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ABSTRACT VOLUME
Broadband Seismic Imaging of Large Earthquake Ruptures

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Broadband Seismic Imaging of Large Earthquake Ruptures

During the last 15-20 years, expansion of the global seismic networks and the installation of a substantial number of regional seismic stations, including observatories with broadband seismic sensors, have yielded high-quality seismic observations. Coupled with increased computer efficiency and substantial reductions in digital data storage costs, and broad, international sharing of seismic observations, these data form a basis for an improved view of seismogenic components of large earthquake ruptures. Although only one interplate subduction event occurred near a dense strong motion network (the 2003 Tokachi Oki, Hokkaido earthquake), more than 20 large events (GCMT moment magnitude greater than or equal to 7.8) have occurred around the globe, including the extremely large 2004 Sumatra megathrust earthquake, 12 large under-thrusting events, a large under-thrusting/outer-rise doublet (2006-2007 Kuril Islands), and an intriguing rupture across a subduction plate boundary (01 April, 2007 Solomon Islands).

I discuss advances in seismic methodology developed by a number of researchers active in rupture imaging, and illustrate our improved capabilities using examples from recent large earthquakes. The increased signal bandwidth (100's to several seconds period) better illuminates the slower (100's of seconds period) rupture processes, and helps define the spatial extent of seismic ruptures better than shorter-period body wave signals, traditionally used to construct seismic "finite-fault" (kinematic) models. Creative adaption of short-period seismic array signals (periods of a few seconds) to image rupture-front propagation have led to additional information on the processes associated with rupture propagation. Improved seismic rupture models for large earthquakes are important to efforts to understand the relation between seismic strain release and processes such as episodic slip and tremor along with longer-term geodetic and geologic evidence of stress transfer across subduction boundaries. Improved seismic rupture models with good resolution of critical rupture parameters spanning seismic time scales (process times from a few seconds to 10's of minutes), will provide better constraints for physical models of large earthquake ruptures. Improved seismic rupture models with good resolution of important rupture parameters spanning time scales from a few seconds to 10's of minutes (seismic time scales), will provide better constraints for physical models of large earthquakes and will contribute to our overarching efforts to understand subduction processes.
Development of cabled seafloor seismo-geodetic network and seafloor borehole observatories in the Nankai Trough

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A scientific submarine cable network called DONET (Dense Ocean-floor Network System for Earthquakes and Tsunamis) is going to be built in the rupture area of Tonankai earthquake in the south of Kii-peninsula, Japan. In this area, the Philippine Sea plate is subducting under the Honshu Island. As a result, large earthquakes occur with recurrence intervals of about 100-150 years, where the last one occurred in 1944. The objectives of the submarine cable network are precision monitoring of the seismic activity of micro to large earthquakes, slow slip of the plate boundary seafloor deformation, and Tsunamis generated due to large earthquakes. Availability of no seafloor data is large limitation for us to observe these events in the seafloor. We aim, by DONET installation, not only to improve detection ability of events, but to model these events quantitatively with better accuracy.

We designed our submarine cable observation system to increase the number of observatories significantly (in an order of ten) from present submarine cable network systems for earthquake monitoring which allow only several seismometer installed in each observation node. Increased number of observatory may be installed by extending cable from each observation node [1]. Using multiple extension fiber-optic cables from observation node, our design allow maximum of 40 observatories from five observation nodes connected to backbone submarine cable.

In the initial installation of DONET, by optimizing observatory density and location, we plan to install 20 seafloor observatories distributed densely, covering the area from the trench axis to the main rupture area of the last Tonankai earthquake (Fig. 1). This distribution of observatory enables us to precisely determine hypocenter of small to large earthquakes and detect relatively small ground deformation in the seafloor. We evaluated these ability of DONET network by computer simulation. By simulating with different DONET observatory distribution, we optimized our network so that area of good hypocenter location is maximized, yet there is no obvious gap of such area in and around the DONET network.

We also evaluated detection ability of ground deformation due to small precursory slip event. With precision observation of seafloor pressure change in densely distributed seafloor quartz pressure gauges, we expect to identify occurrence of small ground deformation. By such observation, slow slip event on the plate boundary may be detected. An event of moment magnitude 6 slip on the plate boundary in the seafloor was evaluated for detection by DONET network. Our simulation result suggests that such detection is possible if such event occur below the DONET network, and seafloor pressure gauge has resolution of 1 cm or better. Such detection of events in the seafloor, is impossible only with current GPS geodetic observation network which are dense, but only on land.

The observation targets of DONET, such as small to large earthquakes, slop-slip events on the plate boundary, Tsunamis, require precision seismometers and pressure gauges. Small earthquakes has very small amplitude and typically observed in frequencies higher than 1 Hz. Large earthquakes show very large acceleration up to 2 G or so. On the otherhand, slow slip events may be observed between 0.01-0.1 Hz, or even lower frequencies such as days or months. In all, dynamic range and frequency band of DONET observation target are wide (smaller than $10^{-9} \text{m/s}^2$ to 2 G) and broad (from 1/years to 100 Hz). To cover the dynamic range and frequency
band, we plan to combine two types of seismometer and three types of pressure gauges installed in each observatory. Two types of seismometer are a broadband seismometer to cover weak motion in the frequency band of 1/360 Hz to 100 Hz and a strong motion accelerometer to cover strong motion in the frequency band from DC to 100 Hz. The three types of pressure gauges are quartz pressure gauge to observe Tsunamis and seafloor deformation by absolute pressure from DC to approximately 1 Hz, a differential pressure gauge [2] to observe broadband seismic waves as a small change of seafloor pressure from 1/200 Hz to 20 Hz, and a hydrophone to observe high frequency acoustic waves. A differential pressure gauge is very sensitive and can detect pressure change of 0.1 Pa or smaller in frequencies 0.02-0.08 Hz, where very low frequency earthquakes are known to be observed.

We evaluated noise characteristics of seismometers of different kind in a vault of Matsushiro Seismological Observatory, Japan Meteorological Agency. Evaluated seismic sensors were three types of broadband seismographs (Streikeisen STS-2, Guralp CMG-3T, prototype version of Kinematics Cronos), three types of strong motion accelerometers (JAE JA-5 typeIII, JAE JA-40G, Metrozet TSA-100S), and four types of geophones. As well to monitor Tsunamis generated in and around the network, to monitor ground deformation in vertical direction, quartz pressure gauge, that gives depth of seafloor in terms of seafloor pressure, is used. Quartz pressure gauges are stable over years typically better than 0.5 psi/year. Effect of seafloor deformation due to slip events on the plate boundary is usually very small. Therefore, the stability of quartz pressure gauge used is very important. We evaluated quartz pressure gauges for their long-term stability in environment similar to the seafloor built in a laboratory. Manufacturer of tested quartz pressure gauges were Hewlett Packard, Paroscientific, and Clark Oilfield Measurement. The laboratory test for more than continuous 150 days period was conducted to determine the type of quartz pressure gauge for the DONET observatory.

To isolate seismometers from the effect of seafloor current flow, we plan to design the seismometer package to enable surfacial burial ([3], [4]) in the sediment, while the pressure gauge package will be installed in the seafloor (Fig. 2). From experience of previous seafloor deployments of Tsunami-meters [5], care will be taken to minimize temperature change of pressure gauges. These are the part of actions taken to achieve very low noise observation by the future DONET observatory.

Furthermore, the technology developed for the DONET network can be applied to connect sensors installed in deep seafloor boreholes. We plan to install three borehole observatories in the NantroSEIZE project in the area of DONET. Drilling of three boreholes (NT2-11 2.5kmbsf, C0002 1kmbsf, and NT2-1 500mbsf in Fig. 1), in the area of transition from aseismic to seismically coupled plate boundary, is planned in 2009 by IODP drilling vessel Chikyu. Sensors will be installed in the following stage, after the drilling in 2009. A set of borehole instruments to monitor ground deformation in the plate boundary will be installed in each borehole. The borehole sensors consist of strainmeters, tilmeters, seismometers (broadband, strong motion accelerometers, and geophones), pressure gauges, thermometers, and electrodes. The borehole observation systems are designed to connect to DONET nodes to achieve long-term observation, some from the beginning, and others after initial off-line observation using batteries.
Figure 1 Planned DONET cable route (red line), observation node (stars), and seafloor observatories (pink circles), and borehole observatories (yellow circles).
Figure 2. Concept of DONET observation sensors. Seismometers are buried in the seafloor and pressure gauges are installed in the seafloor.

References
Interseismic stress build up, co-seismic stress release and afterslip on the Sumatra megathrust

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The Sumatra Megathrust has recently produced a flurry of large interplate earthquakes starting with the giant Mw, 9.15, Aceh earthquake of 2004. All the these earthquakes occurred within the area monitored by the Sumatra Geodetic Array (SuGAr), which provided exceptional records of near field co-seismic and postseismic ground displacements. The geodetic data were combined with field measurements of uplift or subsidence and seismic waveforms to produce well constrained kinematic finite-source models of these ruptures. Similarly well constrained afterslip models could be obtained. We also have some idea of the pattern of interseismic coupling (defined as the ratio of interseismic creep rate to long term slip rate) from the modeling of geodetic data collected before the Aceh earthquake and coral growth records of uplift or subsidence of coastal areas. It turns out that interseismic coupling is quite heterogeneous with both along-strike and depth variations and that the rupture areas of the large interplate earthquakes all fall within strongly coupled patches. It is observed that a same strongly coupled patch can produce similar repeating large events, with the co-seismic slip distribution reflecting more or less the interseismic pattern, or rupture in quite different successive earthquakes. Altogether we conclude that 1-seismic asperities are probably persistent features which arise form heterogeneous strain build up in the interseismic period; 2- the same portion of a megathrust can rupture in different ways depending on whether asperities break as isolated events or cooperate to produce a larger rupture. Temperature is certainly one important factor determining the rheology of the plate interface, but other factors are required to account for the observed along-strike variations. In particular, subduction of the Investigator Fracture Zone could be the cause for low coupling near the Equator where only moderate interplate earthquakes are known to occur. In situ-investigation of the Sumatra megathrust will be most helpful to unravel the physical factors that determine the mode of slip on the plate interface and the conditions under which a large megathrust rupture can develop.
Analysis of Apparent Stress for Subduction Zone Earthquakes Along the Nicoya Peninsula, Costa Rica

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Subduction zones around the world release much of the world’s seismic energy in mega-thrust earthquakes. This energy release varies likely in response to variable strength of the mega-thrust zone. Here we examine the seismic energy along the megathrust at the Middle America Trench, focusing on small magnitude earthquakes at the northwestern margin of Costa Rica, Central America. This area is interesting because seismicity patterns vary along strike of the subduction zone, and there is heterogeneous topography on the incoming Cocos plate that could affect the strength of the interface. We compute source spectra and seismic moment from coda amplitude measurements for about 260 well-located earthquakes from the Nicoya Peninsula portion of the 1999-2001 CR-SEIZE project. Using the coda wave amplitudes provides more stability for magnitude estimates because we minimize effects of energy distortion from crustal heterogeneity. We use the source spectra to examine the source scaling relationships between the large and the small events, and to explore possible spatial distribution of apparent stress. We find that apparent stress is larger for events along the northern and central portions of the Nicoya Peninsula than those in the southern portion of the peninsula, coinciding with the changes in interface dip as well as the subduction of the Fisher seamount group at the southern tip of Nicoya. These results suggest that the apparent stress is not constant within this dataset, and these imply that the subduction zone interface in the northern and central portions of the peninsula is either stronger or experiences higher friction along its surface than in the southern region.
Convergent margins, such as Middle America, are dynamic settings with a wide range of geologic activity including thrusting and deformation, major earthquakes and tsunamigenesis, and hydrogeologic activity driving migration of various chemical species. Studies of these processes at numerous settings worldwide have made it clear that many of these processes are intrinsically linked. In exploring the spatial and temporal characteristics of interface properties, we should aim to address the following questions: 1) Where and to what extent is the current interface locked? 2) Does the associated strain accumulation build fluid pressures that drive flow? 3) Where is the updip limit of seismogenic zone activity, and how is it manifested by microseismicity and geodetic-locking? 4) Is locking partially relieved by episodic aseismic slow slip events? If so, how do these propagate along the interface, and how are they related to fluid flow? 5) Is low amplitude, subduction tremor associated with shallow slow slip events along the interface? 6) How do all these processes interrelate to the larger seismic cycle? 7) How is the hydrological, thermal, and geochemical architecture of the system linked to subduction dynamics?

One good example of a system that is well studied and where many of these processes can be studied is Costa Rica. Importantly, there is already increasing evidence for a variety of dynamic phenomena including earthquakes, slow-slip events both near the toe and in the lower transition of the seismogenic zone, partial seismogenic fault, coupling, hydrologic disturbances, and possibly even tremor-like noise. The on/offshore regions also appear to be highly hydrologically active with ramifications for complex tectono-hydrologic interaction primary subduction factory objectives. It also has a rapid convergence (~9 cm/yr) rate and a narrow offshore forearc in the Nicoya area (~60 km). Large amounts of off and onshore data and infrastructure also already exist. The geometry and currently existing scientific and physical infrastructure, thus, makes the development of observatory financially and intellectually tractable. Further progress in understanding these dynamic settings and these linked processes requires continuous, simultaneous observations. However, in order to reach its full potential as an plate boundary observatory, further investment in infrastructure is required including: additional IODP CORKs, off/onshore geodetics, and seismological and hydrologic/geochemical installations.
Preliminary results from IODP Expedition 315, Nankai Trough

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IODP Expedition 315 was designed to provide the first information on the composition and structural architecture of the hanging wall of a major, probably seismogenic thrust fault. The Expedition drilled two Sites: C0001 located on the upper slope of the accretionary prism and C0002 located on the seaward edge of the Kumono Basin. Both sites penetrated unconformities recognized on seismic reflection data that appeared to separate accreted sediments below from slope cover and basin fill sediments above. At both sites the unconformities are associated with periods of very low rates of sedimentation as well as a significant increase in the number of faults per meter at deeper levels. At C0001 the period of slow sedimentation spans about 2 m.y., starting at about 4 Ma whereas at C0002 the period of slow sedimentation spans nearly 4 m.y., starting at about 6 Ma. The slightly older age for the initiation of the period slow sedimentation at Site C0002 is consistent with the more landward position of this site if the transition to slow sedimentation represents the accretion and uplift of trench or near-trench sediments. The sediments that accumulated during the period of slow sedimentation at Site C0002 (Lithologic Unit III) are dominantly hemipelagic muds with slightly higher porosities than expected for these depths and host a plethora of unusually large “dewatering veins.” Both drilling sites record substantial increases in rates of sedimentation at about 2 Ma: from ~35 m/m.y. to ~160 m/m.y. at C0001; and from 25 m/my to 600 m/my at C0002, consistent with regional patterns of sedimentation in southwest Japan.

Faults, breccia, tilted bedding and dewatering veins represent the most common structures observed at Sites C0001 and C0002 and preliminary kinematic analyses suggest that sigma 1 is nearly vertical at a both sites. Crosscutting relations and the inversion of fault sets with complex histories also suggest two periods of extension – ~NW-SE recorded at Site C0002 and less strongly at Site C0001, followed by ~NE-SW extension recorded at both drilling sites. Analyses of fault sets from the accreted sediments below the unconformities at both sites show NW-SE horizontal shortening, which is inferred to be the oldest deformational event at both sites. A vertical sigma 1 at both sites is consistent with borehole breakout data obtained during Expedition 314 and with preliminary analysis of stress orientations interpreted from anelastic strain recovery data. The core-based observations, however, define the 3-dimensional state of strain as well as the temporal sequence of faulting and deformation.
Seafloor geodesy: Transitioning to continuous monitoring of plate motion in subduction zones

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Convergence along the subducting plate interface generates stick-slip motion leading to a broad zone of deformation at the oceanic and continental plate surfaces, both on- and offshore. Campaign-style GPS has long been used to measure deformation on the subaerial portion of the continental plate and model the down-dip extent of locking on the interface. More recently, motion of the submerged portion of the continental and oceanic plates has been measured by combining kinematic GPS and underwater acoustics (GPSA). GPS-Acoustics extends to the seafloor the use of GPS for crustal motion studies. GPS determines the precise location of a platform (ship or buoy) while underwater acoustics determines the precise range to seafloor transponders. These campaign-style measurements from a ship now make it possible to measure deformation across the entire subduction zone from incoming oceanic plate to continental plate interior. On land, the advent of continuous GPS networks improved the measurement resolution leading to the capture of small, deep, slow slip events. Seafloor geodetic methods are undergoing a similar transition from campaign-style to continuous monitoring. Continuous seafloor geodetic monitoring will be possible for next-decade subduction zone studies and will provide broad spatial and temporal coverage of aseismic as well as seismic deformations.

Measurements of oceanic plate convergence, interseismic landward contraction, and coseismic seaward release of submerged continental plate from campaign-style GPSA will be reviewed at sites in subduction zones off the Western US, Peru, and Japan. The status of continuous GPS-Acoustic, acoustic-only, and vertical deformation sensors will be examined along with their roles in observatories such as DONET, etc. Possible targets will be discussed such as the regional motion of the updip region and monitoring individual faults (e.g., splay)

General References:

Convergence:

Interseismic:
Coseismic:

Technique:
The Strength of Antigorite Deformed at High Temperatures

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Experiments have been conducted on intact cores of antigorite serpentine in a Griggs-type apparatus at 550°C, 1.5 GPa, and a constant strain rate of ~10^-5/s. In all experiments, despite choosing samples with limited impurities and despite the orientation of the foliation, the samples fractured at 45° to σ_i and underwent frictional sliding. The fracture strength of the sample where fracture and slip occurred parallel to the foliation was ~100 - 200 MPa less than the fracture strength when foliation was at a 45° angle to the fracture. In addition, in the 45° oriented sample, the fracture appears to have initiated upon loading; it is possible that this is related to the mechanical anisotropy of the sample owing to the foliation.

The results from our deformation experiments can be compared to results from antigorite deformed using the D-DIA apparatus at high temperature and pressure (Hilairet et al. 2007). Hilairet et al. (2007) deformed sintered powders of antigorite at 1 and 4 GPa, 300 - 500°C, and constant strain rates of ~10^-4/s to 10^-6/s and were able to determine flow law parameters for serpentine to fit the following power law:

\[ \dot{\varepsilon} = A\sigma^n \exp\left(-\frac{E^* + PV^*}{RT}\right) \]

where \( \dot{\varepsilon} \) is the strain rate, A is a material constant, \( \sigma \) is the differential stress, \( n \) is the stress exponent, \( E^* \) is the activation energy, \( V^* \) is the activation volume, R is the ideal constant, and P and T are the pressure and temperature of deformation. We have used the parameters determined by their deformation experiments to predict the strength of antigorite at our experimental conditions of 1.5 GPa and 550°C using the equation below:

\[ \sigma = \left[ \frac{\dot{\varepsilon}}{A\exp\left(-\frac{E^* + PV^*}{RT}\right)} \right]^{1/n} \]

The strengths predicted by the flow law of Hilairet et al. (2007), ~550 – 850 MPa depending on which data set was used, are significantly lower than the fracture strength of antigorite in this study, which was 690 - 1365 MPa.

The disagreement between the strength values predicted by the flow law of Hilairet et al. (2007) and the measured fracture strengths of our samples, indicate that additional experiments need to be conducted in the Griggs Rig to constrain strength measurements with our apparatus. We will conduct experiments on sintered powders of antigorite to more directly compare our measurements to those of Hilairet et al. (2007). Accurate strength data for serpentine is necessary in order to determine flow law parameters and, ultimately, calculate a viscosity for serpentine that can be incorporated subduction zone models.

Reference:
Mesoscopic Scale Structure in Spot Core from the San Andreas Fault Zone at SAFOD

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Spot cores from the San Andreas Fault Observatory at Depth (SAFOD) provide a remarkable view of the structure of the San Andreas fault (SAF) at the southern limit of the creeping segment near Parkfield, CA. The deviated borehole transects the entire fault zone at a depth of 2.5 to 3.0 km. Drilling and geophysical data, supported by geologic observations of cuttings and core samples, indicate the San Andreas fault at SAFOD is a broad zone of damaged rock cut by localized zones of slip consistent with large cumulative displacement and a history of seismic and aseismic deformation in bedded, clay-bearing, fine-grained host rocks. Active creep has been documented along two narrow zones at 10,480 and 10,830 ft MD. Spot cores spanning these zones each contain a distinct, meters-thick layer of incohesive gouge with a penetrative, microscaly, layer-parallel fabric, and matrix-supported, sub-rounded, mesoscale porphyroclasts (up to 15% by volume) of sandstone, siltstone, and serpentinite. The overall structure is consistent with distributed shear, but where the vast majority of shear displacement within the cored section is confined to the two gouge layers. A marked change in lithology and structure occurs across both the 10,480 ft and 10,830 ft MD gouge layers. West of 10,480 ft is a broad zone of fractured arkosic rock that grades eastward into foliated cataclasites, analogous to that seen in exhumed traces of the SAF to the south. This damage zone is cut by microscale fractures and mesoscale conjugate shears that record contraction at high angles to the SAF, and displays evidence of pervasive secondary mineralization. In contrast, the low velocity zone between 10,480 and 10,830 ft is composed of thinly bedded sandstone, siltstone and shale that has experienced bedding parallel extension via interlayer flow and boudinage along high-angle shears and extensional veins. The low velocity zone northeast of 10,830 ft consists of highly fractured and locally microbrecciated siltstone and shale. Bedded rock and foliated cataclasites near the 10,480 and 10,830 gouge layers display LS mesoscale fabrics consistent with non-coaxial deformation. Ongoing work is focused on using map and CT data to define deformation fabrics and the geographic orientation of Phase 3 spot cores for kinematic and paleostress analyses.
Large Earthquakes and Tsunamis in the Hellenic Arc and Trench System

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The large earthquake-tsunami key events of AD 365, 1303, and 1956, all being of magnitude of the order of 7.5-8.0, influenced drastically populations in many countries and in remote places of the East Mediterranean, such as in Greece, Italy, Egypt, Israel and Turkey. It appears that such events are of long return period. However, their repeat in the future may cause dramatic consequences for many regions due to the drastic increase of vulnerability of local communities. In particular, it appears that the segments ruptured by the 365 and 1303 earthquakes are strongly coupled failing to rupture by large earthquakes in the last centuries, which may imply that big earthquakes are under preparation. Therefore, it is urgent need to study more systematically the western and eastern segments of the Hellenic Arc. More precisely, we need to determine the degree of plate coupling, to identify potential sources of future large events, to estimate the thickness of the seismogenic layer, to identify palaeoearthquake and palaeotsunami events and, finally, to approach reliably the mean repeat times of large events.
Using pressure as a proxy for strain: A review of ODP/IODP "CORK" technology and observations

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Instrumentation to monitor formation pressures and temperatures in Ocean Drilling Program boreholes was developed in 1990 and first deployed on the Juan de Fuca Ridge in 1991. Since that time, a total of eighteen holes have been sealed and equipped with similar "CORK" (circulation obviation retrofit kit) hydrologic observatory systems, and some have provided more than a decade of continuous data. Modifications to the original design have allowed pressure data and fluid samples to be obtained from multiple isolated levels. Recent improvements in pressure sensing technology now enable absolute pressures to be determined to a precision of roughly 10 ppb of full sensor scale (e.g., about 0.5 Pa) at a measurement frequency of up to 1 Hz.

Primary objectives were originally focused on determining the average formation state and driving forces for fluid flow in the hydrothermally or tectonically active environments chosen for study, but it quickly became clear that the records also contained interesting time-varying signals, including ones that reflected regional co-seismic and aseismic strain transients. Consideration of constituent elastic properties leads to an estimate of strain-to-pressure conversion efficiency of the order of 5 kPa / microstrain. The instrumental measurement precision thus allows volumetric strain sensitivity down to roughly 0.1 nanostrain, although "environmental noise" from oceanographic loading (interesting in its own right) imposes a practical limitation to strain determination of about 20 x 10^-9.

Examples of pressure signals from the Nankai, Mariana, and Costa Rica subduction zones and the Juan de Fuca Ridge reveal both positive and negative co-seismic pressure steps that are consistent in sign with the regional strain patterns predicted using simple dislocation theory constrained by earthquake moment tensors, but the magnitude of the pressure-derived strain is often much larger than that predicted, suggesting significant seismic inefficiency. Records also contain signals that suggest the presence of long-term post-seismic transient strain, and interseismic secular strain.

While quantitative calibrations are badly needed (via co-located strain and pressure observations), the demonstrated sensitivity of pressure as a volumetric strain proxy, along with a more efficient deployment scheme under development, offers a cost-effective opportunity for monitoring strain in offshore regions with a spatial density appropriate for studying both steady and episodic strain accumulation and relaxation above and seaward of the "locked" portions of subduction thrusts at locations like Nankai. Such observations would be highly complementary with ones made on land, and the combination would allow slow and fast strain events to be observed across the full widths of seismogenic plate boundaries.
Criteria for Splay Fault Activation During Dynamic Rupture Propagation

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Critical taper wedge concepts suggest that as material is added to the accretionary prism or removed from the forearc, the material overlying the plate interface must deform to maintain a wedge structure. This internal deformation is achieved by slip on splay faults branching from the main detachment, which are possibly activated as part of a major seismic event. As a rupture propagates updip along the plate interface, it will reach a series of junctions between the shallowly dipping detachment and more steeply dipping splay faults. The amount and distribution of slip on these splay faults and the detachment determines the seafloor deformation and the tsunami waveform. Numerical studies by Kame et al. [JGR, 2003] of fault branching during dynamic slip-weakening rupture in 2D plane strain showed that branch activation depends on the initial stress state, rupture velocity at the branching junction, and branch angle. They found that for a constant initial stress state with the maximum principal stress at shallow angles to the main fault, branch activation is favored on the compressional side of the fault for a range of branch angles. By extending the part of their work on modeling the branching behavior in the context of subduction zones, where the angle that the principal stress makes with the main fault is shallow, but not horizontal, we hope to better understand the conditions for splay fault activation and the criteria for significant moment release on the splay. Our aim is to determine the range of initial stresses and relative frictional strengths of the detachment and splay fault that would predict seismic splay fault activation. In aid of that, we conduct similar dynamic rupture analyses to those of by Kame et al., but use explicit finite element methods, and take fuller account of overall structure of the zone (rather than focusing just on the branching junction). Critical taper theory requires that the basal fault be weaker than the overlying material, so we build on previous work by incorporating the effect of strength contrasts between the basal and splay faults. Wang and Hu [JGR, 2006] suggest that it is the coseismic stress state and friction response that dictates the wedge geometry, so our parameter choice is aided by observations of wedge geometry. We use the wedge mechanics concepts to guide the choice of initial stress state in the modeling, and we are able to apply a depth dependent stress state to see how the slip distributions on the splay fault are altered by the incorporation of depth dependent stresses and free surface effects, and how this effects the tsunami waveform.
P-wave velocity modeling using onshore/offshore passive seismic networks along the Middle America subduction zone, Costa Rica and Nicaragua

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The seismogenic zone of the Middle America subduction zone along Costa Rica and Nicaragua has been a focus site for the NSF Margins and German SFB programs. The margin transitions from subduction of thicken oceanic crust associated with the Cocos Ridge in southern Costa Rica to subduction of thinner, but pervasively faulted and hydrothermally cooled, crust along Nicaragua. The overlying volcanic arc also exhibits a high degree of geochemical and spatial variability along strike. Here, we combine arrival time information from six onshore/offshore passive networks deployed along this margin from 1999-2006. We use data from the Osa and Nicoya networks collected as part of CRSEIZE (PIs. S. Schwartz/L. Dorman) and the Jaco/Quepos, Nicaragua, and Nicaragua outer-rise networks collected as part of the SFB 574 program (PIs. E. Flueh/W. Rabbel). The combined networks provide ~600 km of along-strike coverage of the seismogenic zone. The networks did not overlap in time but did overlap in space. We are testing multiple earthquake tomography methods to resolve P-wave heterogeneity and investigate along-strike spatial and temporal variability in microseismicity and seismic velocity. By relaxing some quality criteria, such as greatest azimuthal P-wave separation, we can retrieve crossing rays between networks. Initial results suggest this approach will improve coverage of velocity along the boundaries and between networks, and in particular provide improved images of the seismogenic zone and potentially serpentinized oceanic plate updip of the abrupt transition in the volcanic arc from Costa Rica to Nicaragua. Within each network, initial results are consistent with previously published local earthquake tomography studies. This initial study should help guide ongoing efforts to integrate Margins SEIZE/SFB 574 seismic data collected within Costa Rica and Nicaragua.
Transient Strain Events in Costa Rica

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Transient strain events have been observed in many of the world's subduction zones and are beginning to be observed and characterized in Costa Rica using a new NSF-funded network. The network consists of about a dozen GPS receivers and seismometers with several levels of communication. This network became operational in mid-2008 and is able to delineate the timing and up-dip slip locations. However down-dip resolution is poor. The events detected so far with this network will be discussed, as well as plans for future upgrades.
The CRSEIZE experiment of 1999-2000 (DeShon and others, 2006), an array of 14 "ONR" OBSs were deployed in an array across the forearc of the subduction zone west of Costa Rica. The station spacing was about 15 km and the array was about 35km by 60km. Half the sensors were PMD broadband electrochemical seismometers and half were 1-Hz inertial sensors. Since the length of this deployment was about six months, the dataset offers an opportunity to exploit recently-developed techniques exploiting microseismic noise as a tool for structural analysis. See Shapiro and others, 2005, as a starting point. For this technique to work, there must be coherent observations of propagating seismic waves between pairs of stations. Practically, this means that there must be some frequency ranges where propagating seismic signals are not contaminated by local non-propagating noise. Twelve-hour samples of field data, which were sampled at 64 Hz, were desampled to 1 Hz for this reconnaissance analysis. Data from the vertical sensor were whitened and cross-correlated. The resulting correlograms were noisier than the best data which is being shown from land sensors but there are recognizable arrivals, mostly at periods of around 7 and 3.3 seconds. Several instruments located near the OOST showed fluid flow anomalies correlated with seismic noise (Brown and others 2006). The fluid flow has been modeled successfully by a propagating dislocation (Labonte, Brown and Fialko, manuscript). These instruments also show instrument-instrument correlation signals which are not fixed in time lag. These are recognizable over a 10-day interval. It is tempting to attribute these to a moving noise source, and that source is the same as the source of the fluid flow anomalies. The time lag changes by about 2.7 seconds/day. The locus of events corresponding to a fixed time offset is a hyperboloid of revolution symmetric about a line connecting the stations. If the sources are confined to a plane (say the boundary between the subducting slab and the overlying wedge) this locus becomes a hyperbola. If these signals are traveling from the source through a medium of 6 km/s velocity, this corresponds to a distance change of 16 km/day. This velocity is a lower bound, occurring for events on the line mentioned above, an unlikely occurrence. Studies of this phenomenon would benefit from a denser deployment of OBSs at the base of the wedge.
Records of Seismicity from the Shallow Thrust Zone of the Northern Mariana Islands

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The Mariana subduction zone earthquake record shows a lack of large seismicity, and is traditionally considered ‘decoupled.’ During the 2003-2004 Mariana Subduction Factory Imaging Experiment, local shallow earthquakes were recorded throughout the central and northern regions of the Marianas forearc. These records show small earthquakes (ML < 6.0) occurring within patches down-dip from two prominent serpentinite seamounts, Celestial and Big Blue, at depths between 25-50 km. In order to better constrain the location and depth of the earthquakes, a local velocity model was introduced into our absolute and relative location techniques. Further, the focal mechanisms for the largest earthquakes in our dataset were computed by waveform modeling. Results indicate thrust faulting mechanisms, with moment magnitudes ranging from 4.0 – 5.5. Clusters of earthquakes to the west of the seamounts at depths of 25-50 km are interpreted to be events occurring on the shallow thrust plate interface of the Marianas as indicated by the focal mechanisms obtained in the region. Because earthquakes extend to at least 50 km, but crustal thickness in the region is less than 20 km, it is clear that the crust-mantle transition does not control the down-dip limit of seismogenesis. Earthquake depth distributions reveal that most events occur in the 25-45 km depth range, with a noted lack in shallower earthquakes. Harvard Centroid Moment Tensor (CMT) records from 1976 to 2005 however, do not suggest a lack of thrust earthquakes in this shallow part of the seismogenic zone. We hypothesize that the scarcity of seismicity beneath the serpentinite seamounts is either a result of a locked portion of the shallow plate interface, similar to findings from Costa Rica, or an effect of the posited stability of serpentinite minerals, which may result in stable sliding throughout most of this depth range.
Variations in shallow structure across the Sumatran Forearc based on a high resolution single-channel seismic reflection survey

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A high resolution single-channel seismic reflection survey (SEATOS) across the rupture area for the Mw 9.2 Sumatran 12/26/04 earthquake depicts variations in shallow structure across the forearc and forearc basin, with evidence for ongoing deformation based on growth strata and locally, fault offset of the ocean bottom. In 17 lines that cross the trench fill and outer forearc, the deformation front is represented by a syncline; the outermost forearc is a steep (8-12°) dip slope that forms the back limb of an arcward vergent fold. From the deformation front to the forearc high, a distance of approximately 55 km, folds with wavelengths of 10 km or greater verge arcward, with parasitic folds (1-4 km wavelength) associated with small thrusts that cut the surface to form scarps. Based on the structure at the toe of the prism, we interpret the outer forearc as a triangle zone, with landward vergent folding of a passive roof detached from the seaward-directed thrusts of a plate boundary duplex system. Across the 110 km-wide upper slope of the forearc, the long wavelength topography is characterized by a gentle slope with a central depression between two forearc highs. Superimposed on these gentle slopes are symmetric folds with ~15-km wavelength. Continuous fold growth is recorded by sediments deposited in linear basins between anticlines; parasitic folds with 1-4 km wavelength decrease in amplitude up section and thin onto the flanks of structural highs. A 25-km-wide inner slope region drops from the forearc high into the Aceh forearc basin. Folds within this inner slope region verge seaward. The transition from arcward vergence on the outer slope, to symmetric folding across the upper slope, to seaward-vergent folding on the inner slope is consistent with flexural shear of a once continuous slope apron toward the two forearc highs. Similar reversals in asymmetry are observed in the geometry of small folds across anticlinal highs. The consistent wavelength of ~15 km suggests buckling of a mechanical layer 4-6 km thick. The deformation front that separates the accretionary prism from the Aceh forearc basin is near vertical, consistent with strike slip motion on the W. Andaman Fault system. A seismic line that crosses a restraining bend in this strike slip system (i.e., Tuba Ridge) records ongoing shortening in the inner forearc based on growth stratal geometries. The overall structure across the forearc suggests partitioning of oblique plate motions into shortening across the outer forearc and strike slip in the inner forearc. The triangle zone and landward vergent folding at the toe of the wedge indicate that coseismic slip in this region is likely blind, with broad surface uplift and shortening across the forearc driven by elastic rebound of a strong inner wedge beneath the passive roof of folding slope strata.
The Seismogenic Zone at the Alaska-Aleutian Subduction Zone

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Over the last century the Alaska-Aleutian subduction zone has generated an M8+ earthquake about once every 15 years, and it has generated three of the ten largest earthquakes in instrumental history. But the Alaska-Aleutian subduction zone does not display uniform properties along strike. Instead, the shallow plate interface features several distinct segments; individual segments generally have either a very wide zone of high slip deficit (locked zone) resulting in large geodetic strains, or are dominated mainly by aseismic creep and produce little observable strain. The transition from locked to creeping regions can occur over a distance that is short compared to the width of the locked zone, indicating that that depth or temperature does not control this along-strike transition. There is a good first-order correlation between the regions of high slip deficit inferred from geodesy and the regions of high slip in large earthquakes, suggesting that these regions are persistent over time. Further tests of this hypothesis will require both denser geodetic data and more precise earthquake slip models from future earthquakes. Alaska is not unique in showing this along-strike variability; the Hikurangi subduction zone in North Island, New Zealand shows similar along-strike transitions. This variability may be the norm rather than the exception, and it is what should be expected if the genesis of great subduction zone earthquakes is related to the distribution of large, persistent asperities. What controls these large-scale variations? Simple ideas such as temperature, plate convergence rate and so on do not predict what we observe. Correlations with forearc structure are high in some regions, but may not apply everywhere. We cannot truly understand the seismogenic zone until we understand also why some regions appear to be creeping steadily.
Plate Boundary Submarine Paleoseismology


Turbidite Systems of the Cascadia Basin are an ideal place to develop a turbidite paleoseismologic method and record because: (A) a single subduction zone fault underlies the Cascadia submarine canyon systems, (B) multiple tributary canyons and a variety of turbidite systems and sedimentary sources exist to use in tests of synchronous turbidite triggering; (C) the Cascadia trench is completely sediment filled, allowing channel systems to trend seaward across the abyssal plain rather than merging in the trench, (D) the continental shelf is wide, favoring disconnection of Holocene river systems from their largely Pleistocene canyons, and (E) excellent stratigraphic datums, including the Mazama ash (MA) and a distinguishable Holocene/Pleistocene boundary (H/P) are present for correlation of events and anchoring the temporal framework in turbidite systems within the northern two thirds of the basin.

Multiple channels in a wide variety of turbidite systems with different sedimentary sources contain 13 post-Mazama Ash and 19 Holocene turbidites in Cascadia Channel, Juan de Fuca Channel off Washington, Hydrate Ridge slope basin, and Astoria Fan off northern and central Oregon. All of these events are also recorded on Rogue Apron of Southern Oregon, with the addition of 19 smaller local events recorded as silt or mud turbidites in southern Cascadia.

Stratigraphic correlation is accomplished with P-wave velocity, gamma-ray density, RGB color reflectance, magnetic susceptibility, high-resolution imagery and AMS $^{14}$C ages. The Holocene turbidite record along the Cascadia margin passes several tests for synchronous triggering, including relative timing tests, stratigraphic correlation between sites, and somewhat less compelling radiocarbon dating, and also corresponds well to the shorter onshore paleoseismic record. We examine the applicability of other regional triggers such as storm waves and tele-tsunami specifically for the Cascadia margin. The synchronicity of a 10,000 year turbidite event record for 500 km along the northern half of the Cascadia Subduction Zone is best explained by paleoseismic triggering by great earthquakes. Similarly, we find a synchronous record in southern Cascadia, including correlated additional events along the southern margin.

The average age of the oldest Holocene turbidite is 9830 +/- 180 cal BP and the youngest was deposited in AD 1700, (250 cal. BP) thus the northern events define a Holocene great earthquake recurrence of ~ 530 years. The recurrence times and averages are also supported by the thickness of hemipelagic sediment deposited between turbidite beds. The southern Oregon and northern California margins represent at least three segments that include all of the northern ruptures, as well as ~ 19 thinner turbidites of restricted latitude range that are correlated between multiple sites. At least two Northern California sites, Trinidad and Eel Canyons, probably also record numerous small sedimentologically or storm triggered turbidites, particularly during the early Holocene when a close connection existed between these canyons and associated river systems.

The shorter rupture extents and thinner turbidites of the southern margin correspond reasonably well with spatial extents interpreted from the onshore paleoseismic record, supporting margin segmentation of southern Cascadia. The total of 38 events define a Holocene recurrence for the southern Cascadia margin of ~ 260 years. Probabilities for segmented ruptures range from 7-9% in 50 years for full margin ruptures, to ~ 78% in 50 years for a southern segment rupture.

The long earthquake record established in Cascadia allows tests of recurrence models rarely possible elsewhere. Correlatable turbidite mass along the Cascadia margin reveals a consistent record of turbidite mass per event along the margin for many of the Cascadia turbidites. We infer that larger turbidites likely represent larger earthquakes, and therefore the correlation with following time intervals suggests that Cascadia full margin ruptures may follow a time-predictable model. The long paleoseismic record also indicates a repeating pattern of clustered earthquakes that includes three Holocene cycles of 5 earthquakes followed by gaps of 700-1000 years.
We suggest that the pattern of long time intervals and longer rupture for the northern and central margin may be a function of high sediment supply on the incoming plate smoothing asperities and potential barriers. The smaller southern Cascadia segments correspond to thinner sediment supply and potentially greater interaction between lower plate and upper plate heterogeneities.

The long Cascadia paleoseismic record allows examination of this record together with a similar record established for the adjacent Northern San Andreas Fault (NSAF). The NSAF record was developed using 74 cores along the northern California continental margin. Evidence from stratigraphic correlation and merging of turbidity currents at channel confluences supports synchronous triggering of turbidity currents during the Holocene, when other sources such as storm river flows are less unlikely to reach the abyssal plain. During the last ~2800 years, 15 turbidites including the great 1906 earthquake establish an average repeat time of ~200 years, similar to the onshore value of ~210 years.

The combined land and marine paleoseismic record from the southern Cascadia subduction zone includes a similar number of events in the past 3000 years. While the recurrence interval for full margin Cascadia events is ~530 years, the southern Cascadia margin has a Holocene repeat time of 260 years, similar to that of the NSAF. Comparing the time series with a variety of methods, we observe that considering the difference in peak PDF ages, 12 of the previous 15 NSAF events were preceded by Cascadia events by ~4-30 years suggesting a temporal link (as compared to ~150-200 years if Cascadia follows the NSAF).

We model the coseismic and cumulative postseismic deformation from great Cascadia megathrust events and compute related stress changes along the NSAF in order to test the possibility that Cascadia earthquakes triggered the penultimate, and perhaps other NSAF events. The Coulomb failure stress (CFS) resulting from the viscous deformation over ~60 years does not contribute significantly to the total CFS on the NSAF. However, the coseismic deformation increases CFS on the NSAF by a maximum of about 9 bars, in the section of the fault offshore of Point Delgada, most likely enough to trigger that fault to fail in north-to-south propagating ruptures. Triggering of Cascadia by the NSAF is also possible, though not favored by the paleoseismic data.

Recently, we have begun to examine cores from the Sumatra margin to investigate the paleoseismic record from great earthquake rupture in the Holocene. 99 piston, gravity, kasten, and multicores were collected along the length of the Sumatra margin, from the 2004 rupture zone in the north, to the southern tip of Sumatra Island. Cores were collected in the trench and in lower slope piggyback basins. The trench lithology was dominated by fine mature quartz sand, consistent with the well known Himalayan source of the accreting Bengal and Nicobar fans, and contained several tephras. Slope basins contained similar lithology, with abundant forams, and significant organic debris in those basins near the offshore islands of the Sumatran forearc. Our strategy was to densely sample both trench and basin sites to test correlations between sites to determine whether observed turbidites are earthquake generated. If so, the sampling density may allow discrimination of segment boundaries as well as event histories for margin segments. Preliminary analysis suggests that turbidites can be stratigraphically correlated between sites and in Cascadia and the NSAF, and can be correlated between slope basins and the trench, effectively testing synchronous triggering. The Sumatra forearc basin effectively limits sediment input to these basins from Sumatra Island sources. The cores also contain turbidites most likely generated by the 2004 and 2005 northern Sumatra great earthquakes. These are represented by a large shallow multipulse event overlain by a smaller single pulse event at the seafloor, with no observed hemipelagic sediment between them. Ongoing CT imaging, 14C and Pb210 dating with stratigraphic correlation will test the origins and connectivity of these and numerous other Holocene turbidites.
The Thermal Structure of the Costa Rica Margin along the Middle America Trench

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The thermal structure of continental margins provides critical information related to the geodynamics associated with active plate margins. We are integrating multichannel seismic data showing bottom simulating reflectors (BSRs), in-situ thermal data, data from ODP cores, and numerical models of subduction to estimate the thermal structure along the Middle America Trench of Costa Rica. Seismic reflection data from the cruises SO81 and BGR99 show that BSRs are widespread and are clearly observed between the lower slope and shelf edge. These BSRs reflect the pressure-temperature-conditions at the base of the gas hydrate stability zone and can be used to estimate geothermal gradients along the margin. These estimates are calibrated against in-situ thermal data collocated with BSRs in seismic images. Thermal conductivity data comes from both in-situ measurements and needle probe measurements on ODP cores. Additional heat flow data seaward of the trench is being used to initialize thermal models of subduction. With the exception of offshore the northern Nicoya Peninsula values of heat flow decrease landward, consistent with the BSR distribution and subduction advecting heat downwards. Estimates of the thermal structure of the margin are coupled to a conduction-advection thermal model of subduction and temperature estimates of the subduction thrust are investigated.
Seismic Reflection Imaging of Along-Strike Changes in the Hikurangi Margin Subduction Interface, North Island, New Zealand

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Seismic reflection data from the subduction margin off the east coast of the North Island, New Zealand, show first-order structural features in the upper plate and subducting slab geometry that we relate to plate coupling at the subduction interface. Beneath the eastern coastline of North Island, New Zealand, the subducted Pacific plate dips at less than 3 degrees to the northwest and is at a depth of less than 15 km. This shallow geometry is optimum for detailed geophysical studies of the subduction decollement across the up-dip seismic-aseismic transition using both active-source and passive-source experiments. In 2005 and 2007 two government sponsored industry seismic reflection surveys were undertaken offshore of the east coast and north of the Raukumara Peninsula. In total, over 5000 km of data were recorded along the margin, much of it using a 12 km streamer. These data reveal first-order structural features of the upper plate and along-strike changes in subducting slab geometry. We suggest that these along-strike changes reflect the transition from a coupled plate interface in the south to decoupled in the north, a feature of the Hikurangi subduction system supported by interpretation of GPS velocities, location of slow slip events, and the location of moderate to large historical earthquakes.
Hydraulic and frictional properties of natural clay-rich sediments from ODP Leg190 Nankai Trough and IODP Expedition 311 Cascadia Margin Hiroko

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Understanding mechanical and hydraulic properties of sediments in accretionary subduction zones undergoing progressive consolidation and localized shear under a wide range of loading rates is crucial to understand the mechanics of subduction earthquakes and accretion processes. Several suites of experiments on sediment samples recovered from Nankai Trough and Cascadia Margin subduction zones during ODP Leg 190 and IODP Expedition 311 have been conducted to investigate the effects of rate and temperature on mechanical behavior during consolidation and sliding friction. Hydrostatic consolidation experiments have been conducted on samples collected from across the proto-decollement zone at ODP Leg190 Site 1173 (360 and 450 mbsf), at elevated pressure and temperature up to 70MPa and 150°C, respectively. Volumetric strain increases with the effective pressure and is much greater at higher temperature or after long times, and for the samples taken from above, relative to those from below, the proto-decollement. The pronounced temperature-time sensitivity observed reflects thermally-activated mechanisms of consolidation such as intergranular friction during grain rearrangement, mineral dehydration reactions including the smectite-illite transition, dissolution, and intracrystalline plasticity. Both low-speed (0.015-15 *10^-6 m/s) and high-speed (0.1-1.3 m/s) friction experiments were conducted on disaggregated samples from the decollement zone at ODP Leg 190 Site 1174 (839 mbsf). In the low-speed friction experiments, friction coefficient ranges from 0.33 to 0.5 and the velocity stepping tests show velocity strengthening behavior, with variable b-value; negative b-value is observed at 0.15*10^-6 m/s only after the sample experiences the higher slip rate of 15*10^-6 m/s. In the high-speed friction experiments, the initial friction coefficient is approximately 1.0 and subsequent dynamic weakening is observed only at the slip rate of 1.3 m/s where the friction coefficient drops over 10 m of slip to a steady state value of approximately 0.1. The friction behavior significantly varies with slip rate, and the dynamic weakening during high-speed frictional sliding may be caused by local increases in temperature from frictional heating. All results suggest that both temperature and rate have significant effects on the hydraulic and frictional properties of sediments in accretionary subduction zones.
Coseismic Stress Transfer Between the Seismogenic Zone and the Shallow Portion of the Subduction Fault and its Effects on Wedge Taper

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In a subduction zone accretionary prism, active permanent deformation takes place mainly in the most frontal part (the outer wedge), where the surface slope is generally steeper. The flatter inner wedge undergoes much less permanent deformation. We argue that this contrast in morphology and deformation pattern contains important information on the location of the updip limit of the megathrust seismogenic zone. The dynamic Coulomb wedge model postulates that the outer wedge overlies the rate-strengthening updip, and the inner wedge overlies the rate-weakening seismogenic zone. It is mainly the coseismic strengthening (stress increase) of the updip zone that is responsible for the permanent deformation of the outer wedge. In this work, we use a numerical model of stress transfer to investigate how the coseismic stress increase of the updip zone is related to the coseismic stress drop of the seismogenic zone. We define a “critical strengthening” (CS), that is, the stress increase required to prevent the rupture from breaking the trench, as a reference measure of the coseismic strengthening. We show that CS depends on the force drop of the seismogenic zone, defined as the product of the average shear stress drop and the area of the seismogenic zone. In a simple model of uniform material properties with a few MPa average stress drop over a seismogenic zone of 120 km downdip width, the CS for a 30 km wide updip zone is an increase in the effective friction coefficient by about 0.05 which produces a few MPa average stress increase. Using the Coulomb wedge theory, we demonstrate that this level of stress increase can readily cause permanent deformation to the overlying outer wedge. If the stress increase is greater than CS, the rupture is able to propagate into the updip zone only slightly, causing localized wedge compression in the area of slip termination. We examined wedge geometry of twenty-three subduction zones and found that the surface slope of these wedges can be explained using the dynamic Coulomb wedge model including coseismic strengthening of the shallow portion of the megathrust. The model-estimated frictional properties of the subduction fault are to be constrained by direct sampling, and the predicted deformation field in the overlying plate need be validated through borehole monitoring.
Enormous heat and fluid fluxes driven through mid-plate outcrops on ocean crust

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Seafloor hydrothermal circulation on ridge flanks, areas far from the magmatic influence of plate creation, extracts ~30% of oceanic lithospheric heat and impacts numerous tectonic, magmatic, and biogeochemical processes, but little is known about the magnitude of ridge-flank fluid and heat fluxes at a regional (1,000’s of km2) scale. Quantifying hydrothermal fluxes at this scale has been limited by a lack of high-resolution collocated bathymetric, seismic reflection, and heat flux data. We have collected and analyzed multiple data sets from a large area of 18–24 Ma seafloor on the Cocos Plate, seaward of the Nicoya Peninsula, Costa Rica. We have resolved massive flows of heat and fluid discharging from a few, widely-spaced crustal outcrops that penetrate seafloor sediments. The conductive seafloor heat flux through 14,500 km2 of the survey area is 10–40% of lithospheric, requiring an integrated advective power output of 800–1,400 MW. Scattered basalt outcrops in this area allow hydrothermal fluids to enter and exit the crust and bypass low-permeability sediments, with the smallest outcrops being favoured sites of fluid and advective heat discharge. Based on the inferred distribution and number of discharging outcrops, each discharging outcrop must convey 200–350 MW of heat from the crust to the ocean. This is equivalent to the heat output of a high-temperature black-smoker vent field, as typically seen in ridge-crest environments. Low hydrothermal fluid temperatures (5–40°C) in this region require that at least 4–80 x 10^3 L/s of fluid must continuously enter and exit the crust regionally (1–20 x 10^3 L/s from each discharging outcrop) to sustain the advective heat output.
Controls of the Seismogenic Zone of Subduction Thrusts

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The following is the abstract for my article published a year ago in the Dixon and Moore volume: "The Seismogenic Zone of Subduction Thrust Faults". For the workshop I propose to update this summary review. 2007 Abstract. The seismogenic zone of subduction thrust faults: what we know and don’t know There have been great advances recently in characterizing and understanding earthquakes on subduction thrust faults; this article discusses some of the many questions that remain. Important seismic characteristics of subduction thrust faults and their physical associations, include: (1) The maximum thrust earthquake magnitude, Mx, is highly variable among subduction zones; Mx may be related to the downdip seismogenic width, i.e., updip and downdip rupture limits, or to physical characteristics and stress on the fault. (2) The term “seismic coupling”, i.e., fraction of relative motion that is accommodated seismically, needs careful definition. Meaningful use of the term requires specification of the downdip seismogenic width. Some subduction zones appear to be completely locked, with no aseismic slip between megathrust events; others have mostly aseismic slip. (3) The term “seismic asperity” also needs careful definition; it commonly describes fault regions that had especially large slip in a great earthquake. However, inferences that such areas always have larger earthquake displacement and that they are associated with fault physical characteristics, are not yet firmly established. (4) Subduction thrust faults are concluded to be weak. The commonly favoured explanation is regionally elevated fluid pressures, but weak fault zone materials and dynamic rupture processes also have been proposed. (5) Most subduction thrusts have consistent updip and downdip seismogenic limits, i.e., an updip aseismic zone 10’s of km wide commonly limited by a temperature of 100-150°C. There is not yet agreement on the mechanism responsible. The downdip limit is frequently the intersection of the thrust with the forearc Moho, i.e., ~40 km for continent subduction, less for island arcs. However, deeper thrust events have been observed in some regions. For very hot subduction zones, a critical seismogenic temperature limit of ~350°C is reached at a shallower depth. (6) The reflection character of subduction thrust faults appears to change from a usually strong negative reflection in the updip aseismic zone, to a thin sharp but weaker interface for the seismic portion, to a broad shear zone for the deeper aseismic zone. (7) Displacements on subduction thrust faults occur over a range of speeds, from earthquake rupture (seconds), to rates that generate tsunamis (minutes), to slower slip seen only in geodetic data. The speed controls are still unclear. (8) Immediately downdip of the seismogenic zone, the slip on the aseismic zone in some areas occurs in slow slip events lasting a few weeks to months with intervals of a year to a few years. There are associated seismic tremors with no clear onset.
Frictional and Hydrologic Properties of Clay-Rich Fault Gouge
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Fault slip capable of generating large magnitude earthquakes commonly occurs within thin zones containing large amounts of clay-rich sediment. The mechanisms of earthquake seismicity are intimately linked with the mechanical and hydrologic properties of these sediments, including fault strength, velocity-dependent frictional behavior, and the potential for high pore pressure. Here, we report on laboratory experiments designed to measure the frictional strength, frictional stability, and permeability of a suite of saturated clay-rich fault gouges. Coefficient of friction measurements indicate that clay-rich gouges are consistently weak, with a coefficient of friction of <0.35. We find that montmorillonite gouge is consistently weaker than illite and chlorite gouge. At effective normal stresses within the range of 12-60 MPa, all gouges show velocity-strengthening behavior, which may be an inherent characteristic of non-cohesive, unlithified clay-rich sediments. Permeability of all gouges decreases dramatically with shearing, and to a lesser extent with increasing effective normal stress. Chlorite gouge is consistently more permeable than montmorillonite and illite gouge, and also maintains a higher permeability after shearing. We observe pronounced permeability decrease concurrent with attainment of steady-state shear stress, indicating that permeability reduction may be linked to fabric development within the gouge. This implies that high pore pressure development in fault gouge may be dependent on both clay mineralogy and shear strain.
Very-low-frequency earthquake within accretionary prism along Nankai Trough

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We have detected anomalous very-low-frequency (VLF) earthquakes in the accretionary prism along the Nankai Trough, southwestern Japan [Obara and Ito, EPS, 2005]. Centroid moment tensor inversion analysis reveals that the earthquake hypocenters are distributed at a depth of ~10 km above the upper surface of the subducting Philippine Sea Plate and within 50–70 km landward of the trough axis. The focal mechanisms indicate reverse faulting. The hypocenters are distributed below a deformation zone of the accretionary prism observed in seafloor topography. The strike of the nodal planes is generally subparallel to the trough axis; further, it varies with that of the seafloor topography. Most of the VLF earthquakes occur within the sedimentary wedge of the accretionary prism between the trough axis and the outer ridge, which has a P wave velocity of 2–4 km/s [Nakanishi et al., JGR, 2002]; however, a few occur within older sedimentary wedge that have a P wave velocity of more than 5 km/s.

Using characteristic P wave spectra, we calculate stress drops of the VLF earthquakes. Most of the VLF earthquakes do not show any distinct phases on a raw seismogram, whereas a few show slightly distinct phases. The arrival times of some phases are consistent with the calculated P wave arrival times. The corner frequencies of the VLF earthquakes are calculated by using stacked P wave spectra and assuming an omega-square spectrum. The corner frequency and stress drop of the largest VLF earthquakes with a moment magnitude of 4.1 are 0.10 Hz and 0.2–2 kPa, respectively. All the calculated stress drops are very low, i.e., in the range of 0.1–10 kPa, corresponding to 0.1%–1% of the stress drops of normal earthquakes.

Such extremely low stress drops of the VLF earthquakes indicate that the fault strength within the accretionary prism may have reduced due to high fluid pressures on the thrust faults in the prism. These observations suggest that the occurrence of VLF earthquakes is related to many reverse fault systems within the accretionary prism and that the earthquakes reflect the dynamics of deformation within the prism.
New research project for the Nankai trough seismozenic zone

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1. Introduction
In the Nankai trough, mega thrust earthquakes are occurring with an interval of 100-200 years. Many researches are focusing on the Nankai trough to elucidate the recurrence system of mega thrust earthquakes. As recent research topics, the structural research using refractions and reflections seismic has succeeded to image the key structures to understand recurrences of mega-thrust earthquakes around the Nankai trough, moreover, results of mega thrust earthquake recurrence cycle simulation show that the first ruptures are occurring around the Tonankai earthquake rupture zone in each recurrence cycle. In the fact, initial ruptures of maga thrust earthquakes 1854 and 1944/1946 were starting from the Tonankai seismogenic zone ahead of the Nankai seismogenic zone with intervals of 32 hours and 2 years in each event. Now, we are focusing on the recurrence pattern of the next mega thrust earthquake.

2. New research project
In previous simulation researches, the result of recurrence cycle simulation indicates the difference patterns and intervals of mega-thrust earthquake recurrences in each cycle. These results are consisted with recent historical earthquakes in 1854, 1944/46 around the Nankai trough. The estimation of recurrence cycle between the Tonankai and Nankai earthquake is very important for disaster preventions. Furthermore, the estimation of huge in coupled mega thrust earthquakes around the Nankai trough such as Sumatra earthquake 2004 is important too. Therefore, new project is focusing on the time difference between the Tonankai EQ. and the Nankai EQ and the pattern of next mega thrust earthquakes. New project includes research planes as follows,

1) Construct the detailed crustal structure around the Nankai trough using seismic surveys with controlled sources and seismic tomography.
2) Construct the crustal medium model for understanding the detailed crustal activities and advanced simulation researches.
3) As a preceding research, observations of crustal activities will be carried out off Miyagi and Nemuro seismogenic zones in northeastern Japan.
4) Develop simulation researches using physical properties with conditions of mega thrust EQs. coupling.
5) Construct data base to understand the crustal deformation in the past 120 years.
6) Analysis the past records of mega-thrust EQs. using tsunami sediments
7) Improve the hazard maps of earthquake and tsunamis
Nankai Trough shallow splay and frontal thrust: IODP Expedition 316

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Integrated Ocean Drilling Program (IODP) Expedition 316 is the third drilling expedition of the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE), which is designed to investigate the processes that govern the strength and nature and distribution of slip along subduction zone plate boundary fault systems.

The first target of Expedition 316 was the shallow portion of the megasplay fault system, just seaward of the break in slope marking the boundary between the inner and outer accretionary wedge. The scientific objectives of drilling the shallow portion of the megasplay fault system are to characterize the slip, deformation, and fluid flow behavior and evolution of the shallow portion of the megasplay, in particular to assess whether it is an active blind fault or an inactive fault. Two sites were drilled to investigate the shallow region of the megasplay fault system. Site C0004 was selected to cross the splay fault at a depth of ~300 mbsf; the total drilling depth was 400 mbsf to sample the slope basin material that was being underthrust. Site C0008 sampled the material of the slope basin 1 km seaward of Site C0004. This site was selected to provide age control on splay fault movement and reference material for sediments being overridden by splay fault movement. As a result of drilling, the fault zone sample was successfully recovered and showed a long term history of activity for a few millions of years.

The second target of Expedition 316 was the frontal thrust system. The scientific objectives of drilling this region are to understand the function of the frontal thrust, including its slip and fluid flow behavior, with respect to large earthquakes. An important component of this understanding is to reveal why the frontal thrust behaves distinctly (as evidenced by its longevity and large taper angle) relative to other accretionary margins. The result presents that the lowest part of accretionary prism is composed of Plio-Miocene Upper Shikoku Basin sediments and abruptly changes to very coarse underthrust trench filling deposits through the thin plate boundary frontal thrust. Thrust faults within the frontal part of the prism appear to be inactive and start to gravitationally collapse due to over-critical state.
Great and Giant Subduction Earthquakes and Regional and Transoceanic Tsunamis That They Spawn: Global Trends, Exceptions to the Trends and Geohazards Implications

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Subduction systems vary greatly in the seismic expressions of the subduction process: from the zone of bending beneath the outer rise and outer trench slope, to the zone of interplate thrust zone and forearc faulting, and to the depths of intraslab events and intra-arc events to shocks in back-arc basins. Some of this variability is evident when considering differences in plate tectonic inputs, such as plate age, seafloor spreading fabric in the incoming plate in relation to trench azimuth, relative plate motions across trenches (including the degree of obliquity of motions), and the effects of subduction of volcanic features such as seamounts and volcanic ridges. For interplate thrust earthquakes, factors that influence seismic moment release include plate age, the presence or absence of back-arc spreading and trench migration, sediment influx, and forearc structure. Finally, the first-order variation of intraslab earthquake numbers and moment release seems to be controlled by slab thermal structure and slab morphology, as are certain patterns of arc volcanic activity. Curiously, some of the largest intraslab earthquakes occur near the depth limits of intraslab events in a particular sector.

A strategy for selecting subduction systems with the greatest impact on earthquake and tsunami hazard appraisal must consider the modern historical and instrumental records of large destructive earthquakes, i.e., such investigations need to go to sectors where great and giant earthquakes have occurred in the instrumental era. Also, the community should consider those margins that have been neglected by modern marine investigations and yet are very seismically active. Among such margins, the Aleutian arc stands out as an especially fruitful subduction sector to study. Three giant (M≥8.5) interplate thrust earthquakes have occurred there in the instrumental record (1946, 1957, 1965) that raised destructive far-field tsunami waves. These were followed by great interplate thrust events in 1986 and 1996. The M8.6 Scotch Cap earthquake of 1 April 1946 raised 31 m tsunami waves on Unimak Island near the source and this event remains one of the most destructive tsunami sources in the whole Pacific Basin in the instrumental era. It is also a charter member of the enigmatic slow-rupture earthquake class, one of the most dangerous of tsunami sources. Exploratory excavation at 21 m above the mean high tide line on the Pacific coast of Sedanka Island in the Adreanof Islands revealed five tsunami sand layers laid down in the last few thousand years, including what is thought to be tsunami sand deposits from the 1957 subduction earthquake on the top. The M7.8 outer-rise earthquake that occurred in 1965 is one of the largest events in that class in the subduction systems of the Americas.

A comprehensive investigation of the Aleutian margin from both the hazards and subduction science perspectives is called for with the aim of understanding the processes that govern outer-rise bending deformation and depth of faulting in the Aleutian Trench, interplate rupture segmentation, seismic deformation of the forearc by splay faulting, the tectonics of the outer arc ridge, and the physics of active block rotation in the central and western Aleutians. In many ways the Aleutian subduction system is a neglected active margin. A plan might include: regional swath mapping from the outer rise to the very shallow-water offshore, active seismics in the source regions of the biggest subduction earthquakes with a full complement of marine geophysics and onshore receivers, passive OBS arrays for detection of ambient offshore seismicity with good depth control, and onshore investigations of tsunami deposits and paleoseismic work to extend the chronology of seismic and tsunami events.
Dynamic Velocity under Stress: Interrogating Elastic Material Properties in Actively-Deforming Plate Margins

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In support of the scientific objectives of the San Andreas Fault Observatory at Depth project to better understand the material properties and dynamics of large-scale plate boundary systems, we are establishing a technique to measure P and S-wave velocity dynamically during shear of fault material taken from core samples taken from IODP expeditions 315 and 316 along the accretionary prism of the Nankai Trough. By measuring velocity through gouge material as it is deformed under laboratory conditions in a double-direct shear configuration, we can observe the changing elastic and mechanical properties of this material as a function of applied stress, strain rate, strain accumulation, presence or absence of pore fluids, and other parameters that may affect its strength and deformation characteristics. In addition deformed material taken from cores intersecting major fault zones, we also test the properties of “synthetic” fault gouge prepared by crushing material taken from cores of undeformed material in the vicinity of the fault. Since the frictional properties of gouge layers play a large part in determining the behavior of faults, it is important to characterize them separately from the undeformed lithologies they pass through. This study will further the understanding of the role material properties and fault mechanics play in the structural development and seismic signatures of faults and wall rock in the uppermost few kilometers of the accretionary prism at Nankai.
Forearc Motion and Cocos Ridge Collision in Central America

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We present the first regional surface velocity field for Central America, showing crustal response to interaction of the Cocos and Caribbean plates. Elastic half space models for interseismic strain accumulation on the dipping subduction plate boundary fit the GPS data well, and show strain accumulation offshore and beneath the Nicoya and Osa Peninsulas in Costa Rica, but not in Nicaragua. Since large subduction zone earthquakes occur in Nicaragua, we suggest that interseismic locking in Nicaragua and some other parts of Central America occurs but is mainly shallow, <20 km depth, too far offshore to be detected by our on-land GPS measurements. Our data also show significant trench-parallel motion for most of the region, generally interpreted as due to oblique convergence and strong mechanical coupling between subducting and overriding plates. However, trench-parallel motion is also observed in central Costa Rica, where plate convergence is perpendicular to the trench, and in the Nicaraguan forearc, where trench-parallel motion is fast, up to 11 mm/yr, but mechanical coupling is low. A finite element model of collision (as opposed to subduction) involving the aseismic Cocos Ridge also fits the GPS surface velocity field, most significantly reproducing the pattern of trench-parallel motion. We infer that buoyant, thickened CNS-2 - Cocos Ridge crust resists normal subduction, and instead acts as an indenter to the Caribbean plate, driving crustal shortening in southern Costa Rica and contributing to trench-parallel forearc motion in Costa Rica and perhaps Nicaragua as a type of tectonic escape.
Geometry, Kinematics and Relative Ages of Core-scale Structures from IODP Expeditions 315 and 316: Core, Thin Section and CT-Scan Constraints

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Drilling at sites C0001 and C0002 during IODP Expedition 315, and at sites C0004 and C0008 during IODP Expedition 316 yielded cores that provide clues about the nature of mechanical interactions across an out-of-sequence thrust (i.e., the megasplay fault) outboard of the Kumano basin. These samples provide geometric, kinematic, physical property and relative age constraints for a suite of microstructures, including faults, shear zones, deformation bands, shear zones, vein structures and rare kink bands. Analyses to date indicate that the megasplay hangingwall at Site C0001 is dominated by NE-SW maximum stretching accommodated by normal faults. A small number of steeply dipping thrust faults near the base of the hangingwall suggests NW-SE shortening. The predomiance of trench-parallel stretching and crustal thinning in the hangingwall at site C0001 may reflect (1) a releasing stepover in a strike-slip fault at the margin of a forearc sliver, or (2) the upper plate response to recent addition to the prism of a thrust slice of finite length. Structures within the accretionary prism (below ~220 m core depth below seafloor, CSF) are more numerous and display more diverse kinematics. Fault-plane solutions indicate kinematics similar to in the hangingwall with the addition of strike-slip faults accommodating NW-SE shortening. Overall these preliminary results suggest some degree of mechanical decoupling across the deformation zone at ~220 m CSF with plate convergence driven shortening more well developed in the rocks of the footwall. On the basis of preliminary shipboard observations, the structures at Site C0001 appear to reflect three phases of deformation: (1) NW-SE shortening by thrust faulting and lesser strike-slip faulting; (2) NE-SW stretching by normal faulting; and (3) N-S stretching by normal faulting. Establishing robust relative age constraints for these structures is important because of the possibility that the strain regimes reflect different parts of the seismic cycle. Alternatively they reflect changes over timeframes much greater than the seismic cycle, and thus changing long-term boundary conditions. XRay Computed Tomography (CT) scan images provide constraints on the 3D geometry, physical properties (i.e., radio density) and cross-cutting relations between faults, deformation bands, kink bands, vein structures and shear zones in cores from Expeditions 315 and 316. Core from Site C0001 contains numerous thin, steeply dipping bright zones in CT scans that core logging reveals to be vein structures likely related to dewatering. Several of these persist in core over dm scales suggesting they are nearly vertical. The existence of steeply dipping normal faults in cores from Site C0001 suggests the possibility that some of these faults may have originated as dewatering structures. The CT scans also reveal varying degrees of radio density suggesting different degrees of densification for different microstructures. Many of the normal faults appear as slightly bright to neutral and commonly cut shear zones that are considerably brighter. These differences may correlate with degrees of fracture conductivity as inferred during the logging-while-drilling activities of Expedition 314, however this has not yet been confirmed. During June 2008 structures in core collected at Site C0002 within the Kumano basin, and Sites C0004 and C0008 of IODP Expedition 316 will be examined. This work will be followed by detailed analyses of CT scans for core collected at Site C0001. The structural geometries derived from CT scans, core analyses and thin sections will be used to invert for partial stress and/or strain tensors. The relative age of structures will also be examined. Similar analyses will be carried out on samples from Sites C0002, C0004 and C0008, thereby providing trench normal constraints on geometry, kinematics, physical properties and stress/strain.
Crustal Thickness and Depth to the Subducting Slab Underneath Northern Costa Rica based on Receiver Function Analysis

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Costa Rica is located near the southern end of the Middle American Trench (MAT) in a complicated tectonic setting controlled by the interaction of the Cocos, Caribbean, and Nazca plates. The oceanic Cocos plate subducts to the northeast underneath the Caribbean plate creating a volcanic arc located 150 km away from MAT. In Northern Costa Rica the arc basement is represented by part of the Caribbean Plateau that includes flood basalts, mafic oceanic rocks, serpentinized peridotites, silicic sediments, and turbidites. For this study, P and PP wave receiver functions have been calculated using teleseismic earthquakes recorded in Northern Costa Rica by broadband stations of the CRSeize, Pocosol, and Corisubmod experiments, and stations JTS and HDC from the Global Seismology Network and the Geoscope Project, respectively. The goal of this survey is to constrain the major boundaries such as the base of the continental crust and the top of the subducting Cocos slab as well as Vp/Vs ratios to estimate the composition and physical state of the lithosphere. Receiver functions are computed using an iterative pulse stripping time domain deconvolution technique. The depth and average Vp/Vs ratio to the discontinuities (i.e. Moho) is estimated using a stacking algorithm which sums receiver function amplitudes of direct Ps and its PpPs and PpSs+PsPs multiples. Our preliminary results show that the crustal thickness varies underneath Costa Rica. The Moho discontinuity is visible at depths of 36 km beneath the stations of the Pocosol Network located in the back-arc region, 41 km underneath HDC located in the volcanic arc, and 36 km beneath JTS in the forearc region. There is a complicated structure underneath the CRSeize stations in the Nicoya peninsula where the continental Moho signal is absent and instead a signal at depths from 19 to 40 km is visible and might be correlated with the subducting Cocos slab. The descending slab is also visible at depths of 76 km underneath JTS, and 74 km underneath HDC. High average Vp/Vs ratios of 1.8-1.9 beneath the Nicoya peninsula are consistent with serpentinization of the mantle wedge proposed in previous studies. In many subduction zones the down dip rupture limit of large earthquakes coincides with the intersection between the subducting slab and a serpentinized forearc mantle wedge. Understanding the nature, physical state (degree of serpentinization), and thickness of the crust is then a relevant topic as it provides a velocity structure that directly improve earthquake locations and a description of the extent of the serpentinized forearc mantle wedge that could determine the downdip rupture limit of large earthquakes.
Role of fault dilatancy in subduction zone aseismic deformation transients

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Numerical simulation in the framework of rate and state friction shows that aseismic deformation transients can emerge spontaneously, or be triggered by small stress perturbations, for certain effective stress and friction parameter variations with depth. Short-period (~ 1 yr) transients arise when interstitial fluids are present and pore pressure \( p \) is near-lithostatic but time-invariant. This is precisely the situation that Segall and Rice [1995] suggested fault stabilization by induced suction from dilatancy during increased shear rates becomes most important. In this study, we analyze the conditions for short-period aseismic transients of a fluid infiltrated subduction fault using the rate and state dependent friction model including dilatancy and pore compaction effects. Linearized perturbation analysis of a single-degree-of-freedom spring-slider model shows that under undrained conditions effective normal stress \( \tilde{\sigma} = \sigma - p \) must exceed \( f_0 \varepsilon / \beta (b - a) \) for instabilities to nucleate, where \( f_0 \) is steady state friction, \( \varepsilon \) is a dilatancy coefficient representing porosity changes in response to velocity steps, \( \beta \) is a combination of fluid and pore compressibility, \( a \) and \( b \) are rate and state friction parameters. In particular, we explore the effects of the following non-dimensional properties: \( f_0 \varepsilon / \beta (b - a) \tilde{\sigma} \), fluid pressure re-equilibration time \( V_{ss} T_p / L \) (\( V_{ss} \) is steady state slip rate, and \( L \) is characteristic slip distance) and \( W/h^* \) (length ratio of the velocity-weakening region under near-lithostatic \( p \) and the critical nucleation patch size). As the fault gouge becomes more undrained (higher \( V_{ss} T_p / L \) ) or more dilatant (higher \( f_0 \varepsilon / \beta (b - a) \tilde{\sigma} \)), transient slip rate decreases and transient recurrence interval increases. With the dilatancy stabilizing effect, self-sustained slip rate oscillations remain aseismic at large \( W/h^* \) (greater than 20), which results in earthquakes under time-invariant pore pressure. This also suggests that subduction fault extending well down-dip of the limit of seismogenesis could nevertheless be frictionally unstable \( (a - b < 0) \) but undergoes no seismic slip due to effective dilatancy stabilization, thus has implications to the depths of thrust earthquakes and slow slip events in subduction zones and to the total slip budget in an earthquake cycle.
Comparing proposed subduction zone segments with slip distributions from recent Andean earthquakes and long-lived surface cracks

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A basic question of subduction zone earthquake phenomenology is whether earthquakes occur randomly along strike within subduction zones or if some physical properties encourage or discourage repeated rupture of a more-or-less spatially invariant segment. We use geophysical and geological observations within a single subduction zone of northern Chile and southern Peru to test whether there are any long-lived forearc characteristics that are consistent with subduction zone segmentation. First, we use seismic and geodetic data to infer the detailed rupture area and slip distribution from 6 recent large earthquakes (Mw > 7) and explore their relationships to the bathymetry of the subducting plate, structure of the over-riding plate and coastline morphology. Second, we present maps of meter-scale surface cracks in the northern Chile and southern Peru forearc that we think were formed during repeated ruptures of nearly the same seismic segment. These cracks have been observed to form during and/or shortly after strong subduction earthquakes, are preserved for very long time periods throughout the Atacama Desert, demonstrate evidence for multiple episodes of reactivation, and show changes in orientation over spatial scales similar to the size of earthquake segments. Our observations and models show that crack orientations are consistent with dynamic and static stress fields generated by recent earthquakes. We suggest that the meter-scale cracks can be used to map characteristic earthquake rupture segments that persist over many seismic cycles, which encourages future study of cracks and other small-scale structures to constrain better the persistence of asperities in other arid, tectonically active regions.
Why subduction causes mountain building in the Andes, but not in the Cascadia?

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Subduction causes crustal shortening in the upper plate, leading to the Andean-type mountain building. Recent GPS measurements have shown ~30-40 mm/yr crustal shortening across the central Andes, and ~10-20 mm/yr of crustal shortening in forearc of the Cascadia. Whereas such crustal shortening has produced the world’s second largest mountain belt in the Andes, no significant mountain building has occurred in the Cascadia since Eocene. Hence much of the GPS-measured crustal shortening in the Cascadia is transient and would be recovered during trench earthquakes or slip events. We have explored the factors controlling mountain building in the subduction zones using a 2D viscoelastic-plastic finite element model. Our results show that interplate mechanical coupling and lithosphere rheology of the upper plate are the primary factors. Strong plate coupling and weak upper plate lithosphere favor accumulation of permanent strain (plastic strain), or mountain building, such as in the Andes. Conversely, weak plate coupling prefers viscoelastic lithosphere deformation, and interseismic strain is recovered by co-seismic and post-seismic rebounds, as in the Cascadia. Other factors, such as the westward drift of the upper plate relative to the mantle, may have also contributed to the mountain building in the Andes.
Mechanics of the seismogenic zone: Frictional properties and hydro-mechanical processes related to the updip transition from stable to unstable faulting

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Subduction zone megathrusts host the world’s largest and most damaging earthquakes. Determining the location and extent of the seismogenic zone is a central problem in earthquake and fault mechanics and is of paramount importance in assessing tsunami risk and earthquake hazard. While it is generally agreed that the down-dip limit of seismicity is controlled by the onset of crystal plasticity there is little consensus regarding the mechanisms that determine the updip limit of the seismogenic zone.

Two main hypotheses for the updip stability transition have been proposed. The clay mineral hypothesis posits that a thermally-driven transition from a hydrous (smectite) to an anhydrous (illite) clay structure produces the transition. According to this view, smectite clays within the shallow portion of subduction faults promote stable, aseismic behavior, whereas illite-rich fault gouge exhibits potentially unstable behavior. An alternative idea, which we refer to as the lithification hypothesis, posits that cementation and consolidation of the fault zone and surrounding rocks causes a stability transition due to changes in \( D_c \), the critical friction slip distance, and the friction rate parameter \( a-b \). According to this view, aseismic behavior is associated with distributed deformation in the fault region, whereas highly localized shear within the fault zone leads to the necessary and sufficient conditions for instability. Each of these hypotheses have merit and neither can be ruled out by existing laboratory or field observations.

In this talk, we summarize recent work that has moved beyond descriptions to improve our understanding of the mechanisms and processes that determine the upper boundary of seismogenesis in plate boundary megathrusts. Recent studies show that frictional properties and hydro-mechanical processes play a central role in determining the spatiotemporal character of fault zone failure. In many settings, the nature of seismic and aseismic faulting are determined in part by the rheology of clay rich fault gouge. Recent results suggest that fault zone dilation may limit dynamic rupture speed and determine characteristics of slow and low frequency earthquakes.

We focus primarily on results from laboratory experiments designed to investigate the frictional behavior of candidate fault zone materials. Results are presented from double-direct shear friction experiments using the traditional, unconfined thin-layer geometry and tests conducted in a true triaxial system under saturated conditions. Materials include natural samples and synthetic fault gouge composed of kaolinite, smectite, illite, chlorite, and quartz. We report porosity and strength changes associated with perturbations in strain rate during steady state frictional sliding. Layers dilate upon a step increase in strain rate and, consistent with previous work, we find that the magnitude of the induced porosity change scales with the log of the slip velocity jump ratio. Transients in pore fluid pressure in response to fault gouge dilation resulting from changes in shearing velocity are important. The laboratory work shows that montmorillonite, chlorite, and illite gouges are consistently velocity strengthening, and the friction rate parameter \( a-b \) tends to increase with increasing sliding velocity. We
discuss results for sliding velocities from 1 to 300 µm/s and normal stresses from 10 to 150 MPa. At higher normal stress, the rate-state friction parameter b decreases to zero. We report results from clay fabric intensity analysis using X-ray texture goniometry. Our data suggest that true contact area between clay minerals saturates at high normal stress. This implies significant changes in the friction critical slip distance as a function of normal stress. We review laboratory friction data and constitutive laws in the context of requirements for stable and unstable faulting.
Tectonic geomorphology and paleoseismology along the Nicoya Peninsula seismogenic zone, Costa Rica

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The Nicoya Peninsula, Costa Rica deforms in response to rapid NE subduction of the Cocos plate at the Middle America Trench (9 cm/yr). This emergent outer forearc peninsula lies only 60-80 km inboard of the trench axis and coincides with a locked segment of the seismogenic zone. The Nicoya segment is a high-potential seismic gap, with an apparent slip deficit of nearly 5 m since the last major earthquake (M7.7, 1950). That event produced widespread damage and up to 1.0 m of coseismic coastal uplift. During ensuing decades, the Nicoya coast has experienced gradual interseismic subsidence, reflecting strain accumulation leading toward the next earthquake. While elastic seismic-cycle strain produces decadal-scale shoreline fluctuations on the Nicoya Peninsula, net tectonic uplift has resulted in coastal emergence throughout the late Quaternary. This longer-term uplift is recorded by emergent marine terraces at the coast, and by incised alluvial fill within interior valleys. This investigation examines both short-term seismic cycle deformation and the longer-term geomorphic imprint of forearc uplift associated with the Nicoya Peninsula seismogenic zone. Ongoing field mapping, surveying, and isotopic dating have provided new constraints on net Quaternary deformation patterns and upper-plate faulting. Observed differences in coastal uplift along the Nicoya Peninsula coincide with three contrasting domains of subducting seafloor offshore (EPR, CNS-1, CNS-2). Uplift rates vary from 0.1-0.2 m/k.y. inboard of EPR crust (north of Punta Guiones), 0.2-0.3 m/k.y. inboard of CNS-1 crust (south of Punta Guiones), and 1.0-2.0 m/k.y. inboard of CNS-2 seamounts impacting Cabo Blanco (the peninsula’s southern tip). Tectonic segmentation of the upper-plate may reflect along-strike variations in subducting plate roughness, thermal structure, fluid flow, plate coupling, and seismogenic zone structure (e.g., dip angle, length and width, limits of up-dip and down-dip locking). In addition, local geomorphic anomalies reveal shallow faults that may accommodate a significant fraction of net forearc deformation (crustal shortening and/or lateral sliver transport). Seismic cycle elastic strain accumulation and release produce significant changes in local tidal levels, wave erosion, and littoral sediment dynamics. As a result, coastal wetlands and beaches on the Nicoya Peninsula may preserve stratigraphic records of vertical shoreline fluctuations and tsunami associated with prior earthquake cycles. Sediment coring at strategic sites may produce useful paleo-seismic records. In addition, detailed pre- and post-earthquake topographic surveying of the Nicoya coast (using LIDAR and/or differential GPS) may also establish important constraints on seismic cycle deformation patterns. These approaches represent promising new avenues for our ongoing studies of upper plate deformation along the Nicoya seismogenic zone. Based on the rapid convergence rate (9 cm/yr) and the frequency of historic seismicity, the recurrence interval for large Nicoya earthquakes has been estimated at 50-60 years. While these events may produce meter-scale coseismic uplift along the Nicoya coast, a large fraction is recovered during interseismic subsidence. The net result is gradual uplift and the emergence of Quaternary marine terraces at the observed rates. Our ongoing investigation is aimed at developing further constraints on both short- and long-term deformation patterns within the upper plate. The results may have implications for understanding the rupture behavior, paleoseismology, and earthquake hazards of the Nicoya Peninsula seismogenic zone.
FEMs of seismogenic deformation: Accounting for material property contrasts associated with a subducting slab.

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The nature and behavior of a seismogenic zone are manifest in geodetic (GPS) data that measure deformation at the Earth’s surface. Models provide the linkage between the observed surface deformation and the source of the deformation – the inaccessible plate boundary interactions, such as fault-slip or plate-coupling at depth. We use the terms fault-slip and plate-coupling interchangeably. Substantial effort has gone into the development of inverse models that strive to quantify the characteristics of fault-slip, based on observed deformation and presupposed deformation models. In practice, little attention is given to the implications of the presupposed deformation models. A suitable model of deformation in a subduction zone must account for a relatively stiff slab subducting under relatively compliant overlying material. To date, studies of SEIZE targets (Central America and Nankai) overwhelmingly assess and interpret observed deformation using models that simulate dislocations embedded in homogeneous elastic half-spaces, a configuration that is computationally inexpensive, but bears little semblance to a subduction zone. By contrast, Finite Element Models (FEMs) can be used to solve elastic and transient poroelastic and viscoelastic equations in a problem domain, partitioned to account for the 3D geologic complexity of a subduction zone. We take advantage of the high signal-to-noise ratio of deformation data associated with the 2004 M9 Sumatra-Andaman earthquake to demonstrate an approach for simulating fault-slip, in which FEMs are implemented in inverse models of deformation. Results of this study suggest that fault-slip characteristics (distributions and magnitudes) estimated from observed GPS data via inverse methods are significantly sensitive to the material property contrasts associated with the subducting slab and overriding forearc wedge. Furthermore, the calibrated FEMs are readily extended to transient poroelastic and/or viscoelastic simulations that can quantitatively address transient stress-coupling and slow-slip migration. The FEM-based techniques presented here allow for deformation models that can directly integrate and honor complementary geologic and geophysical SEIZE data. These models will advance the reliability of modeling-based assessments and predictions of seismogenic deformation, stress-coupling, and tsunami genesis for SEIZE targets.
Interdisciplinary approaches to offshore geohazards and onshore risk analysis

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Our team of civil engineers, earth scientists and social scientists is researching offshore geohazards and the resulting risks they pose under a US National Science Foundation Partnership in International Research and Education grant. The goal of this grant is to foster international education and collaboration while working toward better understanding of the hazards and risks associated with offshore landslides, and to a somewhat lesser extent, earthquakes. Our partners in Norway (the Norwegian Geotechnical Institute and the International Center for Geohazards) and Australia (Center for Offshore Foundation Systems) have expertise in the interaction between unstable offshore sediments and infrastructure, as well as risk analysis. By fostering collaboration with them, we both benefit from exchanges of ideas and exposure to a variety of environments. On the geoscience and engineering side of our team, we are researching methods to better characterize the physical properties of seabed sediments, in situ pore-pressures, the spatial variability of geomorphic and acoustic signals, and identify triggering mechanisms. We are developing new methods to ascertain sample quality using shear waves generated by bender elements, measuring sediment strength using full flow penetrometers, and working on a narrow-gauge piezometer to measure in situ pore pressures over shorter periods of time. Once we are able to constrain the sediment strength parameters, we are working on using the statistical variability to tie in the physical properties with acoustic data from regional seismic surveys and predict regional stability regime. Also on a regional scale, we are using the morphologic variability of the seafloor that develops over millennia of overprinting landslides to determine scales of roughness that could possibly relate to a characteristic landslide triggered by some event of a given temporal frequency (e.g. earthquakes or sea level change). Once the hazards are identified and somewhat constrained, the social science side then looks to the vulnerability of exposed communities as far as disaster preparedness, response and mitigation. These risk reduction studies are focusing on changes in food security following a tsunami. Are there dietary changes following a tsunami? If so, how should agencies, both governmental and non-governmental, focus their efforts following a disaster? How can an affected area be rebuilt in a more sustainable and safe way? This interdisciplinary approach is critical to reducing the risks posed by disasters, which will ultimately lead to reduction of losses, both monetary and human.
Interactions Between Seismic and Aseismic Fault Slip
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As seismic and geodetic observatories have become more plentiful, it has become clear that faults fail in a wide variety of transient ways with inherent time scales ranging from years to weeks to hours to seconds. It is becoming increasingly clear that even predominately aseismic slip events are associated with considerable amounts of seismic radiation not only in the form of tremor, but also as an enhanced rate of microseismicity. These bursts of microseismicity associated with slow earthquakes are often referred to as an earthquake swarm and are observed in subduction zones [Ozawa et al., 2007], transform boundaries [Lohman and McGuire, 2007], and volcanic regions [Wolfe et al., 2007]. While many aseismic slip transients show conditionally stable frictional behavior [McGuire and Segall, 2003; Miyazaki et al. 2006], the increased awareness of microseismicity swarms triggered within the region of slow slip events [Lohman and McGuire, 2007; Ozawa et al., 2007] indicates that frictional stability may vary on extremely short length scales on a given fault. Thus, the microearthquakes can function as an in situ stress meter that provides one of the most direct and sensitive windows into the space-time variations of stressing-rate on plate boundary faults [Llenos, McGuire, and Ogata, 2008]. Moreover, as we understand more about the earthquake sequences triggered by aseismic slip, it appears that aseismic transients can be the event that brings a seismic cycle to its close by triggering a large earthquake [McGuire, 2008]. The updip end of subduction seismogenic zones should be one of the most geometrically advantageous regions in the world to study these phenomena as they are relatively shallow and spread out horizontally. To date, only a few ocean bottom experiments have targeted this region, but as a number of seafloor observatory projects come online in the next few years, there is a great opportunity to improve our understanding of earthquake triggering and its relationship to aseismic processes.
Seismic Reflection and Refraction Structure of the Middle America Trench, Nicaragua and Costa Rica

Kirk McIntosh

Much of the Middle America convergent margin of Nicaragua and Costa Rica is now imaged with seismic reflection and refraction data. These data and three drilling programs suggest that the margin is currently largely non-accretionary to erosional, featuring a margin wedge of older accreted material and/or the western edge of the Caribbean large igneous province. The subducting Cocos plate dips steeply into the trench and is heavily faulted offshore Nicaragua. Along the Middle America Trench (MAT) to the southeast, bending-related fault throw and dip of the plate decrease and the trench is dramatically shallower, reaching < 2000 m where Cocos ridge is underthrust. One of the most consistent features of the margin is the ~400 m thick sedimentary section on the Cocos plate, consisting of a lower pelagic unit and an upper hemipelagic section with generally minimal trench fill. In most cases this relatively thin section is entirely underthrust at the trench, although small amounts of sedimentary underplating is suggested on some sections. On typical reflection profiles the plate boundary zone is well-defined only near the trench, with a more diffuse zone of reflections typical under the middle and upper slope—approaching the seismogenic zone. Plate boundary seismicity appears to be influenced by the expected factors, including increasing temperature and pressure and dehydration reactions. In addition, seismicity along the margin is clearly focused by subducting seamounts and plateaus, in some cases at relatively shallow levels of the subduction system. While significant progress has been made through the SEIZE and SUBFAC initiatives of the Margins program and earlier research programs, there are still fundamental unknowns regarding the margin structure and processes. For example, the margin wedge is largely un-sampled other than at its toe, so its history, composition, and physical properties are poorly known. Further, the inferred erosional processes remain unclear as 2-D seismic imaging is inadequate to provide sufficient structural detail in this complex environment. Finally, although some amplitude changes are apparent on plate boundary zone reflections, diagnostic reflection patterns related to seismogenic behavior have not yet been clearly documented in this area.
Picturing the seismic cycle along ancient décollement thrusts: the ultrafine-grained fault rocks of Pasagshak Point, Kodiak Island, AK.

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Subduction mega-thrusts cut through fluid-rich sediments, and fragments of oceanic sequences, and generate the most destructive earthquakes and tsunamis. An important issue facing seismic hazard assessment is the identification of the physico-chemical processes active during the seismic cycle. Ancient, now exhumed, subduction thrusts represent a crucial tool to achieve this goal, as they record the evolution of subducting sediments through burial, compaction, dewatering, shearing, accretion, and intra-wedge deformation and exhumation. However, evidence for seismic ruptures in exhumed fault rocks is controversial, with the only universally accepted seismic rocks being pseudotachylytes, i.e. solidified friction-induced melts. The process of fluidization of cataclasites is seen as a good alternative to the process of frictional melting during seismic rupture in presence of fluids. Despite the prevalence of great earthquakes in the subduction zones, evidence for pseudotachylytes in this setting is scarce. We have studied an exhumed megathrust in a paleo-décollement mélange of the Kodiak accretionary complex (Alaska), active at 12-14 km depth. The fault zone is made of tens meter-thick foliated cataclasites, cut by decimeter-thick black ultrafine-grained rocks. We here report on the structure and composition of the black fault rocks and present our argument that these rocks record multiple events of seismic slip along the preserved ancient mega-thrust. High resolution scanning electron microscopy, associated with detailed geochemical characterization of these fault rocks allowed us imaging a complex internal layering in each black rock fault vein. Particularly, micron-scale feldspars microlites with complex oscillatory zoning in some layers has been interpreted as evidence of crystallization from a melt, while granular homogeneous texture, poor sorting, roundness of grains and fluidized ductile deformation, as flow and entainment structures, in other layers allowed us interpreting these last ones as fluidized comminuted gouges. We then interpret these fault rocks as “cemented slurries” including solidified melts and fluidized gouges: the black fault rocks formed by a combination of two processes recognized in literature as active at seismic slip rates, i.e. coseismic. Therefore, the studied exposure allows reconstructing the entire seismic cycle from aseismic creeping (foliated cataclasites) to seismic slip (backs fault rock veins).
Structural and Stratigraphic Setting of the NanTroSEIZE Kumano Transect From 3D Seismic Data

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In spring, 2006, we contracted a commercial seismic company (PGS) to collect a 3D seismic data set across the NanTroSEIZE transect. Using 4 hydrophone cables of 4500 m, spaced 150 m apart, and alternately firing two G-gun arrays of 3090 in³ yielded 8 CMP lines per sail line with 6.25 m x 37.5 m CMP spacing. The 12 x 56 km 3D box extends from the Kumano basin seaward to the deformation front in the dip direction and extends along strike ~ 4 km northeast and ~ 8 km southwest of the NanTroSEIZE drilling sites. Pre-processing by CGG included noise and multiple removal and binning at 12.5m inline and 18.75m crossline spacing. A full 3D pre-stack migration was carried out at IFREE/JAMSTEC in 2007.

The 3D volume images the frontal accretionary prism, where the frontal detachment/décollement is a strong, continuous positive-polarity reflection through most of the frontal region. Thrust packages in the frontal prism are highly variable along strike, due to several oblique ramps. The thrust packages are overlain by slope basin sediments that are progressively more deformed with depth.

A megasplay fault rises from the oceanic crust at ~ 10 km depth, cutting across the older part of the accretionary prism all the way to the seafloor in the frontal prism region. This splay fault reflection exhibits areas of reverse polarity, possibly reflecting fluid flow from the seismogenic zone to the surface. The hanging wall is composed of a few hundred meters of Recent to upper Pliocene hemipelagic slope sediments overlying strongly deformed lower Pliocene strata that are believed to have been accreted at the toe of the accretionary prism. The block is truncated at its seaward edge, presumably by a steeply-dipping back thrust.

As the hanging wall advances, it is blanketed by hemipelagic slope sediments that slump off steep slopes and into the adjacent trench slope basin. The more consolidated (and thus stronger) hanging wall block then overrides these redeposited slope sediments. The slope sediments in the footwall are 100-400m thick and are faulted and folded as they are overridden.

More than 2200m of sediment in the Kumano forearc basin are imaged. The deepest part of the section is strongly folded, while the seaward portion is progressively tilted landward due to repeated motion on the megasplay fault. The forearc basin strata onlap older slope sediments, which in turn overlie an older part of the accretionary prism.
World’s Thickest Seismogenic Fault Rock from a Subduction Complex, Kodiak Islands, Alaska

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We have discovered the thickest seismogenic fault rock known from a subduction complex. These paleoseimogenic indicators comprise a series of decimeter-thick, dense, black rocks crosscut a 10s of m-thick cataclasites, which in turn cut a classical mélangé. We know that these black fault rocks are seismogenic because they include intervals with igneous textures (pseudotachylytes) that are seamlessly intercalated with highly comminuted ultracataclasite. These black fault rocks also show structures indicative of fluidization at very low viscosities.

The seismogenic fault rocks are very low porosity, homogenous with respect to the enclosing cataclasite, and sufficiently thick to be distinct in borehole resistivity imaging. Thus, they could be identified in borehole logs. Secondly, the microscopic and ultramicroscopic textures of the seismogenic fault rocks, in both the melted and comminuted states, are distinct from those of the enclosing cataclasite and mélangé. Their textures could be identified from borehole cuttings.

These seismogenic fault rocks occur in a series of abandoned décollements, of the Kodiak accretionary complex of Alaska. These rocks were incrementally underplated beneath the accretionary prism 60 my ago, at 12-15 km depth and ~ 270° C. The structural progression from classical mélangé (100s of m thick) to cataclasite (10s of m thick) to paleoseismogenic fault rock (dm-thick) indicates progressive strain localization. All three fault rock types are cross cut by a steep solution cleavage trending parallel to overall structural strike. This latter feature indicates continuing margin-perpendicular shortening after accretion.
Rapid uplift in the outer forearc of the Central American convergent margin inboard of the Panama Triple Junction, Burica Peninsula

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New geomorphic and structural mapping on the Burica Peninsula, a ~10 km wide outer forearc peninsula, reveals a history of Plio-Quaternary rapid uplift inboard of the Panama Triple Junction along the Middle American convergent margin. At the triple junction, the Panama Fracture Zone subducts beneath the Caribbean Plate, which results in a large bathymetric step along the subduction boundary. This bathymetric step occurs due to the juxtaposition of thick Cocos plate subducting west of the Panama Fracture Zone against thinner Nazca plate to the east. Propagation of the Panama Triple Junction to the southeast requires that the upper plate of this system at the Burica Peninsula override this bathymetric step, causing shortening and uplift evident throughout the peninsula. Uplift is recorded by a flight of up to five marine terraces that surround the outer margins of the peninsula, the highest of which is presently more than 100 m above modern sea level. The distribution and elevation of these terraces suggest that they may be formed during coseismic events. Radiocarbon dating of a suite of seven shell samples (4 conventional and 3 AMS) within the lowest terraces located ~ 1.5 – 2 m above modern sea level yields Holocene ages that range between 510 +/- 40 and 10,650 +/- 50 YBP. These ages combined with known terrace elevations and facies constraints suggest that the peninsula has experienced uplift within the Holocene at a rate as high as ~3 mm/yr. This uplift and possible east-directed tilting of marine deposits results from slip along a predominant NE-dipping thrust fault located offshore of the peninsula. This fault roots within the Cretaceous basement of the Nicoya Fm and is responsible both for exposures of the Nicoya Fm throughout the northwestern half of the peninsula, as well as the pervasive eastward tilting of Pliocene mudstones and siltstones of the Charco Azul Fm. Recent onshore mapping shows that this fault contains a NW-striking thrust splay that is identified by uplifted and sheared Nicoya Fm overlying an overturned syncline in the Charco Azul Fm. Uplift of the peninsula along deeply rooted thrust faults is a conjecture that runs counter to prior interpretations that posture that the peninsula is dominated by right lateral strike slip as an upward continuation of the subducting Panama Fracture Zone. This new model for deformation on Burica Peninsula suggests that forearc shortening and crustal thickening occurs mainly in response to forcing of the upper plate over the bathymetric step between the subducting plates rather than differences in basal traction across the subducting Panama Fracture Zone.
Reassessing the roles of dewatering processes in seismogenesis

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It seems to be emerging that the temperature of the aseismic-seismic transition appears to be quite similar at erosive and accretionary margins, despite large differences between them in the material input into the seismogenic subduction channel that composes the ‘megathrust’ plate interface. This fact, and the recent laboratory demonstration that both smectite and illite are velocity-strengthening in creep, suggests that the oft-postulated change in mechanical behavior of the megathrust due to a smectite-illite clay mineral transformation at ~150°C may not be the cause of the onset in seismogenesis at these temperature conditions within the subduction channel. Field observations from fossil megathrust zones suggest that a temperature-dependent change in the availability of in-situ fluid is likely to play a key role in the onset of seismogenesis. Perhaps the causal link is to metamorphic dewatering reactions that liberate water at ~150°C, under conditions where these reactions are an important local source of hydrous fluids? Field studies of fossil megathrusts support the hypothesis that fluids ‘control’ seismogenesis, and indicate that there are large fluid pressure variations during the seismic cycle. In the fossil erosive megathrust system preserved in the Apennines, two décollements are simultaneously active at the roof and base of the subduction channel. The uppermost (non-seismogenic) portion of the megathrust even appears to alternate between tensional and compressional modes of failure during the seismic cycle along the deeper portions of the megathrust.
A PROBLEM IN THE ANDEAN SUBDUCTION ZONE

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Classical seismological studies have shown outstanding along-strike variations in the slab geometry in the Andean subduction zone, with striking flat segments in areas of Ecuador, Peru and central Chile and Argentina. In these areas heat flow is low (less than about 40 mW/m2). When thermal and gravity data, together with rheological properties of rocks, are used to determine the brittle/ductile transition in the lithosphere along the Andes region, results are in agreement with maximum depths of seismic events located (or relocated) in the crust of areas of ‘normal’ or high heat flow from the northern to the southern Andes. In areas of generally low heat flow in Ecuador, Peru and central western Argentina, the rheological zonation describes a brittle/ductile transition occurring at depths of 70-110 km in the continental lithosphere within the upper mantle, indicating that seismic activity at these depths may not be associated to flat subduction of the oceanic lithosphere as thought in the standard view of the Andean subduction zone. In recent studies Michaud et al. (2006), Aleman (2006) and Creixell et al. (2006) have advanced that in these areas there is no obvious correlation between the subduction of oceanic ridges—a main subject for the flat-slab hypothesis—and deformation processes and structural styles of the orogenic phases. In Ecuador, Guillier et al. (2001) determined earthquakes foci in the continental mantle reaching depths of about 55-75 km from both the ISC database and data from a dense temporary network within the Ecuadorian network of telemetred stations, whereas dipping Wadati-Benioff zones were only determined with foci located with the temporary network. In northern central Peru, for explaining time residuals observed in seismological stations, a velocity model for a flat subducting slab at 80-100 km depth was obtained using a ‘festooning’ ray with several reflections inside the slab (Norabuena et al., 1994); the model resulted in velocities in excess for the flat structure that could not be explained by any effects, and that were found to be inconsistent with studies of the thermal structure in subduction zones and with the mineralogy of slabs. Anderson et al. (2007) have presented a comparison between ISC earthquake locations (with reporting stations located at about 32-34 °S in Chile and Argentina) and locations obtained by using the grid-search multiple-event (GMEL) relocation algorithm for data of a more appropriate seismic network deployed in the area. While the ISC locations show two main branches of seismicity, one in a nearly flat structure at about 100 km depth and a Wadati-Benioff zone dipping at an angle of about 30°, the GMEL locations show only the first one for the same events. Minor differences between the two types of locations are found just below the easternmost area—where ISC locations should be more inaccurate—and these locations have been used to argue about the bending and plunging of the ‘flat-slab’. Also, it is not clear why the GMEL locations do accord with classical ISC locations determining the dipping Wadati-Benioff zone at 34-36 °S where the ISC locations should be at least as inaccurate as to the north because of fewer stations and a less appropriate network. The striking results obtained by Anderson et al. (2007) would indicate that the knowledge of the slab geometry along South America is very uncertain. Questions concerning electrical conductivity and seismic attenuation in some areas of the Andean subduction zone will be addressed also.
Geodetic and Seismic Characteristics of the Middle America Trench: Focus on Northern Costa Rica and Nicaragua


Subduction zone megathrusts produce the majority of the world's largest earthquakes and tsunamis, but because they exist under the sea floor they are most often studied with land-based techniques more than 50 km from the active interface. However, the Nicoya Peninsula, in Costa Rica, is uniquely situated nearly over the collisional interface between the subducting Cocos and overriding Caribbean plates, making it ideal for near-field land-based studies, and hence were the focus of the 1999-2001 NSF-MARGINS CRSEIZE project to study the ongoing deformation, earthquake activity and seismic structure there.

Here we will examine the character and geometry of modern seismicity and locking in Costa Rica, as observed by the CRSEIZE experiment, and other datasets.

1) Because accurate interface structure is necessary for developing regionally appropriate geodetic models of subduction dynamics, we will report on ongoing work to develop an improved region-wide plate-interface model for the region that incorporates hypocentral seismicity from a number of catalogs, tomographic structure, and seismic lines.

2) We examine the microzonation of the observed seismogenic coupling efficiency as determined by the occurrence of large earthquakes in the past 100 years. With modest assumptions about the seismogenic width and mechanisms of early seismicity, we find that regional efficiency is highly variable along-strike, changing between 25 to less than 5% efficiency, suggesting that coupling is significantly controlled by changes in the down-going plate.

3) Combined measurements of microseismicity and GPS deformation has yielded valuable information about the state of locking along the interface. Geodetic modeling that directly inverts for locking (backslip) along the subduction interface suggests the region is generally weakly locked, but with a strong (>60% locked) portion just offshore central Nicoya (Norabuena et al., 2004). While, power-law statistics on the occurrence of small to large earthquakes along the interface shows the same locked region to have implied higher stresses (from low $b$-values) with increased variability near subducted seamounts just to the south (Ghosh et al., 2008).

4) Finally we examine the results of cross-network relocation study that illuminates an abrupt offset in the updip limit of seismicity at the transition between Nicoya and Nicaragua. This offset is of particular interest because it either highlights a steady-state change in the region of seismogenic initiation, with a yet to be understood cause, or it is a transient trenchward shift in the seismogenic zone caused by the 1992 shallow tsunami earthquake off of Nicaragua. If this feature is transient, the question remains as to whether northern Costa Rica is capable of producing a large earthquake with a similar trenchward extent.
Deformation and interaction between the Pacific and Philippine Sea slabs subducting beneath Tokyo, central Japan.

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The Pacific, Philippine Sea, and Eurasian plates form a trench-trench-trench triple junction offshore of central Japan. This results in a plate configuration where the Pacific and Philippine Sea subducting slabs are stacked at very shallow depths directly beneath metropolitan Tokyo. The shallowest slab interface between the downgoing Philippine Sea plate and the overlying Eurasian plate is the setting for intense megathrust earthquakes which have damaged Tokyo and nearby cities. This includes the 1703 Genroku and the 1923 Great Kanto earthquakes, of which the latter caused over 100,000 fatalities. This megathrust source fault (top of Philippine Sea plate) has been the focus of much recent geological and geophysical study including seismicity and 3D tomography studies, seismic profiling, earthquake rupture and megathrust slip processes, and active deformation via geodesy and terrace uplift histories. However, significant other shallow seismicity exists within the Pacific and Philippine Sea subducting slabs which are hazardous to the Tokyo region. We analyze phase data from the Japan Meteorological Agency and other cooperating Japanese organizations in order to produce high resolution 3D tomography and earthquake relocations. We use P wave arrival times and locations for earthquakes between October 1997 and March 2003. Out of the more than 556,000 events in the catalog we chose for tomographic imaging 24,653 events that fall within the region of 34-38N and 137-141E which have at least 19 arrivals. The seismic tomography and relocated earthquakes along with focal mechanisms derived by the National Research Institute for Earth Science and Disaster Prevention (NIED) combine to define the 3D structure of each of the two descending plates beneath greater Tokyo. The deeper Pacific plate slab is well imaged. The Philippine Sea plate can be divided into four zones of differing seismicity, tectonics, and velocity structure. Beneath eastern Tokyo the Philippine Sea plate appears to be resting atop the Pacific slab and exhibits elevated amounts of seismicity. The focal mechanisms of these earthquakes vary widely and are not related to the Philippine Sea megathrust. We suggest this increased density of earthquakes is due to interaction between the two slabs: (a) interslab earthquakes due to oblique collision between the two slabs plus (b) intraslab earthquakes with deformation propagated back updip within the Philippine Sea plate as its downdip toe hits the Pacific slab. These increased seismic events represent potential magnitude 5 and 6 earthquakes situated between 10-100 km beneath Tokyo. Geodynamical modeling of two slabs of similar dip polarity show that internal zones of deformation can develop due to one slab affecting the other. We suggest that the interaction of the Pacific and Philippine Sea slabs raises the amount of shallow seismicity beneath Tokyo.
Seismicity Reveals Clear Segmentation and Differences in Coupling along the Costa Rica Subduction Zone

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Seismicity over the last century along the Pacific coast of Costa Rica reveals strong differences in behavior of the seismogenic zone in this subduction zone. These differences include: a) frequency of background seismicity; b) occurrence or not of large earthquakes; c) recurrence time of large earthquakes, and d) degree of coupling from seismic moment release. A segmentation of the subduction zone is proposed based on these differences and the characteristics of both the upper and subducting plate. Two segments stand out as excellent sites for seismogenesis studies: Nicoya, already a focus site of the Seismogenic Zone Experiment initiative, and Osa, another peninsula lying over the seismogenic zone where an aseismic ridge subducts underneath it. Although not a typical subduction zone, Osa has the great advantage over most, if not all, seismogenic zones of having the potential to be drilled from land.
Costa Rica seismogenesis Project (CRISP), a Complex Drilling Proposal at the iODP.

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CRISP is a project to understand the initiation, propagation and arrest of seismic rupture of large earthquakes by drilling on either side of the updip limit of the seismogenic zone. CRISP is designed to investigate the processes leading to seismogenesis at erosional convergent margins. At least 50% of the world’s subduction zones are erosional margins. Erosional convergent margins have a subduction channel containing material removed from the overriding plate mixed with sediment from the incoming plate. The nature and physical properties of this material are currently unconstrained. Similarly, the volume, distribution and chemistry of fluids at erosional plate boundaries are poorly known. Drilling will for the first time sample eroded material and fluids in the subduction channel and investigate plate boundary fault mechanisms during tectonic erosion. Drilling will also provide the core material for detailed laboratory experiments designed to isolate the processes and physical conditions that control the onset of seismogenesis.

CRISP consists of two Programs that will involve sampling, downhole observatories, and laboratory experiments on the recovered materials. Program A focuses on the incoming oceanic plate, the decollement at the margin’s front where slip is aseismic, and the shallow structure of the overriding plate. Program B will investigate the plate boundary in the transition from stable slip to unstable slip by drilling and monitoring at two sites. One site is located updip, but near, the end of the seismogenic zone, and a second site is drilled into the seismogenic zone.

The non-riser drill Program A will provide cores to characterize lower plate igneous basement rock and its hydrology. Paleo-depth indicators will allow a first estimation of eroded debris and trench sediment thickness input by the subduction channel into the seismogenic zone. Program B consists of a detailed investigation of subduction earthquake processes and to sample and monitor the plate boundary where temperatures range ~100-200˚C. Previous work indicates that key processes become active in that temperature range and control the onset of seismicity.

The scientific objectives of CRISP are to test five main hypotheses central to understanding structure and seismogenesis at erosional plate boundaries:

1) Landward of the frontal sediment prism, the transition from stable to unstable slip parallels the transition from a fluid-rich and broad fault zone, with distributed slip, to a narrower zone of active deformation with localized shear and fluid compartmentalization.

2) Fluid pressure gradients and fluid advection affect the migration and coupling of erosional plate boundaries both temporally and spatially.

3) The lithology, physical properties, and structure of eroded materials influence fault mechanics and the transition from stable to unstable slip at subduction interfaces.

4) Fluid chemistry, P-T conditions and residence time affect the state of eroded material through basement alteration, diagenesis and low-grade metamorphisms.

5) Lateral variability in subducted plate relief, subduction channel thickness, material properties and fluid distribution affect seismogenesis and rupture propagation.

These hypotheses will be tested by A) direct observation of the lithology, physical properties and structure of the plate boundary and surrounding rock, B) monitoring temperature, stress, pore-fluid pressure and chemistry, and seismicity, C) laboratory experiments on core samples,
and D) dedicated geophysical surveys designed to expand regionally the results from drilling and monitoring.

The subduction zone offshore Osa Peninsula (Costa Rica) provides the tectonic setting to reach CRISP goals. The low subduction angle and high temperatures bring to shallow depth processes that elsewhere occur at greater depth, beyond the reach of riser drilling. **Program A and B**, have been positively evaluated by the Science Planning Committee (SPC) and await for scheduling by the Operations Task Force (OTF). In addition, a complementary proposal has been submitted to NSF seeking support for the collection and processing of a 3D volume of seismic data to guide deep riser drilling and analyse physical properties of the plate boundary zone.
Bringing MARGINS Science to the Classroom – Examples from SEIZE

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NSF-MARGINS has undertaken an effort over the past year to provide a rich library of resources for inquiry-based learning in undergraduate geosciences classes. A NSF Course, Curriculum, and Laboratory Improvement (CCLI) grant to develop web-based undergraduate classroom teaching modules has funded this effort, highlighting the results of the four major research initiatives. The products of the initial effort can be accessed through the web site at Science Education Resource Center (http://serc.carleton.edu/margins/index.html) for testing and assessment. These materials can be incorporated into classroom lectures or used in laboratories section, from general education courses for the non-science major to upper division major and courses, which are both content-rich and research-based. Examples of these materials range from images and animations drawn from computer presentations at research workshops and audio/video clips from web sites, to “mini-lessons” which focus on a single learning object, as well as use of data repositories, some of which can be accessed through GeoMapApp, a data exploration and visualization tool developed as part of the Marine Geoscience Data System by researchers at the LDEO (http://www.geomapapp.org/).

Educational resources based on the SEIZE initiative hold great promise in capturing the imagination of undergraduate students, and the public in general, because of the societal relevance. Examples of SEIZE-based research used in undergraduate classes will be presented, including the use of multichannel seismic data provided through the Marine Seismic Data Center of UTIG to study subduction zone processes at convergent plate boundaries. We will also present the initial development of a web-based virtual expedition for use in undergraduate classes, based on the 3-D seismic survey associated with the NanTroSEIZE program of NSF-MARGINS and IODP to study the properties of the plate boundary fault system in the upper limit of the seismogenic zone off Japan. A third effort will create an archive library of podcasts based on many of the papers presented at this workshop.
Internal Structure and Deformation History of an Ancient Analogue of a Shallow Erosive Subducting Plate Boundary

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This study concentrates on the shallow portion of a fossil erosive subduction channel exposed in the Northern Apennines of Italy. The subduction channel is the shear zone, 500 m thick, marking the plate boundary and defined by gradients in the flow velocity of the deforming material in respect to the upper and the lower plate. The subduction channel (SC) formed during the Tertiary transition from oceanic subduction to continental collision, and it has been preserved by the late deactivation and fossilization of the plate boundary as a tectonic mélangé, the Sestola-Vidiciatico tectonic unit (SVU). At present, the SVU is sandwiched between the overlying Late Cretaceous/early Eocene Ligurian accretionary prism (i.e., the frontal part of the European plate margin) and the underlying fold-and-thrust belt formed by Adriatic continental units. New detailed study of the thermal conditions inside the SC confirms that the temperature reached 150°C. The material delivered to the subduction channel by subduction erosion was coming from both the overlying and no longer active accretionary prism and its sedimentary cover. In particular, besides the more common basal subduction erosion we recognized also frontal erosion that progressively incorporates sections of the frontal prism. The boundaries of the subduction channel are formed by a basal and a roof décollement. The internal organization of the channel is in minor units that we can envision as sub-horizontal bodies separated by tectonic surfaces parallel to the boundaries of the subduction channel itself. These bodies are organized so that those with younger sediments lay closer to the basal décollement, whereas those containing older sediments lay closer to the roof décollement. This suggests that more than one décollement was active within the subduction channel and that they were moving at different velocities. Evidence for décollement deactivation is present, the most important being the complete locking of the basal décollement in the deeper portion of the subduction channel. At shallow depths extension was a key deformation component within this erosive convergent plate boundary, and slip occurred without an observable fluid pressure cycle; the strain concentrated in the not-completely lithified slope deposits, while the already lithified blocks remained undeformed and acted as rigid blocks in a weak matrix. At depths greater than about 3 km a fluid cycle is clearly shown by the development of shear veins and associated extensional veins all along the décollements and the alternation of fast and slow slip accommodated by pressure-solution. The data suggest the onset of discontinuous movement, at high fluid pressure conditions, inside the SC at temperature lower than 150°C.
What do small earthquakes tell us about the nature of interplate coupling in the southern North Island, New Zealand?

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Recently GPS instruments have provided estimates of the spatial distribution of coupling at the Hikurangi subduction thrust, as well as areas of slow slip on the thrust. At the same time, tomographic inversions for the seismic velocities (Vp and Vp/Vs) and attenuation (1/Qp) have provided images of the three-dimensional structure of the plates surrounding the thrust. One suggestion coming out of this work is that competent geological terranes in the overlying plate may act as aquicludes, increasing pore pressures in the rocks below. This begs the question of whether such terranes might control the distribution of coupling at the subduction thrust. This seems to be the case in the southern North Island, where the Permian-Triassic Rakaia terrane impacts the shallow part of the subduction thrust. GPS measurements indicate that this region is currently strongly coupled. If the overlying plate does in fact modulate fluid conditions at the plate interface and within the subducted plate, we should see this reflected in the distribution of small earthquakes. After all, nearly all earthquakes will involve fluids, even those within the mantle of the subducted plate, where dehydration embrittlement provides a ready fluid source. To this end, we have relocated all earthquakes in the southern North Island shallower than 100 km that occurred between 1990 and 2005 inclusive (over 66,000 events in total), using our new three-dimensional seismic velocity model. We have then partitioned these events into those in the overlying plate and those in the subducted plate, using both the distribution of seismicity in the dipping seismic zone and constraints from active source experiments. We have further subdivided events in the subducted plate into those within the upper plane of the dipping seismic zone (i.e. within 15 km of the plate interface and thus in the subducted crust) and those in the lower plane in the uppermost mantle. The relocated seismicity shows a good correlation with the distribution of coupling at the plate interface deduced from GPS. In particular, activity in the lower plane of the dipping seismic zone shows a very good correlation with the 20 mm/yr slip rate deficit contour, with seismicity concentrating on the edges of the strongly coupled region. In the upper plane of the dipping seismic zone, seismicity is more clustered within the strongly coupled region, with earthquakes defining sub-vertical faults, oriented along the strike of the subduction zone. Incremental slip on these faults suggests a fluid-rich subducted crust beneath the strongly coupled region. In the overlying plate, seismicity concentrates downdip of the strongly coupled region, and is distributed throughout the crust and uppermost mantle. The seismicity and structural data suggest a model where plate coupling is controlled by the ability of fluid to cross the plate interface. When an impermeable terrane in the overlying plate prevents such fluid flow, plate coupling appears to be strong.
Borehole Strainmeters: Instruments for Measuring Aseismic Deformation in Subduction Zones

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Borehole strainmeters in terrestrial boreholes have recorded numerous examples of transient aseismic deformation in seismically active areas. In particular, the relatively large aseismic strains accompanying transient aseismic slip in subduction zones are ideally suited for study with borehole strainmeters. However, terrestrial deployments primarily provide data on the locked and down-dip transition zones of the subduction thrust. Observations from seafloor boreholes of fluid pressure and discharge changes have been interpreted as evidence for aseismic strain associated with subduction zone and ridge-spreading processes. Borehole strainmeters have far better resolution than fluid pressure records, so the probability is strong that strain signals of interest would be recorded were it possible to deploy borehole strainmeters in offshore scientific boreholes. Currently there are technological barriers to deploying strainmeters in seafloor boreholes, especially those deep enough to penetrate the subduction thrust. To date, the deepest successful borehole strainmeter installation is at 1 km depth in Japan. Most present-day strainmeters are designed to operate at temperatures of 80°C or below. What types of engineering development would be needed to overcome these limitations and allow deep scientific drillholes or seafloor boreholes to house successful strainmeter installation? The most challenging aspects of a borehole strainmeter installation are finding a suitable installation interval, and obtaining a high-quality bond between the strainmeter and the formation. While there is considerable experience with these issues, quantitative guidelines should be developed before attempting to install in a seafloor borehole where re-drilling is not an option. Redesign of strainmeter housings to withstand higher pressures would also be a challenge, inasmuch as very high precision and attention to material stability are required to obtain a well-functioning strainmeter. An important design choice for a borehole strainmeter installation is how to bring the signal to the surface. A possible strategy is to use downhole digitizing with high-temperature capable electronics, sending the digital signal through a cable encased in steel tubing. Developing strainmeters that return high-quality data in deep drillholes would require a substantial engineering development phase, but the value of continuous deformation measurements, particularly offshore where GPS data are difficult to acquire, could be very great.
From the trench to the seismogenic zone: Establishing links between, fluid pressure, low-T metamorphism, and fault stability

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Fluid pressure within subduction zones profoundly affects fault strength and sliding stability through its control on effective stress. Quantifying the factors that control pore pressure development, its spatial distribution, and its relationship to observed fault mechanical behaviors is needed as a first-order test of conceptual models that suggest fluid content or pressure control the updip limit of seismogenesis. Here, we discuss our work on the well-studied Nankai and Costa Rican margins, with the aim of constraining fluid pressure from the trench to the uppermost seismogenic zone. We use a combination of laboratory consolidation tests, porosity data from drilling near the trench, and porosity inferred from seismic reflection velocities to constrain in situ effective stress and pore pressure immediately beneath the megathrust, from the deformation front to ~20 km downdip of the trench. As a second, independent approach to estimate pore pressure, we use a forward model of loading and pore pressure diffusion. We define sediment hydraulic and mechanical properties through extensive geotechnical testing of sediments from ODP Legs 190 (Nankai margin) and 205 (Costa Rican margin). We use constant rate of strain (CRS) consolidation experiments to define coefficient of consolidation (cv), coefficient of volume compressibility (mv), and permeability (k), at effective stresses from 0 - 90 MPa. Permeabilities derived from the CRS tests are supplemented by flow-through tests in which a hydraulic gradient is imposed across a sample. Modeled pore pressures are in good agreement with those derived from consolidation tests, and from inferred and observed porosities. Our results show that high pore pressures and associated underconsolidation persist to tens of km from the trench, leading to low effective stress and potentially suppressing unstable slip in the updip region. At both margins, we also observe that drainage allows the zone of minimum effective stress to migrate down section, which may partly control downstepping of the décollement. Notably, the onset of drainage - and concomitant reduction in underconsolidation and increase in effective stress - are broadly coincident with the location of diminished seismic reflection amplitude, decollement downstepping, and the updip termination of coseismic slip. One key implication is that at both accretionary and erosional margins, drainage and the dissipation of fluid pressure are spatially correlated with the updip limit of the seismogenic zone. This is consistent with conceptual models in which the plate boundary transitions with depth from a fault with high water content that slips stably, to a relatively “dry” fault capable of failing seismically.
Three sectors of north Pacific region subduction zones, Cascadia, Alaska-Aleutian, and Nankai, are bordered by trenches with a thick (>1-1.5 km) sequence of pelagic, hemipelagic, and turbiditic deposits. The base of each margin is edged by a frontal prism of accreted trench-floor deposits that has attained a stable width of 30-40 km. North Pacific convergent margins flanked by thinly-sedimented trenches (< ~0.6 km -- e.g., Middle America, Mexico, Kamchatka-Kuril, Japan, and IBM) are bordered by narrow (5-20 km) frontal prisms constructed dominantly of tectonized slope deposits and mass wasting debris. Inboard of frontal prisms, which are actively deforming bodies, the margin's inner prism of much older and stronger framework rock is deforming only broadly. But this expanse of the margin, which extends seaward to within 5-40 km of the trench, is where elastic strain is stored that can generate large subduction zone earthquakes. Commonly, a seaward verging system of splay faults and margin-parallel strike-slip shears separates the two prisms. For Cascadia, the inner prism is the early Eocene mafic crust of Siletzia. The inner prism for the Alaska margin is exhumed, accretionary underplates of early Tertiary and Mesozoic age, and that for the contiguous Aleutian sector to the west is the Eocene igneous massif of the Aleutian Ridge. The inner prism of strong framework rock for the Nankai forearc is exhumed underplated material of the early Miocene to Cretaceous Shimanto Complex. When compared side-by-side, the rock and structural fabric of the three sectors are similar. Each has a frontal prism of thrust-stacked trench deposits of late Cenozoic age, each has a broadly deforming inner prism of much older material (by 20 to 50 myr), and each exhibits evidence of high-angle thrust (splays) and strike-slip shear zones separating the frontal and inner prisms. With respect to these characteristics, the geologic, tectonic, and structural architecture of the Cascadia, Alaska-Aleutian, and Nankai subduction zones are similar to other Pacific region forearcs fronted by sediment-nourished trenches (e.g., Colombia, south central Chile, southern Chile, Hikurangi).
Slow Slip- An Ubiquitous Yet Poorly Understood Mode of Strain Release

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It has been known for a long time that slip accompanying earthquakes accounts for only a fraction of plate tectonic displacements. However, only recently has a fuller spectrum of strain release processes, including slow slip events, low and very low frequency earthquakes and seismic tremor been observed. Strain transients, accompanied by low frequency seismic activity, are the most important discovery made at convergent margins during SEIZE’s 10 year history. Large programs in Cascadia (PBO/Earthscope) and Japan (GEONET and Hi-Net), where hundreds of GPS and seismic instruments are deployed, are responsible for this landmark discovery. Studies from these regions reveal that slow slip is frequent, always accompanied by seismic tremor, surprisingly regular and occurs at the downdip frictional transition from stick-slip to stable sliding where temperatures reach 450-550° C. These observations suggest that a transition in frictional stability is required for slow slip and that slow slip and tremor reflect the same process involving fluids liberated from the subducted slab. However, observations of slow slip and seismic tremor from other subduction zones indicate significant variation that may be exploited to better understand their generation. At some convergent margins, slow slip and tremor occur within the seismogenic zone and/or seismic tremor is undetectable or sporadic during slow slip events. Slow slip and tremor have been observed at relatively cold margins presenting a challenge to the “hot fluid-rich” scenario believed critical for their generation at the Cascadia and Japan margins.

I suggest we consider a new strategy for the next decade of SEIZE where large scale experiments are initiated to tackle the most compelling scientific problems. A major deployment of geodetic/seismic instrumentation on a scale approaching Earthscope/GEONET at a subduction boundary that differs in important ways from Cascadia and Japan will allow the physical mechanism of slow slip phenomena to be revealed.
Seismogenic Zone Studies in the Next Decade

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The last decade has seen an explosion of studies associated with the seismogenic zone, including earthquake, seismic reflection, geodetic, laboratory, hydrogeologic, drilling, and surface processes. These studies have been justified in part because of the significant role that subduction earthquakes play as a primary global geohazard. During the coming decade it will be incumbent on us to move from purely science-driven studies to those that provide guidance to population centers at risk from this hazard. We are facing this task at a time when budgets for very large scientific experiments are suffering major cuts in real buying power, when ocean drilling is slashing activity to about 50%, and when major seismic experiments are facing severely limitations. The way forward will require: Integration of existing datasets and ongoing studies Integration of deep experiments with near-surface observations Integrated long-term time series to understand the relation between deep and shallow processes Integrating laboratory experiments with field observations Modeling of the seismogenic system A long-term goal should be the ability to understand critical behavior of the seismogenic zone from long-term near-surface observations.
SEISMIC STRONG MOTION ARRAY PROJECT (SSMAP) TO RECORD FUTURE LARGE EARTHQUAKES IN THE NICOYA PENINSULA AREA, COSTA RICA

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The seismic strong motion array project (SSMAP) for the Nicoya Peninsula in northwestern Costa Rica is composed of 10 – 13 sites including Geotech A900/A800 accelerographs (three-component), Ref-Teks (three-component velocity), and Kinemetric Episensors. The main objectives of the array are to: 1) record and locate strong subduction zone mainshocks [and foreshocks, “early aftershocks”, and preshocks] in Nicoya Peninsula, at the entrance of the Nicoya Gulf, and in the Papagayo Gulf regions of Costa Rica, and 2) record and locate any moderate to strong upper plate earthquakes triggered by a large subduction zone earthquake in the above regions. Our digital accelerograph array has been deployed as part of our ongoing research on large earthquakes in conjunction with the Earthquake and Volcano Observatory (OVSICORI) at the Universidad Nacional in Costa Rica. The country wide seismographic network has been operating continuously since the 1980’s, with the first earthquake bulletin published more than 20 years ago, in 1984. The recording of seismicity and strong motion data for large earthquakes along the Middle America Trench (MAT) has been a major research project priority over these years, and this network spans nearly half the time of a “repeat cycle” (~ 50 years) for large (Ms ~ 7.5-7¾) earthquakes beneath the Nicoya Peninsula, with the last event in 1950. Our long time co-collaborators include the seismology group OVSICORI, with coordination for this project by Dr. Ronnie Quintero and Mr. Juan Segura. The major goal of our project is to contribute unique scientific information pertaining to a large subduction zone earthquake and its related seismic activity when the next large earthquake occurs in Nicoya. We are now collecting a database of strong motion records for moderate sized events to document this last stage prior to the next large earthquake. Several recent events (2006-07; M=4.3) located 20 km northwest of Samara were recorded by two stations (Playa Carrillo and Nicoya) at distances of 25-30 km with maximum acceleration of 0.15-0.2g.
Effects of fluid circulation in subducting crust on megathrust temperatures in Nankai margin

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Temperatures within subduction zones have been suggested as controls on the updip and downdip limits of the megathrust seismogenic zone due to their influence on diagenetic and metamorphic reaction progress. We suggest that fluid circulation in the subducting crust may be an important control on the temperature distribution in the Nankai margin. Most thermal models of subduction zones have not included hydrothermal circulation within ocean crust. While heat advection by fluid flow through the wedge, décollement, and underthrusting sediment is likely negligible, fluid flow in high permeability fractured basaltic basement may redistribute large quantities of heat and affect temperature distribution along the megathrust. We simulate temperatures in the Nankai margin with a model that approximates the effect of fluid circulation homogenizing temperatures within the basement aquifer of subducting crust. Fluid circulation in subducting crust helps explain two previously enigmatic thermal anomalies on the Nankai margin, namely anomalously high heat flux in Nankai Trough and an anomalously steep drop in heat flux with distance landward on the margin wedge. Vigorous fluid circulation in the subducting crust reduces decollement temperatures by 20 C at the updip limit of seismicity and 100 C at the downdip limit relative to thermal models that do not include hydrothermal circulation.
Active subduction to continental collision within the New Zealand continent: studies on crustal structure and mantle deformation.

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The sub-aerial portion of the New Zealand continent is bisected by the Australian – Pacific plate boundary. Twenty five years of crustal and upper mantle studies provide insight into how the plate boundary and associated seismicity changes in character from north to south. Three distinct regions are observed: 1/ Beneath central North Island is a classic ocean-continent subduction zone (the Hikurangi margin) that is freely slipping in the north with rapid back-arc spreading occurring in the overlying (Australian) plate; 2/ Beneath southern North Island the subduction interface becomes progressively sticky as indicted by high strain anomalies that are transmitted into the over-riding plate, and a flexural downwarp and minor compression in the back-arc area. Despite the semi-locked nature of the plate interface here, subduction still occurs with a dipping Waditi-Benioff zone seen to a depth of ~ 200 km; 3/ Further south, into central South Island, is the third distinct region of plate interface behaviour. Here the plate interface region, and associated seismicity, changes dramatically. Collision is more oblique and is continent-continent in character. Surface manifestation of the collision are the development of the Southern Alps and the Alpine fault, across which ~ 10mm/y of convergence is occurring. Teleseismic P-wave delays show the mantle lithosphere thickening and deforming into a vertical blob-like body directly beneath the crustal root of the Southern Alps. Seismic anisotropy studies suggest the thickened mantle lid here is also being sheared laterally. Contrasting seismogenic behaviour is experienced in all three plate boundary regions. New Zealand has recently developed a network of broad-band seismometers and permanent GPS sites to monitor and study the deformation and seismicity of the country. This array is being supplemented by additional, semi-permanent arrays to study regions of particular interest. For example, funding has just been approved to install a bore hole array in the central Southern Alps to learn about seismogenic properties of the mid to lower crust in the plate boundary zone. New attention is on the seismogenic potential of Hikurangi subduction and its effects onto the overlying North Island.
Integrated core sample researches of Taiwan Chelungpu-Fault Drilling Project and the understanding of fault dynamics of the Chi-Chi earthquake.

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The Taiwan Chelungpu-fault Drilling Project (TCDP) started in 2002 to investigate a unique slip behavior of the 1999 Chi-Chi earthquake (Mw 7.6) [Ma et al., 2003]. Two boreholes (total depth, 2003.0 m in Hole A; 1352.6 m in Hole B), near the town of Dakeng in the northern part of the rupture zone, were drilled to penetrate the Chelungpu fault. In Hole B, three major fault zones of the Chelungpu fault system were identified. Nondestructive continuous physical property measurements were conducted on all core samples, and detailed chemical and physical properties measurements are also conducted on the fault zones. High magnetic susceptibility anomaly, low inorganic carbon clay mineral contents were observed at the black ultracataclasite, which infer the frictional heating during the slip. The result of advanced magnetic analyses and high velocity frictional tests showed that high magnetic susceptibility is caused by the newly formation of ferromagnetic minerals due to frictional heating at above 400 °C. Siderite, pyrite and chlorite could be favorable minerals that caused thermal decomposition. Numerical analysis of the thermal pressurization mechanism during the 1999 Chi-Chi earthquake using laboratory measured transport and frictional properties showed that pore pressure at the fault zone increased dramatically during slip, whereas temperature increased only moderately to 400 °C at the end of slip. The relative increase of temperature is consistent with the result from the magnetic and geochemical analysis. Our results support the hypothesis that thermal pressurization was responsible for the large slip distances observed on the northern part of the Chelungpu fault.
In situ Properties, Structure, and State of Stress in the NanTroSEIZE Transect: Logging While Drilling results from IODP Expedition 314

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IODP Expedition 314 Scientific Party

IODP Expedition 314 took place from September through November, 2007, and was both the inaugural scientific drilling mission of the new vessel, Chikyu and the first step in the multistage Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE). During Expedition 314, our primary goals were to obtain a comprehensive suite of geophysical logs and other downhole measurements at sites along a transect from the incoming plate to the Kumano forearc basin using state-of-the-art logging-while-drilling (LWD) technology. Drilling and logging was successfully completed at four sites, ranging in depth below the seafloor from 400 to 1400 m, with partial success at a fifth site. These sites included the frontal thrust and toe region of the outer accretionary prism near the trench, the fault zone and associated thrust sheet of a major out-of-sequence thrust system (the “megasplay” fault), a 1000 m thick forearc basin section, and highly deformed rocks of the interior of the accretionary prism.

The principal goals of the LWD program were to document in situ physical properties; stratigraphic and structural features; sonic to seismic scale velocity data for core-log-seismic integration; and stress, pore pressure, and hydrological parameters through both scalar and imaging log measurements. Logging included the measurement of natural gamma radiation, azimuthal gamma ray density, neutron porosity, full waveform sonic velocity, azimuthal resistivity imaging, zero-offset vertical seismic profile, ultrasonic caliper, and annular fluid pressure, though not all logs in this suite were collected at all sites.

Preliminary results indicate that the megasplay thrust sheet is composed of highly deformed and fractured rocks that are anomalously well indurated relative to their present depth below the surface, indicating substantial uplift. Major thrust faults are marked by zones of strong fracturing and brecciation of the formation. Present-day stress orientation, documented by borehole breakout, varies markedly along the NanTroSEIZE transect, and stresses in the upper 1.4 km are apparently strongly compressional in the outer, active accretionary prism but extensional in the forearc basin. An oblique component of the tectonic stress in the outer accretionary prism is apparently partitioned onto distinct convergent and transcurrent structures.
NanTroSEIZE: The IODP Nankai Trough Seismogenic Zone Experiment

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Investigation of the processes governing the interplate seismogenic faulting in subduction zones is the overall goal of the MARGINS SEIZE program, and the Nankai Trough of southwestern Japan has been a prime focus site from the inception of MARGINS. Seismogenic zone studies include geophysical imaging and monitoring, field-based geological studies, laboratory and numerical experiments, and direct access to the seismogenic zone, which can only be accomplished through drilling. The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) comprises all of those aspects, but the centerpiece is the IODP effort to access the plate interface near the up-dip limit. The fundamental goal of the NanTroSEIZE science plan is the creation of a distributed observatory spanning the up-dip limit of seismogenic and tsunamigenic behavior at a location where great subduction earthquakes occur, thus allowing us to observe the mechanical behavior of subduction megathrusts and the aseismic to seismic transition of the megathrust system. This involves drilling of key elements of the active plate boundary system at several locations off the Kii Peninsula of Japan, from the shallow onset of the plate interface to depths where earthquakes occur.

The principal elements of the project include (a) the 2006 3D seismic survey of the intended transect, (b) four planned stages of IODP drilling, sampling, and downhole measurements, and (c) long-term real-time monitoring of the plate interface. Stage 1 took place with three IODP expeditions in 2007 and 2008 and accomplished riserless drilling, logging, and sampling of 8 sites as deep as 1400 meters below the sea floor. Planned effort in 2009 (Stage 2) will include the first riser drilling in IODP to establish an upper-plate borehole observatory directly above the outer portion of the presumed locked zone at a depth of 2500 m, as well as sampling the inputs of crust, sediments, and fluids. Stages 3 and 4 are focused on drilling an ultradeep hole to the plate interface and placing long-term monitoring instruments in the network of boreholes. In an allied program, Japan plans a seafloor cable network in the NanTroSEIZE transect region, which will provide the capability to deliver power and stream real-time data from the borehole observatory instruments.
Low angle thrust earthquakes in the "locked zone" beneath the central Cascadia continental margin

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In the summer of 2004, two clusters of "repeating" earthquakes occurred beneath the continental shelf of the central Cascadia subduction zone near 44.5N, 124.5W where the subduction megathrust is thought to be locked or transitional (Fig. 1A). The largest event in each cluster had moment magnitude M=4.8-4.9. Seismicity has continued since with small (M<3) earthquakes occurring in each cluster on August 23-25, 2007 (Fig 2). Moment tensor analysis for the main shock in each cluster indicates thrusting on a 6-15° eastward dipping fault plane (Fig. 3). These earthquakes are occurring on a transect along which crustal structure is well known from active source seismic experiments, and raytracing through this crustal model to match observed relative arrival times of secondary phases places the mainshocks within 1 km of the plate boundary (Fig 1B). This segment of the forearc also displays several anomalous characteristics including: a subducted ridge on the downgoing plate; a "bright spot" on the plate boundary at a depth of ~15-20 km; a transition in plate coupling indicated by inversion of GPS data; geologic indications of active folding in the upper plate; and anomalous deformation in the adjacent oceanic plate. We have recently deployed the Central Oregon Locked Zone Array (COLZA), which comprises 15 ocean bottom seismometers (3 broadband, 12 short period) and 4 (soon to be 6) EarthScope USArray Flexible Array stations (Fig. 2). A primary objective of COLZA is to better define the spatial and temporal patterns of seismic activity in the nominal "locked zone," the neighboring Juan de Fuca plate, and the adjacent down-dip region, where episodic tremor and slip is occurring.
The seismic slip in accretionary prisms

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We have examined the thrust zones in the Nankai and Shimanto accretionary complexes in southwest Japan. During IODP Expedition 316 at the Nankai accretionary margin, we identified the extreme slip localization along the 2-10 mm thick dark layers from the megasplay fault and the frontal thrust at depths below 500 m (Kimura et al., 316PR, 2008). This suggests that even at shallow depths the slip may be localized along the thin slip zone during subduction earthquakes. The studied thrust zones in the Shimanto accretionary complex were developed at seismogenic depths (4-6 km) and thus could be ancient analog of the seismogenic thrust zones at the Nankai accretionary margin. We found the pseudotachylytes and ultracataclasites from the thrust zones and demonstrated (1) the frictional melting of illite-rich slip zone at temperature higher than 1100 degreeC (Ujiie et al., JSG, 2007a) and (2) the thermal pressurization-induced fluidization of basalt-derived comminuted material (Ujiie et al., EPSL, 2007b; Ujiie et al., Geology, 2008). We also conducted the high-velocity shear experiments and the numerical modeling to estimate (1) the changes in the mechanical property of the frictional melt associated with increase in depth and (2) the slip weakening distance during the thermal pressurization of subducted material. We hope that our study contributes to understand the seismogenic thrust zone at convergent plate boundaries.
Sediment Inputs to The Seismogenic Zone

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Lithostratigraphic architecture exerts a first-order influence over the material properties and tectonic behavior of subduction zones. Compartments of excess pore-fluid pressure are, in many depositional systems, set up initially by confined sand-body geometries. Generic facies models for trenches show upward thickening and coarsening trends (from basalt at the base through pelagic ooze, hemipelagic mud, silty turbidites, and sandy turbidites), but there are many exceptions to this paradigm that can affect fault-zone behavior. The amount and types of clay-size particles also affect micro-fabric, coefficient of friction, and permeability. Some minerals (e.g., smectite and opal) significantly increase fluid production during diagenesis. The Costa Rica segment of Middle America Trench is starved of terrigenous sediment, so basement there is overlain successively by open-ocean calcareous ooze and diatomaceous smectite-rich hemipelagic mud. Spatial variations in the thermal structure of the Cocos plate modulate diagenetic reaction progress, fluid production, pore pressure, and effective stress, both within and beneath the plate boundary. Inputs to Nankai Trough are much different and change in three dimensions because the irregular basement topography of Shikoku Basin deflected turbidity currents during early stages of abyssal-floor sedimentation. Sandy turbidites are the norm, rather than the exception, beneath the frontal décollement. The content of smectite also changes along strike in Shikoku Basin because of local perturbations of heat flow and pre-subduction diagenesis. As the Seismogenic Zone Experiment progresses into its second decade, the community will need to quantify the thermal and compositional inputs to these (and other) systems in three dimensions before pin-pointing how and why geotechnical and hydrogeologic properties change near the up-dip limit of the seismogenic zone. Coring the subduction inputs to Nankai Trough remains a first-order priority. That part of the NanTroSEIZE science plan has been placed on the IODP schedule three times already, but budget shortfalls, long delays in refurbishment of JOIDES Resolution, and other setbacks have resulted in de-scheduling three times. In the meantime, participants in this workshop can consider the coring results from Stage 1A, which targeted the shallow mega-splay fault, Kumano forearc basin, and the frontal thrust of the accretionary prism.
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We have developed a suite of thermal models for a large number of 2D cross sections through the world's subduction zones. The models are based on high resolution finite element models that incorporate olivine rheology in the mantle wedge following Van Keken et al. (Gcubed, 2003). The principle input parameters are the age and speed of the incoming plate, the amount of sediments on the incoming plate and estimates of the amount of erosion of these sediments upon subduction, the age and structure of the overriding plate and the depth of decoupling between subducting plate and mantle wedge. The latter parameter is varied depending on availability of independent physical observations of the presence of a 'cold nose' in the fore-arc mantle and the location of the volcanic arc. The generation of the cold corner in thermal models is an essential requirement to satisfy heat flow observation and seismic constraints. It is not clear at the moment what the constitution of the cold corner is (beyond that it is low temperature, low attenuation and presumably hydrated) and it is also not clear how it is maintained. Dynamical considerations point to the need for an extension of the seismogenic zone by aseismic creep processes that are localized and effectively decouple the descending slab to a depth of about 80-90 km in most subduction zones. A systematic investigation of the subduction zone suite does not reveal a single simple controlling parameter. Suggestions that the depth of decoupling is guided by the brittle-ductile transition governed by temperature or temperature-strainrate (e.g., Conders, PEPI, 2002) cannot be corroborated, which suggests that the depth of decoupling is governed by more complicated rheology or by alternative mechanisms or subduction zone inputs.
Shallow décollements and outer wedges in subduction EQ cycles

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Deep sea drilling offshore Costa Rica provides structural observations which support a new model for the geometry and deformation response to the seismic cycle of the frontal sedimentary prism and décollement with more quantitative estimation of the relationship among the displacement, thickness and repeated slip along the décollement. At shallow, aseismic depth the décollement damage zone is a few tens of meters in width and it asymmetrically develops mainly within the frontal prism. A clear cm-thick fault core is observed at the base of the damage zone. Analysis on the breccia forming the upper portion of the décollement damage zone indicate that shearing was accompanied by different or additional fracturing processes. Microscopic analysis also confirms that extension fracturing in the upper part of the damage zone farthest from the fault core is frequent, while both extension and shear fracturing occur approaching the fault core. The coexistence of extensional and shear fracturing seems to be best explained by fluid pressure variations in response to variations of the compressional regime during the seismic cycle. During the co-seismic event, sub-horizontal compression and fluid pressure increase, triggering shear fracturing and fluid expulsion. Fractures migrate upward with fluids, contributing to the asymmetric shape of the décollement, while slip propagates. In the inter-seismic interval the frontal prism relaxes and fluid pressure drops. The frontal prism goes into diffuse extension during the interval when plate convergence is accommodated by creep along the ductile fault core. Plate convergent rate at the Costa Rica margin is about 88m/y, meaning that the part of décollement drilled during ODP legs 170 and 205 at 0.6 km from the deformation front is about 6.8 kyr old and that at 1.6 km is about 18 kyr old. Integrating the geologic record of repeated slip with the recurrence time of M>7 earthquake, about 50yr, then the décollement at 0.6 km slipped about 140 times and that at 1.6 km about 360 times. Currently magnitude 7 earthquakes with ~1m slip are known to occur, and have been proposed to rupture to the updip limit of the décollement. Assuming similar slip partitioning occurred during the past 20kyr, we would estimate that ~25% of the displacement on the décollement occurred as co-seismic slip, and ~75% as aseismic slip.
MODELING THE POTENTIAL INFORMATION FROM A 3D MASSIVE VSP

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The potential of a 3D Vertical Seismic Profile (VSP) to image a high resolution 3D volume around the seismogenic plate interfaces was explored with synthetic modeling. The 3D VSP modeled is at a proposed site for a 1 to 1.5 km deep open hole proposed for drilling in the CRISP transect off Costa Rica. By adding 5 to 9 days to drill ship time on site and a shooting ship a 6 km x 12 km grid of shots with a surface ship the VSP will illuminate a ~4 km x 7 km area of the plate interface fault zone with 1000 to more than 2000 hits per 100m cubic bin. The VSP seismic image resolution falls between the ~10m lateral resolution of borehole information and 150m and greater resolution of 3D surface ship seismic images. Due to the use of three component geophones the VSP can further record high fidelity S wave data to invert for physical properties, shear wave splitting for directions of strain, and pore pressure above and below the plate interface fault. The 3D VSP is an added a tool that can improve the approach to direct observations in the seismogenic zone. Fossil plate interface shear zones are roughly 100 m thick. The 3D VSP can potentially resolve structure and physical properties within the active interplate shear zone where a 3D surface ship survey has located an area of interest. If an area is in range of riser drilling capability the VSP can show the optimal path to the target area. The 3D VSP can also be used to survey areas deeper than drilling capability for comparative study such as the asperities in deep and shallow portions of subduction zones or asperities of tsunamigenic subduction earthquakes. If deployed for longer periods they can record and accurately locate microseismic activity at very low magnitudes.
Exploring the thermal and metamorphic controls on the seismogenic zones of subduction thrust faults

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The updip and the downdip limits of the seismogenic zones of subduction thrust faults are thought to be controlled by changes in the mechanical behaviour (stable-sliding/stick-slip) of the material along the faults. There are a number of suggested causes for this change, such as variations in the metamorphic state of the underthrusting or overriding material and the amount of fluids released from the underthrusting material. These variations, for a given composition of the associated rock material, depend strongly on temperature. We develop thermal models for a number of subduction zones, including Nankai, and investigate the thermal conditions at the updip and downdip limits of seismogenic zones that are constrained by seismic and geodetic data. These models include frictional heating along the interface, and for accretion margins, the thermal effect of sedimentation on the incoming plate is also incorporated. The modeling results show that temperatures along the interface at shallow depths (≤70 km depths) generally decrease with increasing age of the subducting slab and vary significantly among different subduction zones. The thermal conditions of the updip and downdip limits do not seem to be as consistent as those suggested by previous studies. To accurately assess the thermal control on the seismogenic zone, variations in the composition (including water content) and the distribution of the underthrusting and overriding material among different subduction zones may need to be considered.
Observing a Subduction-zone Earthquake Cycle Within a Decade

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Earthquake-cycle deformation at the scale of the forearc-back arc system is delineated mainly by land-based geodetic and seismic observations. Coseismic and immediate post-seismic deformation is characterized by a seaward motion of the coastal area, with the size and rate of the displacement rapidly decreasing landward, as is currently observed at Sumatra where a M ~ 9.2 earthquake occurred in 2004. Deformation a few decades after a giant earthquake shows a pattern of opposing motion, with the coastal area moving landward but the arc-back arc area continuing to move seaward, as is currently observed at Chile and Alaska where M > 9 earthquakes occurred in 1960 and 1964, respectively. Centuries after a giant event (or years to decades after a small event), all the land area moves landward with the rate decreasing landward, as is currently observed at Cascadia where a M ~ 9 event occurred in 1700. The direction and speed of the land motion and their change with time yield critical information on the locking state of the megathrust and the rheology of the earth, and they have been modeled using various fault slip and viscoelastic stress relaxation models.

Earthquake-cycle deformation around the updip end of the megathrust seismogenic zone is technically more difficult to constrain because the area is offshore. Limited near-field monitoring and analyses of seismic waveforms indicate that coseismic rupture tends to peak at greater than 5-10 km depths and taper towards the trench, reflecting a coseismic strengthening behaviour of the shallowest part of the megathrust updip of the seismogenic zone. This strengthening behaviour and its impact on the coseismic slip distribution have tremendous implications to tsunamigenic seafloor deformation, splay faulting, and permanent deformation of the overlying forearc wedge. It has been proposed that repeated coseismic compression over numerous earthquake cycles is responsible for the morphology and structure of the outer wedge. The coseismically strengthened shallowest portion of the fault must relax after the earthquake, but the mode and timescale of the relaxation, as well as the interseismic stress evolution of the updip end of the seismogenic zone, have not been observationally constrained. Relation of the normal faults in the outer and inner wedges, very-low-frequency earthquakes in the accretionary prism, and fluid pressure/flux variations in the splay and megathrust faults with great earthquakes still remains enigmatic because of the paucity of near-field observations. There is also urgent need to understand the phenomenon and mechanism of the widely reported “partial locking”, and possible episodic motion, of the seismogenic zone during interseismic periods.

Despite large differences in the kinematics and dynamics of plate convergence, different subduction zones share similar primary characteristics in their earthquake-cycle deformation. The only way of efficiently characterizing the earthquake-cycle deformation is to recognize such similarity and observe subduction zones that are presently at different stages of their earthquake cycles. From Sumatra to Cascadia, there is a spectrum of short-term postseismic, long-term postseismic, interseismic, and perhaps pre-seismic deformations (as proposed for southern Sumatra). With proper scaling with earthquake size and careful study of site-specific effects, installation of wide-aperture, cost-effective multidisciplinary borehole monitoring systems in a few selected subduction zones may allow us to piece together the picture of a full earthquake cycle over a relatively short time period.
Chemical Data for Deep-seated Fluids in Convergent Margins

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Chemical analysis of fluids from two sealed borehole observatory (CORK) provide constraints for pressure, temperature, and chemical reactions at depth. One CORK was deployed on South Chamorro Seamount, an active serpentinite mud volcano in the Mariana forearc to explore subduction-related processes on a nonaccretionary, convergent plate margin. Formation fluid was overpressured relative to ambient hydrostatic conditions. Fluid flowed from the borehole at ~0.2 L/s when the observatory was opened to recover instruments two years after it was installed. The chemical composition of the formation fluid is similar to that extrapolated from trends in pore water data collected during Ocean Drilling Program Leg 195 when the observatory was established. Reduced sulfur is present in this highly-alkaline (pH 12.4) formation fluid, indicative of microbial activity at or below the depth of the screened casing, 149-202 m below the seafloor. Discharge from the open borehole continued for 37 days, until the observatory was resealed. This discharge requires significant permeability at depth (> 6 x 10^{-14} m^2). Zones of high permeability may be associated with the formation of headwall scarps, consistent with numerous slumps on the southeastern flank of the seamount, and likely shape a geochemical environment suitable for an active microbial community. Two other CORKS were deployed during Leg 205 of the Ocean Drilling Program (ODP). These two CORKs were drilled into active hydrologic formations on the Costa Rica margin west of the Nicoya Peninsula. One borehole penetrated through the overriding plate into the décollement at ODP Site 1255. The other borehole penetrated through the subducting sediment section and plate into permeable igneous basement at ODP Site 1253. Instruments associated with these CORKs provide a continuous record of pressure, temperature, fluid flow velocity, and fluid chemical composition within the formation. The 1.5-yr pressure and two-year temperature, fluid velocity, and fluid chemical composition records collected to date have provided a basic knowledge of formation properties, although fluids within the boreholes had yet to reach “steady state” with the surrounding formations. The data also provide evidence that tectonic forcing related to subduction results in measurable transients in pressure, temperature, fluid velocity, and fluid composition within the décollement. While the initial data provide a baseline for approaching several important scientific and technical questions, they have raised new key questions.
Opal cementation of hemipelagic sediment: influence on sediment consolidation

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Previous studies at ODP sites 1173 and 1177 offshore southern Japan within Shikoku Basin suggest that a minor amount of opal-CT cement inhibits consolidation of hemipelagic sediment approaching the Nankai Trough subduction zone. Additional ODP and DSDP sites offshore Japan (Sites 297, 442, 443, 444, 582), Alaska (178), California (Site 1020), and Guatemala (Site 495) are examined to determine if opal cementation of hemipelagic sediment is common and what affect this cement has on sediment strength and pore deformation. Within sediment from these sites, the presence of opal-CT is detected through secondary and backscattered electron (SEM and BSE) images. In SEM images, opal-CT appears as a coating at grain contacts; in BSE images it appears as cement within volcanic glass shards and zones of clastic material. The measured silica content at sites 297, 442, 443, 444, and 582 is higher within the Upper Shikoku Basin (USB) sediment than the Lower Shikoku Basin (LSB), similar to results for sites 1173 and 1177. This higher silica content supports the idea that opal-CT cementation may be a common feature throughout Shikoku Basin. Results from Alaska, California, and Guatemala sites will help determine if this cementation is common where conditions are right for triggering of opal diagenesis.
**Strain localization and fluid flow in porous sedimentary rocks**

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Recent field and laboratory studies have demonstrated that different modes of strain localization occur in porous sandstones in response to different stress conditions. Because natural environments often include preexisting heterogeneities that are reactivated during tectonic loading, different modes of strain localization coexist. Laboratory experiments on porous sedimentary rocks indicate that dilatant shear localization affects the initiation and growth of compaction localization. Specifically, under low confining pressures, stable sliding along the pre-existing fracture surface was observed. With increasing confinement, however, sliding along the fracture surface was inhibited, and compaction localization occurred in the fractured porous rocks. These compaction bands generally initiated at the fracture interface and gradually developed into a series of deformation bands along the fault. The differential stress required to initiate compaction localization in pre-fractured samples are considerably less than that in intact samples. These faulting associated compaction bands shed light on the formation of the observed “kink-bands” in the sediments from the Nankai accretionary prism [Byrne et al, 1990; Maltman et al, 1993]. The morphological and physical characteristics of the observed “kink-bands”, such as their volume loss, their association to shear bands and their orientation with respect to regional compressional stress are consistent with compaction localization in porous rocks. Because dilatant shear localization generally provides conduits that enhance pore fluid discharge, the compaction localization tends to be hydraulic barriers that significantly reduce fluid flow. The faulting associated compaction localization may provide new insights into the hydromechanical behaviors of subduction wedges.