Review:

Main Results from the Program Promotion Panel for Subduction-Zone Earthquakes

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Understanding the occurrence mechanism of subduction zone earthquakes scientifically is intrinsically important for not only forecast of future subduction earthquakes but also disaster mitigation for strong ground motion and tsunami accompanied by large earthquakes. The Program Promotion Panel for Subduction-zone earthquakes mainly focused on interplate megathrust earthquakes in the subduction zones and the research activity included collection and classification of historical data on earthquake phenomena, clarifying the current earthquake phenomena and occurrence environment of earthquake sources, modelling earthquake phenomena, forecast of further earthquake activity based on monitoring crustal activity and precursory phenomena, and development of observation and analysis technique. Moreover, we studied the occurrence mechanism of intraslab earthquakes within the subducting oceanic plate. Five-year observational research program actually produced enormous results for deep understanding of subduction zone earthquakes phenomena, especially in terms of slow earthquakes, infrequent huge earthquakes, and intraslab earthquakes. This paper mainly introduces results from researches on these phenomena in subduction zones.

Keywords: subduction zone earthquake, slow earthquake, intraslab earthquake, infrequent huge earthquake

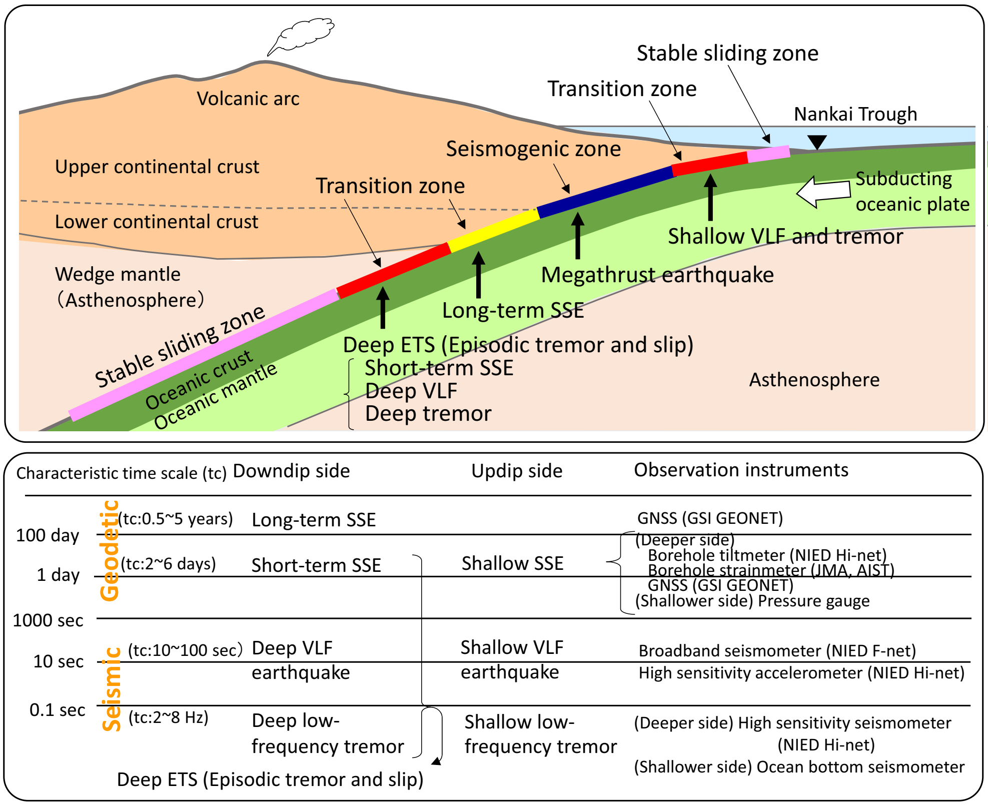
1. Slow Earthquakes

1.1. Introduction

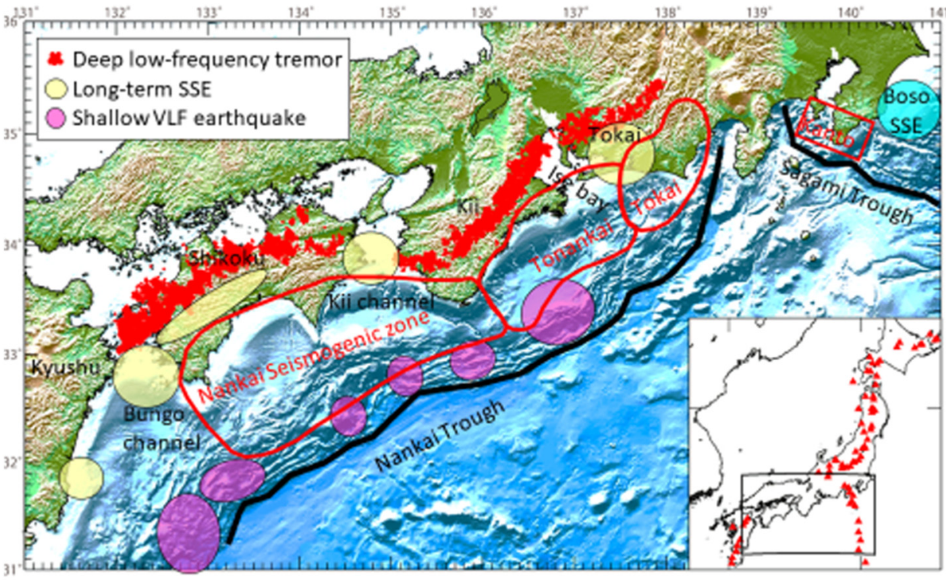
Research on slow earthquakes including low-frequency tremors and slow slip events occurring at the plate interface has intensively progressed especially in the following two viewpoints. One is the observation-based research on detailed occurrence history, source process in various places and interaction between slow earthquakes. Another is the research to understand the occurrence environment around the source of slow earthquakes like as seismic velocity, attenuation and electric resistivity structures. Slow earthquake research is currently one of the most advancing research topics in the solid Earth science. Not only observation-based research by using real-time data monitoring, but also experimental and simulation researches are leading our program promotion panel. Those researches includes rock friction experiment to understand frictional property, numerical simulation of slow earthquake by using a constitution law of fault friction, data assimilation by using data from Global Navigation Satellite System (GNSS) observation and simulation of fault slip aiming simultaneous estimation of frictional parameters and future behaviors and so on.

1.2. Monitoring of Subducting Plate Interface and Possible Connection to Huge Earthquakes

Because slow earthquakes frequently occur at the transition zone between locked and stable sliding zones where regular earthquake seismicity is inactive, they may provide important information for monitoring the temporally variable status of the plate interface. The relationship between slow and megathrust huge earthquakes (**Fig. 1**) is summarized into the following three key aspects by Obara and Kato [1]; (1) Analog: slow earthquake activity similar to that of huge earthquake, (2) Stress meter: slow earthquake activity pattern possibly indicating stress change at seismogenic zone, and (3) Stress transfer: slow earthquake possibly triggering huge earthquake, and they contributed to development of the study on interplate earthquake by using slow earthquakes. As for the stress transfer from slow earthquake to the surrounding area, precursory slow slip events (SSEs) detected by ocean floor pressure gauges [2] and repeater analysis [3] before the rupture initiation of the 2011 off the Pacific coast of Tohoku Earthquake are well known. Recent studies revealed that the 2014 Iquique earthquake (M_w8.1) in Chile and 2014 Papanoa earthquake (M_w7.3) in Mexico are associated with a precursory SSE near the coseismic slip region [4, 5]. These results indicate a possibility of triggering huge earthquake by SSE. Similar observational facts are accumulating with expanding GNSS observation network (e.g., [6]). Therefore, the occurrence of huge earthquakes triggered by stress transfer from slow earthquakes is considered to be not rare phenomena. The anal-



(a)



(b)

Fig. 1. (a) Classification of various slow earthquakes along the subducting plate interface in Nankai. Slow earthquakes are spatially separated into updip and downdip parts of the seismogenic zone and mainly classified into geodetic and seismic phenomena in spectrum domain. Geodetic slow earthquakes are separated into long-term and short-term slow slip events (SSEs) with duration of months to years and days to weeks, respectively. Seismic slow earthquakes are separated into very low frequency (VLF) earthquake and tremor with dominant frequency of 0.02–0.05 Hz and 1–10 Hz, respectively. Recently SSEs have been detected in the shallow portion as explained in the text. (b) Distribution of various slow earthquakes in the Nankai subduction zone. Dots at the most downdip part indicate deep low frequency tremor usually associated with short-term SSEs and deep VLF earthquakes. The simultaneous occurrence of three types of slow earthquakes is called episodic tremor and slip (ETS). Long-term SSEs and shallow VLF earthquakes are distributed between the ETS and seismogenic zones and between the seismogenic zones and Nankai trough, respectively. Boso SSEs located in central Japan also occur along the subducting Philippine Sea plate.

ysis of repeating earthquakes and GNSS data along the Japan-Kuril trenches revealed periodic occurrence of SSE at recurrence interval of several years and indicated that the seismicity of large earthquakes greater than M5 is activated by the periodic SSEs [7]. Although we need more advanced research works to reveal the condition for triggering huge earthquakes by SSE, this five-year project has indicated a possibility that monitoring SSE will contribute to forecasting occurrence probability of huge earthquakes based on advanced development of an analyzing technique for GNSS data (e.g., [8, 9]) and interplate slipping by using repeaters [10].

1.3. Understanding Fault Friction Property

On the other hand, the research on fault frictional property based on rock experiments in laboratory and numerical simulation forms a foundational research theme of our research project for especially forecast of earthquake occurrence as the ultimate purpose of our project, and there are significant achievements mainly in the slow earthquake study during the five years. Based on rock samples from the ocean floor and deep drilling by offshore marine survey, fault friction experiment by using materials composing interplate fault zone were carried out to investigate the dependence of frictional property on the composition of the fault gauge, condition of temperature and pressure, and a slip rate at the fault. As a result, various faulting behaviors including both seismic and aseismic slips occur under various sediment materials and rocks even if at the same depth condition (e.g., [11]). Laboratory experiments by using materials composing the fault zone at the seismogenic zone of 2011 Tohoku Earthquake revealed the condition for the occurrence of slow earthquake with decreasing effective normal stress (e.g., increasing pore fluid pressure) with the frictional parameter a-b of around zero in the shallow seismogenic zone [12]. The simulation study on the occurrence condition of both regular and slow earthquakes for the heterogeneity of geometry and material property of the fault plane revealed that the macroscale slip behavior becomes stable with increasing the roughness at the fault plane. Moreover, frictional parameters of the fault are estimated based on spatiotemporal evolution analysis for fault slip of SSEs in the Boso peninsula and Yaeyama islands (e.g., [13, 14]). Data assimilation study combined with simulation of fault slip based on a friction constitution law and observed data succeeded to estimate frictional parameters around the seismogenic zone of the 2003 Tokachi-oki earthquake by using GNSS data [15] (**Fig. 2**). In order to improve the resolution of estimation for fault friction parameters by using the data assimilation, we need to use the data associated with temporal variation of a fault slip rate. Therefore, SSE is the most appropriate phenomenon for a forecast based on data assimilation. In the next research plan, a study for assimilating long-term SSEs in the Bungo channel region is expected to be carried out to demonstrate the performance of forecasting a real slip phenomenon. And then it is hopefully applied to the interplate slip including huge earthquakes and SSEs in the whole Nankai trough region. By the way, an interplate huge earthquake is an infrequent phenomenon with a recurrence interval of generally longer than several ten years. It is difficult to accumulate enough case studies for evaluation of models based on monitoring only in and around the Japanese islands. Therefore, we need to promote monitoring studies in oversea research fields like as New Zealand in order to increase the case studies and simulation study to evaluate the condition of SSE triggering huge earthquakes and leading time from an SSE to a huge earthquake in the next research plan.

1.4. Underground Structure as Occurrence Environment of Slow Earthquakes

Studies on underground structure at and around the interplate fault including slow earthquake source regions have achieved many results. Based on studies carried out in the Nankai and Sagami trough areas, one of common features revealed in many places including some regional differences is that the source region of slow earthquakes is characterized by high Vp/Vs, high attenuation, and clear detection of reflected phase [16–18]. These results suggest that the existence of high pore pressure fluid is related to the occurrence condition of slow earthquakes. Nakajima and Uchida [19] confirmed the temporal correlation between the occurrence of slow earthquakes and temporal change of seismic wave attenuation structure in a southwestern part of Ibaraki prefecture, central Japan (**Fig. 3**). This research clearly indicates the relationship between fluid and slow earthquake. In addition to the existence of fluid, configuration of fault and property of fault material are considered to control the slip behavior. Therefore, we need to reveal the relationship between underground structure of the plate interface, property of incoming oceanic plate in aspect of material science, and huge and slow earthquakes.

1.5. Ocean Floor Observation

In addition to above research results, the most important progress for the five-year research program is new discovery of various offshore phenomena on the basis of development of ocean floor observation technology for seismic and geodetic observation and deployment of these instruments at the ocean floor. In order to catch a weak signal from interplate earthquakes, ocean floor observation is essentially required because most of these earthquakes occur in the offshore region. GNSS-Acoustic measurement (GNSS-A) has detected detail spatiotemporal change of crustal deformation along the Japan trench [20, 21] and Nankai trough [22, 23] based on the integration of observation technique and data analysis methods, and frequent measurements. The result from the Japan trench revealed spatiotemporal evolution of postseismic effect following the 2011 Tohoku Earthquake and provided the information on underground rheological structure and frictional property on the plate boundary fault [24–26]. Moreover, research result from

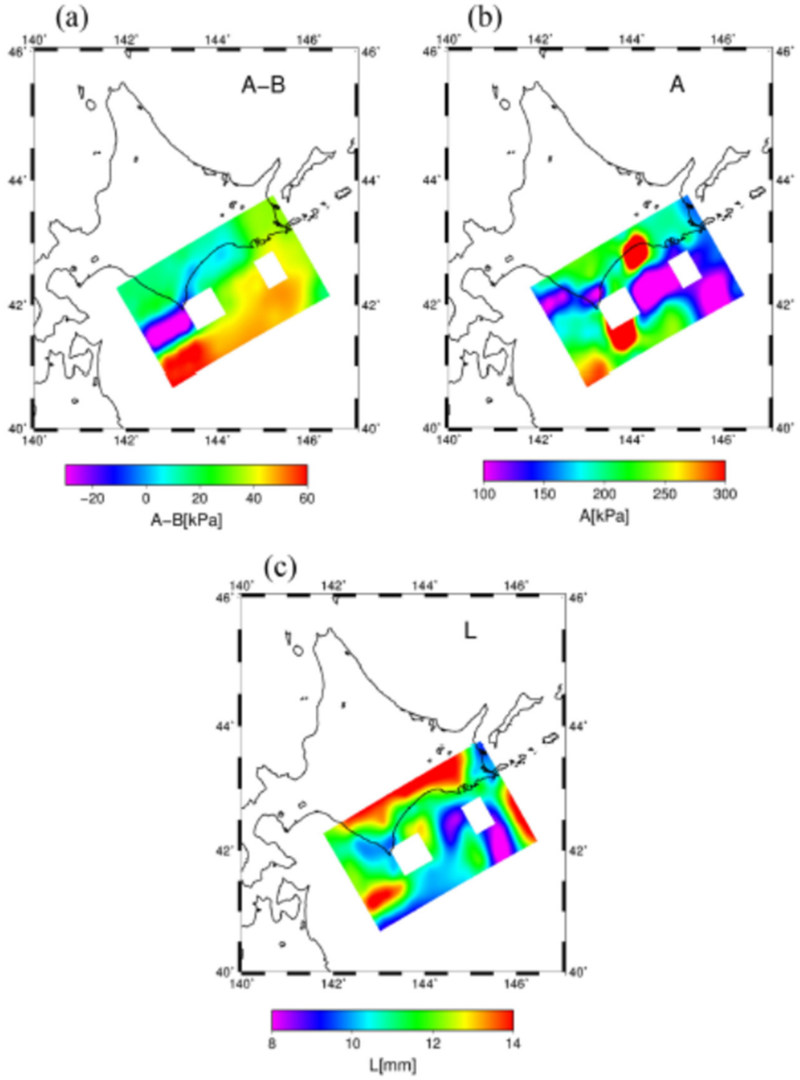


Fig. 2. Frictional parameters on the subduction plate interface estimated from GNSS data along the southern Kuril trench. Parameters are optimized through data assimilation of postseismic displacement of the 2003 M_w8.0 Tokachi-oki earthquake for 15 days. (a) A–B, (b) A, and (c) L. This figure is from Fig. 12 of Kano et al. [15].

the Nankai trough is available for estimation of the current locking situation on the plate interface and revealed the inhomogeneity of the distribution of locking situation in the offshore region where the spatial resolution is usually poor by using only data from inland stations (e.g., [22, 27]). Recently, a temporal variation of the crustal deformation rate is detected off the Kii channel, possibly indicating that the long-term SSE is occurring at the shallow portion of the subducting plate interface [28]. As for the instrumentational development, pop-up type ocean bottom seismometers are revised to record broadband seismic signals [29]. Based on the repeating deployment of long-term observation instrument running for longer than 1 year, the spatiotemporal seismicity change was revealed in the seismogenic zone of 2011 Tohoku earthquake, showing that interplate earthquakes off Sanriku was activated a couple of years after the 2011 Tohoku Earthquake whereas they were very quiet just after the 2011 Tohoku Earthquake (Shinohara et al., personal communication). As for the cabled seismic observation networks, DONET (Dense Ocean floor Network system for Earthquakes and Tsunamis) and S-net (Seafloor observation Network for Earthquakes and Tsunamis along the Japan trench) have been constructed along the Nankai trough and Japan trench respectively, and contribute to new observational finding for offshore slow earthquake activities. DONET succeeded to discover recurrent short-term SSEs at shallow portion of the Nankai trough region based on the measurement of pore pressure and tilt at the ocean floor drilling borehole [30]. Nakano et al. [31] revealed the pore pressure change caused by a short-term SSE [30] is very coincident with the temporal change of cumulative moment from very-low frequency earthquakes beneath the DONET (**Fig. 4**). This result indicates that these slow earthquakes identically occur on the same fault plane.

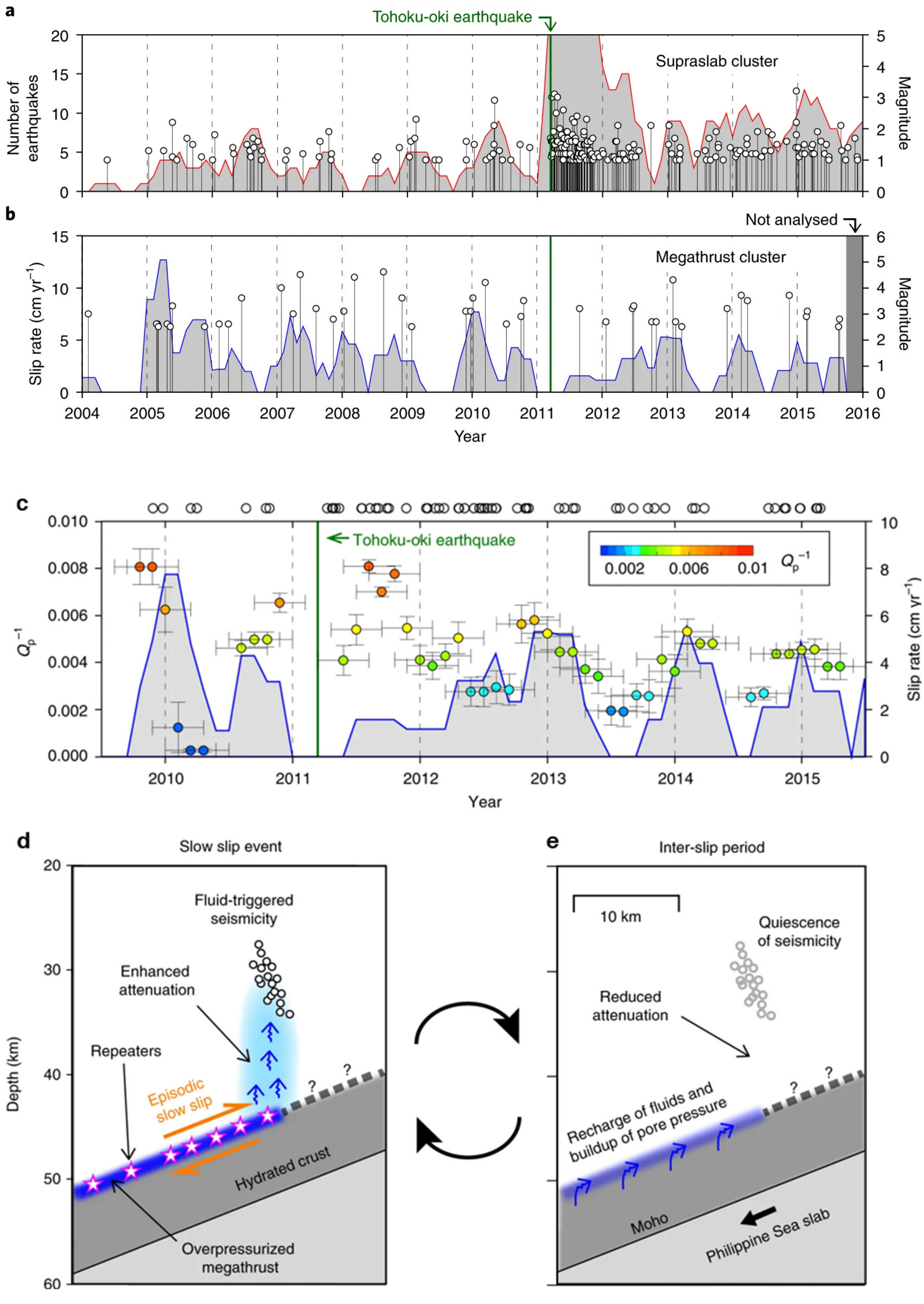


Fig. 3. Correlation among supraslab earthquakes, megathrust slip rates, and P-wave attenuation. (a) The number of supraslab earthquakes counted for 0.4-year time windows with a 0.1-year moving window (grey histogram) and a magnitude (M_{JMA})-time plot (white circles). (b) Average slip rates on the megathrust (grey histogram) estimated from the repeating earthquakes. (c) Temporal variation in P-wave attenuation, $Q_p{}^{-1}$ (circles) with one standard deviation (vertical bars). Horizontal bars denote the time window length of each with taking care of the term, $Q_p{}^{-1}$ estimate. The grey histogram shows megathrust slip rates. The circles above the panel denote the date of analyzed megathrust earthquakes. (d), (e) Schematic interpretation of drainage process during a slow slip event (d) and interslip period (e). The hydrated crust is constrained by tomographic imaging. This figure is modified from Figs. 2, 3, and 4 of Nakajima and Uchida [19].

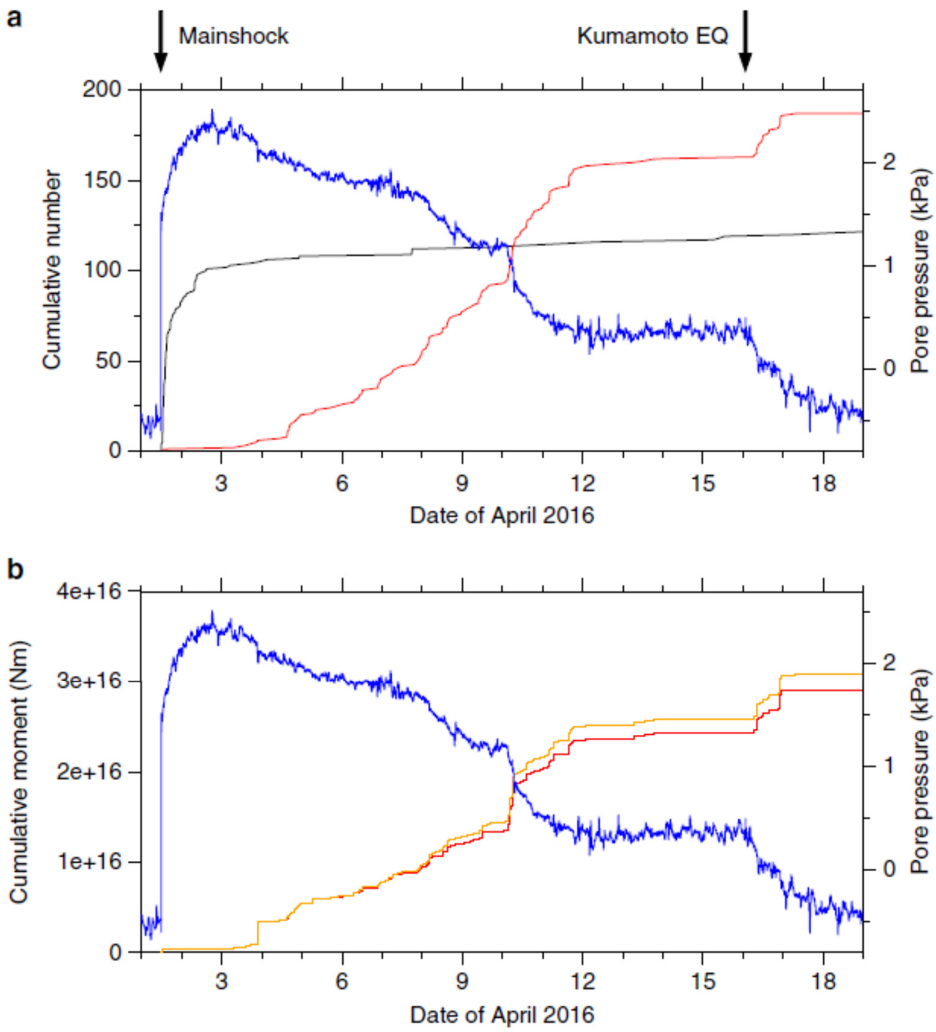


Fig. 4. Temporal evolution of seismic activities and borehole pore-pressure changes in the Kumano-nada region along the Nankai trough, southwest Japan. (a) Cumulative numbers of sVLFEs larger than M_w3, aftershocks of the off-Mie earthquake larger than magnitude 1, and borehole pore-pressure changes. (b) Temporal evolution of cumulative moment due to sVLFEs larger than magnitude 3.0 and all sVLFEs for which a CMT was determined. This figure is from Fig. 4 of Nakano et al. [31].

2. Infrequent Large-Scale Earthquakes

In terms of infrequent huge-scale subduction zone earthquakes, geological and geographical studies like as investigation of tsunami deposits have been actively progressed to reveal the historical behavior of past earthquakes. In northeastern Japan, tsunami flooded areas from the 17 century Kuril trench earthquake, 1611 Keicho Sanriku tsunami earthquake, 1454 Kyotoku earthquake, 869 Jogan earthquake, and so on have been clarified although the results for these earthquakes include some uncertainty [32, 33]. In southwest Japan, tsunami flooded areas have been estimated for each historical Nankai earthquake and suggested that the recurrence interval of earthquakes associated with wider flooded areas is ranging from 400 to 1000 years, which is longer than that of well-known historical Nankai earthquakes [34]. On the other hand, the recurrence interval of large earthquakes was revealed to be much scattered and shorter compared to that of previous studies based on the reinvestigation on uplift dating of coastal terraces in the southern Boso peninsula. This result requires to reconsider the recurrence interval of the Genroku-type Kanto earthquake [35] (**Fig. 5**).

3. Intraslab Earthquakes

Research works based on high resolution hypocenter determination and fault parameters estimation for intraslab earthquake revealed large spatial variation of earthquake stress field and complementary relationship of fault plane of repeaters [37]. Moreover, modeling study of three-dimensional thermal structure considered with slab geometry and oblique subduction revealed the temperature range for occurrence of intraslab and interplate earthquakes in the Tohoku and Kanto regions [38, 39]. Laboratory experiments for frictional deformation with dehydration revealed the deformation property of lawsonite which

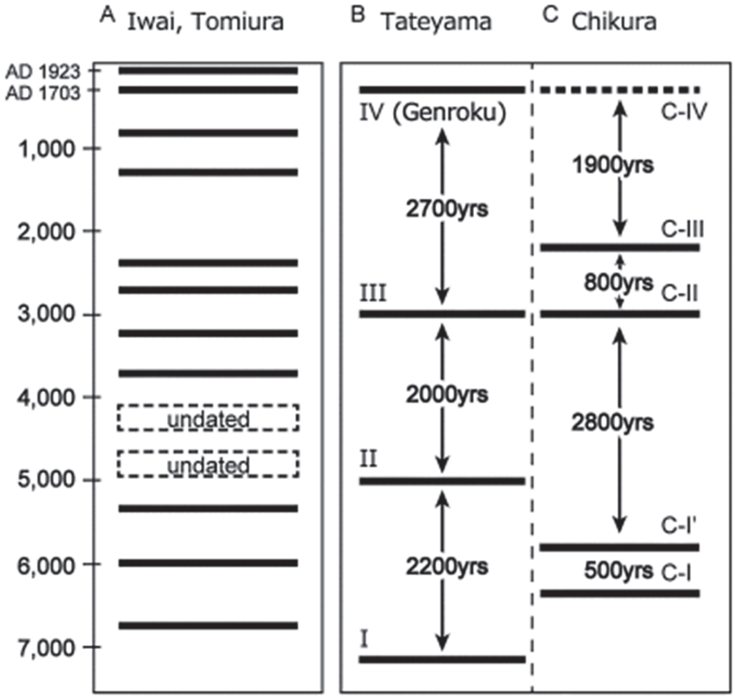


Fig. 5. Distributions of the estimated dates of terrace formation in (A) Iwai and Tomiura, (B) Tateyama, and (C) Chikura (measured in this study) in the Boso peninsula, central Japan. (A) and (B) are from Shishikura et al. [36]. The lower limits of the heights of the terraces are 1–2 m for (A) (indicating the inclusion of Taisho-type earthquakes) and 3 m for (B) and (C) (indicating solely Genroku-type earthquakes). The dashed lines indicate that marine terraces are identified at the corresponding heights but that their dates are not measured. This figure is from Fig. 8 of Komori et al. [35].

is a typical hydrous mineral in the cold slab [40]. Progression of these studies suggests possibilities to evaluate the potential of huge intraslab earthquakes which are presumably caused by dehydration embrittlement.

4. Efforts for Disaster Mitigation

One of important purposes of the Earthquake and Volcano Hazards Observation and Research Program is to contribute to disaster mitigation. On the other hand, our program promotion panel mainly focuses on research for understanding earthquake phenomena. Therefore, very few researches are appeared to be directly connected to disaster mitigation. Especially, the contribution to disaster mitigation based on the forecast for occurrence of earthquake which has been continued from the previous research program is still halfway to the final purpose. However, studies on historical subduction zone earthquakes and tsunami behaviors carried out under this panel recover many historical records of disasters at each region. Such historical records are absolutely essential information to evaluate possible future disasters and greatly contribute to disaster mitigation. Indeed, studies for possible stress transfer to seismogenic zones where previous large earthquakes like as northern off Sanriku occurred revealed by afterslip followed by the 2011 Tohoku Earthquake [26] and possible scenario for the occurrence of the Nankai trough huge earthquake triggered by a Hyuga-nada M7-class earthquake within several years [41] are considered for the review of long-term forecast for subduction zone earthquakes by the Earthquake Research Committee of the Japanese government and the countermeasure for the Nankai trough huge earthquake by the Cabinet Office, respectively. Above examples indicate that our research results are effectively used to social activities on disaster mitigation.

5. Future Perspective

During the five-years research program with the purpose to contribute to disaster mitigation, researchers from social sciences and engineering fields joined in our research program and shared with our research results through annual symposium and other workshops. This collaborative research policy seems to encourage our program promotion panel mainly composed of science researchers to contribute to disaster mitigation from our research output. In our panel, new research project studying including interseismic stress accumulation process, coseismic dynamic rupture process, and generation of strong motion and tsunami based on unified scheme simulation has just started. Such comprehensive research from understanding earthquake phenomena to earthquake and tsunami hazard becomes to be established. In the next research plan, we expect that the observational research studies are continued with keeping the direction of the previous plan and further contribute to disaster mitigation associated with increasing outputs to society.

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