Using Ocean Drilling to Unlock the Secrets of Slow Slip Events

An IODP International Workshop

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Final Report

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1. Introduction: Slow Slip Events and Ocean Drilling

Subduction margins produce the largest and most destructive earthquakes and tsunami on Earth. Knowledge of the mechanics of fault slip behaviour on subduction thrust interfaces is necessary to understand and mitigate the hazards posed by these major plate boundary features. Slow slip events (SSEs) are a new class of shear slip found at subduction margins around the globe, revealing the broad spectrum of fault slip behaviour that exists at subduction margins. SSEs are widely acknowledged as one of the most exciting discoveries of the last decade in the Earth Sciences, and have implications for plate boundary processes and the seismic hazard posed by subduction megathrusts (e.g. Rubinstein et al., 2010; Schwartz and Rokosky, 2007).

Since the first discoveries of episodic slow slip at subduction zones ~15 years ago (Dragert et al., 2001; Hirose et al., 1999), SSEs are now recognized as a globally widespread process observed at most well-instrumented subduction zones (Fig. 1). Geodetic and seismological detection of slow slip and its associated slow seismic phenomena (such as non-volcanic tremor, low-frequency and very-low frequency earthquakes) have transformed our understanding of the spectrum of fault slip behaviour (e.g. Ide et al., 2007), with implications for deformation mechanisms and rheology on subduction megathrusts. Prior to the discovery of slow slip, most studies of fault behaviour assumed that slip on faults occurs either as steady creep, or suddenly in an earthquake. Despite the fact that there is now abundant, widespread evidence for episodic slow slip behaviour that bridges the gap between the stick-slip and stable sliding end-members, the physical mechanisms leading to slow slip are unknown at present.

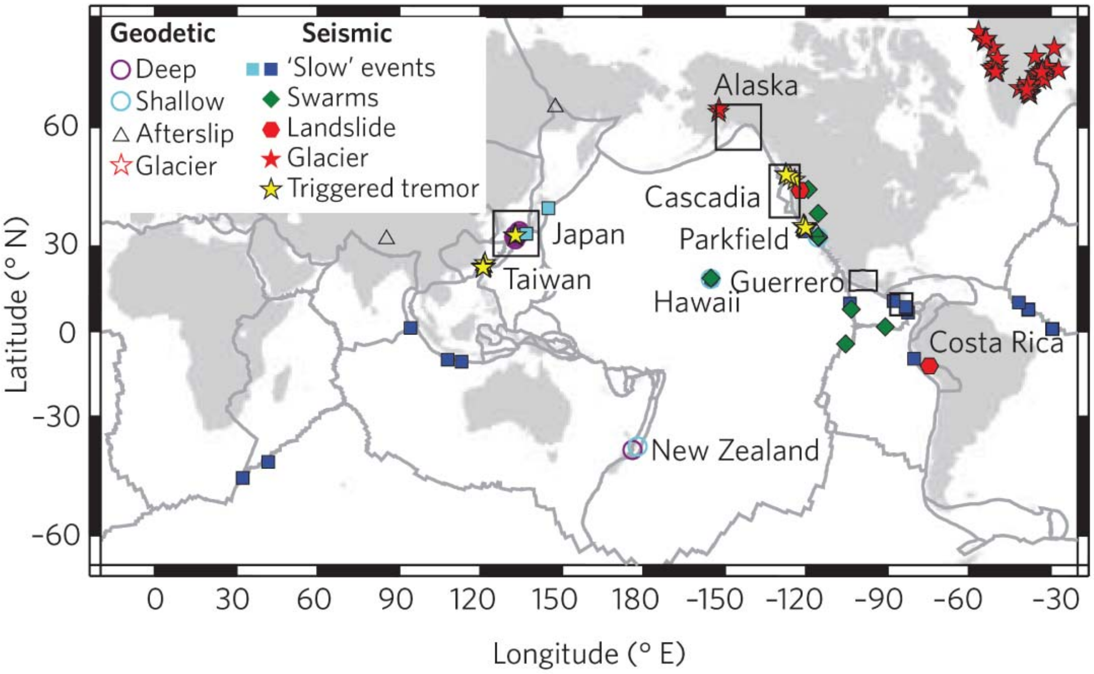

Figure 1: Map showing the global distribution of seismically and geodetically observed slow slip phenomena, from Peng and Gomberg (2010). Note that this map includes slow earthquakes and/or slow slip behaviour from all fault types (not just restricted to subduction zones), and slow phenomena observed in landsliding and glacial settings.

A variety of theories regarding the origin of SSEs have been proposed; many consider episodic slow slip as a consequence of high fluid pressures within a conditionally stable frictional regime (e.g. Liu and Rice, 2005; Liu and Rice, 2007; Schwartz and Rokosky, 2007; Shibazaki and Iio, 2003). These proposed mechanisms for episodic SSE behaviour arise largely from theoretical and modelling studies

(Liu and Rice, 2005; Liu and Rice, 2007; Shibazaki and Iio, 2003), and interpretations of physical properties from seismic attributes (Audet et al., 2009; Kodaira et al., 2004; Song et al., 2009). However, to test theories concerning the fundamental physical mechanisms governing slow slip, sampling of material from within the SSE zone, continuous logging of physical properties and fault zone structure across the source regions, direct measurements of state variables (stress, temperature, and pore pressure), and monitoring temporal changes in seismicity, strain rate, stress, pore fluid pressure, geochemistry of fluids, and temperature near the interface throughout the SSE cycle are required. Because most well-documented subduction SSEs occur at 25-50 km depth on the interface (Dragert et al., 2001; Larson et al., 2004; Obara et al., 2004; Ohta et al., 2006; Ohta et al., 2004) direct monitoring and sampling of most SSE source regions are not possible with current technological capabilities.

The relatively close proximity of SSEs to the seafloor in locations such as New Zealand, central Japan, and Costa Rica allow ocean drilling studies to reach slow-slip thrusts and reveal the physical processes behind SSE occurrence.

While the science is exciting, the practical issues of addressing transient slip behaviour in deep settings such as subduction zones are challenging to say the least, and will require extensive discussion, planning, and debate to define the conceptual basis for developing the science and practical strategies for achieving it. To this end, an **IODP workshop was held in Gisborne, New Zealand from 1st- 3rd August 2011** to discuss the use of scientific ocean drilling to unlock the secrets of slow slip.

The outcomes of this workshop include a full assessment of the scientific questions related to the slow slip process that could be investigated by ocean drilling, a compilation of existing and required auxiliary datasets in areas of potential exploration, and an action plan for the future. These outcomes are discussed in this report.

The workshop conveners were Laura Wallace, Nathan Bangs and Eli Silver, and the steering committee consisted of Rebecca Bell, Stuart Henrys, Joshu Mountjoy and Ingo Pecher. The workshop involved a total of 72 participants (Appendix A) and was funded by IODP-MI, New Zealand Ministry of Science and Innovation, the Consortium for Ocean Leadership, and GeoPrisms.

2. Scope and Summary of the Workshop

The workshop consisted of three days of oral presentations, poster sessions, break-out group discussions, and full group discussions (see Appendix B). The primary objectives of the workshop were to: 1) establish the main scientific questions to be addressed by drilling and instrumenting subduction SSE source regions; 2) compile a comprehensive list of subduction zones worldwide where drilling studies could reveal the conditions leading to SSE behaviour, 3) develop a strategy for determining the physical processes behind the origin of SSEs using ocean drilling studies.

The first part of the workshop (day 1) focused on introductory presentations on the slow slip process and lessons learned from scientific drilling projects at other subduction zones. Presentations on the first day were intended to get all participants up to speed on the latest developments in SSE science, as well as giving those with little or no IODP experience some context for what can be learned from scientific drilling. The presentations over viewing SSE processes included global distribution and characteristics of SSEs, seismic phenomena associated with SSEs, geophysical environment of SSEs, and current hypotheses on the physical properties of fault zones which experience SSEs (see Section 3 of this report).

The introductory SSE talks were followed by several talks focused on lessons learned from previous and current IODP drilling projects at subduction margins, including NanTroSEIZE and CRISP. This session was followed by a breakout session related to discussions of what ocean drilling measurements and experiments could be done to understand the origins of slow slip. The workshop participants broke into three thematic groups discussing: i) What could we learn about SSEs from auxiliary (site-survey) studies accompanying ocean drilling?, ii) What could we learn from monitoring studies including borehole monitoring?, and iii) What types of sampling and experiments are needed to understand the physical properties of SSE zones? (see Section 4 of this report).

The second and third days of the workshop focused on specific locations where using ocean drilling to understand SSEs seems feasible. The second day started with presentations related to specific sites where SSEs are potentially within range of modern drilling capabilities, including the a) northern Hikurangi, New Zealand, b) central Japan and c) Costa Rica margins. The presentations were followed by breakout sessions focused on developing strategies for how the origins of slow slip could be analysed from a thematic point of view at each of the localities (see Section 5 of this report). These thematic breakout groups were organized in a similar way to the first day's breakout session (e.g., auxiliary studies, monitoring studies, and in situ physical properties).

The third day of the workshop began with reporting on the previous day's breakout sessions. Following the reports, geographically-themed breakout sessions (Costa Rica, central Japan, and Hikurangi) were convened to develop implementation plans for drilling projects at the three shallow SSE locations, followed by break-out reporting and workshop-wide discussion on the plans for each margin. The workshop concluded with a final set of presentations on the recent 2011 Tohoku earthquake in Japan and a wrap up discussion.

These presentations were supplemented by posters that were available throughout the workshop, and during a dedicated poster session on the afternoon of Day 2 (Appendix C).

Several key unanswered questions regarding the slow slip process emerged from the workshop, which could be addressed by scientific drilling:

1) <u>What does a slow slip zone look like? In particular, is slip localised to one or several discontinuities, or is slip distributed throughout a continuous zone of finite thickness?</u>

A SSE source area has never been directly sampled, and it is unknown whether SSEs occur on narrow discontinuous fault planes or within continuous zones of deformation (cf. Fagereng and Sibson, 2010, Fig. 2). Sampling of the SSE source area could reveal important information on the deformation mechanisms that accommodate slow slip. The workshop participants highlighted possible challenges in recognising zones of slow slip deformation when drilling, if deformation is distributed over a wide fault zone. Monitoring of the distribution of strain within the SSE source (possibly by repeated casing deformation surveys), however, would help to define the width of the zone of SSE deformation.

In at least some circumstances, zones accommodating seismic slip may be <10 mm in thickness (Sibson, 2003). Additionally, many low-angle thrust faults in foreland fold-thrust settings appear as 'knife-edge' discontinuities, locally subparallel to bedding, with minimal damage zones (Price, 1988). In contrast, aseismic shearing along creeping portions of the San Andreas Fault is locally accommodated at the surface by continuous shear zones ranging up to tens of metres in thickness which also incorporate local planar slip discontinuities (Burford and Harsh, 1980). Apparently continuous ductile shear zones believed to be the products of aseismic shearing in the exhumed roots of major fault zones in the mid-crust also commonly range in thickness from metres to hundreds of metres in thickness (e.g. Hanmer, 1988). Considerable uncertainty therefore exists on the likely thickness of slip / shear zones giving rise to SSE. Subduction shear zones, for example, are commonly postulated to have thicknesses of the order of 1 km or so (von Huene and Scholl, 1991) and have been imaged as such seismologically (e.g. Kodaira *et al*., 2002). Establishing whether SSE occur on discrete planar discontinuities or across a thick zone of distributed shearing, or involve a mixture of distributed shearing and multiple slip discontinuities would thus be a primary goal of any drilling program.

2) Do slow slip events occur in conditionally stable frictional regimes?

Slow slip events are generally located at the downdip transition from stick-slip (velocity weakening) to aseismic creep (velocity strengthening) behaviour (Dragert et al., 2001; Larson et al., 2004; Ohta et al., 2006; Ohta et al., 2004). This location suggests slow slip events may occur in lithologies that are characterized by a conditionally stable frictional regime (e.g. Scholz, 1998). This hypothesis has been supported by laboratory (Yoshida and Kato, 2003) and numerical modelling (Liu and Rice, 2005; Liu and Rice, 2007) experiments that have been able to produce short-period transient displacements spontaneously in this transition zone.

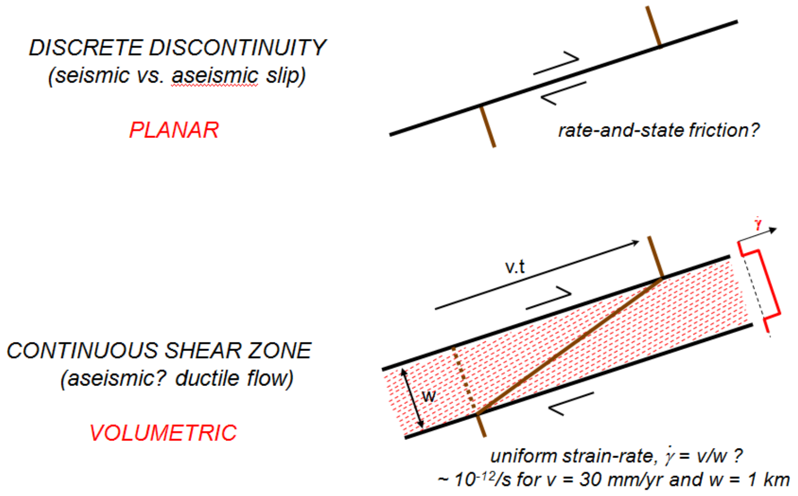

Figure 2: End member models for the subduction thrust interface (after Fagereng and Sibson, 2010)

Numerical models incorporating rate and state friction laws that successfully reproduce SSE behaviour (Liu and Rice, 2007) require that the frictional properties of rocks that host SSEs straddle the threshold between velocity/rate strengthening (aseismic behaviour) and velocity/ rate weakening (seismic slip behaviour). Sampling of material and downhole measurements in the SSE source area, upper plate, and incoming sedimentary section would provide critical insights into the rock types that are hosting SSEs. We expect that laboratory experiments on rock samples from the SSE source will illuminate the role that rock frictional properties play in SSE occurrence.

3) Are slow slip events associated with low effective stress due to high pore fluid pressure?

Fault slip models that incorporate rate-and-state friction require extremely low effective stresses to reproduce episodic SSE behavior, suggesting that high fluid pressures may be needed to generate SSEs (Liu and Rice, 2005; Liu and Rice, 2007). A number of studies that have remotely imaged patches of the subduction interface undergoing slow slip using seismic methods, have generally revealed high amplitude reflectivity and/or Vp/Vs ratios potentially indicative of high fluid content (Bell et al., 2010; Kodaira et al., 2004; Song et al., 2009). Sampling of material and downhole measurements in the SSE source area and within the upper plate would enable pore fluid pressure, permeability, and stress to be quantified, and would reveal the true role fluid pressure plays in SSE occurrence. It is also possible that the abundant fluids are due to mineral dehydration reactions as subducting sediments and basement rocks are buried and heated. Sampling of the material entering the subduction zone and knowledge of the thermal regime experienced by these rocks as they are subducted would enable modelling of these reactions and assessment of their contribution to elevated fluid pressures in the SSE zone.

4) Can a single fault region host both slow slip events and “normal” earthquakes?

If “normal” seismic rupture is incapable of propagating into areas that undergo slow slip, the delineation of slow slip zones could provide an important constraint for the maximum size of megathrust earthquakes on a subduction margin. Due to the currently imprecise location of slow slip and seismicity offshore and to a general lack of offshore seismic and geodetic instrumentation, it is not currently known whether regions of faults that undergo slow slip can also rupture in “normal” earthquakes.

The spatial and temporal relationship between SSE, slow seismic behaviour, and normal microseismicity may reflect small-scale spatial variations in the frictional properties and/or physical conditions at the subduction interface. High-level monitoring of deformation and seismicity close to the SSE source would reveal the spatial and temporal relationships between seismic and aseismic slip, and their implications for spatial variations in the physical properties of the plate interface. Moreover, recent studies have had success using vitrinite reflectance geothermometry on samples recovered from the frontal thrust at the Nankai Trough, which reveal that seismic slip may continue all the way to the trench at Nankai (Sakaguchi et al., 2011). By drilling an SSE, similar methods could be used on material recovered from the SSE source areas to determine whether SSE patches also undergo fast, seismic slip.

5) Are SSEs part of a continuum of slow seismic behaviour?

Ide et al. (2007) showed that similar to earthquakes, slow slip events and slow seismic phenomena (such as low frequency earthquakes, very low frequency earthquakes, and tremor) appear to follow a scaling relationship between moment magnitude (Mo) and duration (T) (Fig. 3). Unlike earthquakes, where $Mo \propto T^3$, SSEs and slow earthquake magnitudes scale linearly with duration ($Mo \propto T^{1\text{-}1.5}$). This important observation has helped to unify these diverse SSE/slow earthquake processes, and indicates that there is likely to be an underlying physical mechanism that dictates the source process of this newly discovered class of earthquakes (Ide et al., 2007). Despite the apparent similarities between SSE and other slow seismic events, there is a large gap in observed slow earthquake behaviour, in the realm of tens of minutes to 1-2 days, with the log of Mo ~15-17 (Fig. 3). While this gap may be due to current technological limitations for observing such events and to the remote location of the geodetic and seismic observing networks relative to the source of slow seismic/aseismic slip behaviour, it may also be due to some rate-limiting mechanical process that produces a gap in the spectrum of slow earthquake/SSE processes. Peng and Gomberg (2010) contended that a full continuum of slow seismic events exists. Installing strainmeters, tiltmeters, seismometers, and pore pressure monitoring equipment in boreholes above and within the source of very shallow SSEs present an opportunity determine if slow earthquake behavior does span a continuum of duration and magnitude characteristics.

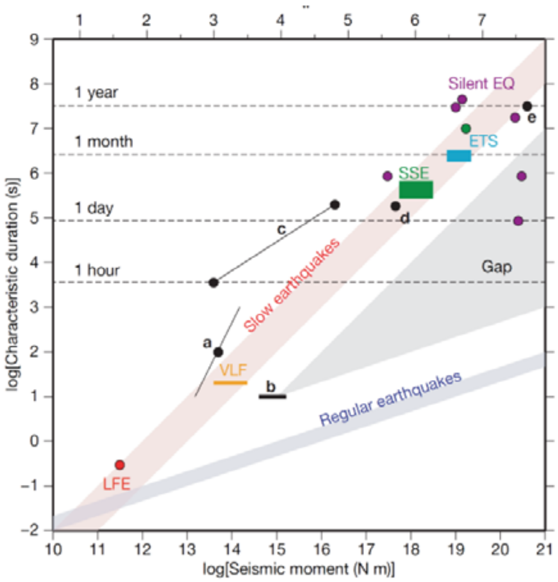

Figure 3: Comparison between seismic moment and the characteristic duration of various slow earthquakes (from Ide et al. 2007). Low frequency earthquakes (LFE, red), very low frequency earthquakes (VLF, orange), and SSE (green) occur in the Nankai Trough while Episodic tremor and slip (ETS, light blue) occur in the Cascadia subduction zone. Purple circles are silent earthquakes. a=SSE in Italy, b=VLF earthquakes Nankai Trough, c= SSE San Andreas Fault, d=SSE Kilauea volcano, and e=afterslip of the 1992 Sanriku earthquake.

6) <u>Are SSEs restricted to a specific pressure or temperature range? Can they propagate all the way to the trench?</u>

We now realize that SSEs occur over a wide range of depths from 25-50 km (Cascadia, southwest Japan, Mexico) to less than 15 km depth (northern Hikurangi, Costa Rica, central Japan). Thus, the range of physical properties (e.g., temperature, mineralogical composition, hydrogeology) that promote SSE behavior may be much larger than previously thought. Does slow slip continue all the way to the trench in some locations? Assessing whether or not slow slip also occurs on the very shallowest portions of the subduction interface has implications for our knowledge of the physical conditions that produce SSEs. However there is a significant loss of resolution of SSE distribution on the offshore portion of subduction thrusts, which cannot be resolved offshore with the extensive geodetic monitoring networks onshore.

These six fundamental questions can be addressed by a strategy that includes geophysical experiments, monitoring shallow instrumented bore holes above SSE source regions, and ultimately direct sampling of the slow slip patch by a deep drill hole. During the workshop the participants discussed generic methodologies to address these questions and developed plans which could be implemented in specific locations around the world.

3. Comparison of subduction margin SSEs worldwide

3.1. Deep SSEs

With the recent increase in geodetic and seismological instrumentation slow slip events have now been detected at well instrumented subduction zones world-wide, suggesting they are a common and fundamentally important part of seismic behaviour at subduction margins. The first slow slip events to be detected were in Cascadia at a depth of 30-40 km, close to the downdip limit of the seismogenic zone (Dragert et al., 2001). Similar deep slow slip events have since been recorded in SW Japan (e.g. Obara, 2010), Mexico (e.g. Vergnolle et al., 2010) and southern Hikurangi, New Zealand (Wallace and Beavan, 2010). These deep slow slip events share similar depth ranges (30 - 50 km), although their durations, moment magnitudes, and recurrence intervals are quite different (Table 1). Deep SSEs occur at depths on the interface that experience a transition from strong interseismic coupling to steady aseismic creep (cf. review in Schwartz and Rokosky), within a temperature range of 350 – 500^0C (Fig. 4). They may also occur at or near the intersection with island arc Moho (e.g. Shelly et al., 2006). There is considerable seismological evidence that deep SSEs occur in regions of locally elevated fluid pressures (e.g. Audet et al., 2009; Kodaira et al., 2004; Reyners and Eberhart-Phillips, 2009; Shelly et al., 2006; Song et al., 2009). The source of significant amounts of fluid at these depths is commonly thought to originate from the basalt to eclogite dehydration reaction that occurs in the ~400^0C temperature range (e.g. Furukawa, 2009). Non-volcanic tremor, which generally accompanies deep slow slip, is thought to derive from the propagation of fluid-filled cracks from regions of high fluid pressure (Furukawa, 2009), and/or the occurrence of shear slip on very small regions of the interface (e.g., Shelly et al., 2006).

	Cascadia	SW Japan	Southern Hikurangi
Aseismic/seismic behavior	Tremor, SSE, up to M~9 earthquakes	Tremor, SSE, VLF, earthquakes[c], great earthquakes	SSE, possible great earthquakes
SSE Duration	~6 - 15 days[a]	Long term (~300 days)[e] and short term (~3 - 9 days) SSEs[c]	> 200 days[d]
SSE Recurrence	14 months[a]	3 – 6 months, short-term SSE[c]	~ 5 years[d]
SSE Magnitude	6.1 – 6.7[a]	5.4-6.2[c]	6.3 – 7.0[d]
SSE Slip amplitude	~ 1.2 – 5.6 cm[a]	~ 1 cm[c] (short-term SSEs)	~15 cm[d]
Plate Convergence	40 mm/yr	Variable. Up to 62 mm/yr[c]	~35 mm/yr
Forearc structure	Accretionary	Accretionary	Accretionary
Subducted plate lithology	Oceanic crust and sediments up to 2.7 km thick[b]	Oceanic crust and pelagic	Plateau, pelagic/turbidites
Temperature	350 – 400 deg[a]	350 – 400 deg	350 – 400 deg
Min. depth to SSE zone below sea level	25 – 40 km[a]	25 – 40 km[c]	25-60 km[d]

Table 1: Summary of deep slow slip event characteristics recorded at Cascadia, SW Japan, and southern Hikurangi. [a]Schmidt & Gao (2010), [b]Flueh et al. (1998), [c]Sekine et al., 2010, [d]Wallace & Beavan (2010), [e]Hirose et al. (1999)

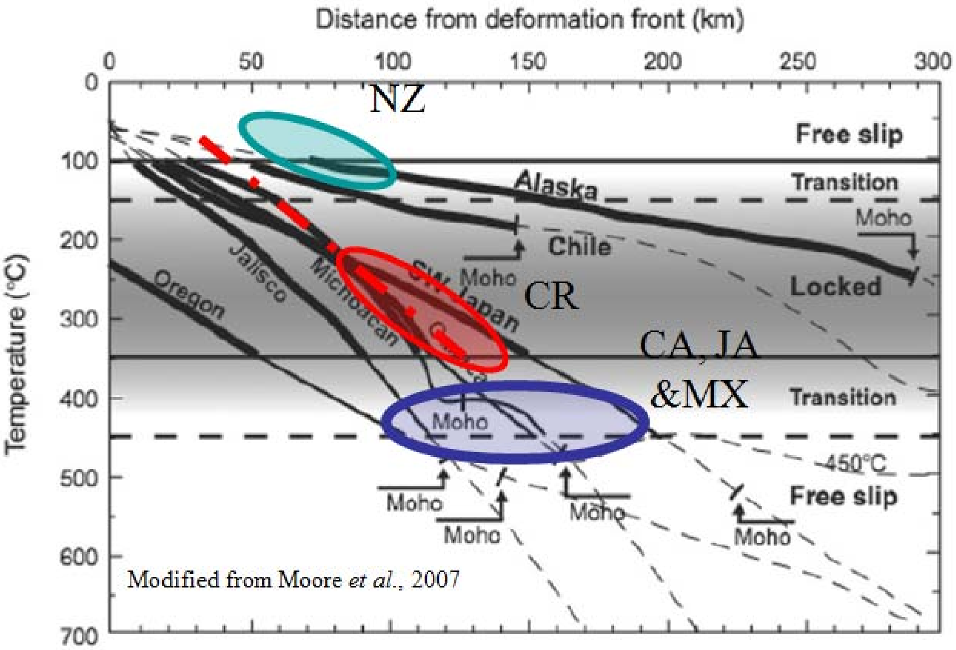

Figure 4: Comparison of the temperature range and distance from the subduction front for slow slip events worldwide. NZ= New Zealand (northern Hikurangi- green ellipse), CR= Costa Rica (red ellipse), CA=Cascadia, JA= SW Japan, MX=Mexico (purple ellipse). Modified from Moore et al. (2007) by S. Schwartz. Bold lines show depth and temperature ranges over which the subduction interface is interseismically locked for different margins.

3.2. Shallow SSEs

The discovery of shallow slow slip events (< 10 – 20 km depth), on parts of the interface cooler than the 100-150 ^{0}C isotherm indicate that neither the basalt to eclogite transition, nor the thermally controlled transition from brittle to ductile behavior can explain all slow slip events and their associated seismic phenomena. Shallow slow slip events have now been detected at Costa Rica (e.g. LaBonte et al., 2009), central Japan (e.g. Sagiya, 2004; Ozawa et al., 2007; Kimura et al., 2010) and the northern Hikurangi margin (e.g. Wallace and Beavan, 2010). Tremor has also been documented in association with shallow slow slip at north Hikurangi and Costa Rica (Kim et al., 2011; Outerbridge et al., 2010). The workshop participants discussed the characteristics of these shallow slow slip events in detail, and revealed a pattern of strikingly similar characteristics between these three sites that has not been acknowledged previously (see Table 2). Each of the three shallow slow slip localities experiences slow slip events with a duration of 10 days to 4 weeks, moment magnitudes of ~6.5 and recurrence intervals of 2 – 6 years, despite variations in the convergence rate, forearc structure, nature of the incoming plate, and overall character of the seismicity at each margin. The duration, magnitude and recurrence interval are all significantly smaller than that recorded for deep slow slip events.

	Northern Hikurangi	Costa Rica	Kanto
Aseismic/seismic behavior	SSE/eq. swarms/tremor/tsunami earthquakes	SSE/tremor/seismic	SSE/eq. swarms/seismic
SSE Duration	2-4 wks[a]	2-3 wks[d]	10 days-1 month[g,h]
SSE Recurrence	2 yrs[a]	~4 yrs[d]	5-6 yrs [h]
SSE Magnitude	~6.5[a]	~6.5[d]	~6.5[h,i]
SSE Slip amplitude	10-15 cm[a]	5-10 cm[d]	10-15 cm[h,i]
Plate Convergence	5-6 cm/yr[b]	9 cm/yr[e]	3 cm/yr[j]
Forearc structure	Erosional	Erosional	Accretionary
Subducted plate lithology	Oceanic plateau; pelagic/tubidites	Oceanic plate; pelagic	Oceanic plate and forearc; terrigenous/volcanic cover
Temperature	Cold (100 – 150^{0}C) [c]	Cold (100 – 150^{0}C)[f]	Cold
Proximity of Trench to land	60 km	60 km	60 km
Min. depth to SSE zone below sea floor	5 km, possibly less[a]	~7 km[d], possibly less[g]	~10 km[h,i]
Water depth above SSE zone	1 km	2 km	2 km

Table 2: Summary of shallow slow slip event characteristics recorded at the northern Hikurangi, central Japan and Costa Rica margins. [a]Wallace and Beavan (2010); [b]Wallace et al. (2004); [c]McCaffrey et al. (2008); [d]Outerbridge et al. (2010); [e]DeMets (2001); [f]Harris and Wang (2002); [g]Brown et al. (2005); [h]Ozawa et al. (2007), [i]Sagiya (2004); [j]Nishimura et al. (2007).

Although the generation mechanism for deep vs. shallow SSEs is likely to be different, they may potentially be related (for example, fluid release caused by dehydration reactions in different temperature ranges). Based on the observations of SSEs over a broad range of depths and temperatures, temperature does not seem to be the primary control on SSE occurrence (Fig. 4) (McCaffrey et al., 2008). However, only the shallow SSEs are potentially within range of modern drilling capabilities, so shallow SSE locations (Table 2) became the focus of the workshop. Because all three locations have very similar characteristics, IODP drilling at any of the three highlighted sites (northern Hikurangi, central Japan, Costa Rica) would likely reveal information that would be applicable to the other sites. While the environments of shallow and deep slow slip occupy different temperature and pressure environments, workshop participants anticipate that IODP sampling of shallow slow slip zones will provide critical clues to the processes of slow slip that operate in both shallow and deep environments.

4. Measurements and experiments needed to understand the origins of slow slip

A key aim of the workshop was the development of a methodology that could help to guide future IODP drilling projects, and associated site-survey experiments to reveal new information on the slow slip process. This methodology was developed in breakout sessions during the workshop where we focused on three topics that we determined to be of highest priority for addressing SSEs. These topics are: i) Auxiliary (non-drilling) studies, ii) Monitoring Studies within boreholes, and iii) Direct measurements (via drilling) of upper plate and subduction interface fault zone physical properties.

4.1. Site selection

Potential IODP drill sites to investigate slow slip must possess extensive existing data and continuously operating instrument networks (GPS, seismology) and be broadly characterised in terms of its structure, properties and behaviour. The location needs to satisfy a number of required characteristics, and ideally a secondary set of preferred characteristics.

Required Characteristics

- Slow slip occurring somewhat predictably
- Parts of the interface undergoing SSE shallow enough to reach by drilling
- High frequency of events so multiple cycles can be monitored over a realistic observation period
- SSE of sufficient magnitude to be measurable, resolvable and causative parameters measured and resolved.

Preferred Characteristics

- Small enough target area to maximise return from potential infrastructure and networks
- A location where different phenomena are linked or co-located (i.e. slow slip events and “normal” earthquakes, or slow seismic phenomena occurring in the same general area)
- A location where onshore geology (i.e. accessible samples) may offer an insight into forearc properties
- Relevant input section (undeformed seafloor sediments on the incoming plate) properties either already known and/or potentially accessible
- Close proximity to the coastline, maximising potential for onshore instrumentation to complement offshore infrastructure

Data/networks required to be currently available:

- Geodetically and seismically well-observed SSEs
- Existing 2D seismic reflection profiles characterising structure, interface properties and context for event locations

4.2. Auxiliary Studies

A workshop breakout group was tasked with addressing the needs and strategies for conducting auxiliary (i.e. site-survey) studies that would support and complement specific drilling programs. Additionally, these auxiliary studies are expected to broaden our understanding of SSEs.

The following lists, in order of priority, are auxiliary studies that should be conducted at any site in support of deep IODP drilling to investigate slow slip. These studies are summarised in Table 3.

A. Densify existing networks

The most critical types of study to further our understanding of the SSE process are continued and improved seismicity and geodetic studies of slow slip regions. SSEs are only one form of slip phenomenon and future studies using seismic networks need to record all types of slip including tremor, Very Low Frequency (VLF) earthquakes, and microseismicity to investigate SSEs as part of a continuum of fault slip behaviour. Targeted studies need dense networks of broadband seismometers both onshore and offshore with efforts to reduce noise (buried instruments) to improve focal mechanism and hypocenter locations, to identify and characterize tremor and VLF events, and to systematically quantify seismic attributes/parameters that may relate to SSEs. Characterizing the spatial (along strike and downdip) and temporal variation of seismic and aseismic slip phenomena is key to understanding the relationships between these different classes of shear slip. Increasingly, tremor is being viewed by the seismological community as a proxy for slow slip, and may provide additional information about the spatial distribution of slow slip in the absence of geodetic data. We note that in some cases, shallow slow-slip cycles are short (1-2 years, Table 2) enabling us to capture significant portions of the cycle with OBS deployments. We consider seismic instrumentation both onshore and offshore to be among the highest priority in preparation for IODP drilling of a SSE source area.

Similarly geodetic/GPS studies will continue to be a critical component and a high priority. With GPS stations onshore, and especially with densification of networks, slip can be further characterized and better defined. However, slow slip source areas that are drillable are well offshore and not easily or accurately characterized by onshore GPS networks. Offshore constraints are needed and will most likely come from deployments of ocean bottom absolute pressure gauges (APG's) that can monitor vertical motions of the seafloor during slow slip (if the slow slip events are large enough), possibly attached to OBSs or preferably as part of a cabled network system. Unfortunately, recently developed offshore GPS measurements using buoy systems can only be used for campaign style measurements and do not yet provide the necessary continuous record needed for characterization of slow slip, and are therefore not currently considered viable for studies of SSEs at the present time.

In order to aid in the development of improved networks, we suggest modelling studies to investigate the optimal station spacing for geophysical networks that will adequately resolve SSE distribution and related seismicity without redundancy and to identify significant gaps in coverage. Instruments should be focused in regions that experience large amounts of slow slip regularly.

Data that resolve temporal and spatial variability and distribution of SSEs (along strike and down dip) are necessary in order to decide where to focus IODP drilling efforts. Before a deep hole is drilled into the slow slip zone we must be confident that the zone is really undergoing slow-slip, and is the shallowest possible target to minimise cost.

B. Active and Passive seismic experiments

Structural and physical property characterization of slow slip areas should also be a critical goal of auxiliary studies. The coincident location of the transition from stick-slip to slow slip behavior and indirect indicators of the presence of fluids, such as Vp/Vs ratios, implies a link between fluids or fluid pressure and slip behaviour (cf. Kodaira et al., 2004; Audet et al., 2009; Song et al., 2009). Furthermore, the coincident location of extremely shallow slow-slip behavior and large structures on the subducting plate, such as seamounts along the Hikurangi margin suggests a critical linkage between structure, fluid supplies/sources, and possibly fluid pressures (Bell et al., 2010). Therefore, structural, lithologic, and physical property data will be critical for evaluating these relationships. Active source surveys including both 2-D and 3-D seismic imaging and wide-angle refraction surveys with dense networks of instruments will provide a regional view of structural details to unravel structure, stratigraphy, tectonics, fault zone physical properties, and key material properties such as Vp, Vs, Vp/Vs, attenuation (Qp, Qs) and anisotropy of these properties. These data are key to indirectly inferring lithologies, fluid sources, and fluid pressures. We also note the potential for repeat

3D surveys (4D) to identify or monitor fluid, fluid pressure, or physical property changes within the relatively short cycle of SSEs.

Again, before any seismic experiment, modelling should be conducted to investigate what variation in physical properties is really resolvable by the method.

The workshop noted the possibility of simultaneous OBS deployment and active source seismic acquisition for wide-angle imaging.

C. Additional experiments

While the seismicity, geodetics, and active source seismic work will be a critical component of auxiliary studies, a large number of other efforts will be needed to further support SSE studies. Among these are: 1) heat flow to better constrain temperatures along the plate interface within the SSE source area, 2) magnetotellurics and controlled source electromagnetic data for further refinement of structure and material properties, including imaging of fluid distribution, 3) samples from exhumed systems for conducting experimental work to assess stress, strain, rheology and frictional properties, 4) modeling studies of hydrology, fault properties and slip behavior to guide experiment designs and to provide constraints on resolution. Additional seafloor measurements or observations such as bathymetry, sidescan, or sampling will potentially reveal seeps and provide clues into the sub seafloor fluid flow systems. Geochemical studies of these fluid systems may reveal information about the rock types present within the SSE source deeper down, or may yield clues about the mineralogical reactions and transitions occurring at depth.

In summary, the workshop recommends a broad range of geological and geophysical studies with particular emphasis on collocated, integrated studies using a broad range of geological and geophysical techniques that are designed and constrained with lab and numerical modeling. An ideal outcome is to produce a 3D integrated picture of structure and properties (integrated seismic techniques, plus others), with 4D (time series) where possible.

Priority	Auxiliary study	Result
A	Densify seismic network	Record all types of earthquake phenomena including slow slip, tremor, VLF, microseismicity
A	Densify GPS network onshore/offshore?	Better resolve locations of SSE, potentially resolve propagation of SSEs.
A	Ocean bottom seismometer/absolute pressure gauge and temperature survey	OBS and APG above areas of SSE to investigate offshore limit of slow slip (does it propagate all the way to the trench?).
B	Heatflow data	Heatflow probe data and inferences of heatflow from Bottom Simulating Reflectors are needed to establish the thermal regime of SSEs and the temperatures expected at a given drilling target. Temperature sensors should accompany OBS deployments to constrain water bottom temperature variation for heat flow probe studies.
B	Active and Passive seismic surveys	Define structure and physical properties in the vicinity of SSEs. Remotely measure properties of the fault zone including, large scale velocity structure, Vp/Vs, Attenuation (Q), Qp/Qs, anisotropy, indirect measures of pore fluid pressure, lithology. Additional high quality 2D multi-channel seismic survey data would improve the design of a 3D seismic survey. Possibility for 4D repeat seismic survey over SSE area to assess temporal variation in properties.
C	Magnetotellurics (MT)/ controlled source Electro Magnetics (CSEM)	Resistivity of SSE source area. May help to map the distribution of fluids.
C	Experimental work on forearc material and/or ancient exhumed subduction channels	Remote assessment of frictional and rheological behaviour.
C	Seafloor measurements- bathymetry, sidescan sonar, ROV, fluid and dredge sampling.	Evidence for seeps and fluid flow. Hazard assessment of drill site location.
C	Gravity and magnetic data	Geophysical characterisation of the SSE source area
C	Stress measurements for any existing onshore and offshore boreholes	Stress state in the accretionary wedge
C	Hydroacoustic techniques- T phase	Detect seismic phenomena associated with SSEs using hydroacoustic instruments to supplement seismometers.

Table 3: Summary of auxiliary studies which could reveal further details of the slow slip process

4.3. Monitoring studies

4.3.1 Fundamental Questions to address with monitoring in boreholes

A second workshop breakout group focused on monitoring strategies to investigate SSE processes. The group concluded that a number of the fundamental SSE questions posed in section 2 could be addressed by monitoring an array of deep and shallow boreholes.

Monitoring of instrumented boreholes could be used to address the questions posed in section 2:

Q1) What does a slow slip zone look like? In particular, is slip localised to one or several discontinuities, or is slip distributed throughout a continuous zone of finite thickness?

Monitoring strain, tilt, and repeated borehole casing deformation surveys within the SSE source area at depth would reveal the thickness of the SSE slip zone

Q2) What is the slip distribution of slow slip events on the shallow subduction interface?

- Do they propagate to the trench?
- Is the location of slip patches stable over multiple events?

Monitoring tilt, strain, and pore pressure (indicating volumetric strain) in boreholes accompanied by deployment of OBS with pressure sensors mounted on them would reveal the distribution of slip beneath the offshore portion of the margin.

Q3) Do physical properties (such as stress, temperature) change within the fault zone during the SSE cycle?

- Do temporal changes in these properties influence the ability of the fault to fail in slow slip vs. seismically?

Monitoring changes in these (and other) physical properties within the SSE source area will constrain some of the mechanisms of slip.

Q4) Are slow slip events associated with changes in pore fluid pressure and fluid flow?

- How does pore pressure vary during a SSE?
- If fluid overpressures are present what is their source and the chemical composition of the fluid?
- Do SSE drive fluid flow along faults or through the upper plate?

Monitoring fluid flow and continuous sampling of fluids to detect geochemical changes *at the SSE source and within the upper plate* using a CORK (Circulation Obviation Retrofit Kit) system equipped with an OsmoSampler and OsmoFlowmeter, as well as pore pressure sensors would help to resolve this.

Q5) Can a single fault region host both slow slip events and “normal” earthquakes?

- Is there seismicity during the SSE cycle?

Borehole seismometers in a network overlying the source of shallow SSEs accompanied by deformation instrumentation (tilt, strain, pore pressure) above and within the SSE source area would allow resolution of this.

Q6) Are SSEs part of a continuum of seismic behaviour?

- What is the moment of SSE? Are there small SSE not previously detected?

Measurements of tilt in seafloor boreholes would resolve smaller, shorter SSEs than previously possible from onshore geodetic measurements which are further away from the SSE source.

All of these questions can be addressed effectively with monitoring in boreholes. Some are well suited to a strategy of drilling an array of shallow monitored boreholes, including Q2, Q4 (in terms of fluid flow through the upper plate) Q5, and Q6. To fully answer Q1, Q3, and Q4 a monitoring within a deep borehole penetrating the SSE source area is required.

4.3.2. Monitoring strategy

The workshop agreed that a phased approach to drilling would be effective. The first phase would start with a shallow borehole monitoring network. The results from coring and initial monitoring in these holes during Phase 1 would then be used to refine the location for and monitoring objectives for a Phase 2 deep hole to actually penetrate to the zone where SSEs are generated. The shallow holes drilled for Phase 1 would all be less than 1 km deep and hence within current capabilities of the JOIDES Resolution.

The group agreed the best possible distribution of the Phase 1 shallow boreholes would involve both a down-dip and along-strike transect in order to assess spatial variability of SSE behavior. The ideal number and arrangement of shallow boreholes is illustrated in Fig. 4. During Phase 2, these shallow holes would then be joined by one deep hole penetrating the SSE source area, where monitoring instrumentation would be installed within the SSE source area. The importance of each of these holes is described below:

Phase 1

Hole 1: Input section < 1km deep

This hole would penetrate a representative section of the undeformed incoming plate material. This hole would aim to sample material that is incorporated into the accretionary wedge, and also material that is likely forming the subduction interface decollément. This strategy would allow an assessment of physical properties of the incoming section prior to deformation, and provide insight into the likely composition of the protolith of material likely to be hosting slow slip deeper down along the subduction interface. The workshop participants concluded that at some subduction margins more than one hole may be required to sample the full complexity of the input section.

Hole 2: Accretionary wedge toe < 1km deep

This hole penetrates the narrow toe of the accretionary prism, potentially sampling splay faults or even the shallow part of the subduction interface. The role of this hole is to investigate the up-dip limit of SSE and the role of fluid flow in the shallowest part of system. If slow slip is eventually found to propagate all the way to the trench, this hole could serve as an access to the SSE source area.

Hole 3: Inner wedge pilot hole < 500 m deep

The hole would act as a pilot hole for the deep hole (Hole 7) aimed to drill down to the SSE source region. This hole could also be instrumented to investigate SSE slip distribution and variation in physical properties in the wedge during the slow slip cycle.

Hole 4: Inner wedge above deeper SSE zone < 500 m deep

This hole would be situated landward of the pilot hole (Hole 3), lying directly above deeper parts of the interface which experience SSEs. It would be instrumented to monitor fluid pressure variations during the SSE cycle. This hole would provide a critical link between the offshore and land-based monitoring networks.

Holes 5 and 6: Along-strike inner wedge < 500 m deep

These holes would monitor variations in physical properties along strike. Participants agreed that the along-strike component should not cross segment boundaries where the overall character of the seismicity and slow-slip events change radically.

Phase 2

Hole 7: Deep hole ~5 - 7 km deep below the sea floor

The aim of this hole is to sample the SSE source region. It could also be instrumented to monitor changes in fluid pressure, pore fluid chemistry, seismicity, etc., of the source region during the SSE cycle.

Determing the best location for hole 7 critically depends on better resolution of the depth to the zone of slow-slip, information which we anticipate will come out of the auxiliary studies (Table 3), particularly i) a denser GPS network; ii) OBS and APG; and iii) active source seismic surveys. Results from holes 2-6 will also help to constrain SSE depth.

The group agreed that at an absolute minimum useful initial shallow-hole program would involve three-holes in dip transect, including the input section (Hole 1), Accretionary wedge toe (Hole 2) and inner wedge above SSE region (Hole 4).

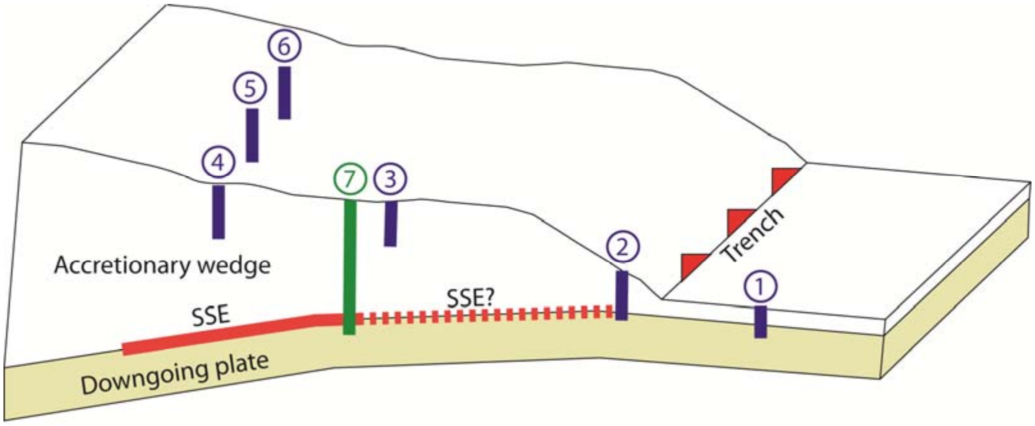

Figure 5: Schematic illustration of a borehole monitoring scheme which could be applied to address primary SSE questions. See text for details. Not to Scale. Red patches on the subduction interface show where SSE are constrained from onshore instruments. The position of the deep hole, 7 is constrained by current knowledge of the shallowest part of the interface undergoing SSE. The dashed red line shows a possible extension of SSE behavior. Offshore instrumentation is needed to constrain the updip limit of SSE (see section 4.1).

A major outcome of this workshop is the development of a generic monitoring and drilling strategy which could be applied at any location where shallow slow slip has been detected. The workshop has discussed the ideal configuration of monitoring sites to tackle questions regarding the slow slip process (Fig. 5) and the necessary monitoring and sampling techniques which are required in each hole (Table 4).

Hole Number	Depth	Purpose of hole	Types of Monitoring	Logging strategy	Sampling
1	< 1km	Properties of incoming material	None	WL, LWD	Coring, rock deformation experiments
2	<1km	Possibly intersect SSE. Monitor variations in properties during SSE cycle	Hydrological, Fluid geochemistry, deformation and seismic monitoring	WL, LWD	Coring, rock deformation experiments
3	< 500 m	Pilot hole for deep hole 7	deformation, seismic, and pore pressure monitoring	WL, LWD	Coring, rock deformation exp.
4	< 500 m	Monitor along-strike SSE	seismic (nearby OBS?) and pore pressure monitoring	LWD	No
5	< 500 m	Monitor above SSE	Hydrological, Fluid geochemistry, deformation and seismic monitoring	LWD	No
6	< 500 m	Monitor along-strike SSE	seismic (nearby OBS?) and pore pressure monitoring	LWD	No
7	~ 5-7 km	Penetrate SSE source are	Hydrological and deformation monitoring at SSE source	WL, LWD	Coring, but not whole section, possibly sidetrack coring close to SSE source

Table 4: Summary table describing a generic strategy for tackling SSE questions using ocean drilling. See Fig. 4 for location of holes.

4.3.2. Monitoring instrumentation

The workshop breakout groups highlighted the importance of using the minimum amount of instrumentation needed to achieve the science objectives.

In order to address the questions posed in section 2 by a distributed shallow hole array (Holes 1, 2, 3, 4, 5 and 6, Fig. 5) would require at a minimum i) 3-component seismometers (or co-located OBS on the seafloor) to monitor seismicity in all holes, ii) pore pressure sensing in all holes, which can be used to estimate volumetric strain iii) temperature monitoring and fluid sampling and flow rate measurements in the shallow accretionary wedge site (Hole 2). Tiltmeters would provide a useful, highly sensitive measure of deformation, and should be deployed where logistically and financially feasible. There were suggestions that strain meter installation was probably a low priority given its complexity and the existence of other ways to sense strain. Most importantly, volumetric strain can be inferred from pore pressure measurements, which are generally more straightforward and less expensive to make in a borehole than a full strainmeter installation. Deployment of OBS equipped with APG's (to detect vertical deformation in SSEs) would complement the borehole monitoring array nicely, and further improve resolution of the distribution of slow slip beneath the seafloor.

The shallow holes would benefit from CORK type installation of equipment. However, it is probably not necessary to CORK all holes with the full instrumentation. In particular, the along-strike holes (Holes 5 and 6) could be instrumented with simpler SCIMPI (Simple Cable Instruments for Measuring Parameters In-situ ; Moran, 2007) type devices that do not require standard casing installation, and would include pore pressure sensors. Participants also discussed the installation of simple shallow borehole observatories that could include a pore fluid pressure port and a strain/tilt/seismometer package cemented to the formation; such an installation could be similar to – but perhaps considerably less complex than –an installation was recently completed on IODP expedition #332 (Kopf et al., 2011).

The suggested hydrological monitoring observatory at the accretionary wedge site (Hole 2) could be based on previous deployments in Cascadia, Costa Rica, and on the Juan de Fuca ridge flanks, which successfully monitored changes in pore fluid pressure, temperature, and collected in situ formation fluids continuously and simultaneously (Wheat et al., 2003; Solomon et al.,2009; Fisher et al., 2011, Davis et al., 2010). Following a period of recovery, instrumented CORK systems monitor in-situ sub-seafloor conditions and collect time-resolvable fluid samples. Fluids would be collected with OsmoSamplers installed in the CORK system; these consist of an osmotic pump and a sampling coil. Rates of fluid flow could be obtained using an OsmoFlowmeter. For this, a tracer solution is added directly at the center of the flowmeter, and four OsmoSamplers sample at equal distance (1 cm) away from the tracer input in each of the four branches to determine both direction and flow rate of pore waters through the formation. With this approach, extremely subtle fluid geochemical and flow rate signals can be resolved and analyzed. Ultimately these data would be used in concert with pore pressure records, seismological, and deformation data to understand the links between SSE, hydrologic transients, and the source regions of fluids that may be mobilized during SSE.

The deep hole (7) would benefit from instruments to measure seismicity, pore pressure, tilt, hydrological monitoring, and temperature. Because of potential temperature and strain conditions, monitoring the base of the deep hole will be challenging. An effective monitoring system plan will depend on the drilling results. Possibilities range from (a) simply leaving a cased hole in place to run repeat casing deformation surveys in, as was done in the SAFOD main hole (Zoback et al., 2010) to (b) installing a CORK-style long term recording package for deformation, seismic, temperature, and pore pressure sensing. In fact, anything in between these two end-members may be considered.

The workshop recognises the significant expense involved in developing a cabled network to provide access to the data in real time. The key criterion for the cost of a cabled network is the distance to shore. It was noted by participants that simpler cabled systems now exist which significantly reduce the cost of retrieving data from a seafloor network (e.g. the Neptune Project; www.neptunecanada.com). However, it was concluded that even without a cabled network, a lot could be learned from instrumented boreholes over a SSE zone where the data is collected at intervals using ROVs.

4.4. Physical Properties

Recent studies of SSEs have directly implicated properties such as pore fluid pressure and rock frictional properties to slow slip processes. Consequently they are an obvious target for further advances in understanding SSEs and they were a key topic of our breakout discussions. In particular, physical properties within the SSE source and surrounding area have been quantified from previous remote sensing techniques, for example active and passive seismic experiments; however, these analyses are inherently limited by their design and practical constraints, and they remain un-calibrated without ground-truth from drilling. As well as providing drill holes for monitoring, IODP drilling could also sample the subducting plate prior to entering the subduction zone, and potentially sample the SSE source location itself. This material could be used in laboratory experiments to reveal details of the slow slip process.

The physical properties group outlined several hypotheses that could be tested by sampling and making downhole measurements within the upper plate, incoming plate, and at the SSE source area:

1. Slow slip occurs in a distributed shear zone of finite thickness

2. For slow slip to occur, near-zero effective stress modulated by elevated pore fluid pressure is necessary

3. Slow slip occurs in materials near neutral a-b frictional property conditions

4. SSEs are governed by dilatancy hardening during slip (e.g. Segall et al., 2010)

5. Frictional stability changes during dynamic behaviour may influence slow slip (slip rate dependent a-b? e.g. Shibazaki and Iio, 2003).

6. SSEs are governed by dehydration transitions for specific mineralogies

The physical properties break-out group discussed what measurement/samples would need to be taken in SSE areas to test these hypotheses.

4.4.1 Properties to measure

Rock samples from the slow slip zone would allow for direct observation of the lithology, mineralogy, deformation fabrics (micro and macro), and fracture patterns of the material that currently experiences SSEs. Such properties can currently only be inferred from remote observation by geophysical techniques or studies of potentially analogous exhumed rock assemblages. Core-recovery from drilling into a slow slip zone is therefore the primary way to determine these properties.

Recognising the slip / shear zone at c. 6 km depth is, by itself, a major challenge. Possible diagnostics could include lithological juxtaposition, structural discordance, deformation fabrics, and abrupt changes in physical properties. However, some or all of these features may make positive identification difficult given the common tendency of low-angle thrusts to follow bedding anisotropy. While some characteristics of the slip / shear zone may be determined by LWD and wire-line logging, direct sampling of the SSE zone through core recovery is an imperative for determining physical properties and the mechanical processes operating during SSE.

Recovered core should allow the mineral deformation mechanisms and any related characteristics of the slip / shear zone (e.g. formation of extension veins and other forms of dilatant behavior) to be determined. Likely mechanisms at c. 6 km and 100-150°C include cataclasis, particulate flow, clay/phyllosilicate smearing, and diffusive mass transfer (especially if carbonate material is present). Crystal plastic flow is only likely to be important if significant proportions of carbonate are present. Knowledge of the operating deformation mechanisms should make it possible to evaluate the extent to which rate-and-state frictional mechanics provides an adequate representation of slow-slip processes.

Drilling through a slow slip zone would also allow for measurements of *in situ* stress, permeability, strain, porosity, frictional coefficient, temperature, fluid pressure, resistivity, and thermal and elastic properties of rocks both from the slow slip zone and the overlying rock. As such, drilling through the accretionary prism above the slow slip zone also provides critical information in order to fully understand the environment of slow slip (e.g., thermal environment, stress state of the upper plate, porosity and permeability of the upper plate). Once the slow slip / shear zone is defined, the physical environment of deformation (depth, temperature, fluid-pressure level, grain-size, strain-rate, stress tensor) needs to be determined as fully as possible, looking in particular for any gradients and time-dependence of these physical parameters in the vicinity of the SSE source.

Fluids are likely to play important mechanical and possibly chemical roles. Measurement of spatiotemporal fluid pressure variations and direct sampling of fluid chemistry from a borehole will allow for classification of fluid presence in and around the slow slip zone. Hydrothermal veins recovered in core samples also allow for assessment of both fluid chemistry and stress orientations in the drilled zone.

In addition to measuring the values of various properties, the anisotropic properties in and around the slow slip zone are also important to measure. These properties include anisotropy of magnetic susceptibility, seismic velocity, attenuatation, and permeability throughout the drilled interval.

Although there will always be time and financial constraints, it would be ideal to measure all properties for both incoming (relatively undeformed) *and* deformed material, in multiple locations.

4.4.2. Considerations for project planning

When considering drilling a deep hole into the active slow slip zone, it will be critical to first drill shallower targets. Core and drill logs from these targets should then be used to calibrate large-scale geophysical and geological observations, numerical models, and lab results to refine the target for a deeper borehole. These calibrations also allow for intermediate targets, and may lead to significant scientific advances during the project before a deep hole is drilled.

When it comes to core recovery from both shallow and deep holes, it must be kept in mind that the core material is likely to degrade very quickly. It is therefore important to have a system in place on the ship to take care of core quickly, and take appropriate measures to recover information in such an order that core degradation does not significantly affect scientific results. It was also pointed out that, at least in the fault damage zones, core recovery is a priority, although logs are also important (could be done in separate holes / side-tracks).

4.4.3 How to measure the physical properties

Table 5 summarizes the break-out group's assessment of how each physical property can be measured, both without and with boreholes. Note that most properties can be measured to some degree without a borehole, albeit remotely and perhaps non-diagnostically. Ultimately drilling one or more boreholes will allow the calibration and integration of remotely sensed, large-scale data and direct, small-scale, observations.

Property	Without a borehole	With boreholes
Lithology	Dredge samples, remote sensing	Core (ideally), cuttings, Logging while drilling (LWD)
Velocity	Active and passive seismology	LWD/wireline logs, VSP, core measurements
Temperature	BSRs, surface heat probes	Borehole temperature, thermistor strings
Fluid pressure	Vp-Pf empirical relations, anisotropy, Vp/Vs?	LWD, hydraulic tests
Fluid chemistry	Seeps	Direct sampling
Frictional properties	Dredge samples, analogues	Core samples
Permeability	MT	Single- and cross-hole tests, CORK
Stress	Focal mechanism analysis. Numerical models, anisotropy?	Breakouts/tension cracks, ASR, fracture patterns?
Strain/deformation	GPS, numerical models, onshore tilt/strain meters, OBS with pressure sensors	Borehole tiltmeters, AMS, pore pressure sensors
Elastic properties	Regional seismic vel. studies	ASR, sonic logs
Electrical properties	MT	LWD/wireline logs

Table 5: Summary of ways to measure physical properties in and around SSE source areas- BSR = bottom simulating reflector, MT = magnetotellurics, AMS = anisotropy of magnetic susceptibility; LWD = Logging while drilling, VSP = Vertical seismic profiling, ASR = Anelastic Strain Recovery

5. Experiments to conduct at specific shallow SSE localities

This workshop has identified three locations worldwide where shallow SSEs have been recorded (Boso Peninsula, Costa Rica, and the northern Hikurangi margin). Although, we have found that shallow SSEs share a number of similar characteristics (magnitude, duration, thermal environment) the specific scientific questions which could be addressed vary between these sites. Each site also varies in the types and quality of data that have already been collected, and the experiments which still need to be conducted before drilling.

5.1. New Zealand, northern Hikurangi

Since 2002, the installation of a continuous GPS network in New Zealand has enabled the discovery of 15 slow slip events along the Hikurangi subduction margin. Inversion of horizontal and vertical displacements of cGPS sites suggest that SSEs at the northern Hikurangi margin occur at depths of < 5-15 km on the subduction interface (e.g. Wallace and Beavan, 2010). The updip limit of SSEs is currently unconstrained, due to the absence of offshore geodetic data. SSEs may propagate shallower than has been modelled in Fig. 6, perhaps all the way to the trench.

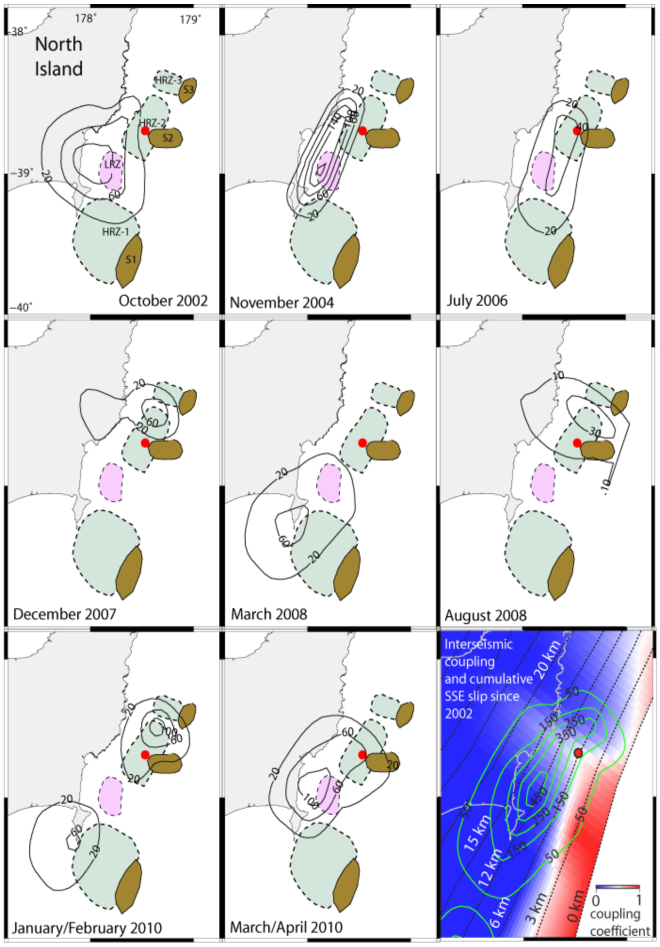

Figure 6: Contours show slip on the subduction interface in SSEs from inversion of horizontal and vertical cGPS site displacement between 2002 – 2010 (Wallace and Beavan, 2010). Interface seismic characteristics (high amplitude reflectivity = HRZ, blue shaded; low amplitude reflectivity=LRZ, pink shaded; subducted seamounts=S, brown shaded) from (Bell et al., 2010)

The close proximity of these SSEs to the Earth's surface enables high-resolution imaging of the interface in the SSE source area using conventional seismic reflection techniques. The Hikurangi subduction thrust is identified as an interface between an undeformed subduction sequence and a thrust-imbricated wedge at ~5-6 km below sea level at a distance 15-40 km from the trench (Barker et al., 2009, Fig. 7). Water depths range from < 200m on the shelf, to about 3 km at the trench. Multichannel (MCS) seismic reflection data acquired in 2005 offshore the northern Hikruangi margin reveal regions where the interface (between < 5 km to > 10-16 km) is interpreted as the upper reflector of a thick (1-1.5s TWT) package of high amplitude reflectivity that coincides with the source area of SSEs (Bell et al., 2010, Fig. 7). These authors also identify subducted seamounts updip of the SSE source areas, in regions which have experienced "Tsunami earthquakes" (Kanamori, 1972) in March and May 1947 (Downes et al., 2000). Bell et al. (2010) suggested that the high-amplitude reflectivity zones indicate a relationship between high fluid content, and potentially high fluid pressures in within the source area of north Hikurangi SSEs.

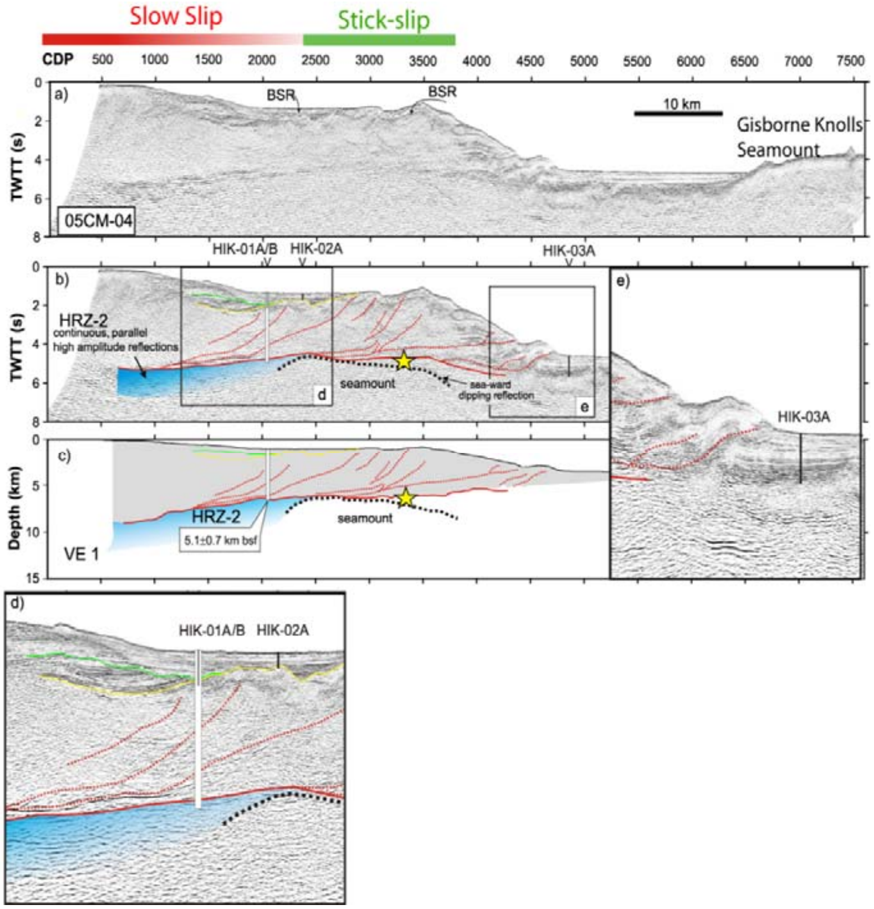

Figure 7: a) Uninterpreted and b) interpreted seismic profile 05CM-04 East of Gisborne. Red line is the subduction interface and dashed red lines are major splay faults. Yellow star denotes the position of the March 1947 tsunami earthquake (Downes et al., 2000).c) Depth converted interpretation based on velocity model of Barker et al. 2009. d) and e) are enlarged parts of 05CM-04 shown in b). Labelled lines indicate potential drill sites from a preproposal submitted to IODP in October 2010 (781-Pre). After Bell et al. (2010).

Northern Hikurangi provides a location where the SSE source area could be sampled at depths within modern drilling capabilities (< 5-6 km below the sea floor in < 2.5km of water). It also offers repeatable SSE every 2 years, with fairly large magnitudes (Mw 6.5-6.8, average slip ~10 cm), allowing excellent monitoring opportunities over a relatively short time period. SSEs are already well characterised along the northern Hikurangi margin due to a dense cGPS and seismometer network (Wallace and Beavan, 2010; Delahaye et al., 2008; Kim et al., 2011) located within 40 km of the proposed deep drilling target. Active and passive seismic surveys have provided significant information on the character of the SSE source area over the last decade (e.g., Bell et al., 2010).

The workshop participants developed a list of existing data along the Hikurangi margin which could be useful in understanding more about SSEs, and highlighted datasets that are still required (Table 6). In particular, the northern Hikurangi margin lacks offshore instrumentation, which would help greatly in elucidating the trenchward extent of the SSE zone. The thermal structure of the margin has previously been investigated remotely using BSRs, however a study involving heatflow probes is necessary to fully constrain the thermal structure offshore and to assess the likely environment for drilling and down hole measurements. An OBS survey, including possibly mounted with APGs and temperature sensors is a key, high- priority experiment offshore the northern Hikurangi margin that needs to be conducted to further our understanding of the extent of SSEs beneath the offshore region.

Passive Seismic Network (onshore, offshore)	Good on-land array nearby, will be densified (10-15 km); previous short-period offshore deployments offshore S. Island, New Zealand. Need more offshore deployments close to the SSE region. Include APGs and temperature probes with 3-component OBS deployments.
Geodesy/GPS (onshore/offshore); pressure gauges	Good on-land cGPS coverage (20-25 km spacing).; Need to densify locally. Offshore geodetic coverage, and tiltmeters (in onshore boreholes) are needed
Seismic for physical props. (Vp, Vs, Q,Qp/Qs,Pf, anisotropy, etc)	Some tomography, Vp/Vs, but limited. Need local onshore-offshore 3-component (OBS) survey.
Seismic reflection data (2D and 3D)	Regional offshore 2D Multi-channel seismic (MCS) lines (20 km spacing); plans to densify. Need 3D MCS survey over SSE site.
Heat flow/thermal structure	Good hydrate BSR coverage; some heat flow measurements elsewhere. CTD bottom water variations need further study. Thermal conductivity, and eventually, seafloor probes are needed.
Magnetollurics and CSEM	Two 2D transects on-land north of Gisborne. Plan for 3D. Offshore magnetollurics desired, but expensive.
Modeling	Geodetic, 3D geodynamic and coupled fluid-mechanical models. Need predictive geodynamic modelling, fault frictional models, landscape response to deformation.
Seafloor measurements (bathy, sidescan, ROV etc)	Good bathymetric data and backscatter; limited sidescan to identify fluid seeps. Need improved bathymetry and targeted ROV.
Gravity and Magnetics	Shipboard and satellite data. Detailed magnetics needed for specific targets.
Onshore borehole studies	No existing borehole studies. Targeted studies would be helpful.

Table 6: Summary of existing (black writing) and required (blue writing) data along the northern Hikurangi margin in areas of shallow SSEs.

5.2. Central Japan, Boso Peninsula

Slow slip events have been detected offshore Japan in a number of locations (Fig. 8). Along the SW Japan margin deep slow slip events have been detected in the range 30 - 40 km accompanied by non-volcanic tremor and VLFs (Shelly et al., 2006). These deep slow slip events have similar properties to those recorded in Cascadia. In the Boso peninsula region of central Japan, however, SSEs have been detected at much shallower depths of 10 - 20 km (Sagiya, 2004; Ozawa et al., 2007). These SSEs have a duration of 10 days and repeat every ~5-6 years (Ozawa et al., 2007; Kimura et al., 2010) (Fig. 8).

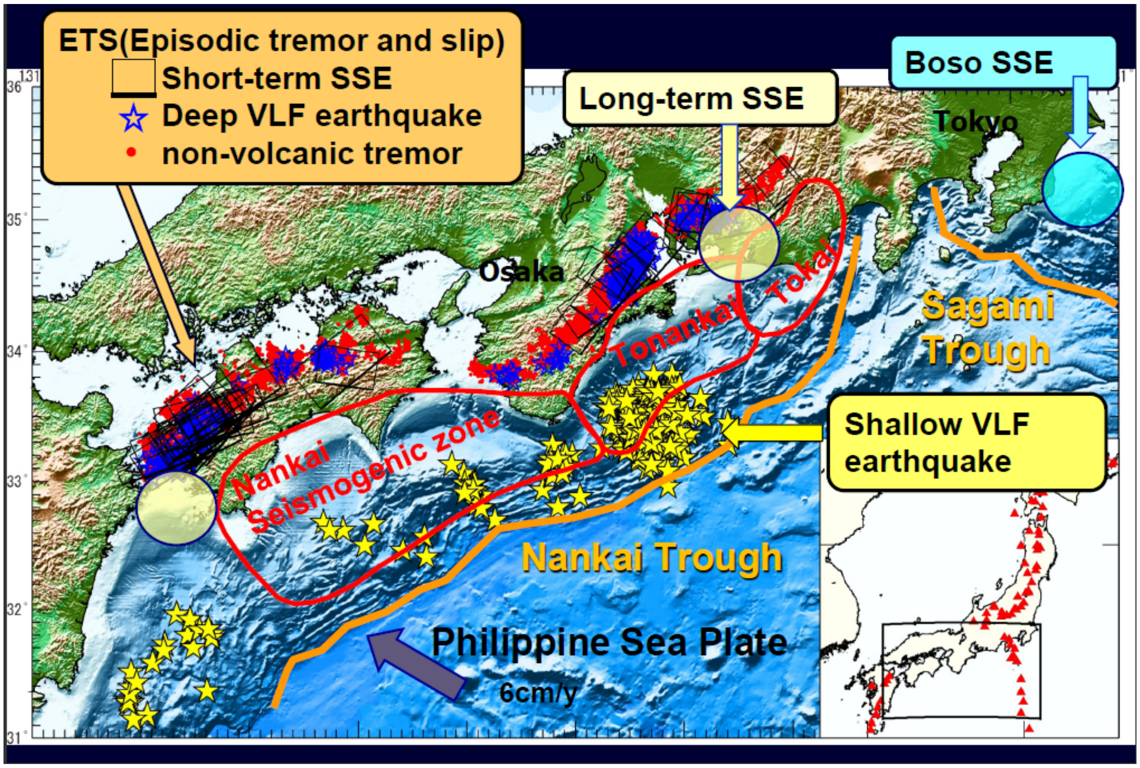

Figure 8: Distribution of types of seismic behaviour along the SW to central Japan margin.

The Boso peninsula SSEs occur at similar depths, and immediately adjacent to parts of the interface that rupture in large earthquakes, for example the Kanto earthquake in 1923. This location is ideal to investigate why these very different types of phenomena (slow slip and large earthquakes) occur at similar depth ranges in the Sagami Trough area, where pressure and temperature conditions are expected to be similar.

The SSEs offshore the Boso Peninsula are therefore a good target to investigate what physical property variations cause some patches of the interface to experience slow slip, while others have “normal” earthquake behaviour. Ultradeep drilling, which proposes to penetrate the plate boundaries in the source region of the Kanto earthquake, is a direct approach for establishing the differences. Lithological differences can be determined by coring, and laboratory experiments on core samples can define frictional properties. Potential lithologic contrasts between the SSE and “normal” earthquake source regions can also be inferred from coring at the corresponding input site on the Philippine Sea plate. Pore pressure, which could foster either cycles of slow slip events or great earthquakes can be measured in boreholes.

Physical parameters are required to accurately model slow slip events and great earthquakes. Monitoring of the slow slip events will give us the high resolution spatio-temporal slip distributions, from which we can infer stress drops. Core samples of ultradeeep drilling and input site samples can be used for estimation of friction parameters, including "a" and "b". Pore pressures, as mentioned above, can also be measured.

An offshore monitoring network of six sites (or a minimum of four) over the Boso SSE region could be used to recognize pre-slips or smaller precursors of the main SSE. Because the plate boundary that harbours both the Kanto slow slip and large earthquake events underlies the greater Tokyo region, the seismic hazard is huge and well recognized. Therefore many of the desired auxiliary studies (described in section 4.2) are already underway. However, two types of auxiliary studies need special attention and are highest priority. These include 2D and 3D seismic reflection data. Various 2D lines have been completed, but additional coverage is necessary, including oblique lines to capture structure along the convergence vector, cross lines at all proposed drilling sites, and 2D wide-angle data to constrain structure and velocities. In spite of the heavy ship traffic, small 3D seismic cubes should be acquired around the proposed deep drilling localities. Secondly, in order to best constrain the P-T conditions of the differing zones of seismicity, heat flow measurements and careful thermal modeling are necessary. Some data has been collected and is being analyzed at the University of Tokyo. Pending these results, additional surveys will be proposed soon.

Many of the auxiliary studies described in Table 7 below are well underway or complete, hence lower immediate priority. In some cases continued monitoring is necessary and improvements in auxiliary data and associated modeling will occur as work proceeds.

Passive Seismic Network (onshore, offshore)	Onshore borehole HI-NET, 30km spacing. Offshore OBS, 20 km spacing. Need deployment during next predicted SSE in 2013.
Geodesy/GPS (onshore/offshore); pressure gauges	GEONET provides 30 km on-shore coverage. Denser coverage desired, w/offshore borehole installations, offshore geodesy. Pressure gauges on OBSs have been planned.
Seismic for physical props. (Vp,Vs, Q,Qp/Qs,Pf , anisotropy, etc)	Active source shooting to OBSs completed in 2010. Further studies helpful.
Seismic reflection data (2D and 3D)	Various 2D lines, but additional coverage needed. Oblique lines to capture structure, 2D-wide angle data to constrain structure. 3D possible?
Heat flow/thermal structure	Limited offshore probe measurements, quality and amount of existing borehole data is unclear. Obtain thermal constraints from hydrate BSRs and targeted seafloor probes. Thermal modelling underway.
Magnetollurics and CSEM	Onshore MT may be available. Marine capability exists in Japan and could possibly be undertaken.
Modeling	Models of earthquake and SSE using realistic constitutive laws.
Seafloor measurements (bathy, sidescan, ROV etc)	Excellent bathymetry data, and some sidescan and ROV data exists. Fluid seeps have been identified.
Gravity and Magnetics	Good published marine magnetic and gravity data.
Onshore borehole studies	Various. Targeted studies would be helpful.

Table 7: Summary of existing (black writing) and required (blue writing) data along the central Japan margin in areas of shallow SSEs.

5.3. Costa Rica, Nicoya Peninsula

The Nicoya Peninsula region of Costa Rica experiences both deep and shallow SSEs, recorded geodetically and seismically (Outerbridge et al., 2010, Fig. 9). The occurrence of shallow SSEs was also previously postulated from fluid flow measurements near the Costa Rica trench during the CRSEIZE experiment (Brown et al., 2005; LaBonte et al., 2009). These shallow SSEs are potentially within range of modern drilling capabilities. The occurrence of megathrust earthquakes in this region would also allow the possibility to drill through a seismogenic portion of the interface at a depth of less than 6 km.

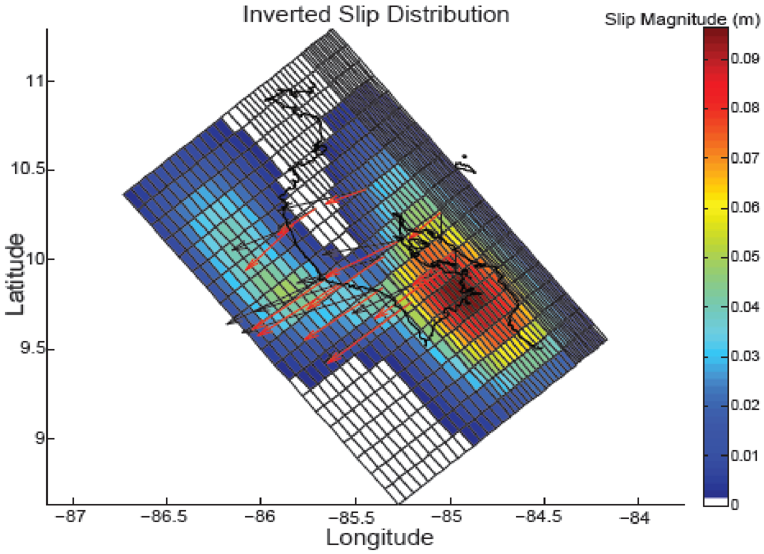

Figure 9: Slow slip distribution beneath the Nicoya Peninsula (Outerbridge et al., 2010)

There is already a lot of information for characterising the subduction interface in the Nicoya Peninsula area. These include: 3D and 2D high resolution seismic lines, seismic refraction profiles, ALVIN dives, ODP and IODP legs, dense heat flow measurements, gravity and geomagnetic surveys, high resolution bathymetry, OBS and flow-meter campaigns, 2 CORK sites and CGPS and seismic networks on shore. In addition it has a simple geometry and fast convergence rate. There are already samples from drill holes offshore Nicoya to extract information on physical properties, particularly samples from fault zones.

The key datasets needed in the future are further analysis of cGPS data to better characterise locations of SSE. Other potential future auxiliary studies are described in Table 8.

Passive Seismic Network (onshore, offshore)	Array of 54 broadband instruments with an 18 month deployment. Previous deployment of 20 offshore broadband instruments. Need improved OBSs focused to catch SSE and tremor.
Geodesy/GPS (onshore/offshore); pressure gauges	Array of 18 continuous GPS stations over Nicoya. Pressure sensors on offshore CORKS. These could be densified locally, and also potential for offshore GPS.
Seismic for physical props. (Vp, Vs, Qp, Qs,Pf etc)	Previous and new tomographic models, active source OBS deployments over potential drill sites, data being processed now.
Seismic reflection data (2D and 3D)	Fairly good 2D coverage over area of interest; 1987 3D survey, but this survey excludes trench. New 3D?
Heat flow/thermal structure	Excellent coverage, thermal modelling.
Magnetollurics and CSEM	Onshore and offshore surveys, spanning the region of SSE. Would higher resolution be useful?
Modeling	Coupled poro-elastic models (2D) offshore Nicoya. 3D modelling would be valuable, constrained by existing data.
Seafloor measurements (bathy, sidescan, ROV etc)	Excellent coverage; bathymetry data and backscatter data have revealed fluid seeps, carbonate mounds, and mud diapirs. Need targeted ROV studies.
Gravity and Magnetics	Excellent coverage
Onshore borehole studies	4 borehole sites on land (German) and previous IODP drilling. Need improved borehole strainmeters (onland).

Table 8: Summary of existing (black writing) and required (blue writing) data along the Costa Rica margin in areas of shallow SSEs.

6. Impact of the Workshop and Recent and Future actions

In summary, the workshop concluded that all of the discussed sites (northern Hikurangi, central Japan and Costa Rica) could be good locations to investigate mechanisms of shallow slow slip. No single margin will likely have all the characteristics needed to fully characterize SSEs, but due to similarities in SSE characteristics observed at different margins the results learned at one margin may be broadly applicable. There was a consensus that the scientific community with an interest in SSEs should work together in developing future proposals, to avoid duplicating efforts by developing three localities and using funding unwisely. To this end, a number of future proposals are to be written by members of the workshop forming new international collaborations.

6.1. IODP proposal development to understand SSEs

Northern Hikurangi margin

A number of the IODP workshop participants are involved in proposals (a Multiphase drilling proposal and an underpinning riserless drilling proposal) to drill the northern Hikurangi margin that were submitted in October 2011. These proposals outline plans for investigating SSEs along the northern Hikurangi margin using an array of shallow and deep boreholes, with a similar configuration to the generic case developed in the workshop (Fig. 5).

These IODP proposals will be supplemented by an array of funding proposals to various agencies in the USA, Japan, New Zealand and Europe to undertake auxiliary and site-survey investigations. One of the priority experiments that is needed is a deployment of offshore OBS instruments, equipped with absolute pressure gauges better constrain the trenchward extent of the SSEs, and types of seismicity associated with Hikurangi SSEs offshore. The OBS should also be mounted with temperature sensors to monitor bottom water temperature variations in the lead-up to a potential heat flow survey. Ideally, the heat flow data acquisition should be timed to occur during the retrieval of the OBS. Teams have been assembled to develop proposals for the OBS/APG study, as well as the heat flow study.

A 2D low-fold seismic survey was undertaken in the area in October 2011. This has provided crossing 2D seismic lines at the proposed drill sites, to augment the 2-D seismic data along the drilling transect that was acquired in 2005. Unlike the earlier 2D profile from the drilling transect (Fig. 7), the crossing seismic line data will not image the subduction interface at the proposed deep drill site, but is more than sufficient for characterizing the shallow, riserless targets. It was agreed in the workshop that an additional 2D and/or 3D MCS surveys will be a logical next step for defining the optimal location for riser drilling in the northern Hikurangi area. A team was developed to initiate proposal writing in an attempt to fund additional seismic surveys.

Central Japan, Boso Peninsula

The Kanto Asperity Project (KAP) proposes a drilling and long-term monitoring program in the southern Kanto region of southeastern Japan with the aim of determining the characteristics of the plate boundary in and around the source regions (asperities) of great earthquakes and SSEs. This region (Tokyo Metropolitan Area) has been subjected to repeated great earthquakes. Both earthquake and slow slip behaviours are observed within similar depth ranges: the 1923 Taisho Kanto earthquake, 1703 Genroku earthquake, and SSEs off Boso Peninsula

A Complex Drilling Project (CDP, which is now called a Multi-phase Drilling Project) of the KAP was submitted on 1 October 2010, and consists of three programs (Program A-C). Proposals for Program A and B were also submitted to IODP on 1 October 2010. A new proposal for Program C will be submitted on 1 October 2012. Program A proposes ultra-deep drilling to intersect plate boundaries in the SSE region and the Taisho asperity, in order to compare the material properties between the two sites. Coring and logging in these locations will also yield realistic frictional properties and effective normal stress, as derived from experiments on recovered materials and from measurements of pore pressure, respectively. Program B proposes long-term monitoring (borehole observatories) for detailed recording of crustal deformation and seismicity during 2-3 cycles of Boso SSEs, enabling testing of the hypothesis that SSEs of moderate magnitudes (Mw6.4-6.6) can be used to assess the validity of earthquake generation models. Program C focuses on the input sites on the Philippine Sea plate and shallow parts of the fault near the trench axis. This program will test a hypothesis that different input materials will cause different types of slip behavior. A number of related auxiliary studies are already underway in central Japan, in large part due to the recognised large seismic hazard that exists beneath the greater Tokyo region.

Costa Rica, Nicoya Peninsula

A lot of new data is available in the Nicoya region and members of the Earth Science community are invited to collaborate with scientists in the area to work on it. Further work, potentially by graduate students, is needed to reprocess cGPS data to better locate SSEs, relocate tectonic tremor and work on preliminary geodynamic modelling to calculate what magnitude of signals (deformation, pore pressure, stress-strain field, tilt,) we can expect offshore to decide on offshore network geometry, density and instrumentation.

A summary paper to be submitted to *Review of Geophysics* is planned that integrates what we know of the Nicoya subduction segment from both on-shore and off-shore data.

There are plans for an ancillary proposal for an ocean bottom array of low noise broadband seismic stations, pressure sensors and flow meters, designed to refine tremor locations. A proposal must be submitted to fund the instrumentation, ship time and maintenance. Some of the auxiliary data can be collected at this stage. Additionally, a proposal requesting funding for CORK instrumentation will be developed and the existing IODP drilling proposal for Costa Rica, Dynaseis will be adapted/rewritten for drilling utilizing the refined tremor/slip locations.

The ocean floor network results will be used to develop the best and cheapest array of instrumented shallow holes to improve location and understanding of SSE and tremor (funding needed for the instrumentation). Both networks could be run simultaneously and the information from these networks used to decide if a deep hole with instruments will provide key information and where will be the best location for it to cross the source of SSE and/or tremor and/or locked seismogenic zone.

6.2. International Cooperation

The workshop participants came from 12 countries and had expertise in slow slip events, scientific ocean drilling, seismology (active and passive source), geodesy, rock/fault mechanics, numerical modelling, subduction tectonics, hydrogeology, geochemistry, and structural geology. The environment provided by the workshop allowed scientists from all disciplines to interact and establish new and exciting collaborations.

In particular, strong collaborations have emerged out of this workshop between Japanese, New Zealand, and American seismologists to conduct OBS+APG deployments at the offshore northern Hikurangi margin to detect seismicity and vertical deformation related to SSEs there. The first such deployment (led by Japanese and NZ scientists) took place in April 2012. The Hikurangi proponent team also convened a working group meeting following the main IODP workshop, which led to the development of proposals to drill the northern Hikurangi margin. These proposals were submitted in October 2012, and included a Multi-Phase drilling proposal and a daughter proposal for the riserless drilling phase. The main IODP workshop and follow-up Hikurangi meeting has led to initiation of collaborations between scientists in New Zealand, the USA, Japan, Canada, and Europe regarding understanding of Hikurangi margin SSEs.

6.3. Publications

The results of the workshop discussion will be written up into a report for *Scientific Drilling and Eos*. Preliminary reports have already been published in the Geoscience Society of New Zealand Newsletter (November 2011) and the GeoPrisms newsletter (Fall 2011). The final IODP report together with these articles will support the writing of future IODP and ancillary proposals.

6.4. Outreach and Education

One of the workshop aims was to increase public awareness of slow slip events, and the great relevance to society of understanding slow slip event and subduction zone processes. Another aim was to educate the public on the ocean drilling program in general. During the workshop a town hall meeting was held in Gisborne where Laura Wallace and Demian Saffer gave a presentation on SSEs and ocean drilling. The workshop generated significant media attention with articles in New Zealand newspapers the Dominion Post and Gisborne Herald. The workshop has also resulted in a number of radio broadcasts, including two high-profile interviews for Radio New Zealand's weekly science programme, "Our Changing World" (Harold Tobin and Lisa McNeill gave an interview on the NanTroSEIZE project, and Laura Wallace, Stephen Bannister, and Philip Barnes gave an interview on the proposed Hikurangi slow slip IODP project).

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Appendix A: Participant List

First Name	Last Name	Affiliation
Nathan	Bangs	Institute for Geophysics, University of Texas at Austin
Stephen	Bannister	GNS Science, Lower Hutt, New Zealand
Dan	Barker	GNS Science, Lower Hutt, New Zealand
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Kate	Chen	Department of Earth Sciences, National Taiwan Normal University
Kate	Clark	GNS Science, Lower Hutt, New Zealand
Harmony	Colella	University of California, Riverside
Jim	Dieterich	University of California, Riverside
Susan	Ellis	GNS Science, Lower Hutt, New Zealand
Ake	Fagereng	Department of Geological Sciences, University of Cape Town, South Africa
Bill	Fry	GNS Science, Lower Hutt, New Zealand
Basil	Gomez	University of Hawaii at Manoa
Rob	Harris	Oregon State University.
Wiebke	Heise	GNS Science, Lower Hutt, New Zealand
Stuart	Henrys	GNS Science, Lower Hutt, New Zealand
Roy	Hyndman	Pacific Geoscience Centre, Sidney, B.C., Canada
Matt	Ikari	Univ. of Bremen, Germany
Yoshihiro	Ito	Tohoku University, Sendai, Japan
Craig	Joseph	Oregon State University
Miriam	Kastner	Scripps Institution of Oceanography
Reiji	Kobayashi	Kagoshima University, Japan
Shuichi	Kodaira	JAMSTEC, Yokohama, Japan
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Lisa	McNeill	University of Southampton, UK
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Casey	Moore	University of California-Santa Cruz
Greg	Moore	University of Hawaii, Honolulu
Julia	Morgan	Rice University, Houston, Texas
Joshu	Mountjoy	National Institute of Water & Atmospheric Research (NIWA), New Zealand
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Marino	Protti	Costa Rica Volcanological and Seismological Observatory, Universidad Nacional
Francesca	Remitti	Università di Modena e Reggio Emilia, Modena, Italy
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Martin	Reyners	GNS Science, Lower Hutt, New Zealand
Demian	Saffer	The Pennsylvania State University
Arito	Sakaguchi	JAMSTEC, Yokohama, Japan
Toshinori	Sato	Chiba University, Japan
Heather	Savage	Lamont-Doherty Earth Observatory, Columbia University
Martha	Savage	Victoria University of Wellington, New Zealand
David	Schmidt	University of Oregon, Geological Sciences
Susan	Schwartz	University of California-Santa Cruz
Charlotte	Severne	National Institute of Water & Atmospheric Research (NIWA), New Zealand
Anne	Sheehan	University of Colorado at Boulder
Rick	Sibson	Department of Geology, University of Otago, New Zealand
Eli	Silver	University of California-Santa Cruz
Rob	Skarbek	University of Oregon, Geological Sciences
Richard	Steele	Gisborne District Council
Michael	Strasser	University of Bremen, Germany
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Marta	Torres	Oregon State University
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Mike	Underwood	Department of Geological Sciences, University of Missouri
Phaedra	Upton	GNS Science, Lower Hutt, New Zealand
Laura	Wallace	GNS Science, Lower Hutt, New Zealand
Kelin	Wang	Pacific Geoscience Centre, Sidney, BC, Canada
Aaron	Wech	Victoria University of Wellington, New Zealand
Charles	Williams	GNS Science, Lower Hutt, New Zealand
Wenlu	Zhu	Department of Geology, University of Maryland
Daniel	Zietlow	University of Colorado at Boulder

Appendix B: IODP Unlocking the Secrets of Slow Slip Workshop, Gisborne, New Zealand- Schedule

Day One

Time	Activity	Speaker
7:00 a.m.	BREAKFAST	
8:15 a.m.	Start of conference. Welcome. Housekeeping.	Laura Wallace
8:30 a.m.	Official welcome	Alex Malahoff
Introductory talks on slow slip processes.		Chair: Eli Silver
8:40 a.m.	Global distribution and characteristics of slow slip	Susan Schwartz
9:00 a.m.	Seismological phenomena associated with slow slip	Kazushige Obara
9:20 a.m.	Imaging slow slip processes	Shuichi Kodaira
9:40 a.m.	Discussion	
10:10 a.m.	MORNING TEA	
10:30 a.m.	Geophysical environments of slow slip	Kelin Wang
10:50 a.m.	Structural Considerations on the Style and Mechanics of Slow Slip	Rick Sibson
11:10 a.m.	Fluids, fault zones and slow slip	Demian Saffer
11:30 a.m.	Modeling the occurrence of slow slip events	Jim Dieterich
11:50 a.m.	Discussion	
12:30 p.m.	LUNCH	
Lessons learned about subduction megathrust processes from previous IODP studies		Chair: Joshu Mountjoy
1:15 p.m.	NanTroSEIZE Drilling Project Overview: Sampling and Monitoring Plate Boundary Fault Processes of the Nankai Subduction Zone	Harold Tobin
1:35 p.m.	Estimation of slip velocity and durations from the fault core, result of IODP NanTroSEIZE stage 1	Arito Sakaguchi
1:55 p.m.	Supralithostatic Fluid Pressures along Faults in the Realm of VLF Earthquakes, Tremor, and the 1944 M 8.1 Tonankai Earthquake, SW Japan	Casey Moore
2:10 p.m.	Geochemical and thermal indicators of fluid flow in an erosional margin and other lessons from IODP Expedition 334	Marta Torres
2:25 a.m.	Ocean drilling and seafloor measures of heat flow: Implications for the thermal state of the subducting Cocos Plate offshore Costa Rica	Rob Harris
2:40 p.m.	Lessons Learned from Long-Term Hydrogeochemical Records from ODP Borhehole Observatories with Focus on the Costa Rica Subduction Zone	Miriam Kastner
3:00 p.m.	Lessons Learned from CORKs: Designs and Observations in Subduction Settings	Keir Becker
3:20 p.m.	Discussion	
4:00 p.m.	AFTERNOON TEA	
4:20 p.m.	Break out sessions: Measurements/experiments needed to understand the origins of slow slip, without reference to a specific subduction zone	
	Breakout 1: Auxilliary studies	Nathan Bangs/Lisa McNeill
	Breakout 2: Monitoring studies	Demian Saffer/Marta Torres
	Breakout 3: Physical Properties	John Townend/Ake Fagereng

6:00 p.m.	End of Day 1 proceedings	
7:00 p.m.	DINNER AT USSCo.	

Day Two

Time	Activity	
7:00 a.m.	BREAKFAST	
8:15 a.m.	Round up of day 1 discussion/housekeeping	

Reporting from Breakout session 1

8:25 a.m.	Breakout 1 reporting	Nathan Bangs/Lisa McNeill
8:45 a.m.	Breakout 2 reporting	Demian Saffer/Marta Torres
9:05 a.m.	Breakout 3 reporting	John Townend/Ake Fagereng
9:25 a.m.	Discussion	
10:10 a.m.	MORNING TEA	

Slow slip processes at specific geographic locations that have potential for using drilling studies to unlock the secrets of slow slip

10:30 a.m.	Overview of Hikurangi margin tectonics and slow slip events	Laura Wallace
10:50 a.m.	Characteristics of the Plate Interface and Offshore Margin in the Northern Hikurangi Slow Slip Event Source Area	Rebecca Bell
11:10 a.m.	Tectonic Setting and Potential for Drilling the Seismogenic Zone of Both, Large Interplate as well as Slow Slip Events off Nicoya Peninsula, Costa Rica	Marino Protti
11:30 a.m.	Costa Rica 2: Dynaseis Nicoya	Kevin Brown
11:50 a.m.	Outline of the Kanto Asperity Project	Reiji Kobayashi
12:10 p.m.	Kanto Asperity Project, Program B: Geodetic and geophysical monitoring of slow-slip events in the southern Kanto region for establishment of earthquake generation models	Toshinori Sato
12:30 p.m.	LUNCH	
1:30 p.m.	Break-out session 2: Specific experiments to do and questions to address at each of the localities	
	Breakout 1: Auxilliary studies	Roy Hyndman/Juli Morgan
	Breakout 2: Monitoring studies	Keir Becker/David Schmidt
	Breakout 3: Physical Properties	Harold Tobin/Heather Savage
4:00 p.m.	POSTER SESSION WITH BEER AND NIBBLES	
6:00 p.m.	End of Day 2 proceedings	
7:00 p.m.	DINNER AT FISHING CLUB	

Day Three

Time	Activity	
7:00 a.m.	BREAKFAST	
8:15 a.m.	Round up of day 2 discussion/housekeeping	Laura Wallace

Reporting from Breakout Session 2

8:25 a.m.	Breakout 1 reporting	Roy Hyndman/Juli Morgan
8:45 a.m.	Breakout 2 reporting	Keir Becker/David Schmidt
9:05 a.m.	Breakout 3 reporting	Harold Tobin/Heather Savage
9:25 a.m.	Discussion	
10:10 a.m.	MORNING TEA	
10:30 a.m.	Break-out session 3: Development of an implementation plan for each location	

	Breakout 1: Hikurangi	Laura Wallace/Stuart Henrys
	Breakout 2: Costa Rica	Marino Protti/TBD
	Breakout 3: Central Japan	Reiji Kobayashi/Casey Moore
12:30 p.m.	LUNCH	
Reporting from Breakout session 3		
1:30 p.m.	Breakout 1 reporting	Laura Wallace/Stuart Henrys
1:50 p.m.	Breakout 2 reporting	Marino Protti/TBD
2:10 p.m.	Breakout 3 reporting	Reiji Kobayashi/Casey Moore
2:30 p.m.	Discussion	
3:00 p.m.	Field trip primer: Tectonic context of the Hikurangi Forearc	Nicola Litchfield/Kate Clark
3:20 p.m.	AFTERNOON TEA	
3:40 p.m.	Tohoku Mw 9.0 earthquake and implications for global subduction zone hazards. Talk 1: Seismological perspective	Yoshihiro Ito
4:00 p.m.	Tohoku Mw 9.0 earthquake and implications for global subduction zone hazards. Talk 2: Offshore response work	Shuichi Kodaira
4:20 p.m.	Effective IODP projects and the current status and future of IODP	Casey Moore/Demian Saffer
4:50 p.m.	Wrap-up discussion	Leaders: Eli Silver and Nathan Bangs
6:00 p.m	End of workshop	
7:00 p.m.	DINNER AT FETTUCCINE BROTHERS	

Appendix C: IODP Unlocking the Secrets of Slow Slip Workshop, Gisborne, New Zealand- Poster Titles

Barker, D.H.N.	GNS Science, Lower Hutt, New Zealand	Depth migrated MCS profile 05CM-04, offshore northern Hikurangi margin
Barnes, P.	NIWA, Wellington, New Zealand	Tectonic variations along the Hikurangi Subduction margin, New Zealand, and relationships to fluid flow and cold seep sites
Clark, K.	GNS Science, Lower Hutt, New Zealand	The search for prehistoric subduction earthquakes along the Hikurangi margin, New Zealand
Colella, H.V.	University of California, USA	Comparison of simulated slow slip events with observations
Ellis, S.	GNS Science, Lower Hutt, New Zealand	Causes and consequences of abrupt change in interseismic locking depth along the Hikurangi plate interface and its relation to slow slip
Fagereng, A.	University of Cape Town, South Africa	The heterogeneous nature of rheology, permeability and metamorphism along the subduction megathrust
Fry, B.	GNS Science, Lower Hutt, New Zealand	Deep triggered tremor along the Hikurangi margin
Fulton, P.M.	University of Texas, USA	The Hydrogeologic Setting of Subduction Zone Slow Earthquakes
Gomez, B.	University of Hawai'i, Honolulu, USA	Tectonic signals in lake and marine sediments
Heise, W.	GNS Science, Lower Hutt, New Zealand	Electromagnetic image of the Hikurangi subduction interface, Raukumara Peninsula, New Zealand
Henrys, S.A.	GNS Science, Lower Hutt, New Zealand	SAHKE experiment reveals seismic-reflection character of the source region of deep slow slip events, Hikurangi subduction zone, New Zealand
Huihusan Chen, K.	National Taiwan Normal University, Taipei, Taiwan	Triggering and interaction of repeating earthquake sequences at Parkfield, California
Hyndman, R.	Pacific Geoscience Centre, Geological Survey of Canada, and University of Victoria, B.C. Canada	The Landward Limit of Great Earthquake Rupture
Ikari, M.J.	University of Bremen/Pennsylvania State University, USA	Implications of Combined Velocity- and Slip-Dependent Friction for Slow Fault Slip
Marsaglia, K.M.	California State University, USA	The Raukumara Peninsula, a Mass Transport Dominated Forearc since late Oligocene Subduction Inception?
Mountjoy, J.J.	NIWA, Wellington, New Zealand	Active upper-plate thrust faulting in regions of low plate-interface coupling, repeated slow slip events,

		and coastal uplift: Hikurangi Margin, New Zealand
Pecher, I.A.	GNS Science, Lower Hutt, New Zealand	Constraints on temperatures at the subduction interface from BSR depth
Remitti, F.	Università di Modena e Reggio Emilia, Italy	Slip increments recorded in quartz and calcite slickenfibres in ancient subduction complexes: examples from the Northern Apennines of Italy and the Chrystalls Beach Complex, South Island, New Zealand.
Reyes, A.G.	GNS Science, Lower Hutt, New Zealand	What lies below the Hikurangi forearc-evidences from fluid compositions
Reyners, M.	GNS Science, Lower Hutt, New Zealand	The Hikurangi Margin: subducting an old subduction zone sideways
Savage, H.	Lamont-Doherty Earth Observatory, New York, USA	Exploring Frictional Stability Transitions and Tremor Signals in Laboratory Experiments
Schmidt, D.	University of Oregon, USA	Slow slip events in Cascadia inferred from GPS
Sheehan, A.	University of Colorado at Boulder, USA	Seafloor Seismic Observations flanking the South Island of New Zealand: the MOANA Ocean Bottom Seismic Experiment
Underwood, M.	University of Missouri, Columbia, USA	Three-Dimensional Variations in Subduction Inputs: How Strata in the Shikoku Basin Influence the Plate Interface of Nankai Trough
Wech, A.G.	Victoria University of Wellington, New Zealand	A continuum of stress, strength and slip in the Cascadia subduction zone
Zhu, W.	University of Maryland, Washington, USA	Slip instability associated with decreasing effective normal stress: an experimental investigation on slow slip events