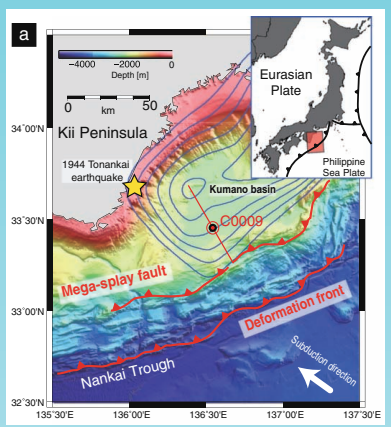
Earth, Planets and Space

New Perspective of Subduction Zone Earthquake



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Yours sincerely,

Prof. Yasuo Ogawa
Editor-in-Chief, *Earth, Planets and Space*

Earth, Planets and Space

Kimura *et al. Earth, Planets and Space* (2015) 67:123
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PREFACE Open Access

Preface for the special issue of "New Perspective of Subduction Zone Earthquakes"

Gaku Kimura[1*], Juichiro Ashi[2], Masataka Kinoshita[3], Christie Rowe[4] and David Shelly[5]

Giant subduction zone earthquakes such as the recent 2004 Sumatra and 2011 Tohoku-oki earthquakes and their accompanying tsunamis cause significant damage to human society, and it is our earnest desire to scientifically elucidate how they occur. In the Nankai Trough, Japan, great earthquakes and tsunamis have occurred repeatedly, and more are predicted for this site in the near future. Super-deep drilling by the drilling vessel *Chikyu* will enable us to directly sample seismogenic faults as well as conduct analyses, experiments, and in situ borehole measurements. These efforts should significantly improve our understanding of pre- and co-seismic processes of great subduction zone earthquakes. The Integrated Ocean Drilling Program (IODP, 2003–2012) and International Ocean Discovery Program (2013–2022) have decided to promote the Nankai Trough Seismogenic Zone experiments (NantroSEIZE) using *Chikyu*, although the deep target of the plate boundary fault has not yet been reached as of 2015.

We created a Japanese partnership program with NantroSEIZE (new perspective on great subduction zone earthquakes from super deep drilling: Kakenhi for the Nankai trough megaquakes, KANAME program, with financial support from the Ministry of Education, Culture, Sports, Science, and Technology from 2008–2015). The scientific objective of the program is to improve our understanding of pre- and co-seismic processes of great subduction zone earthquakes by directly sampling seismogenic faults and conducting analyses, experiments, and in situ borehole measurements in the Nankai Trough region. To realize this goal, our strategy consists of the following three schemes: (1) understanding the overall framework of the Nankai Trough seismogenic zone, (2) revealing the materials and mechanical and hydrologic properties of seismogenic faults, and (3) construction and verification of a comprehensive model for pre- and co-seismic processes.

On March 11, 2011, during the middle phase of the KANAME program, the Tohoku-oki earthquake and tsunami took place. *Chikyu* was damaged by the tsunami in the Hachinohe harbor in northeast Japan, and all programs that had been planned for implementation using *Chikyu* had to be delayed or canceled, including NantroSEIZE and KANAME. On the other hand, IODP immediately planned and conducted drilling at the Japan Trench, at the site of the Tohoku-oki earthquake, after *Chikyu* was repaired. We modified the KANAME project to include research on the Japan Trench and drilling at other subduction zones, such as Costa Rica. Many new findings and papers have been produced as a result of the KANAME project. The project was completed in 2015, but the NantroSEIZE effort is ongoing. This special issue presents some of the results of the KANAME project, mainly by scientists who took part in the project, although many papers have already published in other journals. Drs. Shelly and Rowe were invited as guest editors in addition to our internal guest editors (Kimura, Kinoshita, and Ashi).

This issue includes 33 papers:

(1) The Nankai trough (14 papers; Sugihara et al. 2014, Yamano et al. 2014, Tsuji et al. 2014, Idehara et al. 2014, Akuhara and Mochizuki 2014, Hyodo et al. 2014, Ashi et al. 2014, Tanikawa et al. 2014, Takahashi et al. 2014, Yamada and Shibanuma 2015, Hamada et al. 2015, Takeshita et al. 2014, Hino et al. 2015, and Toki et al. 2014)
(2) The Japan trench (6 papers; Aochi and Ide 2014, Nakamura et al. 2014, Koge et al. 2014, Lin et al. 2014, Sawai et al. 2014, and Boston et al. 2014)
(3) Other trenches and fault zones (4 papers; Maekawa et al. 2014, Namiki et al. 2014, Ishikawa et al. 2014, and Yabe et al. 2014) and ancient accretionary complexes and faults on land (7 papers; Schumann et al. 2014, Hamahashi et al. 2015, Fukuchi et al. 2014,

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Kameda et al. 2014, Yamaguchi et al. 2014, Kogure et al. 2014, and Hashimoto and Yamano 2014)
(4) Theoretical treatments of fracture and earthquake (2 papers; Kame et al. 2014 and Nishiyama et al. 2014)

The papers are also categorized into three scientific issues, focusing on different regions within each topic:

(1) Framework and setting of the seismogenic zone from the view point of seismicity in the Nankai trough (Idehara et al. 2014, Akuhara and Mochizuki 2014), Japan Trench (Aochi and Ide 2014), Hikurangi margin (Yabe et al. 2014), or from the geological and geophysical points of view for the Nankai Trough (Tsuji et al. 2014, Ashi et al. 2014, Sugihara et al. 2014, Yamano et al. 2014) and Japan Trench (Boston et al. 2014, Koge et al. 2014, Nakamura et al. 2014, Lin et al. 2014)
(2) Material and physical properties or conditions of the fault for the Nankai Trough (Takahashi et al. 2014, Tanikawa et al. 2014, Hamada et al. 2015), the Japan Trench (Sawai et al. 2014), and the Costa Rica margin (Namiki et al. 2014)
(3) Analysis of water–rock interaction with faulting in an ancient accretion complex and fault in the Shimanto Belt, Japan (Schumann et al. 2014, Hamahashi et al. 2015, Fukuchi et al. 2014, Kameda et al. 2014), Chelunpu Fault, Taiwan (Maekawa et al. 2014), Alaska (Yamaguchi et al. 2014), Median Tectonic Line, Japan (Ishikawa et al. 2014), crustal rocks on land (Kogure et al. 2014), and theoretical treatment of fracturing, friction, and earthquakes (Nishiyama et al. 2014, Kame et al. 2014)

Traditional research on earthquakes is physics-based, but physico-chemical processes and their geological record in fault rocks, both in active and inactive fossilized rocks, are of recent concern. Many studies of natural records of seismic faulting have been conducted in terms of their physico-chemical processes. The Japanese islands are composed mainly of ancient and modern accretionary complexes, some of which were exhumed from the seismogenic depth of the plate boundary megathrust and yield the best analog of seismogenic fault rocks in the subduction zone. This special issue will present such examples.

Authors' contributions
GK wrote the draft of the paper and others confirmed the contents. All authors read and approved the final manuscript.

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FRONTIER LETTER Open Access

Regional and global variations in the temporal clustering of tectonic tremor activity

Koki Idehara*, Suguru Yabe and Satoshi Ide

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Abstract

The temporal distribution of tremor activity exhibits a highly non-Poissonian behavior, and its maximum period of non-Poissonian clustering statistically describes the recurrence interval of major tremor bursts. Here, we examine variations in the temporal clustering properties of tremor activity by assessing their characteristic times, which are determined by the maximum period of the non-Poissonian distribution. By applying a two-point correlation integral to some of the world's major tremor zones, including Shikoku, Kii-Tokai, and Kyushu in Japan; Cascadia, Jalisco, and Guerrero in Mexico; southern Chile; Taiwan; and Manawatu in New Zealand, we reveal local spatial variations in the temporal clustering properties in each tremor zone and show global-scale variations in tremor activity. The spatial variation in local tremor activity is characterized by a gradual transition in the along-dip direction and shorter-wavelength heterogeneities in the along-strike direction, possibly associated with a spatial change in frictional conditions at the plate interface and rheological conditions in the surrounding materials. The characteristic time correlates positively with locally measured median tremor duration, implying an inherent correlation between the moment release rate and the recurrence interval of tremors.

Keywords: Tectonic tremor; Non-Poissonian clustering; Episodicity; Recurrence interval

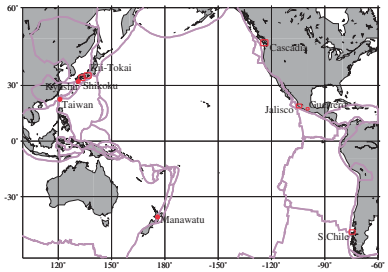

Figure 1

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FRONTIER LETTER Open Access

Frictional properties of sediments entering the Costa Rica subduction zone offshore the Osa Peninsula: implications for fault slip in shallow subduction zones

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Abstract

We examined the frictional properties of sediments on the Cocos plate offshore the Osa Peninsula, Costa Rica, and explored variations in the intrinsic frictional properties of the sediment inputs to the Costa Rica subduction zone. Sediment samples were collected at Site U1381A during the Integrated Ocean Drilling Program Expedition 334, and include hemipelagic clay to silty clay material (Unit I) and pelagic silicic to calcareous ooze (Unit II). The frictional properties of the samples were tested at a normal stress of 5 MPa under water-saturated conditions and with slip velocities ranging from 0.0028 to 2.8 mm/s for up to 340 mm of displacement. The experimental results reveal that the steady-state friction coefficient values of clay to silty clay samples are as low as ~0.2, whereas those of silicic to calcareous ooze samples are as high as 0.6 to 0.8. The clay to silty clay samples show a positive dependence of friction on velocity for all tested slip velocities. In contrast, the silicic to calcareous ooze samples show a negative dependence of friction on velocity at velocities of 0.0028 to 0.28 mm/s and either neutral or positive dependence at velocities higher than 0.28 mm/s. Given the low frictional coefficient values observed for the clay to silty clay samples of Unit I, the décollement at the Costa Rica Seismogenesis Project transect offshore the Osa Peninsula likely initiates in Unit I and is initially very weak. In addition, the velocity-strengthening behavior of the clay to silty clay suggests that faults in the very shallow portion of the Costa Rica subduction zone are stable and thus behave as creeping segments. In contrast, the velocity-weakening behavior of the silicic to calcareous ooze favors unstable slip along faults. The shallow seismicity occurred at a depth as shallow as ~9 km along the Costa Rica margin offshore the Osa Peninsula (M_w 6.4, June 2002), indicating that materials characterized by velocity-weakening behavior constitute the fault zone at the depth of the seismicity. Fault slip nucleating along a fault in Unit II would be a likely candidate for the source of the shallow earthquake event.

Keywords: Friction; Costa Rica; Earthquake; Subduction zone; *a* – *b*

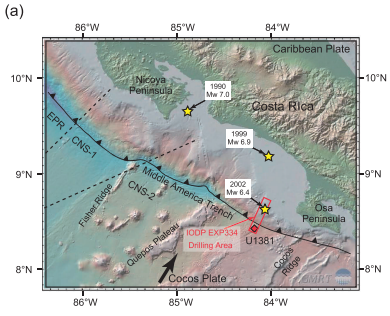

Figure 1

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FRONTIER LETTER Open Access

Q_P structure of the accretionary wedge in the Kumano Basin, Nankai Trough, Japan, revealed by long-offset walk-away VSP

Ryota Hino*, Takeshi Tsuji, Nathan L Bangs, Yoshinori Sanada, Jin-Oh Park, Roland von Huene, Gregory F Moore, Eiichiro Araki and Masataka Kinoshita

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Abstract

We determined the seismic attenuation structure of the Kumano Basin, a forearc basin in the central part of the Nankai subduction zone. Despite its importance for understanding the physical condition of the Earth's interior and seismic wave propagation processes, the attenuation factor Q has been poorly estimated in the crustal layers of the offshore areas of Nankai because severe attenuation occurring in the seafloor sediments prevents the reliable estimation of Q from conventional active source seismic surveys. In the present study, we derive Q values from the diminishing rate of the high-frequency contents of seismic energy during propagation through sub-seafloor layers. The records of vertical seismic profiling acquired at approximately 1,000 m below the seafloor, which have fewer effects from shallow attenuation, enabled us to elucidate depth variation of Q of P waves (Q_P), the attenuation factor of P waves, down to approximately 8 km below the seafloor. Assuming that the frequency dependence of Q is small and using a previously obtained P-wave velocity structure model for the basin, we inverted the fall-off rate of the spectral ratios at various shot-receiver distances to obtain Q_P in the three sub-bottom layers. The Q_P values for the upper two layers with P-wave velocity (V_P) < 2.7 km/s are 34 and 57. These values are almost identical to those obtained in the North Atlantic, suggesting the broad consistency of Q_P within seafloor sediment. The basement layer (V_P approximately 4 km/s) has a much higher Q_P value of 349, which is comparable to the value estimated for crustal layers exposed onshore. This Q_P value is higher than the value previously assumed in a simulation of strong ground motion associated with megathrust earthquakes along the Nankai margin. We interpret that the high Q_P, low seismic attenuation in the basement layer reflects tectonic stability of the inner wedge of the accretionary margin. Our first estimates of Q_P in the present study provide a strong basis for future studies of seismic structure and strong ground motion prediction.

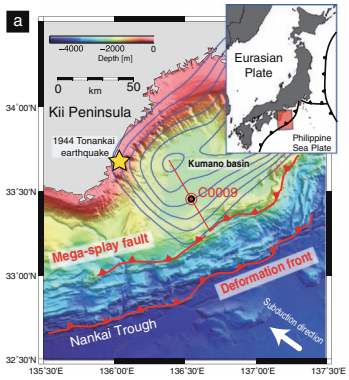

Figure 1

Keywords: Seismic attenuation; Q; Nankai Trough; VSP; IODP

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FULL PAPER Open Access

Quartz deposition and its influence on the deformation process of megathrusts in subduction zones

Jun Kameda*, Kuniyo Kawabata, Yohei Hamada, Asuka Yamaguchi and Gaku Kimura

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Abstract

We present a quantitative examination of the liberation and subsequent deposition of silica at the subduction zone plate interface in the Mugi mélange, an exhumed accretionary complex in the Shimanto Belt of southwest Japan. Frequency and thickness measurements indicate that mineralized veins hosted in deformed shales make up approximately 0.4% of the volume of this exposure. In addition, whole-rock geochemical evidence suggests that the net volume of SiO_2 liberated from the mélange at temperatures of < 200°C was as much as 35%, with up to 40% of the SiO_2 loss related to the smectite-illite (S-I) conversion reaction, and the rest attributable to the pressure solution of detrital quartz and feldspar. Kinetic modeling of the S-I reaction indicates active liberation of SiO_2 at approximately 70°C to 200°C, with peak SiO_2 loss at around 100°C, although these estimates should be slightly shifted toward lower temperature conditions based on X-ray diffraction (XRD) analyses of mixed-layer S-I in the Mugi mélange. The onset of pressure solution was not fully constrained, but has been documented to occur at around 150°C in the study area. The deposition in deformed shales of quartz liberated by pressure solution and the S-I reaction is probably linked to seismogenic behavior along the plate interface by (1) progressively enhanced velocity-weakening properties, which are favorable for unstable seismogenic faulting, including very-low-frequency earthquakes and (2) increasing intrinsic frictional strength, which leads to a step-down of the plate boundary décollement into oceanic basalt.

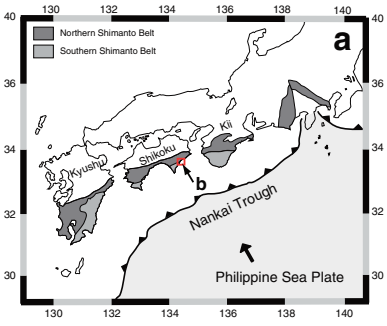

Figure 1

Keywords: Subduction zone; Diagenesis; Veining; VLFE

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FULL PAPER Open Access

Geochemical and mineralogical characteristics of fault gouge in the Median Tectonic Line, Japan: evidence for earthquake slip

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Abstract

We carried out geochemical and mineralogical analyses on fault-zone rocks from the Anko section of the Median Tectonic Line in Nagano Prefecture, Japan, to investigate coseismic physicochemical processes in the fault zone. The latest fault zone in the Anko section contains cataclasite, fault breccia, and fault gouge of granitic composition, and brecciated basic schist. Protoliths of the granitic composition are from the Ryoke metamorphic belt and those of the basic schist from the Sambagawa metamorphic belt. X-ray diffraction analyses show a selective decrease of clay minerals coupled with an increase of amorphous phase in an intensely deformed layer of black gouge (5- to 10-cm thick). SEM observation reveals that the black gouge is characterized by a drastic reduction of grain size and abundant ultrafine particles of submicrometer to several tens of nanometers with well-rounded spheroidal shapes. These observations for the black gouge are indicative of strong mineral lattice distortion and granulation associated with earthquake slip. Geochemically, the black gouge is characterized by distinctly higher Li content and $^{87}Sr/^{86}Sr$ isotope ratio than surrounding cataclasites, breccias, and gouges, which have similar major element compositions. Model analysis reveals that the trace element composition of the black gouge is consistent with high-temperature (up to 250°C) coseismic fluid-rock interactions. Thermal and kinetic constraints indicate that there have been repeated slips on the fault at moderate depths (e.g., 600 m), although the tectonic process by which the fault zone has been uplifted and exposed in this area is not well understood.

Keywords: Active fault; Frictional heat; Fault gouge; Trace elements; Isotope ratios

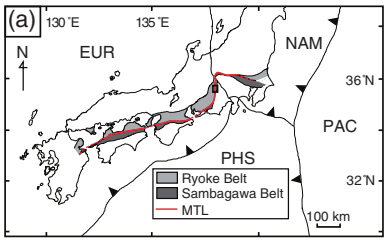

Figure 1

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FULL PAPER Open Access

Feasibility of acoustic monitoring of strength drop precursory to earthquake occurrence

Nobuki Kame*, Kohei Nagata, Masao Nakatani and Tetsuya Kusakabe

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Abstract

Rate- and state-dependent friction law (RSF), proposed on the basis of laboratory experiments, has been extensively applied to modeling of earthquake stick-slip cycles. A simple spring-slider model obeying RSF predicts a significant decrease of the frictional strength Φ (the state of contact) that is localized within a few years preceding the earthquake occurrence. On the other hand, recent laboratory experiments successfully monitored the history of the strength by simultaneously measuring the P-wave transmissivity $|T|$ across the frictional interface using a 1-MHz transducer. This suggests a possibility of earthquake forecast by monitoring the strength of a natural fault by acoustic methods. The present paper explores the feasibility of such monitoring in the field on the basis of the physics of RSF combined with the linear slip model (LSM) employed in the classical acoustic methodology for monitoring an imperfectly welded interface. The characteristic frequency f_c, around which $|T|$ (or reflectivity $|R|$) has a good sensitivity to the interface strength, is shown to be proportional to the strength and inversely proportional to the representative scale of real contacts. For natural faults, f_c is estimated to be 1 to 100 Hz, which is practicable in the field. The changes of $|T|$ and $|R|$ depend on the ratio of the strength drop to the absolute strength level, the latter of which is not constrained by RSF simulations. Expected changes in wave amplitude in the preslip period would be several percent for strong faults and several tens percent for weak faults, which may be detectable by acoustic methods such as seismic reflection surveys.

Keywords: Fault strength; Earthquake cycle; Rate- and state-dependent friction; Precursor; Linear slip model; Acoustic monitoring; Reflection survey

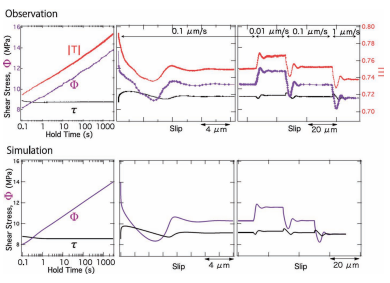

Figure 1

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FULL PAPER Open Access

Ground motions characterized by a multi-scale heterogeneous earthquake model

Hideo Aochi* and Satoshi Ide

Earth, Planets and Space 2014, **66**:42 doi:10.1186/1880-5981-66-42
Received: 22 January 2014, Accepted: 30 April 2014, Published: 29 May 2014

Abstract

We have carried out numerical simulations of seismic ground motion radiating from a mega-earthquake whose rupture process is governed by a multi-scale heterogeneous distribution of fracture energy. The observed complexity of the *Mw* 9.0 2011 Tohoku-Oki earthquake can be explained by such heterogeneities with fractal patches (size and number), even without introducing any heterogeneity in the stress state. In our model, scale dependency in fracture energy (i.e., the slip-weakening distance D_c) on patch size is essential. Our results indicate that wave radiation is generally governed by the largest patch at each moment and that the contribution from small patches is minor. We then conducted parametric studies on the frictional parameters of peak (τ_p) and residual (τ_r) friction to produce the case where the effect of the small patches is evident during the progress of the main rupture. We found that heterogeneity in τ_r has a greater influence on the ground motions than does heterogeneity in τ_p. As such, local heterogeneity in the static stress drop ($\Delta\tau$) influences the rupture process more than that in the stress excess ($\Delta\tau^{excess}$). The effect of small patches is particularly evident when these are almost geometrically isolated and not simultaneously involved in the rupture of larger patches. In other cases, the wave radiation from small patches is probably hidden by the major contributions from large patches. Small patches may play a role in strong motion generation areas with low τ_r (high $\Delta\tau$), particularly during slow average rupture propagation. This effect can be identified from the differences in the spatial distributions of peak ground velocities for different frequency ranges.

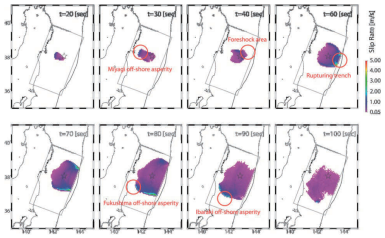

Figure 1

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FULL PAPER Open Access

Frictional properties of the shallow Nankai Trough accretionary sediments dependent on the content of clay minerals

Miki Takahashi, Shuhei Azuma, Hidenori Ito, Kyuichi Kanagawa* and Atsuyuki Inoue

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Abstract

We conducted triaxial friction experiments on the shallow Nankai Trough accretionary sediments at confining pressures, pore water pressures, temperatures close to their *in situ* conditions, and axial displacement rates (V_{axial}) changed stepwise among 0.1, 1, and 10 μm/s. The results revealed that their frictional properties change systematically according to the content of clay minerals, smectite in particular. The steady-state friction coefficient (μ_{ss}) at $V_{axial} = 1$ μm/s decreases with increasing clay mineral content, shown in weight percent, from 0.82 for a sandstone sample (6 wt%), through 0.71 for a tuff sample (≈17 wt%), and 0.53 to 0.56 for siltstone samples (29 to 34 wt%), to 0.25 for a claystone sample (42 wt%). Slip-dependent frictional behavior changes accordingly from slip hardening for the sandstone sample, through quasi steady-state slip for the tuff and siltstone samples, to distinct slip weakening for the claystone sample. Although all samples exhibit velocity-strengthening behavior upon stepwise changes in sliding velocity, the ratio of the $(a-b)$ value to the velocity dependence of steady-state friction ($\Delta\mu_{ss}/\Delta\ln V_{sliding}$) decreases with increasing clay mineral content, which implies that the friction component decreases while the flow component increases accordingly. Thus, faulting in the shallow Nankai Trough accretionary prism is likely controlled by the clay mineral content, in particular the smectite content, in the sediments as well as in the fault zones.

Keywords: Accretionary sediments; Nankai Trough; Friction; Clay mineral content

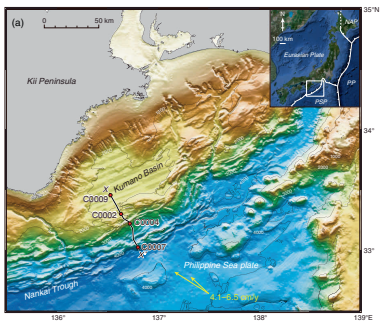

Figure 1

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FULL PAPER Open Access

Application of cluster analysis based on waveform cross-correlation coefficients to data recorded by ocean-bottom seismometers: results from off the Kii Peninsula

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Received: 7 March 2014, Accepted: 18 July 2014, Published: 30 July 2014

Abstract

Waveform cross-correlation coefficients (CCs) have often been used to investigate clustering of earthquakes. Such techniques, however, have rarely been applied to waveform data recorded by ocean-bottom seismometers (OBSs). The data recorded by some OBSs are strongly influenced by site effects such as the existence of unconsolidated sediment layers. The resulting waveforms tend to have a monotone frequency so that the calculated CCs stay artificially high, and false delay times are obtained at certain multiples of the period. This effect also varies from place to place. To overcome such problems, CC measurements were first performed using multiple time windows with different lengths in order to reject unstable results. Station-specific CC thresholds were then objectively determined based on the CC distributions. This method was applied to seismic measurements obtained by OBSs deployed off the Kii Peninsula from 2003 to 2007 in order to identify characteristic hypocenter patterns. Two types of earthquake clusters were found. The first occurred within the oceanic mantle, and the component events were linearly aligned along the NNE direction. Such earthquakes are considered to occur on preexisting faults due to dehydration of the serpentinized mantle. The second type of cluster consisted of interplate earthquakes that occurred at the southern tip of the Kii Peninsula. These are thought to be the result of stress caused by local structural heterogeneity of the dense rock body.

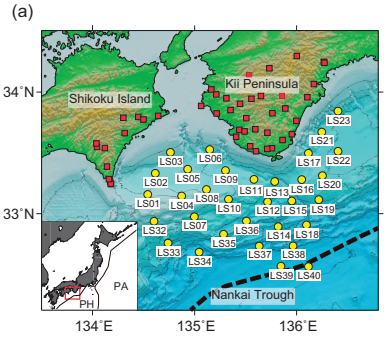

Figure 1

Keywords: Cross-correlation coefficients; Ocean-bottom seismometers; Subduction zone; Earthquake cluster

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FULL PAPER Open Access

Subgrain boundary analyses in deformed orthopyroxene by TEM/STEM with EBSD-FIB sample preparation technique

Toshihiro Kogure*, Hugues Raimbourg, Akihito Kumamoto, Eiko Fujii and Yuichi Ikuhara

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Abstract

High-resolution structure analyses using electron beam techniques have been performed for the investigation of subgrain boundaries (SGBs) in deformed orthopyroxene (Opx) in mylonite from Hidaka Metamorphic Belt, Hokkaido, Japan, to understand ductile deformation mechanism of silicate minerals in shear zones. Scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) analysis of Opx porphyroclasts in the mylonitic rock indicated that the crystal orientation inside the Opx crystals gradually changes by rotation about the b-axis by SGBs and crystal folding. In order to observe the SGBs along the b-axis by transmission electron microscopy (TEM) or scanning TEM (STEM), the following sample preparation protocol was adopted. First, petrographic thin sections were slightly etched with hydrofluoric acid to identify SGBs in SEM. The Opx crystals whose b-axes were oriented close to the normal of the surface were identified by EBSD, and the areas containing SGBs were picked and thinned for (S) TEM analysis with a focused ion beam instrument with micro-sampling system. High-resolution TEM imaging of the SGBs in Opx revealed various boundary structures from a periodic array of dissociated (100) [001] edge dislocations to partially or completely incoherent crystals, depending on the misorientation angle. Atomic-resolution STEM imaging clearly confirmed the formation of clinopyroxene (Cpx) structure between the dissociated partial dislocations. Moreover, X-ray microanalysis in STEM revealed that the Cpx contains a considerable amount of calcium replacing iron. Such chemical inhomogeneity may limit glide motion of the dislocation and eventually the plastic deformation of the Opx porphyroclasts at a low temperature. Chemical profiles across the high-angle incoherent SGB also showed an enrichment of the latter in calcium at the boundary, suggesting that SGBs are an efficient diffusion pathway of calcium out of host Opx grain during cooling.

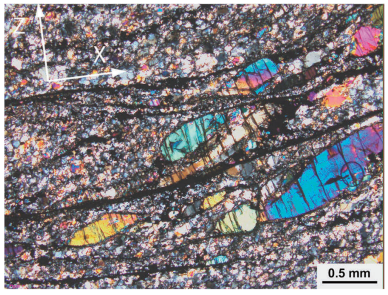

Figure 1

Keywords: Deformation; Dislocation; Pyroxene; Subgrain boundary; TEM/STEM

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FULL PAPER Open Access

Re-evaluation of temperature at the updip limit of locked portion of Nankai megasplay inferred from IODP Site C0002 temperature observatory

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Abstract

In 2010, the first long-term borehole monitoring system was deployed at approximately 900 m below the sea floor (mbsf) and was assumed to be situated above the updip limit of the seismogenic zone in the Nankai Trough off Kumano (Site C0002). Four temperature records show that the effect of drilling diminished in less than 2 years. Based on *in situ* temperatures and thermal conductivities measured on core samples, the temperature measurements and heat flow at 900 mbsf are estimated to be 37.9°C and 56 ± 1 mW/m^2, respectively. This heat flow value is in excellent agreement with that from the shallow borehole temperature corrected for rapid sedimentation in the Kumano Basin. We use these values in the present study to extrapolate the temperature below 900 mbsf for a megasplay fault at approximately 5,200 mbsf and a plate boundary fault at approximately 7,000 mbsf. To extrapolate the temperature downward, we use logging-while-drilling (LWD) bit resistivity data as a proxy for porosity and estimate thermal conductivity from this porosity using a geometrical mean model. The one-dimensional (1-D) thermal conduction model used for the extrapolation includes radioactive heat and frictional heat production at the plate boundary fault. The estimated temperature at the megasplay ranges from 132°C to 149°C, depending on the assumed thermal conductivity and radioactive heat production values. These values are significantly higher, by up to 40°C, than some of previous two-dimensional (2-D) numerical model predictions that can account for the high heat flow seaward of the deformation front, including a hydrothermal circulation within the subducted igneous oceanic crust. However, our results are in good agreement with those of the 2-D model, which does not include the advection cooling effect. The results imply that 2-D geometrical effects as well as the influence of the advective cooling may be critical and should be evaluated more quantitatively. Revision of 2-D simulation by introducing our new boundary conditions (37.9°C of *in situ* temperature at 900 mbsf and approximately 56 mW/m^2 heat flow) will be essential. Ultimately, *in situ* temperature measurements at the megasplay fault are required to understand seismogenesis in the Nankai subduction zone.

Keywords: Seismogenic zone; Scientific drilling; Nankai Trough; Thermal regime; Heat flow; Thermal conductivity; Logging while drilling; Long-term bore hole observatory; Integrated Ocean Drilling Program (IODP)

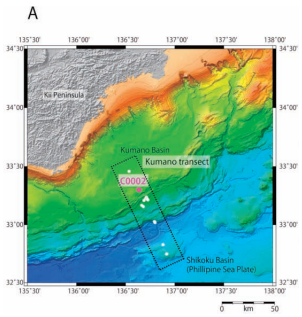

Figure 1

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FULL PAPER Open Access

Mechanical and hydraulic behavior of a rock fracture under shear deformation

Satoshi Nishiyama*, Yuzo Ohnishi, Hisao Ito and Takao Yano

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Abstract

With regard to crystalline rock that constitutes deep geology, attempts have been made to explore its hydraulic characteristics by focusing on the network of numerous fractures within. As the hydraulic characteristics of a rock are the accumulation of hydraulic characteristics of each fracture, it is necessary to develop the hydraulic model of a single fracture to predict the large-scale hydraulic behavior. To this end, a simultaneous permeability and shear test device is developed, and shear-flow coupling tests are conducted on specimens having fractures with varied levels of surface roughness in the constant normal stiffness conditions. The results show that the permeability characteristics in the relation between shear displacement and transmissivity change greatly at the point where the stress path reaches the Mohr-Coulomb failure curve. It is also found that there exists a range in which transmissivity is not proportional to the cube of mechanical aperture width, which seems to be because of the occurrence of channeling phenomenon at small mechanical aperture widths. This channeling flow disappears with increasing shear and is transformed into a uniform flow. We develop a simulation technique to evaluate the macroscopic permeability characteristics by the lattice gas cellular automaton method, considering the microstructure of fracture, namely the fracture surface roughness. With this technique, it is shown that the formation of the Hagen-Poiseuille flow is affected by the fracture microstructure under shear, which as a result determines the relationship between the mechanical aperture width and transmissivity.

Keywords: Shear-flow coupling test; Constant normal stiffness; Fracture surface roughness; Mohr-Coulomb failure; Lattice gas cellular automaton; Modified cubic law; Hagen-Poiseuille flow

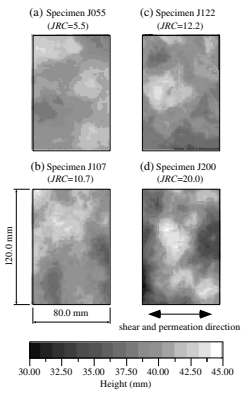

Figure 1

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FULL PAPER Open Access

Changes in illite crystallinity within an ancient tectonic boundary thrust caused by thermal, mechanical, and hydrothermal effects: an example from the Nobeoka Thrust, southwest Japan

Rina Fukuchi*, Koichiro Fujimoto, Jun Kameda, Mari Hamahashi, Asuka Yamaguchi, Gaku Kimura, Yohei Hamada, Yoshitaka Hashimoto, Yujin Kitamura and Saneatsu Saito

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Abstract

Illite crystallinity (IC), the full width at half maximum of the illite (001) peak in clay-fraction X-ray diffraction (XRD), is a common geothermometer widely applied to various tectonic settings. Paleotemperature estimation using IC presents methodological ambiguity because IC is not only affected by background temperature but also by mechanical, hydrothermal, and surface weathering effects. To clarify the influences of these effects on IC in the fault zone, we analyzed the IC and the illite 001 peak intensity of continuous borehole core samples from the Nobeoka Thrust, a fossilized tectonic boundary thrust in the Shimanto Belt, the Cretaceous-Paleogene Shimanto accretionary complex in southwest Japan. We also carried out grinding experiments on borehole core samples and sericite standard samples as starting materials and investigated the effect of mechanical comminution on the IC and illite peak intensity of the experimental products. We observed the following: (1) the paleotemperatures of the hanging wall and footwall of the Nobeoka Thrust are estimated to be 288°C to 299°C and 198°C to 249°C, respectively, which are approximately 20°C to 30°C lower than their previously reported temperatures estimated by vitrinite reflectance; (2) the fault core of the Nobeoka Thrust does not exhibit IC decrease; (3) the correlation of IC and illite peak intensity in the hanging wall damage zone were well reproduced by the grinding experiment, suggesting that the effect of mechanical comminution increases toward the fault core and; (4) the abrupt increase in IC value accompanied by high illite peak intensity is explained by hydrothermal alterations including plagioclase breakdown and the formation of white micas. Our results indicate that IC has potential for quantifying the effects of mechanical comminution and hydrothermal alteration within a fault zone.

Keywords: Illite crystallinity; Nobeoka thrust; X-ray diffraction; Comminution; Hydrothermal alteration; Tectonic boundary thrust

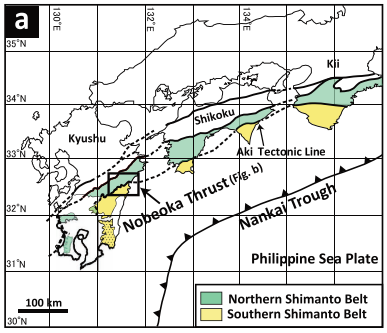

Figure 1

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FULL PAPER Open Access

Strike-slip motion of a mega-splay fault system in the Nankai oblique subduction zone

Takeshi Tsuji*, Juichiro Ashi and Yasutaka Ikeda

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Abstract

We evaluated the influence of the trench-parallel component of plate motion on the active fault system within the Nankai accretionary wedge from reflection seismic profiles, high-resolution seafloor bathymetry, and deep-towed sub-bottom profiles. Our study demonstrated that a large portion of the trench-parallel component of oblique plate subduction is released by strike-slip motion along a fault located just landward of and merging down-dip with a mega-splay fault. The shallow portion of the splay fault system, forming a flower structure, seems to accommodate dominant strike-slip motion, while most of the dip-slip motion could propagate to the trenchward décollement. Numerous fractures developed around the strike-slip fault release overpressured pore fluid trapped beneath the mega-splay fault. The well-developed fractures could be related to the change in stress orientation within the accretionary wedge. Therefore, the strike-slip fault located at the boundary between the inner and outer wedges is a key structure controlling the stress state (including pore pressure) within the accretionary prism. In addition, the strike-slip motion contributes to enhancing the continuous mega-splay fault system (outer ridge), which extends for approximately 200 km parallel to the Nankai Trough.

Keywords: Strike-slip fault; Mega-splay fault; Nankai Trough; Oblique subduction; Stress boundary

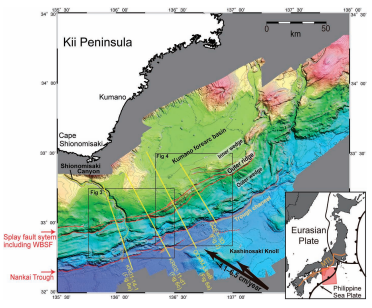

Figure 1

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FULL PAPER Open Access

Seismic imaging and velocity structure around the JFAST drill site in the Japan Trench: low *Vp*, high *Vp*/*Vs* in the transparent frontal prism

Yasuyuki Nakamura*, Shuichi Kodaira, Becky J Cook, Tamara Jeppson, Takafumi Kasaya, Yojiro Yamamoto, Yoshitaka Hashimoto, Mika Yamaguchi, Koichiro Obana and Gou Fujie

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Abstract

Seismic image and velocity models were obtained from a newly conducted seismic survey around the Integrated Ocean Drilling Program (IODP) Japan Trench Fast Drilling Project (JFAST) drill site in the Japan Trench. Pre-stack depth migration (PSDM) analysis was applied to the multichannel seismic reflection data to produce an accurate depth seismic profile together with a P wave velocity model along a line that crosses the JFAST site location. The seismic profile images the subduction zone at a regional scale. The frontal prism where the drill site is located corresponds to a typically seismically transparent (or chaotic) zone with several landward-dipping semi-continuous reflections. The boundary between the Cretaceous backstop and the frontal prism is marked by a prominent landward-dipping reflection. The P wave velocity model derived from the PSDM analysis shows low velocity in the frontal prism and velocity reversal across the backstop interface. The PSDM velocity model around the drill site is similar to the P wave velocity model calculated from the ocean bottom seismograph (OBS) data and agrees with the P wave velocities measured from the core experiments. The average *Vp*/*Vs* in the hanging wall sediments around the drill site, as derived from OBS data, is significantly larger than that obtained from core sample measurements.

Keywords: Japan Trench; Seismic image; P and S wave velocities; JFAST

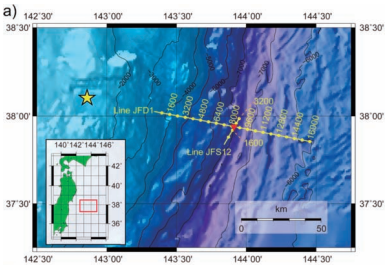

Figure 1

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The possibility of deeper or shallower extent of the source area of Nankai Trough earthquakes based on the 1707 Hoei tsunami heights along the Pacific and Seto Inland Sea coasts, southwest Japan

Mamoru Hyodo*, Takane Hori, Kazuto Ando and Toshitaka Baba

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Abstract

To validate the abundance of scenarios of large earthquakes in the Nankai Trough, we examined the effects of both lateral and vertical expansions of the source areas on maximum tsunami heights along the Pacific coast and Seto Inland Sea. The recently proposed Nankai Trough earthquake scenario ($M_w = 9$) has a maximum slip of 20 m near the trough axis. However, the predicted tsunami heights exceeded those obtained from historical records of damage caused by the 1707 Hoei tsunami event at Tosa Bay and along the Pacific coastlines near the Kii Channel, owing to the large slip on the up-dip extension of fault segments off Shikoku Island. Such discrepancy indicates that for segments off Shikoku Island, the slip near the trough axis was unremarkable, even for the 1707 Hoei earthquake event, which is considered one of the larger historical Nankai Trough earthquake events. For segments east of the Kii Peninsula, the large slip on the up-dip end might be ineffective. While the proposed M_w9-class scenario also includes large slip of several meters on the down-dip side (down to about 35-km depth), coseismic crustal subsidence reached further landward than is usual for Nankai Trough earthquakes. For the Seto Inland Sea region, this resulted in maximum subsidence of about 1 m, and such crustal subsidence effectively increased the height of the tsunamis. Furthermore, simulated tsunami heights, corrected for crustal subsidence, were in good agreement with those obtained from historical records of the damage caused in the Seto Inland Sea region.

Keywords: Nankai Trough earthquake; Historical tsunami; Earthquake scenario

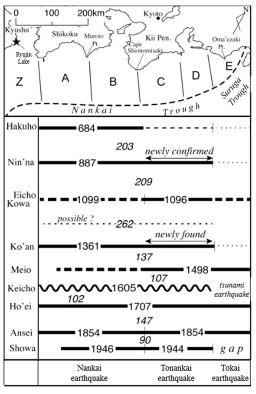

Figure 1

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FULL PAPER Open Access

Geotechnical behavior of mudstones from the Shimanto and Boso accretionary complexes, and implications for the Nankai accretionary prism

Kai Schumann*, Jan H Behrmann, Michael Stipp, Yuzuru Yamamoto, Yujin Kitamura and Christof Lempp

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Abstract

Triaxial shear tests on mudstone samples from the Shimanto Belt and the Boso accretionary complexes (SW Japan and central Japan) were carried out. Pre-exhumation burial depths in the two paleo-accretionary prisms were up to 9,000 m and about 1,000 m for the Shimanto and the Boso samples, respectively. Three methods were applied: (1) pressure stepping tests at increasing confining pressures between 25 and 65 MPa and pore pressures between 20 and 52 MPa; (2) constant confining pressure tests at 55 and 65 MPa, with stepwise pore pressure decrease from 80% to 50% and 25%, and from 90% to 60% and 30% of the confining pressure; and (3) a cyclic loading test on one sample from Boso (19 cycles to 70-MPa differential stress). After some contraction due to pressurization in the first cycles, the sample showed tendencies to creep rather than to fracture.
Effective shear parameters show that angles of internal friction between 30° and 50° are in part quite high in both sample subsets, and ranges of cohesion are between about 2 and 6 MPa (Boso) and 13 and >30 MPa (Shimanto). The mechanical results from these paleo-accretionary prisms are taken to constrain the shear parameters of rocks in the deeper parts of the present Nankai accretionary wedge and forearc. Static friction resembles results from experiments on a wide range of phyllosilicate-quartz-feldspar gouges and shows that the forearc is composed of relatively strong rock. Cohesion increase due to diagenesis and/or very low grade metamorphism is of overriding importance and probably permits stresses of up to 18 MPa to be transmitted to the updip end of the seismogenic zone at depth and 5 to 13 MPa to the backstop of the actively deforming frontal prism.

Keywords: Shimanto Belt; Boso accretionary prism; Nankai; IODP; Triaxial shear test; Mudstone; Subduction zone

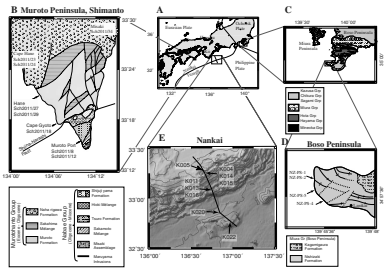

Figure 1

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FULL PAPER Open Access

Along-strike variations in temperature and tectonic tremor activity along the Hikurangi subduction zone, New Zealand

Suguru Yabe*, Satoshi Ide and Shoichi Yoshioka

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Abstract

In the Hikurangi subduction zone, situated along the east coast of the North Island, New Zealand, where the old oceanic Pacific Plate is subducting beneath the Australian Plate, several slow slip events and tectonic tremors have recently been documented. These observations are somewhat surprising because such slow seismic phenomena tend to be common in subduction zones where relatively young oceanic plate is subducting. The locations of tectonic tremors, down-dip limit of slow slip events and seismic coupling transition change along strike from greater depths in the south to shallower depths in the north, suggesting significant along-strike variations in the characteristics of the plate interface. Similar along-strike variations have been observed for other characteristic features of the Hikurangi subduction zone. Here, we demonstrate that along-strike variations observed for tectonic tremors, slow slip events, and seismic coupling can be explained by lateral differences in the thermal structure of the subduction zone, which are controlled mainly by variations in convergence rate and friction along the plate interface. To demonstrate this, we first confirm that tectonic tremors occur around the plate interface. Then, we calculate the thermal structure of the Hikurangi subduction zone using a two-dimensional finite difference code. To explain the along-strike variation in the heat flow observed in the forearc region, temperatures along the plate interface should be systematically higher in the northern region than in the southern region, which we interpret as a consequence of higher convergence rates and greater frictional heating in the northern region. We compare the along-strike variation of seismic characteristics with calculated thermal structure and highlight that this along-strike variation in temperature controls the depth of the brittle-ductile transition, which is consistent with the observed spatial variations in tectonic tremors, down-dip limit of slow slip events and seismic coupling. Our results suggest that tectonic tremors recorded within subduction zones reflect the transient rheology of the materials being subducted, which is controlled by variations in temperature along the plate interface.

Keywords: New Zealand; Subduction zone; Tectonic tremor; Slow earthquake; Thermal structure

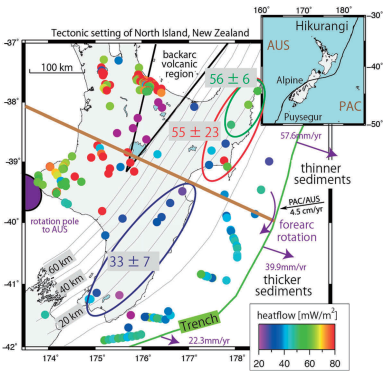

Figure 1

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FULL PAPER Open Access

Origin and transport of pore fluids in the Nankai accretionary prism inferred from chemical and isotopic compositions of pore water at cold seep sites off Kumano

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Abstract

We used push corers during manned submersible dives to obtain sediment samples of up to 30 cm from the subseafloor at the Oomine Ridge. The concentrations of B in pore water extracted from the sediment samples from cold seep sites were higher than could be explained by organic matter decomposition, suggesting that the seepage fluid at the site was influenced by B derived from smectite-illite alteration, which occurs between 50°C and 160°C. Although the negative $\delta^{18}O_{H2O}$ and δD_{H2O} values of the pore fluids cannot be explained by freshwater derived from clay mineral dehydration (CMD), we considered the contribution of pore fluids in the shallow sediments of the accretionary prism, which showed negative $\delta^{18}O_{H2O}$ and δD_{H2O} values according to the results obtained during Integrated Ocean Drilling Program (IODP) Expeditions 315 and 316. We calculated the mixing ratios based on a four-end-member mixing model including freshwater derived from CMD, pore fluids in the shallow (SPF) accretionary prism sediment, seawater (SW), and freshwater derived from methane hydrate (MH) dissociation. However, the Oomine seep fluids were unable to be explained without four end members, suggesting that deep-sourced fluids in the accretionary prism influenced the seeping fluids from this area. This finding presents the first evidence of deep-sourced fluids at cold seep sites in the Oomine Ridge, indicating that a megasplay fault is a potential pathway for the deep-sourced fluids.

Keywords: Cold seep; Pore fluid; Nankai Trough; Accretionary prism; Kumano; Boron; Lithium; Clay mineral dehydration; Methane hydrate dissociation

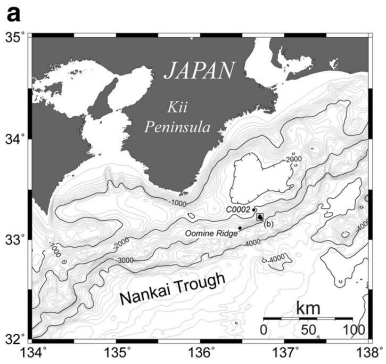

Figure 1

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FULL PAPER Open Access

Outer-rise normal fault development and influence on near-trench décollement propagation along the Japan Trench, off Tohoku

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Abstract

Multichannel seismic reflection lines image the subducting Pacific Plate to approximately 75 km seaward of the Japan Trench and document the incoming plate sediment, faults, and deformation front near the 2011 Tohoku earthquake epicenter. Sediment thickness of the incoming plate varies from <50 to >600 m with evidence of slumping near normal faults. We find recent sediment deposits in normal fault footwalls and topographic lows. We studied the development of two different classes of normal faults: faults that offset the igneous basement and faults restricted to the sediment section. Faults that cut the basement seaward of the Japan Trench also offset the seafloor and are therefore able to be well characterized from multiple bathymetric surveys. Images of 199 basement-cutting faults reveal an average throw of approximately 120 m and average fault spacing of approximately 2 km. Faults within the sediment column are poorly documented and exhibit offsets of approximately 20 m, with densely spaced populations near the trench axis. Regional seismic lines show lateral variations in location of the Japan Trench deformation front throughout the region, documenting the incoming plate's influence on the deformation front's location. Where horst blocks are carried into the trench, seaward propagation of the deformation front is diminished compared to areas where a graben has entered the trench. We propose that the décollement's propagation into the trench graben may be influenced by local stress changes or displacements due to subduction of active normal faults. The location and geometry of the up-dip décollement at the Japan Trench is potentially controlled by the incoming outer-rise faults.

Keywords: Japan Trench; Subduction; Normal faults; Outer rise; Trench; Oceanic plate

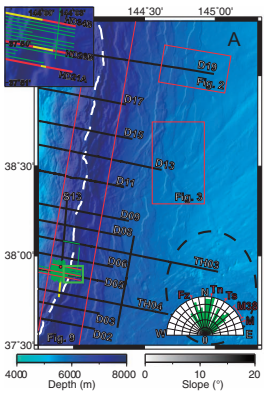

Figure 1

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FULL PAPER Open Access

Stress reversal recorded in calcite vein cuttings from the Nankai accretionary prism, southwest Japan

Toru Takeshita*, Asuka Yamaguchi and Norio Shigematsu

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Received: 7 March 2014, Accepted: 14 October 2014, Published: 29 October 2014

Abstract

The Nankai Trough subduction zone in southwest Japan is a typical convergent margin where the Philippine Sea plate subducts in the northwest direction beneath the Eurasian plate, and devastating earthquakes have repeatedly occurred in this region in the past. In order to investigate the evolution of the stress state in the subduction zone, we analyzed deformation microstructures and the preferred orientation of calcite grains in two cuttings of calcite veins from Hole C0002F that was drilled through the inner wedge of the Nankai accretionary prism during the Integrated Ocean Discovery Program (IODP) Expedition 338 in 2012. For both samples collected at depths of 1,085.5 and 1,885.5 meters below the sea floor (mbsf), the *c*-axes of calcite grains are preferentially oriented perpendicular to the vein wall, which is indicative of competitive growth of calcite during the vein opening caused by a vein normal extension. Also, mechanical e-twins were developed in both samples, and these are inferred to have been developed under the same stress field as that responsible for the formation of calcite veins based on the paleostress analyses in grains with *e*-twins. For the calcite vein retrieved at the depth of 1,885.5 mbsf, kink bands were also developed by the compression in the direction perpendicular to the vein wall, which is indicative of stress reversal after the formation of mechanical *e*-twins. Although we could not reach a definite conclusion for the cause of the stress reversal, it could have occurred during either fold development or seismic cycles in the Nankai accretionary prism.

Keywords: IODP expedition 338; Nankai accretionary prism; Calcite vein; Stress reversal; Paleostress analyses

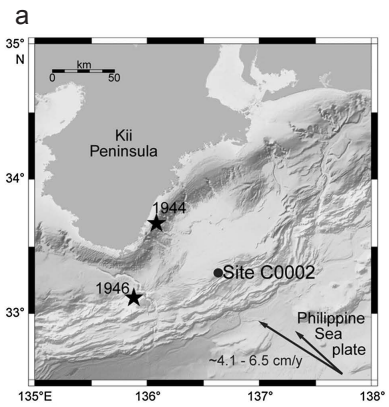

Figure 1

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FULL PAPER Open Access

Multiple damage zone structure of an exhumed seismogenic megasplay fault in a subduction zone - a study from the Nobeoka Thrust Drilling Project

Mari Hamahashi*, Yohei Hamada, Asuka Yamaguchi, Gaku Kimura, Rina Fukuchi, Saneatsu Saito, Jun Kameda, Yujin Kitamura, Koichiro Fujimoto and Yoshitaka Hashimoto

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Abstract

To investigate the mechanical properties and deformation patterns of megathrusts in subduction zones, we studied damage zone structures of the Nobeoka Thrust, an exhumed megasplay fault in the Kyushu Shimanto Belt, using drill cores and geophysical logging data obtained during the Nobeoka Thrust Drilling Project. The hanging wall, composed of a turbiditic sequence of phyllitic shales and sandstones, and the footwall, consisting of a mélange of a shale matrix with sandstone and basaltic blocks, exhibit damage zones that include multiple sets of 'brecciated zones' intensively broken in the mudstone-rich intervals, sandwiched by 'surrounding damage zones' in the sandstone-rich intervals with cohesive faults and mineral veins. The fracture zones are thinner (2.7 to 5.5 m) in the sandstone-rich intervals and thicker in the shale-dominant intervals (2.3 to 18.6 m), which indicates a preference of coseismic slip and velocity-weakening in the former, and aseismic deformation in the latter. However, the surrounding damage zones observed in the current study are associated with an increase in resistivity, *P*-wave velocity, and density and a decrease in porosity, inferring densification and strain-hardening in the sandstone-rich intervals and strain-weakening in the mudstone-rich intervals. These observations indicate that the sandstone-rich damage zones may weaken in the short term but may strengthen in the geologically long term, contributing to a later stage of fault activity. In contrast, the mudstone-rich damage zones may strengthen in the short term but develop weak structures through longer time periods. The observed shear zone thickness in the hanging wall is thinner (2.3 to 18.6 m) compared to the footwall damage zones (12 to 39.9 m), possibly because faults in the hanging wall were concentrated and partitioned between the preexisting turbiditic sequence of alternating shale/sandstone-dominant intervals, whereas in the footwall, faults were more sporadically distributed throughout the sandstone block-in-matrix cataclasites. A splay fault may evolve and be characterized by physical property contrasts, the lithology dependence of deformation, and the variability of damage zone thickness due to a heterogeneous lithology distribution in the hanging wall and footwall. The deformation patterns observed in the Nobeoka Thrust provide insights to the strain-hardening/weakening behaviors of sediments along megathrusts over geological timescales.

Keywords: Subduction zone; Megasplay fault; Shimanto Belt; Physical property; Damage zone; Nobeoka Thrust

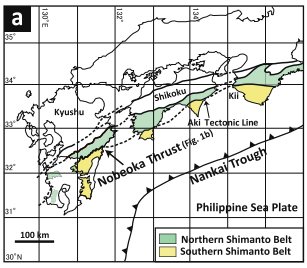

Figure 1

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FULL PAPER Open Access

Estimation of slip rate and fault displacement during shallow earthquake rupture in the Nankai subduction zone

Yohei Hamada*, Arito Sakaguchi, Wataru Tanikawa, Asuka Yamaguchi, Jun Kameda and Gaku Kimura

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Abstract

Enormous earthquakes repeatedly occur in subduction zones, and the slips along megathrusts, in particular those propagating to the toe of the forearc wedge, generate ruinous tsunamis. Quantitative evaluation of slip parameters (i.e., slip velocity, rise time and slip distance) of past slip events at shallow, tsunamigenic part of the fault is critical to characterize such earthquakes. Here, we attempt to quantify these parameters of slips that may have occurred along the shallow megasplay fault and the plate boundary décollement in the Nankai Trough, off southwest Japan. We apply a kinetic modeling to vitrinite reflectance profiles on the two fault rock samples obtained from Integrated Ocean Drilling Program (IODP). This approach constitutes two calculation procedures: heat generation and numerical profile fitting of vitrinite reflectance data. For the purpose of obtaining optimal slip parameters, residue calculation is implemented to estimate fitting accuracy. As the result, the measured distribution of vitrinite reflectance is reasonably fitted with heat generation rate ($\dot{Q}$) and slip duration (t_f) of 16,600 J/s/m^2 and 6,250 s, respectively, for the megasplay and 23,200 J/s/m^2 and 2,350 s, respectively, for the frontal décollement, implying slow and long-term slips. The estimated slip parameters are then compared with previous reports. The maximum temperature, *T*max, for the Nankai megasplay fault is consistent with the temperature constraint suggested by a previous work. Slow slip velocity, long-term rise time, and large displacement are recognized in these fault zones (both of the megasplay, the frontal décollement). These parameters are longer and slower than typical coseismic slip, but are rather consistent with rapid afterslip.

Keywords: Nankai Trough; Shallow part of megathrust; Vitrinite maturation; Fault slip parameters

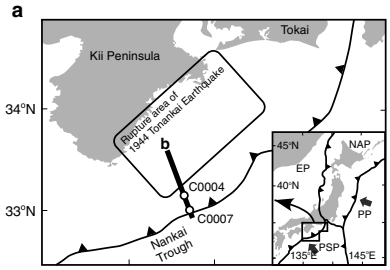

Figure 1

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LETTER Open Access

Estimation of slip parameters associated with frictional heating during the 1999 Taiwan Chi-Chi earthquake by vitrinite reflectance geothermometry

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Abstract

To estimate the slip parameters and understand the fault lubrication mechanism during the 1999 Taiwan Chi-Chi earthquake, we applied vitrinite reflectance geothermometry to samples retrieved from the Chelungpu fault. We found a marked reflectance anomaly of 1.30% ± 0.21% in the primary slip zone of the earthquake, whereas the reflectances in the surrounding deformed and host rocks were 0.45% to 0.77%. By applying a kinetic model of vitrinite thermal maturation together with a one-dimensional heat and thermal diffusion equation, we determined the shear stress and peak temperature in the slip zone during the earthquake to be 1.00 ± 0.04 MPa and 626°C ± 25°C, respectively. Taking into account the probable overestimation of the temperature owing to a mechanochemically enhanced reaction or flash heating at grain contacts, this temperature should be considered an upper limit. The lower limit was previously constrained to 400°C by studies of fluid-mobile trace-element concentrations and magnetic minerals. Therefore, we inferred that the peak temperature during the Chi-Chi earthquake was 400°C to 626°C, corresponding to an apparent friction coefficient of 0.01 to 0.06. Such low friction and the previous evidence of a high-temperature fluid suggest that thermal pressurization likely contributed to dynamic weakening during the Chi-Chi earthquake.

Keywords: Carbonaceous material; Thermal maturation; Fault friction; Chelungpu fault

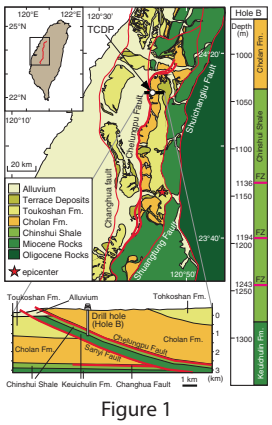

Figure 1

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LETTER Open Access

Thermal conductivities, thermal diffusivities, and volumetric heat capacities of core samples obtained from the Japan Trench Fast Drilling Project (JFAST)

Weiren Lin*, Patrick M Fulton, Robert N Harris, Osamu Tadai, Osamu Matsubayashi, Wataru Tanikawa and Masataka Kinoshita

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Received: 26 February 2014, Accepted: 20 May 2014, Published: 5 June 2014

Abstract

We report thermal conductivities, thermal diffusivities, and volumetric heat capacities determined by a transient plane heat source method for four whole-round core samples obtained by the Japan Trench Fast Drilling Project/Integrated Ocean Drilling Program Expedition 343. These thermal properties are necessary for the interpretation of a temperature anomaly detected in the vicinity of the plate boundary fault that ruptured during the 2011 Tohoku-Oki earthquake and other thermal processes observed within the Japan Trench Fast Drilling Project temperature observatory. Results of measured thermal conductivities are consistent with those independently measured using a transient line source method and a divided bar technique. Our measurements indicate no significant anisotropy in either thermal conductivity or thermal diffusivity.

Keywords: Thermal conductivity; Thermal diffusivity; Volumetric heat capacity; Anisotropy; Core sample measurement; JFAST

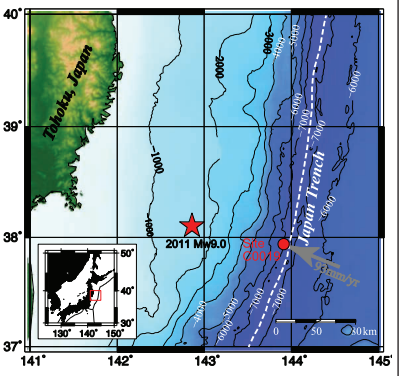

Figure 1

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LETTER Open Access

Accumulation of an earthquake-induced extremely turbid layer in a terminal basin of the Nankai accretionary prism

Juichiro Ashi*, Ritsuko Sawada, Akiko Omura and Ken Ikehara

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Abstract

Seismic shaking is a major trigger for sediment redistribution in subduction zones, and clouds of dilute suspended sediment have been reported in association with large earthquakes. Dive observations in a basin on the slope of the central Nankai accretionary prism soon after the 2004 off-Kii Peninsula earthquakes documented a layer of suspended sediment with extremely high turbidity. We estimated the thickness of this bottom turbid layer to be more than 2.5 m by comparison of seafloor depths between surveys in 2004 and 2010 and about 2.6 m from instrumental evidence involving the submersion of a heat-flow probe. A high-resolution subbottom profiling survey across the basin revealed acoustically transparent layers thicker than 2 m. Because the slope basin is a terminal basin completely enclosed by topographic highs, we examined the possibility that the uppermost transparent layer was deposited as a consequence of the 2004 earthquakes. Considering the sediment source area and the volume of the basin fills, the mobilization and redeposition of thin surface sediments on the prism slope can account for the volume of the transparent layer. We conclude that the 2004 earthquakes caused widespread disturbance of the prism slope and concentrated surface sediments in this terminal basin. Our results emphasize the utility of a terminal basin in a subduction zone as an earthquake recorder.

Keywords: Suspension cloud; Terminal basin; Slump; Sliding; Gravity flow

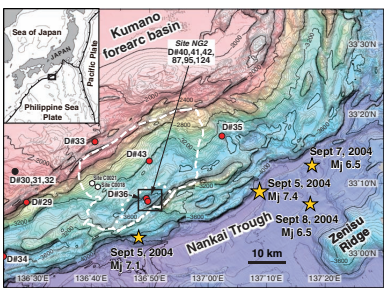

Figure 1

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LETTER Open Access

Fluid-rock interaction recorded in black fault rocks in the Kodiak accretionary complex, Alaska

Asuka Yamaguchi*, Tsuyoshi Ishikawa, Yasuhiro Kato, Tatsuo Nozaki, Francesca Meneghini, Christie D Rowe, James Casey Moore, Akito Tsutsumi and Gaku Kimura

Earth, Planets and Space 2014, **66**:58 doi:10.1186/1880-5981-66-58
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Abstract

Ultrafine-grained black fault rocks (BFRs) in the Pasagshak Point Thrust of the Kodiak accretionary complex are examples of fault rocks that have recorded seismicity along an ancient subduction plate boundary. Trace element concentrations and $^{87}Sr/^{86}Sr$ ratios of BFRs and surrounding foliated/non-foliated cataclasites were measured to explore the nature of fluid-rock interactions along a subduction thrust. Foliated and non-foliated cataclasites do not show significant geochemical anomalies, suggesting that they were formed by slowly distributed shear. BFRs are characterized by Li and Sr enrichment, Rb and Cs depletion, and a low $^{87}Sr/^{86}Sr$ ratio. These geochemical signatures can be explained by fluid-rock interactions at >350°C, which result in preferential removal of Rb and Cs and formation of plagioclase under the presence of fluids with high Li and Sr concentrations and low $^{87}Sr/^{86}Sr$ ratios. Geochemical anomalies recorded by the BFRs indicate both frictional heating and external fluid influx into the subduction thrust.

Keywords: Subduction zone; Seismogenic zone; Pseudotachylyte; Fluid-rock interaction

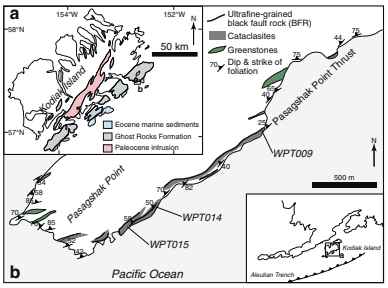

Figure 1

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LETTER Open Access

Frictional properties of incoming pelagic sediments at the Japan Trench: implications for large slip at a shallow plate boundary during the 2011 Tohoku earthquake

Michiyo Sawai*, Takehiro Hirose and Jun Kameda

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Abstract

The 2011 Tohoku earthquake (Mw 9.0) produced a very large slip on the shallow part of a megathrust fault that resulted in destructive tsunamis. Although multiple causes of such large slip at shallow depths are to be expected, the frictional property of sediments around the fault, particularly at coseismic slip velocities, may significantly contribute to large slip along such faults. We have thus investigated the frictional properties of incoming pelagic sediments that will subduct along the plate boundary fault at the Tohoku subduction zone, in order to understand the rupture processes that can cause large slip in the shallow parts of subduction zones. Our experimental results on clayey sediment at the base of the sedimentary section on the Pacific Plate yield a low friction coefficient of <0.2 over a wide range of slip velocities (0.25 mm/s to 1.3 m/s), and extremely low fracture energy during slip weakening, as compared with previous experiments of disaggregated sediments under coseismic slip conditions. Integrated Ocean Drilling Program (IODP) Expedition 343 confirmed that the clay-rich sediment investigated here is identical to those in the plate boundary fault zone, which ruptured and generated the Tohoku earthquake. The present results suggest that smectite-rich pelagic sediment not only accommodates cumulative plate motion over interseismic periods but also energetically facilitates the propagation of earthquake rupture towards the shallow part of the Tohoku subduction zone.

Keywords: 2011 Tohoku earthquake; Friction; Fracture energy; Smectite; DSDP Leg 56; IODP Expedition 343

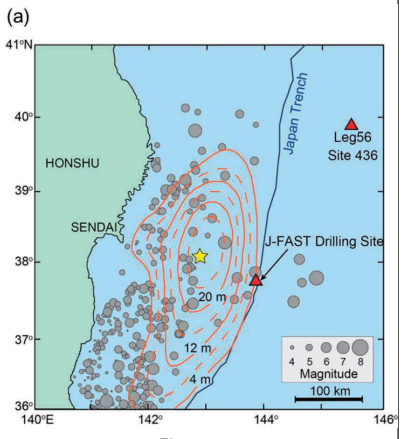

Figure 1

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LETTER Open Access

Pressure dependence of fluid transport properties of shallow fault systems in the Nankai subduction zone

Wataru Tanikawa*, Hideki Mukoyoshi, Weiren Lin, Takehiro Hirose and Akito Tsutsumi

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Received: 25 February 2014, Accepted: 6 August 2014, Published: 13 August 2014

Abstract

We measured fluid transport properties at an effective pressure of 40 MPa in core samples of sediments and fault rocks collected by the Integrated Ocean Drilling Program (IODP) NanTroSEIZE drilling project Expedition 316 from the megasplay fault system (site C0004) and the frontal thrust (site C0007) in the Nankai subduction zone. Permeability decreased with effective pressure as a power law function. Permeability values in the fault zones were 8×10^{-18} m^2 at site C0004 and 9×10^{-18} m^2 at site C0007. Stratigraphic variation in transport properties suggests that the megasplay fault zone may act as a barrier to fluid flow, but the frontal thrust fault zone might not. Depth variation in permeability at site C0007 is probably controlled by the mechanical compaction of sediment. Hydraulic diffusivity at shallow depths was approximately 1×10^{-6} m^2 s^{-1} in both fault zones, which is small enough to lead to pore pressure generation that can cause dynamic fault weakening. However, absence of a very low permeable zone, which may have formed in the Japan Trench subduction zone, might prevent facilitation of huge shallow slips during Nankai subduction zone earthquakes. Porosity tests under dry conditions might have overestimated the porosity.

Keywords: Permeability; Porosity; Integrated Ocean Drilling Program; Expedition 316 (NanTroSEIZE); Hydraulic diffusivity

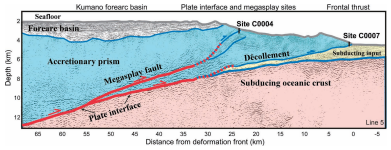

Figure 1

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LETTER Open Access

Heat flow survey in the vicinity of the branches of the megasplay fault in the Nankai accretionary prism

Makoto Yamano*, Yoshifumi Kawada and Hideki Hamamoto

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Abstract

Heat flow measurements were conducted at four sites in the Nankai accretionary prism southeast of the Kii Peninsula, around the area where the megasplay fault reaches the surface, in conjunction with long-term monitoring of bottom water temperature at nearby stations. Analysis of the obtained data showed that variations in bottom water temperature seriously affect surface heat flow measurements in the areas with water depths of less than about 2,800 m. This effect can reach up to 20% to 30% and may have significantly contributed to a large scatter in the heat flow values previously measured in the study area. The temperature records were also used to determine heat flows from sediment temperature profiles disturbed by bottom water temperature variations. Results of measurements at sites deeper than 2,800 m indicate that the regional heat flow, corrected for surface disturbances including the influence of bathymetric relief, is about 65 mW/m^2, which is consistent with the value calculated using subduction thermal models. Local high heat flow values were obtained in the vicinity of the tips of the branches of the splay fault, suggesting advective heat transport by upward pore fluid flow along the faults.

Keywords: Nankai Trough; Heat flow; Accretionary prism; Splay fault; Cold seep; Bottom water temperature; Pore fluid

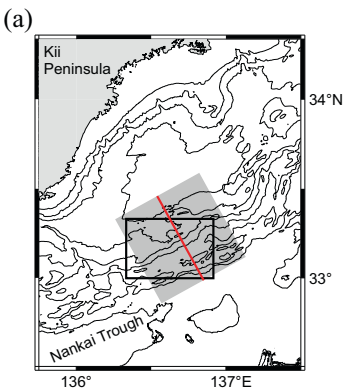

Figure 1

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LETTER Open Access

Geological evidence for shallow ductile-brittle transition zones along subduction interfaces: example from the Shimanto Belt, SW Japan

Yoshitaka Hashimoto* and Natsuko Yamano

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Abstract

Tectonic mélange zones within ancient accretionary complexes include various styles of strain accommodation along subduction interfaces from shallow to deep. The ductile-brittle transition at shallower portions of the subduction plate boundary was identified in three tectonic mélange zones (Mugi mélange, Yokonami mélange, and Miyama formation) in the Cretaceous Shimanto Belt, an on-land accretionary complex in southwest Japan. The transition is defined by a change in deformation features from extension veins only in sandstone blocks with ductile matrix deformation (possibly by diffusion-precipitation creep) to shear veins (brittle failure) from shallow to deep. Although mélange fabrics represent distributed simple to sub-simple shear deformation, localized shear veins are commonly accompanied by slickenlines and a mirror surface. Pressure-temperature (P-T) conditions for extension veins in sandstone blocks and for shear veins are distinct on the basis of fluid inclusion analysis. For extension veins, P-T conditions are approximately 125 to 220°C and 80 to 210 MPa. For shear veins, P-T conditions are approximately 185 to 270°C and 110 to 300 MPa. The P-T conditions for shear veins are, on average, higher than those for extension veins. The temperature conditions overlap in the range of approximately 175 to 210°C, which suggests that the change from more ductile to brittle processes occurs over a range of depths. The width of the shallow ductile-brittle transition zone can be explained by a heterogeneous lithification state for sandstone and mudstone or high fluid pressure caused by clay dehydration, which is controlled by the temperature conditions.

Keywords: Shallow ductile-brittle transition zone; Tectonic mélange; Shear vein; Pressure-temperature condition; Accretionary complex; Shimanto Belt

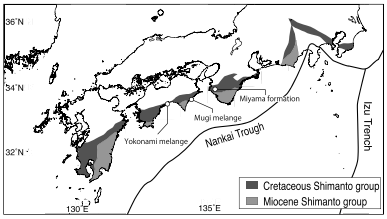

Figure 1

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LETTER Open Access

Friction properties of the plate boundary megathrust beneath the frontal wedge near the Japan Trench: an inference from topographic variation

Hiroaki Koge*, Toshiya Fujiwara, Shuichi Kodaira, Tomoyuki Sasaki, Jun Kameda, Yujin Kitamura, Mari Hamahashi, Rina Fukuchi, Asuka Yamaguchi, Yohei Hamada, Juichiro Ashi and Gaku Kimura

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Abstract

The 2011 Tohoku-Oki earthquake (Mw 9.0) produced a fault rupture that extended to the toe of the Japan Trench. The deformation and frictional properties beneath the forearc are keys that can help to elucidate this unusual event. In the present study, to investigate the frictional properties of the shallow part of the plate boundary, we applied the critically tapered Coulomb wedge theory to the Japan Trench and obtained the effective coefficient of basal friction (μ'_b) and Hubbert-Rubey pore fluid pressure ratio (λ) of the wedge beneath the lower slope. We extracted the surface slope angle and décollement dip angle (which are the necessary topographic parameters for applying the critical taper theory) from seismic reflection and refraction survey data at 12 sites in the frontal wedges of the Japan Trench. We found that the angle between the décollement and back-stop interface generally decreases toward the north. The measured taper angle and inferred effective friction coefficient were remarkably high at three locations. The southernmost area, which had the highest coefficient of basal friction, coincides with the area where the seamount is colliding offshore of Fukushima. The second area with a high effective coefficient of basal friction coincides with the maximum slip location during the 2011 Tohoku-Oki earthquake. The area of the 2011 earthquake rupture was topographically unique from other forearc regions in the Japan Trench. The strain energy accumulation near the trench axis may have proceeded because of the relatively high friction, and later this caused a large slip and collapse of the wedge. The location off Sanriku, where there are neither seamount collisions nor rupture propagation, also has a high coefficient of basal friction. The characteristics of the taper angle, effective coefficient of basal friction, and pore fluid pressure ratio along the Japan Trench presented herein may contribute to the understanding of the relationship between the geometry of the prism and the potential for generating seismo-tsunamigenic slips.

Keywords: Japan Trench; Topography; Critical taper; Tohoku-Oki earthquake; Basal friction; Surface slope angle; Seismo-tsunamigenic slip; Taper angle; Pore fluid pressure ratio; Prism

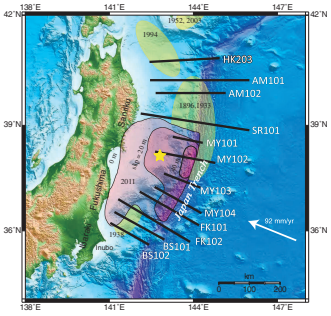

Figure 1

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LETTER Open Access

Small-scale stress fluctuations in borehole breakouts and their implication in identifying potential active faults around the seismogenic megasplay fault, Nankai Trough, SW Japan

Yasuhiro Yamada* and Jun Shibanuma

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Abstract

Borehole breakouts are enlargements and elongation of a borehole in a particular direction, caused by failure of the borehole wall rock due to concentration of stresses around the borehole, and thus, have been widely used to determine the in situ stress orientation. We used electrical borehole wall images obtained during offshore scientific drilling (IODP) that penetrated through a seismogenic megasplay fault in the Nankai Trough, off SW Japan, and extracted a number of borehole breakouts. Most of the breakouts show directions that can be explained by the regional convergence, but some are obviously rotated by faults and fractures in the megasplay fault zone and in its hanging wall. Stress magnitudes estimated from the width of the breakouts also show some decrease in the horizontal stresses, suggesting that slip along the faults and fractures release shear stress affecting these surfaces. Since such surfaces may have the capability to reactivate where the stresses affecting the surface are geometrically appropriate, the method presented in this paper may contribute to identifying active fault surfaces. This knowledge allows us to identify which surfaces need to be examined in detail to assess their potential for future activity.

Keywords: Borehole breakout; Stress rotation; Active fault identification; Nankai Trough; IODP

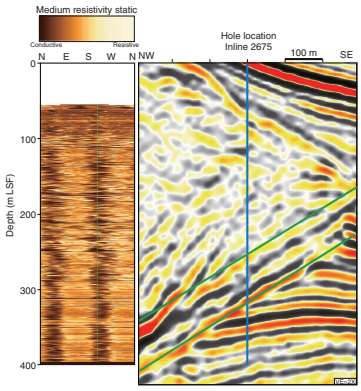

Figure 1

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Contents

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