Workshop report: **Tracking the Tsunamigenic slips Across and Along the Japan Trench (JTRACK): Investigating a new paradigm in tsunamigenic megathrust slip with very deep water drilling using the D/V Chikyu**

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Shuichi Kodaira
Research and Development Center for Earthquake and Tsunami, Japan Agency for Marine-Earth Science and Technology, 3173-25 Showa-machi, Kanazawa-ku, Yokohama, 236-0001, Japan

Jim Mori
Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan

Saneatsu Saito
Research and Development Center for Ocean Drilling Science, Japan Agency for Marine-Earth Science and Technology, 2-15 Natsushima-cho Yokosuka, 237-0061, Japan

Michi Strasser
Geological Institute, ETH Zurich, NO G 46, Sonneggstrasse 5, 8092 Zurich Switzerland

Jamie Kirkpatrick
Department of Geosciences, Colorado State University, 1482 Campus Delivery, Fort Collins, CO, 80523, USA

James Sample
School of Earth Sciences and Environmental Sustainability, Northern Arizona University, 602 S Humphreys, Flagstaff, AZ, 86011, USA

1. Introduction

1.1 JTRACK: Tracking tsunamigenic slip at the Japan Trench

Among the global efforts to understand and mitigate earthquake hazards, investigations and resources for understanding the causes and effects of tsunamis have been relatively few compared to the many studies of strong earthquake shaking. Yet worldwide over the last decade, nearly a third of the loss of human life from earthquakes is attributed to tsunamis (~247,000 from tsunamis and ~535,000 from earthquake shaking for 2002 to 2012). On March 11, 2011 the Mw9.0 Tohoku-oki earthquake ruptured a huge portion of the Japan Trench, resulting in an enormous tsunami that caused thousands of casualties and billions of dollars of damage in northern Japan. The Tohoku-oki earthquake was the first event whose entire activity was recorded by modern dense geophysical, seismological and geodetic networks located close to the rupture zone. Despite the significant instrumentation for earthquake monitoring, the magnitude of the 2011 earthquake, amount of coseismic slip and size of the accompanying tsunami were largely unexpected by the geophysical community.

Understanding the dynamic processes and properties that control earthquake and tsunami occurrence is one of the main themes of the International Ocean Discovery Program Science Plan for 2013-2023. The JTRACK (Tracking Tsunamigenic Slips in the Japan Trench) project aims to investigate the controls on fault slip behavior and deformation along subduction plate boundaries by drilling into the rupture area of the 2011 Tohoku-oki earthquake (IODP Science Challenges 12 and 14). Building on a pre-proposal (IODP Proposal 835-Pre) submitted in October 2013, a workshop was held in Tokyo, Japan from May 15-17, 2014 to begin development of a full IODP drilling proposal.

Slip on the shallow part of the megathrust plate boundary during the 2011 Tohoku-oki earthquake that promoted the devastating tsunami was the largest ever observed (e.g. Ide *et al.*, 2011; Fujiwara *et al.*, 2011; Lay *et al.* 2011). To investigate the conditions and processes that facilitated the large slip, the D/V Chikyu successfully penetrated and partially sampled the rupture zone of the 2011 earthquake in unprecedented water depths of nearly 7000 m during IODP Expedition 343/343T in April and May 2012 (Chester *et al.*, 2013a). Logging while drilling data and cores recovered from depths down to ~840 meters below sea floor (mbsf) defined the location and composition of the plate boundary fault. Temperature data from an observatory installed during Expedition 343T and recovered nine months later by R/V Kairei showed a temperature anomaly at the megathrust horizon, which was used to infer a very low dynamic friction coefficient of 0.08 (Fulton *et al.*, 2013), consistent with lab measurements of the frictional properties of core samples at seismic slip velocities (Ujiie *et al.*, 2013; Sawei *et al.*, in press).

Results from Expedition 343/343T and supporting geophysical and geological data (Fujiwara *et al.*, 2011; Kodaira *et al.*, 2012), highlighted several fundamental characteristics of the earthquake slip near the trench: 1) the co-seismic displacement reached all the way to the trench axis; 2) the co-seismic megathrust slip was apparently confined to a narrow (<5 m) zone of a very weak clay layer on the Pacific Plate (Chester *et al.*, 2013b; Fulton *et al.*, 2013; Ujiie *et al.*, 2013); 3) there is no evidence to date that fluid overpressure contributed to slip; 4) trench-fill sediments are deformed by trenchward movement of the overriding block (Strasser *et al.*, 2013); and 5) turbidities from previous earthquakes are preserved in the trench fill and might provide a paleoseismic record (Ikehara *et al.*, 2012; Ikehara *et al.*, submitted). The very weak materials in the fault zone provided negligible resistance to slip at Site C0019. However, outstanding questions regarding the mechanical behavior of the subduction interface remain.

1.2 Details of the JTRACK pre-proposal

A new drilling program (JTRACK) was proposed in 2013 (IODP Proposal 835-Pre) to build on the success of Expedition 343/343T with the following overarching scientific objectives:

1. Understand the variations of physical and chemical properties of sediments and fluids of the near-trench megathrust that enable huge fault displacements and generate very large tsunamis.

2. Develop and implement new methods for determining the recurrence of giant tsunamigenic earthquakes in the sediment record of the trench fill.

JTRACK was developed to focus on the Japan Trench subduction margin, which is part of the recent global surge in great earthquakes (Figure 1). The margin is exceptionally well instrumented, long records of historical earthquakes are available, and extensive geophysical surveys have characterized the overall structure of the margin (e.g. von Huene *et al.,* 1982; Tsuru *et al*., 2005). Historical records indicate that tsunamigenic earthquakes occurred at different times along different parts of the margin. The 2011 Tohoku-oki earthquake (Mw 9.0) ruptured the central part of the margin produced a gigantic tsunami generated by the seafloor deformation (Ide *et al.*, 2011; Fujiwara *et al.*, 2011; Lay *et al.* 2011). Events causing similar tsunamis include the 1896 Sanriku earthquake, and 1677 Enpou-Boso earthquake that occurred on the northern and southern portions of the margin respectively (Figure 1).

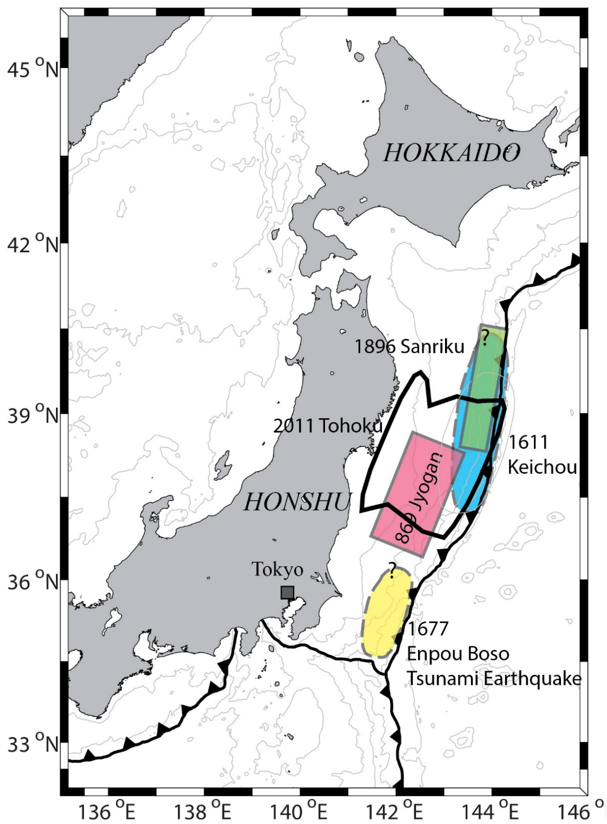

Figure 1. Map of the Japan Trench east of Honshu where the Pacific plate subducts beneath Japan.The estimated rupture areas of signficant recent and historical earthquakes are shown (Tanioka, personal communication).

This history of tsunami-generating earthquakes indicates a need to revise the widely accepted conceptual model that in a seismogenic subduction zone the shallow portion of the megathrust slips largely aseismically (e.g. Bilek and Lay, 2002). The central goal of the JTRACK project was therefore to determine why earthquake slip ruptures to the trench during some earthquakes. The Tohoku-oki earthquake further demonstrated that the short instrumental and historical records are inadequate to characterize the complex and multi-scale seismic behavior of subduction zones, including the occurrence of proposed "superquakes" with very long recurrence intervals (Sieh *et al.*, 2008; Goldfinger *et al.*, 2013). In addition to the three transects, a trench-parallel transect was proposed to efficiently capture the record of great earthquakes in the sedimentary record to complement findings from the other transects. Tsunamis are global phenomena; the JTRACK project aims to establish fundamental mechanical controls that can be transferred to other margins worldwide to enhance societal appreciation of tsunami hazard. The scientific objectives were developed in a way that individual, stand-alone goals might be reached by short, targeted drilling operations. The short expeditions would be close to the Japanese coastline and could be designed to fit into opportune openings in the D/V *Chikyu* schedule.

2. Tokyo workshop overview

A workshop was held in Tokyo, Japan (May 15-17), to bring together scientists interested in all aspects of subduction processes to discuss and define the most important scientific objectives that could be addressed with scientific ocean drilling at the Japan Trench. The main goal of the workshop was to define the critical unresolved questions about a system that can generate such large earthquakes and damaging tsunamis and develop a research plan that would form the basis of a full proposal to IODP.

The workshop was attended by ~70 scientists from 7 countries and 29 organizations or institutions, including 10 from US institutions. The workshop and participant costs were funded by the National Science Foundation U.S. Science Support Program (USSSP), the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and the European Consortium for Ocean Research Drilling (ECORD). Tokyo was chosen as the location for the workshop because of the proximity to the Japan Trench and to emphasize the ongoing scientific community response to the devastating 2011 Tohoku-oki earthquake.

An icebreaker on the first night was followed by two days discussing scientific goals of JTRACK and developing a consensus on how to proceed with the full proposal. The second day began with an overview of workshop goals, the approach put forth in the JTRACK pre-proposal, and some logistics of the workshop. A representative of CDEX informed the participants about some of the technical limitations of drilling in the Japan Trench. A member of the Science Evaluation Panel (SEP) presented information about the IODP proposal process, and summarized the main recommendations made by SEP in their review of the pre-proposal. Keynote science talks were given about the current state of knowledge of earthquakes and tsunami at the Japan Trench, and results from the first drilling expedition to the Japan Trench (JFAST Expedition 343/343T). In the afternoon the participants were divided into breakout groups on topics of mechanical stratigraphy and structural geology, paleoseismology, geochemistry, logging science, post-drilling monitoring, and site characterization. Participants discussed the scientific motivations for future investigations into the Japan Trench subduction zone. Breakout groups were charged with reporting back to the workshop as a whole about their most important science questions, including a prioritization for what to address first. The third day of the workshop focused on working toward a consensus of which areas and sites along the Japan Trench merit the highest priority for the first stage of a drilling program. This was accomplished first by reconstituted breakout groups and then workshop participants as a whole. The primary science targets for the next stage of drilling are summarized in the next sections.

3. Revised JTRACK science objectives

The workshop participants agreed that the recent and historical tsunamigenic earthquakes at the Japan Trench demand further investigation. Outstanding questions regarding the causes of large, shallow slip associated with tsunami generation extend to both the mechanical properties of the plate boundary fault and the history of past great earthquakes along the margin. The causes of the extraordinary slip near the trench during the 2011 Tohoku-oki earthquake remain enigmatic. However, several hypotheses have been proposed to explain the shallow slip: that the fault is composed of intrinsically weak material, of dynamically weak material, or that the inertial effects from the rupture dominate over the local physical characteristics.

The workshop participants proposed that the JTRACK project should establish the primary control on shallow earthquake slip at the Japan Trench by testing the hypothesis that *the fault zone material properties control shallow slip*. This can be achieved by drilling at multiple sites along the trench that experienced different slip amounts in a single earthquake rupture. If the composition of the plate boundary fault does not change, the slip was not sensitive to composition. 'Material properties' refers to the elastic moduli, frictional strength, frictional stability, permeability, porosity, consolidation state, and mineral composition of the fault zone and adjacent rocks. Specific questions encompassed by this central hypothesis include:

- What rock properties control the earthquake coseismic and postseismic deformation?
- How does the presence of frictionally weak, velocity-weakening pelagic clay in the incoming plate influence the variable seismic behavior of the plate boundary? Is it possible to correlate the seismogenic behavior of the margin with variations in the stratigraphy of the input section?
- Is there proxy evidence for repeated, large slip at shallow depths on the plate boundary décollement?
- Are there differences in fault characteristics in regions that rupture in 'tsunamigenic' earthquakes compared to great earthquakes?
- What are the permeability values of rocks in and around the fault zone and how do they contribute to fluid flow and maintenance of excess fluid pressures and reduction in effective stress in the fault zone.
- What is the shear strength and consolidation history of slope sediments and how do they contribute to slope failure during seismic activity?
- How quickly does the plate boundary fault recover and start to build up stress again after a great earthquake?

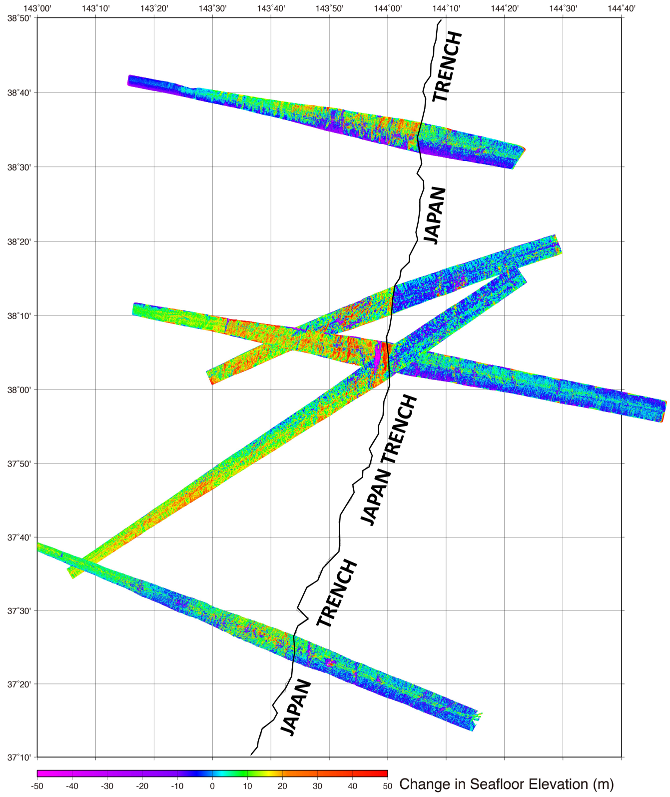

Figure 2. Results of five bathymetric surveys showing the differential bathymetry pre- to post-Tohoku 2011 (Fujiwara in preparation). The resolution of differential bathymetry is around 20 m. The largest observed vertical motion occurred at around 38°N close to site C0019. Transects further north and south of 38°N are unable to resolve significant vertical changes, implying the changes are less than 20m.

Results from Expedition 343/343T indicate that the plate boundary fault in the region of maximum slip is localized on a layer of extremely weak pelagic clay. However, the rupture extended hundreds of kilometers along strike. Although slip models based on geodetic, tsunami or teleseismic details provide little constraint on the slip distribution near the trench (far from the observation GPS or seismometers), all results show the slip was heterogeneous near the trench. A more robust constraint on the slip distribution is available from repeated bathymetric surveys from before and after the 2011 Tohokui-oki rupture (Figure 2). These show slip of the order of 50 m near site C0019 but bound the slip to less than 20 m tens of kilometers to both the north and south. Slip therefore varied within the earthquake rupture area, providing opportunity to target useful sites for drilling.

Workshop participants also prioritized the second objective of the JTRACK project: to investigate the history of past great earthquakes along the margin. At the workshop, participants first reviewed results from two recent shallow subsurface coring efforts (> 10 long gravity and piston cores) that demonstrate the high preservation potential of seismo-turbidites, and documented at least three turbidite units that correlate to previous mega-earthquakes (including the 869 AD Jogan Earthquake; Ikehara *et al.*, 2012; Ikehara *et al.*, submitted). The specific sedimentological characteristics and setting of the trench-fill basins were assessed by these studies and show high potential for long-term seismo-turbidite records. Further development of this record is possible by accessing several separate trench-fill basins along strike of the entire margin and obtaining samples from deeper subsurface depths by giant piston coring and/or drilling. The results would address the following scientific questions:

- What are the sedimentological, physical, chemical, biogeochemical proxies that allow for recognition and dating of past earthquakes

- What is the spatial and temporal distribution of such “proxy-data” and how do they relate to earthquake rupture pattern, earthquake and or tsunami magnitude?

Addressing these scientific questions will eventually allow for constructing a great earthquake chronology to test the hypothesis that the great earthquake recurrence pattern of the Japan Trench subduction zone includes modes and intervals not recordable in instrumental and historical data

The JTRACK pre-proposal sought to address the mechanics and rupture history of the Japan Trench subduction zone with a coordinated program of along-strike drilling to capture the variation in stress state and material properties in regions of the trench that generated tsunamis at different times in the past. However, following feedback from the SEP and extensive discussion regarding the logistics, timing and short drilling expedition strategy, one of the key outcomes of the Tokyo workshop was a consensus that the scientific goals and logistical planning would be more achievable if the scope of a future proposal to IODP were more geographically focused. The JTRACK proposal will focus on the 2011 Tohoku-oki rupture area.

4. Drilling locations and strategy

Two locations within the 2011 Tohoku-oki rupture area were proposed to address the primary JTRACK goal of establishing whether the material properties control the mechanical behavior of the shallow megathrust: one in the region of maximum slip and one where the slip is observed to be substantially lower. A third additional location was highly prioritized outside the 2011 rupture area but within the region that slipped during the 1896 Sanriku tsunamigenic earthquake where large, shallow slip occurred in a M8.2 event.

In order to answer some of the questions outline above, the research plan developed during the workshop included across-strike transects at each location with the following generalized drilling objectives (see Figure 3):
1. Sample a reference input section on the incoming plate as a baseline for comparison with regional geophysical surveys, sediments in the prism and materials in the plate-boundary décollement.
2. Obtain cores from approximately 100 m long intervals in the shallow portion of trench-fill sediments to extend the seismoturbidite record back over 10 ka. This effort will be paired with non-drilling sediment sampling (giant piston coring and conventional sediment coring) along-strike the entire margin.
3. Continuously core the frontal prims, fault zone and downgoing plate to the basaltic basement in multiple locations to ensure the plate boundary fault is penetrated and determine representative fault rock properties by structural analysis and laboratory experiments.
4. Measure the physical and pore fluid property changes over time following an earthquake with a sub-seafloor observatory to establish how quickly the plate boundary recovers.
5. Investigate the role of fluids in the mechanical behavior of the plate boundary with geochemical and physical property data from continuous cores through the frontal prism.

6. Characterize the prism stress state from borehole and sediment property measurements and geodetic monitoring.

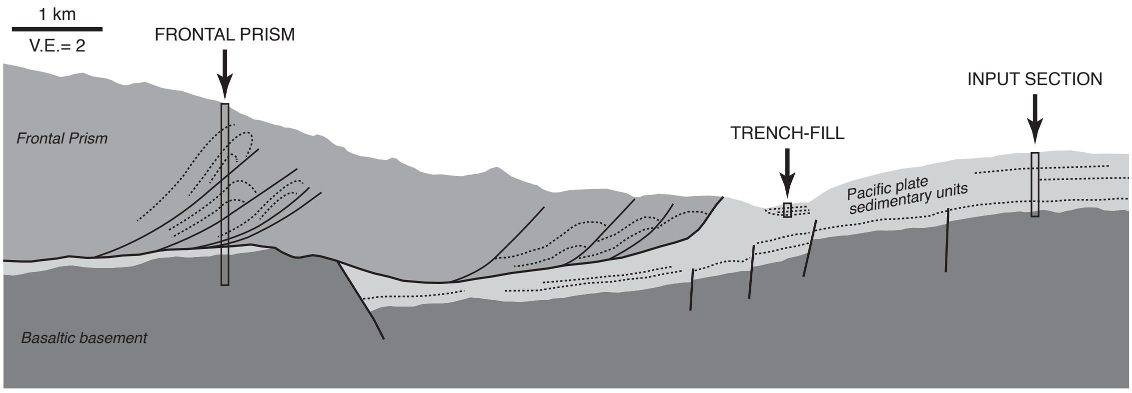

Figure 3. Representative section through the Japan Trench based on seismic surveys of site C0019 showing the structure of the margin (solid lines are faults, dashed lines show bedding attitudes observed in seismic reflection survey data; after Chester et al., 2013; Nakamura et al., 2013). Three sites defining an across-strike transect at each location were prioritized by the JTRACK workshop participants, which are shown by vertical arrows. Open rectangles indicate depth of penetration of coring holes at each site.

4.1 Region of maximum slip: Site C0019 (latitude 38°N)

Site C0019 was chosen for study during Expedition 343/343T because it is located within the region of maximum slip during the 2011 Tohoku-oki rupture area (e.g. Mori *et al*., 2012) and because the megathrust décollement could be penetrated at <7 km in suitable water depths for wellhead deployment and R.O.V. operation. These characteristics are critical to some aspects of the proposed work for the JTRACK project, which includes coring and LWD characterization of the plate boundary fault and deployment of long-term observatories requiring R.O.V. and underwater TV for completion. Additionally, existing ocean floor bathymetry data, high-resolution seismic data and the results of Expedition 343/343T make this site the best characterized place along the Japan Trench. Three holes were successfully drilled during Expedition 343/343T, including a hole that was occupied by a temperature observatory for nine months. The results confirm the viability of drilling at this site, and provide good constraints on the location of the plate boundary fault and other structures, key intervals for targeted coring, and Expedition 343/343T MWD data can be used to efficiently plan future drilling operations.

4.2 Region of low slip (latitude 38° 30'N)

Direct measurements of the coseismic slip during the 2011 Tohoku-oki rupture have been made through repeat bathymetry surveys across the Japan Trench. Five recently acquired repeat surveys (Figure 2; Fujiwara, in preparation) show that the coseismic slip at the trench was spatially variable. The JTRACK workshop participants prioritized a site along the northernmost repeat bathymetry survey (at around latitude 38° 30'N; Figure 2) where the data provide an upper bound of 20 m for the coseismic slip. This is less than half of the inferred slip at site C0019, but near the center of the rupture area. A site at this latitude therefore offers the possibility of determining whether the mechanical difference is because the material properties of the fault are spatially variable. Site characterization data are currently minimal at this latitude, but indicate the water depth is approximately the same as site C0019 (Figure 4). Acquisition of high-resolution seismic data is planned for October 2014, which will allow a specific site at this latitude to be defined.

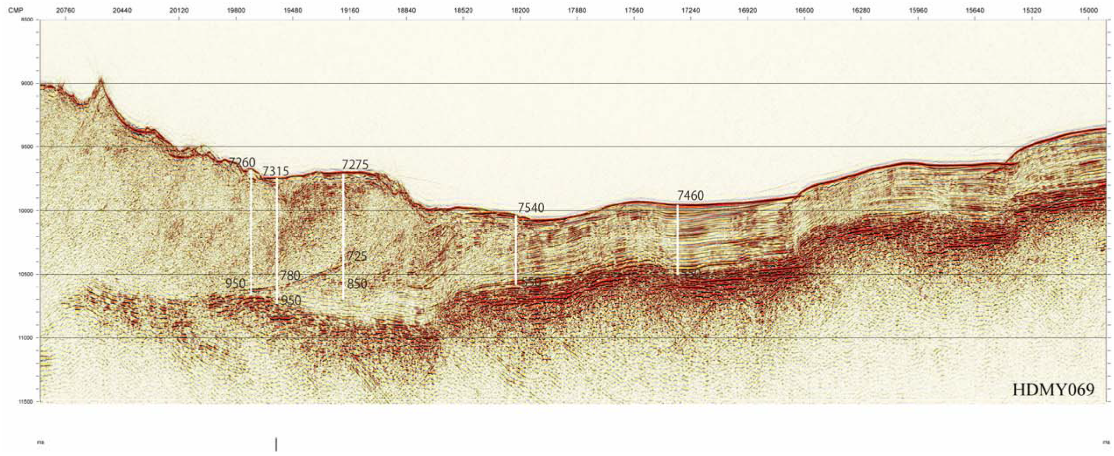

Figure 4. High resolution seismic reflection survey through the Japan margin ~2 km south of the repeat bathymetry line at 38° 30’N. Estimated water depths and depths to prominent reflectors shown.

4.3 1896 Sanriku rupture area (latitude 39° 30’N)

The 1896 M8.2 Sanriku earthquake caused a large tsunami and is inferred to have ruptured the shallow part of the northern Japan Trench with large slip (Tanioka and Satake, 1996). The occurrence of large, shallow slip is a similar characteristic to the 2011 Tohoku-oki rupture, and highlights the possibility that the same material properties that control megathrust mechanics in the central portion of the margin are important further north. Furthermore, this portion of the margin is seismically active and has ruptured in M7 and M8 events in the past few decades, none of which ruptured to the trench. Creep rates inferred from repeating earthquakes indicate that the shallow portion of the plate boundary is creeping, but at a rate substantially less than the plate convergence rate. These observations suggest that the shallow portion of the plate boundary fault is conditionally stable. The JTRACK workshop proposed drilling into the plate boundary fault within the rupture area of the 1896 Sanriku earthquake at a latitude of around 39° 30’N, which is north of the rupture area of the 2011 Tohoku earthquake. Site survey data are currently unavailable for this region so no specific site was selected.

Three fundamental data acquisition methods will be required for the JTRACK project: 1. logging while drilling measurements of formation properties and stress field orientations, 2. cores throughout the input section, trench-fill sediments, the frontal prism, plate boundary fault and subducted plate, 3. subseafloor observatory measurements providing long time series measurements of temperature, water pressure, fluid geochemistry and strain variation.

5. Summary: outcomes and future perspectives

Participants at the JTRACK workshop were asked to prioritize the science objectives and drilling locations outlined in the pre-proposal in light of the Science Evaluation Panel feedback. To develop a focused full proposal to IODP, the workshop participants concluded that the highest priority should be to concentrate on the mechanical controls on the unprecedented coseismic slip during the 2011 Tohoku-oki earthquake rupture. The group decided that three locations offered the chance to establish whether material properties control the seismogenic behavior of the shallow décollement and to probe the trench-fill record for evidence of past tsunamigenic ruptures. Further work is required to fully characterize the causes of large, shallow slip and to broaden the impact of the results to globally relevant conclusions. A full proposal will therefore be prepared by the group in the near future for further coring, logging and deployment of a long-term observatory at site C0019 and at latitude 38° 30’N where the coseismic slip was relatively low. Addressing variability along strike at the Japan Trench, and the specific mechanical properties of the margin to the north where the 1896 Sanriku rupture occurred will follow in one or more additional proposal once site characterization work can be scheduled.

6. Acknowledgements

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7. References

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8. List of Participants

	Last Name	First Name	Affiliation
1	Aoike	Kan	Center for Deep Earth Exploration, JAMSTEC
2	Azuma	Wataru	JAMSTEC
3	Behrmann	Jan-Hinrich	GEOMAR | Helmholtz-Zentrum für Ozeanforschung Kiel
4	Boston	Brian	Department of Geology & Geophysics, University of Hawaii
5	Brodsky	Emily E.	Department of Earth and Planetary Sciences University of California, Santa Cruz

6	Byrne	Timothy	Geosciences, University of Connecticut
7	Conin	Marianne	Georessources, Geomodeling Department, Universite de Lorraine
8	Cook	Becky J.	Ocean and Earth Science, University of Southampton
9	Eguchi	Nobu	Center for Deep Earth Exploration, JAMSTEC
10	Fujie	Gou	Research and Development Center for Earthquake and Tsunami, JAMSTEC
11	Fujiwara	Toshiya	Research and Development Center for Earthquake and Tsunami, JAMSTEC
12	Fulton	Patrick	Seismology Laboratory, University of California Santa Cruz
13	Hamada	Yohei	Kochi Institute for Core Sample Research, JAMSTEC
14	Hashimoto	Yoshitaka	Department of Applied Science, Faculty of Science, Kochi University
15	Hirano	Satoshi	Department of Marine & Earth Sciences, Marine Works Japan Ltd.
16	Hyndman	Roy	Geological Survey of Canada
17	Ikari	Matt	Center for Marine Environmental Science (MARUM), University of Bremen
18	Ikehara	Ken	National Institute of Advanced Industrial Science and Technology
19	Ishikawa	Tsuyoshi	Kochi Institute for Core Sample Research, JAMSTEC
20	Kanagawa	Kyuichi	Department of Earth Sciences, Chiba University
21	Kanamatsu	Toshiya	Research and Development Center for Earthquake and Tsunami, JAMSTEC
22	Kawaguchi	Shinsuke	Department of Subsurface Geobiological Analysis and Research, JAMSTEC
23	Kido	Yukari	Center for Deep Earth Exploration, JAMSTEC
24	Kimura	Gaku	Department of Earth and Planetary Science, University of Tokyo
25	Kirkpatrick	James	Geosciences, Colorado State University
26	Kitajima	Hiroko	National Institute of Advanced Industrial Science and Technology
27	Kodaira	Shuichi	Research and Development Center for Earthquake and Tsunami, JAMSTEC
28	Kuramoto	Shin'ichi	Center for Deep Earth Exploration, JAMSTEC
29	Kyaw	Moe	Research and Development Center for Ocean Drilling Science, JAMSTEC
30	Kyo	Nori	Center for Deep Earth Exploration, JAMSTEC
31	Lin	Weiren	Kochi Institute for Core Sample Research, JAMSTEC
32	Maeda	Lena	Center for Deep Earth Exploration, JAMSTEC
33	McNeill	Lisa	Ocean and Earth Science, University of Southampton
34	Miyazaki	Eigo	Center for Deep Earth Exploration, JAMSTEC

35	Moor	Alexander de	Geology and Geophysics, Oregon State University
36	Moore	J. Casey	Earth and Planetary Sciences, University of California, Santa Cruz
37	Mori	James	Disaster Prevention Research Institute, Kyoto University
38	Nakamura	Yasuyuki	Research and Development Center for Earthquake and Tsunami, JAMSTEC
39	Obana	Koichiro	Research and Development Center for Earthquake and Tsunami, JAMSTEC
40	Ohira	Akane	Research and Development Center for Earthquake and Tsunami, JAMSTEC
41	Ohkouchi	Naohiko	Department of Biogeochemistry, JAMSTEC
42	Omura	Kentaro	National Research Institute for Earth Science and Disaster Prevention
43	Ono	Shigeaki	Research and Development Center for Ocean Drilling Science, JAMSTEC
44	Regalla	Christine	Hobart and William Smith Colleges
45	Saito	Saneatsu	Research and Development Center for Ocean Drilling Science, JAMSTEC
46	Sample	James	School of Earth Science & Environmental Sustainability, Northern Arizona University
47	Sanada	Yoshi	Center for Deep Earth Exploration, JAMSTEC
48	Saruhashi	Tomo	Center for Deep Earth Exploration, JAMSTEC
49	Sawada	Ikuo	Center for Deep Earth Exploration, JAMSTEC
50	Schleicher	Anja	Department of Earth and Environmental Sciences, University of Michigan
51	Strasser	Michael	Geological Institute, ETH Zurich
52	Takase	Koji	Center for Deep Earth Exploration, JAMSTEC
53	Tanioka	Yuichiro	Institute of Seismology and Volcanology, Faculty of Science, Hokkaido University
54	Toczko	Sean	Center for Deep Earth Exploration, JAMSTEC
55	Uemura	Yoshinori	Center for Deep Earth Exploration, JAMSTEC
56	Ujiie	Kohtaro	Graduate School of Life and Environmental Sciences, University of Tsukuba
57	Usami	Kazuko	National Institute of Advanced Industrial Science and Technology
58	Vannucchi	Paola	Department of Earth Sciences Royal Holloway, University of London
59	Wada	Ikuko	Research Center for Prediction of Earthquakes and Volcanic. Eruptions, Tohoku University
60	Wang	Kelin	Pacific Geosicence Centre, Geological Survey of Canada
61	Wu	HungYu (Sonata)	Research and Development Center for Ocean Drilling Science, JAMSTEC
62	Yamaguchi	Asuka	Atmosphere and Ocean Research Institute, University of Tokyo
63	Yamano	Makoto	Earthquake Research Institute, University of Tokyo
64	Yamasaki	Eri	Ocean Floor Geoscience Section 2, Marine Works Japan Ltd.

65	Yokoyama	Takahiro	Center for Deep Earth Exploration, JAMSTEC