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*Geodynamic Processes at Rifting and Subducting Margins*



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## SEISMIC IMAGING CONSTRAINTS ON MEGATHRUST FAULT ZONE PROPERTIES

Abers G., Keranen K. M., Nale S., Shillington D. J., Bécel A., Li J., Saffer D. M., Miller P.

Thrust zones must change in their material properties across both the updip and downdip limits of seismogenesis. Both fluid pressure and the nature of material within a possible subduction channel change through compaction, deformation and metamorphism. Seismic reflection data often shows a relatively thin high-reflectivity surface with occasional bright spots, indicating strong impedance contrasts over length scales of tens of meters. Coda of teleseismic P waves, or receiver functions, often shows a thin low-velocity layer atop the subducting plate. Both have been seen in sections of the Alaska subduction zone, with high-reflectivity bright spots varying in character with depth off the Alaska Peninsula and low-velocity high- $V_p/V_s$  channels imaged beneath Kenai. To understand these strong signals, we are reanalyzing these data and quantitatively modeling the velocity structures needed to produce the observations. We also measure seismic velocities from deformed metasediments exhumed from 12-15 km depth, for suitable protoliths. Those highly sheared samples show low velocities and high anisotropy, even in the absence of high porosity. Preliminary comparisons suggest that contrasts between similar fault-zone rocks and undeformed, anhydrous country rock can produce much of the observed velocity signals without requiring thick layers of high porosity.

## **GEOPHYSICAL CONSTRAINTS ON GEODYNAMICAL PROCESSES AT CONVERGENT MARGINS: A GLOBAL PERSPECTIVE**

Artemieva I.M., Thybo H., Shulgin A.

We review global geophysical data in order to illustrate the effects of the plate tectonic processes at convergent margins on the crustal and upper mantle structure and geometry of subducting slab. We present global maps of free-air and Bouguer gravity anomalies, heat flow, seismicity, seismic Vs anomalies in the upper mantle, and plate convergence rate, as well as 20 profiles across different convergent margins. A global analysis of these data for three types of convergent margins, formed by ocean-ocean, ocean-continent, and continent-continent collisions, allows us to recognize the patterns for plate convergence rate and depth distribution of seismicity versus the type of convergent margins; dip angle of the subducting slab versus the age of subducting oceanic slab and the convergence rate, as well as the [absence of] patterns for local isostasy, heat flow, and upper mantle Vs seismic velocities beneath the convergent margins.

## TWO YEARS OF DEEP SLOW SLIP IN NEW ZEALAND, IN FITS IN SPURTS

Bartlow N., Wallace L.

From early 2013 to early 2014, continuous GPS stations maintained by GeoNet in New Zealand recorded slip on the Kapiti slow slip patch of the Hikurangi subduction zone plate interface. This patch previously hosted slow slip events (SSEs) in 2003 and 2008 (Wallace and Beavan, JGR, 2010). The 2014 Kapiti SSE is unique because it was rapidly decelerated following increased normal stress (clamping) caused by a nearby M 6.3 earthquake (Wallace et al., GRL, 2014). However, GPS data indicates that slip did not stop entirely, and soon after the adjacent Manawatu slow slip patch ruptured. The Manawatu slow slip patch is directly adjacent to the Kapiti patch along strike, to the northeast. The patch previously had large SSEs in 2004/2005 and 2010/2011. Given the previous repeat interval of ~5.5 years, the currently ongoing 2014/2015 Manawatu SSE is early; however with only 3 SSEs it is difficult to tell how regular SSEs on this patch are usually. Here we show Network Inversion Filter derived models of slow slip for the various phases of the Kapiti and Manawatu SSEs, which indicate a possible continuous migration of slip from the Kapiti SSE patch to the Manawatu SSE patch.

## **RESIDUAL TOPOGRAPHY AND GRAVITY ANOMALIES REVEAL STRUCTURAL CONTROLS ON CO-SEISMIC SLIP IN THE 2011 Mw 9.0 TOHOKU-OKI EARTHQUAKE**

Bassett D., Sandwell D. T., Fialko Y., Watts A. B.

Of the five earthquakes since 1900 that had moment magnitudes ( $M_w$ )  $\geq 9$ , the March 2011 Tohoku-oki earthquake had the smallest rupture area by 50% and the largest maximum displacements by 75%. But it is not clear what physical or structural characteristics have controlled either the rupture extent or the amplitude of slip. Here we use residual topography and gravity anomalies to constrain the geological structure of the overthrusting plate in NE Japan. These data reveal an abrupt SW-NE striking forearc segment boundary, across which gravity modelling indicates a south-to-north increase in the mean density of rocks overlying the megathrust of  $\sim 150\text{-}200 \text{ kg m}^{-3}$ . We suggest this boundary represents an along-strike lithological transition between forearc segments predominantly comprised of granite-batholiths (north) and accretionary complexes (south). The megathrust north of this boundary is strongly coupled, has a history of large earthquakes and produced peak slip exceeding 40 m in the Tohoku-oki earthquake. The megathrust south of this boundary is weakly coupled, has not generated an earthquake with  $M_j \geq 7$  since 1923, and experienced relatively minor (if any) co-seismic slip in 2011. We propose that the structure and frictional properties of the overthrusting plate control megathrust coupling and seismogenic behavior in NE Japan.

## **PLATE BOUNDARY AND MAJOR FAULT SYSTEM IN THE OVERRIDING PLATE WITHIN THE SHUMAGIN GAP AT THE ALASKA-ALEUTIAN SUBDUCTION ZONE**

Bécel A., Shillington D. J., Li J., Nedimovic M. R., Abers G., Keranen K., Delescluse M., Saffer D., Webb S. C.

The Alaska-Aleutian margin is characterized by along-strike changes in plate interface coupling over relatively small distances. Here, we present trench normal multichannel seismic (MCS) profiles acquired across the Shumagin gap that has not broken in many decades and appears to be weakly coupled. The deep penetration MCS data were acquired as part of the NSF-ALEUT project. This dataset gives us critical new constraints on the interplate boundary and on the detailed upper plate fault structure and forearc morphology. Clear reflections in the overriding plate appear to delineate one or more large faults that cross the shelf and seem to branch at depth and connect to the plate interface. We compare the reflective structure of these faults to that of the plate boundary and examine where it intersects the megathrust with respect of the expected downdip limit of coupling. We also compare this major structure with the seismicity recorded in this sector. These large-scale structures imaged in the overriding plate are probably sufficiently profound to play a major role in the behavior of the megathrust in this area, segmentation of great earthquake rupture area, tsunami generation and may influence the frictional properties of the seismogenic zone at depth.

## **SOURCE PARAMETERS FOR REPEATING EARTHQUAKES ALONG THE MIDDLE AMERICA TRENCH**

Bilek S.

Repeating earthquakes, with their similar locations and similar waveforms, are often thought to represent slip along the same patch of fault. Analysis of these earthquake clusters can provide useful information about the nature of the fault and earthquake interaction. Here we focus on sequences of repeating earthquakes along both the Nicoya Peninsula, Costa Rica and along the Oaxaca segment of Mexico, as both megathrust faults have been well instrumented in recent years with local seismic networks able to record the small magnitude earthquakes. These regions have also experienced large megathrust earthquakes as well as non-volcanic tremor and slow slip, suggesting a complex fault system that allows a wide spectrum of slip. We can use source characteristics of the repeating earthquakes to probe this fault complexity. Along the Nicoya Peninsula, there are over 370 repeating earthquakes (M 0.5-3.3) in the 3 months following the 2012 Mw 7.6 megathrust earthquake grouped into 55 distinct clusters. Along Oaxaca, the earthquake clusters or swarms (M 1.5-5.5) span a wider spatial and temporal range.

## **MANTLE FLOW AND ANISOTROPY- TESTING TEXTURAL EFFECTS ON RHEOLOGY & SEISMIC STRUCTURE**

Blackman D., Boyce D., Castelnau O., Dawson P.

Observations of seismic anisotropy provide insight into mantle wedge processes at subduction zones. While other mechanisms may play a role, flow-induced alignment of minerals is considered a key link between upper mantle deformation patterns and seismic signature. In this study we consider the rheologic effects of crystal preferred orientation (CPO) that develops during mantle flow, as well as the associated anisotropic seismic signature. We employ a second-order visco-plastic self consistent method, linking these texture and viscosity solutions to an Isaiiah FEM calculation of regional flow. Asthenosphere viscosity for all iterations after the starting model, which uses scalar values, employ viscosity tensors specific to each finite element. The viscosity tensors can be anisotropic and are based on the computed response of a mineral aggregate having texture that developed along a flowline tracked from the base of the model to a given finite element. Results thus far confirm that CPO can impact flow pattern by altering rheology in directionally-dependent ways, particularly in regions of high flow gradient. Work is still underway, but results for initial cases appear to be robust; so far we have focused on flow beneath a spreading center, a subducting slab has not yet been introduced. However, the nature of the feedback between flow and CPO that we have determined should be relevant for upper mantle flow fields that are shaped by plate kinematics. We will discuss our approach, including issues that impact convergence of the model, and show results for a slow-spreading case.

## SEISMIC ANISOTROPY BENEATH THE JUAN DE FUCA PLATE SYSTEM: EVIDENCE FOR HETEROGENEOUS MANTLE FLOW

Bodmer M., Toomey D.R., Hooft E.E., Nábělek J., Braunmiller J.

Here we use SKS shear-wave splitting observations predominately from ocean-bottom seismometer data to infer patterns of mantle deformation beneath the Juan de Fuca plate and its adjoining boundaries. Our results indicate that the asthenosphere beneath the Juan de Fuca plate responds largely to absolute plate motion with an anisotropic layer developing rapidly near the ridge and persisting into the subduction zone. Geographically restricted deviations from this pattern indicate the presence of secondary processes. , rapidly developing an entrained layer which persists into the subduction zone; however, there is also evidence for a secondary process influencing the observations. At discrete plate boundaries, such as the Blanco Transform fault, seismic anisotropy is attributed to relative plate motion within a narrow zone (<50 km) . Beneath the deforming southern Gorda region — a diffuse plate boundary — the splitting observations similarly suggest deformation dominated by relative motion between the rigid Juan de Fuca and Pacific plates but distributed over a broad zone (~200 km). Our results are inconsistent with toroidal flow around the southern edge of the subducting slab due to rollback, as suggested by onshore studies. Instead, reorganization of upper mantle flow associated with plate



# **FOREARC SLOPE DEFORMATION ABOVE THE JAPAN TRENCH MEGATHRUST: IMPLICATIONS FOR SUBDUCTION EROSION**

Boston B., Moore G.F., Nakamura Y., Kodaira S.

Analysis of multichannel seismic reflection collected after the 2011 Tohoku earthquake and bathymetric data reveal the detailed structure of the overriding plate near the earthquake epicenter. Regional-residual separation of the local bathymetry helps to constrain fault scarp extents and local landward dipping forearc basins. Seismic sections also show landward dipping horizons within multiple basins indicating another deep process than only subduction erosion. A regional unconformity mapped ~150 km along-trench has a highly variable relief indicating forearc slope subsidence contains multiple wavelengths indicating multiple different stages and sources of deformation. Sediment overlying the unconformity is as great as ~3 km thick. We characterize the upper and middle slope transition and propose that this region may be the landward limit of major subduction erosion and also the main region for large mass wasting. Normal fault scarps in this region contain lateral connectivity as great as ~30 km indicating that they are not regional tectonic features. Our results provide new implications for where subduction erosion may occur and other processes affecting the Japan Trench forearc slope.

## **DOES LONG-TERM REDUCTION IN SLAB DIP BEND THE UPPER PLATE AND PRODUCE NORMAL FAULTING DURING A MEGATHRUST EARTHQUAKE?**

Buck W.R., Petersen K. D.

Unprecedented data for the Tohoku-oki earthquake suggest that the near-trench seafloor motion that produced a massively destructive tsunami was linked to normal fault offset. For the first time extensional aftershocks in a broad region of the upper plate were shown to follow a megathrust earthquake. A recently observed correlation between extensional aftershocks and production of large tsunami suggest that co-seismic extension may add to tsunami hazards in other regions. Large normal faults have been identified in the upper plate of other subduction zones, including one section of the Alaska GeoPRISMS focus area. We present numerical models showing how long-term reduction in the dip of a subduction zone can affect the deformation on the time scale of a seismic cycle. Such a dip change, that appears to have happened for the Japan Trench slab during the last few million years, can bend the upper plate and enough to cause normal faulting over a broad region. During the inter-seismic period extensional fault slip is suppressed by the relative compression of the upper plate. Models show that dynamic weakening of the megathrust can trigger a release of bending-related extensional strain energy and may produce increased near-trench deformation.

## THE WATER CONTENT OF THE JUAN DE FUCA PLATE ENTERING THE CASCADIA SUBDUCTION MARGIN

Canales J. P., Carbotte S. M., Nedimović M. R., Carton H.

At Cascadia observations interpreted as resulting from slab dehydration suggest that the Juan de Fuca (JdF) plate is significantly hydrated, contrary to predictions based on the young age and warm thermal structure of the oceanic plate. Despite its importance for understanding subduction processes beneath this region of North America, the hydrated state of the JdF plate remains unconstrained. We present water content estimates for the JdF plate prior to entering the subduction zone derived from an active-source seismic tomography profile along the Cascadia deformation front. Most of the water is stored at upper crustal levels, with variations associated with basement highs and pseudofaults. The lower crust is mostly dry (except locally at pseudofaults) offshore Washington, and its water content increases southward due to increased faulting induced by bending stresses. The upper mantle is mostly dry, with only modest amounts of waters stored within 45°-46°50'N latitude. Our results indicate that water released into the Cascadia subduction system originates predominantly in the subducted sediments and upper crustal part of the slab, with very limited oceanic mantle-derived fluids. The along-margin variations in hydration state of the JdF plate may be linked to the segmentation of some of the characteristic of the Cascadia margin.

## **BLUESCHIST BLOCKS IN THE SHALE-MATRIX MELANGE OF THE FRANCISCAN COMPLEX OF CALIFORNIA: METAMORPHIC AUREOLES AND SUBDUCTION CHANNEL UPWELLING**

Cloos M., Ukar E.

The subduction channel concept postulates that where oceanic lithosphere converges faster than ~2 cm/yr, the plate boundary is best approximated as a viscous shear zone. Channel capacity can abruptly decrease where there is a sharp increase in the pressure gradient along the top of the shear zone. Where this occurs, subducted sediment can upwell and flow back towards the inlet. The Central Belt of the Franciscan Complex is up to tens of km wide and extends from where subduction continues in Oregon to the Nacimiento Block, west of the San Andreas fault. The scaly shale matrix outcrops poorly along the 1500+ km belt because it is weakly metamorphosed (100-200°C, pumpellyite±lawsonite-bearing). The best exposures are found near San Simeon. Coarse blueschist blocks are fragments of a metamorphic aureole formed during subduction initiation that were later detached from the base of the ophiolitic leading edge of the North American plate. Later, tectonic melange was generated by subduction-driven shearing that caused upwelling of shale-rich sediment. Slabs of blueschist were boudinaged and mixed with fragments of greenstone and chert detached from seamounts. Blueschist block incorporation into upwelling melange is a kind of subduction erosion akin to plucking by glaciers.

## **3-D MANTLE FLOW AND CRUSTAL PRODUCTION ALONG THE LAU BACK-ARC SPREADING CENTER**

Tarlow S., \*Conder J. A.

Geochemical and geophysical studies show a decrease in subduction enhanced melting moving north along the backarc spreading centers near Tonga with a rapid stepwise decrease in subduction influence and melt production as the spreading center axis sweeps away from the volcanic arc. Furthermore, the Eastern Lau Spreading Center (ELSC) has an anomalously thin crust and subdued morphology while Valu Fa (VF) near the southern end of the system exhibits much thicker crust and an axial high despite spreading at half the rate of ELSC. Implementing 3-D numerical experiments of mantle flow and hydration show that including a viscosity reduction in the mantle wedge due to slab hydration is key to understanding the observed ELSC thinner crust, while the hydration increase in melting accounts for the thick VF crust. The low viscosity region results in a “saddle” shaped decrease in relative melting north of 20.9°S. This saddle structure derives from a reversal in along axis flow towards the southeast. Warmer mantle is drawn from below the ELSC into the lower viscosity region beneath VF, accounting for the thin crust observed at the ELSC.

\* *Presenter*

## **SEDIMENT PATHWAYS ACROSS TRENCH SLOPES: RESULTS FROM NUMERICAL MODELING**

Cormier M. H., Fujiwara T., Seeber L., McHugh C., Kanamatsu T., King J. W.

Until the 2011 Mw9.0 Tohoku earthquake, the role of giant tsunamis and earthquakes as agents of sediment dispersal and accumulation at erosional trenches was largely under-appreciated. Decades of seismic reflection surveys and sediment coring did document a general sedimentation pattern. Terrigenous sediments accumulate across the trench slope as a relatively thin slope apron, whereas sediments at the trench axis are either accreted to the small frontal wedge, or subducted. A series of cruises carried out after the 2011 earthquake and tsunami revealed a variety of unexpected sediment dispersal mechanisms, such as tsunami-triggered sheet turbidites. The combined dataset suggests that giant earthquakes and tsunamis may be important agents for dispersing sediments across the trench slope. To complement these new observational data, we have calculated the theoretical pathways of sediments across the trench slope using existing multibeam bathymetric grids, and further applied the same modeling technique to the Cascadia, Nankai, Costa Rica, and Sumatra trenches. Pathways are modeled based on the simple assumption that transport direction is dictated by the slope azimuth. Preliminary results highlight the varying “personalities” of each trench, but commonalities as well.

## **VOLCANIC TO PLUTONIC TRANSITION IN THE CRETACEOUS ALISITOS ARC, BAJA MEXICO, AN OUTSTANDING FIELD ANALOG TO THE IZU BONIN ARC**

DeBari S., Morris R., Busby C., Medynski S.

Exposed paleo-arcs provide an opportunity to explore the evolution of arc crust through time. Remarkable 3-D exposures of the Alisitos Arc record crustal generation processes in the volcanic rocks and underlying plutonic rocks. We explore the physical and geochemical connection between the plutonic and volcanic sections of this arc, and elucidate differentiation processes responsible for generating them. These results provide an outstanding analog for extensional active arc systems, such as the Izu-Bonin-Mariana (IBM) Arc.

Upper crustal volcanic rocks have a coherent stratigraphy that is 3-5 km thick and ranges in composition from basalt to dacite. The transition to deeper plutonic rocks is clearly an intrusive boundary, where plutonic units intrude the volcanic units. Most, but not all, samples are low K. REE patterns are relatively flat with limited enrichment. Plutonic and volcanic units have similar geochemical relationships, where liquid lines of descent show the evolution of least to most evolved magma types.

We are currently investigating the geochemical chemical variations that accompanies the transition of this arc from an extensional phase (dominantly intermediate compositions) to a rifting phase (bimodal basaltic to rhyolitic compositions) and how that affected the depth and characteristics of this volcanic-plutonic transition.

# TEMPORAL VARIATIONS OF INTERMEDIATE-DEPTH INTRAPLATE EARTHQUAKE ACTIVITY FOLLOWING THE 2011 TOHOKU-OKI EARTHQUAKE

Delbridge, B., Bürgmann, R., Kita, S., Matsuzawa T.

In this study we examine the temporal changes of intraplate earthquake activity following the 2011 Mw 9.0 Tohoku-oki earthquake. Due to the large rupture area and displacement of the Mw 9.0 thrust event, we expect that the stress changes within the slab from the coseismic displacement and postseismic changes in stressing rate due to mantle relaxation and afterslip could be comparable with those from slab pull and bending. Consequently, we examine if the intermediate-depth earthquakes down plate from the locked region reflect the stress change from the slab decoupling and corresponding postseismic processes. Capitalizing on insights into the large-scale and long-term behavior of deformation in subduction zones using models of thin sheets, we quantify the effect of slab bending on subduction zone seismogenesis. We combine laboratory-based rheological models, precise estimates of slab shape from relocated earthquake hypocenters, estimates of the state of stress in the plate from intraplate focal mechanisms, and response to the 2011 Tohoku-Oki earthquake to provide constraints and insights for intraplate subduction zone seismogenesis.



## **PHYSICS OF SHALLOW EARTHQUAKES IN SUBDUCTION ZONES**

Denolle M. A., Shearer P. M., Day S. M.

Shallow earthquakes in subduction zones are direct seismic and tsunami hazards to nearby populations. Due to the scarcity of instruments near the trench for most subduction zones, seismologists have to rely on earthquake records at teleseismic distances to construct a global view of earthquake dynamics in subduction zones. The Earth's free surface affects the propagation of earthquake ruptures and the excitation of seismic waves. We aim to extract accurate and unbiased measures of earthquake dynamics (e.g., stress drop and radiated energy) from seismic waves. We develop new empirical tools to use full seismic waveforms (body waves and surface waves) to remove global wave propagation effects and describe new theoretical tools to extract earthquake rupture information using numerical simulations. Using these methods, we estimate stress drop and radiated energy using teleseismic P waves for earthquakes of magnitudes M5.5 to M8 along subduction zones.

## **SSEs IN NEW ZEALAND AND CASCADIA OVER THE LAST 6.5 YRS**

Dimitrova L. L., Wallace L. M., Haines A. J., Bartlow N., Willaims C. A.

Slow slip events are now recognized as a major player in the accommodation of plate motion at subduction margins. We extend a new method of determining Vertical Derivatives of Horizontal Stress (VDoHS) rates (Haines et al. in press) to cGPS time series data to detect and characterize SSEs at high spatial and temporal resolution over the last 6.5 yrs in Cascadia and New Zealand. For selected events we compare our results with those from the Network Inversion Filter. Our results show that some SSEs may have started earlier than previously detected. We identify and characterize a spectrum of SSEs with varying sizes including a smaller (~1 mm surface displacement) event from June 29-July 7 in southern Cascadia, which had not been identified previously. This demonstrates that our new method lowers the threshold of geodetically detectable SSEs. VDoHS rates also reveal the boundaries between the locked and unlocked portions of the megathrust. For example, in Cascadia sections of the thrust interface unlock prior to some SSEs and lock thereafter, with the locked zone propagating downdip and eastward after the SSEs over weeks to months.

## **DEFORMATION WITHIN THE SUBDUCTED NAZCA SLAB FROM SEISMIC ANISOTROPY**

Eakin C., Long, M.D., Scire, A., Beck, S.L., Wagner, L.S., Zandt, G., Tavera, H.

Seismic anisotropy is a useful tool for investigating the dynamics of subduction zones. It has proven difficult, however, to observe the anisotropic properties of the subducted slab itself with traditional techniques. Here we analyze shear wave splitting of local and teleseismic S phases from earthquakes beneath Peru for a set of raypaths that have long path lengths in the Nazca slab. Both source-side and local S measurements exhibit similar and substantial delay times ( $\sim 1.4$  s), with fast directions sub-parallel to the local slab contours. Modeling of fossil olivine fabric from seafloor spreading preserved within the slab cannot reproduce the observations. Instead, a search for the orientation of olivine LPO that provides the best fit to the data yields fast axes parallel to the slab strike. This suggests modification of the internal slab anisotropy consistent with along-strike extension induced by the regional flat-slab morphology. Our observations place important new constraints on the deformation and rheology of the subducting Nazca slab.

## **RECORD OF SUBDUCTING TOPOGRAPHY REVEALED IN 3D SEISMIC IMAGING OF PLEISTOCENE UNCONFORMITIES, OFFSHORE SOUTHERN COSTA RICA**

Edwards J., Kluesner J., Silver E.

3D seismic reflection data (CRISP) collected across the southern Costa Rica forearc reveals broad, survey-wide erosional events in the upper ~1 km of slope sediments in the mid-slope to outer shelf. The upper 0-280 m of continuous, weakly deformed sediments, designated by IODP Expedition 344 as structural domain I, is bounded by a major erosional event, (CRISP-U1, dated near 1 Ma), suggesting wave-plain erosion from the present shelf break out to 25 km seaward, to a present-day water depth of 900-1300 m. The eastern toe of its surface is characterized by a large drainage system, likely including submarine channels that eroded to depths >1500 m below present-day water depth. CRISP-U1 is variably uplifted by a series of fault propagation folds and cut by an intersecting array of normal faults. Another, major erosional event, (CRISP-M1, approximately 2 Ma) extended from the outer shelf to the mid slope and removed 500-1000 m of material. Overlying CRISP-M1 is up to 1 km of sediments that are more deformed by fault propagation folds, back thrusts, and intersecting arrays of normal faults. Unconformities with smaller areal extent are variably found in these overlying sediments across the mid-slope to outer shelf, at present-day water depths >220.

## **MECHANICS OF THE HIKURANGI MEGATHRUST: NUMERICAL EXPERIMENTS INFORMED BY WEDGE RECONSTRUCTIONS AND AN EXHUMED SUBDUCTION MELANGE**

Ellis S., Ghisetti F., Barnes P., Webber S., Reyes A., Fagereng A., Barker D., Henrys S., Wallace L., Harris R.

GPS data show that the shallow part of the northern Hikurangi subduction thrust fault is creeping, while the southern segment is locked to greater depths and appears capable of producing great earthquakes. Wedge morphology and deformation also change along-strike, with a wide accretionary imbricate wedge in southern and central Hikurangi transitioning to a non-accreting, steep wedge in the north that experiences periodic subduction erosion from seamount subduction. We use wedge structure from depth-converted seismic sections restored to 2 Ma as an initial condition for forward modelling. We compute fluid release from porosity loss as sediment enters the margin to calculate fluid pressure evolution and its influence on effective stresses and permeabilities, and test the range in décollement friction and fluid overpressure compatible with wedge deformation over the last 2 M.y. Results show how the along-strike change in wedge morphology is influenced by the rougher incoming plate in the north and does not necessarily indicate a stronger décollement there. The central and southern Hikurangi accretionary wedges approximate growth of a critical wedge geometry, while northern Hikurangi margin morphology episodically cycles as seamounts enter the margin.

Both northern and southern Hikurangi wedge evolution requires a low-strength décollement consistent with weak clay minerals and/or moderately high fluid overpressure. The subduction of seamounts in the north allows a thick package of sediment to subduct to depth, which we argue enhances disruption of bedding and formation of melange structures there. Melange rheology constrained by an exhumed subduction complex at Chrystalls Beach, New Zealand is used to investigate megathrust stress and slip cycling. We model a two-phase mélange dominated by large, competent brittle-viscous blocks surrounded by a weak non-linear viscous matrix. Stress cycling is accompanied by mixed brittle plastic-viscous deformation, and occurs as a consequence of geometric reorganisation and the progressive development and breakdown of stress bridges as blocks mutually obstruct one another.

## **TRENCH OUTER RISE FLEXURE MODELS WITH LATERALLY VARIABLE PLATE RIGIDITY DERIVED FROM OCEANIC LITHOSPHERE STRENGTH PROFILES**

Garcia E.S., Sandwell D. T., Bassett D. G.

We generated model bathymetry and free-air gravity grids for the seafloor seaward of subduction zones that capture the broad trends of deformation due to lithospheric flexure. By using a thin elastic plate formulation with rigidity variations along both horizontal dimensions and incorporating the effects of plastic yielding, our models are able to reproduce the observed rapid change in curvature at the outer trench wall. Forward models for flexural deflection and plate rigidity are fitted to satellite altimetry-derived marine gravity anomalies jointly with shipboard bathymetry. The estimated parameters are the applied vertical shear and bending moment at the trench axis. Short-wavelength features in the gravity and bathymetry data such as seamounts are isolated using a directional median filter and then excluded from the parameter estimation process. Preliminary results from regions across the Pacific Rim, including the Aleutian Trench, show that the plate rigidity progressively decreases with increasing proximity to the trench axis. These zones of plate weakening correspond to the occurrence of trench-parallel seafloor fractures at the outer trench wall as seen in high-resolution bathymetry data. We are interested in whether a correlation exists between the distribution of these fractures and the trend in the rigidity decrease of the incoming plate.

## **MAGMA MIXING AND DEGASSING PROCESSES IN THE MAGMA CHAMBER OF GORELY VOLCANO (KAMCHATKA): EVIDENCE FROM WHOLE-ROCK AND OLIVINE CHEMISTRY**

Gavrilenko M., Ozerov A., Nikulin A.,

Gorely is a shield-like volcano in southern Kamchatka currently in an eruptive phase. It is comprised of three main structural units: ancient (middle Pleistocene) edifice called 'Old-Gorely' volcano; thick ignimbrite complex, associated with a caldera forming eruption (40 ka); modern edifice named 'Young Gorely' growing inside the caldera. Gorely lavas consist of a suite of compositions ranging from basalt to rhyolite (calc-alkaline series). In this study we describe the mixing processes in magma chamber based on analysis of whole-rock and mineralogical data in an attempt to compare the magma evolution pathways for 'Old Gorely' and Young Gorely volcanoes. Our results indicate that fractional crystallization (FC) is the dominant process for 'Old Gorely' magmas, while 'Young Gorely' magmas are the result of mixing of primitive and evolved magmas in Gorely magma chamber.

We present results of olivine high-precision electron microprobe data analysis, alongside traditional methods (WR diagrams, mineral zonation) to demonstrate the difference between 'Old' (FC) and 'Young' (mixing) Gorely magmas. We estimated magma H<sub>2</sub>O (3%) content for Gorely magma using independent methods. We show that degassing (H<sub>2</sub>O removal) is necessary for strong plagioclase fractionation, which is observed in Gorely evolved lavas.

## **SEDIMENT MELT AT THE EDGES OF THE AEOLIAN ARC: IMPLICATIONS FOR HOT SUBDUCTION ZONE MODELS**

Gazel E., Zamboni D., Cannatelli C., Atlas Z. D., Lucchi F., Trela J., Mazza S. E., De Vivo B., Ryan J. G.

Our recent work using light elements (Be, B, Li, As) together with other trace elements and radiogenic isotopes in the Aeolian Arc, Italy, provides new evidence to discriminate between fluid vs melt components in this arc. B, Li, and As are strongly fluid-mobile elements, enriched in altered oceanic crust and seafloor sediments while Be is a melt mobile element, highly concentrated in seafloor sediments. We found enrichments in B increasing from the western segment of the arc to the eastern, with the highest B content in Stromboli, while Be content significantly increases towards the margins of the arc. We also noted similarities in subducting components between the Aeolian Archipelago and other volcanic arcs/arc segments around the world (e.g., Sunda, Cascades, Mexico, and Phlegrean Volcanic Province) where the signature of a melt component is also evident. We suggest that the melt components in all these locations resulted from an increase in the mantle wedge temperature by inflow of asthenospheric material that allowed sediment melts. from tears/windows in the slab or from around the edges of the sinking, rolling-back slab. These processes, rather than just the age of the subducting slab, could explain the temperature conditions recorded on subduction-channel related terranes.



## **VoiLA: VOLATILE RECYCLING AT THE LESSER ANTILLES ARC**

Goes S., Blundy J., Collier J., Davidson J., Henstock T., Harmon N., Macpherson C., Rietbrock A., Rychert K., van Hunen J., Wilkinson J., Wilson M.

In the VoiLA project, we target the Lesser Antilles Arc, one of only two zones that subducts lithosphere formed at the slowly spreading Mid-Atlantic Ridge. Atlantic lithosphere is more hydrated, especially in the mantle part, than lithosphere consumed at Pacific and Indian Ocean trenches, making it a key endmember to advance understanding. In 5 project components, we will test

- (1) where volatiles are held within the incoming plate;
- (2) where they are transported and released below the arc;
- (3) how the volatile distribution and pathways relate to the construction of the arc; and
- (4) their relationship to seismic and volcanic hazards and the fractionation of economic metals.

Finally, (5) the behaviour of the Lesser Antilles arc will be compared with that of other well-studied systems to improve our wider understanding of the role of water in subduction processes.

To address these questions we will conduct an active seismic experiment on the incoming plate, a passive seismic experiment across the fore- and back-arc regions of the Lesser Antilles, geochemical and petrological analyses of magmas and cumulates from samples along the arc, and numerical modelling of slab-wedge dynamics and its consequences on dehydration and melting.

## **PRELIMINARY RESULTS FROM NSF SHARED PLATFORM R/V MARITIME MAID 2015 LEG 3: WESTERN ALEUTIANS**

Grant E. R., Kelley K. A., Cottrell E., Coombs M., Pistone M., Sheppard K., Jackson M.

Among the characteristics shared by arc magmas and continental crust is calc-alkaline affinity, an early decrease in magmatic Fe concentration. Our work aims to address how subduction zone magmas acquire calc-alkaline affinity, with particular focus on the roles of magmatic H<sub>2</sub>O and  $fO_2$  in influencing magmatic chemico-physical differentiation. Here we report on preliminary results from a field campaign aboard the R/V Maritime Maid, part of the NSF-funded Shared Platform for Aleutians research for the 2015 field season. This September our cruise will sample the Western Aleutian Islands of Buldir, Kiska, Segula, Little Sitkin, Semisopochnoi, Gareloi, Tanaga and Kanaga, which compositionally range from mildly tholeiitic to strongly calc-alkaline, providing an ideal suite of samples to constrain magmatic evolution as a function of H<sub>2</sub>O and  $fO_2$ . Ultimately, we will use melt inclusions from collected tephra samples to assess mantle conditions, primary/parental magma compositions, and magmatic evolution as a function of water content and oxygen fugacity.

## **THE 2009 REDOUBT ERUPTION OBSERVED WITH GPS: ASEISMIC INFLATION, MID-CRUSTAL REMOBILIZATION AND NET-DEFLATION**

Grapenthin R., Freymueller J.

The 2009 eruption of Redoubt Volcano, Alaska, was observed by a mix of 14 continuous, temporary continuous and campaign GPS sites. Data from a single continuous site 28 km NE of the volcano reveals subtle pre-eruptive motion radially outward from the volcano beginning as early as May 2008, which reversed with the onset of explosive activity. We link the precursory activity to a point source intrusion at ~13.5 km below sea level (bsl). During the explosive phase about 0.05 km<sup>3</sup> of magma were evacuated from a prolate spheroid with its centroid at ~9 km bsl. The final effusive activity is inferred to come from the same source, decreasing in volume by about 0.01-0.02 km<sup>3</sup>. We hypothesize a mid-crustal two reservoir system with magma from >20 km flowing in at about 13.5 km depth and reheating residual material in the proposed spheroid. The mixture migrated to shallower depth (2-4.5 km bsl) and reheated material there. As this residual magma erupted, it was replaced with material from the deeper source, rendering the shallow source undetectable for geodetic instruments.

## DEEP LONG-PERIOD EARTHQUAKES (DLPs) BENEATH MOUNT ST. HELENS

Han J., Vidale J. E.

The volcanic deep long-period earthquakes (DLPs), located at the mid- to lower-crust and/or uppermost mantle, have been observed for a long time but remain poorly understood. Hypotheses associated with magmatic process have been proposed for the mechanisms of these DLPs, including dehydration embrittlement, flow of magma and/or magmatic fluid and cooling of magma.

We use seismic data from iMUSH (imaging Magma Under St Helens) and nearby network to study the DLPs beneath Mount St. Helens. Catalog DLPs are taken as templates to search for repeating events that might be too small to be detected otherwise. So far, we have found 399 repetitions, with only 13 events already in the catalog.

Overall the detected DLPs show an episodic activity with a period of roughly fourteen months. Several, but not all, episodes are temporally correlated with the subduction zone tremor activity west of St. Helens. Also, these DLPs show a plausible temporal connection with seismicity at the shallow conduit.

We are investigating the spatial and temporal relation between subduction zone tremor, DLPs and shallow seismicity, expect some hints for the dynamic process of the volcanic system from the deep to the shallow.

## SEISMIC REFLECTION IMAGING OF THE JUAN DE FUCA PLATE PRIOR TO SUBDUCTION

Han S., Carbotte S.M., Canales J.P., Nedimović M., Carton H., Gibson J., Horning G.

We present pre-stack time migrated multi-channel seismic images of two cross-plate transects extending from the Juan de Fuca (JdF) Ridge to the deformation front (DF) of Cascadia Subduction Zone offshore Oregon at 44.6°N and Washington at 47.4°N, and one ~400 km long trench-parallel transect to study crustal structure, extent of faulting and associated hydration of the JdF plate prior to subduction. We observe numerous small offset faults within the sediment section in the plate interior beginning 50-70 km from the ridge axis. On the Oregon transect within 40 km from the DF, fault offset increases markedly, accompanied with bright fault plane reflections that cut through the crust and extend 6-7 km into the mantle. On the Washington transect, a small increase in fault offset and faint fault plane reflections confined to the upper-middle crust are imaged near the DF. The trench-parallel transect also show deeper-penetrating crustal reflections offshore Oregon than offshore Washington. We attribute the more extensive faulting and potentially more hydration of the JdF plate offshore Oregon than Washington to greater subduction bending. This regional difference in bending faulting is inconsistent with the spatial distribution of intermediate-depth intraslab seismicity at Cascadia.

## **HYDROGEOLOGICAL AND SEISMIC RESPONSES TO INCOMING MATERIALS AT THE NON-ACCRETING SUBDUCTION MARGIN, OFFSHORE OSA PENINSULA, COSTA RICA**

Harris R., Kameda, Shimizu, Ujiie, Tsutsumi, Ikehara, Uno et al.

Dehydration models of the incoming sediments at the Costa Rica Seismogenesis Project (CRISP) reference site (Integrated Ocean Drilling Program Expedition 334 Site U1381) show peak dehydration landward of the updip limit of seismicity (Arroyo et al., 2014). We estimate the incoming fluid budget using porosity and bulk mineral assemblage. The porosity combined with the water content in smectite and biogenic silica, leads to a total sedimentary water influx estimate of  $6.9 \text{ m}^3/\text{yr}$  per m of trench length. The dehydration source term is calculated with respect to silica and clay diagenesis. Sediment temperatures are based on 2D numerical models. Models suggest peak mineral dehydration occurs at temperatures of approximately  $\sim 100 \text{ }^\circ\text{C}$ , 40-30 km landward of the trench and 5-10 km landward of the shallowest seismicity. These results suggest that in this region the presence of subducting bathymetric relief capped by velocity weakening nanofossil chalk is more important in influencing the updip extent of seismicity than the thermal regime. This interpretation is consistent with the observed patchy seismicity. Our results emphasize the importance of frictional heterogeneities along the subduction thrust and may be more pronounced at margins where the incoming sediment thickness is small relative to the size of bathymetric relief.

## THE ROLE OF PLATEAU COLLISION-SUBDUCTION ON OVERRIDING PLATE DEFORMATION IN ALASKA

Haynie K., Jadamec M.

Properties of subducting slabs can have a first order control on the surface deformation of overriding plates. For example, when oceanic plateaus subduct beneath continental lithosphere, increased interplate coupling may cause an increase in uplift accompanied by deformation further inland. The Pacific-North American plate boundary in south-central Alaska is characterized by flat slab subduction where the Yakutat plateau is currently colliding and subducting. However, the lateral extent and three-dimensional (3D) configuration of this oceanic plateau are not well understood due to a lack of constraints at depth on the plateau's subducted morphology. Previous 3D geodynamic models using the modern flat slab shape can explain the first order features in south-central Alaska, but the models over-predict subsidence where the center of the subducted plateau is expected to reside and predict only a limited amount of deformation in the interior. As a first step in understanding the dynamics of plateau subduction in Alaska, a set of two-dimensional (2D) geodynamic models investigating the role of slab dip on dynamic topography are analyzed. In addition, a 3D Yakutat configuration and 2D gravity models are examined in order to constrain thickness, density, and geometry of the plateau, which are critical parameters in understanding plateau subduction.

## **MAGMA DIFFERENTIATION PROCESSES THAT DEVELOP AN “ENRICHED” SIGNATURE IN THE IZU BONIN REAR ARC: EVIDENCE FROM IODP SITE 1437**

Heywood L., DeBari S., Schindlbeck J., Escobar R.

The Izu Bonin rear arc represents a unique laboratory to study the development of continental crust precursors at an intraoceanic subduction zone. In the Izu Bonin rear arc, volcanic output is compositionally distinct from the Izu Bonin main volcanic front, with med- to high-K and LREE-enrichment similar to the average composition of the continental crust. Drilling at IODP Site U1437 in the Izu Bonin rear arc obtained volcanoclastic material that was deposited from at least 13.5 Ma to modern day. This study presents fresh glass and mineral compositions (obtained via EMP and LA-ICP-MS) from unaltered tephra layers in mud/mudstone (Lithostratigraphic Unit I) and lapillistone (Lithostratigraphic Unit II) <4.5 Ma to examine the geochemical signature of Izu Bonin rear arc magmas. Unit II samples are coarse-grained tephra that are mainly rhyolite (72.1-77.5 wt. % SiO<sub>2</sub>, 3.2-3.9 wt. % K<sub>2</sub>O and average Mg#24) and LREE-enriched. Rear-arc rhyolite trace element signature is distinct from felsic magmas from the Izu Bonin main volcanic front, but has similar trace element ratios to rhyolites from the adjacent but younger backarc knolls and actively-extending rift regions. Given these unique characteristics, we explore models for felsic magma formation and intracrustal differentiation in the Izu Bonin rear arc.



## THREE-DIMENSIONAL UPPER MANTLE RHEOLOGY: FROM SUBDUCTION ZONE AND BEYOND

Hu Y., Bürgmann R., Freymueller J. T., Banerjee P., Wang K.

The well-recorded viscoelastic postseismic deformation of great earthquakes in the last two decades help us better constrain the three-dimensional (3D) heterogeneity of the upper mantle rheology. We have analyzed the GPS time series of the postseismic deformation of three great earthquakes, the 2002 Mw7.9 Denali, 2011 Mw9.0 Tohoku and 2012 Mw8.6 Indian Ocean earthquakes, that occurred within the continental crust, over the megathrust and within the oceanic crust, respectively. We have developed 3D viscoelastic finite element models to study the rheology heterogeneity of the upper mantle that is represented by the bi-viscous Burgers rheology. We assume that the transient Kelvin viscosity is one order of magnitude lower than that of the steady-state Maxwell viscosity. Our model have determined the Maxwell viscosity of the mantle wedge to be at the order of  $3 \times 10^{19}$  Pa s. Tests of the 2002 earthquake indicate that the viscosity of the upper mantle beneath the stable continental plate is about one order of magnitude higher than that of the mantle wedge. A 30 km oceanic asthenosphere with a low viscosity of  $\sim 5 \times 10^{17}$  Pa s and the oceanic mantle of  $\sim 10^{21}$  Pa s are required to reproduce the observed postseismic deformation of the 2012 earthquake.

## **ELASTIC PROPERTIES OF SUBDUCTION ZONE MATERIALS IN THE LARGE SHALLOW SLIP ENVIRONMENT FOR THE TOHOKU 2011 EARTHQUAKE: IMPLICATIONS OF A COMPLIANT WEDGE ON EARTHQUAKE RUPTURE AND TSUNAMIGENESIS**

Jeppson T. N., Lotto G. C., Tobin H. J., Dunham E. M.

The 11 March 2011 Tohoku earthquake ruptured through the shallowest part of the subduction zone, producing tens of meters of displacement at the seafloor and a devastating tsunami. Because elastic and mechanical properties of faults and wallrocks are controlling factors in earthquake generation and propagation, an understanding of these properties is essential to understanding and accurately modeling earthquake rupture. Laboratory ultrasonic velocity measurements for samples of rock surrounding the Tohoku earthquake principal fault zone recovered by drilling during IODP Expedition 343 (JFAST) have shown that materials in the frontal prism have P-wave velocities of 2.0-2.4 km/s, S-wave velocities of 0.7-1.0 km/s, and rigidities ranging from 1.0-2.2 GPa. In order to better understand the elastic properties of shallow subduction zone sediments, our measurements from the Japan Trench are compared to similar shallow drill core samples from other subduction zones. We find that shallow subduction zone sediments in general have low rigidity. We present a model of the rigidity of the Japan Trench based on laboratory and field measurements that can be used in dynamic rupture models of the megathrust. Preliminary results indicate that the presence of low rigidity materials off-fault lead to greatly increased slip velocity, slip, and seafloor deformation.

## USING U-SERIES ISOTOPES TO INVESTIGATE THE EFFECTS OF THICK CONTINENTAL CRUST ON ARC VOLCANICS

Kant L. B., Sims K. W. W., Matthews T. P., Scott S. R., Garrison J. M., Blichert-Toft J., Yogodzinski G. M., Reagan M. R., Hidalgo S., Mothes P. A., Hall M.

In continental back arcs, magma storage in the crust can significantly influence lava compositions. To test the hypothesis that in continental back arc settings melts stall at the crust-mantle boundary and/or in shallower magma plumbing systems over time periods long enough to produce changes in the U-series isotopes, we have measured U-series, Nd, Sr, Hf and Pb isotopes and major and trace element concentrations in 17 historic samples and 6 unknown age samples from Reventador, a back-arc volcano, in the northern volcanic zone (NVZ) of Ecuador.

Nd, Hf and Sr isotopes show that Reventador has one of the most crustal signatures of the NVZ. Ten samples have  $(^{230}\text{Th}/^{238}\text{U}) > 1$  suggesting deep melting with residual garnet. Three samples have  $^{238}\text{U}$  excesses, and overall  $(^{230}\text{Th}/^{238}\text{U})$  is well correlated with fluid mobile trace elements suggesting the influence of a fluid component. Known age samples have  $(^{226}\text{Ra}/^{230}\text{Th}) > 1$ . Although fluid addition is often invoked to explain Ra excesses in arcs, the lack of correlation between  $(^{226}\text{Ra}/^{230}\text{Th})$  and measures of fluid addition make this unlikely at Reventador. Instead we suggest that complex crustal processing developed Ra excesses.  $(^{210}\text{Pb}/^{226}\text{Ra}) > 1$  for all historical age samples, suggesting magma was stored in a shallow chamber undergoing Rn degassing.

## **ROLE OF THE SUBDUCTION FILTER IN ARC MAGMA GENESIS AND MANTLE RECYCLING**

Kimura J. -I., Gill J. B., Skora S., van Keken P. E.

Subduction modifies the descending basaltic and sedimentary oceanic crust and generates arc magmas and continental crust. Studies of element mass balances in the subduction zone therefore reveal the evolution of the Earth's two major geochemical reservoirs: the continental crust and mantle. We use the Arc Basalt Simulator ver.4 (ABS4) to model the geochemical mass balance during dehydration by prograde metamorphism and melting of the slab followed by subsequent flux melting of the wedge mantle caused by the addition of slab-derived liquids. The geochemistry of high-Mg andesite or adakite formed in a hot subduction zone is akin to the present-day bulk continental crust and to the Archean (>2 Ga) Tonalite-Trondjemite-Granodiorite composition. Therefore, the residual slab and the metasomatized mantle wedge at hot subduction zones should be the most plausible sources for materials recycled back into the deep mantle. Model calculations of isotopic growth in the residual slab and mantle formed in hot subduction zones reproduce fairly well the EM2-EM1-FOZO-HIMU isotope arrays found in ocean island basalts of deep mantle plume origin, although FOZO with high  $^3\text{He}/^4\text{He}$  is not generated by this slab recycling process. Subduction filter is thus the key process to understand growth of the Earth's crust and mantle.

## **MAGMA RESERVOIRS FROM THE UPPER CRUST TO THE MOHO INFERRED FROM HIGH-RESOLUTION $V_p$ AND $V_s$ MODELS BENEATH MOUNT ST. HELENS**

Kiser E., Levander A., Palomeras I., Zelt C., Harder S., Schmandt B., Hansen S., Creager K., Ulberg C.

Here we present the first high-resolution 2D  $V_p$  and  $V_s$  models derived from travel-time data from the iMUSH (imaging Magma Under St. Helens) 3D active-source seismic experiment. Directly beneath Mount St. Helens we observe a high  $V_p/V_s$  body, inferred to be the upper/middle crustal magma reservoir, between 4 and 13 km depth. Southeast of this body is a low  $V_p$  column extending from the Moho to approximately 15 km depth. A cluster of low frequency events, typically associated with injection of magma, occurs at the northwestern boundary of this low  $V_p$  column.

Outside of the inferred magma bodies that feed Mount St. Helens, we observe several other interesting velocity anomalies. In the lower crust, high  $V_p$  features bound the low  $V_p$  column. One explanation for these features is the presence of lower crustal cumulates associated with Tertiary ancestral Cascade volcanism. In addition, a low  $V_p$  channel northeast of Mount St. Helens between 14 and 18 km depth correlates well with the location of the Southern Washington Cascades Conductor. This body has been hypothesized to be a broad region of partial melt in the middle and lower crust.

## **IN-SITU STRESS, ROCK STRENGTH, AND FAULT RHEOLOGY AT THE NANKAI SUBDUCTION ZONE: INSIGHT FROM LABORATORY EXPERIMENTS**

Kitajima H.

Investigation of in-situ stress, absolute fault strength and fault rheology is crucial for understanding the wide spectrum of fault slip behaviors observed in plate boundary faults in subduction zones. I present the results of laboratory experimental studies on modern clay-rich sediments subducting at the Nankai Trough to constrain in-situ stress, porosity, rock strength and fault rheology in the Nankai subduction zone. Based on uniaxial and triaxial experiments on mudstones, combined with seismic velocity data from geophysical surveys in the Nankai Trough, porosity along the plate boundary decreases from ~40% at the trench, to ~5% at 50 km from the trench (~8 km depth), and in-situ pore pressure increases from hydrostatic at the trench to ~80% of lithostatic pressure at 50 km from the trench (~8 km depth) due to the effects of horizontal tectonic loading. The experimental results also suggest that as the clay-rich sediments subduct, their deformation behavior will transit from ductile to brittle and their strength of the clay-rich sediments will increase but not as high as that of sandstones or carbonates.

## **SEISMOLOGICAL STUDY IN THE NORTHWESTERN PACIFIC SUBDUCTION ZONE; FROM OUTER-RISE TO BACK-ARC BASIN**

Kodaira S., Nakamura Y., Fujie G., ObanaK., Miura S.

In this poster, we summarize geophysical and geological projects we have been carrying out in the southern Kuril Trench, the Japan Trench, the Nankai Trough, the Ryukyu trench, the Izu-Bonin Trench, the Japan Sea back-arc and the Okinawa Trough back-arc basin. In particular, we will focus on results of active-passive seismic studies around the fault zone of the 2011 Tohoku earthquake.

## **STRUCTURE AND DYNAMICS OF THE PERUVIAN FLAT SLAB: RESULTS FROM THE PULSE EXPERIMENT**

Long M. D., Wagner L., Beck S., Tavera H., Eakin C., Knezevic Antonijevic S., Kumar A., Scire A., Bishop B.

The Peruvian flat slab is the largest region of flat slab subduction in the world today, but many aspects of its structure, dynamics, and evolution remain poorly understood. Between 2010 and 2013, we deployed 40 broadband seismic stations over the southern portion of the Peruvian flat slab as the PerU Lithosphere and Slab Experiment (PULSE). Analysis of these data using techniques such as shear wave splitting, body and surface wave tomography, receiver functions, and earthquake hypocenter and focal mechanism determinations are shedding light on how flat slabs form and evolve through time.



## **PROBING SUB-SLAB ANISOTROPY BENEATH CENTRAL AMERICA AND TONGA USING GEODYNAMIC MODELS**

Lynner C., Long M. D.

A number of conceptual models have been proposed to explain trench parallel shear wave splitting observations beneath subducting slabs. Recently, Lynner and Long [2014] tested several of these conceptual models against a quasi-global source-side shear wave splitting dataset and found that a model in which sub-slab dynamics varies with the age of the down-going plate best matches the observations. A major limitation of that study, however, was the employment of very simplified dynamics; especially in cases that invoked 3-dimensional return flow. Here, we examine sub-slab shear wave splitting patterns from geodynamic models aimed at mimicking real world subduction beneath Central American and Tonga; which exhibit entrained and 3D return flow patterns, respectively. Using a variety of olivine LPO and other anisotropic fabrics, we compare shear wave splitting from these models against source-side shear wave splitting measurements in order to better understand sub-slab deformation. We find that in Tonga, E-type LPO fabric is the best match to the source-side observations, while in Central America, C-type LPO best fits the data. Although the data fit is not perfect, especially in the case of Tonga, these results suggest the sub-slab mantle beneath Tonga is less well hydrated than that beneath Central America.

## **NUMERICAL MODELING OF INITIAL SLIP AND POROELASTIC EFFECTS OF THE 2012 COSTA RICA EARTHQUAKE USING GPS DATA**

McCormack K., Hesse M., Stadler G.

We formulate a Bayesian inverse problem to infer the slip distribution on the plate interface using an elastic finite element model and GPS surface deformation measurements. We present an application to the co-seismic displacement during the 2012 earthquake on the Nicoya Peninsula in Costa Rica. The results are used as an initial condition in a coupled poroelastic forward model. From this study we identify a horseshoe-shaped rupture area with a maximum slip of approximately 2.5 meters surrounding a locked patch that is likely to release stress in the future. We model the co-seismic pore pressure change as well as the pressure evolution and resulting deformation in the months after the earthquake. The results of the forward model indicate that earthquake-induced pore pressure changes dissipate quickly near the surface ( $< 1\text{km}$  depth), resulting in relaxation of the surface deformation in the seven to ten days following the earthquake. Near the subducting slab interface, however, pore pressure changes are approximately an order of magnitude larger and may persist for many months after the earthquake.

# **SR AND O ISOTOPE GEOCHEMISTRY OF VOLCÁN UTURUNCU, ANDEAN CENTRAL VOLCANIC ZONE, BOLIVIA: RESOLVING CRUSTAL AND MANTLE CONTRIBUTIONS TO CONTINENTAL ARC MAGMATISM**

Michelfelder G. S., Feeley T. C.

This study reports oxygen isotope ratios of mineral separates and in situ Sr isotope ratios from andesitic to dacitic composition lava flows erupted from Volcán Uturuncu in the Central Volcanic Zone. Variation in  $\delta^{18}\text{O}$  values for the lava suite is large and the data as a whole exhibit no simple correlation with any parameter of compositional evolution. Plagioclase separates from nearly all rocks have  $\delta^{18}\text{O}$  values higher than expected for production of the magmas by partial melting of little evolved basaltic lavas erupted in the back arc regions of the CVZ. Most Uturuncu magmas must therefore contain high  $^{18}\text{O}$  crustal material. This hypothesis is further supported by textures and isotopic variation within single plagioclase phenocrysts suggesting repeated mixing followed by crustal contamination events occurring in the shallow crustal reservoir. Results demonstrate on a relatively small scale the strong influence that intrusion of mantle-derived mafic magmas can have on modifying the composition of pre-existing continental crust in regions of melt production. Given this result, similar, but larger-scale, regional trends in magma compositions may reflect an analogous but more extensive process wherein the continental crust becomes progressively hybridized beneath frontal arc localities as a result of protracted intrusion of subduction-related basaltic magmas.

## **SEDIMENT ACCRETION NOT EROSION DURING HORST AND GRABEN SUBDUCTION ASSOCIATED WITH THE TOHOKU OKI M9 EARTHQUAKE, NORTHERN JAPAN**

Moore J. C., Chester F.

Key Points: The Northern Japan Trench subducts a continuous sequence of horsts and grabens formed during flexure of the incoming oceanic lithosphere. Such horst and graben terranes have been invoked as a “chain saw” that would erode the upper plate of the trench. The accretionary propensity of such systems reflects faults preferring the weakest rock. Off Northern Japan accreted sediments have a unique stratigraphy with a younger over older sequence overlying the plate boundary thrust. This sequence is due to the plate boundary fault propagating along a weak pelagic clay both over the top of the horst and downward through the adjacent graben on the seaward edge of the horst. Shortening of the sediments in the graben develops a small proto-accretionary prism that ultimately rides up the normal fault on the landward edge of the next incoming horst creating a late Cenozoic over early Cenozoic thrust sequence. The propensity of the weak fault zone to slide over the top of the horst and through the depths of the graben minimizes subduction erosion and allows accretion to dominate.

## **GEOCHEMICAL RELATIONSHIPS BETWEEN VOLCANIC AND PLUTONIC UPPER TO MID CRUSTAL EXPOSURES OF THE ROSARIO SEGMENT, ALISITOS ARC (BAJA CALIFORNIA, MEXICO): AN OUTSTANDING FIELD ANALOG TO THE IZU-BONIN-MARIANA ARC**

Morris R., DeBari S., Busby C., Medynski S.

3-D exposures of the Rosario segment (Alisitos Arc, Baja California) record crustal generation processes in the volcanic rocks and underlying plutonic rocks. In this study, we explore the physical and geochemical connection between the plutonic and volcanic units of the extensional Alisitos Arc, and elucidate differentiation processes responsible for generating them. These results provide an analog for extensional active arc systems, such as the Izu-Bonin-Mariana Arc.

Upper crustal volcanics have a coherent stratigraphy that ranges in composition from basalt to dacite. Phenocrysts in the volcanic units include plagioclase +/- amphibole and pyroxene. The transition to deeper plutonic rocks is intrusive, where plutonic units intrude the volcanic units. Plutonic rocks are dominantly a quartz diorite with a more mafic, gabbroic margin. Plutonic mineral assemblages include plagioclase +/- quartz, biotite, amphibole and pyroxene.

Most samples are low K. REE patterns are relatively flat with limited enrichment. Normalization diagrams show LILE enrichment and HFSE depletion, where trends are similar to average IBM values. We interpret plutonic and volcanic units to have similar geochemical relationships, where liquid lines of descent show the evolution of least to most evolved magma types. We provide a model for the formation and magmatic evolution of the Alisitos Arc.

## PRELIMINARY EVENT DETECTION AND LOCATION OF EARTHQUAKES USING THE CASCADIA INITIATIVE DATASET

Morton E., Bilek S. L.

The Cascadia subduction zone (CSZ) produces a range of slip behavior along the plate boundary megathrust, from great earthquakes to episodic slow slip and tremor (ETS). Unlike other subduction zones that produce great earthquakes and ETS, the CSZ is notable for the lack of small and moderate magnitude earthquakes recorded.

The seismogenic zone extent is currently estimated to be primarily offshore, thus the lack of observed small, interplate earthquakes may be partially due to the use of only land seismometers. The Cascadia Initiative (CI) community seismic experiment seeks to address this issue by including ocean bottom seismometers (OBS) deployed directly over the locked seismogenic zone, in addition to land seismometers. We select a subset of small magnitude ( $M_{0.1}$ -3.7) earthquakes from existing earthquake catalogs, based on land seismic data, whose preliminary hypocentral locations suggest they may have occurred on the plate interface. We window the waveforms on CI OBS and land seismometers around the phase arrival times for these earthquakes to generate templates for subspace detection, to find earthquakes that have gone undetected by the land-based networks. Here we present event detections from the first year of CI deployment and preliminary locations for the detected events.

## **MAPPING POROSITY OF THE COCOS OCEANIC CRUST AT THE MIDDLE AMERICA TRENCH WITH MARINE EM**

Naif S., Key K., Constable S., Evans R. L.

We use marine controlled-source electromagnetic data to infer the porosity structure of Cocos oceanic crust before and after the onset of bending faults at the outer rise. Prior to faulting, the electrical resistivity of the crust is relatively 1D, where our porosity estimates agree well with independent constraints. At the onset of bending faults, a heterogeneous electrical resistivity structure emerges. Sub-vertical conductive channels that are 1-3 km wide correlate with the location of fault scarps, indicating that the migration of fluids are concentrated along fault damage zones. The porosity of the intrusive crust increases progressively with proximity to the trench axis, reaching peak levels within 20 km of the trench. The amount of crustal pore water subducting is equivalent to a 200 m thick layer, compared with 120-140 m of water based on constraints from the abyssal plain crust. Our results suggest that significantly more water is input into the margin than previously thought.

## RECOVERING ALL GEODETIC STRAIN ALONG THE NICOYA SUBDUCTION INTERFACE

Newman A. V., Kyriakopolous C.

Nicoya, Costa Rica is a unique peninsula that puts land directly above the seismogenic component of a very active subduction megathrust that generates mid-magnitude 7 earthquakes approximately every 50 - 60 years. Because of its location, it's enabled detailed land-based geophysical imaging of the subduction megathrust, an environment normally occurring entirely offshore. Using GPS data collected from campaign and continuous sites going back approximately 20 years, we've imaged the evolution of the region from the late interseismic period [e.g. Feng et al. JGR 2012], including numerous slow slip events [e.g. Dixon et al., PNAS, 2015], a large Mw 7.6 earthquake in 2012 [e.g. Protti et al., Nat. Geosc, 2014], and now through postseismic recovery [Malservisi et al., G3, 2015]. The derived images of interface locking and slip published for each of these behaviors use different model geometries, different weighting schemes, and modeling algorithms limiting their use for fully characterizing the transitions between zones. Here, we will report on our initial work to unify our understanding of the continuum of slip, with special attention to transitions between interseismic locking and slow slip, with coseismic rupture, using the new seismically defined slab interface of Kyriakopoulos et al [JGR, 2015].



## **HIKURANGI CRUSTAL AND SUBDUCTION ZONE STRUCTURE AS ILLUMINATED BY THE SAHKE GEOPHYSICAL TRANSECT, NORTH ISLAND, NEW ZEALAND**

Henry S., Stern T., Savage M., \*Okaya D., Sato H., Kurashimo E., and the SAHKE team

The Hikurangi subduction margin is defined by the Pacific plate subducting beneath the Australian plate at North Island, New Zealand. Based on prior geophysical and geological studies, the dipping Pacific plate is known to be shallow beneath southern North Island which includes the capital city of Wellington. An international collaboration of New Zealand, Japan, and USA scientists carried out the Seismic Array Hikurangi Experiment (SAHKE) in order to identify the specific geometry of the subduction zone. Seismic observations were collected in 2010-2011 and included a double-sided seismic onshore-offshore transect, land explosion reflection/refraction profiling, a six-month 2D short period passive array, and a transect broadband array. Seismic tomography, reflection processing and diffraction-stack imaging indicate the subduction interface dips at 15 degrees when the Pacific slab enters the overlying Australian mantle (Henry et al., G-Cubed 2013). Continuous recording of densely spaced active-source instrumentation allowed for the extraction explosion gathers with very long traveltimes. These gathers reveal 45+ sec phases that are interpreted as LAB reflections (Stern et al., Science 2014). We will present these results and initial results of new tomography and imaging associated with the subduction zone.

\* *Presenter*

## **UNSTABLE FAULT SLIP INDUCED BY LAWSONITE DEHYDRATION IN BLUESCHIST: IMPLICATION FOR THE SEISMICITY IN THE SUBDUCTING OCEANIC CRUSTS**

Okazaki K., Hirth G.

Intermediate-depth earthquakes in cold subduction zones are observed within the subducting oceanic crust, as well as the subducting mantle. In contrast, intermediate-depth earthquakes in hot subduction zones predominantly occur just below the Moho. These observations have stimulated interest in potential relationships between blueschist-facies metamorphism and seismicity, particularly through the dehydration reactions involving lawsonite. The rheology of these high-pressure and low-temperature metamorphic minerals is largely unknown.

We conducted experiments on lawsonite accompanied by monitoring of acoustic emission (AE) in a Griggs-type deformation apparatus. Deformation was started at the confining pressure of 1.0 GPa, the temperature of 300 °C, and constant displacement rates of 0.16 to 0.016  $\mu\text{m/s}$ , that correspond to equivalent strain rates ( $\epsilon$ ) of  $9 \times 10^{-5}$  to  $9 \times 10^{-6}$  1/s. In these experiments, temperature was increased at the temperature ramp rate of 0.5 to 0.05 °C/s above the thermal stability of lawsonite (600 °C) while the sample was deforming to test whether the dehydration reaction induces unstable fault slip. In contrast to similar tests on antigorite, unstable fault slip (i.e., stick-slip) occurred during dehydration reactions in the lawsonite gouge layer, and AE signals were continuously observed. Microstructural observations indicate that strain is highly localized along the fault ( $R_1$  and B shear), and the fault surface shows mirror-like slickensides. The unloading slope (i.e., rate of stress drop as a function of slip) during the unstable slip follows the stiffness of the apparatus at all experimental conditions regardless of the strain rate and temperature ramping rate. A thermal-mechanical scaling factor in the experiments covers the range estimated for natural subduction zones, indicating the potential for unstable frictional sliding within natural lawsonite layers to induce seismicity in cold subduction zones.

## **PROVENANCE OF TECTONIC STRESSES AND EFFECT ON SURFACE PLATES**

Petersen R. I., Stegman D. R., Tackley P. J.

The state of stress in tectonic plates and at the plate interface of convergent zones along with the strength of the plates at the surface and at depth control the style of convection. Sources of stress within the system are manifold; they arise from the subducting plate moving past the overriding plate, the interaction of the subducted slab and the lower mantle and interaction of the overriding plate interacting with the mantle wedge. Plate strength is a function of plate viscosity, the dimensions of the plate and the material properties of the plate.

We present the results and analysis of computational models of subduction systems wherein we modify the stress and strengths of the plates and slabs. We compare the different mechanisms that make these modifications and the behavior of subduction systems. This provides a framework for identifying physical processes that lead to more Earth-like behavior in fully dynamic computational models.

## **IMAGING THE JUAN DE FUCA PLATE INTERFACE USING COAST MULTI-CHANNEL SEISMIC REFLECTION DATA OFF THE COAST OF WASHINGTON STATE**

Peterson D., Keranen K. M., Webb S. I., Tobin H. J., Holbrook W. S., Fortin W. F., Kent G.

In the Cascadia subduction zone, the location and physical properties of the subducting plate interface are poorly understood due to sparse seismicity. In July 2012, the R/V Langseth COAST cruise acquired 9 seismic reflection profiles across the locked portion of the Cascadia subduction zone. Initial processing shows sparse hints of reflectivity from the top of the down-going slab below the accretionary prism. However, CDP gathers reveal strong reflectivity from the plate interface down to ~15 km depth. Reflectivity from the deeper slab is discontinuous, likely influenced by scattering above the slab. A subset of gathers show two distinct bands of reflectivity near the expected plate interface, interpreted as the top and bottom of a low velocity zone above oceanic crust. Comparison with receiver functions on land and offshore (Abers et al., 2009; Janiszewski and Abers, 2015) indicate that a low velocity zone is present in this region, thicker landward. Synthetic modeling of the MCS gathers will provide constraints on the velocity and structure of this zone. We will use enhanced multiple removal techniques to image the deep reflectivity, with the ultimate goal of better understanding slab structure and properties of the plate interface within the seismogenic zone.

## **ZONED GARNET GEOCHRONOLOGY AS A TOOL FOR CONSTRAINING RATES IN SUBDUCTION ZONES**

Pollington A. D., Dragovic B., Baxter E.

Geochronology of rocks and minerals from subduction zones can provide constraints on the timing and rates of a wide range of processes including plate movement, dehydration reactions, fluid movement, and exhumation. In this work we focus on geochronology of the major rock forming mineral garnet. This mineral, almost ubiquitous in rocks from subduction zones, can record changes in pressure, temperature, and fluid composition while simultaneously recording the timing of such events. By applying sample preparation and high-precision analytical techniques developed over the past decade, discrete zones can be sampled from individual porphyroblasts and individual ages can be calculated from the core to rim of a single crystal. Combining these ages with detailed thermodynamic modeling can yield precise information about the pressure-temperature-composition (P-T-X) evolution of the rock through time (t). The resulting P-T-X-t curves generated from these types of samples can provide useful information about the rates of diverse processes that can be used as conditions in modeling of subduction zones.

## **HIGHLY VARIABLE STRUCTURE ALONG THE BANDA ARC IMAGED BY AMBIENT NOISE TOMOGRAPHY**

Porritt R., Miller, O'Driscoll, Harris, Roosmawati

The tectonic configuration of the Banda region in southeast Asia captures the spatial transition from subduction of Indian Ocean lithosphere to subduction and collision of the Australian continental lithosphere beneath the Timor Sea, which can be considered as the temporal transition of the initiation of continental collision. An ongoing broadband seismic deployment funded by NSF is aimed at better understanding the mantle and lithospheric structure in the region and the relationship of the arc-continent collision to orogenesis. Here, we present results from ambient noise tomography in the region utilizing this temporary deployment of 30 broadband instruments and 38 permanent stations in Indonesia and Australia. Despite having only a year of data from the new experiment and about 2.5 years of data in total, we are already able to measure stable dispersion curves for several paths resulting in good recovery for the Savu Sea, Timor Leste, and the Nusa Tenggara Timur (NTT) region of Indonesia. The resulting initial three dimensional shear velocity model indicates significant lateral heterogeneity along the plate boundary. The model contains clear anomalies associated with the subducting oceanic lithosphere, subducted Australian continental lithosphere, and perhaps delaminated oceanic sediments forming the core of the island of Timor.

## **LONG- TO SHORT-TERM VERTICAL DEFORMATION ACROSS THE FOREARC IN THE PECULIAR MEXICAN SUBDUCTION ZONE**

Ramírez-Herrera M. T., Gaidzik K., Forman S., Kostoglodov V., Bürgmann R.

Spatial scales of the earthquake cycle, from rapid deformation associated with earthquake rupture to slow deformation associated with interseismic and transient slow-slip behavior, span from fractions of a meter to thousands of kilometers (plate boundaries). Similarly, temporal scales range from seconds during an earthquake rupture to thousands of years of strain accumulation between earthquakes. The complexity of the multiple physical processes operating over this vast range of scales and the limited coverage of observations leads most scientists to focus on a narrow space-time window to isolate just one or a few process. We discuss here preliminary results on the vertical crustal deformation associated with both slow and rapid crustal deformation along a profile across the forearc region of the central Mexican subduction zone on the Guerrero sector, where the Cocos plate underthrusts the North American plate. This sector of the subduction zone is characterized by a particular slab geometry (with zones of rapid bending-unbending of the slab), irregular distributed seismicity, exceptionally large slow slip events (SSE) and non-volcanic tremors (NVT). We discuss questions and preliminary results on associations of the topography and river characteristics with the Cocos slab geometry, slow earthquakes, crustal deformation, and interseismic deformation.

## **DEFORMATION AND (DE)HYDRATION OF THE NORTHERN JUAN DE FUCA PLATE: PRELIMINARY RESULT WITH FULL-WAVE AMBIENT NOISE TOMOGRAPHY**

Rathnayaka S., Gao H.

To address slab deformation and (de)hydration processes at the Cascadia subduction zone, we construct a shear-wave velocity model beneath the northern Juan de Fuca plate from the crust to the uppermost mantle using full-wave ambient noise seismic tomography. Data from year 1 and year 3 of the Cascadia Initiative deployment are processed and analyzed, in combination with 40 inland broadband seismic stations. We extract the empirical Green's functions (EGFs) from continuous seismic records on the vertical components of OBS and land station pairs using frequency-time normalization method. High-quality Rayleigh-wave signals within periods of 7-50 s can be extracted. We simulate wave propagation within a 3D earth structure with the finite difference method to generate station Strain Greens Tensors and synthetic waveforms. The sensitivity kernels of Rayleigh waves on the perturbations of  $V_p$  and  $V_s$  are calculated based on the Strain Greens Tensors. We then invert for the velocity perturbations from the reference model and progressively improve the model resolution. Our preliminary results indicate that, (1) low-velocity anomalies from 9 km to 40 km beneath west side (onshore) of the Washington state and (2) a low-velocity zone on the oceanic crust near the trench, which may indicate serpentinization.



## **BONIN FORE-ARC DRILLING (IODP EXP 352): THE VOLCANIC ARCHITECTURE OF SUBDUCTION INITIATION**

Reagan M. K., Pearce, J. A., and the IODP Expedition 352 scientific team

Drilling in the Izu-Bonin-Mariana (IBM) fore-arc during IODP Expedition 352 and DSDP Leg 60 recovered stratigraphic sequences of “fore-arc basalts” (FAB) basalts and boninites reminiscent of those found in many ophiolites. FAB erupted close to the trench and have ages of about 51.5 Ma. Boninites erupted further from the trench approximately 2-3 m.y. later. First results from IODP Expedition 352 suggest that FAB were generated by decompression melting during near-trench sea-floor spreading, and that fluids from the subducting slab were not involved in their genesis. Temperatures appear to have been unusually high and pressures of melting appear to have been unusually low compared to mid-ocean ridges. Spreading rates at this time appear to have been robust enough to maintain a stable melt lens. The oldest boninites have relatively high concentrations of fluid-soluble elements, low concentrations of REE. Younger boninites, have even higher concentrations of fluid-soluble elements and lower REE concentrations. Melting pressures and temperatures apparently decreased through time, mantle became more depleted through time, and spreading rates waned during boninite genesis. Subduction zone fluids involved in boninite genesis appear to have been derived from progressively higher temperatures and pressures over time as the subducting slab thermally matured.

## **THREE-DIMENSIONAL MANTLE FLOW PATTERN NEAR THE FLAT-SLAB SECTION OF THE MEXICAN SUBDUCTION ZONE**

Rosas J. C., Pimentel F. C., Currie C., He J.

We report the first three-dimensional (3D) finite-element thermal model of the Mexican subduction zone. The most important feature of this subduction zone is the flat-slab section at a depth of 50 km below central Mexico, extending 250-300 km landward from the trench. Further west, the dip increases to 45-50°. As indicated by anisotropy studies, this geometry leads to a 3D mantle flow that departs from the classical 2D subduction-driven corner flow. Our objective is to assess the effects of this flow on subduction temperatures. For an isoviscous mantle, our model shows that dip variations induce an along-strike flow of 2 cm/yr from the normal-dipping section toward the flat slab region; this flow geometry is consistent with seismic anisotropy observations. Temperatures can be as high as 1230° C below the volcanic arc. For a non-Newtonian rheology, previous studies indicate the along-strike velocity can be significantly higher than for the isoviscous case. Our next models will investigate the combined effect of 3D non-Newtonian mantle flow and hydrothermal circulation on melting temperatures in the wedge, as well as dehydration and metamorphic reactions within the slab.

## **COMPOSITION WITHIN AND BETWEEN TONGA ARC/LAU BASIN BACKARC ERUPTIONS REVEAL WIDE VARIETY OF PARENT MELTS LINKED TO ERUPTION STYLES**

Rubin K. H., Michael P., Jenner F., Clague D., Glancy S., Hellebrand E., Arculus R., Gill J., Todd E., Lupton J., Embley R.

The Northern Tofua Arc and adjacent NE Lau Basin host a wide variety of volcano types reflecting dynamic and diverse tectonic settings all in close spatial proximity. Frequent contemporaneous eruptions of high-MgO magmas and their differentiates from closely spaced volcanoes provide an uncommonly detailed view of the diversity of parent magma types formed in the broader suprasubduction zone environment. They show how mantle lithological variations couple with local tectonic setting to control magmatism, and influence magma accumulation, storage, and subsequent eruption. The results of 6 recent research expeditions to this relatively small region show how these attributes collectively result in systematic relationships between eruption style, inferred duration, size, intensity, location, and compositional variability. In particular, we can constrain magmatic conditions and timescales from single eruption deposits that we sampled with high-spatial-resolution in the context of detailed deposit mapping, high resolution  $^{210}\text{Po}$ - $^{210}\text{Pb}$  eruption chronologies, and U-Th-Ra disequilibrium. At the same time, variations between eruption deposits reveal how quickly parent melt compositions drawn from the mantle wedge can change in space and time. We will discuss and interpret diverse phenomena from the region, including high rates

## LOCAL REDOX GRADIENTS INDUCED DURING MAGMA MIXING

Ruprecht P., Fiege A., Simon A.

Diffusion-couple time series experiments between a crystal-bearing basaltic andesite and a mostly aphyric dacite were performed to investigate the physicochemical processes at the mixing interface. In particular, we explore the evolution of redox gradient at the interface as the compositionally distinct melts move towards equilibrium. We combined  $\mu$ -XANES spectroscopy at Fe K-edge with two-oxide oxybarometry to measure redox profiles within our experiments. Here,  $fO_2$  decreased towards the interface within the dacite and increased towards the interface within the andesite. This discontinuous  $fO_2$  evolution, with a sharp redox gradient of  $\sim 1.8 \log fO_2$  units at the interface was maintained throughout the time-series despite the externally imposed  $fO_2$  of the vessel. We suggest that this redox gradient is the result of (1) ferrous iron liberation during cpx- and opx-dissolution in the basaltic andesite and diffusion into the dacite and (2) the formation of a charge imbalance as charged ions diffuse across the interface; the latter we consider to be more important.

We suggest that this (metastable) redox layer can help to explain the contrasting Au/Cu ratios observed for arc-related porphyry-type ore deposits. Moreover, these results may have implications for the interpretation of  $SO_2$  emission data associated with volcanic eruptions.

## **IN SITU CONDITIONS AND THE MECHANICS OF SLOW EARTHQUAKES ALONG SUBDUCTION MEGATHRUSTS: INSIGHTS FROM LABORATORY EXPERIMENTS**

Saffer D., Kitajima H., Leeman J., Ikari M., Marone C., Scuderi M.

Over the last several years, seismic and geodetic observations have led to the discovery that fault slip occurs across a continuous spectrum of slip rates and durations, ranging from normal earthquakes that last seconds to minutes, to low frequency and very low frequency earthquakes (LFE and VLFE), to slow slip events that unfold over weeks to months. In many, though not all cases, slow earthquake phenomena occur near the updip and downdip edges of the seismogenic portion of faults that rupture coseismically. Although observations of these events are widespread, their mechanics and the in situ conditions in their source regions are not well known. Here, we report on two sets of laboratory investigations aimed at better understanding the processes that underlie slow earthquakes, with a focus on subduction megathrusts.

First, we integrate laboratory measurements of acoustic velocity and consolidation behavior for sediments from the Nankai Trough with a well-constrained regional seismic velocity architecture, to estimate in situ pore pressure and stress in the outer forearc where swarms of VLFE nucleate. We show that the VLFE occur exclusively in the region of highest predicted fluid overpressures, where normalized pore pressures are 74–87% of lithostatic. In this region, estimated horizontal stresses are also anomalously low, ~30% of the value expected for fully drained conditions. This result is consistent with similar observations suggesting elevated pore pressures in the source area of slow slip events at other margins, including Hikurangi and Costa Rica.

Second, we describe laboratory friction experiments that illustrate mechanisms that may explain the emergence of slow earthquakes. In a suite of carefully controlled experiments on fine-grained quartz gouges, we show that repeated laboratory slow stick-slip events occur near the transition between stable and unstable slip, controlled by the interplay of fault frictional properties, effective normal stress, and elastic stiffness of the surrounding rock. Notably, stick-slip event velocity and duration vary systematically as the stability threshold is approached; regular stick-slip events occur in the unstable regime and slow slip and chaotic modes occur near the stability phase boundary. We also show that natural sediment and fault zone samples from subduction zones exhibit rate-weakening behavior at low slip velocity, transitioning to rate-strengthening at higher slip velocity. These characteristics could allow slow unstable sliding in these materials, but would suppress rapid unstable slip.

## **HIGH-MG ANDESITES FROM MOUNT BAKER AND GLACIER PEAK, WASHINGTON: UNDERSTANDING SLAB, MANTLE, AND CRUSTAL CONTRIBUTIONS TO MAGMA PETROGENESIS IN THE NORTHERN CASCADE ARC**

Sas M.

High-Mg andesites (HMA) and basaltic andesites (HMBA) have unusually high Mg# relative to their SiO<sub>2</sub> contents, in addition to elevated La/Yb and Dy/Yb that are interpreted to result from separation of melt from a garnet-bearing residuum. Debate centers on the garnet's origin (subducting slab? deep mantle? thick lower crust? basalt fractionated at high pressure?) and specifically whether slab melt contributes to magma generation. Recent work has shown that slab melt is involved in magma petrogenesis in the southern Cascade arc (Walowski et al., 2015). By examining HMA from northern Washington, this study sheds light on slab melt contribution to magma genesis in the northern Cascade arc. Clinopyroxene geochemistry of Tarn Plateau HMBA (Mount Baker) suggests an origin similar to that of Aleutian adakites, where slab-derived melts interact with the overlying mantle to become Mg-rich and subsequently mix with mantle-derived magmas. High whole rock Sr/P in the Glacier Creek HMA (Mount Baker) and Lightning Creek HMBA (Glacier Peak) imply an origin from a mantle that was hydrated by an enriched slab component (fluid ± melt). Our results indicate that in addition to slab-derived fluids, slab-derived melts also have an important role in the production of HMA in the north Cascade arc.

## DEHYDRATION INDUCED POROSITY WAVES AND EPISODIC TREMOR AND SLIP

Skarbek R, Rempel A.

Slow slip and tremor in subduction zones take place where there is abundant evidence for elevated, near lithostatic pore pressures along the plate interface, and commonly occur at depths (~30-45 km) where the main source of fluids must be attributed to chemical dehydration reactions. Here we simulate fluid and heat flow in a subducting slab by tracking the location of a vertically oriented, one-dimensional column of material as it is subducted through the slow slip and tremor zone. The material in the column is subjected to a pressure and temperature dependent, generalized dehydration reaction described by a nonlinear kinetic reaction rate law. The column deforms poro-elastically and includes a viscous component that depends linearly on the porosity. In these simulations the dehydration reaction generates traveling porosity waves that transport increased fluid pressures within the slow slip region. We explore the possibility that the observed periodicity of slow slip and tremor in subduction zones can be explained by the migration of such porosity waves. We derive a dispersion relation from the governing equations that accurately describes the numerical results, and also derive an expression for the thickness of the dehydrating layer as a function of the parameters in the reaction rate law.

## **INTERPRETING SEISMIC ANISOTROPY IN SUBDUCTION ZONES: THE ROLE OF DEFORMATION HISTORY**

Skemer P., Boneh Y.

Flow in the mantle wedge is of great significance to the broader study of subduction zones and the deformation cycle. Flow patterns influence mass and heat transport and should also allow us to understand better the mechanical coupling between the slab and mantle wedge. Our primary tool for determining flow patterns is seismic anisotropy, either through inverse or forward modeling approaches. However, interpreting seismic anisotropy in terms of mantle flow is not straightforward, especially in complex settings. Typically, the interpretation of seismic anisotropy is predicated on the assumption that the crystallographic preferred orientation (CPO) of olivine rapidly orients itself to reflect the most recent flow kinematics. However, recent work has demonstrated that this assumption is problematic when flow directions or deformation conditions change over short length scales. In this presentation we show the results of laboratory experiments in which different deformation histories are imposed and the resulting CPO and anisotropy quantified. We then show how these experiments compare to widely used models of CPO evolution. In each scenario we show that olivine CPO is influenced strongly by previous stages of deformation. As such, seismic anisotropy in subduction settings may reflect a long integrated deformation path, not the instantaneous flow field.



## **CRUSTAL RECYCLING BY SUBDUCTION EROSION IN THE CENTRAL MEXICAN VOLCANIC BELT**

Straub S. M., Gomez-Tuena A., Bindeman I. N., Bolge L. L., Brandl P. A., Espinasa-Perena R., Solari L., Stuart F. M., Vannucchi P., Zellmer G. F.

Subduction erosion is an important mechanism of crustal destruction at convergent margins. Obtaining evidence of the recycling of eroded crust from arc magmas, however, is challenging owing to the compositional similarities between eroded crust, subducted trench sediment and arc crustal basement. We addressed this problem by a Hf-O-Pb isotope study of a previously well-characterized series of olivine-phyric high-Mg# basalts to andesites in the central Mexican Volcanic Belt. These magmas are hybrids of primary basaltic to dacitic mantle melts from olivine-free, secondary pyroxenite lithologies which escaped crustal contamination during ascent. The olivine phenocrysts combine high-Ni (up to 0.67 wt% Ni) with high  $^3\text{He}/^4\text{He} = 7-8 \text{ Ra}$  and high  $\delta^{18}\text{O} = +5.3-6.6\text{‰}$  (or  $\delta^{18}\text{O} = +6.3-8.5\text{‰}$  of host melt) which attests to the presence of a crustal component in the mantle melts that must derive from slab. However, Hf-Nd isotope and trace element systematics rule out the pelagic trench sediment as crustal component and imply a major contribution from eroded crust that became entrained in the subduction channel either via the following landward surface erosion, or by abrasion of the underside of the upper plate. Overall, the mass of the eroded continental crust dwarfs the mass of the recycled pelagic sediment.

## **MOHO AND MAGMATIC UNDERPLATING IN CONTINENTAL LITHOSPHERE**

Thybo H., Artemieva I.

Underplating was originally proposed as the process of magma ponding at the base of the crust and was inferred from petrologic considerations. This process not only may add high density material to the deep crust, but also may contribute low density material to the upper parts of the crust by magma fractionation during cooling and solidification in the lower crust. Separation of the low density material from the high-density residue may be a main process of formation of continental crust with its characteristic low average density, also during the early evolution of the Earth. Despite the assumed importance of underplating processes and associated fractionation, the available geophysical images of underplated material remain relatively sparse and confined to specific tectonic environments. Direct ponding of magma at the Moho is only observed in very few locations, including volcanic arcs.

# THERMOBAROMETRIC CONSTRAINTS FROM PRIMITIVE ARC MAGMAS: A REVIEW

Till C. B.

Erupted magmas remain the best tools we have to ascertain the mantle processes that give rise to the compositional diversity and spatial distribution of near-primary magmas at volcanic arcs. Here I review the mantle pressure-temperature constraints from natural primitive magmas at subduction zones to date and summarize their implications. Three methods of constraining the pressures and temperatures of natural primitive arc magmas in the mantle are considered: 1) experimental studies to locate the multiple saturation points of natural arc magmas, 2) thermobarometric calculations for natural primitive arc minerals and melts, and 3) thermobarometric calculations for primitive arc melt inclusions. These techniques produce estimates of the conditions of arc magmas in the mantle of ~1000-1600°C at ~6-50 kbars, with the majority of samples recording 1150-1350° at 8-18 kbar. When compared to mantle melting models, the results suggest the pressures and temperatures recorded by primitive arc magmas reflect the conditions of the melt's re-equilibration with the mantle during ascent rather than the magma's point of origin. Thus this dataset as a whole is useful for understanding melt migration and the temperature structure in the uppermost part of the mantle wedge below arcs, rather than conditions at the onset of melting.

## TRANSITION FROM FLUID-FLUXED TO DECOMPRESSION MELTING IN THE TONGA ARC

Turner S.

The Fonualei Spreading Centre affords an excellent opportunity to evaluate geochemical changes with increasing depth to the slab in the Lau Backarc Basin. Along the Fonualei Spreading Centre, key geochemical parameters change smoothly with increasing distance from the arc front and increasing slab surface temperatures. The latter may range from 720 to 865°C, based on decreasing H<sub>2</sub>O/Ce ratios. Consistent with experimental data, the geochemical trends are interpreted to reflect changes in the amount and composition of wet pelite melts or supercritical fluids and aqueous fluids derived from the slab. With one exception, all of the lavas preserve both <sup>238</sup>U excesses and <sup>226</sup>Ra excesses. We suggest that lavas from the Fonualei Spreading Centre and Valu Fa Ridge are dominated by fluid-fluxed melting whereas those from the East and Central Lau Spreading Centres, where slab surface temperatures exceed ~ 850-900°C, are largely derived through decompression. A similar observation is found for the Manus and East Scotia backarc basins and may reflect the expiry of a key phase such as lawsonite in the subducted basaltic crust.

## **TOMOGRAPHIC IMAGING OF THE MAGMATIC SYSTEM AT MOUNT ST. HELENS WITH THE iMUSH BROADBAND ARRAY**

Ulberg C., Creager K., Levander A., Kiser E., Moran S., Abers G., Schmandt B., Vidale J., Houston H., Denlinger R., Williams M.

We deployed 70 broadband seismometers in the summer of 2014 to image the velocity structure beneath Mount St. Helens (MSH), Washington, USA as part of a collaborative project called imaging Magma Under St. Helens (iMUSH). Our goal is to illuminate the MSH magmatic system, using active- and passive-source seismology, magnetotellurics and petrology. The broadband array has a diameter of ~100 km centered on MSH with an average station spacing of 10 km, and will remain deployed through summer 2016. It is augmented by dozens of permanent stations in the area. We determine P-wave arrival times using Antelope software and incorporate permanent network picks for the region. We use the program struct3DP to invert travel times to obtain a 3-D seismic velocity model and relocate hypocenters. There were more than 500 useable local events during the first year of iMUSH broadband recording, including 23 active shots that were set off in the summer of 2014 as part of the iMUSH experiment. Our model interpretation will incorporate results from active-source and ambient noise tomography, receiver functions, magnetotellurics, and petrology.

## **MANTLE WEDGE FLOW PATTERN AND THERMAL STRUCTURE IN NORTHEAST JAPAN: EFFECTS OF OBLIQUE SUBDUCTION AND 3-D SLAB GEOMETRY**

Wada I., He J., Hasegawa A., Nakajima J.

We develop a 3-D thermal model for the Northeast Japan subduction margin, using a realistic slab geometry for the subducting Pacific plate, and investigate the effects of oblique subduction and 3-D slab geometry on the mantle wedge flow pattern and the thermal structure. In the Tohoku region, the mantle wedge flow pattern is nearly two-dimensional resulting in a thermal structure similar to those obtained by a 2-D model, owing to the simple slab geometry and subduction nearly perpendicular to the margin. However, in Hokkaido, oblique subduction leads to 3-D mantle wedge flow with northerly inflow and west-northwestward outflow and also results in lower temperatures in the shallow part of the mantle wedge than in Tohoku due to lower sinking rate of the slab. Between Hokkaido and Tohoku, the slab has a hinge-like shape due to a relatively sharp change in the dip direction. In this hinge zone, northerly mantle inflow from Hokkaido and westerly mantle inflow from Tohoku converge, discouraging inflow from northwest and resulting in a cooler mantle wedge. The model-predicted mantle wedge flow patterns are consistent with observed seismic anisotropy and may explain the orientations of volcanic cross-chains.

## SLAB MELTING AND MAGMA FORMATION BENEATH THE SOUTHERN CASCADE ARC

Walowski K. J., Wallace P. J., Hauri E., Wada I., Clynne M. A., Rasmussen D. J., Weis D.,

Volatiles ( $H_2O$ ,  $CO_2$ , S, Cl) play a key role in magmatic processes at subduction zones. In this study, the dissolved volatile contents of olivine-hosted melt inclusions from cinder cones in the Lassen segment of the Cascade arc are used to investigate dehydration of subducted oceanic lithosphere and magma formation in the sub-arc mantle wedge. The hydrogen-isotope and trace-element compositions of melt inclusions, when integrated with thermopetrologic modeling, demonstrate that fluids in Cascade magmas are sourced from hydrated peridotite in the deep slab interior and that the oceanic crustal part of the slab extensively dehydrates beneath the forearc. In contrast to their slab-derived H, the melt inclusions have B concentrations and isotope ratios that are similar to mid-ocean ridge basalt (MORB), requiring little to no slab contribution of B, which is also consistent with extensive dehydration of the downgoing plate before it reaches sub-arc depths. Correlations of volatile and trace element ratios in the melt inclusions ( $H_2O/Ce$ ,  $Cl/Nb$ ,  $Sr/Nd$ ) demonstrate that geochemical variability in the magmas is the result of variable amounts of addition of a hydrous subduction component to the mantle wedge. Radiogenic v isotope ratios require that the subduction component has less radiogenic Sr and Pb and more radiogenic Nd than the Lassen sub-arc mantle and is therefore likely to be a partial melt of subducted Gorda MORB. These results provide evidence that chlorite-derived fluids from the deep slab interior flux-melt the oceanic crust, producing hydrous slab melts that migrate into the overlying mantle, where they react with peridotite to induce further melting.

## **STRUCTURE AND ESTIMATED PHYSICAL PROPERTIES OF THE CASCADIA SUBDUCTION ZONE ACCRETIONARY WEDGE, GRAYS HARBOR, WASHINGTON**

Webb S. I., Tobin H. J., Everson E. D., Fortin W. F., Kent G., Holbrook W. S., Peterson D., Keranen K. M.

While the Cascadia margin has experienced large historical earthquakes, the location of the offshore portion of the seismogenic zone is unknown. Detailed structural interpretation of multichannel seismic data from the Cascadia Open Source Seismic Transect (COAST) offshore Grays Harbor, Washington, allows us to document the position and relative timing of large thrust faults within the accretionary prism. This section of Cascadia is characterized by a thick incoming sediment section, landward fault vergence, and a low wedge taper angle. High sedimentation rates and deformation of slope basins on the outer wedge allows us to determine the relative timing of fault activity. This analysis indicates out-of-sequence thrusting in the outer wedge, as well as potential fluidized sediment movement in the lower-slope terrace, where the taper angle of the wedge is zero. To complement structural interpretation of the accretionary prism, porosity estimates from velocity models are used to calculate effective stress through the wedge, and at depth where a decollement is inferred. By combining structural and sedimentary interpretation of the accretionary prism with physical properties and stress estimations, we shed light on the development of the outer wedge of the accretionary prism, and may help constrain the updip limit of the seismogenic zone.



## **MANTLE MELTING BENEATH THE LAU BACK-ARC BASIN FROM SEISMIC IMAGING**

Wei S. S., Wiens D. A.

In order to investigate the distribution of partial melt beneath the Tonga arc and Lau back-arc basin, we conducted tomographic studies of surface wave velocity and body wave attenuation using seismic data from a local OBS array and island-based stations. Tomographic results show strong signals of low velocity and high attenuation within the upper 100-km of the mantle beneath the back-arc basin, suggesting perhaps the lowest shear velocity ( $V_{SV} = 3.5$  km/s) and highest seismic attenuation ( $Q_P < 35$  and  $Q_S < 25$ ) known in the mantle. These anomalies require not only the abnormally high temperature but also the existence of partial melt. The inferred partial melt aligns with the spreading centers at shallow depths, but shift westwards away from the slab, indicating a passive decompression melting process governed by the mantle wedge flow pattern. The along-strike variations of mantle porosity filled with melt show opposite trend to those of the melt production and the water content of magma, implying the extraction of melt is significantly enhanced by the water released from the subducting slab.

## **SEGMENTATION OF SLOW SLIP EVENTS IN SOUTH CENTRAL ALASKA CONTROLLED BY SLAB GEOMETRY AND PORE-PRESSURE VARIATION**

Wei M., Li H., Li D., Liu Y.

Slow slip events (SSEs) have been observed in many subduction zones and are believed to affect the timing and size of future large earthquakes. However, the underlying mechanism that controls the spatial and temporal evolution of slow slip events is still unclear. Segmentation of SSEs behavior at subduction zones was observed in Cascadia [Brudzinski and Allen, 2007], southwest Japan [Obara 2010], Mexico [Brudzinski et al., 2010] and New Zealand [Wallace et al., 2012]. The possible causes include along-strike variations of pore-pressure related to silica enrichment [Audet and Burgmann, 2014], strength variation due to composition change of upper geological terraces [Brudzinski and Allen, 2007], variation of interseismic coupling depth [Wallace and Beavan, 2010], and variations of effective normal stress [Liu et al., 2013; Watkins et al., 2015] and slab geometry [Li et al., 2014]. Here we build a comprehensive 3D model in rate-and-state friction to investigate the factors that control the SSE evolution in South Central Alaska, where the 1964 M9.0 earthquake and two recent M>7 SSE occurred. We found that most SSEs are in the region of small dip angle the subduction zone, whereas few SSEs occur in the steep area of the slab, which is consistent with GPS observations.

## **THE ISOLATED 678-KM DEEP 30 MAY 2015 MW 7.9 OGASAWARA (BONIN) ISLANDS EARTHQUAKE**

Ye L., Lay T., Zhan Z., Kanamori H., Hao J.-L.

The largest recorded deep-focus earthquake (MW 7.9) in the Izu-Bonin slab struck on 30 May 2015 beneath the Ogasawara (Bonin) Islands, isolated from prior seismicity by over 100 km in depth, and followed by only 2 small aftershocks. Seismicity indicates along-strike contortion of the Izu-Bonin slab, with horizontal flattening near a depth of 550 km in the Izu region and progressive steepening to near-vertical toward the south above the location of the 2015 event. Analyses of a large global dataset using short-period back-projection, subevent directivity, and broadband finite-fault inversion indicate that the mainshock ruptured a shallowly-dipping fault plane with patchy slip that spread over a distance of ~40 km with variable expansion rate (~5 km/s down-dip initially, ~3 km/s up-dip later). During the 17 s rupture duration the radiated energy was  $\sim 3.3 \times 10^{16}$  J and the stress drop was ~38 MPa. The radiation efficiency is moderate, intermediate to that of the 1994 Mw 8.2 Bolivia and 2013 Mw 8.3 Okhotsk earthquakes, indicating a continuum of processes. The isolated occurrence of the event suggests that localized stress concentration associated with the pronounced deformation of the Izu-Bonin slab likely played a role in generating this major earthquake.

## **AMPHIBIOUS MAGNETOTELLURIC INVESTIGATION OF THE ALEUTIAN ARC: MANTLE MELT GENERATION AND MIGRATION BENEATH OKMOK CALDERA**

Zelenak G., Key K., Bennington N., Bedrosian P.

Previous coarse resolution seismic studies have inferred a crustal magma reservoir beneath Okmok Volcano in the Aleutians. In June-July 2015 we carried out an amphibious geophysical survey to investigate various aspects of the magmatic system, including: how fluids impact melting, how melt ascends through the corner flow regime of the mantle wedge, and how melt migrates and is stored within the upper mantle and crust. Because melt and aqueous fluids are a few orders of magnitude more electrically conductive than melted peridotite, the conductivity-mapping magnetotelluric (MT) method is well-suited to imaging fluids and melt beneath arc volcanoes. Twenty-nine onshore MT stations and 10 offshore stations were collected in a 3D array covering Okmok. An additional 43 offshore MT stations completed a 300km amphibious profile starting at the trench and crossing to the backarc. Thirteen onshore passive seismic stations were also installed and will remain in place for one year to supplement the twelve permanent seismic stations. Data collected by this project will be used to map seismic velocity and electrical conductivity variations within the arc, providing unique constraints on temperature, mineralogy, and fluid content related to arc magmatism. Here we discuss preliminary work on the 300km long amphibious MT profile.