Workshop reports on Bend-fault serpentinization (BFS) and Bend-Fault Hydrology in Old Incoming Plate (H-ODIN)

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Jason P. Morgan, Royal Holloway, University of London, UK
Gou Fujie, JAMSTEC, Japan
Ingo Grevemeyer, GEOMAR, Germany
Tim Henstock, University of Southampton, UK
Tomoaki Morishita – Kanazawa University, Japan
Damon Teagle, University of Southampton, UK

1. Introduction and workshop goals

Crustal hydration at mid-ocean ridges by hydrothermal circulation has been considered to be the first-order control on the degree of the oceanic plate hydration (see 'Primary Hydration' region on Fig. 1). Previous ocean drilling projects have aimed to reveal hydration processes and their extent of oceanic crust at spreading centers (e.g., Alt et al., 1996; Bach et al., 2003; Wilson et al., 2006).

Recently, hydration due to plate bending-induced normal faults (bend-faults) in the region between the trench axis and outer rise (outer rise hereafter) has also drawn considerable attention (see 'Rehydration' region on Fig. 1). During the last decade, multiple independent geophysical structure studies have revealed that plate bending-induced normal faults in outer rise regions around the world are associated with significant hydration along (e.g., Grevemeyer et al., 2007; Ivandic et al., 2008; Key et al., 2012; Fujie et al., 2013). This bend-fault-linked hydration and Bend-Fault Serpentinization (BFS), with its associated physical and chemical changes is one of the most significant geological discoveries of the last 15 years. It has the potential to reshape our understanding of Earth's deep water and carbon cycles, the ecology and evolution of species in deep-sea chemosynthetic environments, and even the fundamental mechanism by which slabs bend and unbend, thereby driving Plate Tectonics.

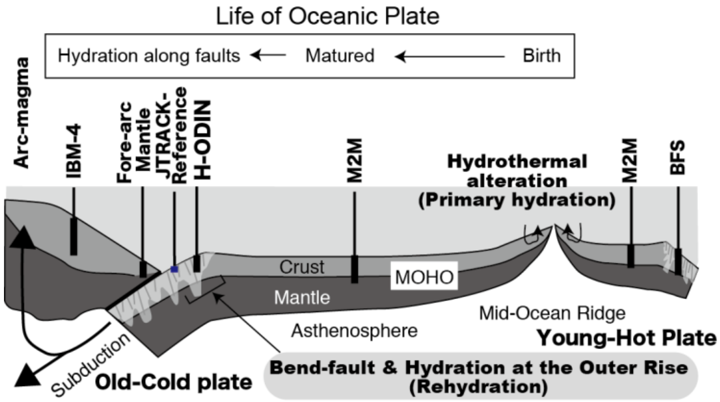

Fig. 1. Schematic tectonic diagram showing the life cycle of an Oceanic Plate with the targets of bend-fault hydration: H-ODIN (= Hydrology of the Old Incoming Plate: 886-Pre) for the Northwestern Pacific region and BFS (=Bend-Fault Serpentinization: Oceanic Crust and Mantle Evolution from Ridge though Trench: 876-Pre) for the Middle American region. Oceanic plates are initially hydrated at mid-ocean ridges by hydrothermal activity (Primary hydration). Much more limited hydrothermal circulation as the plate ages and cools is followed by another pulse of hydration along active bend-faults in the outer rise region that are the target focus of the proposals discussed at this workshop. Several additional IODP proposals relevant to the study of bend-fault hydration are also shown: JFAST = IODP LEG 343 (e.g., Chester et al., 2013), JTRACK = Tracking Tsunamigenic Slips Across and Along the Japan Trench: Investigating a new paradigm in tsunamigenic megathrust slip with very deep water drilling using the D/V Chikyu (835-Full) (Kirkpatrick et al., 2015), M2M= Moho to Mantle (805-MDP), Direct sampling fore-arc peridotite (Fore-arc Mantle), and The middle crust in the continent (IBM-4). JTRACK and M2M sites can be used as reference sites for the incoming plate prior to hydration along the bend-faults at the outer rise region, and the CRISP site (not shown at right-hand site) is also a potential reference for the forearc..

Bend-fault hydration will depend on various conditions such as temperature, the state of stress, and rock and fault permeability to fluid flow. Ideally, comparing subduction zones in several contrasting geodynamic states (e.g. Old plate vs Young plate, bend-faults being reactivated abyssal hill faults vs. newly formed horst-and-graben faults, etc.) is likely to be the most promising exploration approach to expand our knowledge of bend-fault hydration processes. In order to deepen our understanding of bend-fault hydration processes and their effects on changing in physical properties in incoming oceanic plate in many subduction zones, two pre-proposals: Bend-Fault Serpentinization: Oceanic Crust and Mantle Evolution from Ridge through Trench (BFS), and Bending fault hydrology of the Old Incoming Plate (H-ODIN) were developed. Their proposed work aims to obtain and analyze in-situ physical properties, lithofacies, biofacies, and fluids in active bend-fault systems by ocean drilling in the middle America (young, hot) and northwest Pacific (old, cold) regions of oceanic plate subduction, respectively (Fig. 1).

In order to further develop this research effort, thirty-eight scientists from 7 countries and 14 organizations/institutions attended the IODP workshop, "Bend-Fault Serpentinization, drilling proposals using the D/V *Chikyu*", was held in London, 19–21 June 2016. The workshop was sponsored by CHIKYU IODP Board (CIB), the UK-IODP, and the European Consortium for Ocean Research Drilling (ECORD).

The drilling-oriented goals of the workshop were to refine scientific objectives, drill sites, and strategies for scientific drilling in the outer rise region to understand the nature of the bend-fault hydration in the incoming plate. We also hoped to reach – and did reach – a consensus on the best approaches to make the most rapid progress towards better understanding this frontier area of Earth Science.

2. Rationale for drilling into two outer rise regions: Middle American and Northwest Pacific regions

2.1. Middle American Region

In this region, bend-faulting using reactivated MOR normal faults is associated with bright fault-like reflectors that continue from surface bend-faults through the crust and into the upper mantle (Ranero et al., 2003). The normal mantle, seismic P-wave speeds ~ 8 km/s, away from regions of plate bending does not have bright reflectors. The bright reflectors in this region are conjectured to be caused by partial serpentinization around a fault, which would result in a lower seismic wave velocity. Seismic refraction and tomographic delay-inferred wave velocities for the Middle American region are all consistent with ~10-20% serpentinization (Ranero et al., 2004; Ivandic et al., 2008; 2010; van Avendonk et al., 2011).

Regional heat flow above this area of active bend-faulting is only ~20% of the conductive heatflow expected for lithosphere of the studied age (Grevemeyer et al., 2005; Iyer et al., 2012). This low conductive heatflow implies large-scale regional hydrothermal inflow into the faulting region. Finally, electromagnetic imaging of the Middle American region suggests an increasing of porosity along bending-fault planes, which might act as fluid pathways required for serpentinization of the uppermost mantle (Key et al., 2012; Naif et al., 2015). In addition to this region being one of the best-characterized bend-faulting regions, it is the shallowest exemplar of well-developed bend-faults and BFS. It also provides a unique opportunity to ultimately drill a compact 'flowline' from the East Pacific Rise, through an off-axis EPR-lithosphere MoHole reference site to characterize on and off-axis chemical transformations, to a BFS site that documents the final chemical transformations and interactions between seawater, crust, and mantle before the plate subducts into the mantle.

2.2. Northwest Pacific region

The world's largest dense onland seismic observation network has been developed in NE Japan. In addition, a large number of onland/offshore seismic surveys have been conducted off-Tohoku region, both before and after the 2011 Tohoku earthquake (Nakamura et al. 2013, 2014). This network and surveys provides an invaluable data set to study subduction zone processes, and the high seismic hazard associated with this system makes it have key societal impact.

Geochemical analyses and their quantitative modeling on volcanic rocks have also been extensively studied in the northeastern Japan arc (e.g., Kimura et al., 2009; Kimura & Nakajima, 2014), arguably the world’s most densely studied volcanic arc system. Drilling results coupled with these existing data will allow us to most accurately quantify geochemical recycling at this subduction zone.

Horst-and-graben bend-fault structures are the extremely well developed in the northwestern Pacific subduction system. This region has very old, cold, subducting oceanic plates, hence is likely to be associated with the deepest extents of bend-fault hydration, which is reflected in it having the greatest depth-separation between the upper and lower planes of its double Wadati-Benioff zone (Iyer et al., 2012). Detailed Vp/Vs variations within the incoming plate have been determined so far only in the NW Pacific region. The Vp/Vs ratio is high at the outer rise area where bend-faults start to be developed (Fujie et al., 2013). The Vp/Vs ratio, in addition to Vp, provides good constraints on lithology, porosity, and the presence of fluid (e.g. Christensen, 1996; Takei 2002).

Anomalously high heat flow values, significantly higher than that expected for seafloor of this age, are found to be pervasively distributed in the off-Tohoku outer rise region (Yamano et al., 2014). (Note this is exactly the opposite regional signal to that found in the BFS region offshore Middle America; both regions are anomalous, but in opposite directions.) This heat flow anomaly has been attributed to vertical heat transport by fluid circulation in a permeable layer in the oceanic crust, which thickens towards the trench due to the development of bend-faults (Kawada et al., 2014).

The off-Tohoku region also provides a rare opportunity to study a place where the local stress state is likely to have changed significantly since the 2011 Tohoku Earthquake, to a current transient state favoring the deepest water penetration into the bending plate. Intraplate earthquakes after the 2011 Tohoku Earthquake have normal-faulting focal mechanisms at depths up to about 40km, whereas those occurring before the Tohoku Earthquake had normal-faulting at depths shallower than 20km and had reverse-faulting mechanisms, i.e., a compressional stress field, at depths of around 40km (Obana et al., 2011).

Ocean bottom seismograph observations constrain detailed microseismic activity that is considered to be related to actively deforming bend-faults (Obana et al., 2012, 2014). Relationships between the projection of epicenters of microearthquakes after the 2011 Tohoku Earthquake and topographic lineations of horst and graben structures in the outer rise region (white arrows in the middle figure), suggesting that bend-faults are strongly associated with ongoing microearthquakes (Obana et al., 2012).

2.3. Why do we need to drill into both regions?

Discussion at the workshop reemphasized that there are major differences in the style of bend-faulting between the Northwestern Pacific and the Middle American regions, differences possibly linked to plate age/thickness/thermal structure and the obliquity between inherited ridge seafloor fabric/magnetic anomaly lineations and the trench axis.

We agreed that the best approach would be to compare and contrast the behavior of these two distinct end-member systems — as distinct in morphology and behavior as the differences between (slow) median valley and (fast) axial high spreading centers. We therefor discussed plans to simultaneously understand the bend-fault system at a young/reactivated ridge-fault system (Middle American region) and an old, horst-and-graben style with newly created bend-faults system (Japan Trench/Northwestern Pacific region).

At the sedimentary scale, these two sites also differ considerably. This is likely to lead to different mechanical responses when the fault breaks through sediments. Differing sediments are also anticipated to also play a key role in the hydrology of a bending-fault hydration system (affecting near-surface uptake and discharge of the system). We know that the Northwestern Pacific region and the Middle America region have strikingly different heat-flow responses to plate bending, (considerably higher-than average heat flow vs. considerably lower-than-average heat flow), and anticipate that an ‘impermeable’ sediment barrier at the Japan Trench vs. frequently permeable seafloor-to-bend-fault connections at the Middle American Trench may be responsible for this first-order difference.

We also recognized that it will be very important to obtain experience in drilling these potentially difficult drill-site targets, and that the combination of drilling in two-different styles of bend-fault systems is likely to lead to the most rapid progress in learning how to drill in bend-fault environments. We envision that two different platforms will be used for this drilling because of current drilling realities. The *Chikyu* is essential for Japan Trench drilling, whereas the JR is capable to execute the proposed initial Middle American region drilling (see below). The Middle American region has potential for later deeper drilling to get in-situ mantle samples that will allow us to understand the implications of bend-fault hydration for mid-lower crustal and mantle alteration.

3. Recommendations on scientific objectives and testable hypothesis from the workshop

The objective of the present pre-proposal for the Middle American region (876-Pre) is to drill through the ocean crust in an area of active bending-fault serpentinization. A dual-mode drilling strategy is proposed: (Stage I), D/V JOIDES Resolution or D/V Chikyu drilling through the upper parts of the bend-fault system to better understand the chemistry and shallow fluids, fluid flow, and bend-fault-linked microbial ecosystems, and also assess and improve drilling through bend-faults, and (Stage II), a MoHole-type drilling strategy to sample an intact crustal and mantle section through 1km below the ~5.5km-deep crust-mantle boundary.

During the workshop, we reached the important decision to drill at similar target-depths with a similar overall drilling strategy for both regions that will allow us to address the scientific objectives shown below. A new proposal using the JR for the Middle America region will be discussed in the future. Here we will describe common scientific objectives for both regions and potential drilling sites for the Northwestern Pacific region in the following section.

3.1. The following questions on the nature of bend-fault hydration were raised at the workshop.

3.1.1. Science target 1: Bend-fault material and structure.

1. Identify 'fault': a single fault plane or thick fault zone? What is the near-surface evolution of a bend-fault: Feedbacks between petrography, fluid flow, and fault dynamics.
2. What are key geological properties associated with a bend-fault? In:
   Sediment: slip propagation to seafloor, or not?
   Basalt: nucleation of outer rise earthquakes, faulting in strong and immature (or semi-mature) oceanic crust
   Strength profile of the boreholes: Is the fault strong or weak? Thickness of a weak zone(s), if present?
   Estimate maximum size of past earthquakes (displacement, duration time)

3.1.2. Science target 2: Bend-Fault Stress State and monitoring stress-state and fluid flow

3. What is the present-day stress state from the seafloor through the basaltic layer through a fault (or a fault zone)? Does, and where does the incoming plate reach a compressional state?
4. Monitoring fluid flow associated with earthquake activity. This is important to understand the whole trench system including possible impacts shaping megathrust earthquakes.

3.2. Testable hypotheses and unique questions

1. Did seismic slip in outer rise earthquakes reach the seafloor? (core)
2. Was all the displacement at this horst-graben system formed by seismic slip? (core)
3. Is the fault within basalt strong or weak? （core, logging, drilling parameters）
4. (1) Development of stress environment (core, logging, monitoring)

   (2) Are small EQs triggered by fluid migration from mantle? (monitoring)

3.3. For science target 2 (monitoring)

a. Characterize the stress state from sediment through the basaltic layer through the fault using borehole (borehole breakout) and rock property measurements (Anelastic Strain Recovery; ASR) and long-term observatory monitoring (data can be accumulated in collaboration with JTRACK)
b. Monitoring fluid flow (pressure and temperatures) associated with earthquake activity by long-term observatory and earthquake monitoring at the seafloor using short-duration OBS arrays
c. CORK measurements (future observatory proposal)

4. Recommendations from the workshop on potential sites and drilling strategies

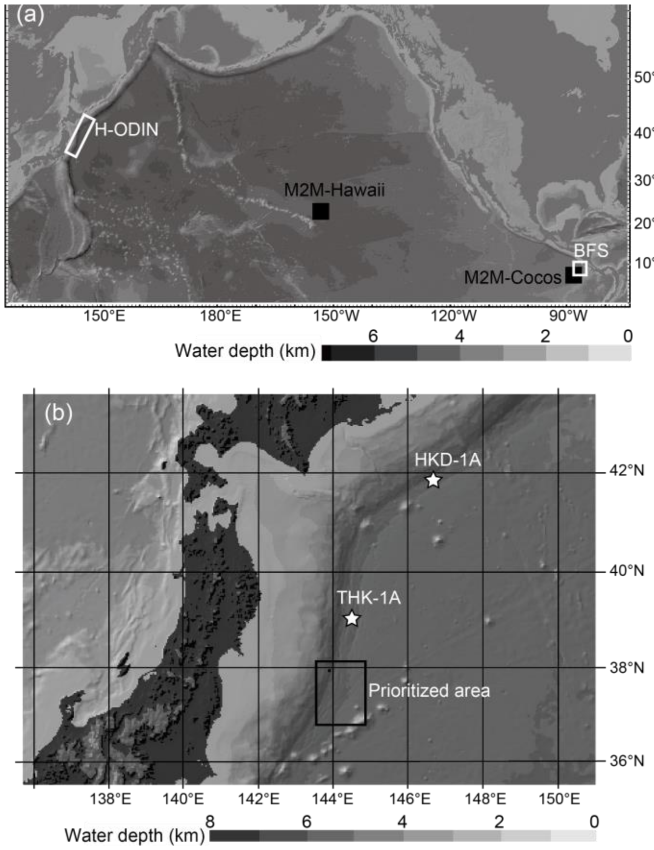

Figure 2. (a) Bathymetric map of the Pacific Ocean showing the locations of two IODP pre-proposals on hydration in the incoming plate (H-ODIN of the Northwest Pacifc and BFS of the Middle American) and two potential sites for the Moho to Mantle (M2M) drilling project (M2M-Hawaii and M2M-Cocos) (Umino et al., 2013). H-ODIN = Bending Fault Hydrology in the Old Incoming Plate, BFS = Bend-Fault Serpentinization: Oceanic Crust and Mantle Evolution from Ridge through Trench. (b) Bathymetric map of the northwest Pacific area showing the locations (shown by stars) of the potential H-ODIN sites offshore Tohoku (THK-1A) and offshore Hokkaido (HKD-1A) area shown in the IODP pre-proposal (886-Pre). The new potential area favored in the workshop is shown by the box marked ‘Prioritized area’. Bathymetric maps were prepared by GeoMapApp developed at Lamont-Doherty Earth Observatory, Columbia University, USA.

We discussed advantages and disadvantages in three potential sites (two from the Japan Trench and one from the Kuril Trench) of the Northwestern Pacific region. The Japan Trench site seems best for understanding links between bend-induced hydration and the outer rise seismic cycle. (especially optimal now as we are in a rare phase between a giant megathrust event and its potential outer-rise doublet.). Another key difference is that the oblique Japan Trench mode of faulting must involve the creation of some new bend-faults, as documented by seafloor bathymetry. We also see the Kurile trench of the Northwestern Pacific region is a potential 3^{rd} ‘style’ of bend-faulting with horst-and-graben style bend-faults forming by reactivation of prior MOR-generated abyssal hill faults. This could justify parallel study in the future.

4.1. We prefer the Japan Trench site: Why?

1. We have 1933 Sanriku earthquake as an example. Now is a rare moment just after the 2011Tohoku earthquake where an associated major outer-rise event has yet to happen: unique opportunity within a long-duration EQ cycle.
2. Huge data accumulation in Japan Trench, comparable to JTRACK
3. Kuril Trench is viewed as a lower priority because of its apparent lower relevance to understanding Japan Trench Seismogenesis.

5. Recommendations for Drilling, Monitoring and Experimental Strategies (Fig. 3)

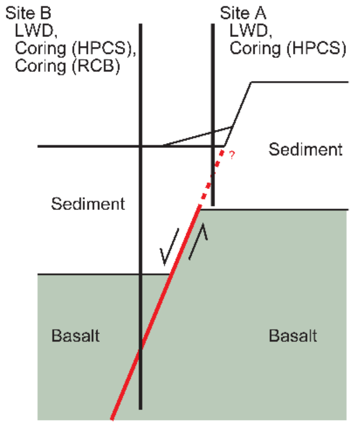

Fig. 3. Schematic diagram showing recommended drilling, monitoring and experimental strategies

a. Two drill sites are absolute minimum requirement (Site A: fault within sediment, Site B: fault within basalt)

Site A: LWD and HPCS-coring; Site B: LWD, HPCS&ESCS-coring and RCB-coring

b. Obtain representative fault and surrounding rock samples for structural analyses and laboratory experiment
c. Analyses of fault rock to detect temperature anomalies and alteration (XRD, XRF, Raman spectroscopy, etc.) and their distribution across a slip zone
d. Friction experiments to test rupture propagation (high-velocity friction) and slip instability (*a*-*b* of rate-and-state friction law, velocity step test)
e. Fault within sediments could provide pore fluids from a deep source, and carbonaceous material is very useful for detecting paleotemperature anomalies (vitrinite reflectance and Raman techniques)
f. Mass-Transport deposits (MTD) and seismogenic turbidites associated with normal faulting

g. Fluid circulation along faults within basalt can be assessed by fluid inclusions in veins
h. Strength profiles can be estimated from the drilling parameters

6. Other points:

6.1. Pre-drilling research: MCS crossing lines at several target sites are needed for pre-drilling research. It would also be very desirable to have better heat flow site-survey characterization, and near-bottom seawater or bottom sediment seawater/pore-fluid sampling and characterization.

6.2. Scientific Team: We need to consult with microbiologists about optimal biological sampling techniques and strategies at these target regions.

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Workshop schedule

Day 1 Sunday		Royal Holloway Meeting on Bend-Fault Serpentinization (Talks)
9:00 – 9:15	Morgan, Morishita	Introduction
9:15 – 10:00	Morgan, Rietbrook,John	Overview on Bend-Fault Serpentinization as a Geological Process
10:00-10:30	Kodaira	Geophysical Constraints on Subduction-Related Deformation and Serpentinization in Western Pacific
10:30-11:10		40 min Coffee/Tea Break (and poster setup)
11:10-11:40	Grevemeyer, Ranero	Geophysical Constraints on Subduction-Related Deformation and Serpentinization in Middle America
11:40-12:00	Naif	E-M results offshore Middle America
12:00-12:25	Sass	Serpentinization and Life
12:25-13:30		Lunch (and poster setup, if not yet done)
13:30-14:10	Katayama, Kagoshima	Hydrothermal processes along Bend-Faults
14:10-14:50	Kimura, Yamaguchi	Geology and Petrology in Western Pacific
14:50-15:25	Henstock, Grevemeyer	Geophysics in Eastern Pacific (II): Current and Future State of Geophysical Surveys (also follow-up and discussion of points raised in the morning geophysics talks)
15:25-16:00		Tea (35 min)
16:00-16:20	Morishita	Current H-ODIN Science Plan
16:20-16:40	Morgan	Current BFS Science Plan
16:40-17:00	Umino	Current M2M Science Plan
17:00-17:20	Eguchi	How to prepare a Chikyu-drilling proposal
17:20-19:00		Posters (with Drinks)
19:00–19:30		Workshop Photo (Founders Courtyard outside Banquet)
19:30-		Workshop Banquet, Founders Picture Gallery

Day 2 Monday		H-ODIN Proposal Discussion and Preparation
9:00-9:10	Ono	Introduction （SEP REVIEW）
9:10-10:10	Fujie, Obana, Yamano	Geophysical characterizations around the proposed drilling site in NW Pacific
10:10-10:50	Kuroda(Saito), Park	Cretaceous sediments in the NW Pacific Core-log seismic integration
10:50-11:20		30 minute Coffee/Tea Break
11:20-12:00	Saito & Fujie	Finding fault by logging-while-drilling & Site candidates and site survey perspective
12:00-12:30	Chair: Morishita Morgan	Preparation for H-ODIN full-proposal I Make a list of scientific topics, assign teams and team-leaders for each topics (Short presentations are welcome)
12:30-14:00		Lunch
14:00-16:00		Breakout Session Preparation for H-ODIN full-proposal II Site selection and site survey Drilling Strategy
16:00-16:30		Coffee/Tea
16:30-17:30	Chair: Ildefonse, Yamano	Presentation from each group Preparation for H-ODIN full-proposal III Report out each group outline plan for each section and drafts/sketches/lists of associated figures
17:30-18:00	Chair: Fujie, Saito	Beer/wine/coffee/snack break. Discuss site selection and site characterization. Also discuss and get feedback on the known barriers and problem areas that still need to be resolved in order to complete our IODP proposal-writing task.

Day 3		BFS Proposal Discussion and Preparation
9:00-9:10	Teagle	Introduction
9:10-10:10	Chair:Teagle	BFS Discussion to refine prioritized, staged, drilling objectives for the Middle America Trench. Alert of possible ~5 drilling days during JR 2019 transit through Panama.
10:10-10:40		30 minute Coffee/Tea Break
10:40-11:40	Chair: Ildefonse	Begin to outline and discuss full-proposal sections
11:40-12:00		20 minute Coffee/Tea Break
12:00-12:30	Chair: Morishita	identify possible overlap/common targets to be studied with MAT and JT drilling and drilling-linked seafloor observation
12:30-14:00		Lunch
14:00-15:00	Smaller Groups?	Continue to outline and discuss full-proposal sections
15:00-15:30	Chair: Morgan	Assign teams and team-leaders for each section
15:30-16:00		Coffee/Tea
16:00-16:30	Teams	Continue to outline and discuss full-proposal sections
16:30-17:00	Morgan, Morishita	Task-list for BFS: outline plan for each section and drafts/sketches/lists of associated figures
17:00-19:00		Beer/wine/coffee/snack break. Discuss where we stand after this session of BFS planning. Also discuss and get feedback on the known barriers and problem areas that still need to be resolved in order to complete our IODP proposal-writing task.
19:00-		Smaller group meets offsite to decide on prioritized list of post-workshop work-tasks for each workshop participant.

List of Participants

	Surname	Name	Institution	Country
1	Abe	Natsue	Jamstec	Japan
2	Clarke	Alexander	Royal Holloway	UK
3	Eguchi	Nobuhisa	Jamstec	Japan
4	Fujie	Gou	Jamstec	Japan
5	Grevemeyer	Ingo	GEOMAR	Germany
6	Henstock	Tim	Southampton	UK
7	Ichihara	Hiroshi	Kobe	Japan
8	Ildefonse	Benoit	Montpellier	France
9	John	Timm	Berlin	Germany
10	Kagoshima	Takanori	Tokyo	Japan
11	Katayama	Ikuo	Hiroshima	Japan
12	Kimura	Jun-Ichi	Jamstec	Japan
13	Kodaira	Shuichi	Jamstec	Japan
14	Malatesta	Cristina	Genova	Italy
15	Mateeva	Tsvetomila	Liverpool	UK
16	Morgan	Jason	Royal Holloway	UK
17	Morishita	Tomoaki	Kanazawa	Japan
18	Nakamura	Yasayuki	Jamstec	Japan
19	Obana	Koichiro	Jamstec	Japan
20	Ono	Shigeaki	Jamstec	Japan
21	Park	Jin-Oh	Tokyo	Japan
22	Ranero	Cesar	CSCIC	Spain
23	Rietbrock	Andreas	Liverpool	UK
24	Saito	Saneatsu	Jamstec	Japan
25	Scambelluri	Marco	Genova	Italy
26	Schwarzenbach	Esther	Berlin	Germany
27	Tamura	Yoshihiko	Jamstec	Japan
28	Teagle	Damon	Southampton	UK
29	Umino	Susumo	Kanazawa	Japan
30	Vannucchi	Paola	Royal Holloway	UK

31	Yamaguchi	Asuka	Tokyo	Japan
32	Yamano	Makoto	Tokyo	Japan