Workshop to Integrate Subduction Factory and Seismogenic Zone Studies in Central America

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ABSTRACT VOLUME
A tephra-stratigraphic and volcanic hazards study was made for the upper part of Barva volcano, which belongs to the Costa Rican’s Central Volcanic Range. The lower visible deposits of the tephra sequence, only crop out in Sacramento and Concordia towns (some 3.2 km southwestward from the summit). It consists of lapilli, ash tuff and paleosol sheets, related with airfall and surge deposits. They are overlain by Carrizal Fito-tuff, an organic enriched tuff (~38 ka) corresponds to a surge event. Sacramento and Guarani andesitic-basaltic lava flows (~25-30 ka) are correlationed to the previously described Bambinos Member from Barva volcano, and are the latest effusive events registered. The Holocene tephra is marked by a paleosol (~8.2 – 13.4 ka), overlain by a pumiceous airfall-lapilli sheet (subplinian eruption) cropping out overall the volcanic complex (~8.2 ka). Field survey showed an upper heterogeneous tephra deposit, which consists of tuff sheets associated with small surge and airfall events. The latest explosive activity registered on Barva volcano consists of a ~0.5 ka scoriaceous lapilli (strombolian eruption), restricted only to the summit of the volcanic edifice. Based on the tephra-lava record, and using Pyle’s method we calculated eruption’s volume, and made a volcanic hazard analysis. There are three different scenarios: short- (<0.1 ka), middle- (0.1-1 ka) and long-term (1-10 ka). For the first case, an explosive eruption would not affect nearby towns to Barva’s summit. While for the middle-term case the populations located within the most hazardous area would be Sacramento and Concordia, for the long term scenario (sub-plinian to plinian eruptions), Concordia and Sacramento populations would be the most affected ones. Nevertheless, in this case, the hazard could be extended to other towns as Fraijanes, Sabana Redonda, Sabanilla, Setillal, Birri, San José de la Montana and San Miguel, all of these located within a radius of 20 km around the eruptive vent.
Major unsolved and/or controversial geological problems in Central America, with particular emphasis in the Chorotega block

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Several major questions about the geological evolution of Central America remain unanswered and many of the models remain controversial, particularly those for the southern part of the isthmus. Some of these hypotheses and models are discussed in the compilation of Bundschuh and Alvarado (2007). From the large to small scale, one of the most controversial models is on the geotectonic evolution of Central America since Cretaceous time. Researchers are divided between two major models for the origin of the Caribbean Plate: the allochthonous Pacific model (about 60% of the researches) and the Caribbean or Intraplate model (the rest of the authors). More research on the basic igneous complexes (ophiolites) and arc volcanism during the Cretaceous is needed to link them through all of Central America. The paleogeographic models are more or less coherent from Eocene time to present. However, studies on the evolution of paleo-arcs throughout Central America are in their infancy, and suggest a complex tectonic migration since the Paleocene (particularly in the Chortis block) that needs to be explained in the framework of changes in the angle of the subducted plate, tectonic erosion and/or different polarity of the subducted margin. Furthermore, Central America does not have typical arc morphology. A more recent problem, geologically speaking, is that the present volcanic front has several segments with breaks in strike, which could be related to change in the angle of the subduction (plate segmentation) and/or major strike slip faults. Another unsolved problem is the geological boundary between the Chortis block and the Chorotega block, which is located somewhere between the Hess escarpment and the central part of Costa Rica. In addition, although most authors are in favor of an oceanic origin of the basement in the Chorotega and Chocó blocks, there are some geophysical and geological evidences of crystalline crustal blocks that still need to be evaluated. Geophysical research in progress will be clarified the signature of the crustal under Costa Rica. Clearly, the magmas in the Cordillera Central show an OIB signature similar to the CLIP basement, but there are several processes that can explain them. In the southern part, the uplift of the Talamanca range and the 175-180 km volcanic gap between Turrialba (Cordillera Central, Costa Rica) and Barú (Panama) volcanoes are explained, at least in part, by the subduction of the Cocos ridge. However, the ages postulated for its arrival and subsequent uplift range from the Miocene to Middle Pleistocene. In addition, another process like the collision of the Panama and the Cocos plates is needed to explain the rapid exhumation of the Talamanca range. The presence of adakites since the Pliocene in the Talamanca (Costa Rica) and the Cordillera Central (Panama) ranges and surrounding areas, is still a problem because most of the models (e.g. slab window, tear faults, etc.) does not satisfactorily explain their origin from the melt of the subducted plate. These are some of the exciting problems in explaining the geological evolution of the Central America, and particularly Costa Rica.

On the active tectonics of northern Central America and Middle America Trench: Constraints from finite element modelling.

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We have developed an elastic finite element model in order to study the role of the different forces acting on the northwestern part of the Central American Volcanic Arc. The zone of interest is the segment of the arc on the Chortis Block, where the Cocos plate is subducted beneath this continental crust. As has been shown by different researchers, the strain in this part of the volcanic arc (at least in the El Salvador and Nicaragua area) is transtensional, and the majority of the focal mechanisms reported are of strike-slip motion. However, the geomorphology along the arc is very variable.

We can divide the volcanic arc of Northern Central America in three main segments: Guatemala, El Salvador and Nicaragua. The limits between these segments coincide with tectonic features on the Chortis Block: The Ipala graben, and the Gulf of Fonseca, the latter as an extension of the Honduras depression and/or the Guayape fault. Between these segments there are differences in the direction of the arc, the height of the volcanic edifices, the height of the base of the arc, the structural features, and other morphotectonic markers. These geomorphological variations must be related with the tectonic history and the interaction between the Chortis Block and the Middle America Trench. The characteristics of the subducted plate in the Middle America Trench are more or less constant or at least with low variability: Slab age, dip, velocity and obliquity. Only the trench towards Costa Rica is varying in its depth as well as the depth of the oceanic plate towards the Cocos ridge.

We have developed different models testing the influence of the considered main forces: Subduction-related arc-normal forces, subduction-related arc-parallel forces and Caribbean drift related forces. Our results show that, to achieve a transtensional state of stress on the volcanic arc, it must be modelled as a lithospheric weak zone, which is coherent with its thermal state, and the forces related with the eastward drift of the Caribbean plate must be higher than those related with the subduction. This means that the coupling on the subduction interface must be low, with or without strain partitioning due to the obliquity of the subduction. The peculiar characteristics of the arc in Guatemala are due to the geometry of the boundary between the plates of North America and Caribe, and the closeness to the Middle America Trench at this point. Here the western edge of the Chortis block is pinned against North America, even with low trench-normal forces, supporting the hypothesis of Malfait and Dinkelman (1972) (later defended by Plafker (1976)), and making this triple junction between the Cocos, North American and Caribbean plates a zone of diffuse deformation. The extension in the western part of the Chortis block, from Guatemala to the Honduras depression, is explained by the geometry of the North American - Caribbean plate boundary and the direction of motion of the Caribbean plate with respect to North America; although in the models without Caribbean-drift forces applied, the extension still happens under the compression related to the subduction as a mechanism of escape-tectonics. The direction of extension is always E-W regardless the magnitude of the applied forces. In short, the state of stress in the northern part of the Central American Volcanic Arc is a combination of the stresses due to the Caribbean-drift and the stresses of the subduction (as is argued by Guzmán-Speziale (2005)), but the latter should not be high and therefore the coupling of the subduction interface should be low or very low, as is calculated by Pacheco et al. (1993) and Lyon-Caen et al. (2006).
Geochemical composition of volcaniclasts from Costa Rica and inferences on subduction parameters of the Late Cretaceous–Paleogene Arc

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Lava clasts in Late Cretaceous to Eocene debris flows are manifestations of the earliest Costa Rican volcanic arc. This study characterizes the petrography and geochemistry of volcaniclasts from four sample locations (Punta Samara, Isla Paloma, Quebrada Buenaventura, and Playa Soley) to determine the subduction parameters for the primitive arc. Low totals from major element analyses, the Weathering Index of Parker (WIP), and an evaluation of the rare earth element (REE) pattern were used to identify altered samples, and only the “freshest” samples were included in this study. Geochemical compositions of the primitive arc lavas (50 to 66 wt% SiO₂) are compared to samples from the volcanic front from the modern arc, concentrating on the Costa Rican and Nicaraguan segments. Selected trace element ratios of these clasts are used to infer subduction parameters including mantle source (Zr/Nb), degree of mantle melting (La/Yb), slab input (Ba/La), and sediment addition (Ba/Th, U/Th). The majority of primitive arc lava clasts originated from a depleted, mantle source (MORB-like), and have higher Zr/Nb ratios than those from modern central Costa Rica (CCR). However, two lava clasts have Zr/Nb ratios similar to CCR volcanics, indicating a contribution from a more enriched mantle source. The degree of mantle melting increases (low La/Yb) with an increase in slab signal (high Ba/La) in the primitive arc clasts, and these values are more similar to what is observed in modern western Nicaragua than in modern Costa Rica. This may be a reflection of a steeper angle of subduction offshore Costa Rica during the Late Cretaceous to the Eocene, possibly because the Farallon Plate was older, colder, and denser than the modern day Cocos Plate. The primitive arc lava clasts have high Ba/Th and low U/Th ratios indicating that the sediment subducted in the primitive arc likely had a carbonate component (high Ba/Th), but lacked the hemipelagic sediment component (high U/Th) that is subducted in the modern arc.
The convergent margin along the Middle America Trench off Costa Rica has been the focus of the first stage of the project SFB574 “Volatiles and Fluids in Subduction Zones”, which aims to better understand the processes involved in the exchange of fluids on erosive margins. The central Pacific region of Costa Rica has the highest seismicity rate along this sector of the trench, coinciding with the subduction of rough-relief ocean floor, which includes seamounts and ridges. The area has generated earthquakes with magnitude up to seven in the past, most recently a Mw-6.9 event in 1999 and a Mw-6.4 in 2002. Precise local earthquake locations and detailed knowledge of the three-dimensional velocity structure provide valuable insights into the dynamics and structure of the shallow part of the subduction zones, including the limits and geometry of the seismogenic zone. As part of the project, 23 ocean bottom sensors and 15 land stations were deployed from April to October 2002 in an area where several subducted seamounts have been detected. Additional readings from 10 of the permanent land stations of the Red Sismológica Nacional (RSN) were included in the database improving the coverage to the expected downdip end of the seismogenic zone. More than 2000 earthquakes were recorded in the target area over the six-month period. Most of them originated offshore, beneath the continental slope and along the plate interface. Fewer were generated close to trench and within the subducting slab. A simultaneous inversion for hypocentre locations and 3D P-wave velocities was performed using a high-quality subset of 595 events including 11310 P-wave arrivals. The microseismicity along the plate interface is distributed in a tightly packed clustering of hypocenters following a clear 20° dipping alignment. It is located on top a low-velocity anomaly (absolute velocities of 5.0 to 7.0 km/s), from 14 to 26 km depth, 59 to 84 km from the trench, respectively. The presence of subducted seamounts on the plate interface locally shallows the onset of seismicity. The downdip limit of the interface seismicity corresponds with the intersection of the slab with the continental Moho. Intraslab seismicity starts few kilometers downdip the end of the interplate seismicity, and coincides with a dipping low-velocity anomaly. We further present the characteristics of the seismogenic zone based on the tomographic results, and review the results in the light of heat flow and controlled source seismology data for this area.
Crustal Thickness of the Central American Arc

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Magmatism resulting from subduction is a source of continental crustal growth, for which crustal thickness is often used as a proxy. Central American subduction is of particular interest due to the extreme variations in geochemical indicators of the depth and degree of melting along the arc. The upper limit of both of these indicators is crustal thickness. Crustal velocities reflect bulk composition. This study focuses primarily on crustal thickness and Vp/Vs for these reasons. Teleseisms recorded on broadband seismometers during the eighteen month PASSCAL deployment of the TUCAN network have been used to determine crustal thickness, Vp/Vs and to develop receiver function images. For each event, a single incident wavefield is deconvolved from each of the 59 P and PP teleseismic arrivals, to generate 1742 receiver functions. The inclusion of PP arrivals is necessary to provide adequate azimuthal coverage. Applying a moveout correction using velocities derived from tomography converts time to depth for the direct P-to-S conversion as well as the first two surface reflected phases. The resulting depth-corrected receiver functions are stacked for a best fit of crustal thickness and Vp/Vs for each station. Along the back arc, crustal thickness is fairly constant ranging from 29-34 km. Crossing the arc in Costa Rica, crustal thickness ranges from 32-39 km dipping from the forearc to the backarc, with the thickest crust just past the volcanic arc. The Nicaraguan transect has more variation in crustal thickness ranging from 25-41 km thinning from the coast to the arc and thickening to the back arc. The thinning below the arc is opposite to what is expected, as magmatism should thicken the crust. It is possible that the image is not the Moho, however it shows continuity. The arc in this location follows the Nicaragua graben, so crust may be stretched and thinned. This may result in a focusing of arc magmas to a region of thin crust. Along the forearc crustal thickness ranges from 25 km in Nicaragua to almost 50 km at the far end of the forearc transect in Nicaragua. Vp/Vs ranges from 1.66 to 1.88 with uncertainty. The most notable variation in Vp/Vs is along the back arc where a clear transition between a low and high Vp/Vs delineates the transition from continental crust to accreted arc terranes. Images are created of the crust and upper mantle through stacking of receiver functions for each section and smoothing along a given transect. All cross sections reveal layered structure in the upper crust. The most striking feature is a dipping structure between the subducing slab and the Moho beneath Nicaragua present in the first three converted phases. If interpreted as a discontinuous feature this may be the base of a magma chamber or a region of varying composition. If interpreted as a continuous feature, this may be a portion of slab from a previous subduction event.
The Farallon plate break-up: Plate tectonic reconstructions and implications for the Central American subduction zone

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The break-up of the Farallon plate was the most important event during the Early Miocene plate tectonic reorganization of the East Pacific. The opening of a new oceanic spreading center perpendicular to the existing Pacific spreading is unique and probably had far-reaching consequences for the active continental margins of Central- and South America. Most of the original fissure where the Farallon plate split into the Cocos plate and the Nazca plate has already been subducted beneath Central- and South America together with much of the oceanic crust that was formed during the early phase of Cocos-Nazca spreading. This made a full reconstruction of plate kinematics in the area back to the time of the opening poorly constrained and left many questions open about the mechanisms involved and the subduction zones affected by this event.

During a R/V Sonne cruise in late 2004 the area conjugate to the Farallon remains offshore Costa Rica and Ecuador was investigated in the Central Pacific around 120°W, just south of the Equator. With the new magnetic data it was possible to identify seafloor spreading anomalies between chrons 7 and 5A for a large area in the Central Pacific. In combination with picks of the same anomalies from the Cocos- and Nazca plates it was possible to trace back the history of the Farallon break-up in a three-plate reconstruction. The plate motion of the Pacific plate in the hotspot reference frame provides the absolute position of the initial triple junction and the strike direction of the newly formed Cocos-Nazca spreading center, revealing its close relation to the Galapagos hotspot and the Central American subduction zone. The multibeam bathymetry data from the research area highlight the details of an increased magmatic activity near the newly formed triple junction and the reorganization of the seafloor spreading that followed the break-up and which finally resulted in a major ridge jump at the East Pacific Rise during chron 6.

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Different Cl reservoirs have unique ($\delta^{37}$Cl) signatures, thereby making chlorine stable isotopes a potentially powerful tracer of chlorine sources in subduction zones. We have developed a sample preparation method for volcanic gases trapped in Giggenbach flasks, based on the oxidation and acidification method of Eggenkamp (1994), with careful modification to remove excess sulfur. Samples with high concentrations of Cl- are analyzed using the dual inlet method ($I_f = \pm 0.1^\circ$). Analyses on low [Cl-] samples are analyzed using continuous flow (20 1/4g Cl- per analysis; $I_f = \pm 0.3^\circ$). The Cl isotope composition of volcanic gases (gas fumarole and gas condensate samples), associated hydrothermal waters from volcanic centers, and ash from along the Central American arc (CA) have a remarkable range in ($\delta^{37}$Cl) values from $-4$ to $+12^\circ$. Volcanoes along the CA have a bimodal distribution based on ($\delta^{37}$Cl) values: very positive ($+4.0$ to $+12.1^\circ$) and slightly negative ($-0.6$ to $-4.0^\circ$). Gas fumarole samples from Poás (Costa Rica) (T range from 112 to 153ºC) have the most positive ($\delta^{37}$Cl) values ($+5.2$ to $+12.1^\circ$) of all volcanoes analyzed. However, the crater lake and side streams at Poás has near zero ($\delta^{37}$Cl) values with little to no variation over time. Nearby, Turrialba and Irazu (Costa Rica) (fumarole T for both volcanoes <100ºC ) have negative ($\delta^{37}$Cl) values (both averaging $\sim -2^\circ$). Santa Ana (El Salvador) and Momotombo (S. Nicaragua) (fumarole T's = 400ºC and 750ºC, respectively) have ($\delta^{37}$Cl) values of $+6.3$ and $+4.0^\circ$, respectively. San Jacinto, San Cristobal, and Cerro Negro (N. Nicaragua) (fumarole T for all three volcanoes <100ºC ) have negative ($\delta^{37}$Cl) values (ranging from $-2.2$ to $-1.6^\circ$). Fuego (Guatemala) (fumarole T <100ºC ) is $-0.6^\circ$. Preliminary analyses of ash samples from Cerro Negro and Momotombo range from 0.8 to 1.6º, significantly different from volcanic gas analyses from respective volcanoes.

In order to evaluate the isotope data and Cl behavior in a volcanic system, HCl liquid-vapor fractionation experiments were conducted (Sharp and Barnes, 2006). There is no fractionation of highly concentrated HCl at room temperature. However, there is a large liquid-vapor fractionation ($\sim8^\circ$) of dilute HCl at 100ºC, which is most relevant to natural samples.

Although additional fractionation experiments are necessary and the effect of hydrothermal systems on ($\delta^{37}$Cl) values must be evaluated, some tentative conclusions can be drawn from the present data. The highly positive fumarole ($\delta^{37}$Cl) values from Poás may be explained by Cl fractionation in a boiling system based on our experimental results with Poás recording a mantle-like signature. Further north, Momotombo and Santa Ana are high temperature systems recording little to no Cl fractionation and a sediment-like signature. Fuego, San Jacinto, and San Cristobal are low temperature systems and their negative ($\delta^{37}$Cl) values may be due to sediment contribution as a residue of vaporization or the vapor of pore fluid contribution. However, large fractionations associated with hydrothermal systems may limit the applicability of chlorine isotopes as a geochemical tracer in volcanic system, but volcanic ash samples may prove highly useful.
On November 20, 2004 a strong earthquake was felt through most of the Costa Rican territory. The earthquake had a magnitude Mw 6.2 and its epicenter was located at the central Pacific coastal region. It originated a great amount of damage to the nearby populations (many houses and stores). There were severe cracking and soil settlement as well as liquefaction phenomena, because the epicentral area is located on an alluvial plain, crossed by many unstable rivers and a coastal area constituted by sandy beaches and mangrove areas. The earthquake provoked 8 indirect deaths and economic loss was estimated in 5 million dollars. The maximum intensity recorded was VII (MM) at the epicentral area. The tectonic of the central Pacific region of Costa Rica is regulated by the subduction process of the Cocos Plate under the Caribbean plate, but other important horst and graben structures, transverse to the subduction, were responsible of the November 20, 2004 earthquake.
Studies of both large and small magnitude earthquakes in the Central America subduction zone show a significant amount of heterogeneity in earthquake occurrence and rupture history. An unusual tsunami earthquake occurred along the Nicaragua margin in 1992, yet not along the Costa Rica margin. Additionally, large earthquake occurrence along the Costa Rica margin appears to be segmented in conjunction with structural features on the incoming Cocos Plate. These variations in large earthquakes also affect smaller magnitude seismicity, as microearthquakes can cluster in certain locations, some in regions of past bathymetric feature subduction, possibly indicating along-strike coupling variations. We characterize this heterogeneity in several ways and present results from several ongoing seismic studies of the region. First we will present slip distributions for a series of large earthquakes within the Costa Rica subduction zone, including events in the region of the proposed CRISP drilling efforts. These slip distributions show significant variability in the level of slip complexity, mimicking variations in the subducting plate. We will focus on a few of these events to look at earthquake triggering effects. For example, the 1990 Nicoya underthrusting event triggered both interface aftershock events as well as inland seismicity within the months following the event. These results suggest variations in the stress conditions along strike. Finally, we will present new estimates of earthquake stress drop along the Costa Rica plate interface based on earthquakes recorded by the CRSEIZE experiment. These estimates again support the claim of significant along-strike variation, similar to other ongoing work of earthquake b-value variations between coupled and uncoupled portions of the margin.
**Time-sequential apatite volatile histories**

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Apatite is a commonly occurring phenocryst phase in melts of a wide variety of compositions, and is potentially useful as a barometer for many volatile species including H, C, F, S, and Cl. We report exciting new results in the world of apatite chemistry which suggest that apatite may not only provide useful constrain on pre-eruptive water contents, but also on the timescales of crystal residence and volatile activity fluctuations in magmas.

Secondary ion mass spectrometry (SIMS) profiles of hydrogen concentrations generated from ~8µm analyzed areas in polished apatite phenocrysts demonstrate that all analyzed apatites contain unzoned core regions with a mean concentrations of ~4000 ppm. Distinctively oscillatory but decreasing OH concentrations toward C-axis terminations are observed, along with oscillatory variations in chlorine that are inversely correlated with OH in some regions of the crystals.

We suggest that apatite core OH concentrations reflect diffusive equilibrium with a quiescent water-rich host magma over timescales of one or more months. Rapid overgrowth of apatite occurred under greatly varying conditions, with crystallization and subsequent residence time not exceeding a few days. Despite probable modification by diffusion, these overgrowths are the time-sequential record of variations in OH, Cl and F in the apatite. All crystals contain similar patterns until late in their crystallization histories, when in some cases they diverge greatly, suggesting that different crystals record different parts of the same magmatic story. Experimental determination of the relationship between OH in apatite and H2O in the host melt will allow us to relate observed variations in OH content in apatite to magmatic variations.

The next step in our MARGINS-funded project designed to determine the utility of apatite as a volatile barometer is to apply it to volcanic apatite phenocrysts from the Central American volcanic arc. In addition to our successful measurements of OH, we hope to use carbonate in apatite as an effective measure of carbon in the host melt, an effort that has been to date limited by surface contamination and low carbon concentrations in volcanic apatite crystals.
We would like to inform the general Costa Rica margins community proposed DYNASEIS IODP initial plan that includes three instrumented CORK sites in the mid to upper slope region of the subduction forearc of Nicoya. These sites will augment the two existing ODP Leg 205 CORK sites at the toe and on the incoming plate to form a transect of instrumented observatories across the margin. The additional sites would be positioned with one seaward and one landward of the proposed locked region of the seismogenic fault determined by land geodesy. These positions would allow us to study both the continuous build up of strain in the interseismic period as well as the nature and timing of episodic strain release, and associated seismic noise, earthquake, pore pressure, pore fluid chemistry, and tilt phenomena that should be observed along the upper portions of the seismogenic region of the subduction fault. In addition, a future ORION-type offshore marine geodetic buoy and acoustic communication system (such as the recently funded GEOCE system; PI’s Kevin Brown, Dave Chadwell, Uwe Send, and Mike Tryon at SIO) could be coupled to the IODP boreholes to build a fully integrated plate boundary observatory system in the future. Such an integrated system could include both near real-time communications and allow the NSF Margins community to simultaneously measure xyz seabed displacements, subsurface tilt, pore pressure transients, and any related seismic activity emanating from the subduction system.

The Middle America subduction forearc is a natural laboratory for the study of a wide variety of geodynamic, geochemical, and hydrologic interactions. In this setting there are distinct variations in earthquake behavior, plate coupling, incoming plate topography, and forearc deformation that suggest these characteristics can be linked to systematic changes in the behavior of the subduction thrust and thus reveal the geodynamics of the forearc as well as the origins of the changes in arc geochemistry. For example the presence or absence of seamounts and large normal fault offsets in the incoming plate could well be significant factors controlling the margins behavior. This margin is also highly active hydrologically and it is probable that the geodynamic activity may also be at least partially controlled by fluid flow and resulting heat flow patterns.

We propose, given the probability that significant arc parallel changes in plate, forearc, and arc behavior are coupled, there is a case to be made for drilling more than one transect along the margin. This would allow us to compare and contrast processes occurring, for example, in a region of Cocos Ridge and associated seamount subduction (CRISP) with the subduction of relatively smooth incoming plate in Nicoya (DYNASEIS). The types of accretionary/erosional and seismogenic processes appear to be very different between these two settings so comparisons would reveal much about the fundamental underlying causes of along strike variations in margin behavior. We welcome anyone interested in participating in DYNASEIS to join us. Just some of the people active in this program are: Kevin Brown (kmbrown@ucsd.edu), Nathan Bangs (nathan@utig.utexas.edu), Susan Schwartz (susan@pmc.ucsc.edu), Kirk McIntosh (kirk@utig.utexas.edu), Andrew Newman <anewman@gatech.edu>, and Glen Spinelli (spinelli@ees.nmt.edu). Ralph Stevens (rstephen@whoi.edu), Shermin Ge (ges@spot.colorado.edu), Miriam Kastener (mkastner@ucsd.edu), Barbara Bekins (babekins@usgs.gov), Time Dixon (t Dixont@rsmas.miami.edu), Peter lafemina (plafemina@geosc.psu.edu)
Mass Wasting, Seamount and sediment Accretion in the Osa Peninsula, hanging wall of the Middle American Trench (Eocene-Miocene, Southern Costa Rica)

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The Osa Peninsula (OP), located in southern Costa Rica, is part of the exposures of the trailing edge of the Caribbean Plate (CP) that form the hanging wall of the Middle American Trench in Costa Rica and western Panama. Since its first exploration by Dengo (1962), the OP has generally been considered to be part of the Nicoya Complex (NC). However, recent studies have shown important differences in comparison with the NC: 1. Sediment ages associated with the lavas of the OP are Campanian-Maastrichtian and thus younger in age than in the NC. 2. The outer part of the OP is formed of sediments that have been produced by mass wasting and have been emplaced in an accretionary prism. 3. The geochemistry of the igneous rocks is different from the NC. We present a new geological map, tectonostratigraphy and genetic interpretation of the OP, based on mapping (at 1:5000 scale), sedimentology, foraminifer and radiolarian biochronology, structural interpretation, and geochemical analysis of igneous rocks. The OP can be divided in two geological complexes: 1. The Osa Igneous Complex (OIC), on the inner, northeastern side of the peninsula. 2. The Osa-Caño Accretionary Complex (OCAC), on the outer, southwestern side of the peninsula and on Caño Island. OIC is mainly constituted by basaltic rocks that contain only minor amount of siliceous, calcareous and clastic sediments. The OIC is formed by four tectono-stratigraphic units which are separated by highly deformed paleo-sutures, that likely resulted from accretion processes. They provide access to deeper parts of the accreted crust. Later (post mid Miocene) tectonic processes, that occurred in response to the subduction of the Cocos Ridge beneath the OP, did not alter the global arrangement of the accreted units. The rare sediments (<1% of total volume) have provided biochronological ages ranging from Campanian to Eocene. Variations of sediment composition and age correlate with variations of igneous geochemistry, and suggest that the OIC is made of accreted slices of seamounts, defined here as different lithological units. The OCAC, which is entirely composed of a mélange, has been divided into three units on the basis of sediment associations and biochronological ages. Our more recent 1:5000 mapping of the coastal and river outcrops indicates that the mélange adjacent to the OIC is composed of tectonized tuffaceous, calcareous and siliceous sediments which locally contain variable amounts of igneous blocks and megablocks and reworked shallow-water limestones. On the basis of textural and lithological observations, we concluded that the mélange is made of variably deformed, accreted sedimentary series, mainly of arc provenance. New geochemical data of the OCAC confirm that the mélange contains a major proportion of arc-derived sediments and volcanic blocks. On the other hand, the mélange also contains blocks of oceanic (sea mount) origin that share an identical sedimentology and igneous geochemistry with the OIC units. To us, this indicates that a certain volume of the OCAC was generated by mass wasting (gravity reworking) of already accreted seamounts of the OIC. We therefore interpret the OIC as the backstop against which the OCAC accreted, principally during the Eocene. The OP offers the unique chance to carry out on-land studies of the uplifted hanging wall of the Middle American Trench that recorded seamount accretion, mass wasting and mélange formation. Numerous exposures give direct insights into processes, such as gravitational emplacement, brittle fracturing, accelerated diagenesis and hydrothermal alteration in a high fluid pressure environment, as well as larger scale tectonic processes related to decollement. Further studies will help to better constrain our models of subduction processes in intra-oceanic areas.
Geoacoustic investigations of cold vents and sedimentary processes at the active continental margin offshore Nicaragua

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The amount and mechanisms of volatile and fluid recycling along subduction zones is an important question for an estimation of their feedback on the global climate, and their capability to trigger natural disasters like submarine landslides, earthquakes, or volcanic eruptions. To locate and investigate such cold seep sites on the seafloor and in the shallow sub-seafloor, geoacoustic methods are applied. This presentation shows examples of cold vents and seeps in the forearc region of the active continental margin offshore Nicaragua imaged with multibeam bathymetry and associated amplitude measurements, high-resolution, 75 kHz deep-towed sidescan sonar and corresponding 2–10 kHz chirp subbottom profiler, and hull-mounted parametric echosounder. Ground truthing is available from camera system surveys and coring on several of the structures.

The area investigated is characterized by a high number of so-called mound structures visible in the multibeam bathymetry, and various intensity anomalies without a significant topographic expression but showing high backscatter in the sidescan sonar image. The increased backscatter on mounds and intensity anomalies is mainly attributed to an increased seafloor roughness or hardgrounds like authigenic carbonate formations. A significant influence of the seafloor topography on to the sidescan sonar signal is ruled out for the IFM-GEOMAR DTS-1 system.

Based on their morphology, backscatter signal and fluid venting activity a classification of the seep sites with three end members is suggested. (1) Mid-sized and dome-shaped mounds have diameters around 700–1000 m and heights of 50–100 m, and show bright backscatter due to authigenic carbonates with some fluid vents and an associated vent fauna. (2) Small mounds with very little topographic expression have diameters around 500 m and show irregular outlines. Authigenic carbonates are sometimes covered with sediments, the mounds show no signs of erosion. A wide range of vent biota indicates stronger fluid venting activity. (3) Very large and steep mounds have diameters exceeding 1000 m and heights up to 150–200 m. The plateau areas show widespread, thick authigenic carbonates. Subbottom profiles show no sediment coverage. Vent fauna is rare indicating little to none fluid venting activity. The calculated ratios of mound volume to base area show no clear clustering matching the mound types, but are a measure of how much a mound is exposed above the seafloor.

The shaping of the mounds is strongly affected by erosional processes which are active on the slope, like it is shown very clearly where canyons incise deep into the slope. The mounds which consist of a mixture of mud and authigenic carbonates have a higher resistivity against erosion and form topographic highs over time. The geoacoustic data show no signs of mud volcanism like mud flows or other deposits of eruptive processes. However, subbottom profiles do show signs of upward moving sediments in the shallow subsurface which are interpreted as diapirc processes. In which depth such sediment mobilization is originating is unknown. It is speculated that the sediments are mobilized by the dissociation of gas hydrates in the shallow subsurface. The hydrates in turn are decomposed by upward travelling warmer fluids from larger depths.
Volcanic arcs that form above subduction zones represent the accumulated magmatic output of the subduction process. Understanding of this output, along with a well-constrained input, is critical if we are to reach an understanding of the melting processes that occur within the subduction factory. During 2005 we carried out a large active source seismic experiment in Costa Rica to examine melting within the Costa Rican segment of the Central American arc. Two transects were surveyed: 1) Across-arc from the Pacific to Caribbean oceans and 2) Along the strike of the volcanoes from Panama to Nicaragua. A total of 742 vertical component geophones were deployed at an average spacing of 200 m along the across-arc transect and 372 m on the along-arc transect. Seismic sources were spaced approximately evenly along the lines with a total of 20 shots recorded across the arc and 15 along the arc.

We present here data and results from the 153 km long across-arc transect. Shot sizes ranged from 300 to 1025 kg of buried explosive, depending on local site conditions, and consistently allow us to observe strong arrivals to >70 km offset. In many cases refracted energy is observed at >100 km offset. Deep reflection events can be observed on several shots and are interpreted as Moho reflections. We show the velocity structure across the Central American arc to the back-arc basin: we have very good sedimentary and upper crustal velocity constraints along the entire transect.
Evolution of the Recent Coastal and Alluvial Systems at Parrita-Quepos Area, Central Pacific of Costa Rica

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The evolution of the coastal and alluvial morphology during the past 50 years in part of central pacific area (From Esterillos to Quepos) has been analyzed. The clearest evidence of change at the coastal zone is the Damas sand bar migration. The possible causes of this migration are a combination of local agents (e.g. tectonic setting). An increment in the amount of water transported by the principals streams channels; an the increase of waves, tides and currents energy are the possible responsible for the morphological changes of Damas sand bar.

Because of tectonic factors, normal sea level rise, and climatic changes the sedimentary system at the zone is transgressive. The analysis of the morphological and sedimentological changes associated with the local tectonic setting suggests a SE inclination of the zone. The alluvial system presents a meandric belt (Parrita River), which migrated SE the actual alluvial plain. This “abnormal” situation would have been generated by the SE inclination of the area.
Three tectonic factors shape the volcanic font in Central America and affect the geochemistry of lavas. First, Central America does not have the convex outward arc-shape typical of oceanic arcs. The center of the arc, Nicaragua, is the furthest out of position. The large trenchward migration of the Nicaraguan volcanic front from Oligocene to the present and the current steep dip of the Nicaragua segments of the arc suggest that subduction related forces are deforming the Central American margin toward an island arc shape. The geochemical pattern that correlates with this is the pronounced along strike variation in slab signals such as Ba/La, U/Th, Sr, Nd, Be and O isotopes. The most robust variation, Ba/La, can be traced back 25 My (Plank et al., 2002). The favored explanation for the geochemical variations is linkage between the degree of melting in the mantle wedge and the concentration of hydrous fluxes entering from the slab. This suggests a requirement for fluid mechanical models of Central America: steeper dip and more concentrated flow from slab to mantle wedge at the centre of the margin, compared to the flanks.

The second tectonic factor is the pattern of right steps in the volcanic front. The geochemical signal (Bolge, 2005) that mimics the steps is comprised of abrupt changes in Nb depletion across each step: with Nb depletion higher at the volcano closest to the trench. Between steps, Nb depletion decreases to the SE, creating a saw-tooth pattern. These strong variations in Nb depletion are best explained by a smooth, unsegmented Benioff zone which allows the saw-tooth variation in Nb depletion to reflect change in the depth to the seismic zone. Most of the volcanic lines in Central America cross-cut rather than parallel the isobaths to the seismic zone. With regard to the consistent right steps, Central America is unusual among the global set of arcs. An ad hoc structural model is required, linked perhaps to the oblique motion of the margin relative to the fixed hotspot frame.

The third tectonic factor is the uneven distribution of volcanic output along the volcanic front. This is similar to the segmented pattern caused by the right steps but differs because the largest volcano is usually not at the step but 50-100 km SE of the step. This suggests that the magma generating region is both chemically zoned (from high Nb depletion at shallower depths to low Nb depletion at greater depths) and has an optimal depth for magma productivity, close to the shallow end but not at it. The largest volcanoes appear to get the full variety of magmas produced flux melting and back-arc decompression melting. However, their high productivity favors long-lived magma chambers that allow mixing to obscure the variety of inputs.
Subduction input, fluid processes and magma source of the Central American Volcanic Arc: A trench to arc perspective from lithium isotopes

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Lithium is moderately incompatible in magmatic systems and is therefore enriched in the crust relative to the mantle. It is highly soluble in aqueous fluids. Its two stable isotopes (6Li and 7Li) readily fractionate during near surface processes. Their distribution in the subduction zone provides valuable information on the movement of crustal material through the subduction system. Below is a summary of work done at the Central American Volcanic arc (CAVA), which consists of a systematic study of oceanic crust before the trench (ODP site 504B), sediment, pore water and tephra at the Costa Rica subduction zone (ODP 1039 and 1040), and the lavas from the volcanoes in Guatemala, El Salvador, Nicaragua and Costa Rica.

Alteration of oceanic crust by seawater at low temperatures results in enrichment in Li and d7Li (7Li/6Li ratio relative to L-SVEC) due to incorporation of seawater Li into secondary phases. Conversely, hydrothermally altered crust is depleted in Li and isotopically light. Clay-rich sediments before the trench (Sit 1039) have d7Li of 2 to 8°. Associated pore fluids show large variations of Li abundance and isotopic ratio reflecting ion exchange, ash alteration, and injection of basement fluids into the sediment column. At site 10401, fluid within the decollement is distinctly enriched in Li and lighter than the adjacent pore fluids, providing evidence of migration of a deep-seated fluid possibly originated from the transformation of smectite to illite.

Lithium contents (Li/Y = 0.2 to 0.5) and d7Li (4.1 to 6.4°) of basaltic lavas from the arc are moderately enriched relative to the upper mantle. During metamorphic dehydration reactions, Li partitions into the fluid with preferential enrichment of 7Li. Li/B ratio increases from Nicaragua to Costa Rica revealing different fluid release patterns as a function of subduction zone temperature. The relatively narrow Li isotopic range of arc lavas has been attributed to equilibration of slab-derived fluids with the subarc mantle (Tomascak et al., 2002). Despite this, Li isotope values of Nicaragua lavas are well correlated with other subduction-related properties suggesting addition of slab-derived fluids that are enriched in 7Li to the mantle domains. Tephra samples recovered from cores at the forearc region of Costa Rica permits reconstruction of tectonic erosion since 2.5 Ma. Li/Y and d7Li (to 14°) are elevated in rhyolitic lavas suggesting addition of heavy Li through forearc tectonic erosion and crustal assimilation.

In summary, Li isotope studies of CAVA reveal fluid expulsion through the accretionary prism, the control of fluid release by the thermal structure, Li isotope fractionation during metamorphic dehydration, enrichment of arc magma by slab components, and forearc erosion in the past.

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Monitoring thermal activity at Santa Ana volcano, El Salvador.

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Abstract: Spaceborne and land-based remote sensing provides an effective way of monitoring the highly active volcanoes of the Central American arc. Satellite remote sensing techniques are used to conduct a detailed study of thermal activity as it relates to eruption conditions at Santa Ana volcano, El Salvador. Thermal anomalies recorded by high spatial resolution (15-90m) multispectral satellite sensors, e.g. ASTER and LANDSAT, as well as moderate spatial resolution (1km) sensors, e.g. MODIS and AVHRR, provide a regular proxy for thermal output from eruptive and passive activity at volcanic centers like Santiaguito, Fuego, Pacaya, Arenal, and Santa Ana. At Santa Ana, anomalous pre-eruptive fumarolic activity was observed prior to the 2005 eruption.
Decompression and slab melting have long been regarded as minor processes relative to flux melting at volcanic arcs. Existing geochemical evidence for these mechanisms has often been viewed as indicating anomalous dynamic conditions such as arc extension or the vicinity of slab edges because geodynamic models of subduction zones throughout the 80s and 90s did not show the required upwelling to produce decompression melting and predicted slab surface temperatures (SSTs). As geodynamic models have continued to improve, decompression and slab melting mechanisms for magma generation now appear likely without requiring anomalous conditions. The simple jump from geodynamic models with a constant viscosity structure to temperature-dependent viscosity result in a change of corner flow regime from no upwelling to one with upwelling of hot asthenosphere beneath the arc. Likewise, a temperature-dependent viscosity structure results in increase of 100-200 degrees C predicted slab surface temperatures as more cold lithospheric material is sequestered in the upper plate and inhibited from “coating” the slab with an insulating layer. This increase brings slab surface temperatures close to that of the sediment solidus. Better treatment of the fault zone using a strain-rate and temperature-dependent rheology increases the predicted slab surface temperatures even more. Other processes such as asthenosphere flow around slab edges and frictional heating will only add to these increases, indicating that melting at arcs may involve multiple processes at any one time.

Moreover, arc-parallel shear wave splitting and geochemical observations imply along-strike flow at numerous Pacific subduction zones. These observations present a challenge to geodynamic models of plate-driven subduction systems as plate-driven flow models predict arc-perpendicular fast direction with simple (A-type) mineral texturing. Although B-type mineral texturing would rotate the fast directions 90° relative to A-type and likely occurs in the forearc mantle, such texturing is unlikely in the asthenosphere wedge with its higher temperatures and weaker rheology. The flow velocity in the subarc asthenospheric mantle may be constrained by tracking mineral texturing development within model flow fields including along-strike flow. In the case of the Tonga subduction systems, models without a low-viscosity channel beneath the arc fail to simultaneously satisfy the shear wave splitting and geochemical constraints. The best fit to the observations are models with along-strike flow within a low viscosity channel beneath the arc at rates substantially faster than the plate motion velocities, suggesting that 3D effects may be integral to understanding arc generation processes.
Earthquake Energy: A Reanalysis of M>5.5 Earthquake Rupture Energies in Central America, and Rapid Assessment of Large Earthquake Durations.

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We use the radiated energy to moment ratio, E/M₀, developed by Newman and Okal (1998), to reanalyze seismicity in Central America, particularly along the Middle America Subduction Zone off Costa Rica and Nicaragua. Because tsunami earthquakes, such as the 1992 Nicaraguan Earthquake, have a slow rupture source, they are deficient by more than an order of magnitude in radiated seismic energy, as compared to other earthquakes of similar moment release. We build on a regional study by Okal and Newman (2001), with the inclusion of 6 years of earthquake activity with improved network coverage. We explore the feasibility of additionally incorporating regional and local recordings that are affected by Moho triplications and are highly sensitive to precision in focal mechanism determinations. While the previous study found a modest increase in deficient earthquakes, it was inconclusive. While the current work is preliminary, we hope to develop a more definitive assessment of regional energy release and determine if there are along-strike or along-dip variations along the Middle America Subduction Zone. Such refinements are useful for local real-time detection of slow source “tsunami earthquakes”. Additionally, we will report on another adaptation of the methodology for rapid assessment of earthquake rupture duration of recent global large shallow earthquakes. We find that by examining high-frequency energy rise and fall in near-real time, we can determine the approximate rupture duration of a host of recent large global earthquakes, and tsunami earthquakes. Because the speed of calculations is negligible and only earthquake location, and approximate depth information is necessary, this methodology is effective for rapid, real-time assessment of rupture duration.
Rethinking melt inclusions in solidifying magmas: Cerro Negro, a case study

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Melt inclusions (MI’s) are commonly assumed to represent a discrete point in time or ‘snapshot’ of an entire magmatic system. MI’s, however, may only represent composition of liquid in the immediate surrounding of a host crystal at time of entrapment, and may not reflect the composition of the entire system. Sampling of the boundary layer and re-equilibration by diffusion are two processes known to skew MI compositions from that of the host magma (Qin et al., 1992, Gaetani and Watson, 2000, Faure and Schiano, 2005). Here I show how the nature of crystallization itself causes MI’s to reflect the liquid immediately surrounding the crystal, but not that of the entire system.

In magmas associated with subduction zones, crystal growth has previously been attributed to decompression crystallization due to ascent of a water saturated magma body. During decompression crystallization, crystal growth is pervasive, and the liquid surrounding any crystal, and that trapped within a MI, should be approximately that of the entire body. However, if the magma body stalls, or rises slowly, crystallization is no longer due to decompression, but rather by loss of heat to wall rock. Crystallization is now restricted to within solidification fronts. The composition of the liquid is dynamic within solidification fronts, and MI’s no longer represent just a point in time, but also a discrete point in space (‘photomicrograph’). Even if sampling of the boundary layer and diffusional effects can be assumed, or shown, to be negligible, it remains questionable what MI’s truly represent.
Using Postseismic Observations to Constrain Rate and State Model Parameters for Aseismic Slip Events in Shallowly Dipping Subduction Zones

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In modeling subduction earthquake sequences with rate and state friction, multiple factors influence the predicted slip distributions with depth and time. A low effective normal stress near and somewhat downdip from the base of the seismogenic zone may be the result of a shallowly dipping oceanic crust passing through a series of dehydration reactions beginning at ~250°C (Peacock & Wang, Sci., 1999). Such a stress state can lead, in modeling, to episodic aseismic transient behavior with recurrence times on the order of one year (Liu & Rice, to JGR, 2007). Step-like perturbations of stress by earthquakes in the slab, or simply along-strike variations in rate and state constitutive parameters (a and a – b), can also lead to aseismic slip events without needing to severely lower the effective normal stress, although recurrence intervals may then be of order tens of years. Elevated pore fluid pressures beneath the accreting wedge from compression and smectite dehydration aid slip, whereas dilatant effects during shear should transiently reduce pore pressure and impede rapid motion. The balance between these effects determines how the rupture propagates towards the trench and may affect tsunamigenesis. A two state variable rate and state representation better fits data from rock friction experiments, especially at the high temperatures towards the base of the seismogenic zone (Blanpied et al., JGR, 1998), and the choice of state variable evolution law and the number of state variables changes the transient slip distribution with depth.

To better constrain the representation of these parameters, we are comparing model predictions to known post-seismic slip and deformation in subduction zones. Aseismic transients are observed in shallowly dipping subduction zones and therefore the GPS-constrained 1995 Colima-Jalisco, Mexico, earthquake (slab dip of 17 degrees) is a good candidate for this comparison. We use a 2D continuum model to predict interseismic and postseismic slip distributions. The slip inversion by Hutton et al. (GJI, 2001) for the 1995 Colima earthquake provides a rough along-strike dimension, and we use this to extrapolate an along-strike variation in 3D slip distribution. We calculate surface displacements predicted by rate and state modeling with different parameter choices and compare these to observed GPS displacements to refine the modeling.

Current continuum models show coseismic rupture propagation extending to the trench, while seismic imaging indicates that slip may be transferred to splay faults in the overlying wedge, an observation consistent with fault branching theory (Kame et al., JGR, 2003). The GPS observations indicate a large amount of postseismic slip in the shallow subduction zone, near the trench, but the large coseismic slip predicted in this area in some models limits the predicted amount of postseismic slip there. The incorporation of dilatancy into the rate and state continuum model (e.g., Segall & Rice, JGR, 1995; Taylor, Ph.D. Th., 1998) should act to stabilize an otherwise unstable fault zone, especially at depths where the effective normal stress is low, and thus more accurately represent the coseismic and postseismic slip distribution allowing for better constraints on the effective normal stress and friction parameter distribution.
Nicoya Complex (Costa Rica) - a Cretaceous Plateau containing Middle Jurassic to Cretaceous radiolarite blocks

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We re-examined igneous and sedimentary rocks and radiolarian biochronology in the NW-Nicoya Peninsula, where the Nicoya Complex s. st. was originally defined. The geologic data mapping, and the new Ar/Ar-dates and igneous isotope geochemistry done by other authors, do not confirm either one of the current hypotheses on the tectonostratigraphy of the area. Neither alpine-type nappe structures, nor a threefold magmatostratigraphy, in which an oceanic basement and its Jurassic-Cretaceous sediment cover would be overlain by Upper Cretaceous plateau basalts. Herein, we re-assess field relationships between igneous rocks and radiolarites, and document refined.

We now interpret the Nicoya Complex s. str. as a fragment of a Cretaceous plateau created by uplift and southward tilting during an early Campanian collisional event. The deepest levels of the Plateau are exposed in NW-Nicoya, where over 50 % of the igneous rocks are intrusives (gabbros and plagiogranites) that have a single mantle plume source, common with the basalts. Ar/Ar-dates range from Valanginian to Campanian. Radiolarian-dated, Bajocian (Middle Jurassic) to Albian (middle Cretaceous), Mn-rich radiolarites, are set as stratigraphically incoherent blocks in a “matrix” of multiple basalt flows, subsequent intrusions and cross-cutting dykes and sills. Chilled margins of magmatites, and hydrothermal baking and leaching of the sediments confirm the Ar/Ar-dating of igneous rocks being consistently younger than most of the radiolarian cherts. No Jurassic oceanic basement has been identified so far at the outcrop level in the Nicoya Peninsula, but it could be buried beneath the surface. The Jurassic-Cretaceous chert sediment pile became disrupted and detached from its original basement by multiple intrusions during the formation of the Plateau. Radiolarian-dated, Coniacian - Santonian (Late Cretaceous) thin, Fe-rich radiolarites are largely synchronous and associated with late phases of the Plateau.

Coseismic uplifting of the Caribbean coast of Costa Rica

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Costa Rica is located in the southern Central America. Tectonically, this zone is controlled by several regional structures. In the Pacific face of Costa Rica the subduction of the Cocos plate beneath the Caribbean plate, and the Panama Fracture Zone is the boundary between the Cocos and Nazca plates. In the Caribbean face, the northern edge of the North Deformed Panama Belt is the most remarkable structure. The Limon earthquake took place in April 22, 1991 (Ms7.6) in the Caribbean face of Costa Rica, 1991, with an epicenter located, 36 km SW of the Limon downtown, at 10 km depth (Plafker and Ward, 1992, Goes et al., 1993, Lundgren et al., 1993, Suarez et al., 1995). One of the most spectacular effects of this earthquake, was the coseismic uplifting of the shoreline, ranging between 1.85 m and 0.75 m in the Limon area, and between 0.6 m and 0.5 m in the Cahuita-Gandoca area (Fig. 1). Inland deformation was calculated by surveying of tower lines of ICE (Instituto Costarricense de Electricidad) reaching around 4.5 m of uplifting (see figure). The occurrence of this earthquake put in evidence the stepping-way of Pleistocene land growing of the Caribbean side of Costa Rica, in relation to the action of the North Deformed Panama Belt. Due the presence of coral material in ancient uplifted platforms, it was possible to sample and survey in order to study the history of Holocene tectonic history. We mainly sampled Acropora palmata and Diploria clivosa coral species, same species that were exposed and died in 1991. The study was based on about 20 C-14 ages. The C-14 ages were calibrated and the nowadays elevation was corrected with the eustatic sea level curves. Based on the obtained data we determined the existence of a neotectonic secondary ENE fault in the Cahuita area, where the NW block relatively upped respect to the SE block. The average velocity of uplifting was determined as 1.75 mm/year through the Holocene.
References


Seismogenic zone structure along the Middle America subduction zone, Costa Rica, revealed by high-resolution earthquake locations and seismic velocities

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Most large (MW > 7.0) underthrusting earthquakes nucleate along a shallow region of unstable frictional stability on or near the subducting plate interface termed the seismogenic zone. High-resolution images of seismicity and seismic velocity derived using advanced earthquake location and tomography techniques and local earthquake data can lend insight into the thermal, mechanical, hydrological, and compositional interactions potentially responsible for controlling shallow subduction zone seismicity. We utilize such methods to investigate along-strike spatial and temporal variability in microseismicity and seismic velocity and provide spatial constraints on the updip and downdip limits of microseismicity within the Middle America subduction offshore western Costa Rica. Waveform and initial earthquake arrival data was collected as part of the Costa Rica Seismogenic Zone Experiment (CRSEIZE), a collaborative seismic and geodetic study undertaken from September 1999-June 2001 near the Osa and Nicoya Peninsulas, Costa Rica. We invert for 1D P- and S-wave velocity models, station corrections, and hypocenter parameters for both the Nicoya and Osa datasets to provide the best initial data for further studies. We analyze seismogenic zone structure offshore south-central Costa Rica by calculating absolute and relative relocations of ~300 aftershocks of the 1999 Quepos, Costa Rica, underthrusting earthquake. Subduction of highly disrupted seafloor north of the Osa Peninsula has established a set of conditions that limited the seismogenic zone to be between 10-35 km below sea level, 30-95 km from the trench axis. For the locked, Nicoya Peninsula segment of the subduction zone, we calculate high resolution earthquake locations and P-wave and P-wave/S-wave 3D velocity models using an iterative, damped least squares local tomography method. In the southern Nicoya Peninsula, microseismicity along the plate interface extends from 12-26 km depth, 73-100 km from the trench axis, while in the northern Nicoya Peninsula where hydrothermally cooled oceanic crust subducts, interplate seismicity extends from 17-28 km depth, 75-87 km from the trench axis. Seismic velocity results suggest 10-30% serpentinization of the mantle wedge along the Nicoya Peninsula with the continental Moho occurring at 30-34 km depth.
Correlation Studies of Flow-correlated Seismic Noise

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and others.

A six-month deployment of OBSs and collocated flowmeters (measuring fluid flow through the sea floor) has discovered an intriguing correlation between seismic noise observed on at these same instruments. This offers the opportunity to explain some of the interaction between subducted fluids and the earthquake process. This correlation was observed on three instruments at the toe of the sedimentary wedge off Costa Rica.

Brown, Tryon, Deshon, Dorman, and Schwartz (2005) described the observations and proposed a tectonic mechanism which explained the data, but other models could not be excluded. Their analysis included analysis of vertical component data from individual instruments. We are pursuing this analysis, including horizontal and pressure components. Initial results indicate that coherence between some components exists, so there is cause for hope that additional information from existing data can be brought to bear on this fascinating topic.

There is the potential to determine the mode of propagation of the correlated noise as well as the faint possibility that some directional information can be extracted.

Correlation analyses of OBS data have been used by Bradner (1974), as well as Schreiner and Dorman (1990).
Subduction is the principal driving force for tectonic processes and yet there is still much to understand about these complex systems, particularly the role of water in melt production. It is important to comprehend how the migration of water released from the subducting slab into the overlying wedge interacts with flow and temperature patterns, in addition to the role it plays in reducing the solidus temperature. Porous flow processes, density driven diapirs, or a mode of fracturing typically explains water transport within a subduction zone. We present results from a series of 3D laboratory subduction models, which consider an alternative model or direct advection of the hydrous boundary layer from above the slab up into the wedge corner.

A fiberglass plate and glucose syrup are used to model the slab and upper mantle, respectively. In each case the subduction is run until the slab tip reaches a scaled depth equivalent to 700km. A grid of passive bead tracers is then emplaced above the slab to mark the upper edge of a hydrous boundary layer (HBL). Models are run from this initial condition for a range of imposed (e.g. kinematic) subduction styles and back-arc spreading scenarios to test the feasibility of vertically advecting hydrous mantle into the shallow wedge. Parameters included the separation rate and position of a back-arc spreading center (BASC), the mode of producing back-arc extension (e.g., slab rollback vs. motion of the overriding plate), and changes of the dip angle with time.

Without back-arc extension or rollback, the HBL is dragged downward with the slab. Experiments show episodic HBL advection and hydrous melting events occur in response to complex, time dependent 3D flow driven by a combination of early BASC extension, slab roll back, and changes in dip angle. Slab steepening and larger back-arc trench separation distances limit vertical HLB advection. Retreat of the overriding plate from the trench and a decreasing slab dip (e.g., slab stalling at 670km combined with trench rollback) tend to enhance vertical HLB advection. A simple model is used to calculate characteristics for hydrous melting related to these events.
Subduction dynamics, three dimensional mantle flows and the geochemical evolution of the Trans-Mexican Volcanic Belt

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Despite being mostly underlain by the same plate the Trans-Mexican Volcanic Belt (TMVB) and the Central America volcanic arc (CAVA) show notable differences. The CAVA is relatively narrow and parallel to the trench whereas the TMVB is has a large variation in width and is not parallel to the trench. Both arcs show compositional variations although in the TMVB they are more extreme than in the CAVA. In both arcs slab windows and/or slab detachment have been inferred and the resulting mantle flow may have controlled the geochemical heterogeneity of volcanism.

In the TMVB the evaluation of a geochemical data base (~3,000 samples), constrained by geological and geochronological information, allowed establishing patterns of spatial and temporal geochemical variability, and their relation to changes in the subduction dynamics. These, in turn, were analyzed in three dimensional numerical models which provide insight on the dynamic of subduction and mantle flow. TMVB volcanism began in middle Miocene (19 to 11 Ma) forming a broad arc of central vents in central and eastern Mexico, with calcalkaline, intermediate composition (SiO$_2$: 61.8±5.8), subduction related rocks [e.g., low Nb (<13), relatively high Ba/Nb (24-131), and low TiO$_2$/K$_2$O (<1.0)]. The adakitic character and inland migration of the arc at the end of this episode in the central TMVB suggests a flat subduction geometry. Between ~11.5 to 6.5 Ma (locally until 3 Ma), an eastward migrating pulse of mainly fissural mafic volcanism (SiO$_2$: 50.2±4.0) generated calcalkaline and Na-alkaline magmas; this pulse has been related to the eastward propagation of a slab detachment episode that initiated at the mouth of the Gulf of California after the end of subduction of the Magdalena microplate. From 7.5 to ~3.0 Ma, large calderas and dome complexes of silicic composition (SiO$_2$: 70.3±6.0) were emplaced just to the south of the previous episode. In the western TMVB they were accompanied by low volume OIB-type lavas. We relate the silicic episode to the slowing down of subduction because of the loss of slab pull after the detachment episode, which produced a reduced mantle flux, lower magma production and slab rollback. At the same time OIB lavas suggest infiltration of asthenosphere material into the mantle wedge. In Pliocene-Holocene times, the arc continues migrating toward the trench and magmas display a strong compositional variability. Calcalkaline rocks with high Ba/Nb (<1415) are common throughout the arc; K-alkaline magmas (shoshonitic, lamprophyric) dominate in the arc front; mafic OIB-type volcanism occurs in several sites, sometimes associated to peralkaline rhyolites. Mg#$ and Ba/Nb ratios disminish with distance to trench, and crustal contributions match the wide range of variation in crustal thickness of the region (15 to 47 km). Numerical models show that the increase in slab dip is controlled by the development of a critical volume of low viscosity material forming in the mantle wedge. They also indicate that asthenospheric material from the Gulf of California diverging margin may have infiltrated laterally into the mantle wedge above the free edge of the Rivera plate once the slab started to roll back in latest Miocene.
Mantle structure, dynamics and melting in the Nicaragua-Costa Rica Subduction Zone

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Arc volcanics in the Nicaragua-Costa Rica subduction zone manifest strong along-arc variations in geochemical indicators of slab-derived fluids and extent of melting, making this region key to testing models of subduction zone dynamics and melting processes. A primary goal of the TUCAN Broadband Seismometer Experiment is to image the structure of the subducting slab, mantle wedge and overriding plate beneath this region in order to better constrain thermal structure, hydration, mantle flow, and possible patterns of melting and melt transport. The TUCAN array, funded by the MARGINS program, was in the field from July 2004 to March 2006; it included 48 broadband stations in fore-arc, back-arc, and two dense cross-arc lines. A variety of analyses of TUCAN data are now underway, including: travel-time tomography and earthquake relocation, attenuation tomography, tomographic inversion of shear-wave splitting measurements for three-dimensional anisotropy, crust and mantle interface s from receiver functions, surface wave tomography, aftershock studies, and a search for anomalous low-frequency events.

The velocity and attenuation tomography reveal a high velocity, low attenuation subducting slab, a shallow wedge corner with intermediate attenuation, and a slower, more highly attenuating mantle wedge beneath the arc and back-arc. However, strong regional variations are superimposed on this common subduction zone structure. Beneath Nicaragua, the upper slab is slower and more attenuating than the slab beneath Costa Rica, consistent with greater hydration in the subducted crust and underlying mantle of the Nicaraguan slab. In addition, the deep mantle wedge in Nicaragua is more highly attenuating, a result that is consistent with hotter or more hydrated mantle in the zone of potential melting. These findings correlate with arc geochemical data that suggest a larger influence of slab-derived fluids and greater extents of melting beneath Nicaragua. A particularly intriguing finding is the presence of a column of high Vp/Vs (P-wave velocity/S-wave velocity) rising from the slab interface directly beneath the arc in Nicaragua. This anomaly could reflect the presence of melt.

Shear-wave splitting measurements from local events recorded by the TUCAN array manifest arc-normal fast directions in the fore-arc, where waves sample the shallow wedge corner, while fast directions beneath the arc and back-arc are variable but are dominated by zones of arc-parallel values. We have tomographically inverted these splitting measurements, and in the resulting three-dimensional models of anisotropy, olivine a-axes vary in the mantle wedge beneath the arc and back-arc, but significant volumes of roughly arc-parallel a-axes exist. Splitting in SKS and other teleseismic core phases shows a more uniform pattern of arc-parallel fast directions and much larger splitting times, indicating significant arc-parallel-fast anisotropy is present both deeper in the mantle wedge and/or beneath the subducting plate. Anisotropy with an arc-parallel fast direction in the mantle wedge beneath the arc and back-arc cannot be explained by simple two-dimensional arc-normal corner flow, even allowing for B-type olivine lattice preferred orientation in the shallow wedge corner, but it is consistent with arc-parallel flow.

To test models for upper-plate deformation, we have relocated events in the sequence surrounding a Mw 6.3 earthquake that occurred in Lake Nicaragua in August, 2005. After relocation using a double-difference algorithm, these earthquakes sharply delineate an ENE-striking vertical fault plane that aligns with one of the nodal planes of the mainshock and with its rupture directivity. These results provide evidence in favor of the bookshelf-faulting model of upper plate deformation proposed by LaFemina et al.
Volatiles release from the subducting slab into the mantle wedge plays a central role in initiating melting at subduction zones. The goals of this study are 1) to investigate how efficiently nitrogen and CO2 are transferred from the slab through the wedge to the surface in the Central America subduction zone and 2) how variable gas compositions are at a particular volcano.

We collected a total of ~140 gas samples at fumaroles, hot-springs and mud-pots covering 32 volcanic centers in the arc (Costa Rica: 7, Nicaragua: 8, El Salvador: 10, Guatemala: 7) and 9 centers in the back-arc (Honduras). The same localities were sampled simultaneously for CO2-He isotope systematics. The dry (water free) composition of gas samples is dominated by CO2 (up to 965 mmol/mol). Samples contain from < 1 to ~ 100 mmol/mol N2. We see systematic variations along the volcanic front: Costa Rica and S-Nicaragua have low N2/He (<150), N2/Ar (<80) and negative δ15N (-0.5° to -3.0°), similar to MORB (-5 ± 3° [1]). N-Nicaragua, El Salvador and Guatemala generally have N2/He > 1000, N2/Ar > 80 and positive δ15N up to 6.3°, similar to δ15N measured in seafloor sediments (5.7° [2]). The back-arc has consistently low N2/Ar (< 80) and δ15N ranging from -0.6 to -3.5°. The δ15N of olivines and fumarole gas discharges from the same volcanic centers are indistinguishable within error, suggesting that both media (phenocrysts and gases) sample magmatic volatiles. CO2/N2 varies systematically along the arc: Costa Rica gases have the highest values (up to ~1200 mol/mol); all localities to the north of Costa Rica have low values (< 200); back-arc samples have high values (up to ~2000). CO2/N2 (org. + oxidized C) input is estimated at ~ 320 based on ODP legs off Costa Rica [2]. CO2/N2 and N isotope systematics suggest that sedimentary nitrogen is off-scraped (or released in the fore-arc) in Costa Rica but not in the rest of the arc. CO2 continues to devolatilize from the slab in the back-arc, whereas nitrogen is efficiently released below the volcanic front.

Poás volcano has become more active starting in 2004 with frequent phreatic eruptions in 2006, an increase in lake temperature to 47°C in February 2007, the occurrence of new fumaroles and the increase of fumarole temperatures from boiling (2001 to 2004) to >200° in 2006 and 2007. From 2001 to 2005, we have quantified the following changes at Poas 1) increase in SO2 emissions from 10 tons/day in 2001 to 80 tons/day in 2003 to 500 tons/day in 2005, 2) increase in CO2/He ratio of the gases, 3) a decrease in CO2/Sulfur and CO2/HCl in the gases and 4) an increase in gas equilibrium temperatures. The implications of these changes will be discussed.

The inner forearc of the Middle America Trench records a complex pattern of faulting, uplift, and crustal thickening that contrasts with the subduction erosion and extension of the outer forearc. Quaternary to recent uplift patterns are characterized based on geologic mapping, cross sections, and dating of fluvial and marine terraces. These patterns differ between the area of seamount subduction and the area of Cocos Ridge collision. Inboard of the region of seamount subduction, the inner forearc is segmented by steep faults that allow lateral variations in uplift, with the greatest uplift rates directly inboard of the regions of greatest outer forearc subsidence. We suggest that decoupling can occur at the base of seamounts (i.e., the originally sedimented seafloor on which the seamount lavas are laid down) and that such seamounts can be accreted to the forearc above and lead to coastal uplift. Such basal decoupling is known to occur under active volcanic islands in the open ocean in connection with rifting and gravitational spreading, such as beneath the island of Hawaii. The spatial and temporal patterns of coastal uplift and subsidence on active margins can therefore record the local history of seamount subduction.

In contrast, the inner forearc inboard of the incoming Cocos Ridge is characterized by undethrusting of the outer forearc along a system of out-of-sequence thrust faults, or active faults well arcward of the MAT (i.e., the Fila Costena thrust belt). The thrust belt, which telescopes the forearc basin strata, shows large along-strike variations in shortening in response to 5 cm/yr. lateral migration of the Cocos-Nazca-Caribbean triple junction. After passage of the triple junction, the overriding Caribbean plate is subjected to a large increase in convergence rate and subducting seafloor roughness as well as a decrease in slab dip. In general, the decollement depth and total shortening are greatest directly inboard of the subducting Cocos Ridge. In this region, new mapping depicts a duplex with five horses, with imbricate thrusts rooted at the contact between Eocene limestones and the oceanic basement of the Caribbean plate. The roof thrust wraps around the southeastern edge of the duplex where the shortening decreases dramatically. Given age constraints on the initiation of thrusting, the total shortening from balanced cross sections of the thrust belt (20-30 km) near the onland projection of the PFZ indicates that thrust slip rates represent a significant percentage (10-40%) of the total plate convergence between the Cocos and Caribbean plates. Thus, the onset of rapid, shallow subduction has resulted in locking of the outer forearc, with an arcward shift in the focus of plate convergence to an upper plate shortcut that deforms the fore-arc basin.
Seismicity of Southern Nicaragua and Northern Costa Rica: A Combined Offshore and Onshore study

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As part of the collaborative research center SFB574, the Central America subduction zone is being investigated by a seismological research subproject conducted by Costa Rican and German partners. The general goal of SFB574 is to study the origin and influence of volatiles and fluids in subduction zones. The seismological subproject constitutes the structural and seismotectonical framework of these investigations. Under this framework, several seismological network installations had already been accomplished.

The amphibious network TOMO was operated from November 2005 to May 2006 encompassing the Isthmus of Nicaragua and northern part of Nicoya Peninsula, Costa Rica. The network comprises 19 ocean bottom seismometers provided by IFM-GEOMAR, Kiel and 35 land stations provided by GFZ, Potsdam and Red Sismologico Nationale (RSN), Costa Rica. Approximately 2000 earthquakes were recorded during the observation period. These events are located using a previously defined 1D model for this region. We observe two prominent features: 1.) The intermediate and deep events, giving a preliminary idea of the geometry and the dip angle of the slab. In comparison to central Costa Rica, the dip angle is steeper. 2.) Clusters of events in the region of continental slope which are related to the faults. These faults can be possible pathways for fluid flow. Fluid flow may generate earthquake clusters.

For further insights into the composition and physical state of the lithosphere and the dynamics of the subduction zone, focal mechanism solutions and local earthquake tomography is going to be performed in the continuation of this work.

Non-volcanic tremor studies in Costa Rica

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The general goal of SFB574 is to study the origin and influence of volatiles and fluids in subduction zones. The role of the seismological subproject A2 in this general framework is the exploration of the structural and seismotectonical settings. In addition to other installations an array of 6 short period borehole stations were installed in Nicoya Peninsula in northern Costa Rica. The aim is to observe and investigate non-volcanic tremors (NVT).

Non-volcanic tremors were firstly observed in Japan and are correlated to creep events. NVTs are believed to be indicative for fluid release in the subducting plate. NVTs are usually described with following patterns:

a) They can be detected in a frequency band between 1-5 Hz.
b) The onset is emergent and the P-Phase is not recognizable.
c) Noise amplitudes correlate with several stations.
d) The duration of the tremors is 4-20 minutes.

We found an evidence for the occurrence of non-volcanic tremor events in Costa Rica.
A combined tomographic inversion of two independent amphibious networks in Costa Rica

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The subduction zone structure and related processes have been investigated with local earthquake tomography in central Costa Rica. The data sets of two independent adjacent amphibious networks, JACO and QUEPOS, were combined for a simultaneous inversion of hypocenter locations, 3-D P-wave velocities and Vp/Vs ratios using ~3000 high quality events. The problem of lack of the resolution at the intersection of the two networks was solved by a spatial overlap of the data, which is supposed to provide an improved interpolation. The synthetic tests confirm the reliability of the solutions and indicate that the study area is well constrained down to 50 km depth. Depending on the results, the seismicity of the Wadati-Benioff zone decreases from northwest to south east Costa Rica. Plate interface seismicity extends from 12-20 km below sea level and interplate seismicity begins downdip of the plate interface which correlates with the intersection of the slab and the continental Moho which corresponds to 35-40 km depth.

There are three prominent tectonic features that can be clearly identified from the velocity model and the earthquake distributions: 1) a 4-10% positive velocity perturbation down to 60 km depth related to the Cocos Plate subducting under Costa Rica. The earthquakes of intermediate depth are mostly located in the uppermost part of the slab and are supposed to be caused by dehydration embrittlement associated with metamorphic phase transformations. 2) a 10-20% velocity decrease reaching down to 20 km depth at the margin wedge. 3) negative velocity perturbations under the volcanic arc which can be caused by high content of upwelling fluid and magma, confirming the fluid release from the slab. This interpretation is supported by petrological modelling based on the correlation between the seismic wave velocity, H2O content and metamorphic phase transformations. It provides a better insight into the origin of seismicity of the seismogenic zone, which is supposed to be generated by interactions of thermal, mechanical, hydrological and compositional processes in the subduction factory.
The investigation of widespread tephra formed by highly explosive, mostly Plinian eruptions at the Central American Volcanic Arc (CAVA) yields important data to better understand arc magmatism and subduction-related processes. Two aspects are emphasized here:

Hazard aspects

Widespread tephra are stratigraphic markers, often radiometrically dated, that put time constraints on volcanic evolution. They reveal the explosive eruptive history of individual volcanoes as well as the approximate ages of more local, smaller-scale volcanic events producing deposits intercalated between the tephra. Such temporal constraints allow to estimate probabilities of future volcanic activity. Plinian activity of the Chiltepe volcanic complex and surtseyan/strombolian eruptions at the Nejapa-Miraflor lineament in Nicaragua are used to demonstrate working examples.

About a third of the widespread tephra produced at the CAVA, and almost half of those produced in Nicaragua, have basaltic to basaltic-andesitic compositions. Mafic Plinian eruptions, presently considered as exotic events, are in fact a common phenomenon at the CAVA that is not yet appreciated in hazard assessments.

Arc magma production

Widespread tephra represent 65% of the total magma mass erupted to the surface at the CAVA during the past c. 300,000 years. Integrated over this period, the average magma production rate per unit length of the CAVA as evidenced by volcanic edifices and widespread tephra was 2.6 g/ms. However, the highly explosive part, and probably the entire arc magmatism, apparently evolved through cycles of increased activity with periods of about 100,000 years. Moreover, when considering production rates for tectonic segments of the arc separately, these increase systematically from Costa Rica/Nicaragua to a maximum at northern El Salvador to then drop toward Guatemala.

Arc magmas are generally believed to be produced by hydrous melting of the mantle wedge metasomatized by fluids from the subducting slab. However, the along-arc magma production rate variation shows no relation to geochemical slab signals of the arc magmas. Previously proposed relations to slab dip are also not evident. The northward increase in magma production rate does, however, increase with the intensity of bend faulting on the outer rise of the subducting plate, which is interpreted as a proxy of pre-subduction hydration of the plate. Seismological and heat flow studies support such hydration offshore Nicaragua, where an input of 5 g/ms of water into the subduction system can be estimated and contrasts with an output of 0.1 g/ms at the volcanic arc. Further studies are needed to address questions such as:

• is the water influx higher at northern El Salvador with its peak magma production?
• is thicker crust responsible for lower production rates at Guatemala?
• where does the subducted water go that does not return via arc volcanism?
• how large is the intrusive component of arc magmatism?
Towards Quantifying Volatile Fluxes and Origins from the Costa Rica Fore-Arc Using Novel Submarine Instrumentation

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Measurements of volatile output and composition at fore-arcs and back-arcs are critical to complete a realistic volatile mass balance for subduction zones. Volatile fluxes at the fore-arc are severely under-constrained, in spite of abundant evidence for fluid venting along submarine margins. We present new dissolved volatile and related flux rate data for submarine seeps in the Costa Rican fore-arc. We report $^3\text{He}/^4\text{He}$ ratios, $\delta^{13}\text{C}$ values as well as He and CO$_2$ abundances for seep fluids issuing at ~1km water depth at Mound 11 and Mound 12. The two mud volcanoes, which are located ~30km arc-ward from the trench, emanate fluids formed by clay-mineral dehydration within the subducted sediments, channeled upwards through the margin wedge along deep-seated faults. Pore fluids yield high concentrations of methane, which is mainly derived from thermal decomposition of organic matter [1, 2].

Seep fluids were collected in copper coils attached to Chemical and Aqueous Transport (CAT) meters [3] deployed for a period of 12 months in June, 2005 with DSV Alvin. The system is designed specifically for serial sampling of fluids and their preservation at ambient pressure for follow-up analysis of the dissolved volatile content. For a first set of analyses, dissolved volatile characteristics were determined in two sampling coils – one yielding the highest flux rate (up to 25m/yr) but normal salinity, B, and Mg content and the other with low salinity and Mg and high B concentration, interpreted to reflect input of deep fluids. Fluids in both coils are supersaturated in CO$_2$ with respect to seawater, indicating addition of extraneous carbon. The large range in $\delta^{13}\text{C}$ values, from -11‰ to -60‰, is consistent with mixing of isotopically depleted CO$_2$ derived from methane oxidation with enriched CO$_2$, possibly originating from the mantle ($\delta^{13}\text{C}=-6$‰). Two additional water samples obtained using major (Ti) bottles during reconnaissance Alvin dives at Jaco Scar yielded slightly elevated $^3\text{He}/^4\text{He}$ ratios of ~1.4R$_A$, suggesting a small but discernable input of mantle-derived He (8R$_A$).

Adopting the approach of Mau et al. [4], we estimate ~800mol/yr of CO$_2$ is released at Mound 11, based on observed flux rates (2-5cm/yr) and CO$_2$ concentrations (up to 0.34 cm$^3$STP/gH$_2$O), and the total area covered by bacterial mats (500-1700m$^2$ [4]). Extrapolated over the 48 mud extrusions along this 350-km long section of the Costa Rica margin, we calculate a total CO$_2$ output of ~4 x 10$^4$ mol yr$^{-1}$ [4]. Carbon loss (CO$_2$ plus methane) through fluid seepage appears to be significantly lower than the carbon potentially available by subducted sedimentary input via the trench (5.7 x 10$^7$ mol km$^{-1}$ yr$^{-1}$ [5, 6]). However, our calculation is based on data from a single mound and only includes CO$_2$ emission from the area covered by the dominant vent fauna. A significant amount of CO$_2$-rich fluid might be lost through channels in sediments and fractures in carbonates [4] and/or via fluid flow along the décollement zone towards the deformation front [7]. In addition, precipitation of authigenic carbonates is regarded as a major sink of methane-derived carbon at cold seep sites [8]. Alternatively, the system might not operate at steady-state, i.e. subducted sedimentary carbon might be temporarily stored by underplating in the fore-arc region. [1] (Hensen et al., 2004), [2] (Schmidt et al., 2005) [3] (Tyron et al., 2001), [4] (Mau et al., 2006), [5] (Li and Bebout, 2005), [6] (De Leeuw et al., 2007), [7] (Kopf et al., 2000), [8] (Han and Suess, 1989).
Tectonic Mechanisms for the Opening of the Nicaragua Depression

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Lakes Nicaragua and Managua are the two largest lakes in Central America and cover a combined area of ~9800 km² of the presently active Central America volcanic arc (CAVA). As part of the NSF Subduction Factory program, we acquired ~1900 km of shallow geophysical data over Lakes Nicaragua and Managua in May, 2006, to establish their late Quaternary structural and stratigraphic history and to better constrain tectonic models for the opening of the Nicaraguan depression. We took a multidisciplinary approach by integrating these data with earthquake relocations, focal mechanisms, NASA Shuttle Radar Topography Mission (SRTM) data, aeromagnetic data, GPS vectors, onland geology, and two previous seismic profiles across the Gulf of Fonseca to investigate upper crustal deformation resulting from forearc sliver transport and/or slab rollback of the Cocos plate.

Both lakes and the Gulf of Fonseca form three isolated sub-basins within the Nicaragua Depression, an elongate, asymmetrical, 40-100-km-wide depression extending the length of Nicaragua and into the Gulf of Fonseca and eastern El Salvador. Across-strike profiles of the Nicaragua Depression using shallow seismic profiles and SRTM topographic data indicate a consistently asymmetrical basin controlled by northeast-dipping faults along its southwestern edge. Prominent northeast-dipping surficial faults have been imaged in the Gulf of Fonseca and south of Lake Managua (Mateare fault zone). In general, surficial faults are well exposed in the absence of volcanoes but absent or subtle adjacent to clusters of stratovolcanoes. We used an aeromagnetic data set to better constrain the subsurface location of other segments of the north-east dipping normal or oblique-slip fault that imparts the prominent asymmetry to the Nicaraguan depression. The fault along the southwestern coast of Lake Nicaragua was not imaged in this study but can be seen as a prominent discontinuity on the aeromagnetic map. Faults imaged in Lakes Managua and Nicaragua mainly strike parallel to the long axis of the valley and are interpreted as antithetic normal faults formed during motion along the larger basin-edge fault to the southwest. One major transverse (east-west) fault was mapped across Lake Nicaragua. This fault is left-lateral and formed a large clastic wedge that we have dated as Holocene in age.

Our new observations can be used to examine previous models for the opening of the Nicaraguan depression which are based either on earthquake data or surficial mapping studies. These models can be divided into two main groups: 1) basin opening along normal faults parallel to the trend of the depression; transverse faults at right angles to the trend of the valley are thought to function as transform or transverse faults during opening; the mechanism of opening is attributed to slab rollback; and 2) basin opening along transtensional strike-slip faulting parallel to the trend of the depression; strike-slip tectonics is related to the northwestward motion of a forearc sliver known from GPS studies. Our studies show that slab rollback is the likely cause of the asymmetrical half-graben basin shape. Strike-slip faulting likely plays a role in modifying these extensional fault structures.
Rhyodacite formation in Central America: U-series disequilibrium and implications for petrogenetic processes in the Central American arc.


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U-series isotopes were measured on rhyodacite whole rocks and mineral separates from three calderas (Ilopango, Apoyeque and Apoyo) in El Salvador and Nicaragua to assess changes in petrogenetic processes for silicic magmas from north to south along the Central American arc. Analyzed whole rocks and mineral separates from the northern-most caldera, (Ilopango, El Salvador) yield Th isotope activity ratios ((230Th/232Th)) of ~ 1.5, whereas a basaltic enclave from a resurgent dome within Ilopango caldera has a slightly higher activity ratio of 1.6. This suggests that the parental magma has a higher (230Th/232Th) than the evolved magma, which may reflect persistent fractionation of trace phases with U>Th. Mineral-separate isochrons from this system are consistent with the young eruption age (1600 yrs) of Ilopango caldera. All samples are characterized by enrichments in 230Th over 238U. In central Nicaragua, where subduction fluxes to the mantle are considered to be significantly higher (e.g. Patino et al., 2000), dacites from Apoyeque caldera have (230Th/232Th) of 2.5- 2.7. Basalts and andesites from this region have (230Th/232Th) = 2.2 - 2.6 and small 238U excesses over 230Th (Thomas et al., 2002). Further to the south, rhyodacites from Apoyo caldera, Nicaragua have (230Th/232Th) of ~ 2.2, which is slightly lower than values measured for lavas from the nearby Masaya and Grenada volcanoes, but significantly higher than a basalt that erupted near the end of the caldera producing episode, which suggests again that the rhyodacites in this system are produced by fractionation of local more mafic magmas. Positive correlations between (230Th/232Th), Ba/Th, and Ce/Pb, as well as large differences in Th isotope ratios north to south suggest that these differences correspond to changes in the amount of subducted sediment involved in magma genesis. Nevertheless, samples from all three systems have 230Th excesses, which is significant because most of the more mafic rocks from this area have 238U excesses that result from fluid addition from the slab. The Sr, Nd, and Pb isotopic compositions of the rhyodacites are similar to those of nearby more mafic magmas, which further illustrates that they are genetically related, and that older crust is not assimilated to any great measure in these lavas. All of the volcanic rocks from the Central American arc have 143Nd/144Nd and 87Sr/86Sr values that positively correlate (e.g. Feigenson et al., 2004), which may be a function of variable fluid addition.

Jurassic to Miocene Costa Rican oceanic complexes: description, geochemistry and sources

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The oceanic complexes of Costa Rica have a special place in Caribbean geology, especially after the influential work of Dengo (1962). Although these oceanic complexes are dismembered and disrupted, they are the only exposures that can be used to understand the uncertain early history of this active margin. The six major exposures are: 1) The Santa Elena Peninsula, comprised of the Santa Elena Nappe - formed in a supra-subduction zone setting and the Santa Rosa Accretionary Complex - an igneous-sedimentary sequence of Aptian-Cenomanian age that includes OIB segments. 2) The Nicoya Peninsula formed by a Jurassic-Cretaceous sequence that is part of the CLIP (Caribbean large igneous province). 3) The Tortugal area comprised of the Tortugal Suite with an OIB signature, surrounded by Nicoya Complex. 4) The Herradura Block divided between the Tulán Formation, which represents a Maastrichtian to Lower Eocene accreted oceanic island and the Nicoya Complex as the basement. 5) The Quepos Block geochemically and geochronologically correlated with the Tulán Formation. 6) The Osa-Burica Block composed by the Golfito and the Burica Terranes geochemically and chronologically correlated to the Nicoya Complex, the Early Paleocene to Early Eocene Rincán Block accreted seamounts, and the Miocene Osa-Cá O Accretionary Complex. The Nicoya Complex and the rest of the CLIP oceanic complexes are characterized by a typical flat chondrite normalized REE pattern, HFSE ratios between EMORB and NMORB, and 207Pb/204Pb ratios of 15.53-15.57 and 206Pb/204Pb of 8.54-19.00. The Cretaceous oceanic islands/seamounts show LREE enrichments of more than 100 times chondritic, HFSE ratios between EMORB and OIB values, and 207Pb/204Pb > 15.57 with a trend toward EMII. The post-Cretaceous ocean islands/seamounts show average LREE enrichments up to 50 times chondritic values, HFSE ratios vary between the those of CLIP and the Cretaceous ocean islands and have 206Pb/204Pb ratios >19.0, with a trend to a HIMU component. Some lavas from the Osa-Cá Accretionary Complex show LREE depletions and HFSE ratios that suggest a major NMORB source component. The Santa Rosa Accretionary Complex together with the Tortugal Suite has OIB signatures and possible a non-Galapagos affinity. In addition, paleo-Tethys fauna have been found in the overlying sequences of these areas. These coincidences can be explained by the existence of an “autochthonous” Cretaceous fragment formed by these two regions. The rest of the CLIP portions and seamounts were accreted from the end of Cretaceous in the northwest to Miocene in the southeast, forming the oceanic basement of Costa Rica, possibly related to the Galapagos hot-spot. Petrological models suggest a mantle potential temperature of 1450° C and a peridotite source for the CLIP related oceanic crust. The OIB suites show a major peridotite source with a minor pyroxenite component evident in the high-Mg samples. Modeled picroites and primary magmas from Quepos show a two pyroxene-bearing source (opx+cpx+ga) that is evidence for the role of recycled oceanic crust in the genesis of this suite.

Magmatic and structural study of Santa Elena Peninsula, Costa Rica

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We present an integrated study of the magmatic and structural relations of the Santa Elena Peninsula, which is divided into three main units: 1) The Santa Elena Nappe an overthrusted, allochthonous unit of ultramafic and mafic rocks; 2) The Santa Rosa Accretionary Complex, a relatively autochthonous basaltic sedimentary suite, and 3) Islas Murciliago dominated by pillow and massive basaltic flows. Three petrological affinities have been recognized in the Santa Elena Nappe: 1) an ultramafic uppermost mantle complex of serpentinitized peridotites and lesser dunites 2) pegmatitic gabbros, layered gabbros, plagiogranites and basaltic dikes with low TiO2 (< 0.9%) and significant LREE depletions; and 3) doleritic
dykes with higher TiO2 (>0.9%). These mafic associations have geochemical signatures suggestive of an island arc origin and petrographic evidence of ocean floor metamorphism and hydrothermal alteration (greenschist facies). The Santa Rosa Accretionary Complex, includes pelagic and volcanoclastic sediments, tuffs and alkaline magmatic rocks, originated by low degree melting of an OIB mantle source that represent portions of an oceanic island incorporated into the accretionary prism. Islas Murcielago pillow and massive basalts show no clear structural relationship with the rest of the units, but are geochemically similar to the dolerites of the Santa Elena Nappe. Sr, Nd, and Pb radiogenic isotopes of Santa Elena Peninsula do not correspond to the Galapagos hot-spot signature and show different mantle reservoirs and geochemical characteristics than the Nicoya Complex. Based on the collected structural data we proposed two major strike-slip faults: 1) Rio Seco Fault with a NE-SW direction and right-lateral movement and Calera Fault with a NW-SE trending and a left lateral moment. We also suggest that the E-W mayor faults (e.g. Murcielago Fault and Potro Grande) pre-date the strike slip systems and correspond to high angle inverse faults probably related with different slabs of overthrusting. The entire sequence is tilted towards the north from 80° in the southern sections (Islas Murcielago) to 40° in the northern parts of the peninsula (sedimentary sequence). A simplified geological history of Santa Elena is proposed; 1) Magma extraction from the peridotite leaving behind a depleted residue in a supra-subduction environment; 2) The intrusion of pegmatitic gabbros into the peridotite when the host was still hot and plastic, 3) The pervasive intrusion of dolerite dikes into the ultramafics leaving some localized metric size patches of the host rock; 4) This igneous sequence was affected by ocean floor metamorphism (greenschist facies) and then overthrust above the relatively autochthonous Santa Rosa Complex, in an accretion prism of an old subduction zone, 5) The entire sequence at Santa Elena was tilted towards the north, which was followed by the strike slip faults.

New insights into the Miocene-Pliocene magmatism of Costa Rica, Central America

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We sampled and analyzed several basaltic units from the remnants of the Miocene-Pliocene magmatic arcs of Costa Rica. We sampled the Jardin (22.2 Ma), Arrepentidos (17.2 Ma) and Hito Sar (12? Ma) units from the Sarapiqui Arc (22.2-11.4 Ma) located in the modern back arc region. We also collected samples from the Cerro de la Muerte area (13-10.5 Ma), Mano del Tigre Formation (14.1 Ma) and Puerto Nuevo Formation-Dominical area (17.5-11.76) Ma, from the Talamanca Range. Finally, we sampled La Cruz Formation (11.35-10.9 Ma), Grifo Alto Formation (5.1-4.04 Ma) and La Garita Formation (3.2 Ma) from the Aguacate Arc (11.5-3? Ma). With the exception of some samples of the Jardin Unit and Mano del Tigre Formation, the units older than 10 Ma show relatively flat chondritic normalized REE patterns that suggest high degrees of partial melting or a depleted source. After a circa 10-6 Ma magmatic hiatus (as suggested by previous works) the REE patterns mimic the patterns of modern Central Costa Rica which suggest lower degrees of partial melting or an enriched source. A geographical comparison of the new data with a database of the Central American Volcanic Arc illustrate that the Miocene Arc (>10 Ma) show lower La/Yb than the modern central Costa Rica but comparable ratios with Miocene arcs of Balsamo in El Salvador and Coyol in Nicaragua, and also similar to the modern volcanic front ratios of both countries. Ba/La and Zr/Nb are higher than central Costa Rica, and within the range of the modern volcanic front segments of northern Costa Rica and southern Nicaragua, and Miocene Balsamo and Coyol suites. La/Yb, Ba/La and Zr/Nb of the Upper Miocene-Pliocene samples are similar to modern Central Costa Rica values. This suggests that the central Costa Rican (OIB) signature appears in the arc after the 6-10 Ma hiatus and is related with a major tectonic process that is poorly understood and should be study in detail.
The Nicoya, Costa Rica, Geodynamic Control Network

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Abstract

A dense geodynamic control network is being installed on the Nicoya peninsula and its surroundings both, to map and understand the seismogenic zone, as well to record deformation changes at different stages within the earthquake cycle. The Nicoya segment of the Middle America Trench has been recognized as a mature seismic gap with potential to generate an Mw>7.5 earthquake in the near future (it ruptured with large earthquakes in 1853, 1900 and 1950). Low level of background seismicity and fast crustal deformation of the forearc are indicative of strong coupling along the plate interface.

With the goals of finding the upper and lower limits of the seismogenic zone, and for documenting the evolution of loading and stress release along this seismic gap, an international effort involving several institutions from Costa Rica, the United States and Japan is being carried out for over a decade in the region. This effort involves the installation of temporary and permanent seismic and geodetic networks. The seismic monitoring has provided valuable information on the geometry and characteristics of the plate interface and the geodetic networks have helped quantify the extend and degree of coupling. The instrumentation includes digital three-component broad-band and short period seismic stations, and the geodetic network includes temporal and continuous GPS stations as well as electronic tiltmeters. Surface mounted tiltmeters are installed in vaults ranging in depth from 1.5 to 5 m and borehole tiltmeters range in depth from 6 to 80 m. Collaborative international efforts are focused on expanding these seismic and geodetic networks to provide improved resolution of creep events and enhanced understanding of the mechanical behavior of the Nicoya subduction segment of the Middle American Trench.
The role of the slab in influencing the lithium isotopic signature of arc lavas and the mantle


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Initial studies on Li isotopes in subduction zones found correlated Li isotope and fluid-mobile element concentration variations consistent with incorporation of Li from altered oceanic crust into arc lava sources (Moriguti and Nakamura, 1998), suggesting that Li isotopes may be a useful tracer of material transported from the slab to the Earth’s surface. However, subsequent studies on across-arc sections and on a global scale indicated that correlations are generally quite restricted, and it was therefore suggested that Li from the slab is removed from slab-derived fluids/melts in the lower part of the subarc mantle (Tomascak et al., 2000). To improve our ability to understand the Li isotopic signature of arc volcanic rocks, it is important to constrain the Li isotopic composition of subducted material and the isotopic changes that may occur during the subduction process. Moreover, an isotopic characterization of the slab material is critical to track recycled Li in the mantle.

One of the few studies on Li isotopes in subduction-related metamorphic rocks showed that the dehydration of subducted oceanic crust leads to residues enriched in isotopically light Li (Zack et al., 2003). These data, obtained from Alpine eclogites, have also shown that the degree of enrichment in isotopically light Li is dependent on the degree of previous alteration as indicated by high Na contents and a relative enrichment in LREE (Zack et al., 2003). Here, were are carrying out a detailed Li isotope investigation on the now exhumed part of a subducted slab from the Raspas complex (Ecuador) that comprises serpentinites, eclogites, blueschists and high-pressure metapelites. The eclogites have MORB-like trace element signatures and are LREE-depleted. Preliminary data show that eclogites have a light Li isotopic composition with 7Li ranging from 0 to 13. These values are considerably lower than those for both fresh and altered MORB, but they overlap with the Alpine eclogites derived from LREE-enriched oceanic basalts, and may suggest Li isotopic fractionation by dehydration at early stages of metamorphism. Associated blueschists have Li isotopic compositions in between the eclogites and MORB, consistent with only minor dehydration. Further questions to be addressed are: How does the Li isotope signature of the sedimentary part of the slab look like, and how does this signature affect our understanding of the effects on Li isotopes found in arc lavas, and the global Li cycling? What is the influence of the serpentinites, interpreted to represent the mantle portion of the subducted slab, on the Li elemental and isotopic budget?
Estimating magma flux rates into the Central American Volcanic Arc (CAVA) using regional SO2 fluxes from quiescently degassing volcanoes

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Balancing of material input and output at subduction zones can provide essential information on the evolution of the Earth’s mantle and crust. We work at putting constraints on both, input fluxes and igneous production at the CAVA. Mass budgets of igneous fluxes from the mantle and into the arcs is hampered by large errors pertaining to the unknown amount of igneous rocks internally added to the crust (underplating), to the lack of sufficient absolute age constrains on volcanic successions, and to the mostly unknown volume of unconsolidated volcanic ashes eroded away through the geologic record.

Here we report compiled regional SO2 fluxes from continuously active CAVA volcanoes over the last 7 to 25 years (1 and unpublished), and compare them with regional Quaternary volcanic magma fluxes estimated using both volcano volumes (2) and detailed reconstructions of Quaternary volcanic ash deposits from extensive field mapping and marine ash chronology studies (3). Using the simplified assumption that 1000 ppm S on average was dissolved in the magmas at depth, the compiled volcanic SO2 flux of 0.025 g/ms for CAVA translates into a magma flux of 25.1 g/ms. This is an order of magnitude higher than the magma flux of 2.6 g/ms calculated from integrated lava and ash volumes, interpreted to correspond to an extrusive to intrusive ratio of 1:10 for CAVA, which is consistent with models on volcano dynamics. Local deviations at single volcanoes between fluxes calculated using quiescent degassing and those obtained from reconstructed volcano and tephra volumes range between factors of 2.5 and 70, probably reflecting the various observational timescales used. Nevertheless, we demonstrate that regional scale measurements of SO2 fluxes from volcanic arcs may give valid estimates of magmatic arc productivity.

(3) Kutterolf S et al. (submitted) Geochem Geophys Geosys
Preliminary Models of the Thermal Structure of the Costa Rica Margin along the Middle America Trench

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The thermal structure of continental margins provides critical information related to the natural hazards and geodynamics associated with active plate margins. We are integrating seismic data of bottom simulating reflectors (BSRs), in-situ thermal data, data from ODP cores, and numerical models of subduction to estimate the thermal structure along the Middle America Trench of Costa Rica. Seismic reflection data from two cruises, R/V Sonne SO-81, and BGR-99, show that BSRs are widespread and are clearly observed between the lower slope and shelf edge. These BSRs reflect the temperature at the base of the hydrate stability zone and can be used to estimate geothermal gradients along the margin. These estimates are calibrated against in-situ thermal data collocated with BSRs seismic images. Sediment thermal conductivity data comes from both in-situ measurements and needle probe measurements on ODP cores. Additional heat flow data seaward of the trench is being used to initialize thermal models of subduction. With the exception of offshore the northern Nicoya Peninsula values of heat flow decrease landward consistent with the BSR distribution and subduction advecting heat downwards. Estimates of the thermal structure of the margin are coupled to a conduction-advection thermal model of subduction and temperature estimates of the subduction thrust are investigated.
Hydrocarbon-bearing fluids in subduction zone eclogites and serpentinized peridotites, Raspas Complex, Ecuador

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The Raspas Complex, one of the rare occurrences of high-pressure rocks in the Andes can be interpreted as a late Jurassic to early Cretaceous metamorphic ophiolite complex. The Raspas Complex consists of partly serpentinized eclogite-facies metaperidotites of the El Toro formation and of eclogites, garnet amphibolites, blueschists and garnet-chloritoid mica schist of the Raspas formation. Associated with the Raspas complex are other units of MORB-type affinities representing togethe

P-T determinations of the high-pressure metamorphic rocks of the Raspas Complex indicate a subduction of the oceanic lithosphere to a depth of about 70 km (Gabriele et al. 2003, Eur. J. Min. 15: 977-989). Understanding the role of fluid phases in subduction settings, the knowledge of the composition and fluid/rock ratio of high-pressure fluids is a prerequisite. Fluid inclusion studies are obtained from eclogites of geochemically different protoliths, like MORB, OIB and metasomatized eclogites which are cut by zoisite veins representing former fluid pathways, as well as from serpentinized peridotite. Microthermometry and Raman spectroscopy on a large number of primary fluid inclusions in eclogite-facies minerals (omphacite, zoisite, garnet and quartz) of the different eclogite types yield a remarkably homogeneous low-salinity aqueous fluid composition characterized by the presence of CH4. In a mm-thin eclogite-facies zoisite vein, beside the previously mentioned inclusion type, a second type of fluid inclusion coexists which contains CH4 with traces of ethane and graphite. Broad zoisite veins partly with interstitial albite, and thus formed later at decreasing pressures, have similar homogeneous fluid inclusion composition in the system H2O-NaCl-CH4 like the eclogite-facies minerals. This indicates that the fluid composition was homogeneous during the eclogite-facies stage and during subsequent exhumation.

In a partly serpentinized peridotite, recrystallized pyroxene contains very small primary fluid inclusions. From one bigger, at room temperature two-phase inclusion (51/4m in size), a Raman spectrum could be obtained, suggesting the occurrence of mixed hydrocarbons. Such a fluid composition has been analyzed already in mantle-derived rocks, like tectonized peridotites in ophiolite sequences and peridotite xenoliths in alkali basalts (Sugisaki and Mimura, 1994, Geochim. Cosmochim. Acta, 58: 2527-2542). At lower pressures lighter hydrocarbon gases such as CH4 are stable. CH4-H2O-rich fluids, however, are typically produced during serpentinization by seawater reaction with ultramafic material (Kelley et al., 2005, Science 307: 1428-1434). Deserpentinization of the underlying oceanic mantle could thus be a realistic source for liberated H2O and CH4. This fluid could infiltrate the overlying eclogite-facies sequences and lead to the homogeneous fluid composition in the analyzed rocks.
Crustal source components for NW Central American Volcanic Arc lavas

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We evaluate along and across arc geochemical variations in the NW Central American Volcanic Arc from NW Nicaragua to Guatemala. The input from the subducting Cocos Plate consists of carbonate to hemipelagic sediments, seawater altered and unaltered igneous crust and serpentinites. Slab dip decreases while the thickness of the continental crust increases beneath the volcanic front (VF) to the NW. Continental crustal thickness also increases behind the VF.

Our comprehensive geochemical data set consists of major elements, a wide variety of trace elements and Sr-Nd-Pb-Hf-O isotope data. As shown previously by the Carr group, ratios of fluid mobile to less fluid mobile elements (e.g. Ba/La, Ba/Th and U/Th), 143Nd/144Nd and 176Hf/177Hf decrease and Pb isotope ratios increase systematically from Nicaragua to Guatemala. These geochemical variations suggest a decreasing role for a hydrous fluid component and an increasing role for a sediment or continental crustal melt component in volcanic rocks towards Guatemala (NW) along the VF and behind the volcanic front (BVF). Samples from the backarc in Honduras have the most mid-ocean-ridge basalt (MORB) like compositions and are believed to represent the composition of the mantle wedge. Samples from the Nicaraguan VF have similar Nd but higher Sr isotope compositions most likely reflecting enrichment with slab derived fluids containing subducted sediment or seawater Sr.

A positive correlation in 206Pb/204Pb vs. 207/Pb 204Pb isotope ratios for VF and BVF volcanic rock samples from El Salvador and Guatemala trends towards granitic basement. Combined eNd vs eHf isotope data for VF and BVF samples from Nicaragua to Guatemala tend from high eNd and eHf MORB like compositions towards continental crust like compositions with increasingly lower eNd and eHf values, providing further support for a continental crustal component in the generation of the NW CAVA magmas.
Contrasting magmatic processes on El Valle Volcano: 5 ma and 100 ka volcanism

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El Valle Volcano is located in Panama, on the easternmost extent of the Central American Volcanic Arc, where volcanism is related to subduction of the Nazca Plate. Two periods of volcanic activity are constrained by 40Ar/39Ar dating. Andesites characterized a 5 m.y. magmatic activity interval, dated at the base of the sequence by Lissina et al (in press) at 10 ma and at 5 ma by this study in stratigraphically higher localities. The older unit displays typical geochemical properties of arc andesites (SiO2 58.22% S.D. 0.33, MgO 4.29% S.D. 0.36, CaO 8.92% S.D. 1.06) including depletion of the HFSEs. Outcrops of this unit are limited to windows on the massive overlying pyroclastic deposits.

After a period of 5 million years of quiescence, volcanic activity on El Valle Volcano resumed with the emplacement of 100 ka dacitic lava flows and dacitic pyroclastic flows. Lava flows conform the north and south flanks of the caldera. The youngest unit, El Hato formation, represents the eruption of an extensive silicic ignimbrite sheet (approximately 300 km2), which resulted in a 20 km2 caldera. The average thickness of the unit is 15 m but 120 m thick deposits in the walls of river canyons are not uncommon.

The recent eruptive products of El Valle contain little chemical variation both with respect to major and trace elements. For example, SiO2 68.7% S.D. 0.7, MgO 1.03% S.D.0.15, CaO 4.16% S.D. 0.18, etc. In contrast to other young ignimbrites in Central America, this limited variation is unusual and must reflect melting of a relatively homogeneous source.

When compared to the 5 m.y. andesite unit, the recent eruptive products contain lower alkalis, low K2O/Na2O, low Y values and higher Sr/Y values and extremely low HREE concentrations. The low HREE values are consistent with melting of a garnet bearing rock as source for the recent volcanics. Differences in trace element variations in the magmatism from the two periods of volcanism can be used to demonstrate a change from predominantly mantle wedge to slab derived melts. This change may have resulted from the subduction of a relatively warm lithosphere.

Paleogeographic restorations (Meschede and Barckhousen, 2001), are consistent with subduction of old and cold oceanic crust generated at the East Pacific Rise from 10 ma to 5 ma beneath the Panamanian trench. Recent volcanism in Panama could be associated with the subduction of young oceanic crust produced at the Cocos - Nazca Spreading center in the last 5 ma, this is consistent with Meschede and Barckhousen (2001) conclusions. Heat flow data (Sass et al, 1974) also supports the idea of a warm oceanic lithosphere arriving at the Panamanian trench.

Subduction of a warm slab may have lead to partial melting of the subducted lithosphere rather than the mantle wedge. Subduction under these circumstances will be characterized by increased buoyancy (decrease in subduction angle), low seismicity, and partial melting of the slab.
Towards understanding CO2 recycling along and across the Central American arc

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We report CO2 and He results (isotope characteristics, relative abundances and absolute fluxes) obtained for actively and passively degassing volcanoes and volcanic regions of Central America. With the aim of understanding the ins/outs of CO2 cycling, we have targeted volcanic plume emissions, high-temperature fumaroles, geothermal wells, boiling mud pots, hot springs and phenocryst-bearing lavas, and have collected ~140 fluid and ~30 lava samples covering a total of 41 volcanic centers in Costa Rica (7), Nicaragua (8), El Salvador (10), Honduras (9) and Guatemala (7). The focus of our flux (mini-DOAS) measurement and long-term monitoring studies has been Costa Rica (Arenal and Poas). Helium isotope ratios (3He/4He) reach a maximum of 8RA (where RA = air 3He/4He) with most values > 5 RA. Nowhere do we observe values > 8RA, indicative of ‘high-3He’ hotspot contributions: He in the majority of Central America volcanic centers is derived from the mantle wedge. CO2/3He ratios vary between 109 and 1013 covering the entire span seen in the terrestrial environment (hotspots, arcs, MORB): however, gas-poor samples and/or samples with crustal He contributions have outlier CO2/3He ratios (< 5 × 109 and > 1012). The vast majority of samples have ratios between 1010 and 1011 in agreement with 13C of the CO2 for the majority of δ13C observations at other arcs. The samples fall between −5 and −1 ‰ (VPDB): however, lower values (~ −12 ‰) reveal degassing and/or crustal contamination effects.

The entire database has been assessed to identify samples uncontaminated by localised crustal processes (~80% of total) thereby defining the He and CO2 systematics of the underlying mantle source. The provenance of the CO2 released along the volcanic front is dominated by subducted carbon (90-93% of the total) which can be resolved into carbon of marine carbonate (L) and sedimentary (S) (organic) origin. Significantly, there are along-strike differences in the proportions of these components: L/S varies between 5.6 (El Salvador) and 3.8 (Costa Rica) – all values being lower than the L/S ratio of incoming sediment (11; [1]). Coupling the (output) L/S ratios with estimates of output CO2 fluxes ([2-3] and our unpublished data for Costa Rica), we model the proportions of the incoming slab stratigraphy needed to supply the output flux assuming that the L/S ratio of individual sediment units of the slab is not fractionated during subduction [4]. In the case of Costa Rica and El Salvador, we show that sediment only (no crustal basement) is needed to supply CO2 to the volcanic front, albeit with different proportions of the uppermost sedimentary sections off-scraped at each segment. This results in calculated recycling efficiencies (output/input) of 11 and 30% for Costa Rica and El Salvador, respectively [5]. This approach also allows estimation of (a) the potential slab-derived CO2 flux to the fore-arc region (e.g. 7 × 107 gC/km/yr for Costa Rica assuming loss of 74m of upper sedimentary unit U1 [5]). We compare this value to estimates of submarine cold seep CO2 fluxes measured offshore Costa Rica [6]. (b) the L/S ratio of the back-arc (Honduras) in the event of continued volatile loss from the slab. We show that the low L/S ratio inferred for behind-the-front volcanism in Honduras precludes such a mechanism for fluxing volatiles to the back-arc mantle. (c) CO2 fluxes to the deeper mantle. For the Costa Rica segment, we estimate this flux to be ~1.3 × 109 gC/km/yr for the sedimentary sequence alone. For Guatemala and Nicaragua, present-day degassing rates for CO2 [2-3] are higher than potential sedimentary inputs [1] implying either a contribution of CO2 from oceanic crust or that flux rates for these sections of the arc are unrepresentative. The latter explanation is preferred based upon low L/S ratios of output gas (oceanic basement would have a high L/S ratio) and observations of large increases in SO2 (and CO2) fluxes at monitored volcanoes (e.g. Poas) over the last 6 years.


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Collaborative research center SFB574 at the University of Kiel investigates the role of fluid and volatile cycling in the Central American subduction zone through integrated geological, geophysical, volcanological, petrological and geochemical studies. Twelve scientific projects are evenly distributed between three major themes: 1) Subduction zone structure and tectonics, 2) fore-arc volatile turnover and fluid flow, and 3) transfer of fluids/volatiles from the slab through the wedge and arc to the atmosphere. Extensive on- and offshore campaigns have been carried out along the entire Central America subduction system extending from Guatemala to Panama. Highlights include physical and chemical characterization of the input, in particular, demonstrating the presence of serpentinites in areas where faults created by bending of the incoming oceanic plate penetrate into the upper lithospheric mantle offshore of Nicaragua to Guatemala. These serpentinites may provide the major source of water causing melting beneath some parts of the subduction zone. Hundreds of fluid venting sites at mud mounds, faults, landslide scarps and fractures have been mapped along the continental slope off Nicaragua and Costa Rica with geochemical studies of pore water indicating that the source of the fluids is the dehydration of minerals in subducting sediments. The end of fluid release by dehydration of subducting sediment at the 150°C isotherm, where the smectite to illite transition is complete, is concurrent to the updip limit of occurrence of interplate thrust earthquakes (seismogenic zone), suggesting that seismic activity may be coupled with a sharp decrease in fluid release from subducting sediments (clays). Systematic changes in the isotopic composition of volcanic front rocks from Nicaragua to Costa Rica appear to reflect changes in the subduction input whereas changes in isotopic composition from Nicaragua to Guatemala most likely reflect interaction with increasingly thick continental lithosphere towards Guatemala. Fluxes for magma, H2O, S, F and Cl have been determined and vary along the Central American volcanic arc in response to tectonic conditions. Modelling of volatile input into the atmosphere is being carried out to determine the impact on the climate and atmosphere composition. The eruptive behavior of volcanoes along the arc over long time scales helps to constrain future hazards. Investigations in the erosive Central America subduction system are presently being concluded and work is beginning in the accretionary segment of the Chilean subduction system.
Preliminary Results from the TICO-CAVA Seismic Refraction Survey

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Project TICO-CAVA (Transects to Investigate the Crustal Origin of the Central American Volcanic Arc) is a key part of the MARGINS Subduction Factory initiative in Central America. The principal goal of this project is to quantify, characterize, and understand the volcanic crust produced in the Central American Subduction Factory in Costa Rica by seismically imaging its volume, extent, seismic properties, and lateral variability. From this information we hope to estimate the major-element composition of the arc crust and draw inferences about the processes controlling volcanic output of the subduction factory in Central America. We will do this with two intimately linked seismic surveys, an onshore explosion refraction survey, and an onshore-offshore airgun survey. Here we give a status report of this ongoing project and present preliminary results from Phase I of the project, an onshore explosion seismic refraction survey of the volcanic arc. Phase II of the project, a large onshore-offshore seismic survey in both the Atlantic and Pacific oceans, will occur in early 2008 when the R/V Langseth, the new U.S. seismic research vessel, comes on-line.

In 2005 we acquired seismic refraction/wide-angle reflection data on two long lines. Line 1 crosses the Central American isthmus on a 155-km-long transect from the Pacific Ocean to the Caribbean Sea in central Costa Rica, intersecting the main volcanic arc at Volcán Barva. Line 2 is a 280-km-long line that spans the entire length of the active arc in Costa Rica, from north of Volcán Orosí near the Nicaraguan border, to south of Volcán Irazú, the southernmost active volcano in Central America. These two lines are designed to enable us to accurately determine volume and lateral variability of magmatically produced crust in the arc. In all, we drilled and loaded 39 holes, of which 37 successfully fired (2 shots were “duds” and failed to fire). Approximately 750 portable seismometers were deployed on each transect, resulting in a ~200-meter receiver spacing on Line 1 and ~370-meter spacing on Line 2. Data quality ranges from fair to excellent.

Data on the cross-arc line (Line 1) show upper-crustal refractions that can be tracked from coast to coast and, at the longest offsets, a handful of deep reflections that may be Moho reflections. Sediments on the Atlantic coastal plain (2-3 km/s) are about 1.5 km thick; beneath this and beneath the volcanic arc is a low-velocity carapace of volcanic material (3-5 km/s) that is 2-4 km thick. Beneath the low-velocity velocities reach 6.0-6.4 km/s at 5-10 km depth. Deeper structure is unresolved at this time, but will become clear as analysis continues and the onshore-offshore data are collected. The along-arc line (Line 2) shows evidence for distinctly different crustal structure beneath the Guanacaste volcanos and the Cordillera Central. In addition, low-velocity zones that may represent magma chambers exist beneath Poás volcano and between Irazu and Turrialba volcanos.

Acknowledgments. For the successful completion of the difficult and complex onshore explosion work, we would like to thank Drs. Teresita Aguilar and Marino Protti, Error! Contact not defined., Daniel Murillo, Cesar Villalta, German Leandro, Francisco Arias, FUNDEVI (Error! Contact not defined.), and Roberto Guillén, Explotec, the IRIS/PASSCAL Instrument Center, and the dozens of people from Costa Rica and the U.S. who conducted over 3000 seismometer deployments.
A seismic wide-angle and refraction experiment was conducted offshore of Nicaragua in the Middle American Trench to investigate the impact of bending related normal faulting on the seismic properties of the oceanic lithosphere prior to subduction. Based on reflectivity pattern of multi-channel seismic reflection (MCS) data it has been suggested that bending-related faulting facilitates hydration and serpentinization of the incoming oceanic plate. Seismic wide-angle and refraction data were collected along a transect which extends from the outer rise region not yet affected by subduction into the trench northwest of the Nicoya Peninsula, where multibeam bathymetric data show prominent normal faults on the seaward trench slope. Coincident MCS data indicates that the thickness of the incoming oceanic crust is remarkably uniform. A tomographic joint inversion of seismic refraction and wide-angle reflection data yields anomalously low seismic P-wave velocities in the crust and uppermost mantle seaward of the trench axis. Crustal velocities are reduced by 0.2-0.5 km/s compared to normal mature oceanic crust. Seismic velocities of the uppermost mantle are 7.6-7.8 km/s and hence 5-7% lower than the typical velocity of mantle peridotite. These systematic changes in P-wave velocity from the outer rise towards the trench axis indicate an evolutionary process in the subducting slab consistent with percolation of seawater through the faulted and fractured lithosphere and serpentinization of mantle peridotites. If hydration is indeed affecting the seismic properties of the mantle, serpentinization reaches 12-17%.
Subduction zones are the places on Earth where quantitatively the largest mass transfer rates exist and element fractionation occurs between crust and mantle. The agents, which are central to these processes, are aqueous fluids, supercritical fluids, or melts. Field evidence found in formerly subducted rocks shows that the preferential flow field of released slab fluids is highly channelized and that these fluids tend to react with parts of their wall rocks. Thereby they are able to serve as agents for mobilization and transport for most trace elements. I will describe a model for fluid flow within slabs that suggests that slab melting must not necessarily be invoked for mobilization of so-called fluid-immobile trace elements. For this model it is critical that permeabilities in the subducting slab appear to be too low and dihedral angles between fluid and relevant minerals too high to allow for pervasive porous flow, hence the fluids to tend to localize while flowing. I will outline how fluid channelization controls reaction rates and element redistributions during metamorphism of the subducting plate as well as trace element composition of subduction-related fluids during flow. Channelized fluid flow predicts that most formerly subducted material will show only very limited evidence for fluid flow, consistent with the rarity of observed high fluid fluxes in subduction-related rocks. Aqueous fluid produced by dehydration reactions will not percolate through large rock volumes, but rather will be carried away from the dehydration sites by a veining network. Indeed evidence for significant aqueous-fluid fluxes have been found in high-pressure veins with adjacent selvages. In such selvages, large lithophile elements (LILE’s) generally show the highest mobilities, followed by light (L) rare earth elements (REE) and then heavy (H) REE. Compared to high field strength elements (HFSE), even Th shows higher mobilities. Equilibrium between aqueous fluid and surrounding rock will only be approached at sites of fluid production and mineral reaction. However, this fluid can be significantly modified while moving upwards through a veining network where the wallrocks are out of equilibrium with the fluid. In a subducting slab, such reactive fluid flow can preferentially dissolve minerals and release their trace elements. The degree of change in aqueous fluid composition will depend on the amount of fluid-mineral surface interaction and the ratio between the kinetics of the mineral reactions and the velocity of the passing fluid.

In this talk I will focus on the evidence for reactive fluid flow in localized channel networks in high-pressure metamorphic terranes and its distinct chemical signature that is a direct counterpart to that in arc magmatism. I will exemplify some principles outlined above and will combine field relations and petrographical observations with trace-element data. The case studies are from different prime field examples that are indicative for the dehydration of upper oceanic crust (Tianshan, China) and serpentinite dehydration and fluid flow through the overlying lower oceanic crust (Zambezi Belt, Zambia).
Advanced ocean floor observatory for mega-thrust earthquakes and tsunamis around the Nankai Trough, Southwestern Japan

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The Nankai Trough, southwestern Japan is well known as the mega-thrust earthquake seismogenic zone. In many researches focusing on the mega-thrust earthquakes around the Nankai trough, the structural researches using refractions and reflections seismic has succeeded to image the key structures to understand recurrences of mega-thrust earthquakes around the Nankai Trough. Moreover, results of earthquake recurrence cycle simulation show that the first ruptures seems to occurred around the Tonankai earthquake rupture zone in each recurrence cycle, and the clear segment boundary between the Tonankai and Nankai earthquake rupture zones off the Kii peninsula was analyzed using tsunami data. In 1854, 1944/46, the initial rupture were starting from the Tonankai seismogenic zone ahead of the Nankai seismogenic zone with intervals of 32 hours and 2years in each event. The simulation results of recurrence cycle is consisted with recent historical events in 1854, 1944/46.

Therefore, based on these researches, we will deploy the advanced ocean floor network around the Tonankai seismogenic zone to monitor the crustal activity, improve the recurrence cycle model and provide the high quality early warning information for the next mega-thrust earthquake.

The 1944 Tonankai and the 1946 Nankai earthquakes, each hypocenter was located off the Kii peninsula. So, the imaged irregular structure such as a key structure at the segment boundary between the Tonankai and Nankai earthquake rupture zone seems to be the controller of the Nankai Trough mega-thrust seismogenic zone system.

By the advanced simulation study of recurrence cycles of mega-thrust earthquakes around the Nankai Trough, these irregular structures seem to act as a controller of recurrence cycle and pattern of mega-thrust earthquakes in the Nankakai trough. Based on these researches, we proposed and have been starting to deploy the dense ocean floor observatory network system equipped with multi-kinds of sensors such as seismometers, pressure gauges etc., focusing on the understanding of crustal activities off Kii peninsula including the Tonankai/Nankai earthquake rupture zones.

This observatory system will be the one of most advanced scientific tools to understand the mega-thrust earthquakes around the Nankai trough. This advanced dense ocean floor observatory network system has useful functions and purposes as follows,

1) Redundancy, Extension and advanced maintenance system using the looped cable system, junction boxes and the ROV/AUV etc.
2) Speedy evaluation and notification for earthquakes and tsunamis.
3) Provide observed data such as ocean floor deformation derived from pressure gauges to improve the simulation and modeling researches about the mega-thrust earthquakes.
4) Understanding of the interaction between the crust and upper mantle around subduction zone.
5) Develop the advance network technologies for long term monitoring.

We will deploy the advanced ocean floor network off Kii peninsula as a local system. In the second step, we would like to develop and deploy the advanced ocean floor network as a regional system and in the third step, we would like to collaborate with international network systems as the global network to progress geosciences and contribute the early warning system for large earthquakes and tsunamis.
Effects of calcium fluxes on authigenic carbonate formation at mud volcanoes off Costa Rica: a numerical model approach

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The forearc of the convergent margin off Costa Rica is characterized by active fluid venting related to mud diapirism and volcanism. A significant portion of bicarbonate generated through anaerobic oxidation of methane (AOM) precipitates as authigenic carbonates in the near surface sediments. The purpose of our study is to thoroughly investigate the major parameters controlling authigenic carbonate formation, such as fluid composition and advection rate. These efforts will help to further our understanding of turnover rates at mud volcanoes at the erosive margin off Costa Rica and better constrain the use of authigenic carbonates as archives for past fluid flow. Preliminary studies focus on the variability of venting activity along the slope and aim at the derivation of local methane budgets.

Pore water profiles of four sites on the southern Costa Rica margin show that all fluids are low in chloride and methane rich. Specifically, fluids of Quepos Slide and Culebra Fault are enriched in calcium, barium and bromine, which points to an influence from anoxic diagenesis. In contrast, fluids of Mounds 11 and 12 are low in calcium.

We present results of a numerical reactive-transport model used to quantify the effects of calcium fluxes and fluid flow rates on carbonate precipitation and methane discharge. At active vent locations of Mounds 11 and 12, 98% of the methane is released into the overlying bottom waters due to exceptionally high advection rates (100-200 cm a-1), which corresponds to a very low efficiency of AOM. The lower methane turnover by AOM at Mounds 11 and 12 causes a reduced alkalinity production and hence a lower degree of authigenic carbonates formation. In comparison, moderate flow rates (0.1-40 cm a-1) at Culebra Fault and Quepos Slide lead to reduced methane output (7% - 40%) from the sediment. Higher efficiency of AOM and Ca fluxes here increase the calcium carbonate precipitation rates. Thus, higher Ca fluxes from below, at the moderate flow rates seen at Quepos Slide and Mound Culebra induce more precipitation of calcium carbonate compared to Mounds 11 and 12.

Further steps are in progress to better constrain the impact of calcium enriched fluids on carbonate precipitation by application of systematical variations of fluid flow rate and Ca 2+ concentrations in the ascending fluids.
Continuous Chemical and Flux Monitoring at the Costa Rica Subduction Zone

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Two fluid flow systems were identified during ODP Legs 170 & 205, at the Costa Rica Subduction Zone (SZ). The first was inferred to be in the uppermost oceanic basement on the incoming plate, where lateral flow of seawater (SW) cools the oceanic crust. The second, sampled in the décollement and a prism thrust fault, taps a deeply sourced fluid originating arcward. Two borehole observatories were installed successfully, one in a fractured igneous formation on the incoming plate (Site 1253 about 0.2 km seaward of the trench) and one in the décollement zone (Site 1255 about 0.4 km arcward). Downhole instruments recorded pressure (P), temperature (T), and the rate of fluid flow in these hydraulic horizons through time, and collected a time series of fluids (OsmoSamplers [OS]) with T loggers for later analysis of dissolved and gaseous species. The OS fluids were sampled at weekly resolution. The data obtained provide new information on the relations between physical and chemical processes, on fluxes through the system, and on links between processes occurring in different parts of the subduction system with implications for the subduction factory.

Within the uppermost igneous basement at Site 1253, the less than hydrostatic P, by 6 kPa, indicates that it is highly permeable and hydrologically connected to distant ventilation points. Ca and Mg concentrations are about 3 times and about 1/2 seawater (SW) value, respectively; the average Sr concentration is 23% greater and the average Li concentration is ~2 times SW value, indicating active lateral advection of an altered fluid that has evolved from SW values to concentrations similar to ridge flank hydrothermal fluids. The chemistry of this fluid suggests that the permeable basement at Site 1253 is hydrologically connected to points of SW recharge at distant igneous outcrops, with a basement fluid similar to that sampled ~30 km seaward of Site 1253 during the TicoFlux expeditions. The 87Sr/86Sr values, however, place severe constraints on the subsurface hydrology. They are in between modern SW value and average global subducted sediment (0.7173), suggesting interaction with a radiogenic source, from a consolidating sediment section within the SZ, implying that the permeable basement acts as a fluid flow pathway for deeper sourced fluids being expelled from the SZ.

At Site 1255, the décollement and overlying prism are super-hydrostatic ~200kPa; pressures at the two intervals are offset by 30kPa. Overprinted on these trends are two secondary excursions manifested by chemical changes that correlate with P and T increases in the décollement and with fluid flow rate changes. The second may be related to an aseismic slip event on the subduction thrust beneath the Costa Rica coast documented by GPS. After the first event, both P and fluid flow rates increased appreciably and remained constant. After the initial 2 months, the composition begins to evolve towards a composition that is characteristic of pore waters from the décollement for most chemical species (e.g. Ca, Sr, Li, NH4). The near steady-state concentrations of major, minor, and trace elements provide clues for the origin of the fluid sampled.

This is the first high-resolution time series data set of chemistry and fluid flow at a SZ, with direct implications for seismogenic zone activity, and chemical fluxes to the ocean and to the arc volcanoes.
Modeling the relationship between slab-transition zone interaction and subduction mode: Implications for episodic slab melting.

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Subduction of oceanic lithosphere represents a dominant mechanism for driving convective motion within the upper mantle and both thermal and chemical exchange through arc systems. Many models of subduction zone processes focus on characterizing circulation and thermal-chemical transport for steady conditions. Geochemical and seismic data sets reveal significant spatial and temporal variability within subduction zones and between subduction zones. We present results of three-dimensional laboratory models of dynamic subduction which highlight non-steady aspects of this process, where the mode of slab sinking (downdip versus rollback motion) is strongly influenced by the interaction of the plate with the mantle transition zone and deeper mantle convection. Kinematic subduction models which recreate these patterns in subduction mode are then used to characterize how transitions in slab sinking style influence spatial and temporal patterns in slab temperature and melting.

Results show that transitions from downdip to rollback dominated subduction produce high amplitude, short duration pulses in slab temperature. The thermal response of the plate varies along strike and is strong enough to trigger significant slab melting.
The Effect of Three-dimensional Slab Geometry on Deformation in the Mantle Wedge: Implications for Shear Wave Anisotropy

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Three-dimensional solid-state creep may play an important role in a variety of processes that occur in the mantle wedge of subduction zones. Three-dimensional flow may control along-strike geochemical trends observed in some arcs and affect thermal structure, which is a fundamental control on arc magma genesis and slab metamorphism. Three-dimensional flow may also control rock fabric development and patterns of seismic anisotropy. In this study we quantify the effects of 3D slab geometry on flow geometry and finite strain in the mantle wedge of subduction zones. Temperature, velocity, and strain are calculated with high-resolution three-dimensional subduction zone models that include Non-Newtonian olivine rheology. Cases with both parameterized slab geometry and geometry based on intermediate depth seismicity are considered. General subduction zone models show that significant trench-parallel stretching and flow focusing can occur in systems with a transition to shallow dipping slabs over 500km. Strong trench-parallel stretching is also observed in systems with curved trenches. These results have important implications for the origin of trench-parallel shear wave splitting observed in many subduction systems (e.g. Andes, Marianas, Ryukyu, and C. America).
Ash plumes of numerous plinian, phreatoplinian and ignimbrite-forming eruptions from calderas and stratocones along the Central American Volcanic Arc (CAVA) were dispersed westward across the Pacific. The mostly non-erosive submarine environment preserves an almost complete record of those large eruptions. The intercalation of deposits from different volcanic sources facilitates the relative and absolute timing of their activities. Mapping of the marine ash layers is thus essential to constrain the magnitudes of single eruptions as well as to assess lateral and temporal variations in magma production along the volcanic arc.

Gravity cores were collected during SONNE Cruise SO173/3 and METEOR Cruises M54/2 and M66/3 offshore Central America on the lower continental slope and on the oceanic plate, at distances of 150-350 km from the CAVA. 56 cores reaching up to 11 m below seafloor contain a total of 207 ash-bearing horizons. Ash layer thickness ranges from 0.5 to 23 cm with typical grain sizes from medium silt to coarse sand. Correlations between the cores and well dated on-land tephras as well as regional sources of non-correlative marine ashes are constrained by petrographical and stratigraphical criteria, major element geochemistry of glasses and minerals, and trace element data from LA-ICP-MS analyses. 4800 glass shard analyses facilitate 118 correlations between cores, and to 27 eruptions from CAVA volcanoes. Correlated tephras of known age allow to determine pelagic sedimentation rates which, in turn, are used to constrain ages of undated ash layers. The resulting stratigraphic framework of Plinian deposits along the CAVA allows to make the following observations:

1) Frequent highly-explosive activity periods alternate with periods of low activity at 110-150 ka and >320 ka (to possibly 400 ka) suggesting CAVA volcanism was not steady but evolved in cycles.
2) In the past 400 ka, Plinian eruption frequency decreased toward Costa Rica.
3) Basaltic Plinian eruptions form a major component of Plinian volcanism in Central Nicaragua to Southern El Salvador, accounting for 50% in Central Nicaragua.
4) Coarser-grained ash layers suggest more intense, mainly silicic Plinian eruptions at northern El Salvador and Guatemala; this is discussed in the context of increasing crustal thickness.
Earthquake Cycle to Long-term Deformation of the Central American Convergent Margin

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The interaction of the Cocos ridge (CR) with the Central American convergent margin has led to the development of this margin as a complex plate boundary. The role of CR in upper plate deformation has been discussed by many authors and include the uplift of the Talamanca and cessation of active volcanism, crustal shortening across the inner forearc and back arc, uplift of the outer forearc and formation or modification of the North Panama and Central Costa Rica deformed belts, potential boundaries for the Panama block. We suggest that the CR also causes forearc sliver transport of the Costa Rican and Nicaraguan forearcs.

We present the first regional surface velocity field for Central America, showing the crustal response to interaction of the Cocos and Caribbean plates. Our data show significant trench-parallel motion for most of the region, including central Costa Rica where plate convergence is perpendicular to the trench. Interseismic strain accumulation is observed in the outer forearc Nicoya and Osa Peninsulas, but not in the forearc of Nicaragua. However, large subduction zone earthquakes occur in Nicaragua (e.g., September 2, 1992, Mw 7.6). We propose that interseismic locking in Nicaragua and other parts of Central America is mainly shallow, <25 km depth (most subduction seismogenic zones extend to ~50 km depth), too far offshore to be detected by on-land sensors. Inboard of Cocos Ridge, southern Costa Rica, velocity vectors are parallel to convergence and up to 44 mm yr\(^{-1}\). We present a collision model involving CNS-2 - Cocos Ridge crust; young, hot-spot thickened crust, and compare our model results and geodetic observations to geological and geophysical data for the region. CNS-2 - Cocos Ridge crust resists normal subduction, instead acting as an indenter to the Caribbean plate, driving crustal shortening in southern Costa Rica at rates of ~35 mm yr\(^{-1}\) across the fore arc and back arc. The indenter, rather than oblique convergence, drives trench-parallel forearc motion in Costa Rica and Nicaragua at rates up to 14 mm yr\(^{-1}\). In total, our results indicate how strain is partitioned at multiple temporal and spatial scales due to collision of a rigid indenter.
A 3D synoptic model of Central America inferred from gravity data interpretation.

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Large portions of the Central American Isthmus have served as key areas for the collaborative research program (SFB 574) and its goal to understand orogenic processes at convergent margins, such as the volatile and fluid cycle and the relationships between tectonism and magmatism. The research presented here is part of the SFB 574 research.

Crustal structures of the southern part of the Central American subduction zone have been investigated for many years. In particular the oceanic crust and the margin wedge were objects of intensive research and therefore are well defined. Recent seismological work in Central and northern Costa Rica provides new insight in the subduction system. Gravity data from both on- and offshore has been gathered from various institutions (ICE Santa Cruz, RECOPE, Santa Cruz, GETECH, Leeds and has been combined in a homogeneous data set. The wealth of data was recently made available through the data portal of the SFB 574.

Due to difficult access to the high mountains the coverage by gravity observations remains rather incomplete mainly in the area of southern Costa Rica and eastern Nicaragua. Station complete Bouguer anomalies, Free Air anomalies and isostatic residual anomalies maps were compiled as a result of the homogenization of gravity field data. Blending various gravity anomaly compilations and the geological map of Central America we already found correlations between anomalies and geological structures. ICE also provided a map of magnetic total field anomalies. However, this compilation has been used for comparison reasons only and magnetic field data are not yet included in the 3D modeling.

First analyses of the gravity field using curvature methods helps to separate density provinces in the crust. Dip curvature analysis of isostatic residual gravity shows that elongate zones of maximum curvature correspond remarkably well with the structural grain defined by first-order folds and faults. A comparison with the geological map shows a good correlation with tectonical units in most of the region and provides possibilities for crustal segmentation. Sources of the gravity anomalies were investigated by the Euler deconvolution method. From the theoretical viewpoint this method allows estimations of the source depths of density anomalies in the lithosphere. Source point clusters in depths of 10 km and 30 km were obtained which can help to design a regional density model of Central America including Pacific and Caribbean lithosphere.

For the first time a 3D density model has been accomplished by combining the results of curvature and Euler analysis with other constraining data. These data stem from geological maps which cover the surface of the model, structural information from older seismic profiles and/or earthquake hypocenters. In collaboration with the seismological task group of the Collaborative Research Center 574 the new tomographic results were used to constrain deeper portions of the model: velocities were converted into densities following the method of Babeyko and Sobolev and Hacker and Abers and assuming typical gradients of temperature and pressure conditions in volcanic areas. Therefore, the 3D density model provides a synoptic picture of the investigated area down to the upper mantle. It can help to identify the border between larger tectonic blocks e.g. the Chortis block in the north or the Chorotega block in the south. The modeling was used to visualized the gravity effects of serpentinization of oceanic lithosphere at the Pacific side. At a more local scale our 3D modeling provides insight into the upper crustal parts under the volcanoes of Central Costa Rica. Surprisingly the area of central volcanic chain in Costa Rica is covered by negative Bouguer anomalies whereas further to the north the volcanic chain is located in an area with positive anomalies. This points to a different composition of crust which causes regional density anomalies in both areas which should be also reflected by different seismic velocities.

For the purpose of comparison we also show a cross section of a 3D density model which was compiled in the area of the Central Andean along the latitude 21 deg. S.
It has been documented that bending-related normal faulting at the trench-outer rise can cut deep into the mantle of the incoming plate at a subduction zone and allow seawater to penetrate into and react with the lithospheric material, causing serpentinization. This would change the degree of hydration of the incoming plate which in turn changes all subduction zone processes linked to the dehydration of subducting oceanic crust and upper mantle. However, the depths these faults cut into the mantle and the amount of water that is carried into it still remain under debate.

A local earthquake monitoring network has been installed at the outer rise offshore Nicaragua to investigate typical hypocenter depths of earthquakes in this area and to determine focal mechanisms. The maximum hypocenter depth of these earthquakes, which is directly linked to the maximum depths that the bending-related faults cut into the mantle, was found to be <20 km beneath seafloor. Further, the determination of focal mechanisms gave the faults geometry and helped us to distinguish between a tensional regime in the upper mantle and a compressional one beneath.
FOOTWALL-HANGINGWALL PLATE INTERACTION CONSTRAINED BY BACKGROUND SEISMICITY: CENTRAL COSTA RICA

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Earthquake focal mechanisms solutions for 135 small-magnitude events are modeled for best-fitting strain-rate tensors that characterize the contemporary strain in five areas in Central Costa Rica that span the westernmost margin of the Panamá microplate. The results indicate the predominance of subhorizontal maximum stretching oriented parallel to the Middle America Trench (MAT) and that this stretching is likely accommodated on recently mapped strike-slip faults. Local changes in the trajectory of maximum stretching occur at a scale that is comparable to that of topographic anomalies on the downgoing Cocos plate at the MAT, suggesting that the small-magnitude events provide constraints on the detailed response of the hangingwall to the subduction of topographic features. In addition, the results shed light on the geometry of non-recoverable strain associated with realizing strike-slip faults bends in the region between the inactive volcanic Cordillera de Talamanca and the active volcanic arc of the Cordillera Volcánica Central.
Insights into the mantle underlying northern Costa Rica: evidence from xenoliths of Cerro las Mercedes

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Over 80 ultramafic xenoliths, some with diameters of at least 3cm, open a window into the mantle beneath Cerro Mercedes, Costa Rica. This quaternary vent is 70km behind the active volcanic front and near the northern boundary of the Caribbean Plateau. Both xenoliths and host lava remain well preserved in spite of substantial soil development in a rain forest environment. We analyzed the host lava and a subset of 30 rocks for bulk and mineral chemistry, which include both peridotite and pyroxenite populations.

The host rock is Plio-Quaternary potassic alkaline basalt; depleted in SiO2 and Al2O3 and enriched in MgO and P2O5 relative to both present day and Miocene volcanics. In terms of trace elements, the host basalt has enriched LREEs and relative depletion of HFSEs, typical of island-arc basalt, both present and past. The coarse-grained pyroxenites have trace element chemistry akin to the volcanic front lavas of Costa Rica, although they are closer to chondritic values. Although there is enrichment in incompatible elements such as Ba and U and depletions in HFSEs, common in island arc basalts, the pyroxenites have a strong positive Pb anomaly that is characteristic only of the Miocene arc, not present day lavas. The presence of fluid signatures indicates the possibility that the pyroxenites are cumulates.

The peridotite population includes dunites, spinel lherzolites and lherzolites. These rocks have Mg-numbers ranging from 89 – 92 and Cr-numbers ranging from 6 – 61. Whole rock geochemistry indicates that the peridotite xenoliths are fragments of mantle associated with the western Caribbean Plateau. In projections of major oxide data (particularly SiO2, FeO and Al2O3 vs. MgO) several Cerro Mercedes peridotites plot in fields consistent with hot residues that would form in a plume environment. Trace elements show that most samples have a degree of subduction signature, with enrichment of Ba and U, and depletion in HFSEs, indicating variable extents of melt-rock reaction and/or metasomatism. At the same time, all the peridotites have the same positive Pb anomaly as the pyroxenites indicating that the Pb is not simply a fluid signature, but may reflect the composition of the mantle source. REE patterns break the peridotites into three populations, each with different degrees of fluid modification. Sr-isotopes also show variable fluid modification in the peridotites. Fortuitously, a few samples have flat REE patterns, indicating that reactions modifying the rocks’ chemistry are constrained to grain boundaries.

Aggregated fractional melting models show the least modified peridotites to be the source of the Sarapiqui basalts, which are part of the Central American Miocene arc environment that existed prior to a westward shift. Taken together, the Cerro Mercedes xenoliths provide a geochemical record of both the protolith and metasomatic history of the lithosphere below the Caribbean plateau.

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In-situ benthic fluxes at the Costa Rica convergent margin

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Active convergent margins are important regions for element recycling between crust, ocean and atmosphere. The input into subduction zones is by sediments and altered oceanic crust and the return flow of volatile elements may take various transport pathways from the frontal deformation front to the volcanic arc. Along the erosive convergent margin off Costa Rica, mounds on the mid slope and landslides of various sizes and origin at the mid and upper slope have been identified as important for the submarine reflux of water and volatiles, in particular methane. Chemosynthetic vent communities, authigenic carbonates, and methane plumes in the water column are manifestations of that activity. The aim of our group is the determination of benthic fluxes and turnover at specific types of vent settings to evaluate the source strength for methane from these structures as well as to understand the role of the benthic filter within the upper sediment column and at the interface to the bottom water. Different approaches were followed to achieve these goals. The inventory of the methane emitted into the water column from individual structures was assessed by water column surveys, and the fate of the gas was followed by addressing its carbon stable isotopic signature. The distribution of vent-indicative fauna was quantitatively assessed on some of the active sites using seafloor video-survey data. Benthic flux measurements were obtained by a video-guided Benthic Chamber Lander (BCL) and chambers deployed by ROV at vent sites located in the most active part of these structures. The lander was equipped with 4 independent chambers covering adjacent areas of the seafloor, allowing the recording of benthic fluxes as well as the recovery of the sediment after the end of the incubation phase.

Among the most interesting findings of our investigations in the area are an extreme enrichment of methane in the semi-enclosed Jaco Scarp, a landslide with steep walls caused by the subduction of a sea mound, the large scale decay of methane emissions from 2002 to 2003, most likely linked to a change in seismic activity, and an assessment of fluxes from different active vent settings by in situ lander experiments interpreted with a transport-reaction model.
Crustal Thickness in Northern and Central Costa Rica: Preliminary Results using Teleseismic Receiver Function Analysis

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Costa Rica is located near the southern end of the Middle American Trench (MAT) in a complicated tectonic setting controlled by the interaction of four major crustal blocks: the Cocos, Caribbean, and Nazca plates and the Panama microplate. The oceanic Cocos plate subducts to the northeast underneath the Caribbean plate and the Panama microplate, creating a volcanic arc located 150 km away from MAT. The back arc region is located to the northeast of the volcanic arc.

For this study, Receiver Functions have been calculated using teleseismic events (mb > 5.4) recorded by the Pocosol Seismic Network, an NSF-funded array of three stations deployed by Rutgers University in Northern Costa Rica, and teleseismic events (mb > 5.9) recorded by station JTS from the Global Seismology Network and HDC from the Geoscope Project.

Our results show that the crustal thickness varies underneath the Costa Rican Isthmus. The Moho discontinuity is visible at depths of 36 km beneath stations of the Pocosol Network located in the back-arc region, 41 km underneath HDC located in the volcanic arc, and 37 km beneath JTS in the forearc region. Moho depths were estimated using a stacking algorithm which sums the amplitudes of receiver function of direct and multiply-converted phases. Our preliminary results also suggest that there is a much more complicated crustal structure underneath the forearc and the volcanic arc compared to the back arc region.

Future work will attempt to map out the lateral variation of Moho depth underneath Costa Rica from Receiver Functions that will be computed using more available broadband data from five stations of the CORISUBMOD Experiment deployed by the Institut fur Geophysik (ETH, Zurich) located in northern Costa Rica.

Relationship between Peak Ground Acceleration and Modified Mercalli Intensity in Costa Rica

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We have developed the first relationship between Modified Mercalli Intensity (MMI) scale and both the horizontal (h) and vertical (z) components of Peak Ground Acceleration (PGA) for the Costa Rican region using regression analysis of 110 earthquakes (2.9 < Mw < 7.7) that occurred between 1983 and 2004 (Fig. 1). PGA and MMI were acquired from the Laboratory of Earthquake Engineering (LIS) at the University of Costa Rica and the National Seismological Network of Costa Rica (RSN). Additionally, isoseismal maps were made for three significant events: the 2002 Bijagua (5.2 Mw), 2002 Burica (6.2 Mw), and 2003 Christmas (6.6 Mw) earthquakes.

For each instrumentally recorded event, a single MMI value was assigned based on the general proximity to one or more MMI observations. A total of 364 values of PGA in both the horizontal and vertical components were associated to a single MMI value. The general correlation obtained was: MMI = 2.74 log (PGAh) + 0.1759 and MMI = 2.30 log (PGAz) + 0.3739, where h and z refer to the horizontal and vertical component, respectively. Slightly different correlations were obtained when MMI and PGA were plotted separately for earthquakes occurring at different source depths (crustal and subduction earthquakes) and soil type at the seismic station (rock, hard, soft).
Previous studies in other regions of the world have shown that MMI and instrumental ground motion relationships are region specific and thus these relationships should be carefully assessed for each area. In Costa Rica the seismic intensity is the only available parameter from which to quantify the level of ground shaking of the historical earthquakes and is still the only ground shaking parameter observed in much of the country because the coverage of seismic instruments is limited.
Crustal structure along strike beneath the Costa Rican arc

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We have recently completed the land portion of a major active-source seismic experiment in Costa Rica designed to delineate the basic architecture of arc crustal construction and estimate the total volume and bulk composition of arc crust. We present preliminary analyses of data from the along-arc profile of this experiment, which extends from the Nicaragua border, through Guanacaste and central Costa Rica to the northern edge of the Talamancas. We find that the crustal structure beneath the Guanacaste volcanoes differs substantially from those of central Costa Rica. We find evidence for what appears to be a sizable magma chamber (low seismic velocity anomaly) that is shared by Irazu and Turrialba volcanoes and a similarly sized but high velocity anomaly extending northward from Poas volcano, possibly a crystallized former magma body. These bodies are present within the 3- to 7-km-thick, 2- to 5-km/s upper-crustal carapace. Below this carapace, velocities increase from ~6 to 6.5 km/s at ~20 km depth. The carapace beneath Guanacaste is thinner, shows no evidence of large intrusions, and the underlying velocities are somewhat higher, reaching 6.5 km/s just beneath the carapace.
Remote sensing observations along with detailed field mapping, borehole cores, shafts, geophysics and collections of several thousands of fault-slip markers and populations of focal solutions are used to reconstruct the kinematic and dynamic evolution of a section of the Tórрабa basin, directly and dynamically influenced by the nearby subduction zone, past and presently acting at the Middle America Trench less than 100 km from the studied localities.
Dehydration of subducting lithosphere likely transports fluid into the mantle wedge where the viscosity is decreased. Such a decrease in viscosity could form a low viscosity wedge (LVW) or a low viscosity channel (LVC) on top of the subducting slab. Using numerical models, we investigate the influence of low viscosity wedges and channels on subduction zone structure. Slab dip changes substantially with the viscosity reduction within the LVWs and LVCs. For models with or without trench rollback, overthickening of slabs is eliminated by LVWs or LVCs. Two divergent evolutionary pathways have been found depending on the maximum depth extent of the LVW and wedge viscosity. Assuming a viscosity contrast of 0.1 with background asthenosphere, models with a LVW that extends down to 400 km depth show a steeply dipping slab, while models with an LVW that extends to much shallower depth, such as 200 km, can produce slabs that are flat lying beneath the over-riding plate. Slab can be decoupled from the over-riding plate with a LVC if the thickness is at least a few 10s of km, the viscosity reduction is at least a factor of two and the depth extent of the LCV is several hundred km. These models have important implications for the geochemical and spatial evolution of volcanic arcs and the state of stress within the over-riding plate. The models explain the poor correlation between tradition geodynamic controls, subducting plate age and convergence rates, on slab dip. We predict that when volcanic arcs change their distance from the trench, they should be preceded by changes in arc chemistry. We predict that there could be a larger volatile input into the wedge when arcs migrate toward the trench and visa-versa. The transition of a subduction zone into the flat lying regime could be preceded by changes in the volatile budget such that the dehydration front moves to shallower depths. Our flat slab models shed some light on puzzling flat subduction systems, like in Central Mexico, where there is no deformation on the overriding plate above the flat segment. The lack of in-plane compression in Central Mexico suggests the presence of a low viscosity shear zone located above the flat slab.
The Nicoya Peninsula, Costa Rica deforms in response to rapid NE subduction of the Cocos plate at the Middle America Trench (9-10 cm/yr). This emergent outer fore arc peninsula lies 60-80 km inboard of the trench, and directly above a locked segment of the seismogenic zone. The Nicoya segment is a high-potential seismic gap, with a slip deficit of >5 m since the last major earthquake (M7.7, 1950). That event produced widespread damage and up to 1.0 m of coseismic uplift at the coast. Net Quaternary deformation on the Nicoya Peninsula is recorded by emergent marine terraces along the coast, and by uplifted alluvial fill within interior valleys. Recent field mapping, surveying, and isotopic dating provide new constraints on deformation patterns and upper-plate faulting. Local uplift anomalies reveal upper plate faults that may accommodate a significant fraction of fore arc deformation (shortening and/or lateral sliver transport).

Recent fieldwork along the Morote Valley, within the Nicoya Peninsula’s interior, reveals geomorphic evidence of active deformation along the NW-striking Morote fault (e.g., uplifted and incised alluvial fill, irregular drainage networks, active stream piracy, and abrupt mountain front facets). Uplifted Pleistocene alluvium with a deep red soil horizon (La Mansion surface) is incised 5-40 m by local stream networks. At one site, uplifted fluvial gravels overlie a gray paleosol formed on fine-grain wetland deposits, 10 m above local base level. In some areas, the surface gradient of the paleo-valley floor is opposite that of modern incised streams, indicating capture and drainage reversal.

The Morote fault forms a prominent NW-trending lineament oriented sub-parallel to the subduction zone. Preliminary seismicity data (OVSICORI) indicate recent earthquake activity along this trend. A composite focal mechanism shows dextral slip for the NW-striking nodal plane (Hansen et al, 2006), consistent with NW escape of a forearc sliver. The Morote fault underlies several large towns and may represent a significant seismic hazard. Ongoing field studies aim to establish better constraints on fault kinematics and deformation rates along this trend.

At the Nicoya Peninsula’s southern tip (Cabo Blanco), a prominent uplifted marine erosion surface (Cobano surface) encompasses at least three distinct Pleistocene terraces at 30-220 m elevation. Preliminary OSL dating yields terrace ages consistent with OIS 3-5 sea level high stands (30-120 ka), indicating net uplift at 1.0-2.0 m/k.y. A NW-striking thrust fault (Delicias fault) offsets the upper terrace by 40 m, thrusting Cretaceous basalt over Pleistocene terrace deposits. Radiocarbon ages for adjacent Holocene terraces (Cabuya surface) indicate recent uplift at 1.5-3.5 m/k.y.

Recent mapping and surveying, along the peninsula’s southern coastline (Puerto Carrillo to Playa Camaronal) reveals a set of marine terraces (Carrillo-Camaronal surface) and associated fluvial straths (Rio Ora) at 20-35 m elevation. Preliminary correlations with dated Cobano terraces and Quaternary sea level curves suggest terrace formation between 80-215 ka (OIS 5-7) and net uplift rates of 0.2-0.3 m/k.y.

Along the northern Nicoya coast (Tamarindo to Nosara), a 3 km wide wave-cut surface (Iguanazul surface) includes three treads with paleo-shorelines at 10-45 m elevation. Age correlations (as above) suggest terrace formation between 80-215 ka (OIS 5-7) and net uplift rates of 0.1-0.2 m/k.y. Radiocarbon ages for Holocene beachrock horizons are consistent with recent uplift at <0.5 m/k.y. Apparent terrace offset across the Río Andamojo (10 m, SE side up) suggests Quaternary slip along a local fault.

Regional variations in net Quaternary uplift and upper-plate fault kinematics on the Nicoya Peninsula may be controlled by such factors as convergence rate and obliquity, contrasts in subducting plate roughness, and characteristics of the underlying seismogenic zone (e.g., percent locking, asperity geometry, dip angle, and depth of up-dip and down-dip limits).
The CORISUBMOD project: Seismic-petrologic subduction model for Costa Rica

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In the scope of the CORISUBMOD project, we operated a temporary network of 15 digital broadband stations in Costa Rica. This was done in collaboration with our partner institutions in Costa Rica: ICE, UCR, and UNA-OVSICORI. The locations of the stations were chosen to augment existing seismic networks in Costa Rica with three-component, broadband instruments. We used STS-2 and Lennartz 5 s sensors. Over the last two years our stations recorded more than 2000 local earthquakes with a magnitude over 3.0 and about 85 teleseismic events.

The data collected during the CORISUBMOD project will be used to compute detailed tomographic images of three-dimensional (3D) structure of lithosphere and asthenosphere beneath Costa Rica in terms of P-wave velocity (Vp), P- to S-wave velocity ratio (Vp/Vs), and attenuation (Q). These seismic parameters are important to access composition and physical state of the subducting oceanic lithosphere and the overriding continental lithosphere. In addition, improved 3D velocity models combined with a high-quality data set collected in this project will enable us to obtain high-precision hypocenter locations of earthquakes occurring in the subducting oceanic and in the overlying lithosphere. Since these earthquakes are driven by subduction-zone related processes, their spatial and temporal distribution gives further insights into the dynamics of subduction and its associated processes.

To gain deeper insights in subduction processes such as release and transport of fluids, and generation and differentiation of magma we will combine tomographic images of the CORISUBMOD project with results of ongoing petrophysical experiments at ETH Zurich. These experiments, including the measurements of seismic velocities on hydrous high-pressure phases and on partially molten hydrous silicic magmas, provide important constraints in interpreting tomographic images.

At the workshop we will present data from the CORISUBMOD project and preliminary results of local earthquake and teleseismic tomography studies to image the structure of lithosphere and asthenosphere beneath Costa Rica.
We have recorded seismic and other geophysical data across the Nicaragua margin from the Cocos Plate to the Central American volcanic arc. These data demonstrate relatively long-term stability in the forearc region punctuated with periods of deformation, particularly along its landward and southeast boundaries. We are currently using stratigraphic relationships in the forearc basin to provide regional timing constraints for the observed deformation as well as trying to better define structural styles. Along much of the Pacific coast, both onshore and offshore, a belt of Miocene and younger convergent deformation has been recognized. Subsequently, the active volcanic arc has migrated, or jumped westward and becomes very near the Pacific coast in northwestern Nicaragua. Here not clear whether arc processes have influenced or obscured the compressional belt, but no anticlines are present in the offshore area, only a consistent seaward-dipping section of uplifted strata is present, and onshore the area is covered by Quaternary volcanics. Two seismic profiles into the Gulf of Fonseca, crossing the current volcanic arc, suggest that compressional deformation was absent or limited here. These profiles indicate that the arc has intruded the Sandino forearc basin stratigraphic section and they also delineate the Nicaragua depression. Here the magmatic edifice is marked by seismic velocities and potential field data, and an abrupt fault boundary occurs to the northeast where young, very-low-velocity sediments fill the depression. This zone may be part of a pull-apart zone related to northwestward forearc sliver motion as numerous high-angle faults occur with complicated cross-fault structural relationships.
We present new data set of 45 naturally quenched melt inclusions, trapped in olivine (Fo90-70) from Irazu volcano (tephra of 1963 eruption). Major, trace element and volatiles (H2O, S, Cl and F) in Irazu magmas along their liquid line of descent were estimated using electron- and ion-microprobe analyses of melt inclusions and numerical techniques. Our results suggest at least two contrasting types of magmas participated in the Irazu magmatic system. Inclusions in high-Fo olivines have primitive basaltic composition with typical arc-type trace element pattern. They are enriched in volatile components (S, H2O) and were likely derived from the subduction modified mantle wedge. Low-Fo olivines trapped H2O- and S-poor but Cl-rich (up to 4000 ppm) andesitic inclusions with OIB-like HFSE-enriched trace element patterns. We interpret these andesitic melts as likely products of low-degree melting of the Caribbean LIP crust underlying volcano, although melting of Galapagos-type material subducted with the Cocos Plate or eroded from the fore-arc ophiolites also can not be excluded. Irazu rocks and groundmass glasses have intermediate composition and can be produced by fractional, possibly, degassing-driven crystallization of primitive basaltic magmas accompanied by crustal assimilation and mixing with crustal andesitic melts. Our data show that crustal assimilation is likely not restricted to the Guatemalan segment of the Central American Arc and likely occurs in other regions of thickened crust, such as beneath Costa-Rica.
THE RIO ARIO FAULT SYSTEM, THE COBANO PLANATION SURFACE AND THEIR RELATION TO THE SUBDUCTION OF THE FISHER SEAMOUNT CHAIN

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The NE to E-W striking Río Ario fault system, a sinistral to oblique sinistral-normal set of faults located at the southeastern Nicoya peninsula is recognized on the basis of geomorphic and geologic data. The system includes the Manzanillo, Paquera, Pochote and Cobano faults that define the western and northern borders of the Cobano planation surface and the Cabuya fault located at the southern side of the Cobano surface. Rivers and creeks within the fault system have been sinistrally displaced between ~ 1.5 to 4.5 km. Left steps or bends in the Río Ario system have produced transtensional zones along the Manzanillo, Pochote and Cobano faults. The oblique Cobano fault has also facilitated the rotation of the Cobano surface. The rotation occurred in different pulses during the Late Pleistocene as shown by a series of abandoned sea-cliffs identified inside the Cobano surface. The indentation related to the subduction of the Fisher seamount and ridge below the southern tip of the Nicoya peninsula is identified as the driving mechanism for slip along the Río Ario fault system.
Southeast migration of the CO-NZ-CA Triple Junction results in the lateral migration and growth of the Fila Costena Thrust Belt at a current rate of ~55 mm/yr. The Fila Costena Thrust Belt, located in the inner forearc of Costa Rica and western Panama, is created owing mainly to the shallow and rapid subduction of the CO plate under the CA Plate along the Middle America Trench. The on-land projection of the Panama Fracture Zone, which represents the current boundary between the down-going CO and NZ Plates, marks the eastern termination of the Fila Costena. Recent field mapping reveals that four out of five thrust faults terminate laterally or are buried by lahars inboard of the Panama Fracture Zone. Balanced cross-sections confirm that relative shortening rates progressively decrease from the center of the thrust belt to its southeast termination. The incipient and on-going migration of the thrust belt with the CO-NZ-CA triple junction is best observed in the landscape and topography near the thrust belt’s termination. Wind gaps, beheaded streams and transient channel morphology point to reorganization of channel networks due to a growing topographic divide. Multiple suites of fluvial terraces and volcanic flows from nearby Baru Volcano likely record punctuated periods of Quaternary deposition and incision within an active thrust belt.
Discrete numerical simulations using the particle dynamics method (PDM) offer a unique way to study coupled forearc deformation and fault slip along plate boundary megathrusts at convergent margins. PDM approaches simulate the Coulomb frictional rheology of a granular medium, which is a reasonable analog for brittle-plastic accreted sediments and crustal rocks, as well as the fault interface. The simulations capture the discontinuous and unsteady nature of forearc deformation, allowing correlations between fault slip (both seismic and aseismic), upper plate deformation, and the mechanical evolution of the accretionary system. The internal structure and measured surface deformations can be compared to geophysical and geodetic data sets as tests of scientific hypotheses for the origin of steady and transient components of plate boundary interactions. Generic examples will be presented to demonstrate the methodology, and to guide discussions about its application to specific plate boundary settings.
We present an integrated study of the magmatic and structural relations of the Santa Elena Peninsula, which is divided into three main units: 1) The Santa Elena Nappe an overthrusted, allochthonous unit of ultramafic and mafic rocks; 2) The Santa Rosa Accretionary Complex, a relatively autochthonous basaltic sedimentary suite, and 3) Islas Murciálago dominated by pillow and massive basaltic flows. Three petrological affinities have been recognized in the Santa Elena Nappe: 1) an ultramafic uppermost mantle complex of serpentinized peridotites and lesser dunites 2) pegmatitic gabbros, layered gabbros, plagiogranites and basaltic dikes with low TiO2 (< 0.9%) and significant LREE depletions; and 3) doleritic dykes with higher TiO2 (>0.9%). These mafic associations have geochemical signatures suggestive of an island arc origin and petrographic evidence of ocean floor metamorphism and hydrothermal alteration (greenschist facies). The Santa Rosa Accretionary Complex, includes pelagic and volcanoclastic sediments, tuffs and alkaline magmatic rocks, originated by low degree melting of an OIB mantle source that represent portions of an oceanic island incorporated into the accretionary prism. Islas Murciálago pillow and massive basalts show no clear structural relationship with the rest of the units, but are geochemically similar to the dolerites of the Santa Elena Nappe. Sr, Nd, and Pb radiogenic isotopes of Santa Elena Peninsula do not correspond to the Galapagos hot-spot signature and show different mantle reservoirs and geochemical characteristics than the Nicoya Complex. Based on the collected structural data we proposed two major strike-slip faults: 1) Rio Seco Fault with a NE-SW direction and right-lateral movement and Calera Fault with a NW-SE trending and a left lateral moment. We also suggest that the E-W mayor faults (e.g. Murcielago Fault and Potrero Grande) pre-date the strike slip systems and correspond to high angle inverse faults probably related with different slabs of overtrustng. The entire sequence is tilted towards the north from 80° in the southern sections (Islas Murcielago) to 40° in the northern parts of the peninsula (sedimentary sequence). A simplified geological history of Santa Elena is proposed; 1) Magma extraction from the peridotite leaving behind a depleted residue in a supra-subduction environment; 2) The intrusion of pegmatitic gabbros into the peridotite when the host was still hot and plastic, 3) The pervasive intrusion of dolerite dikes into the ultramafics leaving some localized metric size patches of the host rock; 4) This igneous sequence was affected by ocean floor metamorphism (greenschist facies) and then overthrusted above the relatively autochthonous Santa Rosa Complex, in an accretion prism of an old subduction zone, 5) The entire sequence at Santa Elena was tilted towards the north, which was followed by the strike slip faults.
Ultra-Violet Digital Imaging: Application to Volcanic SO$_2$ Plumes

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Measured fluxes of volcanic SO$_2$ emissions are important in the evaluation of the state of activity of a particular volcano. Changes in SO$_2$ emission rates from an established baseline often indicate a coincident change in eruptive activity. SO$_2$ has a characteristic absorption pattern in the ultraviolet range of radiation wavelengths; remote, ground-based measurements can easily be accomplished by measuring the degree of UV absorption by a volcanic plume. Current methods of monitoring volcanic SO$_2$ (e.g., COSPEC, FLYSPEC) are limited to making cross-sectional scans of the plume; a simple one-dimensional profile of plume concentrations is not necessarily representative of the entire plume. These scans are limited to a temporal resolution of one every few minutes at best. Derivation of accurate SO$_2$ fluxes using such a method may be further complicated by changes to the plume between the emission and measurement sites, including plume speed variations, plume dispersion, and loss of SO$_2$ from the plume, as with dry deposition or conversion to sulfate aerosols, none of which are detectable by a single scan through the plume.

In an effort to improve monitoring of passively degassed volcanic SO$_2$, we have constructed and tested a digital camera for collecting two-dimensional images of volcanic plumes. The camera utilizes a bandpass filter to collect photons in the spectral region where SO$_2$ selectively absorbs. SO$_2$ is then quantified by imaging calibration cells of known SO$_2$ concentrations for comparison.

Images of volcanic SO$_2$ plumes were collected at four active volcanoes with persistent passive degassing: Villarrica, located in Chile, and Santiaguito, Fuego, and Pacaya, located in Guatemala. Images were collected from distances ranging between 4 and 28 km away, with acceptable detection up to approximately 16 km. Camera set-up time in the field ranges from 5-10 minutes and temporal resolution of up to 6 images per minute is possible, which combined with the camera’s field of view makes a continuous SO$_2$ dataset attainable. Variable in-plume concentrations can be observed and accurate plume speeds (or rise rates) can readily be determined by tracing individual portions of the plume within sequential images. At Fuego volcano, simultaneous measurements of corrected SO$_2$ fluxes with the camera and a COSPEC agreed within 25%. Experiments at the other sites were equally encouraging, though further work is required to eliminate possible problems caused by variable background sky conditions and the presence of meteorological clouds.

UV cameras may eventually be utilized as a means to obtain a high-resolution time series of volcanic plume imagery, offering insight into the relationship between SO$_2$ fluxes and eruptive activity. Knowledge of such a correlation could potentially be used to assess the hazard level of a volcano at any given time.
Near-Trench Interface Locking? Geodetic and Seismic Tools useful for identifying Developing Strain Energy to be Released in Future Large and Tsunamigenic Earthquakes

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Subduction zone megathrusts produce the majority of the world's largest earthquakes and tsunamis, however, because they exist under the sea floor they are most often studied with land-based techniques more the 50 km from the active interface. However, the Nicoya Peninsula, in Costa Rica, is uniquely situated nearly over the collisional interface between the subducting Cocos and overriding Caribbean plates, making it ideal for near-field land-based studies, and hence were the focus of the 1999-2001 NSF-MARGINS CRSEIZE project to study the ongoing deformation, earthquake activity and seismic structure there. The combined measurements of microseismicity and GPS deformation both yield valuable information about the state of locking along the interface. Geodetic modeling that directly inverts for locking (backslip) along the subduction interface suggests the region is generally weakly locked, but with a strong (>60% locked) portion just offshore central Nicoya (Norabuena et al., 2004). While, power-law statistics on the occurrence of small to large earthquakes along the interface shows the same locked region to have implied higher stresses (from low b-values) with increased variability near subducted seamounts just to the south (Ghosh et al., 2007). Unfortunately, with either method, interface locking is only constrained for the intermediate to deep portions of the subduction interface and hence do offer insight into locking in the shallowest interface, the region responsible for devastating tsunami earthquakes, and possible the main tsunami source in the 2004 Sumatran earthquake (Newman and Bilek, 2005). In order to better constrain locking in the shallow tsunami earthquake region it will be necessary to develop low-cost geodetic and seismic tools that can constrain horizontal deformation to better than 1-2 cm/yr over 10s of kms and accurately constrain the microseismic activity to very low magnitudes of completeness (Mc<1.5) in the near-trench region of the sea floor.
Ground- and space-based thermal studies of volcanic activity in Central America

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Space-based thermal monitoring, using data from ASTER and MODIS-MODVOLC, allows a regional and regular inventory of volcanic activity in Central America. At the same time, ground-based studies using thermal cameras (FLIRs) are complementary in that they provide a closer view of activity, though in more sparse acquisitions. We are engaged in a comprehensive study of thermal anomalies in moderate (MODIS-MODVOLC, 1 km) and high (ASTER, 15-90 m) resolution thermal satellite imagery over Central America during 2000-2007. MODIS-MODVOLC data tracked significant eruptive activity at Santiaguito, Fuego, Pacaya and Arenal volcanoes. ASTER data shows non-eruptive thermal activity at numerous volcanoes, including Santa Ana, Izalco, Telica, and San Cristobal, which presumably indicates fumarolic activity. The spaceborne data are augmented by FLIR imagery at Santiaguito volcano in January 2007, to which future data will hopefully be added. Upon the completion of this thermal inventory, the data will be analyzed further to estimate eruption rates and infer eruptive and conduit processes. These data parameterize the duration, intensity and erupted volume of volcanic activity and will be helpful for constraining the output of the volcanic arc, which may then be compared to along-arc trends and subduction processes.
Stratigraphic geochemical variations of the youngest explosive Masaya caldera complex tephras

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The Masaya caldera complex in central western Nicaragua has been the site of highly explosive Plinian and phreatomagmatic basaltic eruptions during the last 6000 years. Three main eruptive periods have been recognized: the older ca. 6000 yrs BP San Antonio Tephra, the 2000 years La Concepción Tephra and Masaya Triple Layer and the widespread phreatomagmatic deposits of the Masaya Tuff with the topmost Ticuantepe Lapilli. Fallout and surge deposits alternate in all three tephras, and the role of magma-water interaction varied during these eruptions. The last event, forming the Masaya Tuff, was predominantly phreatomagmatic and generated widespread base surges that ended with a fall event. The products of the Masaya caldera complex have been recognized relatively homogeneous in composition ranging from basalt to basaltic andesite; no evolved compositions are present (Walker et al. 1993). They also show strong iron enrichment and a tholeiitic trend, as well as high concentrations of large-ion-lithophile (LIL-) elements and of slab signals such as Ba/La, 87Sr/86Sr and 10Be/9Be (Walker, 1990; Walker et al. 1993, Morris et al., 1990; Carr et al., 2004).

The youngest tephra units (SAT, LCT-MTL, MT-TIL) share these chemical characteristics. The SAT and LCT-MTL are basalts whereas MT-TIL are basaltic andesites and are more evolved than the recent lava flows, with MgO contents ranging between 3.9-4.8 wt%. These 3 main groups can be differentiated by bulk rock major and trace element compositions. Incompatible element contents are similar for the LCT-MTL and MT-TIL but much lower for the SAT, especially for REE. Higher values of ratios like La/Yb or Zr/Hf indicate that the SAT originated by higher degrees of partial melting or more strongly slab affected mantle.

Although the chemical variation is limited in the single units, some of them show trends of fractional crystallization in their matrix glass and melt inclusions compositions. Radiogenic isotope data show no significant differences for the tephra units since variations are within error range.

Comparison with the nearby rock suite from the Nejapa-Granada systems seems to indicate some common characteristics with the low-Ti group of Walker (1990). These low-Ti rocks have been interpreted to have formed in mantle areas affected by subducted sediments and fluids, which is supported by the slab signals. We suggest that the main geochemical differences observed at the Masaya Tephra might be a result of changes at the source, probably induced by subduction-related fluids, and not by posterior magma transport and storage processes.
We present new data set on ~650 melt inclusions in olivine from 15 frontal volcanoes in Central America (Santa Maria, Atitlan, Fuego, Acatenango, Agua, Pacaya, Ilopango, San Miguel, Telica, Cerro Negro, Masaya, Nejapa, Granada, Arenal, and Irazu). This data is used to access general systematics of volatiles (H2O, S, Cl, F) in primitive to moderately evolved magmas, along-arc variations and magnitude of their fluxes to the exosphere. We discuss uncertainties of the estimates of the total magma flux in Central America and emphasize importance of incompatible elements, whose fluxes can be more easily obtained, if proportion of different rock varieties is known, and the flux estimate requires no correction for fractionation. By using the composition of primitive melt inclusions, ratios of volatiles to incompatible elements (e.g. potassium) in primitive magmas can be well constrained, providing a basis for accurate flux calculations. Preliminary results on magmatic fluxes of volatiles in Central America will be discussed.
Seismic Observables in the Mariana Subduction System

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Analysis of seismic observables within a subduction zone can place first-order constraints on variations in temperature and water content in the region. Results from attenuation tomography, velocity tomography, and shear wave splitting of the Mariana subduction system can provide a direct comparison to analogous studies in the Central American subduction system. As these two systems are relative end members with regard to thermal structure and incoming plate age, comparison between them can foster comprehensive discussion about subduction dynamics. In 2003, we installed a 12-month deployment of 78 land and ocean-bottom seismic stations throughout the Mariana Islands. Ongoing analysis of the high-resolution dataset is showing new insight into upper mantle dynamics. We use an iterative double-difference tomography method Zhang and Thurber [2003] to obtain high-resolution 3D P and S wave seismic velocity images from local travel times. For attenuation analysis, we follow the method of Stachnik et al. [2004] and compute the amplitude spectra for P and SH arrivals and the S-P ratio for a given local earthquake and simultaneously invert for the path-averaged attenuation parameter for each waveform and the seismic moment and corner frequency for each earthquake. Subsequent inversion of the attenuation parameters shows a low attenuation slab and separate high attenuation regions beneath the arc and beneath the backarc spreading center. We also present local S shear wave splitting results showing dominantly arc-parallel fast directions.

As seismic attenuation is largely indicative of thermal anomalies, final analysis can provide a significant amount of information about backarc spreading processes and, in conjunction with velocity tomography and shear wave splitting, excellent spatial constraints on regions with anomalous temperatures, water content, and possibly partial melt within the mantle wedge. Collaboration with experimentalists and theoreticians and comparisons with results from other subduction zones will likely facilitate a more comprehensive view of upper mantle dynamics throughout subduction zones and may help to create a more complete image of mantle wedge structure.
Segmentation of the Subduction zone off Nicaragua and Costa Rica

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Subduction, under Nicaragua and Costa Rica, of Cocos plate lithosphere with different genesis and geomorphic features produces important changes along the plate interface. The elastic coupling between the Cocos plate and both Caribbean plate and Panama block, changes along the strike of the Middle American Trench from Nicaragua to southern Costa Rica. These changes correlate with the bathymetric features on the subducting ocean floor and are directly related to the genesis and age of the Cocos plate. The age controls the subduction angle, maximum depth of the coupling zone and the intraslab seismicity. The bathymetric features control the size and lateral extend of the asperities. Although the Quesada Sharp Contortion (QSC) is the only, seismically proven, physical segmentation on the Cocos plate, based on the above mentioned features and on differences in seismicity patterns both, historical as well as instrumental, we have divided the subduction zone in southern Central America in five segments.

The Nicaragua-Papagayo segment has a low degree of coupling. Earthquakes on this segment are very frequent and of moderate size (more than 5 events per year with Mw ≥ 5.2); large events here have slow rupture velocities. Cocos plate subducting here is the oldest in this region; the ocean floor has smooth bathymetry and the slab subducts with a steep angle, decreasing both, the coupling area and the normal stress along the plate interface. Earthquakes of different sizes have occurred in this segment in 1750, 1840, 1844, 1863, 1881, 1889, 1901, 1916, 1921, 1956 y 1992.

Cocos plate subducting under the Nicoya segment is also relatively old, has smooth bathymetry and a similar Wadati-Benioff angle as the Nicaragua-Papagayo segment. However, in contrast with the Nicaragua-Papagayo segment, the existence of the Nicoya peninsula in this segment applies an important lithostatic load on the plate interface increasing the normal stress and therefore the coupling between the plates. Due to this strong coupling the Nicoya segment produces large earthquakes and has a low background seismicity level during the interseismic period. Large earthquakes have occurred here in 1826, 1853, 1900 and 1950.

Cocos plate subducting under the Cóbano-Herradura and Quepos-Sierpe segments is young in age and with rough bathymetry consisting of a series of small seamounts. When subducting, these small seamounts reduce the coupling area to small asperities that rupture frequently with moderate size events. The Cóbano-Herradura segment has produced earthquakes of Mw~7 in 1882, 1939 and 1990. The Quepos-Sierpe is the weakest and generates only earthquakes with Mw<7; some of these occurred in 1940, 1941, 1952, 1974, 1982, 1990, 1996 and 1999. Two important features of these two segments is that, due to their weak coupling, they fail every time the neighboring segments of Nicoya to the NE and Osa-Burica to the SE, break with earthquakes of Mw>7; and also that they tend to break with duplets, like the August 28-September 4, 1996 and the August 10 and 20, 1999, pairs.

The Cocos lithosphere subducting under the Osa-Burica segment is not only the youngest, but also the thickest since it carries with it the Cocos ridge. The buoyant effect of both the young lithosphere and the Cocos ridge increases the coupling along the plate interface; the lithostatic weight of the Osa peninsula also helps increase this coupling. For these reasons this segment is capable to generate large (Mw>7) earthquakes like the 1867, 1904, 1941 and 1983 events.
The distinct hydrogeology of convergent eroding margins, and its influence on long-term tectonics and interplate seismogenesis.

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Tectonics at convergent margins is recognized to be intimately related to the distribution and flow of fluid. This relationship has been well documented at accretionary prisms, but at convergent margins where tectonic erosion grinds down overriding plates fluid distribution and its relation to tectonics are more speculative. Only the hydrogeological systems of accretionary margins have been extensively studied, probably because accretionary structure facilitates seismic imaging, which promotes drilling and complementary studies, and fossil analogs can be studied onshore. In comparison the current understanding of the hydrogeology - at margin scale - of erosional systems and the interaction of fluids with tectonics and interplate seismogenesis lags clearly behind.

The integration of geophysical, geochemical and geological observations along the convergent Middle America Trench, where long-term subsidence (millions of years long) of the forearc indicates persistent tectonic erosion, has revealed a distinct hydrogeological system, different from those described at accretionary prisms. The hydrogeological system has been studied by 1) compiling an inventory of seeps detected with multibeam bathymetry, deep-towed side-scan sonar, and ground-truthing with deep-towed video observations, and rock and fluid sampling that further confirmed active fluid flow, 2) mapping the relative distribution of fluid along the plate boundary with multichannel seismic reflection data, and 3) calculating the fluid budget of the margin after estimating fluid-flow rates from thermal structure and pore fluid chemistry.

The observations show how the hydrogeological system influences long-term tectonic erosion and the transition with depth from aseismic to seismogenic behavior along the plate boundary. Where fluid is abundant along the plate boundary, the overriding plate is thinned, and fractures and subsides to form the continental slope. Most fluid migrates from the plate boundary by focused flow across the fractured overriding plate. Seismogenic behavior begins where fluid abundance declines indicating a first order control on subduction zone earthquakes.
The time-scales of basaltic magma generation and differentiation beneath Nicaragua and Costa Rica

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The Th isotopic compositions of basalts and andesites from Nicaragua have near global extreme values of 2.2 to 2.7 (Reagan et al., GCA, 1994; Thomas et al., GCA, 2002). These values mirror the extreme U/Th ratios of the average subducting sediment beneath Central America (Patino et al., CMP, 2000), which is consistent with the involvement of nearly unfractionated bulk sediment in magma genesis. Even so, \((230\text{Th}/232\text{Th}) = 2.0\) at \(10\text{Be}/9\text{Be}=0\), suggesting that the mantle beneath Nicaragua has been influenced by subduction for a period exceeding 4.5Ma. Most Nicaraguan lavas also are characterized by strongly correlated values of \((226\text{Ra}/230\text{Th})\) and \((238\text{U}/230\text{Th})\) (1.2-2.4 and 1.0-1.16 respectively), which suggests that U and Ra are added to the mantle sources of these lavas in a fluid from subducting lithosphere (Reagan et al., 1994; Thomas, R.B., PhD dissertation, U. Minnesota, 2004). This correlation also suggests that melting, melt migration, fractionation, and eruption all occur with a few thousand years of the fluid addition. High-Nb lavas from central Nicaragua, which have La/Nb <1.5, humped REE patterns, and significant 230Th excesses, appear to be remelts of the residual hornblende-bearing mantle that generated the more typical low-Nb lavas.

Young mafic lavas from Irazu and Turrialba volcanoes in Costa Rica have \((230\text{Th}/232\text{Th}) = 1.03-1.25, (238\text{U}/230\text{Th}) = 0.85-0.9, (226\text{Ra}/230\text{Th}) = 1.0-1.2,\) and radiogenic isotopic compositions and most incompatible trace element ratios that are like ocean island basalts (e.g. Reagan and Gill, JGR, 1989; Clark et al., GCA, 1998; Thomas et al., 2002). Based on these observations, generating the parental basalts for these lavas appears to require low degrees of melting of a garnet-bearing, enriched mantle in the presence of a water-rich fluid from subducting altered oceanic crust. High-Nb basalts from Turrialba have U-Th systematics and other trace element and isotopic compositions that are similar to those of the more typical low-Nb basalts. The principal differences are that the low-Nb basalts have slightly higher Ba/La and Sr isotopic compositions compared to the high-Nb basalts. These differences are attributed to an increase in the partition coefficient for Nb in the mantle sources of the basalts when an oxidizing slab fluid is present. Lavas from Arenal have similarly low Th isotopic compositions, but are enriched in 238U over 230Th, reflecting a stronger flux of water-rich fluid from subducting oceanic crust than is found to the south. Like for Nicaraguan lavas, \((226\text{Ra}/230\text{Th})\) values correlate with \((238\text{U}/230\text{Th})\), and thus the flux of subducted fluid to the mantle source of the parental basalts (Tepley et al., JVGR, 2006). 231Pa is significantly enriched over 235U in all lavas, requiring protracted melting, but rapid migration to the surface (Thomas et al., 2002).
Volatile abundances in Central American Lavas: Using Experimentally Determined Solubility Relationships to Understand Natural Melt Inclusions

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Water and CO2 are the two most abundant volatile species in arc lavas. Consideration of the solubility of both species provides an important context for understanding their evolution and abundance during transport from mantle to crust as well as their influence on eruption styles. In Central America the composition of olivine-hosted melt inclusions range from low-CaO to high-CaO (CaO/Al2O3 of 0.50 to 0.98). Importantly, this observed calcium variation dramatically influences volatile solubility and exerts an important control on depth of volatile saturation, inception of degassing and volatile loss and may influence vapor transfer between magmas. A series of water- and CO2-saturated piston-cylinder experiments, using basalts from Guatemala and Nicaragua, as well as a Ca-spiked aliquot, were used to determine solubility relationships at pressures of 3 to 7 kb. The low, moderate and high-calcium basalts have CaO of 9.1, 12.7 and 19.5 wt.% and CaO/Al2O3 of 0.52, 0.78 and 1.33, respectively. Upon quench the fluid from each experimental capsule was collected in a vacuum line and manometrically analyzed. Similarly, glasses were analyzed by FTIR and vacuum manometry. At low pressure (3kb; mole fraction of H2O in fluid ~ 0.42) increasing CaO from low to moderate levels increases CO2 solubility more than 40% (1,900 ppm versus 2,700 ppm)! Given the wide compositional range of natural arc lavas and melt inclusions this result indicates a need for greater assessment of the influence of composition on natural volatile abundances. In the Nejapa and Granada regions of Nicaragua moderate and high calcium melt inclusions occur interspersed. Olivine-hosted melt inclusions from Tiscapa have CaO/Al2O3 ratios of 0.82 to 0.98, CO2 contents from 1,900 to 5,200 ppm and moderate to high water 2.4 to 4.4 wt.%. Such high volatile contents in a low calcium magma might indicate volatile saturation pressures in excess of 6 kb, but new experimental results indicate the calcic Tiscapa melt inclusions represent volatile saturation pressures of ~4kb and below. The fluid ratios (CO2/H2O of 0.09 to 0.13) of Tiscapa melt inclusions are roughly four times higher than elsewhere in the arc (maximum 0.025) and may be consistent with a distinct source for calcic magmas. Phase equilibria experiments are currently being conducted under H2O and CO2 saturated conditions to determine the influence of fluid signature and calcium abundance on arc magma evolution.
At 07:11 (UTC) of December 25, 2003 a strong earthquake of Mw 6.6 shock the whole national territory of Costa Rica and Panamá, causing important damage at the frontier zone between both countries, killing two people and injuring about 75. The earthquake was located 8 km east of Puerto Armuelles, Panamá. It generated numerous damages in buildings and homes at the mesoseismal area. The seismic activity continued with many aftershocks the following weeks, with strong earthquakes such as the January 7 (Mw 5.5) and February 4, 2004 (Mw 5.8). A previous damaging earthquake occurred on July 30, 2002 (Mw 6.2) which injured 8 people and caused the collapse of at least 12 houses.

All these earthquakes were originated at the Panamá Fracture Zone, which lies south of the triple junction of the Cocos, Caribbean and Nazca plates. Other features present in this complex tectonic region are the subduction of the Cocos Plate under de Caribbean plate, and inland, important fault systems such as the Costa Rican Longitudinal Fault.

According to the damage observed from these earthquakes, maximum intensities of VII (MM) were determined for localities near the epicenter such as Laurel in Costa Rica and Puerto Armuelles in Panamá. Several strong motion instruments recorded the earthquakes. The Golfito station is the closest instrument to the epicentral region (40 to 85 km away), it recorded accelerations between 3.2% to 11.6% of g.
Hazards of Volcanic Ash in Central America

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Volcanic ash is of special hazard significance when it is generated as fine (<30 microns in diameter) particles which do not fall quickly. This fine ash is generated in high proportions by pyroclastic flows and perhaps other types of activity. It may be a widespread hazard to aircraft as it is dispersed by winds. It can be scavenged by larger ash particles and hydrometeors and may be concentrated in an extensive fall deposit. The mass, sizes and fate of fine volcanic ash is revealed by laser diffraction grain size studies of ash fall and from satellite based atmospheric remote sensing.
About deformation, reactions, and fluids: combining petrology and modeling to better understand deeper earthquakes

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In order to test which seismic failure modes are feasible at elevated pressures it is necessary to formulate numerical models that integrate deformation, fluid flow, and metamorphism. Major feedback mechanisms between these processes are (i) rheological weakening by fluids and phase transitions, (ii) volume and density changes resulting from metamorphism and (iii) thermal feedbacks through the latent heats of metamorphic reactions.

Two main hypotheses have been proposed to explain intermediate-depth (70-300km) seismicity in slabs and continental root zones: one suggests that high fluid pressures lead to dehydration embrittlement which facilitates seismic failure, the other suggests that melt shear instabilities lead to seismic slip. During dehydration embrittlement, elevated fluid pore pressures counteract the lithostatic pressure and thereby lower the effective pressure to values at which tectonic stresses can lead to seismic failure. The fundamental unknown in this scenario is the pore pressure. Ductile shear instabilities are a different failure mode of rocks. Rapid deformation rates lead to frictional heating and melt lubrication resulting in self-accelerating deformation at seismogenic strain rates. The fundamental unknowns in this failure mode are the conditions at which a small perturbation of the system will self-amplify instead of decaying and thereby lead to extreme localization of deformation and frictional heating. Pseudotachylytes are the only certain geological evidence for paleo-earthquakes and more and more eclogite-facies pseudotachylytes localities have now been discovered. They were found in rocks of the deeply exhumed continental roots and in exhumed fragments of subducted slabs. Their existence indicate that frictional melting is possible and may be a requirement for earthquakes under pressure-temperature conditions reasonable for depths >60-70 km. Here we will present results of a joint field, analytical and modeling approach to better understand the development and evolution of seismogenic shear zones. Field evidence shows that the seismic shear zones contain water-bearing minerals and that those are highly concentrated at the margin towards the wall rock. The formation of the water-bearing minerals produces latent heat. We will present a model in which we incorporate the effect of latent heat release through metamorphic hydration reaction. This new model is mechanically and petrologically consistent and provides good constraints on the conditions at which thermal runway and ductile failure can occur.
THE SABANA REDONDA CINDER CONES: ENRICHED MAGMATIC COMPONENT OF POAS VOLCANO, COSTA RICA.

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We describe the stratigraphy and geochemistry of tephras and lavas related with 5 cinder cones in a north-south alignment on the southern flank of Poás volcano. The local geologic basement is composed mainly by lava flows, with the north-west dominated by the Achiote basaltic-andesites and the rest of the area by Poasito andesites, this last cogenetic with the cinder cones. All of these units are generally covered by a thin layer of the upper section of the Poás Lapilli Tuff. Field evidence suggests that the cinder cones were not contemporaneous but represent different magmatic pulses. The magmas that produced these cinder cones represent the most enriched magmatic component of Poás volcano. Based on the available geochemical data, we define two magmatic components for Poás:
1) The Sabana Redonda component (TiO2 >1%, relatively enriched in HFSE and other incompatible elements), which is also present in the Paleo-Poás, Poás lapilli tuff y and some Botos crater lavas.
2) The von Frantzius component (TiO2 <0.8%), which is present at lavas from the main crater, von Frantzius cone, Hule maar, and in some Botos crater lavas. Intermediate lavas (TiO2 0.8-1%) are hybrids between these two components. Both components share the same OIB-like source, although the Sabana Redonda component requires a relatively lower degree of partial melting, produced primarily by a decompression mechanism, which may be related with the extension generated within the Poás volcanotectonic fracture. The von Frantzius component represents magmas produced primarily by flux melting related with the subduction processes.
Fluid pressure distribution within subduction zones profoundly affects fault strength, sliding stability, and chemical transport, yet few direct measurements of this important quantity exist. Elevated pore pressures are driven by a combination of: (1) rapid tectonic loading of low-permeability sediments, and (2) fluid release by dehydration reactions. Quantifying the factors that control pore pressure development, its spatial distribution, and its relationship to observed fault mechanical behaviors is needed as a first-order test of hypotheses suggesting that fluid content or pressure control the updip limit of the seismogenic zone or fault strength. Additionally, at many subduction zones the geochemistry of pore waters sampled at shallow depths indicates a contribution from deep, high-temperature sources. These observations include pore water freshening, elevated K\(^+\), thermogenic hydrocarbons, and enrichment in volatiles such as B and Li. Identifying the source regions for these tracers is one critical step toward characterizing subduction zone fluid transport systems. Further, linking the expected loci of fluid generation from diagenetic or metamorphic processes with observations of fault mechanical behaviors (such as microseismicity or geodetic locking) provides valuable insights into potential links between the two. Here, I provide a summary of our work at the Costa Rican margin, which is aimed at constraining (1) fluid pressure from the trench to the seismogenic zone, (2) the loci of clay dehydration and its relationship to the updip limit of seismogenesis, and (3) the source regions for other geochemical tracers, which provide insight into margin-scale fluid flow patterns.

At non-accretionary convergent margins such as Costa Rica, underthrusting sediments are the primary source of fluids entering the subduction zone. In these sediments, in situ pore pressure can be estimated indirectly by laboratory consolidation tests on core samples and by observed compaction trends in boreholes. At the Costa Rica subduction zone offshore the Nicoya Peninsula, the two methods yield consistent results, and indicate development of significant overpressures accompanying underconsolidation. Patterns of inferred pore pressure are most consistent with upward drainage to a permeable décollement. Data from other subduction zones follow a similar pattern, and taken together, demonstrate that excess fluid pressures fundamentally result from a balance between loading rate, fluid release, and sediment permeability. These results hold important implications for the role of sediment and fault permeability in affecting fault strength and the updip limit of the seismogenic zone, via their control on pore pressure and effective stress.

As one example, along the Costa Rican subduction zone offshore the Nicoya peninsula, an offset in the updip limit of seismicity coincides with a transition between subduction of warm crust generated at the Cocos-Nazca Spreading Center and cool crust formed at the East Pacific Rise. By combining thermal models with models of dehydration reaction kinetics for opal and smectite, numerical models can be used to estimate the distribution of diagenetic fluid sources. The modeled distribution of diagenetic fluid sources mimics the pattern of the updip limit of seismicity; seismicity begins ~15-20 km landward of most of the smectite-to-illite transition. This suggests that the location of the updip limit of seismicity may be influenced by the dissipation of fluid overpressures landward of smectite-to-illite dehydration.
New 40Ar/39Ar Dates Reveal Episodic Volcanism in Western Nicaragua

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The active arc in Western Nicaragua is separated from the Miocene arc by a temporal gap in the volcanic record during which little or no volcanic material was erupted. Previous work suggested that volcanic production in Nicaragua was limited or nonexistent between 7 Ma and ~300 ka. Because the precise timing and duration of this gap has been poorly constrained, current fieldwork has focused on locating samples that may have erupted close to or even during this apparent hiatus in activity. We report new 40Ar/39Ar dates that show pulses of low-level episodic volcanism at 7 Ma and 1.5 Ma between the active and Miocene arcs with current volcanism beginning ~350 ka. In addition, sample C-51, taken from an inactive area between Cosiguina and San Cristobal, yielded an age of 3.5 Ma—the only sample of that age collected on-strike with the active arc. This raises the possibility that other lavas of this age exist at the bases of the other active volcanoes, but have been buried by subsequent eruptions. Recent fieldwork has produced ~20 new samples that are currently being age-dated as well as analyzed for both major and trace element abundances. The Miocene arc differs from the active arc in Central America in several ways, with the latter having higher Ba/La and U/Th values due to increased slab input and changes in subducted sediment composition. Analysis of sample C-51 and others taken from the same area may shed light on the timing of this shift from low to high Ba/La and U/Th values. More importantly, it may help explain why the arc experienced such a dramatic downturn in production.
Orthogonal subduction of rough oceanic lithosphere along the northwestern flank of the Cocos Ridge imprints a distinctive style of deformation on the overriding Costa Rican fore arc. Spatial variability in Late Quaternary uplift recorded by marine and fluvial terraces is consistent with deformation driven by variations in the bathymetry of the downgoing Cocos plate. Fifty nine published and seven unpublished, radiocarbon dated, marine samples constrain variations in Late Quaternary surface uplift rates along a ~300 km segment of the Pacific coast of Costa Rica between the central Nicoya Peninsula and the Osa Peninsula. All sixty-six samples are analyzed using the most recent (IntCal04) calibration and recent sea level curves to constrain late Quaternary uplift rates. Regions characterized by the fastest (>6 m k.y.-1) long-term uplift rates are confined to portions of the Nicoya and Osa Peninsulas that are opposite where bathymetric highs are presently entering the Middle American Trench (MAT). Kinematic analysis of thirty-four published and seventeen unpublished mesoscale fault populations from along the Costa Rican fore arc provide additional evidence of long-term patterns of upper plate deformation. The fifty-one mesoscale fault populations suggest that the fore arc can be subdivided into three domains that correlate to the geometry and morphology of the subducting plate. Across the central Nicoya Peninsula, where the crust currently entering the MAT is smooth and the Benioff zone defines a steeply dipping slab, mesoscale fault populations are consistent with margin-parallel extension and strike-slip motion. Along the central Pacific coast, steeply dipping, northeast-striking, margin-perpendicular nodal planes accommodate differential uplift associated with ongoing seamount subduction. Further south, inboard of the underthrusting aseismic Cocos Ridge, mesoscale fault populations record active shortening related to an extensive thrust belt. The recognition of uplifted marine and fluvial terraces and calculated rates of vertical uplift, provide a first order estimate of permanent strain along the fore arc in Costa Rica that exceeds rebound of stored elastic strain released during subduction zone earthquakes. The integration of fault kinematic data suggest that permanent uplift of the subaerial fore arc is the result of both underplating and out of sequence thrust faulting. Out-of-sequence thrusting is the dominant mechanism of fore arc thickening along the inner fore arc inboard of the underthrusting Cocos Ridge while underplating is the dominant mechanism elsewhere.
Rayleigh wave tomography in the Nicaragua-Costa Rica Subduction Zone

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The goal of this study is to image crust and mantle structure in the Nicaragua-Costa Rica subduction zone by applying Rayleigh wave tomography to waveforms recorded by the TUCAN Broadband Seismometer Experiment. The 48-station TUCAN array included two dense station lines normal to the arc, one in Nicaragua and the other in Costa Rica, and two sparser lines along the fore-arc and in the back-arc. Stations were in the field from July, 2004, until March, 2006. The method we employ inverts teleseismic event phase and amplitude measurements at different periods for 1) phase velocity in a grid surrounding the array and 2) six parameters that describe the incoming wavefield (the phase, amplitude and propagation direction of two interfering plane waves). We are analyzing events at epicentral distances of 35° to 120° at 19 periods ranging from 15 s to 167 s. Phase velocity maps will then be inverted for regional shear-wave structure.

Ample sources with a good azimuthal distribution were recorded over the duration of the array, and, given the station distribution, we anticipate that good resolution of the overriding plate beneath the region will be possible. Geochemical data in this region contain strong along-arc variations; these are consistent with a mantle wedge beneath Nicaragua that contains a greater depth and extent of melting and larger input of slab fluids than are present in the mantle wedge beneath Costa Rica. Constraints on the thickness of the upper plate lithosphere and its velocity contrast with the mantle wedge should provide useful constraints on subduction zone thermal structure and may help to explain the source of the along-arc geochemical variation.
Strain Release Along the Northern Costa Rica Seismogenic Zone

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The 1999-2001 collaborative Costa Rica Seismogenic Zone Experiment (CRSEIZE) collected abundant seismic and geodetic data in the vicinity of the Nicoya Peninsula, Costa Rica that uncovered various modes of strain release along the subduction plate interface. Precise images of the up and down dip limits of geodetic locking and microseismicity indicate that the GPS defined locked region extends to considerably shallower depth than the microseismicity. We interpret the up dip edge of geodetic locking as the frictional stability transition from stable sliding to stick-slip behavior. The geodetically locked patch between the frictional transition and the deeper onset of interplate microseismicity marks the probable location of major moment release for a future large plate boundary earthquake. The down dip onset of microseismicity marks a change in the mode of strain release from seismic to aseismic or slow deformation. During the interseismic cycle, this region either slips nearly continuously, or episodically in slow slip events that have been recorded in this region by an evolving continuous GPS (CGPS) network that is presently being expanded to 12-15 stations. Surface and borehole observatories are also being deployed to monitor seismic activity and tilt associated with strain transients. The physical processes responsible for strain transients are not well understood; detection and study of their behavior at several locations is important. Relative to other subduction zones, Nicoya has a big advantage for this type of project: the peninsula is quite close to the trench. Instruments deployed here are essentially “perched” directly over the seismogenic zone enabling high-resolution study of plate boundary strain and seismic processes.
Subducting slabs transport volatiles, such as H2O, S, CO2 and N, from the Earth’s surface into the mantle. A certain fraction of these components are cycled back to the surface via arc volcanism. Significant progress has been made over the last few years in evaluating the source of these volatiles and the efficiency of this process at the Central American and Izu-Bonin-Mariana margins. These arc systems have distinct physical and geochemical characteristics, which may influence how volatiles are fluxes through their respective subduction factories. Three different methods used to calculate absolute fluxes of volatiles from volcanic arcs are: 1) remote sensing techniques such as COSPEC or mini-DOAS, 2) direct sampling of fumaroles or geothermal fluids, where gas contents are normalized to 3He and a 3He flux is assumed, and 3) melt inclusion abundances combined with magma production rates.

In the case of CO2, comparison of 3He flux normalisation methods (CO2/3He ratios measured in Costa Rica-Nicaragua then extrapolated to the entire arc) and remote sensing methods yielded similar output fluxes (=7.1 x 1e10 mol/yr vs. 5.8 x 1e10 mol/yr; Shaw et al., 2003). This study reported a recycling efficiency of 14-18% - relatively low as compared to N, which was initially thought to be close to 100% efficient (Fischer et al., 2002). Recent re-evaluation of sedimentary inputs at the Central American margin (Li and Bebout, 2005) has modified these numbers such that the CO2 efficiency is slightly higher (up to 28% of subducted C is recycled through the arc), whereas the N efficiency is significantly lower (50%; Li and Bebout, 2005). The fraction of CO2 recycled through the Izu-Bonin arc has been constrained by volatile studies of melt inclusions, where measured pre-eruptive CO2 contents are combined with magma production rates to obtain an output CO2 flux. Compared to Central America, the Izu-Bonin subduction zone system is a relatively cold subduction zone and modeled CO2 behaviour for low temperature geotherms suggest that little decarbonation would occur at subarc depths (Kerrick and Connolly, 2001). However, fluids can effectively promote decarbonation, and trace element ratios of Izu arc rocks predict that a significant amount of fluid is fluxed through the Izu-Bonin arc system. Based on our studies, we find that between 5 and 15% of CO2 is recycled through the volcanic arc system, depending on whether the highest CO2 content (=1200 ppm) or the modeled pre-degassed CO2 estimate (= 3830 ppm) is considered to best represent source values. This result, combined with revised CO2 budgets for Central America, suggests that 1) a significant fraction of C is potentially cycled deep into the mantle, and 2) decarbonation is indeed more limited in cooler regimes such as the Izu-Bonin arc.

Shaw et al., EPSL v. 214, 499-513 (2003)
Li and Bebout, Geophys. Res. v110, B11202 (2005)
Kerrick and Connolly, Nature v. 411, 293-296 (2001)
A model for subduction erosion off Nicaragua

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Evidence for subduction erosion in Costa Rica is very strong, including massive subsidence of the coastline in the past 6 Ma. However, neither the coastline nor the shelf edge off Nicaragua has suffered nearly as much subsidence, yet the morphology of the margins demands at least as much tectonic erosion. Analysis of the subsidence history of the Sandino basin, along with a reasonable model for the history of the Central American margin over the past 6 Ma provides a reasonable solution to this seeming enigma.
SEISMIC STRONG MOTION ARRAY PROJECT (SSMAP) TO RECORD FUTURE LARGE EARTHQUAKES IN THE NICOYA PENINSULA AREA, COSTA RICA

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The seismic strong motion array project (SSMAP) for the Nicoya Peninsula in northwestern Costa Rica is composed of 10 - 13 sites including Geotech A900/A800 accelerographs (three-component), Ref-Teks (three-component velocity), and Kinemetric Episensors. The main objectives of the array are to: 1) record and locate strong subduction zone mainshocks [and foreshocks, “early aftershocks”, and preshocks] in Nicoya Peninsula, at the entrance of the Nicoya Gulf, and in the Papagayo Gulf regions of Costa Rica, and 2) record and locate any moderate to strong upper plate earthquakes triggered by a large subduction zone earthquake in the above regions. Our digital accelerograph array has been deployed as part of our ongoing research on large earthquakes in conjunction with the Earthquake and Volcano Observatory (OVSICORI) at the Universidad Nacional in Costa Rica. The country wide seismographic network has been operating continuously since the 1980’s, with the first earthquake bulletin published more than 20 years ago, in 1984. The recording of seismicity and strong motion data for large earthquakes along the Middle America Trench (MAT) has been a major research project priority over these years, and this network spans nearly half the time of a “repeat cycle” (~ 50 years) for large (Ms ~ 7.5- 7 3⁄4) earthquakes beneath the Nicoya Peninsula, with the last event in 1950. Our long time co-collaborators include the seismology group OVSICORI, with coordination for this project by Dr. Ronnie Quintero and Mr. Juan Segura. Numerous international investigators are also studying this region with GPS and seismic stations (US, Japan, Germany, Switzerland, etc.). The major goal of our project is to contribute unique scientific information pertaining to a large subduction zone earthquake and its related seismic activity when the next large earthquake occurs in Nicoya. We are now collecting a database of strong motion records for moderate sized events to document this last stage prior to the next large earthquake. A recent event (08/18/06; M=4.3) located 20 km northwest of Samara was recorded by two stations (Playa Carrillo and Nicoya) at distances of 25-30 km with maximum acceleration of 0.2g.
Understanding the physical and chemical processes operating in subduction zones has a wide range of socio-economic implications because these major plate boundaries generate destructive earthquakes and tsunamis. In order to better understand the relations between these processes, CORK IIIs were installed in two fluid flow systems identified during ODP Legs 170 & 205 at the Costa Rica Subduction Zone (SZ). One was installed and instrumented in an igneous basement flow system at Site 1253 (~0.2 km west of the trench) where lateral flow of seawater (SW) effectively cools the oceanic crust, and the other within the décollement flow system at Site 1255 (0.4 km east of the trench). The latter channels a deep sourced fluid originating east of the deformation front. The downhole instrumentation includes pressure (P) and temperature (T) loggers and OsmoSamplers (OS) that continuously monitor fluid chemistry. A newly designed borehole fluid flow meter was deployed at Site 1255, which uses OSs to continuously inject and sample a tracer in two-dimensions. The relative dilution of the tracer across the central injection is then modeled for flow rates. The data obtained by this interdisciplinary effort represents the first high-resolution time-series data set of fluid flow and chemistry at a SZ, with direct implications for seismogenic zone activity and chemical fluxes to the ocean.

There is strong evidence for vigorous shallow flow of SW in the underlying basement at Site 1253. Temperature reaches a steady-state value of 7.94 °C, which is ~15% of the value expected from conductive lithospheric cooling models, and the pressure is ~6 kPa sub-hydrostatic. The P and T records indicate that the basement is highly permeable and hydrologically connected to distant points of seawater recharge and ventilation. Mg, Ca, Sr, and other element concentrations change rapidly from SW values to situ formation concentrations during the first 30 days of the deployment. This quick evolution of fluid composition is consistent with sealing of the hole and formation fluids rapidly flushing out surface and bottom water introduced into the borehole during drilling. The time for solute concentrations to evolve from SW value to steady-state formation concentrations provides an estimate for specific discharge within the basement. Applying a simple steady-state first order sink model to the observed change in concentrations yields a range of specific discharge from 4.2 to 5.6 m/yr. These high flow rates are consistent with a highly permeable basement, suggesting that it may serve as a near hydrostatic flow pathway for fluids being expelled from deeper within the subduction zone.

Pressure in the décollement at Site 1255 was ~230 kPa superhydrostatic and declined steadily over the first 5 months of the deployment. Fluid flow rates and T declined steadily over this period to background values of 0.9 cm/yr and 6.638 °C, respectively. The decline in P, T and flow rates during the first 5 months likely reflects drainage after loading of the formation by SW introduced during drilling. After this period, there are two transient events manifested by increases in P, T, and flow rates that correlate with an abrupt change in chemistry from SW values to concentrations characteristic of pore fluids from the décollement. These events were observed in late May and early October 2003. Both events correlate with data from Nicoya Peninsula GPS stations that suggest aseismic slip dislocations along the subduction thrust initiated near the coast in mid-May and mid-September, 2003, and propagated inland over a period of 2-3 weeks. The increase in P and fluid flow rates during these aseismic events is consistent with the formation experiencing compression during thrust slip, and implies a propagating slip likely caused the strain changes along the décollement. Thus, the coupled P and fluid flow data suggest that a mirrored dislocation may also have propagated updip at a similar rate as that observed on-shore by GPS. The data collected at Site 1255 provide new information for the development of models that link the physical and chemical properties at a major plate boundary. The documented transience in these properties has direct implications for earthquake cycles and geochemical fluxes.
We propose a revised chronostratigraphic frame for Barva Formation (equivalent to Neo-Barva volcano). The Paleo-Barva series, below the Neo-Barva, is mainly composed by andesitic rocks underlying the Tiribi Formation (composed by ignimbrites previously dated at 322 ka) near the top of the volcano. They are laterally correlated to Colima Formation (330-800 ka). Tiribi Formation would mark the end of Paleo-Barva volcano events. Following previous stratigraphic proposals, the main stratigraphy of Barva Formation is: [1] Lavas from Bermudez Member are the first products from Neo-Barva, being the oldest lavas the most distal products of Neo-Barva, possibly of fissural origin. They form several lava fields with a wide range of ages (270-40? ka). [2] The pyroclastic deposits in Barva are lesser in volume; represent diachronically short-time events, as in the case of Carbonal Member, that ranges between 40-27 ka. [3] The andesitic lavas of Los Bambinos Member are divided in two sub-members (Lower and Upper). The age of Los Bambinos Member is established based on new geological observations, geology of drilled wells in the upper part of Barva volcano, and previous and a new radiometric ages. A lahar interbeded between the two sub-members yield a radiocarbon calibrated age of 27.4 ka. [4] The pyroclasts of Porrosati Member could have ages <25 ka, according to ages of tephras overlying Los Bambinos lavas. The huge volume of Barva volcano is explained because the whole edifice comprises the overlapping of Proto-, Paleo- and Neo-Barva series, along some 1 Ma.
INTERNAL TECTONIC STRUCTURE OF THE CENTRAL AMERICAN WADATI-BENIOFF ZONE BASED ON ANALYSIS OF AFTERSHOCK SEQUENCES

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Relocated EHB global seismological data for 10 aftershock sequences were used to analyze the internal tectonic structure of the Central American subduction zone; the mainshocks of several of these were the most destructive and often referenced earthquakes in the region (e.g. the 1970 Chiapas, 1983 Osa, 1992 Nicaragua, 1999 Quepos, 2001 El Salvador earthquakes). The spatial analysis of aftershock foci distribution was performed in a rotated Cartesian coordinate system (x, y, z) related to the Wadati-Benioff zone, and not in a standard coordinate system (latitude, longitude, focal depth). Available fault plane solutions were also transformed into the plane approximating the Wadati-Benioff zone. The spatial distribution of earthquakes in each aftershock sequence was modeled as either a plane fit using a least squares approximation or a volume fit with a minimum thickness rectangular box. The analysis points to a quasi-planar distribution of earthquake foci in all aftershock sequences, manifesting the appurtenance of aftershocks to fault zones. Geometrical parameters of fault zones (strike, dip, and dimensions) hosting individual sequences were calculated and compared with the sea floor morphology of the Cocos Plate. The smooth character of the sea floor correlates with the aftershock fault zones oriented parallel to the trench and commonly sub-parallel to the subducting slab, whereas subduction of the Cocos Ridge and sea mounts around the Quepos Plateau coincides with steeply dipping fault zones. Transformed focal mechanisms are almost exclusively of normal character.
Trench-parallel variations in subduction zone fluid pressure and fault strength resulting from temperature differences.

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Trench-parallel differences in the thermal state of subducting crust offshore Nicoya Peninsula, Costa Rica cause along-strike differences in subduction zone temperature. The resulting along-strike differences in fluid viscosity and hydraulic conductivity lead to variations in fluid pressure on the plate boundary fault. Along-strike differences in fluid pressure, in turn, affect fault strength and may partly control the updip limit of seismicity. Because temperatures along the upper 5 km of subduction zone megathrusts generally span a range of temperatures over which fluid viscosity changes substantially, this process may be important in any subduction zone with along-strike variability in the thermal state of subducting crust. This includes subducting crust with along-strike differences in plate age, patchy hydrothermal circulation, or local off-axis volcanism.
Seismic Stratigraphy and Tectonics of the Sandino Forearc Basin, Offshore Nicaragua

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High-resolution (20-250 Hz) multichannel seismic reflection data, totaling approximately 4620 line km, were collected in November-December 2004 (cruise EW04-12) on the inner shelf to slope in the Sandino forearc basin, offshore Nicaragua and Costa Rica. Approximate age constraints are provided by industry well data. The ultimate goal of the project is to identify and distinguish the Neogene stratigraphic signatures of both global sea-level change and local tectonism.

The Mesozoic basement is uplifted to the southeast as it nears the Cocos Ridge and becomes subaerially exposed on the Nicoya Peninsula. Immediately northwest of the peninsula, only a thin (approximately 0.2-0.4 s) layer of Neogene sediment overlies a prominent unconformity truncating basement. Approximately 50 km farther to the northwest, buried clinoforms that prograde northwestward, nearly perpendicular to the present shelf break, may record episodes of this uplift in the south. Similarly oriented clinoforms are also located still farther to the northwest and are associated with along-strike structural segmentation of the forearc basin.

In general, the basin thickens to the northwest, though some areas are locally uplifted. The northwestern area of the survey images a thick (>4 s) forearc basin, where a series of angular unconformities truncate heavily faulted Cenozoic strata. Dip profiles show strata with steep basinward dips truncated by an angular unconformity near the seafloor at their landward ends. Continuing basinward, these strata are deformed by a series of approximately trench-parallel folds. Near the shelf edge, the subhorizontal strata become clinoformal and the section is commonly cut by landward dipping normal faults. Beneath the slope, the faulted top of basement (margin wedge) is resolved, overlain by approximately 1 s of slope sediment. Faulting occurs within slope sediments and there is evidence of both buried and surficial slope failure. In addition, the slope is incised by both modern and buried canyons. A prominent bottom-simulating reflector (BSR), indicative of the presence of a hydrate layer, occurs on the slope throughout the survey area.

Work is underway to construct a regional stratigraphic interpretation. Isopach maps will be developed and used to develop a chronology for basin evolution and timing of major tectonic events.
How Project IBM can help understand the Central America Subduction Factory

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Synergy between the focus sites of Central America and Izu-Bonin-Mariana has been an important part of the success of the MARGINS Subduction Factory experiment. These were selected because they represent endmember subduction zones, but research in them has shown each has advantages. Central America SubFac benefits from ease of access, marked along-arc variations in subduction inputs, and synergies with SEIZE, whereas IBM SubFac benefits from multiple SubFac outputs across the arc system, well-resolved tectonic history, and absence of continental crust. We should keep the different advantages of Central America and IBM in mind as we plan for continued efforts to develop an integrated model for operation of the Subduction Factory and origin of continental crust. IBM SubFac has also proven to be advantageous studied using scientific ocean drilling, and a Complex Drilling Proposal “Project IBM” is iterating its way through the IODP review process. The objective is to better reconstruct the 4D evolution of IBM as representative of intra-oceanic arc systems and use this to test the idea that continental crust is generated at juvenile arcs. Four holes are in various stages of proposal development and evaluation, and the insights that these holes would provide about the Subduction Factory cannot be obtained by IODP drilling in Central America. IBM-1 would drill into a tract of seafloor (1.2 km of sediments and a few hundred meters of oceanic crust) in the W. Philippine Sea basin where it is thought that crust and sediments existed before IBM subduction began; this will constrain the composition of the pre-subduction mantle, constrain paleogeography and tectonic setting, and track sedimentary responses prior to, during, and after IBM subduction initiation. Proposed sites IBM-2 to 4 define an E-W transect across 32°N. IBM-2 would deepen ODP 786B, one of ODP’s most successful hard-rock holes. 786B drilled 660+ m into a mid-Eocene (~48 Ma) forearc ophiolite, penetrating boninitic lavas and bottoming in sheeted dikes. These formed during an early episode of seafloor spreading when subduction began. IBM-2 would drill 2.5 km into this fore-arc ophiolite, through the sheeted dikes and into gabbros, to better understand how arc crust is initially generated and how subduction zones form. IBM-3 would drill into a rear-arc sedimentary basin to recover “the other half” of subduction factory products, information that is critical for reconstructing the bulk composition of arc crust. IBM-4 would drill deeply (~7km) to reach into low-velocity (Vp=6.0-6.3 km/sec) middle crust identified by crustal geophysical profiling. Project IBM would link results from these holes with geophysical crustal profiles and build on results from on-land fossil arcs (Kohistan, Talkeetna, IBM collision zone) to infer crustal structure at depth and so mark a significant advance towards 4D reconstruction of juvenile arc system.
Seismic Velocities and Earthquake Locations in the Central America Upper Mantle: results from the TUCAN Experiment

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The processes that govern magma generation and extraction at subduction zones are not yet well understood. Velocity tomography and earthquake locations from the TUCAN (Tomography Under Costa Rica and Nicaragua) experiment give insight into the geometry and structure of the Central American subduction zone, which exhibits large variations in geochemistry, downgoing plate roughness and dip, and volcano locations over a short distance along the arc. Approximately 31000 P travel times and 12000 S travel times are used in joint Vp, Vp/Vs and hypocenter inversions. The present-day slab geometry is highlighted by contrasts in dip beneath the two arc sections: a near-vertical slab dip beneath the volcanic front in Nicaragua, similar to that indicated by teleseismic hypocenters and a 30° slab dip beneath central Costa Rica, similar to that indicated by a previous local study. In both regions, the intermediate-depth seismic zone is a single layer as thin as 5 km in some areas and no more than 10 to 20 km thick overall. Tomographic images show that throughout Nicaragua and Costa Rica, the slowest mantle P wave velocities appear below the volcanic front, indicating likely zones of mantle melting extending 80 to 120 km depth. Additionally, a column of high Vp/Vs, thought to be caused by a column of melt, is imaged directly beneath the Nicaraguan volcanoes, whereas a weaker, broader anomaly is imaged beneath the Costa Rican volcanoes, potentially indicating a greater extent of melting beneath Nicaragua. Within the downgoing plate, a low-velocity region is imaged at depths less than 150 km beneath Nicaragua and in the upper 60 km of the slab beneath Costa Rica. This feature may represent a hydrated layer at the top of the downgoing plate, similar to that seen in waveguide studies.
Miocene-Pliocene Ignimbrites of the Bagaces Formation in Northern Costa Rica and Large-Scale Magma Mixing

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Silicic volcanism (>65 wt.% SiO2) in the northern Costa Rican segment of the Central American volcanic arc was widespread from the Miocene through the Middle Pleistocene. Some of the most silicic volcanic rocks in Costa Rica are found in the northern Guanacaste Province, and include ignimbrites of the Bagaces Formation. Bagaces ignimbrites are among the earliest high-silica products in this part of the arc (<10 Ma) and are thus important to understanding its chemical, temporal and spatial evolution. While the northern part of the arc is built upon Paleozoic crust of the Chortis block, the arc in Costa Rica is built upon thick oceanic plateau of the Chorotega block, which is located on the western extent of the Caribbean Large Igneous Province (CLIP). Given the absence of old, evolved crust in Costa Rica, high-silica tuffs of the Bagaces formation may represent the transition from oceanic crust to juvenile continental crust.

Six units of the Bagaces Formation were included in this study: Barbudal Canal, Guardia, Hacienda Ciruelas, Papagayo, Pan de Azucar, and Tajo Pelon (all informally named). Pumice fragments collected from the six units were analyzed for major and trace element composition and 22 thin sections were selected for microprobe analysis. Whole-rock major and trace element trends separate Tajo Pelon and Hacienda Ciruelas units from other ignimbrite units, although each may be related to different subsets of samples collected from an underlying and complexly-deformed Barbudal Canal sequence. A detailed analysis of larger sample suites from the Papagayo and Pan de Azucar units provides evidence of complex and cyclic magma mixing involving a large, presumably long-lived silicic magma body.

The Papagayo and Pan de Azucar Tuffs outcrop north of the Nicoya Peninsula in the Guanacaste Province of northern Costa Rica. The Papagayo Tuff contains pumice fragments with evidence of magma mixing. Petrography, whole-rock chemistry and microprobe data are consistent with the mingling and eruption of rhyolitic and andesitic magma batches. Dacitic pumice fragments from the Pan de Azucar unit are more homogeneous, yet chemically similar to intermediate bulk-rock composition of mingled Papagayo samples. In addition, glass compositions of Pan de Azucar pumice fragments straddle bimodal populations in Papagayo fragments, supporting the hypothesis that the Pan de Azucar magma was a homogeneous version of the mingled Papagayo magmas. However, small differences in composition require modification of the Pan de Azucar by some other process (e.g. magma mixing or crystal fractionation).

The clear evidence for mingling and mixing in these units provides an ideal test case for Polytopic Vector Analysis (PVA). Relatively new to igneous petrology, PVA is a multivariate statistical program that can incorporate all available geochemical analytes to simultaneously analyze samples, finding the number and composition of end members required to explain the variation within the population. For the Papagayo samples alone, PVA yields a three end member solution that describes >97% of the compositional variance among the samples. One end member is andesitic (57 wt.% SiO2) and the other two are both rhyolitic (71 wt.% SiO2). When the Pan de Azucar samples are included with the Papagayo samples, PVA generates a four end member solution that indicates mixing among two rhyolitic end members (71 and 72 wt.% SiO2), a dacitic end member (66 wt.%SiO2), and a basaltic end member (52 wt.% SiO2). It is demonstrated that the solutions are mutually consistent and supported by petrographic and chemical data from the rocks.
Mud mounds, BSRs and associated heat flow anomaly in the Pacific margin Offshore Nicaragua

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During FS Meteor cruise M66, Leg 4a in the framework of SFB574 (volatiles and fluids in Subduction zones) in November/December 2005, an OBH/OBS survey has been carried out offshore Nicaragua in order to verify the apparent absence of the BSRs beneath some mud mounds and complete the mapping of the BSRs in the area. The OBS/OBH profiles were shot along perpendicular and parallel directions to the existing deep tow multichannel seismic lines (DTMCS). Time migrated reflection sections of some OBS/OBH show new BSRs beneath mud mounds, which have not been observed on the DTMCS lines.

In the mapped area offshore Nicaragua, the BSR depths vary between a minimum 150 m and a maximum 580 m below seafloor. The variation of the BSR depth below seafloor is mainly margin parallel and the depth variation seems to be controlled by the distribution of mud mounds. The depth decreases towards the mud mounds and the shallowest depths locate beneath them. Regional distribution of the BSRs suggests its strong relation with the occurrences of the mud mounds, currently on the seafloor or buried below it. Heat flow distribution offshore Nicaragua has been calculated and mapped based on BSR depths. The heat flows vary between a minimum 21 to a maximum 92 mW/m2. The heat flow anomaly seems to be controlled by the distribution of the mounds and the highest value has been observed on the top of the Mound Morpho.
Estimation of the amount of gas hydrate inventories in continental margins were initially done with global assumptions. These estimations were revised by geo-scientific measurements and scientific drilling during the last 40 years. The project HYDRA is funded by the German Research Foundation (DFG) and aims to combine a geophysical and a geochemical approach for quantification of gas hydrate inventories. This combination will benefit from the individual advantages of each approach to increase the knowledge of the gas hydrate distribution. The geophysical approach offers an extensive coverage of a large area by measurements. The geochemical approach offers a selective and well done determination of the gas hydrate potential for one bore hole location. Additionally, the geochemical approach calibrates the geophysical approach at bore hole sites. The data base of the project HYDRA is the pore water and solid phase analysis at the ODP bore holes of leg 170 and the reflection seismic measurements of the cruises SO81 and BGR99 offshore Costa Rica.

The geochemical approach of diagenesis models calculates the biological degradation of organic material into methane. This methane will be buried by proceeding sedimentary processes. Methane will be accumulated at appropriate conditions as gas hydrate in the gas hydrate stability zone (GHSZ). The depth and thickness of the GHSZ can be derived from the geothermal gradient. The geophysical approach is based on the effective medium theory (EMT). It calculates density as well as bulk and shear moduli of a rock package by the knowledge of the pressure, mineral composition of the sediment matrix, porosity, gas hydrate concentration and gas hydrate model. Furthermore the EMT calculates the seismic velocities $v_p$ and $v_s$ from the elastic moduli and the density. An inversion algorithm was developed to invert the interval velocities for the gas hydrate concentration. The number of inversion steps is limited by an error bound.

An assessment was done about the amount of methane under atmospheric condition bound as gas hydrate in the GHSZ with several boundary conditions. The ODP site 1041 is located on the continental margin and contains 460 m$^3$ methane per m$^2$ ocean bottom. The site 1040 is located near the deep sea trench and contains 565 m$^3$/m$^2$ methane based in the used conditions.

A mapping of the depth of the bottom simulating reflector and the sediment bottom line was done as a first step for a laminar compilation of the gas hydrate concentration. On the one hand the BSR depth indicates the bottom line of the GHSZ. On the other hand the BSR depth is necessary to get the geothermal gradient for the geochemical approach. Further more the top of the subducted plate was mapped in the area covered by the data.

In the course of the project HYDRA the gas hydrate inventory will be quantified and mapped offshore Costa Rica. Furthermore an empirical transfer function will be developed to get the gas hydrate distribution from isolated geophysical and geo-chemical parameters.

Acknowledgment
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Blueschist facies re-hydration of eclogites: constraints on subduction channel fluid-rock interaction from the Cyclades (Greece) and the Tian Shan (China).

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In subduction zones oceanic basalts undergo prograde metamorphism usually through the blueschist facies and become subsequently transformed to eclogites. The fluids released during this metamorphic process leading to 'dry' eclogites are believed to be part of the slab fluids that trigger subduction related magmatism. Most of the eclogites descent with the slab into the mantle and it is the eclogite densification reaction that makes the plate subduction self-sustained. On the other hand we find uplifted eclogites cropping out in many orogenic belts, and some of them show a retrograde blueschist-facies overprint. These overprinted rocks may still preserve some relics of a former eclogite stage but newly formed hydrous minerals like glaucophane, mica and epidote are common. Which processes caused the re-hydration of those eclogites, what kind of exhumation path through the subduction zone have they experienced and under which P-T-X conditions did the hydrous minerals grow?

In order to find answers to these questions, eclogites from blueschist belts of the Cyclades and the Tian Shan were sampled and analyzed under petrological and geochemical aspects. Garnet, omphacite and rutile represent the assemblage of the eclogite stage. Typically, omphacite and the rims of garnet grains are in part replaced by glaucophane, white mica and epidote if a blueschist-facies overprint occurred. This re-hydration was associated with massive growth of carbonate, pointing to an infiltration of an H2O and CO2 rich fluid. Major and trace element analyses and mass-balance calculations show an increase of LILE (K, Cs, Rb and Ba), and volatiles, presumably incorporated in white mica. The increase of Mn, Mg, Fe and CO2 leads to the precipitation of carbonate developed as ankerite. Partially dissolved Apatite, epidote minerals and garnets released significant amounts of REE, Pb, Sr, U and Y into the infiltrating fluid. From mass-balance calculations it is evident that up to 25 % of the REE were mobilized while the eclogites have been transformed to blueschists.

The P-T evolution during the re-hydration under blueschist-facies conditions is characterized by contemporaneous cooling and decompression. The most likely tectonic environment for such an uplift path could be the so called 'subduction channel' which is the serpentinized part of the mantle wedge above the downgoing slab. Fluids can infiltrate eclogites, re-hydrate them and forces an uplift because of the decreased density and resulting buoyancy combined with the high H2O-content and the modified rheology of the mantle wedge. The observed chemical changes indicate that the subduction channel fluids do not only change the petrophysical properties due to metamorphic reactions, they also induce metasomatic changes in the reacting rocks. Thus the fluids are responsible for the changes of the element budget and the rheology of the subduction channel, the most likely exhumation path for subducted rocks.
The Effect of Three-dimensional Slab Geometry on Deformation in the Mantle Wedge: Implications for Shear Wave Anisotropy

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We will show preliminary 3D models of the Costa Rica-Nicaragua subduction system with emphasis on the effects of 3D slab geometry on thermal and strain condition in the mantle wedge. The geometry of the slab is determined using intermediate depth seismicity with the recent improvements from the TUCAN seismic experiment. A Cartesian projection is used where the sides of the Cartesian box are parallel to a reference convergence direction for the Cocos Plate. Slab surface velocity is confined to a vertical plane parallel to the convergence direction. This velocity description is a suitable approximation for modeling slab-driven flow, which is primarily controlled by the geometry of the low-pressure region in the corner of the mantle wedge.
Subduction erosion, i.e. the upward migration of the plate boundary, influences the physical parameters affecting seismicity through the flux of material into the subduction channel. DSDP Leg 84 and ODP Leg 170 drilling indicate active and long-lived subduction erosion from Guatemala to Costa Rica. The interpretation is based on long term subsidence of the continental slope from detailed analysis of the benthic fauna preserved in the sediment, which indicates shallowing downward conditions. In Guatemala the progressive subsidence of the slope from bathyal to abyssal depths from the Oligo-Miocene boundary (25 Ma) account for an erosion rate of 11.3-13.1 km$^3$/my-1km$^{-1}$ with a trench retreat of ~16 km in the last 19 Ma. ODP Leg 170 off Nicoya Peninsula provided direct evidence of shallow-water sedimentary rocks, now located in 3900 m water depth on the forearc and marking the slope apron-forearc basement unconformity, proving that the margin has experienced a net loss of crust since ~16 Ma accounting for a trench retreat of ~50 km. The benthic fauna analysis off Nicoya Peninsula indicates that a slow background subsidence of ~20 m/m.y. radically increased to ~600 m/m.y. starting at the Miocene-Pliocene boundary. During the rapid event of tectonic erosion the rate reached 107-123 km$^3$/my-1km$^{-1}$.

The implications of subduction erosion for plate boundary seismicity can be directly sampled offshore Osa Peninsula in SW Costa Rica where the seismogenic zone is within the drilling capability of current IODP drilling technology. CRISP (Costa Rica Seismogenic Project) is a project to understand the processes that control nucleation and seismic rupture of large earthquakes at erosional subduction zones. CRISP aims to reach the plate boundary across the transition from stable to unstable slip through a transect offshore Osa Peninsula in Costa Rica, where the input into the seismogenic zone is the oceanic/ophiolitic rocks of the Caribbean plate. CRISP is a multiphase project which will adopt different drilling platform toward the deep riser drilling through the seismogenic zone. CRISP Program A is the first step, and it focuses on the characterisation of the subducting plate, lithology and fluid system, on sampling the shallow décollement, that most likely brings fluids generated at seismogenic depth, on installing long term monitoring laboratories to record microseismicity, monitor fluid pressure and measure the stress field evolution through the seismic cycle. A first evaluation of the subduction channel thickness, necessary to constrain the structural environment that will be drilled during the deep riser drilling, will be also pursued.

CRISP Program A involves drilling at five sites: two on the incoming Cocos plate; one at the slope toe; two on the middle-upper slope. These two latter sites are the two that will be deepen to reach the aseismic-seismic plate boundary during Program B.
Chemical and mineralogical comparisons of selected Pleistocene silicic ignimbrites from Nicaragua to Panamá

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Abundant silicic ignimbrites (dacite to rhyolite, subordinate andesites to basaltic andesites) and related deposits occur from Nicaragua to Panama. In this report we compare silicic ignimbrites and related deposits from Monte Galán (NIC), Apoyo (NIC), Guachipelín (CR), Alto Palomo (CR) Tiribí (CR) and El Valle (PA) volcanic centers. The Apoyo and Tiribí ignimbrites contain abundant mafic pumice fragments and the compositional variations are bimodal, however the other ignimbrite deposits are unimodal. Means of the higher silica modes (in wt. %) are Monte Galán – 70.4, Apoyo – 67.2, Guachipelín – 72.0, Alto Palomo 70.0, Tiribí – 67.7 and El Valle – 68.9. The chemical variations of the Nicaraguan (high silica mode only) and Panamanian ignimbrites are very small with standard deviations of the SiO2 wt. % silicic samples ranging from 0.6 to 0.9, whereas the Guachipelín and Monte Galán variation is much larger with standard deviations ranging from 2.2 to 2.6. The Tiribí is mingled with a large chemical variation, although the unmingled higher silica population has little variation with a standard deviation of 0.8. All of the silicic pumice samples contain relatively high Sr concentrations (150-950 ppm), which precludes large amounts of plagioclase fractionation. Rare earth element (REE) patterns vary systematically from Nicaragua to Panama with Nicaragua and Panama silicic samples containing the low concentrations of REE and low Ce/Sm ratios. Ce concentrations are low in Nicaragua, increase regularly through Costa Rica and become very low in Panama. El Valle (PA) is unique in that it contains extremely low concentrations of HREEs and Y, as well as very high concentrations of Sr.

In all of the ignimbrites plagioclase is the dominant phenocryst, whereas no K-feldspar is present. Quartz is common only in the El Hato (PA) ignimbrite. Two pyroxenes are common in the Monte Galán (NIC), Apoyo (NIC) and Tiribí (CR) ignimbrites, whereas hydrous mafic phases (amphibole and biotite) are common in Guachipelín (CR), Alto Palomo (CR) and El Valle (PA) volcanic deposits.

Previous work (Vogel et al., 2006) has shown that the $\delta^{18}$O whole rock (magma) calculated from phenocrysts from glassy pumice from Nicaragua and Costa Rica show an increase along the arc in $\delta^{18}$O of 1.5‰, except for a low $\delta^{18}$O excursion in the Guachipelín deposits. The $\delta^{18}$O whole rock (magma) values in Nicaragua are lower than or equal to oceanic basalt but increase to more normal or higher than oceanic basalt values in central Costa Rica. In evaluating fractional crystallization the $\delta^{18}$O of the whole rock should increase about 1.0‰ for a 20% increase in weight percent silica. However, there is no correlation of $\delta^{18}$O with SiO2 variation and we use these data to argue against fractional crystallization from mafic magmas was not an important process in the overall formation of these silicic magmas.

Nb and Ta concentrations and their ratios are variable in these ignimbrite units from Nicaragua to Panama. In some ignimbrite centers eruptive units have distinct Nb and Ta concentrations. We interpret these data as being produced by partial melting of compositionally distinct sources. In addition in El Valle (PA), the high Sr/Y and very low HREEs support earlier suggestions that silicic magmas are produced by melting of a source in which garnet is a residual phase sequestering Y and the HREEs. This is distinctly different from the silicic magmas in Costa Rica and Nicaragua.

The data for the Nicaraguan and Costa Rican silicic ignimbrites are consistent with a model for the generation of these Pleistocene high silica magmas by partial melting of calc-alkaline, mantle-derived evolved magmas that have ponded and crystallized in the mid-crust (or melt extraction from these partially crystallized plutons). A genetic relationship between the silicic magmas and the mafic lavas is demonstrated by the similarity of key trace element ratios, oxygen isotopes, and radiogenic isotopes. Over thirty years ago, Mc Birney made a similar suggestion based on limited major-element and $^{87}$Sr/$^{86}$Sr data (Mc Birney, 1969). Distinct magma batches were produced by chemical differences among the plutons ponded in the mid crust. Thus the silicic ignimbrites were produced by partial melting (or melt extraction from nearly complete solidified) of these ponded plutons.
References:
AN EXPLANATION FOR SOME PARADOXES IN THE TECTONIC STRUCTURE OF THE CENTRAL AMERICAN CONVERGENT MARGIN.

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The tectonic ideas regarding the Central American margin have been marked by major shifts. What was long considered an accretionary margin from seismic images proved to be erosional when drilled. Compressional deformation characterizes the lower slope prism whereas extension is displayed in the middle slope prism. A key to understanding this paradox is presented in the dynamic wedge hypothesis (Wang and Hu, 2006). Multibeam bathymetry and seismic data along Central America provide good examples of structure consistent with the dynamic wedge hypothesis. Dividing the margin wedge into two prisms that behave different from each other during coseismic and interseismic periods can explain the paradox of a frontal prism structured like an accretionary body along an erosional margin and extensional faults in a convergent plate setting.
Constraints on slab fluid compositions from arc melt inclusions and phenocrysts.

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Water is fundamental to magma genesis, evolution, and eruption, but most models make predictions that have yet to be tested against actual pre-eruptive H2O concentrations. This is because few direct measurements of magmatic H2O exist, as rocks found at the surface have extensively degassed upon eruption. Olivine-hosted melt inclusions (MI), trapped at depth, provide a now standard approach to measuring volatiles in undegassed magma, but many volcanic deposits do not contain MI large enough for analysis (>30um). We have used a new Al(IV)-dependent partitioning relationship to calculate magmatic H2O from direct measurements of H2O in clinopyroxene phenocrysts, and are combining these data with trace element indicators in order to better constrain the nature of the subduction fluid in Central America.

We first tested this approach using phenocrysts from four arc volcanoes (Galunggung, Irazu, Arenal, and Cerro Negro), which span the global range in MI based H2O contents (from 0.1 – 6 wt% H2O). In all four volcanoes studied, the maximum, mean and range of magmatic H2O contents calculated from the clinopyroxene measurements agree with MI data from the same samples within 0.6 wt%. Volatile data, along with measures of crystal fractionation (Mg#), indicators of pressure of entrapment (H2O-CO2 in MI), and crystallization temperatures (OL-liquid thermometry) all provide insight into the magmatic history of these volcanoes.

In the Central American samples, H2O also correlates with Sr/Nd in the clinopyroxenes, a common proxy for slab fluids in the arc source. Predicted partitioning of Sr/Nd into source liquids allows us to model the composition of the subduction fluid. In Costa Rica/Nicaragua, the H2O-Sr/Nd trend requires higher Sr/Nd in the fluid than that predicted by most published estimates, consistent with the high Sr/Nd carbonate-rich sediments subducting locally. In addition, preliminary data suggest that along the CR/Nica segment of the arc, Sr/Nd and H2O correlate with depth to slab.

The potential of using phenocrysts to link H2O to trace elements, as well as to magmatic temperature and pressure though traditional thermobarometry, creates a new and powerful tool in igneous petrology and geochemistry. In the coming months, we will expand our collection of MI data, and apply this new method of H2O estimation to samples from 8 other Central American volcanic centers (Platanar, Poas, Turrialba, Nejapa, Telica, Masaya, Maderas, and Mombacho). This will allow us to further constrain the nature of the slab fluid and the melting conditions beneath the arc, and to shed light on the relationship of fluid and sediment inputs to magmatic output fluxes in Central America.
Volatile recycling and element fluxes in the fore-arc of subduction zones

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Volatiles such as water, methane and CO2 are released into the ocean via fluid flow through cold seeps and mud volcanoes located in the fore-arc of subduction zones. The fore-arc fluids are also enriched in trace elements such as boron, lithium, barium and iodine. An overview on diagenetic reactions, fluid compositions, and sedimentary water budgets will be presented together with an order-of-magnitude estimate of global fore-arc fluxes.
Exsolation of magmatic volatiles governing unusual eruptions: constraints on fragmentation and eruptive style of the mafic plinian Fontana eruption, Nicaragua

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The widespread Fontana Tephra (1.1 Gt DRE), erupted in the Masaya-Managua area in west-central Nicaragua, provides an excellent opportunity to investigate the mechanisms involved in the generation of large mafic plinian eruptions. The highly-explosive basaltic-andesitic eruption took place about 30 ka BP, and progressed through several phases of plinian activity, alternating with phreatomagmatically-affected plinian and subplinian pulses.

Constraints on fragmentation processes are of fundamental importance for understanding such unusual eruptive style of mafic melts. Magmatic volatiles, especially water, act as major driving force for explosive eruptions through their exsolution and expansion upon magma ascent. By controlling the way and the extent bubbles form in the melt immediately prior to eruption, they govern the pressure conditions in the conduit and hence the fragmentation regime.

Here we present concentrations of volatile elements (H2O, CO2, Cl, S) in matrix glasses and in melt inclusions hosted in olivine and plagioclase crystals of Fontana Tephra, determined by Secondary Ion Mass Spectrometry (SIMS) and Fourier Transform Infrared Spectroscopy (FTIR). The melt water concentration at time of melt inclusion trapping was about 1.2 wt %, strongly undersaturated for the melt composition and the pressure-temperature conditions in the reservoir. Saturation was reached during rise to the surface at a depth of ca. 740 m and a pressure of ca. 20 MPa. As inferred from residual melt water contents, the fragmentation level of the eruption shallowly fluctuated between 30 and 150 m below surface. In contrast, the observed scoria vesicularities of 68-72 % indicate a greater fragmentation depth of 165 to 195 m, when equilibrium degassing is assumed. This discrepancy is interpreted to reflect a strongly delayed disequilibrium degassing. The absence of microlites suitable as bubble nucleation sites further supports a predominantly homogeneous bubble nucleation, which requires a substantial water supersaturation. We infer that this late, catastrophic bubble nucleation combined with rapid ascent of the hot, low-viscosity magma was responsible for the unusual plinian style of the mafic Fontana eruption.
Seismogenic characteristics and seismic structure of the Mariana Arc System: Comparison with Central America

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This talk will highlight some initial results from the passive component of the Mariana imaging experiment, which consisted of a deployment of 58 ocean bottom seismographs (OBS) and 20 land seismic stations during 2003-2004. These results should provide an important comparison to seismic results from the Central American subduction zone, and allow better understanding of the variability between arcs. Shear wave splitting from S waves propagating from intermediate and deep earthquakes in the Mariana slab to the OBS and land seismic stations show generally along-strike fast axes in the forearc, arc, and extending to the backarc spreading center [Pozgay et al, 2007]. The fast directions rotate towards arc perpendicular in the far backarc beyond the backarc spreading center. We interpret this pattern as indicating a predominance of along-strike flow in a low viscosity channel beneath the arc and spreading center, and slab induced counterflow in the far backarc. Tomographic inversion of P and S wave travel times suggests a low velocity region in the upper 150 km beneath the arc and backarc spreading center. Similarly attenuation tomography shows high attenuation in the same regions, consistent with high temperatures and the possible presence of melt in the upper mantle.

The Mariana arc has been the type example of an “aseismic” or “decoupled” subduction zone since the concept was first proposed by Uyeda and Kanamori [1979]. Compilations generally suggest that less than 1% of the Central Mariana slip is released seismically, making it perhaps the most decoupled seismic zone in the world. Comparative studies of decoupled seismogenic zones are essential for understanding the factors controlling the occurrence of large earthquakes. Our results indicate a lack of significant seismicity in the outer forearc beneath Big Blue and Celestial serpentinite seamounts. A few earthquakes suggest that the shallow thrust zone is located at a depth of 15-25 km beneath the seamounts. Thrust earthquakes extend to depths of 55 km along the shallow thrust zone, demonstrating that the width of the seismogenic zone in the Mariana islands is not anomalously narrow, and that thrust faulting occurs in the forearc mantle, in contrast to some explanations for decoupling. Patches of high seismicity in the shallow thrust zone are located to the west of the seamounts at depths of 30-40 km. The patches are approximately 20 km in diameter and suggest heterogeneous faulting properties along the shallow thrust zone. Another zone of earthquakes at depths of about 60 km initiates beneath the seamounts and extend towards the west, representing faulting within the subducting plate. These events indicate that the lower zone of the Mariana double seismic zone initiates in the forearc and extends continuously to intermediate depths. We suggest that the relatively aseismic character of the outer forearc of the Mariana islands results from large-scale serpentinization of the outermost mantle wedge, as serpentinite is characterized by stable sliding rather than stick-slip behavior. In addition, the lack of large subduction zone thrust earthquakes may also result from the extreme heterogeneity of the shallow thrust interface, as revealed by the patches of high seismicity and aseismicity at depths of 30-40 km.
Imaging Subduction Zones with Marine Magnetotellurics

Tamara Worzewski and Marion Jegen

The electrical conductivity is most sensitive to the presence of fluids in the host rock and may change over orders of magnitude depending on water content, presence of partial melt and connectivity. Electromagnetic experiments, measuring the electrical resistivity distribution, are therefore a method of choice for imaging water and partial melt distributions. Since few marine EM instruments exist worldwide, only two EM amphibious profiles (EMSLAB, Juan de Fuca Ride, Wannamaker et al., 1989; IMTEQ, Southern Chile, current project at FU Berlin) have been carried out so far, although numerical studies have shown (Evans et al., 2002) that both land and marine data are needed to infer electrical resistivities on the continental or marine section of the subduction zone.

Within the framework of the SFB 574 at IFM-GEOMAR and Christian-Albrechts University of Kiel we are building up a marine EM group and constructed 10 highly sensitive marine MT Stations. These were tested offshore eastern Indonesia (Sunda-Banda subduction zone) and will be used 2007 in Central America to conduct an onshore-offshore marine magnetotelluric (MT) experiment to determine electrical resistivity structure and fluid distribution in faults and along the subducting plate and upper mantle.

In this poster we present first results of the data acquired in Indonesia and some numerical modelling studies aimed to discover characteristics of the MT response to fluids in the crust and subducting slab.


Extracting paleoclimate records and the eruptive history of Central American volcanoes from late Pleistocene lake bottom sediments of Lake Nicaragua (Nicaragua)

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A shallow coring program in Lake Nicaragua, the largest lake in Central America, was completed in May/June 2006 by the University of Texas (UT Department of Geography and UT Institute for Geophysics). A total of 35 sediment cores with lengths ranging between 12 cm and 100 cm along with five longer cores (> 5 m) were extracted from the lake using a gravity corer and a modified manual square rod piston corer, respectively. Core locations were sited using a grid of high-resolution seismic reflection and 3.5 khz data collected in the weeks prior to the coring study. Analyses of lake sediments are in progress and have the following objectives: 1) to correlate the geophysical results with the core data to provide a stratigraphic framework for the shallow lake sediments; 2) to constrain past climate variability in this rather poorly investigated area; and 3) to establish a time series of explosive volcanic activity based on the identification and dating of tephra layers in the cores.

Initial results on core description, magnetic susceptibility, dry density and loss on ignition indicated a dominance of fine-grained homogeneous diatomaceous sediments cover most of the lake floor. Increasing values in magnetic susceptibility in the upper part of several short cores most likely reflect increased erosion caused by land-use changes during the Spanish colonial period (1522-1822). First results on the two longest cores from the northeastern (435 cm) and southwestern (496 cm) parts of the lake reveal complete Holocene paleoclimate records in both areas. A lithologic change from homogeneous gyttja (diatomaceous mud) to blue-grayish waxy clay at the bottom of these records marks the Late Pleistocene-Holocene transition as indicated by a radiocarbon dating on plant remains. The latter dense clay forms a distinctive stratigraphic marker in the lake basin. Tephra layers to date were detected in most gravity cores recovered west of Ometepe Island (Volcán Concepción), east of the Island of Zapatera and in a long record nearby the Solentiname Archipelago in 315 cm sediment depth (unknown source, ca. 8,100 interpolated cal 14C years BP).

Planned paleoclimate studies on the longer cores will include detailed analyses of their palynological content and stable isotopes analyses of ostracods and diatoms. Tephra layers deriving from southern Nicaraguan and northern Costa Rican active volcanoes will be used for dating and correlating of lake sediments and will allow correlation to other terrestrial and Pacific marine tephra records. Distal ashes furthermore will provide information about the eruptive histories, volumes of erupted magma, and eruptive intensities of local explosive volcanoes, with the focus on the more recent activity. These data in combination with geochemical analyses on volcanic ash layers will serve to develop models for the petrologic evolution of magmatic systems and better hazard indications of potential eruptive behavior.