The Great Sanriku-oki earthquake of 2 March 1933: Source Characterization Based Regional and Far Field Information and Implications for Off-Trench Normal Faulting Tsunami Sources in Japan and Elsewhere

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Three investigations of the great off-trench earthquake of 2 March 1933 have been completed (Uchida and five others GJI Submitted 2015; Okal, Kirby, and Kaligaris, GJI Submitted, 2016; Kirby, Hino, and Nishizawa, in preparation). Analyses of contemporary data from the early 1930’s have revealed new details of this seismic source that caused the devastating tsunami waves that struck the Sanriku coast that led to more than 3,000 dead or missing. The source region of this remarkable event was in the off-trench of a sector of the Japan Trench characterized by large off-trench gravity and bathymetric anomalies and relatively long and straight normal fault scarps parallel to the relevant trench. These conditions are satisfied in Japan in the Hokkaido-Kurile Trench system south of Hokkaido Island and the southern Kurile Islands and in some sectors of the Bonin and Marianas subduction systems. Analysis of fault scarps and curvature changes in the off-trench seafloor and plate convergence rates suggest that recurrence times for great off-trench normal-faulting range from about 1,000 to 10,000 years, roughly 10 times those for interplate thrust earthquake sources.

Keywords: Japan Trench, Normal fault earthquakes, Tsunami sources

Seismicity and its relation to the bending-related faults in the incoming Pacific Plate along the Japan Trench

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After the 2011 Tohoku-Oki earthquake (Mw 9.0), many M7-class normal-faulting earthquakes occurred in the trench-outer rise region seaward of the largest co-seismic slip area during the 2011 Tohoku-Oki earthquake. Outer-rise normal-faulting earthquakes likely relate to the normal-faults, which cut the oceanic crust and form the horst and graben structures. However, relationships between the outer-rise seismicity and crustal structures are not clearly understood from the observations using land seismic network since the outer-rise area is far away from the coast. After the 2011 Tohoku-Oki earthquake, we have conducted repeated ocean bottom seismograph (OBS) observations in the trench-outer rise region along the Japan Trench. Based on the OBS observations, shallow seismicity within the oceanic crust coincides with the seafloor topographic lineation. Their orientations are both parallel and oblique to the trench axis. The trench-parallel topographic lineation is related to the horst and graben structures formed in the trench outer-rise region prior to the subduction. On the other hand, the topographic lineation oblique to the trench axis is almost parallel to the magnetic anomalies. The seismicity along the topographic lineation oblique to the trench axis suggests reactivation of the pre-existing structures formed at the mid oceanic ridge. The results of the OBS observations indicate both pre-existing and newly created faults within the oceanic plate have actively deformed in the trench-outer rise region. Furthermore, close-up OBS observations in a westward dipping normal fault detected concentrated seismicity west of the fault escarpment on the seafloor. Although we could not obtain a clear image of the normal fault within the oceanic crust in the outer-rise of the Japan Trench through seismic reflection surveys, the seismicity could provide some information of the fault geometry within the crust.

Keywords: normal faults, trench outer rise, horst and graben

Local heat flow variations seaward of the Japan Trench: Implications for development of fractures in the oceanic crust

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Anomalous heat flow values, higher than that expected for the seafloor age, are pervasively observed on the seaward side of the Japan Trench (Yamano et al., 2014). Appreciably high values were obtained within about 150 km of the trench axis, indicating that the anomaly is related to deformation of the incoming Pacific plate associated with subduction. The broad high heat flow zone seaward of the trench can be attributed to efficient vertical heat transport by pore fluid circulation in a permeable layer in the oceanic crust which thickens toward the trench through fracturing due to plate bending (Kawada et al., 2014). Overlapping the broad anomaly, local variations at a scale of a few kilometers were detected through concentrated measurements at some sites. Such short-wavelength anomalies cannot have their origin deep in the plate and may arise from heterogeneity of the oceanic crust.
For investigation of the nature and the origin of the local anomalies, we conducted dense heat flow surveys around 39°N in 2014 and 2015. Most of the measurements were made along an E-W pre-existing multichannel seismic survey line (JAMSTEC SR101), perpendicular to the trench. A detailed heat flow profile was obtained around 60 to 80 km from the trench axis, in the region where immature horst and graben structures are found with no significant surface displacement. Heat flow values along this 20 km transect range from 60 to 110 mW/m^2 and show prominent sawtooth-like variations at a scale of 3 to 5 km. Heat flow variation in the N-S direction, parallel to the trench, was also examined by closely-spaced measurements along a short line crossing the E-W transect at one of the heat flow peaks. The values obtained along the 5 km N-S line has a very high average, about 100 mW/m^2, with a lateral variation as large as the variations along the E-W line. It suggests that high anomalies in this region have elongated shapes extending in the direction parallel to the trench.
The local heat flow variations may have resulted from heterogeneous development of fractures in the oceanic crust. We conducted numerical modeling of heat transport by pore fluid circulation and found that local development of fractures, i.e. sharp lateral variation in the thickness of the permeable layer, would yield heat flow anomalies at the scale of km, with elevated heat flow above more developed fractures. The observed heat flow distribution may therefore indicate that there exist a series of N-S extending well-fractured zones with spacing of several km. Two-dimensional survey of the heat flow distribution on the outer rise would provide information on fracturing process in the oceanic crust.

Keywords: Japan Trench, Pacific plate, heat flow, oceanic crust, fracture, fluid circulation

Visco-elasto-plastic deformation and hydration of oceanic plates at trench-rise sytems

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Over the last decade, bending-related normal faulting and hydration of the incoming oceanic plates has been widely observed at trench-rise systems by geophysical surveys. Along with these observations, 2D numerical models of spontaneously bending oceanic plates have contributed to investigate the dynamical evolution of visco-elasto-plastic deformation patterns and the mechanisms of plate hydration by downward seawater percolation along normal faults. In this contribution, I will discuss the main tectonic processes occurring at the trench-rise system within the incoming plate on the basis of the principal geophysical and numerical experiments conducted so far.

Keywords: slab hydration, plate bending, numerical modelling

Mantle hydration along the outer rise faults inferred from permeability of serpentinites

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Recent geophysical surveys suggested that hydration (serpentinizaiton) of oceanic mantle is related to outer rise fault prior to subduction. Serpentinization of oceanic mantle affects intermediate-depth earthquakes and subduction water flux. Since the chemical reactions forming serpentinite is geologically rapid at low temperature, the rate of water delivery to the reaction front likely controls the extent of serpentinization. Therefore, to estimate the extent of serpentinization along the outer rise fault, we measured permeability of low-temperature serpentinites consisted of lizardite and chrysotile, and hydraulic diffusivity was inferred from laboratory determined permeability. Our experimental results indicate that serpentinization is spread to 8.6 km in the direction normal to the outer rise fault at the uppermost oceanic mantle (7 km depth), while serpentinization is limited to 1.2 km at the tip of fault zone (~12 km depth). We calculate that the global water flux carried by the serpentinized oceanic mantle is estimated to be 2.2×10^{12} kg/year, which is twice as high as water flux by the hydrated oceanic crust. Since the subduction water flux is markedly larger than the output flux through magmatic degassing, the amount of present-day ocean is now decreasing and might be disappeared within 400 million years.

Keywords: permeability, serpentinite, outer rise fault, hydraulic diffusivity, water transport

An outline of Bend-Fault Hydrology in the Old Incoming Plate (H-ODIN) project and its perspective

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Crustal hydration at the mid-ocean ridge by hydrothermal circulation has been considered to be the first-order control on the degree of the oceanic plate hydration. Previous ocean drilling projects have revealed hydration processes and their extent of oceanic crust at spreading centers. Recently, hydration due to plate bending-induced normal faults (bend-fault hereafter) in incoming plate just prior to subduction has drawn considerable attention (e.g., Ranero et al., 2003 Nature). In the last decade, a number of geophysical structure studies have been conducted to test the hypothesis that significant hydration is due to plate bending-induced normal faults just prior to subduction (e.g., Fujie et al., 2013 Geophys. Res. Lett.). However, we really do not know what is the bending-induced fault zone. Bend-fault hydration processes depend on various conditions, such as thermal conditions and stress state. Ideally, comparing subduction zones with several different basic states (e.g. Old cold plate vs Young hot plate) will be the most effective approach to expand our knowledge of bend-fault hydration processes. Two new IODP proposals on hydration in incoming plate of middle America site (Morgan et al., 2014, Pre-876: Bend-Fault Serpentinization (BFS): Oceanic Crust and Mantle Evolution from Ridge through Trench) and northwest pacific site (Morishita et al., 2015 Pre-886: Bend-Fault Hydrology in the Old Incoming Plate) have been submitted. The world's largest dense onland seismic observation network is in NE Japan. In addition, a large number of onland/offshore reflection and refraction seismic surveys have been conducted here, both before and after the 2011 Tohoku earthquake. This network and surveys provides an invaluable data set to study how various subduction zone processes shape subduction inputs, tectonics, and volcanism. The northwestern Pacific is one of the best targets because here horst-and-graben bend-fault structures are the best developed in the world (Nakanishi, 2011, Springer), and this is also one of the world oldest, thus coldest, subducting oceanic plates, hence likely to be associated with the deepest extent of bend-fault serpentinization. The maximum penetration depth of seawater, and thus degree of serpentinization is thought to be inversely proportional to the temperature of the incoming plate, i.e., deeper in cold plate than in hot plate. In the presentation, I introduce the contents and perspective of the new IODP proposals using CHIKYU on hydration of incoming plate prior to subduction.

Keywords: Incoming oceanic plate, Bending fault, Hydrology

Regional variations in the nature of the incoming oceanic plate in the NW Pacific margin

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Various subduction zone processes, such as arc magmatism and generation of earthquakes, are directly or indirectly related to the nature of the subducting oceanic plate, indicating that the regional variations in the nature of the incoming oceanic plate may cause the regional variation of these subduction zone processes.
In the northwestern Pacific margin, the old oceanic Pacific plate (120Ma-130Ma) subducts beneath the northeast Japan arc. Many large interplate earthquakes has occurred in this subduction zone but their distribution are not uniform, suggesting that the interplate seismic coupling is not uniform along this subduction zone as pointed out by the geodetic studies.
The interplate seismic coupling is considered to be dependent on the materials that exist at the plate interface. For example, an ocean drilling after the 2011 Tohoku-oki earthquake (JFAST) revealed that the existence of the pelagic clay layer at the plate interface was a key to the large coseismic slip to the trench (Chester et al., 2013).
Several previous seisemic structure studies on the forearc region of this region pointed out large interplate earthquakes occured outside of areas with low seismic velocities and high Poisson's ratio along the plate interface (Wang and Zhao, 2006; Zhao et al., 2011; Fujie et al., 2013). Similarly, a thin layer with low seismic velocities identified at the depth of the plate interface in a region of low interplate microseismicity (Fujie et al., 2002; Mochizuki et al., 2005). These previous studies suggested that the nature of the incoming Pacific plate, especially its water content, is a key to understanding this regional variation in interplate seismicity.
Since 2009, to investigate structural variations in the incoming Pacific plate, focusing on the amount of water, we conducted extensive active source seismic surveys on the outer rise of the northwestern Pacific margin. We confirmed that seismic velocities gradually reduce and Vp/Vs ratio gradually increase toward the trench axis accompanied by the development of bend faults, suggesting the water penetration into the oceanic plate through the bend faults. In addition, we observed remarkable regional variations in the sediment thickness, crustal thickness, and seismic velocities within the crust and mantle before the area of bend faults.
In this paper, we are going to show these structural variations in the incoming plate and discuss the origin of the variations and possible effects on the subduction zone processes.

Keywords: seismic structure, bending-related faults, subduction zone

Evaluation of coseismic physicochemical processes in fault zones based on geochemical analyses of fault rocks

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Trace element and isotope compositions of rocks record processes associated with their petrogenesis and later modifications. Interactions with fluids and melts are major factors to control chemical characteristics of the rocks. Geochemical analyses of rocks thus can be useful means for understanding nature of such fluid- and melt-related interactions, constituting essential part of broad physicochemical processes occurring in the earth’s interior. Here I focus on an attempt to evaluate coseismic physicochemical processes in fault zones based on rock geochemistry.
Frictional heating in a fault zone during earthquake slip affects the slip behavior itself. Increased temperature on a fault can induce dynamic fault weakening by processes such as pressurization of interstitial fluid by thermal expansion, known as thermal pressurization, and melt lubrication. Recent studies revealed that trace element and isotope analyses of fault rocks combined with geological, mineralogical, structural, and geophysical observations are useful for elucidating such slip weakening processes.
In the Chelungpu fault in Taiwan, which slipped during the 1999 Mw 7.6 Chi-Chi earthquake, the slip-zone rocks showed clear geochemical anomalies, including decreases of Li, Rb, Cs and 87Sr/86Sr and an increase of Sr relative to adjacent host sedimentary rocks (Ishikawa et al., 2008). Model calculations revealed that these anomalies were produced by coseismic fluid-rock interactions at >350°C, which may have caused a dynamic decrease of friction along the fault through thermal pressurization. Ancient slip zone rocks from a major reverse fault in the Boso Emi accretionary complex at 1–2 km depth (Hamada et al., 2011) and from a decollement of the Kodiak accretionary complex at seismogenic depth (Yamaguchi et al., 2014) showed similar evidence for coseismic fluid-rock interactions at high temperatures. The 87Sr/86Sr ratios of the Kodiak slip zone rocks also revealed involvement of fluids derived from subducted oceanic crust during the earthquake slip. Recent high-velocity frictional experiments under wet condition demonstrated that detectable fluid-inducted geochemical anomaly can be produced by a single earthquake event (Tanikawa et al., 2015). For the slip zone rocks from the Shimanto accretionary complex in Kure area, which represent rocks of ancient megaspray fault at 2.5–5.5 km depth, geochemical signals derived from high-temperature fluids overlap with those from melting, indicating coseismic fluid-rock interactions followed by disequilibrium frictional melting (Honda et al., 2011). These results demonstrate that geochemical characteristics of the fault rocks are useful indicators of such physicochemical events. However, further studies are required especially for fault system developed within basaltic crust, for which geochemical characteristics of fault rocks have been poorly understood.
Refs: Ishikawa et al. (2008) Nature Geosci. 1, 679-683; Hamada et al. (2011) JGR 116, B01302; Yamaguchi et al. (2014) EPS 66:58; Tanikawa et al. (2015) GRL 42, 10.1002/2015GL063195; Honda et al. (2011) GRL 38, L06310.

Keywords: geochemistry, fault rocks, earthquakes, fluid-rock interactions

Deep methane and helium emissions at convergent plate boundaries

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Methane plays an important role in the greenhouse effect of the atmosphere and in the chemistry of ozone reduction. Major methane emissions into the atmosphere originate from the biosphere (e.g., wetlands, rice paddies and animals), the geosphere (e.g., hydrocarbon basins and geothermal areas) and anthropogenic activity (e.g., natural gas production and distribution, coal mining). Natural methane emission from the geosphere is generally characterized by a radiocarbon-free signature (age > 50 kyrs) and may preserve information on the deep fluid in the Earth’s crust. In this work, the origin of methane in forearc and volcanic arc regions at subduction zones, and collision zone at convergent plate boundaries is discussed using the carbon isotope composition of methane together with the abundances and isotope signatures of associated volatile elements such as helium, argon and nitrogen. We collected methane-rich natural gas samples in the South Kanto gas field in Japan and from mud volcanoes in South Taiwan. For comparison, we acquired natural gases in the Akita and Niigata gas fields located in the volcanic arc region of Japan. Chemical composition (CH_4, C_2H_6, C_3H_8, CO_2, N_2, O_2, Ar, and He abundances), carbon and nitrogen isotope signatures ($^{13}C/^{12}C$ of CH_4, $^{15}N/^{14}N$), noble-gas isotope ratios ($^3He/^4He$, $^4He/^{20}Ne$, and $^{40}Ar/^{36}Ar$) were measured using a quadrupole mass spectrometer, a continuous flow GC-IRMS system, and a noble gas mass spectrometer, respectively. The methane-rich gas in the South Kanto gas field shows a typical microbial signature characterized by light carbon isotopes, high $CH_4/(C_2H_6 + C_3H_8)$ and low $^3He/^4He$ ratios, while the natural gases in the Akita and Niigata region show a thermogenic signature with prevalence of heavy carbon isotopes, low $CH_4/(C_2H_6 + C_3H_8)$ and high $^3He/^4He$ ratios. These observations are consistent with those reported in the literature. On the other hand, methane-rich gases from mud volcanoes in South Taiwan show heavy carbon isotopes, $CH_4/(C_2H_6 + C_3H_8)$ ratios between microbial and thermogenic signatures and variable $^3He/^4He$ ratios, a part of which cannot be explained by a simple binary mixing of microbial and thermogenic methane. We also measured helium and carbon isotopes of submarine hydrothermal systems close to the Tokara Islands and within Kagoshima Bay. Gas geochemistry of the collected seawater and porewater samples is compared with those from the Japan Trench and the Nankai Trough. Finally, all methane-rich gases from submarine and on-land expressions of fluid emission are discussed within the frame work of the respective geotectonic settings.

Keywords: methane gas, helium isotope, plate boundary

Lithostratigraphic Evolution of the Shikoku Basin, Inputs to the Nankai Trough Subduction Zone

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The Shikoku Basin (Philippine Sea plate) hosts inputs of sediments and igneous crust to the Nankai Trough subduction zone of SW Japan. After five decades of scientific ocean drilling (DSDP, ODP, IODP), and three successful transects across the margin (Ashizuri, Muroto, Kumano), we are beginning to recognize and understand the complexities and idiosyncrasies of the basin’s evolution. This presentation will focus on three elements of that evolution: (a) time-transgressive facies changes; (b) an enigmatic interval of anomalously high porosity; and (c) systematic, gradual changes in detrital clay mineral assemblages over time.
Perhaps the most noteworthy of several time-transgressive facies changes occurs at the base of the uppermost lithostratigraphic unit (hemipelagic-pyroclastic facies). The base of that unit (otherwise known as Upper Shikoku Basin facies) coincides with the deepest discrete layer of volcanic ash. The age of the unit boundary changes considerably along strike, from 3.9 Ma at ODP Site 1177, to 3.3 Ma at ODP Site 1173, to 7.6-7.8 Ma at IODP Sites C0011 and C0012. Those temporal-spatial differences in the onset of substantial pyroclastic influx might be related to a NE-directed migration of the triple junction that joins the Japan, Izu-Bonin, and Nankai subduction boundaries; that migration should have triggered along-strike changes in explosive arc volcanism.
Mudstones within the zones anomalously high-porosity contain unusually large proportions of dispersed volcanic ash (glass shards and pumice). Temperatures at the base of the zones vary from site to site, so thermally driven diagenesis alone cannot account for the anomaly. Instead, dispersed ash affects mudstone microstructure by forming cohesive aggregates that inhibit collapse of intergranular pore space. Partial dissolution of glass shards also contributes silica for precipitation of weak cement. Deeper stratigraphic intervals with smaller amounts of dispersed ash show no such effects, regardless of temperature or depth.
The clay mineral assemblages of Shikoku Basin show consistent temporal changes, particularly over the last 10 Myr, with gradual reductions of detrital smectite and gradual increases in illite and chlorite (moving up-section). At IODP Sites C0011 and C0012, percentages of smectite within bulk mudstones decrease by roughly 3 wt-% for every 1-million-year reduction in age. Causes of this trend are multi-faceted but probably include: (1) intensification of the Kuroshio Current after closure of the Isthmus of Panama (at about 3 Ma); (2) blockage of transport routes from the East China Sea by rifting of the Okinawa Trough and subaerial buildup of the Ryukyu Arc (peaking at about 7 Ma); and (3) progressive uplift and denudation of detrital source rocks in the Outer Zone of Japan, which gradually stripped away the near-surface products of anomalous near-trench magmatism and exposed deeper plutonic roots and surrounding meta-sedimentary strata of the Shimanto Belt. These systematic changes in clay mineral assemblages are important because they modulate friction properties, consolidation behavior, and fluid production from dehydration reactions as the strata move deeper into the subduction zone.

Keywords: Shikoku Basin, clay minerals, anomalous porosity, time-transgressive facies

Variation in Porosity of the Nankai Trough Incoming Sediments off the Kii Peninsula, Southwest Japan

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The Nankai Trough is one of the best subduction-zone to study megathrust earthquake fault. Historic, great megathrust earthquakes with a recurrence interval of 100-200 yr have generated strong motion and large tsunamis along the Nankai Trough subduction zone. At the Nankai Trough margin, the Philippine Sea Plate (PSP) is being subducted beneath the Eurasian Plate to the northwest at a convergence rate ~4 cm/yr. The Shikoku Basin, the northern part of the PSP, is estimated to have opened between 25 and 15 Ma by backarc spreading of the Izu-Bonin arc. The >100-km-wide Nankai accretionary wedge, which has developed landward of the trench since the Miocene, mainly consists of offscraped and underplated materials from the trough-fill turbidites and the Shikoku Basin hemipelagic sediments. Particularly, physical properties of the incoming sediments to the Nankai Trough may be critical for seismogenic behavior of the megathrust fault. We have carried out core-log-seismic integration (CLSI) to estimate 3D acoustic impedance and porosity for the incoming sediments to the Nankai Trough off the Kii Peninsula, southwest Japan. For the CLSI, we used 3D seismic reflection, P-wave velocity, density, and porosity data obtained during IODP (Integrated Ocean Drilling Program) Expeditions 322 and 333. We computed acoustic impedance depth profiles for the IODP drilling sites from P-wave velocity and density data. We constructed seismic convolution models with the acoustic impedance profiles and a source wavelet which is extracted from the seismic data, adjusting the seismic models to observed seismic traces with inversion method. As a result, we have successfully obtained 3D acoustic impedance volume. With the 3D acoustic impedance volume and the porosity data at the IODP sites, we have performed multi-attribute transform that allows us to predict rock properties beyond the well location from seismic attributes calibrated with well-log data. The seismic attributes can be calculated internally, or provided as external attributes. The analysis was carried out in several stages: (1) to examine the log and seismic data at well locations to determine which set of attributes is appropriate; (2) to derive a relationship using multi-linear regression or Neural Networks; (3) to apply the derived relationship to a 3D SEG-Y volume to create a volume of the desired log property. In general, the 3D porosities show decrease with depth. We found a porosity anomaly zone with alteration of high and low porosities seaward of the trough axis. In this talk, we will show detailed 3D porosity of the incoming sediments, and present implications of the porosity anomaly zone for the megathrust fault behavior.

Keywords: Nankai Trough, 3D porosity, Core-log-seismic integration

Role of the subducting plate on the ETS-type phenomena around the mantle wedge corner

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Episodic tremor and slip (ETS) and related phenomena around the mantle wedge corner usually occur in young-slab subduction zones and are most abundant in Nankai, Cascadia, and Mexico. They are rare or absent in old-slab subduction zones such as Japan Trench. The relationship of these ETS-type phenomena with the subducting plate is a question of fundamental importance. In this work, we address this question through thermal modelling using heat flow data as model constraints. Our model employs the hypethesis that extremely high fluid pressure exists around the mantle wedge corner, consistent with relevant seismic and other observations.In young-slab subduction zones Nankai, Cascadia, and Mexico, the subduction fault has two frictional segments, with the first one being shallower than the mantle wedge corner because the viscous strength of the subduction faults is relatively small. Around the mantle wedge corner, the second frictional segment appears, but with abnormally low frictional strength due to the high fluid pressure and possibly the presence of hydrous minerals. We propose this is where the ETS occurs. Between these two frictional segments, the fault exhibits semi-frictional and/or viscous behaviour, which may facilitate long-term slow slip events and/or aseismic creep. For most old-slab subduction zones such as Japan Trench, there is only one frictional segement which extends to deeper than the mantle wedge corner because of the greater viscous strength of its megathrust than in young-slab subduction zones. We think the lack of a second frictional segment retards the development of ETS. However, two frictional segments are present in the old-slab Northern Hikurangi subduction zone because the greater frictional strength of its megathrust causes the termination of the frictional segement to occur shallower than the mantle wedge corner, explaining why ETS-type phenomena are observed here. The greater frictional strength is attributed to the roughness of the subducting seafloor. Our results indicate that both the age and roughness of the subducting plate play a key role on fault rheology which may control the occurence of the ETS-type phenomena.

Keywords: subducting plate, episodic tremor and slip, high fluid pressure, heat flow

