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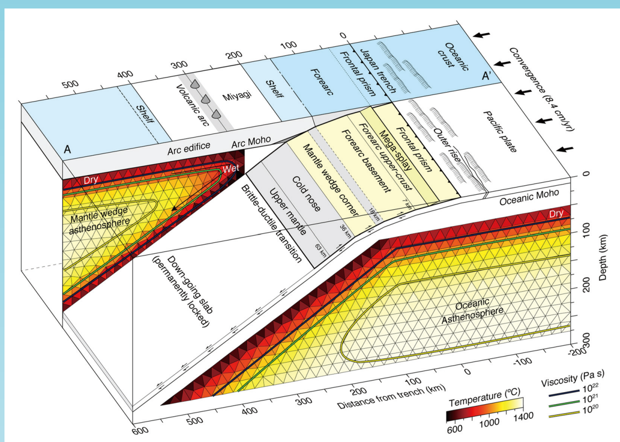
Crustal Dynamics: Toward Integrated View of Island Arc Seismogenesis



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PREFACE

Open Access

Special issue "Crustal dynamics: toward integrated view of island arc seismogenesis"

Toru Matsuzawa[1*], Ichiko Shimizu[2], Takuya Nishimura[3], Christopher J. Spiers[4], Junichi Nakajima[5] and Tatsuhiko Kawamoto[6]

Recent deployments of dense seismic and geodetic observation networks have revealed a detailed pattern of crustal stress and strain rate in tectonically active regions all over the world. Furthermore, the 2011 M9.0 Tohoku-oki earthquake provided a unique opportunity to investigate how the Japanese Islands' crust responds to instantaneous as well as transient stress changes due to the giant fault motion. This special issue includes 28 papers, which are the results of state-of-the-art researches carried out to understand the crustal dynamics and earthquake generation process in the island arc system. The papers might be categorized into several groups: (1) inhomogeneous structures related to earthquakes; (2) inelastic deformation; (3) stress and fault strength; (4) fluids and earthquakes; and (5) characteristic of fluids.

It is evident that inhomogeneous structures affect seismic activities, but the detail of the effect is still ambiguous. Baba and Yoshida (2020) clarified the detailed geological structure in the northeastern Japan forearc and demonstrated a close relationship between seismic activity and the geological structure of the overriding plate. Barbot (2020) constructed a two-dimensional rheological model for the northeastern Japan subduction zone. He showed that most of the partial ruptures of the megathrust are structurally controlled, and the model consistently explains the characteristics of historical earthquakes in the Miyagi segment, the slow-slip and foreshock preparatory phase of the 2011 Tohoku-oki earthquake, the large slip near the trench during the giant rupture, and essential features of its postseismic deformation. Shi et al. (2020) modeled a representative cross-section of the Nankai subduction zone offshore Shikoku Island, where the frictional behavior is dictated by the structure and composition of the overriding plate. They showed that mechanical interactions between neighboring fault segments and the impact from the long-term viscoelastic flow strongly modulate the recurrence pattern of earthquakes and slow-slip events. Miyake and Noda (2019) investigated the effect of viscoelasticity on the transition between seismogenic and aseismic behavior using a numerical simulation. Their results indicate that the transition associated with slow-slip events and tremors is dominated by changes in frictional properties rather than changes in viscoelastic properties.

Not only the large-scale heterogeneity mentioned above, but local to regional scale inhomogeneities will also affect the seismogenesis. Hisakawa et al. (2020) investigated the rupture process of the 2018 Hokkaido Eastern Iburi earthquake, Japan, by using dynamic rupture simulations to show that the observed complexity of the event can be explained primarily by the effect of non-planar fault geometry with multiple bends. Tsuda et al. (2019) estimated the velocity structure in the San-in district, southwestern Japan, using seismic travel-time tomography to find that the lower crust beneath the seismic belt showed lower velocities. They concluded that the seismic belt is generated because the lower crust beneath the belt is weak due to the high temperature in the eastern part and the water dehydrated from the Philippine Sea plate in the western part. Suemoto et al. (2020)

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derived a three-dimensional S-wave velocity model for the San-in area of southwest Japan using ambient noise data from a dense seismic network. In the resulting model, faults and a previously unrecognized tectonic boundary appeared as low-velocity anomalies or velocity boundaries, and the velocity anomalies were also associated with many past earthquake hypocenters.

Since earthquakes release the elastic strain energy accumulated in the plates, elastic strain estimation is crucial to assess large earthquakes' potential. However, inelastic deformation is also essential to understand the topography and stress concentration, both of which are strongly related to earthquakes. Fukuda et al. (2020) investigated cooling/denudation history in the northern part of the northeastern Japan arc using thermochronometry. The results indicate slow denudation rates in the fore-arc side and high rates in the Ou Backbone Range and on the back-arc side, similar to the southern part of the arc. Fukahata et al. (2020) successfully separated plastic/viscous deformation from the observed strain in the northern Niigata–Kobe Tectonic Zone (NKTZ), central Japan, using GNSS data before and after the 2011 Tohoku-oki earthquake. Their results indicate that the strain rate was exceptionally faster before the Tohoku-oki earthquake because of plastic strain, and the discrepancy between the geodetic and geologic strain rates is much smaller in most of the period. Otsubo et al. (2020) investigated the relationship between contractional deformation of sedimentary mass in the upper crust and the geodetic strain rate in a high-strain zone of the mid-Niigata region, central Japan, to find numerous examples of layer-parallel slip (bedding-plane slip) generated by folding. The results support an existing model, based on geodetic observations, of mechanical decoupling between the weak sedimentary layers and basement. Dojo and Hiramatsu (2019) analyzed the temporal variation in coda Q in the northeastern part of the NKTZ in central Japan. They found no statistically significant temporal variations in the spatial distribution of coda Q in the periods before and after the 2011 Tohoku-oki earthquake, which implies the existence of a persistent ductile deformation in the upper crust contributes essentially to the generation process of the high strain rate in the northeastern part of the NKTZ. Tamura et al. (2020) quantified the slip rate attributable to minor faults in the southeastern-central part of the NKTZ to the south of the Atotsugawa Fault, central Japan. Their results indicate that these minor faults contribute 4–24% of the total crustal strain in NKTZ. Meneses-Gutierrez and Nishimura (2020) analyzed GNSS data within the San-in Shear Zone, southwestern Japan, to clarify the width of the inelastic deformation zone in the lower crust beneath it. In eastern Tottori, the estimated inelastic zone's center coincides with the source region of the 1943 Tottori earthquake, while the inelastic zones are located just below the source regions of the 2000 Western and the 2016 Central Tottori earthquakes.

When an earthquake occurs, the shear stress on the fault must be larger than the strength. Thus, investigations of the stress concentration and strength reduction are essential to understand the earthquake generation process. Iio et al. (2020) investigated the temporal changes in the spatial distributions of hypocenters and focal mechanisms of aftershocks of the 2016 Central Tottori Prefecture earthquake, southwestern Japan, using the data from a dense temporary seismograph network. They concluded that the aftershock activity was controlled mainly by stress concentration rather than strength reduction due to high fluid pressure. Mitogawa and Nishimura (2020) calculated the temporal evolution of the Coulomb failure stress changes on the crustal faults in southwest Japan by utilizing viscoelastic modeling of megathrust earthquake cycles. They found that the large inland earthquakes before the megathrust earthquakes can be explained only when the apparent frictional coefficient is less than ~ 0.1. Kameda et al. (2019) demonstrated that the swelling pressure systematically increases with a decrease in sample porosity from experiments using the fault material, composed primarily of smectite, obtained by the IODP Expedition 343 JFAST program. The experiments suggest that the modified effective confining pressure of the fault is quite low or potentially zero, which means the fault may be intrinsically weak. In order to investigate the stress in the seismogenic zones, we need a great many focal mechanisms. Hara et al. (2019) developed a model of the convolutional neural networks (CNNs) to determine P-wave first-motion polarities of observed seismic waveforms automatically. They found that the accuracies of the CNN models were generally high (≳95%) and that regional dependence was insignificant.

Among all the possible causes of strength reduction, an increase in the pore fluid pressure is the most probable candidate. In and around many fault zones, Sibson (2020) found many geological and geophysical characteristics that support his "fault-valve" model, especially in compressional–transpressional tectonic regimes, which are better at containing overpressure and are 'load-strengthening' (mean stress rising with increasing shear stress). Maeda et al. (2019) investigated the focal mechanisms of aftershocks of the 2008 Iwate–Miyagi Nairiku earthquake (M 7.2) in the northeastern Japan arc and detailed Vp/Vs structure there. They concluded that exceptional N–S compressional aftershocks occurred in regions with low strength due to the high pore pressure and with N–S compressional stress caused by the stress change due to the mainshock in a low differential stress regime. Matsumoto et al. (2020) investigated inelastic strain decay rates using aftershock moment tensor data obtained from dense seismic observations in the focal area of the 2000 M7.3 Western Tottori earthquake, southwestern Japan. They found an increase in the spatial variations in the inelastic strain rate, and they concluded that the decay in the inelastic strain rate is mainly controlled by a power-law fluid and slow decay in some regions might be attributed to aseismic slip. Amezawa et al. (2019) found distinct scattered wave packets (DSW) in the waveforms of S-coda from earthquakes around the Moriyoshi-zan volcano in the northeastern Japan arc. Since the DSW origin is located between the large cluster of earthquakes and a low-velocity zone, they concluded that the DSW origin was composed of geofluid accumulated midway in the upward fluid movement from the low-velocity zone to the earthquake cluster. Hutapea et al. (2020) developed a continuous monitoring system of the seismic velocity of the Japanese Islands using seismic interferometry. The system clearly shows spatiotemporal seismic velocity changes that could be related to pore pressure and/or magma variations.

As mentioned above, fluids can be the most responsible for reducing the fault strength. In order to model the strength reduction, however, we have to understand the detailed characteristics of fluids. Kusuhara et al. (2020) showed that the isotopic characteristics of brine samples from the Kashio mineral spring, central Japan, indicated that the Kashio brine could have originated from fluids dehydrated from the Philippine Sea slab as well as the Arima hot spring, located at 250 km west of the Kashio. They evaluated the chemical difference between those two springs with the depths of the subducting Philippine Sea slab and also possible interaction with crustal rocks above it. Koizumi et al. (2019) analyzed daily streamflow data collected in regions with strong ground motion during the 2016 Kumamoto earthquake. They concluded that the postseismic hydrological changes were caused mainly by earthquake-induced surface phenomena and little contribution from a hydrothermal fluid. Sato et al. (2020) investigated long-term hot spring discharge triggered by the 2011 Mw 6.6 Iwaki earthquake, northeastern Japan, and they concluded that such long-term discharge might be explained by the rise of thermal water from the deep part and the permeability changes along the hot spring channels. Fukuda and Shimizu (2019) investigated variation in water contents in quartz in the Sanbagawa Metamorphic Belt, Japan. Using an infrared spectroscopic mapping technique, they measured the quartz's water contents to be 40–310 ppm. The lowest values were obtained for large quartz grains in the high-grade metamorphic zones. They speculated that relatively high water contents in the lowest metamorphic grade zone reflect grain-boundary water. Kuwatani and Toriumi (2020) developed a kinetic model that illustrates the relative roles of intergranular diffusion and surface reactions in overall metamorphic net-transfer reactions involving solid solutions. Their conceptual model can be extended to capture more complex behaviors of metamorphic reactions in natural systems. Watanabe et al. (2019) conducted elastic wave velocity and electrical conductivity measurements in a brine-saturated granitic rock sample in the laboratory. Electron microscopic observation of pores in the sample showed remarkable variation in the aperture of each crack. At high pressures, narrow aperture parts are closed while wide aperture parts are still open to maintain conduction paths, explaining the variations in the seismic wave velocity and electrical conductivity observed in the field.

Abbreviations

CNN: Convolutional Neural Networks; DSW: Distinct scattered wave packets; GNSS: Global Navigation Satellite System; IODP: Integrated Ocean Drilling Program; JFAST: Japan trench FAST drilling project; NKTZ: Niigata–Kobe Tectonic Zone.

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Authors' contributions

All authors of this article are guest editors for this special issue. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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Publisher's Note

FRONTIER LETTER **Open Access**

Frictional and structural controls of seismic super-cycles at the Japan trench

Sylvain Barbot

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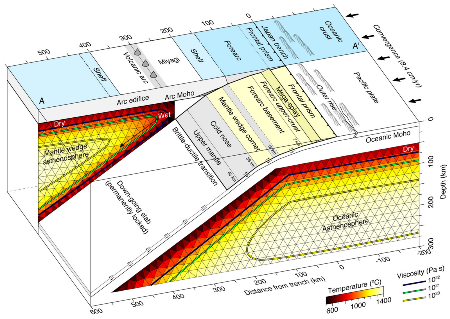
Abstract

The diverse mechanical behaviors of subduction zones during the seismic cycle emerge from the nonlinear dynamics of a complex mechanical system with interacting brittle and ductile deformation. The 2011 Tohoku mega-quake represents the culmination of a super-cycle of partial and full ruptures of the plate interface, but the physical controls on the down-dip segmentation of the megathrust remain unclear. Here, we propose a two-dimensional rheological model of the Japan trench to explain the variability of earthquake size at the Miyagi section, in northern Honshu, during the last century. We simulate seismicity in a continuum with a physics-based rate- and state-dependent constitutive law for fault slip, producing aperiodic earthquake sequences with a power-law distribution of rupture sizes. Although some partial ruptures of the megathrust are the result of self-emergent behavior, others are structurally controlled. The 1978 and 2005 Mj ~ 7 interplate earthquakes took place in a metamorphic belt in the mantle wedge corner bounded up-dip by the arc Moho that constitutes a permanent structural boundary. We explain the succession of the great 1981 Mw = 7.1 and 2003 Mw = 6.9 earthquakes within the forearc and the 2011 giant earthquake as the natural response of a large continuously velocity-weakening fault with a small nucleation size. The shallow segment below the frontal prism only slips in giant through-going ruptures that unzip the whole velocity-weakening interface. The model consistently explains the size, recurrence time, and hypocenter location of historical earthquakes in the Miyagi segment, the slow-slip and foreshock preparatory phase of the 2011 Tohoku earthquake, the large slip near the trench during the giant rupture, and important features of its postseismic deformation. The complex patterns of seismicity at the Japan trench can be better understood by assimilating geological and geophysical observations at various periods of the seismic cycle within an explicative physical framework.

Keywords: Friction, Rheology, Subduction Zone, Seismic cycle, Japan trench



Graphical abstract

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FULL PAPER **Open Access**

Temporal stability of coda *Q* in the northeastern part of an inland high strain rate zone, central Japan: implication of a persistent ductile deformation in the crust

Masanobu Dojo and Yoshihiro Hiramatsu*

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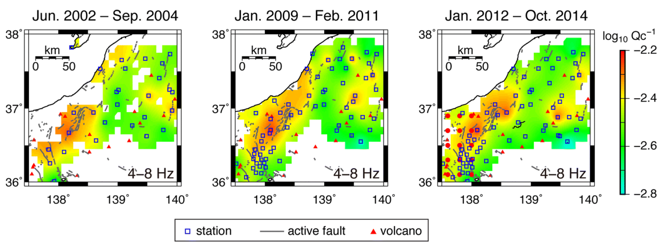
Abstract

We have analyzed the temporal variation in coda *Q* in the northeastern part of an inland high strain rate zone, the Niigata–Kobe Tectonic Zone (NKTZ), in central Japan, to investigate the response of coda *Q* to the modification of the strain field induced by the 2011 Tohoku earthquake (Mw 9.0). We observe no statistically significant temporal variations in the spatial distribution of coda *Q* as the whole analyzed area, implying that the crustal deformation induced by the 2011 Tohoku earthquake has provided no significant temporal variation in crustal heterogeneity as the whole analyzed area. For the middle frequency bands, before and after the 2011 Tohoku earthquake, we have commonly found a negative correlation between the spatial distributions of coda *Q* and the differential strain rate and a positive correlation between the spatial distributions of coda *Q* and the perturbation of S-wave velocity in the upper crust. These features, together with previous works, suggest that the ductile deformation with a high rate in the upper crust plays an important role in generating the high strain rate in the analyzed area not only before but also after the 2011 Tohoku earthquake. In other words, the existence of a persistent ductile deformation in the upper crust contributes essentially to the generation process of the high strain rate in the northeastern part of the NKTZ. It is important to note that the location of the persistent ductile deformation in the northeastern part of the NKTZ, mainly in the upper crust, differs from that in the central part of the NKTZ, mainly in the lower crust.

Keywords: Niigata–Kobe Tectonic Zone, Heterogeneity, Aseismic deformation, The 2011 Tohoku earthquake



Graphical abstract

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FULL PAPER **Open Access**

Causes of the N–S compressional aftershocks of the E–W compressional 2008 Iwate–Miyagi Nairiku earthquake (M7.2) in the northeastern Japan arc

Sumire Maeda*, Toru Matsuzawa, Keisuke Yoshida, Tomomi Okada and Takeyoshi Yoshida

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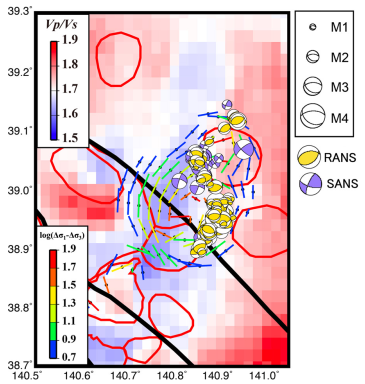
Abstract

In this study, we investigated the influence of local structural heterogeneities on aftershocks of the 2008 Iwate–Miyagi Nairiku earthquake (M 7.2) that occurred in the northeastern Japan arc. Although this area is characterized by an E–W compressional thrust faulting stress regime, many N–S compressional thrust-type and strike-slip-type earthquakes were also observed in the aftershock activity of the 2008 event. The occurrence of such N–S compressional aftershocks indicates that the differential stress was very low before the main shock. We investigated V_p/V_s structure in the aftershock area in detail to find most of the area showed V_p/V_s as low as less than 1.70, which is consistent with the previous studies. Our result shows, however, the aftershock area was dotted with high V_p/V_s small areas, which suggests the locations of abundant fluid-filled cracks. The comparison of the distributions of V_p/V_s, the stress changes due to the mainshock, and focal mechanisms of the aftershocks indicate that the N–S compressional aftershocks are concentrated in regions with high V_p/V_s and large N–S compressional stress change. From these results, we concluded that the N–S compressional aftershocks occurred in regions with low strength due to the high pore pressure and with N–S compressional stress caused by the stress change due to the mainshock in a low differential stress regime.

Keywords: Microearthquakes, Stress field, Heterogeneous structure, Fluid, Geological structure



Graphical abstract

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FULL PAPER **Open Access**

P-wave first-motion polarity determination of waveform data in western Japan using deep learning

Shota Hara*, Yukitoshi Fukahata and Yoshihisa Iio

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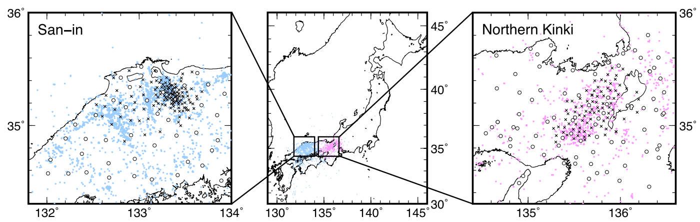
Abstract

P-wave first-motion polarity is the most useful information in determining the focal mechanisms of earthquakes, particularly for smaller earthquakes. Algorithms have been developed to automatically determine P-wave first-motion polarity, but the performance level of the conventional algorithms remains lower than that of human experts. In this study, we develop a model of the convolutional neural networks (CNNs) to determine the P-wave first-motion polarity of observed seismic waveforms under the condition that P-wave arrival times determined by human experts are known in advance. In training and testing the CNN model, we use about 130 thousand 250 Hz and about 40 thousand 100 Hz waveform data observed in the San-in and the northern Kinki regions, western Japan, where three to four times larger number of waveform data were obtained in the former region than in the latter. First, we train the CNN models using 250 Hz and 100 Hz waveform data, respectively, from both regions. The accuracies of the CNN models are 97.9% for the 250 Hz data and 95.4% for the 100 Hz data. Next, to examine the regional dependence, we divide the waveform data sets according to the observation region, and then we train new CNN models with the data from one region and test them using the data from the other region. We find that the accuracy is generally high ($\gtrsim$ 95%) and the regional dependence is within about 2%. This suggests that there is almost no need to retrain the CNN model by regions. We also find that the accuracy is significantly lower when the number of training data is less than 10 thousand, and that the performance of the CNN models is a few percentage points higher when using 250 Hz data compared to 100 Hz data. Distribution maps, on which polarities determined by human experts and the CNN models are plotted, suggest that the performance of the CNN models is better than that of human experts.

Keywords: Machine learning, Convolutional neural network, P-wave first-motion polarity



Graphical abstract

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FULL PAPER **Open Access**

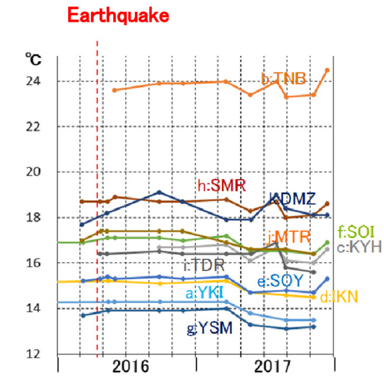
Hydrological changes after the 2016 Kumamoto earthquake, Japan

Naoji Koizumi*, Shinsuke Minote, Tatsuya Tanaka, Azumi Mori, Takumi Ajiki, Tsutomu Sato, Hiroshi A. Takahashi and Norio Matsumoto

Earth, Planets and Space 2019, **71**:128 DOI: 10.1186/s40623-019-1110-y
Received: 2 August 2019, Accepted: 16 November 2019, Published: 29 November 2019

Abstract

The 2016 Kumamoto earthquake, whose main shock was an M7.3 event on April 16, 2016, 28 h after a foreshock of M6.5, caused severe damage in and around Kumamoto Prefecture, Japan. It also caused postseismic hydrological changes in Kumamoto Prefecture. In this study, we analyzed daily streamflow data collected by eight observation stations from 2001 to 2017 in regions that experienced strong ground motion during the 2016 Kumamoto earthquake. We also surveyed 11 water springs in the region several times after the main shock. Streamflow had no or slight change immediately after the earthquake; however, large increases were recorded at some of the eight stations following a heavy rainfall that occurred 2 months after the earthquake. A decrease in the water-holding capacity of the catchment caused by earthquake-induced landslides can explain this delayed streamflow increase. Conversely, earthquake-related changes to the spring flow rate were not so clear. Water temperature and chemical composition of spring waters were also hardly changed. Only the concentration of NO_3^-, which is usually considered to be supplied from the surface, changed slightly just after the earthquake. These results show that the postseismic hydrological changes were caused mainly by earthquake-induced surface phenomena and that there was little contribution from hydrothermal fluid.



Water temperature at the springs

Graphical abstract

Keywords: Kumamoto earthquake, Hydrological changes, Streamflow, Spring, Groundwater, Water-holding capacity

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FULL PAPER **Open Access**

Elastic wave velocity and electrical conductivity in a brine-saturated rock and microstructure of pores

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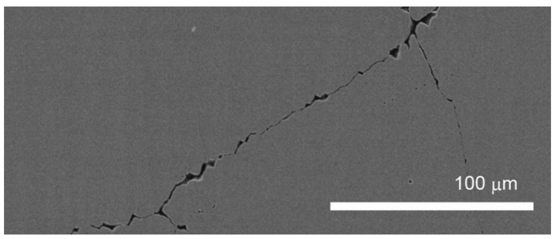
Earth, Planets and Space 2019, **71**:129 DOI: 10.1186/s40623-019-1112-9
Received: 29 July 2019, Accepted: 21 November 2019, Published: 29 November 2019

Abstract

Elastic wave velocity and electrical conductivity in a brine-saturated granitic rock were measured under confining pressures of up to 150 MPa and microstructure of pores was examined with SEM on ion-milled surfaces to understand the pores that govern electrical conduction at high pressures. The closure of cracks under pressure causes the increase in velocity and decrease in conductivity. Conductivity decreases steeply below 10 MPa and then gradually at higher pressures. Though cracks are mostly closed at the confining pressure of 150 MPa, brine must be still interconnected to show observed conductivity. SEM observation shows that some cracks have remarkable variation in aperture. The aperture varies from ~ 100 nm to ~ 3 μm along a crack. FIB–SEM observation suggests that wide aperture parts are interconnected in a crack. Both wide and narrow aperture parts work parallel as conduction paths at low pressures. At high pressures, narrow aperture parts are closed but wide aperture parts are still open to maintain conduction paths. The closure of narrow aperture parts leads to a steep decrease in conductivity, since narrow aperture parts dominate cracks. There should be cracks in various sizes in the crust: from grain boundaries to large faults. A crack must have a variation in aperture, and wide aperture parts must govern the conduction paths at depths. A simple tube model was employed to estimate the fluid volume fraction. The fluid volume fraction of 10^{-4}–10^{-3} is estimated for the conductivity of 10^{-2} S/m. Conduction paths composed of wide aperture parts are consistent with observed moderate fluctuations (< 10%) in seismic velocity in the crust.



Graphical abstract

Keywords: Electrical conductivity, Seismic velocity, Fluid, Crack, Crust

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FULL PAPER **Open Access**

Fault weakening caused by smectite swelling

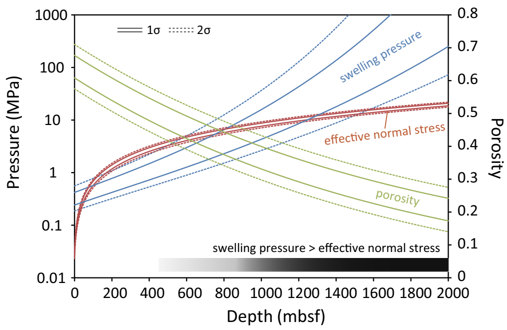
Jun Kameda*, Masaoki Uno, Marianne Conin, Kohtaro Ujiie, Yohei Hamada and Gaku Kimura

Earth, Planets and Space 2019, **71**:131 DOI: 10.1186/s40623-019-1108-5
Received: 25 June 2019, Accepted: 12 November 2019, Published: 2 December 2019

Abstract

The large slip along the shallow subduction interface during the 2011 Tohoku-Oki earthquake (M_w9.0) caused a huge tsunami that struck the northeast coast of Honshu, Japan. The Integrated Ocean Drilling Program Expedition 343 JFAST program revealed that the fault zone is composed primarily of smectite. Our swelling experiments using the fault material demonstrated that the swelling pressure systematically increases with a decrease in sample porosity. Based on in situ porosity estimations in the IODP borehole, the swelling pressure of the fault is as high as 8 MPa, which is comparable to the effective normal stress at the drill site (~ 7 MPa). This also suggests that the modified effective confining pressure of the fault is quite low or potentially zero, meaning that fault strength is governed mainly by cohesion rather than frictional strength. The fault may therefore be intrinsically weak, which could enhance the coseismic displacement toward the trench when earthquake slip propagates from depth.

Keywords: 2011 Tohoku-Oki earthquake, Fault strength, Smectite, Swelling



Graphical abstract

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FULL PAPER **Open Access**

Temporal changes in the distinct scattered wave packets associated with earthquake swarm activity beneath the Moriyoshi-zan volcano, northeastern Japan

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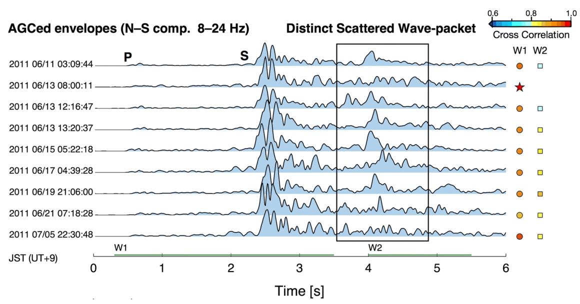
Received: 1 July 2019, Accepted: 23 November 2019, Published: 2 December 2019

Abstract

We investigated temporal changes in the waveforms of S-coda from triggered earthquakes around the Moriyoshi-zan volcano in northeastern Japan. Seismicity in the area has drastically increased after the 2011 off the Pacific coast of Tohoku earthquake, forming the largest cluster to the north of the volcano. We analyzed distinct scattered wave packets (DSW) that are S-to-S scattered waves from the mid-crust and appeared predominantly at the high frequency range. We first investigated the variation of DSW for event groups with short inter-event distances and high cross-correlation coefficients (CC) in the time window of direct waves. Despite the above restriction, DSW showed temporal changes in their amplitudes and shapes. The change occurred gradually in some cases, but temporal trends were much more complicated in many cases. We also found that the shape of DSW changed in a very short period of time, for example, within ~ 12 h. Next, we estimated the location of the origin of the DSW (DSW origin) by applying the semblance analysis to the data of the temporary small-aperture array deployed to the north of the largest cluster of triggered events. The DSW origin is located between the largest cluster within which hypocentral migration had occurred and the low-velocity zone depicted by a tomographic study. This spatial distribution implies that the DSW origin was composed of geofluid-accumulated midway in the upward fluid movement from the low-velocity zone to the earthquake cluster. Though we could not entirely exclude the possibility of the effect of the event location and focal mechanisms, the temporal changes in DSW waveforms possibly reflect the temporal changes in scattering properties in and/or near the origin. The quick change in DSW waveforms implies that fast movement of geofluid can occur at the depth of the mid-crust.

Keywords: Coda waves, Scattering, Triggered earthquakes, Seismic swarm, Geofluid, The 2011 off the Pacific coast of Tohoku earthquake



Graphical abstract

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FULL PAPER **Open Access**

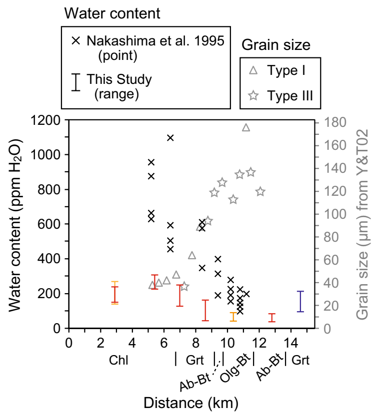
Water distribution in quartz schists of the Sanbagawa Metamorphic Belt, Japan: infrared spectroscopic mapping and comparison of the calibrations proposed for determining water contents

Jun-ichi Fukuda* and Ichiko Shimizu

Earth, Planets and Space 2019, **71**:136 DOI: 10.1186/s40623-019-1117-4
Received: 16 August 2019, Accepted: 23 November 2019, Published: 5 December 2019

Abstract

We evaluated water distributions in deformed quartz in schists along the Asemi River, Central Shikoku, in the Sanbagawa Metamorphic Belt, Japan, using infrared spectroscopic (IR) mapping. The water trapped in quartz as molecular H_2O showed a broad IR absorption band at 2800–3750 cm^{-1}. A necessary step before assessing the quartz water content was to evaluate and compare six previously proposed IR calibrations in terms of the molar absorption coefficients of H_2O (L/mol H_2O cm^2). The coefficients vary from 24,100 to 89,000 L/mol H_2O cm^2, and the values of the coefficients show a rough increase with increasing component of structural –OH in the IR spectra. We used Paterson's calibration, which does not require input regarding the mineral species, but which was modified in his paper for measurements of molecular H_2O in quartz. The absorption coefficient is 38,000 L/mol H_2O cm^2. IR mapping was performed on Sanbagawa metamorphic rocks with increasing grades of metamorphism, where the mean grain size of quartz increases from ~40 to ~120 μm. The absorption bands that are only from the quartz can be distinguished on the basis of microstructural observations and the corresponding mapping results. The IR spectra of quartz commonly show dominant molecular H_2O bands at 2800–3750 cm^{-1} with no additional bands associated with crystalline –OH when only quartz is measured. The water contents of quartz in all our samples were 40–310 ppm, and these values are about one-third of previously reported values measured using point analyses with the unified Paterson's calibration. This difference seems to reflect the incorporation of phyllosilicates in previous measurements that showed a broad band around 3600 cm^{-1}. The lowest and highest water contents in our quartz samples are associated with intragranular water and grain boundary water, respectively. We estimated the grain boundary widths to be at most ~10 nm on the basis of the water contents at grain boundaries.



Graphical abstract

Keywords: Quartz, Water content, Infrared spectroscopy, Calibration, Sanbagawa Metamorphic Belt

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FULL PAPER **Open Access**

Fully dynamic earthquake sequence simulation of a fault in a viscoelastic medium using a spectral boundary integral equation method: does interseismic stress relaxation promote aseismic transients?

Yuki Miyake and Hiroyuki Noda*

Earth, Planets and Space 2019, **71**:137 DOI: 10.1186/s40623-019-1113-8
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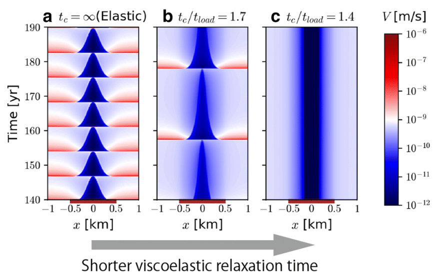
Abstract

Along subduction interfaces or some major faults, a seismogenic layer in the upper crust is underlain by a zone of slow-slip events (SSEs) and tremors, and seismicity disappears at greater depths. The transition between seismogenic and aseismic behavior may be caused by changes in the frictional properties of the fault or changes in viscoelastic properties of the surrounding medium. Although aseismic transients have been numerically generated in previous studies by changing the frictional properties and compared to SSEs, the effect of viscoelasticity on the transition remains to be studied. In this study, we implemented interseismic viscoelastic stress relaxation in a simulation code for two-dimensional antiplane fully dynamic earthquake sequences in a uniform elastic material based on a spectral boundary integral equation method. In the implementation, we developed a suitable algorithm in which the viscoelastic relaxation is calculated by evolution of an "effective slip," which gives viscoelastic stress change on the fault if convolved with a static Green's function. We conducted parametric studies for a fault with a rate-weakening patch on two parameters: viscoelastic relaxation time t_c and characteristic length of the state evolution in the rate- and state-dependent friction law L. The behavior of the simulated fault can be classified into four classes, earthquakes (EQ), aseismic transients (AT), stable sliding (SS), and stuck (ST), in which the central part of the rate-weakening patch has a diminishingly small slip rate and is permanently locked. A phase diagram of the fault behavior shows that there are two different types of seismogenic–aseismic transition. As L increases, an EQ patch changes to an AT patch before becoming an SS patch, as has been reported in previous studies in an elastic limit. The boundary between AT and SS can be explained via linear stability analysis of a system composed of a spring, a dashpot, and sliders. As t_c decreases, the recurrence interval of the earthquakes diverges, and an EQ patch changes to an ST patch unless L is within a narrow range. Therefore, the transition associated with SSEs and tremors is dominated by changes in frictional properties rather than changes in viscoelastic properties.



Graphical abstract

Keywords: Earthquake sequence simulation, Viscoelasticity, Spectral boundary integral equation method, Memory variable method

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FULL PAPER **Open Access**

Contribution to crustal strain accumulation of minor faults: a case study across the Niigata–Kobe Tectonic Zone, Japan

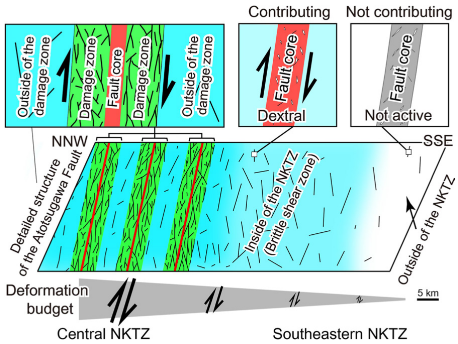
Tomonori Tamura*, Kiyokazu Oohashi, Makoto Otsubo, Ayumu Miyakawa and Masakazu Niwa

Earth, Planets and Space 2020, **72**:7 DOI: 10.1186/s40623-020-1132-5
Received: 3 October 2019, Accepted: 8 January 2020, Published: 20 January 2020

Abstract

Recent global navigation satellite system (GNSS) data for the Japanese Islands have revealed a high-strain-rate region suggesting the existence of a region of broad-scale crustal deformation. The Niigata–Kobe Tectonic Zone (NKTZ), which is the high-strain-rate zone in central Japan, shows a short-term dextral strain rate of ~12 mm/year. The total slip rate of the Quaternary fault zones in the NKTZ has been estimated as ~6.7 mm/year, accounting for just over half the short-term strain rate of the zone. However, this slip rate underestimates the total slip rate on faults within the NKTZ owing to possible distributed deformation on minor faults. This study quantifies the slip rate attributable to these other faults in the southeastern-central NKTZ and reveals the unique deformation structure across the high-strain-rate zone, which comprises a Quaternary fault core, a Quaternary fault damage zone, an incipient brittle shear zone (active background), and an inactive background. The spatial characteristics of the incipient brittle shear zone can be explained in terms of fault density, which increases toward the central NKTZ. Minor faults located >500 m from major Quaternary faults but within the NKTZ have sense of shear consistent with that of the major faults. In contrast, minor faults outside of the NKTZ show sense of shear that differ from the dextral displacement of the high-strain-rate zone and do not contribute to the slip rate of the zone. The total slip rate of minor faults in the southeastern-central NKTZ is estimated to be 0.46–2.88 mm/year (roughly equal to a major Quaternary fault in the zone), which implies 4–24% of crustal strain is stored in the active background.

Keywords: Niigata–Kobe Tectonic Zone, Strain-rate paradox, Minor faults, Brittle shear zone, Slip rate



Graphical abstract

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FULL PAPER **Open Access**

Simple kinetic model for replacement reactions involving solid solutions: the significant role of geofluids

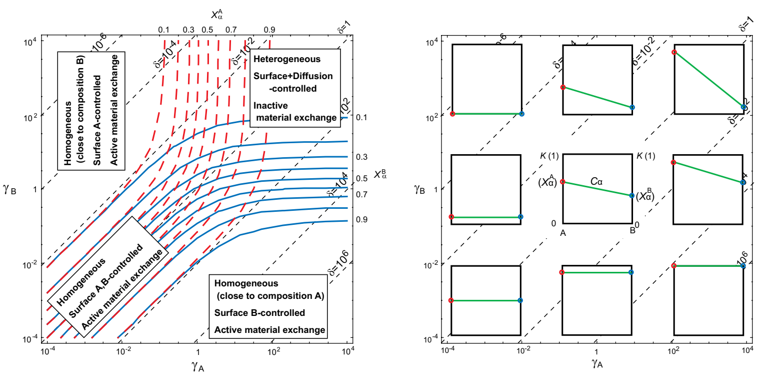
Tatsu Kuwatani* and Mitsuhiro Toriumi

Earth, Planets and Space 2020, **72**:8 DOI: 10.1186/s40623-020-1135-2
Received: 29 August 2019, Accepted: 15 January 2020, Published: 3 February 2020

Abstract

We develop a kinetic model that illustrates the relative role of intergranular diffusion and surface reactions in overall metamorphic net-transfer reactions involving solid solutions. The behavior and state of the system were observed to depend on the non-dimensional parameter(s), defined herein by $\gamma \equiv (k \cdot L \cdot K^{n-1})/D^{\mathrm{eff}}$, where k denotes the dissolution rate constant of the mineral, L denotes the distance between the two minerals participating in the reaction, K denotes the coefficient of the equilibrium abundance ratio of the precipitated component in the intergranular fluid to those in the mineral, n denotes the order of the dissolution reaction, and D^{eff} denotes the effective diffusion coefficient of the precipitated component in the intergranular fluid. When γ is small, the system becomes homogeneous, which is controlled by the surface reaction. In contrast, a large γ implies a heterogeneous system controlled by both surface reaction and diffusion. Geofluid is among the most important influencers of kinetic regimes and reaction textures in metamorphic and metasomatic rocks because the intergranular fluid distribution considerably affects the intergranular diffusivity (D^{eff}). Our conceptual model can potentially reveal the nature of the reaction kinetics and the fluid–rock interactions and capture the complex behaviors of natural systems in future extensions.

Keywords: Kinetics, Fluid–rock interaction, Solid solution, Geofluids, Metasomatism



Graphical abstract

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FULL PAPER Open Access

Identification of a nascent tectonic boundary in the San-in area, southwest Japan, using a 3D S-wave velocity structure obtained by ambient noise surface wave tomography

Yudai Suemoto, Tatsunori Ikeda, Takeshi Tsuji* and Yoshihisa Iio

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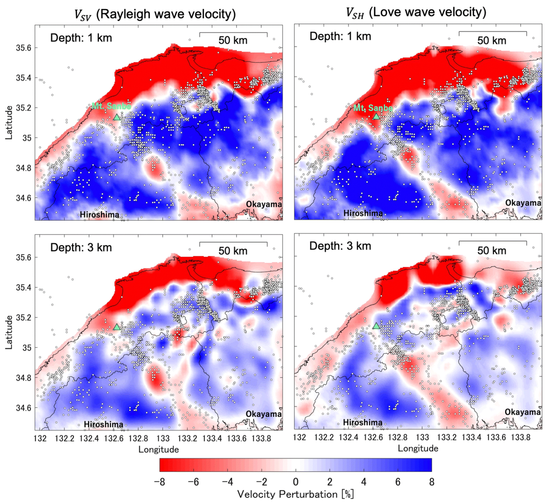
Abstract

We derived a three-dimensional S-wave velocity model for the San-in area of southwest Japan to examine heterogeneous structures such as tectonic faults. Many earthquakes occur in this area, but much of the activity has been relatively recent, so the fault distribution has yet to be fully clarified. Here, we used continuous ambient noise data from a dense seismic network, deployed from November 2009 to extract Rayleigh and Love wave dispersion data between station pairs, and then applied a direct surface wave inversion to the phase velocities of each station pair to determine a three-dimensional S-wave velocity model. In the resulting model, faults and a previously unrecognized tectonic boundary appeared as low-velocity anomalies or velocity boundaries, and the velocity anomalies were also associated with many past earthquake hypocenters. These results contribute to our understanding of heterogeneous structures caused by recent tectonic motion and of possible future tectonic activity, such as intraplate earthquakes. Surface wave tomography using ambient noise recorded in dense seismic networks could also be applied in other parts of the world to reveal new heterogeneous geological structures (i.e., unrevealed tectonic faults) and could contribute to disaster mitigation.

Keywords: Ambient noise, Surface wave tomography, Nascent tectonic boundary, 2000 western Tottori earthquake, San-in shear zone



Graphical abstract

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FULL PAPER Open Access

Detection of plastic strain using GNSS data of pre- and post-seismic deformation of the 2011 Tohoku-oki earthquake

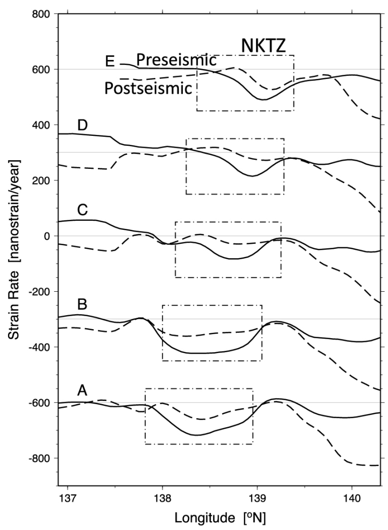
Yukitoshi Fukahata*, Angela Meneses-Gutierrez and Takeshi Sagiya

Earth, Planets and Space 2020, **72**:18 DOI: 10.1186/s40623-020-1144-1
Received: 30 August 2019, Accepted: 24 January 2020, Published: 13 February 2020

Abstract

In general, there are three mechanisms causing crustal deformation: elastic, viscous, and plastic deformation. The separation of observed crustal deformation to each component has been a challenging problem. In this study, we succeed in separating plastic deformation as well as viscous deformation in the northern Niigata–Kobe Tectonic Zone (NKTZ), central Japan, using GNSS data before and after the 2011 Tohoku-oki earthquake, under the assumptions that elastic deformation is principally caused by the plate coupling along the Japan trench and that plastic deformation ceased after the Tohoku-oki earthquake due to the stress drop caused by the earthquake. The cessation of plastic deformation can be understood with the concept of stress shadow used in the field of seismic activity. The separated strain rates are about 30 nanostrain/year both for the plastic deformation in the preseismic period and for the viscous deformation in both the pre- and post-seismic periods, which means that the inelastic strain rate in the northern NKTZ is about 60 and 30 nanostrain/year in the pre- and post-seismic periods, respectively. This result requires the revision of the strain-rate paradox in Japan. The strain rate was exceptionally faster before the Tohoku-oki earthquake due to the effect of plastic strain, and the discrepancy between the geodetic and geologic strain rates is much smaller in usual time, when the plastic strain is off. In order to estimate the onset timing of plastic deformation, the information on stress history is essentially important.

Keywords: Plastic strain, Inelastic strain, NKTZ, Tohoku-oki earthquake, ΔCFF, Strain-rate paradox



Graphical abstract

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FULL PAPER **Open Access**

(U–Th)/He thermochronometric mapping across the northeast Japan Arc: towards understanding mountain building in an island-arc setting

Shoma Fukuda*, Shigeru Sueoka, Barry P. Kohn and Takahiro Tagami

Earth, Planets and Space 2020, **72**: 24 DOI: 10.1186/s40623-020-01151-z
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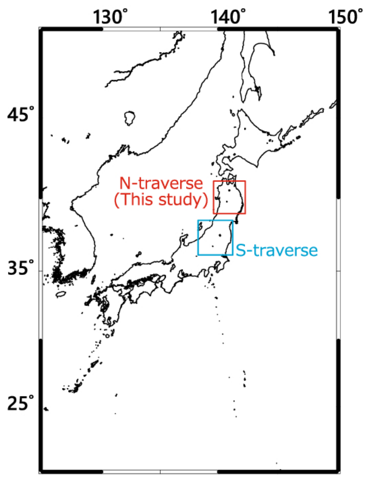
Abstract

Topographic relief in arc-trench systems is thought to be formed by plate subduction; however, few quantitative investigations have so far been reported, with respect to the related mountain building process. This study applies apatite and zircon (U–Th)/He thermochronometry (AHe, ZHe, respectively) to Cretaceous granite rocks in the north part of the northeast (NE) Japan Arc to reveal its cooling/denudation history. Weighted mean AHe ages ranging from 88.6 to 0.9 Ma and ZHe ages from 83.9 to 7.4 Ma were determined for 10 rock samples. Using the AHe data, denudation rates were obtained for each sample. On the fore-arc side, denudation rates of < 0.05 mm/year were calculated, indicating a slow denudation process since the Paleogene. However, in the Ou Backbone Range and on the back-arc side, denudation rates at > 0.1–1.0 mm/year were computed, probably reflecting a recent uplift event since ~ 3–2 Ma. These data indicate a clear contrast in thermal and denudation histories between the tectonic units in this study area, similar to that previously reported from the southern part of NE Japan Arc. A comparison of the thermal/denudation histories between the N- and S- traverses, revealed the arc-parallel trend, the uplift model of the volcanic arc, and some minor variations of thermal/denudation histories in each tectonic unit. This study offers some further insights into the understanding of tectonic processes in an island-arc setting.



Graphical abstract

Keywords: Low-temperature thermochronology, Arc-trench system, Northeast Japan Arc, (U–Th)/He thermochronometry, Thermal/denudation histories

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FULL PAPER **Open Access**

Structural control and system-level behavior of the seismic cycle at the Nankai Trough

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Earth, Planets and Space 2020: **72**:27 DOI: 10.1186/s40623-020-1145-0
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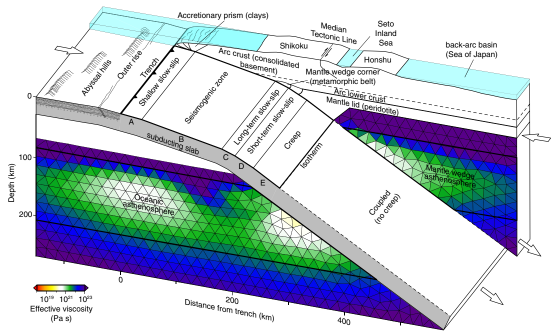
Abstract

The Nankai Trough in Southwest Japan exhibits a wide spectrum of fault slip, with long-term and short-term slow-slip events, slow and fast earthquakes, all associated with different segments down the plate interface. Frictional and viscous properties vary depending on rock type, temperature, and pressure. However, what controls the down-dip segmentation of the Nankai subduction zone megathrust and how the different domains of the subduction zone interact during the seismic cycle remains unclear. Here, we model a representative cross-section of the Nankai subduction zone offshore Shikoku Island where the frictional behavior is dictated by the structure and composition of the overriding plate. The intersections of the megathrust with the accretionary prism, arc crust, metamorphic belt, and upper mantle down to the asthenosphere constitute important domain boundaries that shape the characteristics of the seismic cycle. The mechanical interactions between neighboring fault segments and the impact from the long-term viscoelastic flow strongly modulate the recurrence pattern of earthquakes and slow-slip events. Afterslip penetrates down-dip and up-dip into slow-slip regions, leading to accelerated slow-slip cycles at depth and long-lasting creep waves in the accretionary prism. The trench-ward migrating locking boundary near the bottom of the seismogenic zone progressively increases the size of long-term slow-slip events during the interseismic period. Fault dynamics is complex and potentially tsunami-genic in the accretionary region due to low friction, off-fault deformation, and coupling with the seismogenic zone.



Graphical abstract

Keywords: Friction, Rheology, Subduction zones

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FULL PAPER Open Access

Preparation zones for large crustal earthquakes consequent on fault-valve action

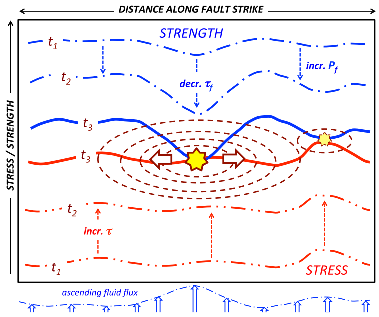
Richard H. Sibson

Earth, Planets and Space 2020, **72**:31 DOI: 10.1186/s40623-020-01153-x
Received: 25 August 2019, Accepted: 18 February 2020, Published: 4 March 2020

Abstract

A combination of geological evidence (in the form of hydrothermal vein systems in exhumed fault systems) and geophysical information around active faults supports the localized invasion of near-lithostatically overpressured aqueous fluids into lower portions of the crustal seismogenic zone which commonly extends to depths between 10 and 20 km. This is especially the case for compressional–transpressional tectonic regimes which, beside leading to crustal thickening and dewatering through prograde metamorphism, are also better at containing overpressure and are 'load-strengthening' (mean stress rising with increasing shear stress), the most extreme examples being associated with areas undergoing active compressional inversion where existing faults are poorly oriented for reactivation. In these circumstances, 'fault-valve' action from ascending overpressured fluids is likely to be widespread with fault failure *dual-driven* by a combination of rising fluid pressure in the lower seismogenic zone lowering fault frictional strength, as well as rising shear stress. Localized fluid overpressuring nucleates ruptures at particular sites, but ruptures on large existing faults may extend well beyond the regions of intense overpressure. Postfailure, enhanced fracture along fault rupture zones promotes fluid discharge through the aftershock period, increasing fault frictional strength before hydrothermal sealing occurs and overpressures begin to reaccumulate. The association of rupture nucleation sites with local concentrations of fluid overpressure is consistent with selective invasion of overpressured fluid into the roots of major fault zones and with observed non-uniform spacing of major hydrothermal vein systems along exhumed brittle–ductile shear zones. A range of seismological observations in compressional–transpressional settings are compatible with this hypothesis. There is a tendency for large crustal earthquakes to be associated with extensive ($L \sim 100$–200 km) low-velocity zones in the lower seismogenic crust, with more local *Vp*/*Vs* anomalies ($L \sim 10$–30 km) associated with rupture nucleation sites. In some instances, these low-velocity zones also exhibit high electrical conductivity. Systematic, rigorous evaluation is needed to test how widespread these associations are in different tectonic settings, and to see whether they exhibit time-dependent behaviour before and after major earthquake ruptures.

Keywords: Compressional–transpressional faulting, Fluid overpressures, Gold transport, Lower seismogenic zone, Dual-driven failure, Fault-valve action, Low-velocity zones, *Vp*/*Vs* anomalies



Graphical abstract

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FULL PAPER Open Access

Dynamic rupture simulation of 2018, Hokkaido Eastern Iburi earthquake: role of non-planar geometry

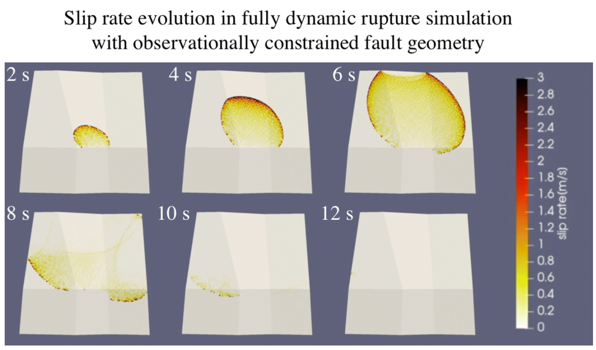
Tatsuya Hisakawa*, Ryosuke Ando, Tomoko Elizabeth Yano and Makoto Matsubara

Earth, Planets and Space 2020, **72**:36 DOI: 10.1186/s40623-020-01160-y
Received: 3 September 2019, Accepted: 3 March 2020, Published: 16 March 2020

Abstract

The 2018, Hokkaido Eastern Iburi, Japan, earthquake is an event characterized by complexity of the rupture process and slip pattern, which may involve both reverse and strike-slip motion depending on the locations on the fault surface. We perform dynamic rupture simulations based on simple physical laws, conditions for stressing and fault friction, and the non-planar fault geometry constrained by the aftershock observation. The complex fault geometry is numerically treated by the boundary integral equation method accelerated by the fast domain portioning method. The fault geometry is characterized primarily by the combination of six fault planes. As a result, we are able to explain several observed features of the event, including the spatial variation of the final fault slip and rupture velocity, which are inferred from the kinematic slip inversion. We also succeed in refining the constraint of the regional stress field in the focal area based on the simulation. Our results show that the overall patterns of the complex rupture event can be reproduced by a relatively simple model of the regional stress and the fault friction, if the geometrical complexity of the fault is properly taken into account.

Keywords: 2018 Hokkaido Iburi Eastern earthquake, Fault geometry, Dynamic rupture, Fast domain partitioning BIEM



Graphical abstract

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FULL PAPER **Open Access**

Deep groundwater discharge after the 2011 Mw 6.6 Iwaki earthquake, Japan

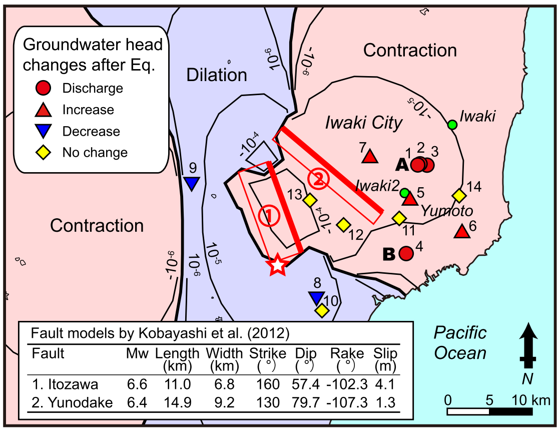
Tsutomu Sato*, Kohei Kazahaya, Norio Matsumoto and Masaaki Takahashi

Earth, Planets and Space 2020, **72**:54 DOI: 10.1186/s40623-020-01181-7
Received: 12 September 2019, Accepted: 23 April 2020, Published: 1 May 2020

Abstract

Hot spring discharge was linked to the 2011 Mw 6.6 Iwaki earthquake. Periodic surveys revealed that the discharge continued for more than 7 years, which is a rare and valuable long-term record of hot spring discharge triggered by an earthquake in a non-volcanic area. In terms of coseismic changes, based on a comparison of the spatial distribution of changes in the coseismic water head and calculated crustal volumetric strain using a fault model, hot spring water discharge was found to be caused by a change in the coseismic crustal volumetric strain. As for the postseismic changes, observations over 7 years revealed a gradual rise in the temperature and chloride ion concentration of the hot spring water. Such long-term hot spring discharge may be explained by the following two causes: the rise of thermal water from the deep part and the permeability changes along the hot spring channels.

Keywords: Coseismic hydrological change, Hot spring water discharge, 2011 Iwaki earthquake, 2011 Tohoku-oki earthquake, Crustal strain, Water temperature, Chloride ion, Sulfate ion, Oxygen stable isotopic ratio



Graphical abstract

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FULL PAPER **Open Access**

Inelastic strain in the hypocentral region of the 2000 Western Tottori earthquake (M 7.3) inferred from aftershock seismic moment tensors

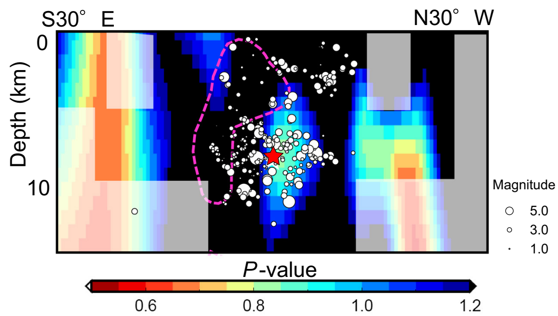
Satoshi Matsumoto*, Yoshihisa Iio, Shinichi Sakai and Aitaro Kato

Earth, Planets and Space 2020, **72**:62 DOI: 10.1186/s40623-020-01186-2
Received: 26 August 2019, Accepted: 24 April 2020, Published: 11 May 2020

Abstract

Inelastic deformation due to seismic activity is an important signal that reflects fault evolution. In particular, aftershock sequences indicate the evolution of damage in a medium that has experienced a large earthquake. Herein, we discuss the inelastic strain rate surrounding the fault that produced the M 7.3 Western Tottori earthquake in 2000 using long-term aftershock analysis. To obtain high-resolution focal mechanisms 18 years after the earthquake occurrence, we conducted dense seismic observations in the focal area. The inelastic strain rate estimated from the aftershock seismic moment tensor data showed spatial variations within a range of 10^{-7}–10^{-11} per year, 18 years after the main shock. By comparing the inelastic strain rates from immediately after the earthquake and 18 years later, we detected the increase in the spatial variations in the inelastic strain rate; the variations are as small as 10^2 (= $10^{-5}/10^{-7}$) for the early stage but as large as 10^4 (= $10^{-7}/10^{-11}$) for the later period. In addition, the decay of the rate during these two periods varied spatially from spatial bin to bin. Certain bins in the northern segment of the earthquake fault, southern edge of the fault, and surrounding the location of the preceding swarm activity to the M 7.3 event showed slower decay rates than the inverse of the lapse time since the occurrence of the M 7.3 earthquake. We modeled this decay rate change as the relaxation response of a power-law fluid to an elastic strain input from the large earthquake. Most parts of the fault can be explained by this model. However, the areas with low decay rates suggest the presence of a dragging mechanism, such as aseismic slip, at or around these locations.

Keywords: Inelastic strain, Fault development, Seismic observation, 2000 Western Tottori earthquake



Graphical abstract

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FULL PAPER Open Access

Geological structures controlled the rupture process of the 2011 M9.0 Tohoku-Oki earthquake in the Northeast Japan Arc

Kei Baba and Takeyoshi Yoshida*

Earth, Planets and Space 2020, **72**:94 DOI: 10.1186/s40623-020-01212-3
Received: 26 August 2019, Accepted: 1 June 2020, Published: 8 July 2020

Abstract

By interpreting the 2D/3D seismic survey data acquired in the surrounding ocean areas of the Northeast (NE) Japan Arc, we clarified the detailed geological structure and demonstrated that the basic structure in the hanging-wall plate of the subduction system consists of many structural blocks (segments) separated by NW–SE trending large transcurrent faults (strike-slip faults). This structural configuration showed a close relationship with the distribution of foreshocks, mainshock, and aftershocks, coseismic slip models of the 2011 M9.0 Tohoku-Oki megathrust earthquake, coseismic slip area of M-7 class earthquakes, quasi-static slip rates, back slip rate, and seismic tomography images. In addition, the coseismic slip models revealed that the trenchward forearc of the structural blocks between the Offshore Hidaka tectonic line and the Honjo-Sendai tectonic line fitted well with the coseismic slip area of the 2011 Tohoku-Oki earthquake. These findings suggest that the structural blocks bounded by these two tectonic lines slipped rapidly trenchward when the mainshock occurred. The M7 earthquakes were also concentrated along these two tectonic lines, thereby suggesting a close relationship between seismic activity and the inherited geological structure of the overriding plate in the NE Japan forearc.

Keywords: 2011 Tohoku-Oki earthquake, Transcurrent fault, Rupture process, Northeast Japan Arc, Hypocenter distribution, Segment boundary, Plate boundary megathrust

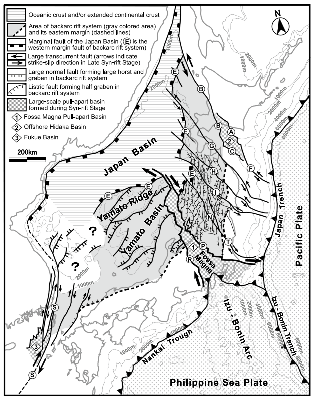

Fig. 1

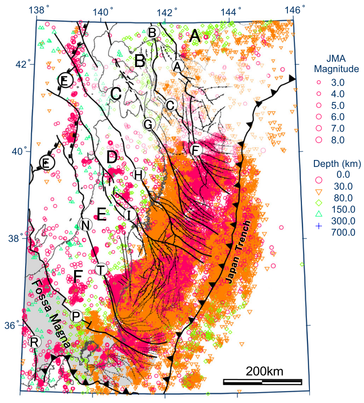

Fig.3b

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FULL PAPER Open Access

Original composition and formation process of slab-derived deep brine from Kashio mineral spring in central Japan

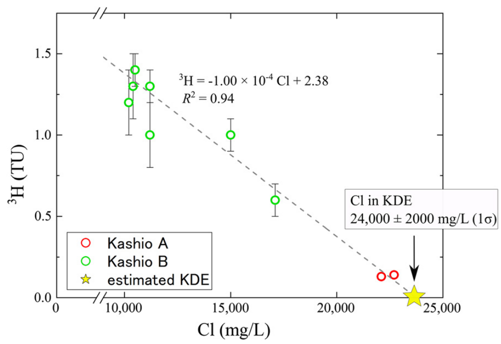
Fumitake Kusuhara*, Kohei Kazahaya, Noritoshi Morikawa, Masaya Yasuhara, Hidemi Tanaka, Masaaki Takahashi and Yuki Tosaki

Earth, Planets and Space 2020, **72**:107 DOI: 10.1186/s40623-020-01225-y
Received: 9 September 2019, Accepted. 30 June 2020, Published: 23 July 2020

Abstract

Brine samples from the wells in the Kashio mineral spring (an "Arima-type" hot spring at Ooshika-Mura, central Japan) were analyzed to determine the original chemical and isotopic compositions of the deep brine end-member before its dilution by meteoric water and to elucidate the origin of the end-member. The trends of variation between Cl, δD, and $\delta^{18}O$ indicated the existence of a two-component mixing system and a systematic variation in the mixing ratio, which were mentioned in previous studies. By carefully tracking the variation in tritium (^3H) and atmospheric noble gas in the brine, the Cl concentration in the end-member was determined to be 24,000 mg/L. This value is consistent with the result of previous studies. Based on the estimated composition and other related data, we inferred that the end-member originated from slab-derived fluid, which in turn may have undergone oxygen isotope exchange reactions with minerals. Although both the Arima and Kashio brines are considered to be derived from fluid dehydrated from the Philippine Sea slab, the chemical and isotopic compositions of the Kashio end-member are different from those of the Arima end-member. In particular, the Kashio end-member is characterized by low Cl concentration (~40% lower than that in the Arima end-member), low hydrogen isotope ratio, and low $^3He/^4He$ ratio (1.4 Ra). These results indicate that the chemical and isotopic compositions of the slab-derived fluid are different for each location. The significant difference in δD could reflect the difference in the dehydration depth. Finally, the low temperature and relatively low $^3He/^4He$ ratio of the brine end-member could be explained by its long residence time within the crust.

Keywords: Kashio mineral spring, Arima-type hot spring, Slab-derived fluid, Chemical and isotopic composition, Tritium, Noble gas



Graphical abstract

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EXPRESS LETTER **Open Access**

Origin of the seismic belt in the San-in district, southwest Japan, inferred from the seismic velocity structure of the lower crust

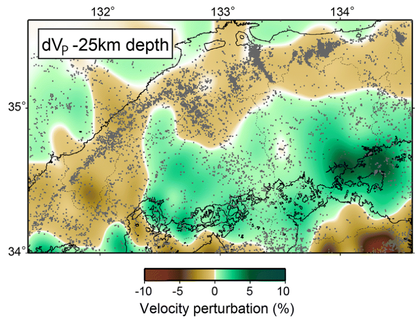
Hiroo Tsuda*, Yoshihisa Iio and Takuo Shibutani

Earth, Planets and Space 2019, **71**:109 DOI: 10.1186/s40623-019-1091-x
Received: 3 July 2019, Accepted: 16 October 2019, Published: 25 October 2019

Abstract

A long linear distribution of epicenters is seen along the Japan Sea coast in the San-in district located in southwestern Japan. This linear distribution of epicenters is called the seismic belt in the San-in district. The localization of intraplate earthquakes in the San-in district, far from plate boundaries, is not well understood. To answer this question, we look at the seismic velocity structure of the lower crust beneath the San-in district using seismic travel-time tomography. Our results show the existence of a low-velocity anomaly in the lower crust beneath the seismic belt. We infer that the deformation was concentrated in the low-velocity zone due to compressive stress caused by the subduction of oceanic plates, that stress concentration occurred just above the low-velocity zone, and that the seismic belt was therefore formed there. We also calculated the cutoff depths of shallow intraplate earthquakes in the San-in district. Based on the results, we consider the possible causes of the low-velocity anomaly in the lower crust beneath the seismic belt. We found that the cutoff depths of the intraplate earthquakes were shallower in the eastern part of the low-velocity zone in the lower crust beneath the seismic belt and deeper in the western part. Thus, the eastern part is likely to be hotter than the western part. We inferred that the eastern part was hot because a hot mantle upwelling approaches the Moho discontinuity below it and the resulting high temperature may be the main cause of the low-velocity anomaly. On the other hand, in the western part, we inferred that the temperature is not high because the mantle upwelling may not exist at shallow depth, and water dehydrated from the Philippine Sea plate reaches the lower crust, and the existence of this water may be the main cause of the low-velocity anomaly.

Keywords: Seismic belt, San-in district, Travel-time tomography, Lower crust, Low-velocity zone, Cutoff depth of earthquakes



Graphical abstract

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EXPRESS LETTER **Open Access**

Inelastic deformation zone in the lower crust for the San-in Shear Zone, Southwest Japan, as observed by a dense GNSS network

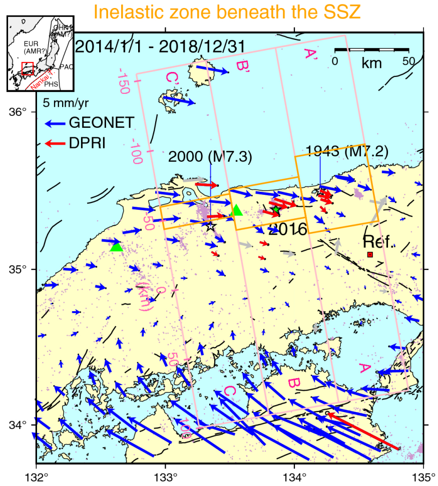
Angela Meneses-Gutierrez* and Takuya Nishimura

Earth, Planets and Space 2020, **72**:10 DOI: 10.1186/s40623-020-1138-z
Received: 31 August 2019, Accepted: 18 January 2020, Published: 3 February 2020

Abstract

We analyze Global Navigation Satellite System (GNSS) within the San-in Shear Zone (SSZ), Southwest Japan, in order to clarify the width of the inelastic deformation zone in the lower crust beneath it. We assumed multiple discrete fault dislocations distributed below the seismogenic depth in a channel to represent inelastic deformation in the lower crust. Kinematic models at 68% confidence level at three profiles indicate that deformation can be explained by a deep inelastic deformation zone with a width of 0.5–56.0 km, 0.5–79.5 km, and 0.0–58.5 km, for the Eastern, Central and Western profiles, respectively; and a relative moving rate between the two blocks sandwiching the zone of 6.2–8.0 mm/year. In Eastern Tottori, the center of the estimated inelastic zone coincides with the source region of the 1943 Tottori earthquake. In Central and Western Tottori, the channel is in agreement with the source regions of the 2000 Western and the 2016 Central Tottori earthquake. Current GNSS network provides a limited contribution to constraining the width of the deformation in the lower crust.

Keywords: San-in Shear Zone, GNSS, Intraplate deformation, Strain concentration



Graphical abstract

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EXPRESS LETTER **Open Access**

Inelastic behavior and mechanical strength of the shallow upper crust controlled by layer-parallel slip in the high-strain zone of the Niigata region, Japan

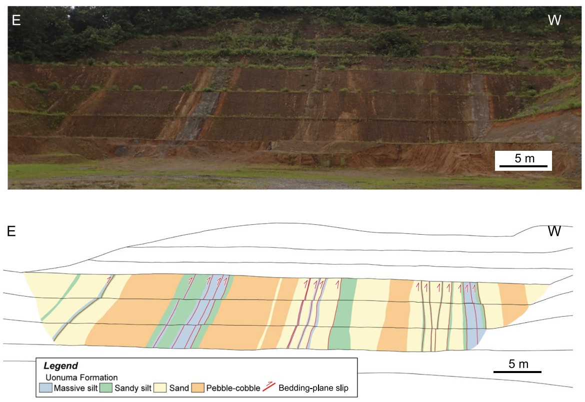
Makoto Otsubo*, Ikuo Katayama, Ayumu Miyakawa and Takeshi Sagiya

Earth, Planets and Space 2020, **72**:30 DOI: 10.1186/s40623-020-01154-w
Received: 27 September 2019, Accepted: 22 February 2020, Published: 4 March 2020

Abstract

We investigated the relationship between contractional deformation of sedimentary mass in the upper crust and the geodetic strain rate in a high-strain zone (part of the Niigata–Kobe Tectonic Zone) of the mid-Niigata region, Central Japan. We observed numerous examples of layer-parallel slip (bedding-plane slip) generated by folding. The slip layers have an average spacing of ~ 3.6 m (measured normal to bedding planes) at the Katagai site. In shallow sedimentary units of the upper crust, numerous bedding-plane slip events act to reduce the mechanical strength (effective elastic thickness) of sedimentary rocks under contractional deformation. The results support an existing model, based on geodetic observations, of mechanical decoupling between the weak sedimentary layers and basement. On the layer-parallel slip, we measured the friction coefficient of gouge generated by bedding-plane slip and of mud around non-slip surfaces using double-direct shear tests, and found no difference in frictional coefficient between slip and non-slip surfaces.

Keywords: Active fold, Bedding-plane slip, Buckling, Deformation, Niigata–Kobe Tectonic Zone



Graphical abstract

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EXPRESS LETTER **Open Access**

Stationarity of aftershock activities of the 2016 Central Tottori Prefecture earthquake revealed by dense seismic observation

Yoshihisa Iio*, Satoshi Matsumoto, Yusuke Yamashita, Shin'ichi Sakai, Kazuhide Tomisaka, Masayo Sawada, Takashi Iidaka, Takaya Iwasaki, Megumi Kamizono, Hiroshi Katao, Aitaro Kato, Eiji Kurashimo, Yoshiko Teguri, Hiroo Tsuda and Takashi Ueno

Earth, Planets and Space 2020, **72**:42 DOI: 10.1186/s40623-020-01161-x
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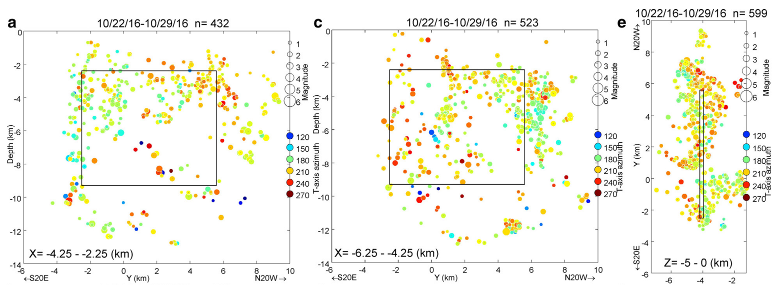
Abstract

To clarify the relationship between earthquake occurrence and fluid, we analyzed data from a dense aftershock-observation network with 69 high-gain short-period seismographs installed immediately after the mainshock occurrence (October 21) in the aftershock area of the 2016 Central Tottori Prefecture earthquake. We determined the hypocenters and focal mechanisms of the aftershocks very precisely in the period from October 22 to December 15. We then investigated the temporal changes in the spatial distributions of hypocenters and T-axis azimuths of focal mechanisms. The distributions of aftershock hypocenters and T-axis azimuths are basically temporally stable, except those in limited portions in the shallow layer near the western edge of the aftershock area, where rapid decrease of aftershocks with T-axis azimuths of WSW to west was observed. If fluid rises from the lower crust due to fault rupture, the locations of aftershocks and focal mechanisms may change over time, especially in the deepest part of the aftershock region. However, the temporal change in these parameters was not apparent at depth. These observations suggest that the aftershock activity of the Central Tottori Prefecture earthquake was controlled mainly by stress concentration rather than strength reduction due to high fluid pressure.

Keywords: Intraplate earthquake, Aftershock, Stress, Strength, Fluid



Graphical abstract

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EXPRESS LETTER Open Access

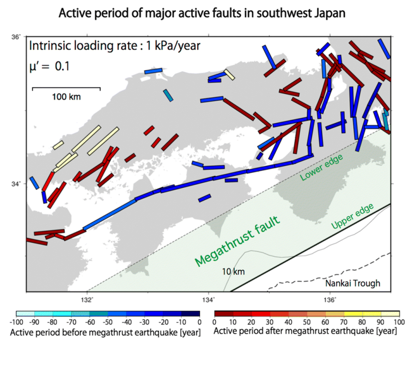
Coulomb stress change on inland faults during megathrust earthquake cycle in southwest Japan

Tsukasa Mitogawa* and Takuya Nishimura

Earth, Planets and Space 2020, **72**:66 DOI: 10.1186/s40623-020-01174-6
Received: 30 September 2019, Accepted: 29 March 2020, Published: 13 May 2020

Abstract

In the subduction zone, megathrust earthquakes may modulate the shallow crustal seismicity in the overriding plate. Historical documents indicate the frequent occurrence of large shallow crustal earthquakes in the overriding continental plate 50 years before and 10 years after the megathrust earthquakes along the Nankai trough in southwest Japan. In this study, we model megathrust earthquake cycles in a simple oblique subduction zone considering the viscoelasticity, and calculate the temporal evolution of the Coulomb failure stress changes (ΔCFS) on the crustal faults in the overriding plate. Further, we examine the variation of ΔCFS depending on the location and fault type, and the active period of crustal earthquakes in which ΔCFS exceeds the previous maximum. Our viscoelastic model suggests that the dependency of the active period on the distance from the megathrust fault is less when the intrinsic loading rate of the inland fault is low. Moreover, it suggests that the viscoelastic stress evolution on faults with negative coseismic ΔCFS renders the active period longer or shorter than those in a pure elastic medium. The temporal evolution of ΔCFS on most major active faults in southwest Japan can be categorized into two groups with the following different characteristics: one is that ΔCFS is positive coseismically and peaks 10 years after a megathrust earthquake. The other is that ΔCFS is negative coseismically, and does not recover to the preseismic one for more than 50 years after a megathrust earthquake. This can explain the temporal sequence of the historical earthquakes in southwest Japan. Our model which includes viscoelastic relaxation successfully expresses the activation of shallow crustal earthquakes in the overriding continental plate not only before the megathrust earthquake, but also after. If the apparent frictional coefficient is less than ~0.1, the coseismic ΔCFS on the source faults of the 1943 M_j7.3 Tottori earthquake, 1596 M7.0 Keicho Iyo earthquake, and 1596 M7.5 Keicho Fushimi earthquake that occurred within 10 years before the megathrust earthquake along the Nankai trough is negative. Therefore, to explain the occurrence of these historical earthquakes, our model suggests that the apparent frictional coefficient must be less than ~0.1.



Graphical abstract

Keywords: Megathrust earthquake cycle, Coulomb stress change, Viscoelasticity, Inland fault, Southwest Japan

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TECHNICAL REPORT Open Access

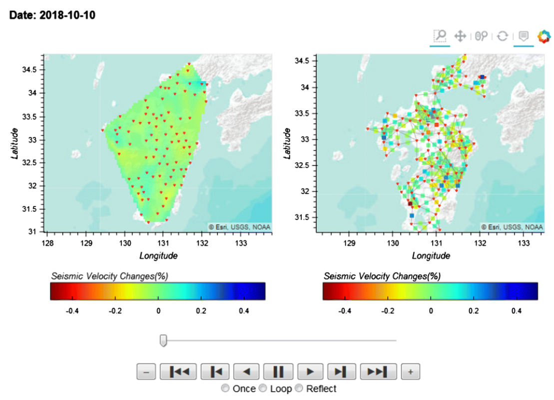
Real-time crustal monitoring system of Japanese Islands based on spatio-temporal seismic velocity variation

Fernando Lawrens Hutapea, Takeshi Tsuji* and Tatsunori Ikeda

Earth, Planets and Space 2020, **72**:19 DOI: 10.1186/s40623-020-1147-y
Received: 9 October 2019, Accepted: 3 February 2020, Published: 14 February 2020

Abstract

To continuously monitor crustal behavior associated with earthquakes, magmatic activities and other environmental effects (e.g., tides and rain precipitation), we have developed a continuous monitoring system of seismic velocity of the Japanese Islands. The system includes four main processing procedures to obtain spatio-temporal velocity changes: (1) preparing ambient-noise data; (2) creating virtual seismograms between pairs of seismometer stations by applying seismic interferometry; (3) estimating temporal velocity variations from virtual seismograms by stretching interpolation approach, and (4) mapping spatio-temporal velocity variations. We developed a data-processing scheme that removes unstable stretching interpolation results by using the median absolute deviation technique and a median filter. To map velocity changes with high stability and high temporal resolution during long-term (i.e., longer-term monitoring), we proposed the "sliding reference method". We also developed evaluation method to select the optimum parameters related to stability and temporal resolution. To reduce computation time for continuous monitoring, we applied parallel computation methods, such as shared memory and hybrid distributed memory parallelization. Using our efficient and stable monitoring system, we succeeded to continuously monitor the spatio-temporal velocity variation of the whole Japanese Islands using ambient-noise data from 767 seismometers. Finally, we developed a web application that displays spatio-temporal velocity changes. In the monitoring results that we open through the website, we identified velocity variation (e.g., pore pressure variation) that could be related to earthquake, aftershock, magmatic activities and environmental effects in a stable manner.



Graphical abstract

Keywords: Crustal monitoring, Seismic velocity, Parallel and high-performance computing, Big data, Seismic interferometry, Ambient noise

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Information for Contributors

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