the subduction at its northern end. Shallow intraslab seismicity is mostly located in the Mendocino triple junction area. At the Central America subduction system both shallow- and intermediate-depth seismicity are abundant, and earthquakes are triggered up to ~300 km below the

Earth's surface (Fig. 5b). If water plays the key role in triggering the intermediate-depth intraslab seismicity, then the amount of water embedded into the subducting plates at the Cascadia and Central America convergent margins must be significantly different. In order to test this hypothesis, I rely here on seismic reflection imaging.

A recent study done offshore Nicaragua and Costa Rica (*Ranero et al.*, 2003) demonstrated that reflection imaging might be a useful tool for determining the magnitude of hydration of the oceanic lithosphere approaching a subduction zone. At the outer Middle America trench, *Ranero et al.* (2003) were able to trace normal faults caused by bending of the slab due to subduction all the way through the sediments, the oceanic crust, and the uppermost mantle up to ~15 km below the crust-mantle boundary (Fig. 6a)[1]. Reflections from fault surfaces within the mostly gabbroic oceanic crust and mostly peridotitic uppermost mantle are possible only if the rocks along the fault surfaces are altered to produce an acoustic impedance contrast. This indicates that these extensional faults are major conduits for fluids. The depth of imageable fault penetration correlates well with the 600 ^{0}C isotherm on thermal models (Fig. 6b). This is the temperature above which serpentinization, the most important hydration mechanism for peridotites of the uppermost mantle, becomes a marginal process (e.g., *Ulmer and Trommsdorff*, 1995).

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[1] It is interesting to note that *Seely et al.* (1974) imaged the faulting of the oceanic crust along the Central America outer trench offshore Guatemala using the reflection technique some 30 years before *Ranero et al.* (2003) published their results. However, at that time, not enough was known about the importance of water for triggering the intraslab seismicity to provide room for speculation about their causal relationship.

To study hydration processes offshore the Cascadia margin, I compiled a database that includes thermal modeling results and reflection profiles from all regional MCS surveys (streamers 3 km or longer) done across the Juan de Fuca, Gorda and Explorer plates. Unlike at the Middle America trench, where the steeply subducting oceanic lithosphere is relatively cold and old (>~20 Ma), the oceanic lihthosphere subducted at the Cascadia margin is young (~<10 Ma old), warm, and descends at a relatively shallow angle. Bending-related normal growth faulting is sparser and subtler at the Cascadia margin but, surprisingly, it begins much further seaward of the trench than offshore Nicaragua and Costa Rica and the fault density is mostly uniform. Fault planes dip steeply and are challenging to image. Where fully imaged, these faults offset the sediments, cut across the crust to Moho and appear to just barely pierce into the uppermost mantle.

Faults are imaged to penetrate ~6 km into the ~30-35 km-thick plate at the Cascadia trench, and to ~20-22 km into the ~50-55 km-thick plate at the Middle America trench. Most remarkably, the depth of imageable fault penetration at the Cascadia margin also correlates well with the 600 ^{0}C isotherm on thermal models. Because bulk of the oceanic plate hydration takes place in the uppermost mantle via serpentinization of peridotites (e.g., *Hacker et al.*, 2003), the amount of water embedded into the subducting oceanic slab at the Cascadia margin must be very limited.

The difference in the depth and extent of hydration at the Cascadia and Middle America margins seems to correlate well with the difference in the density and magnitude of intraslab seismicity at both margins (Fig. 5), indicating that water is indeed the key “element” triggering the intraslab seismicity via the dehydration embrittlement mechanism.

7. Conclusions

Our current understanding of megathrust and intraslab earthquakes is based on data gathered through observational seismology, laboratory P-T studies, thermal modeling of heat-flow data, and dislocation modeling of geodetic data. While these methods have been and still are providing us with a great wealth of information about these events, future breakthroughs may require a broader multidisciplinary approach. In this work, I show how reflection seismology can provide key complementary information about both megathrust and intraslab earthquakes.

Correlation between the character of reflections and the coupling on the megathrust appears to provide a new method, at least at the Cascadia margin, for high-resolution mapping of the locked zones on subduction thrusts. Reflection images from the northern Cascadia subduction zone suggest that the locked zone on the megathrust that ruptures in great earthquakes is possibly ~30 km wider then generally thought. Because the width of the locked zone is extended landward, towards the local urban centers, a somewhat greater megathrust seismic hazard from ground shaking is suggested for these populated areas.

Analysis of both the intraslab seismicity at the Cascadia and Central America margins, and the extent and depth of hydration offshore these margins, supports the hypothesis that the water in the subducting oceanic slabs released by metamorphic reactions is the key factor for triggering the intermediate-depth earthquakes. The limited depth and extent of hydration of the subducting lithosphere at the Cascadia margin is the likely cause for the observed sparse intraslab seismicity, and may restrict the maximum moment magnitude of the Cascadia intermediate-depth intraslab earthquakes to ~7.

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Fig. 1. Schematic cross-sections through a subduction zone showing two phases of the subduction earthquake cycle (adapted from *Hyndman and Wang*, 1995). Phase (a), characterized by stress and strain build-up between events, and phase (b), depicting the subsequent rupture stage, are both described in the text. Darker shade of gray represents the subducting oceanic plate, while the lighter shade of gray represents the overriding continental plate. Locked, transition, slow slip and rupture zones in (a) and (b) are marked by dashed lines of different width and thickness.

Fig 2. Subduction zones of the northeast Pacific Rim studied in this report.

Fig. 3. Locked, transition, and stable slipping sections of the northern Cascadia megathrust inferred from the extent and character of the megathrust reflections are shown in (a) as reflection zones 1, 2 and 3, respectively (*Nedimovic et al.*, 2003). Reflection zone 1 is characterized by thin thrust reflections that are <0.5 km thick. Zone 3 has a reflection band immediately above the oceanic plate that is >4 km thick. Within zone 2, this reflection band thickens from <0.5 to >4 km. Thick black solid lines are the existing crustal scale seismic reflection profiles for the study area. Locations of the details presented in (b) and (c) are shown by arrows. (b) An example of the thin (<2 km) reflection response from the subduction thrust below offshore line 89-06 where the thrust is believed to be locked. The true thickness of the thin reflection zone is likely <0.5 km but for marine data the deconvolution was not able to remove the ringing and the stacking was not optimal. (c) An example of the thick (>4 km) band of reflections imaged on the most southern Vancouver Island line 84-02 overlies the subducted oceanic crust in an area where deep aseismic slip has been observed (*Dragert et al.*, 2001). (d) Locked, transition, and

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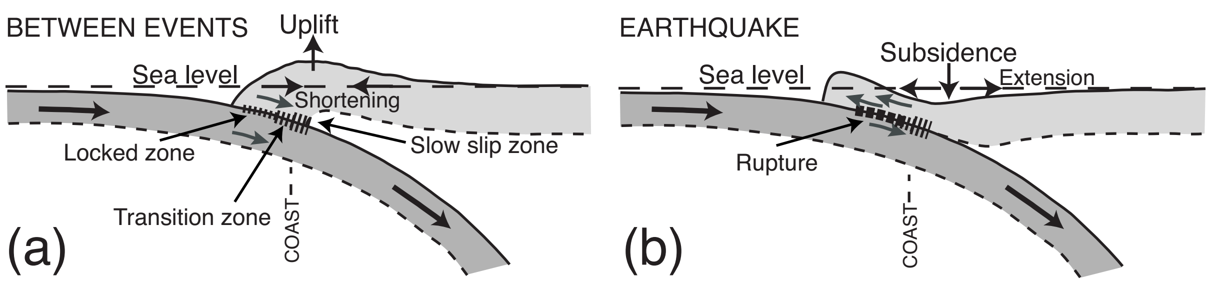
Fig. 5. Comparison of ISC 1973-2002 seismicity for (a) Cascadia and (b) Costa Rica/Nicaragua margins. Epicenters are scaled by magnitude and color coded by hypocentral depth, with 0-60 km green, 60-250 km yellow, and deeper than 250 km red. Most of the plotted events are magnitude 4 or larger. Note the difference in depth, density, and even maximum magnitude of recorded seismicity. Locations of

the reflection and thermal profiles shown in Fig. 6 are marked with black and red lines, respectively.

Fig. 6. Selected 2D seismic reflection and thermal modeling results obtained offshore Central America. (a) Time migrated reflection section of line 39 collected offshore Costa Rica, cruise BGR99 (adapted from *Ranero et al.*, 2003). Gray lines show interpreted locations of the igneous basement and the crust-mantle boundary. Reflections indicated by black arrows are interpreted normal faults caused by plate bending. Imaged faults cut at least up to about 20 km into the incoming oceanic plate. Survey-line location is marked in Fig. 5b with a thick black line. (b) Thermal model of subduction beneath the Nicoya Peninsula, Costa Rica (adapted from *Harris and Wang*, 2002). Profile location is shown in red in Fig. 5b. Contour interval is 100 ^{0}C. Small arrows show flow vectors and circles show earthquake hypocenters. The incoming Cocos oceanic plate, some 24 Ma old at the deformation front, is colder and thicker than the oceanic Juan de Fuca plate.



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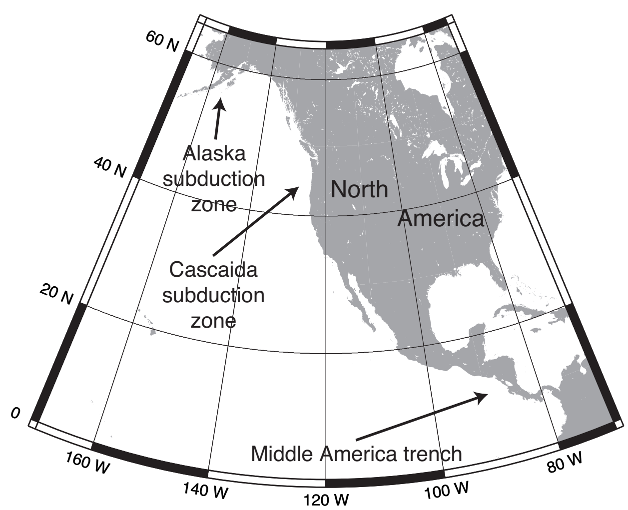
Nedimovic, Figure 2



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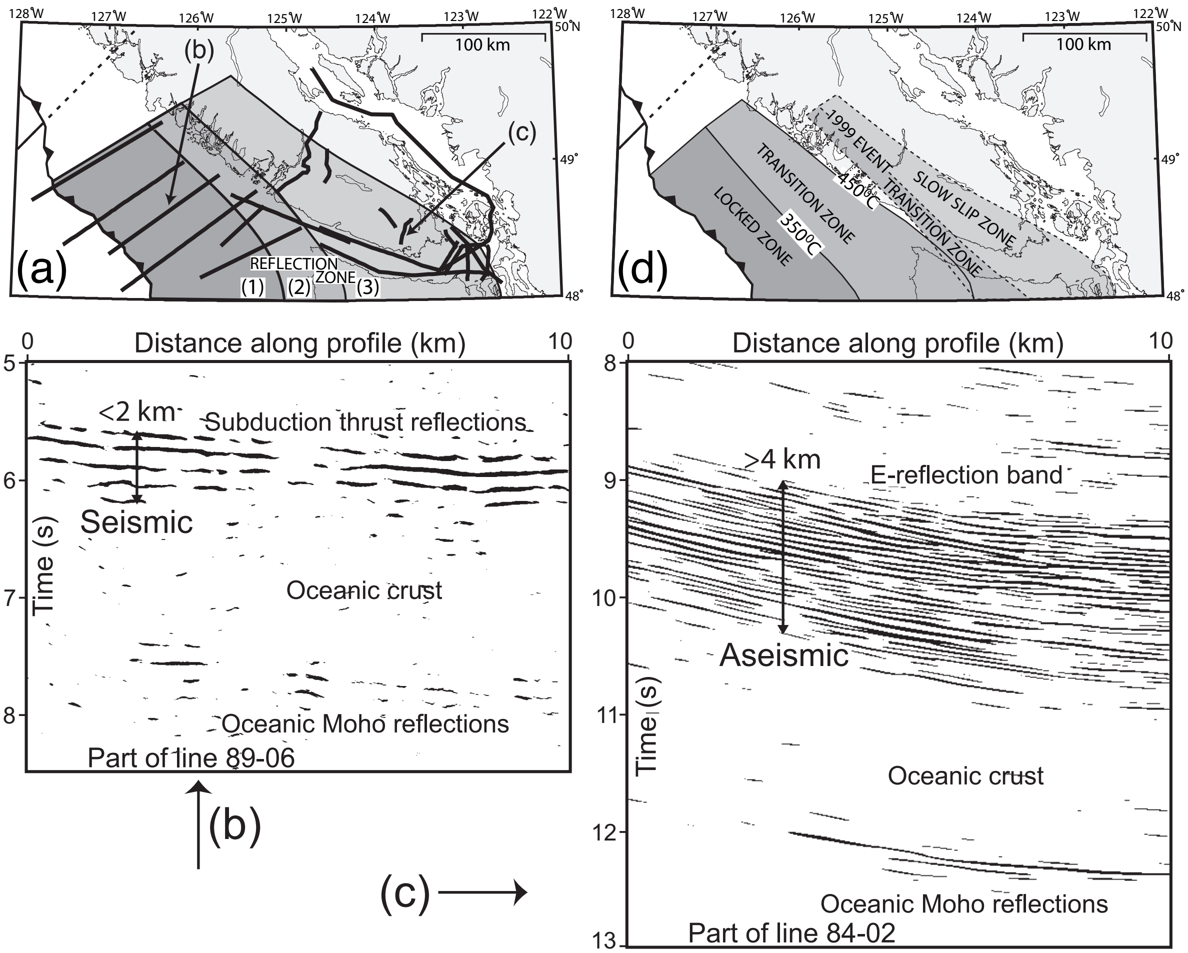

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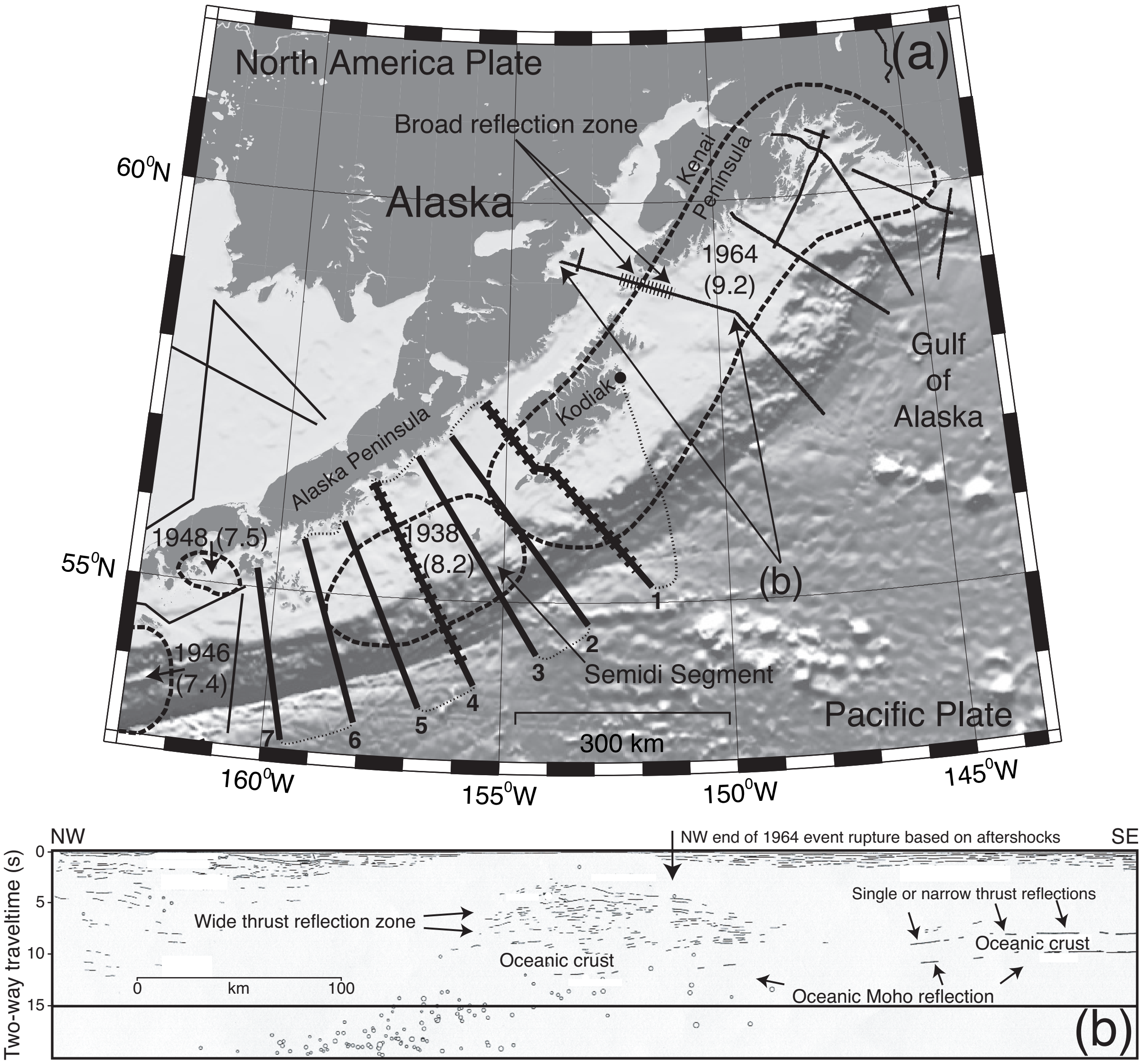

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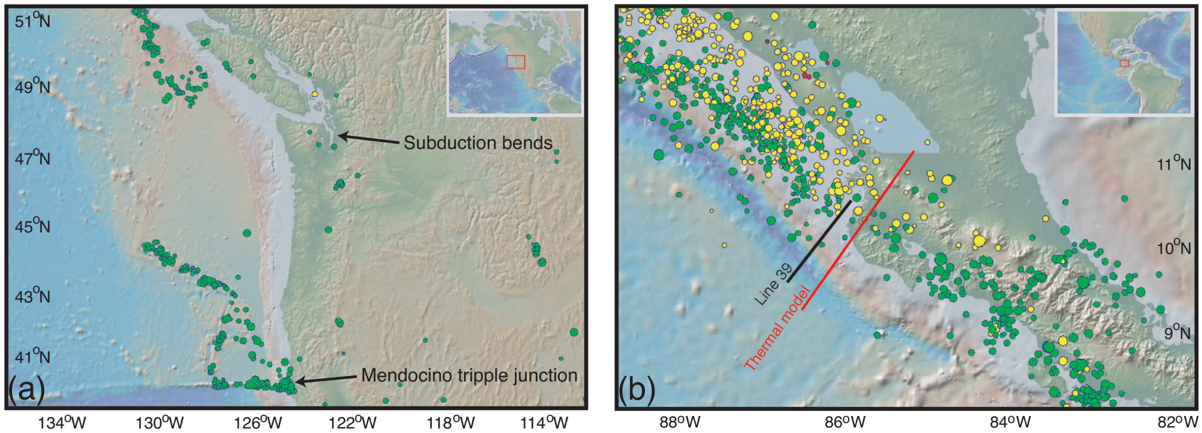

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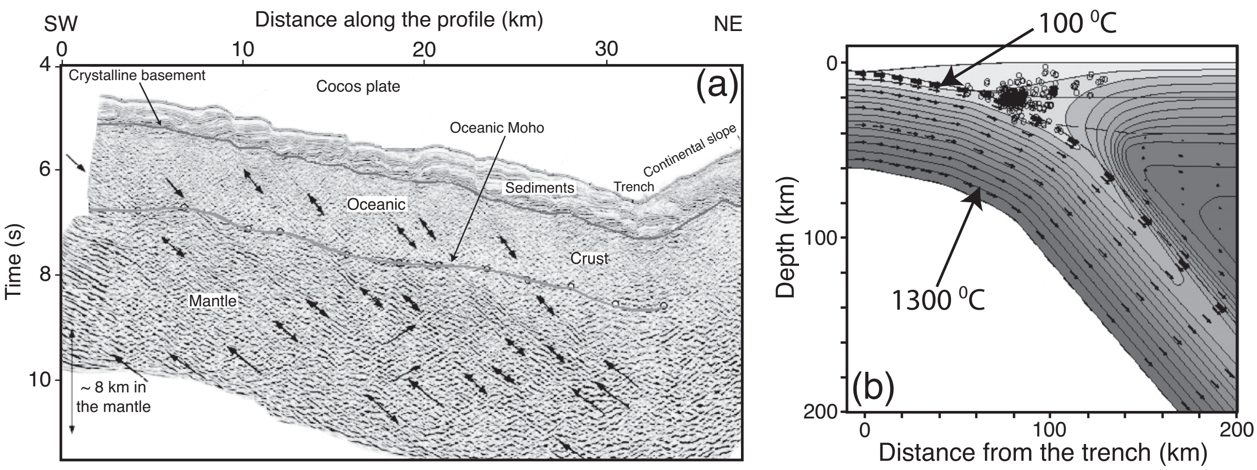

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