

INTERNATIONAL WORKSHOP ON  
**PASSIVE IMAGING IN WAVE  
PHYSICS:**  
**from seismology to ultrasound**  
May 9<sup>th</sup> - May 13<sup>th</sup>, 2011

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**Poster programm  
(preliminary)**

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Session 1 : Monday to Wednesday

- active and passive imaging,
- noise structure

Session 2 : Thursday to Friday

- active and passive monitoring
- methodology

## SESSION 1 (Monday to Wednesday)

### Seismic Velocity Structure of the San Jacinto Fault Zone from Double-difference tomography

*Amir Allam, Yehuda Ben-Zion*

We present initial results of double-difference tomographic images for the velocity structure of the San Jacinto Fault Zone (SJFZ), and related 3D forward calculations of waves in the immediate vicinity of the SJFZ. We begin by discretizing the SJFZ region with a uniform grid spacing of 500 m, extending 140 km by 80 km and down to 25 km depth. We adopt the layered 1D model of Dreger & Helmberger (1993) as a starting model for this region, and invert for 3D distributions of VP and VS with the double-difference tomography of Zhang & Thurber (2003), which makes use of absolute event-station travel times as well as relative travel times for phases from nearby event pairs. Absolute arrival times of over 78,000 P- and S-wave phase picks generated by 1127 earthquakes and recorded at 70 stations near the SJFZ are used. Only data from events with Mw greater than 2.2 are used. Though ray coverage is limited at shallow depths, we obtain relatively high-resolution images from 4 to 13 km, which show a clear contrast in velocity across the NW section of the SJFZ. To the SE, in the so-called trifurcation area, the structure is more complicated, though station coverage is poorest in this region. Using the obtained image, the current event locations, and the 3D finite-difference code of Olsen (1994), we estimate the likely distributions of fault zone head waves as a tool for future deployment of instrument. We plan to conduct further studies by including more travel time picks, including those from newly-deployed stations in the SJFZ area, in order to gain a more accurate image of the velocity structure.

### Velocity Structure of Turkey and Surroundings by Passive Imaging

*Musavver Didem Cambaz, Hayrullah Karabulut*

High-resolution velocity structure of Turkey and surroundings were obtained by using Passive Imaging Technique. A waveform database was constructed from more than 450 temporary and permanent broadband stations operated by 15 networks in the surrounding regions of Turkey. The high number of stations and the amount of data provides sufficient numbers of Green's functions. Determination of the high-resolution group velocity maps by using Passive Imaging Technique provides the finer details of the crustal and upper mantle structure. Together with the estimation of crustal structure the technique will also be used for the investigation of deep basins. The results of this study will help to improve tectonic models proposed for Turkey and surrounding areas.

### Seismic Characters of the Shallow Oceanic Crust, in light of OBS

*Emmy Chang, Gung, Y.C., Lallemand, S.*

Based on the Ocean Bottom Seismometer (OBS) records around offshore Taiwan, we conduct a detailed study of water column velocity and shallow seismic structure of the oceanic crust. In this study, the OBS data are acquired from the multiple OBS deployments respectively in the southwest offshore Taiwan (separately in 2005 and 2006) - near the Manila trench, the east offshore Taiwan (in 2007) - Nanao Basin, and the westernmost extreme of the Okinawa Trough (in 2005). The experiments carried out in the southwest Taiwan and the Nanao Basin adopted the short-period OBS (hereafter denoted as SPOBS), and the one in the Okinawa Trough benefited from two broad-band OBS (BBOBS). We have estimated the seismic impulse responses from ambient noise analysis for all the available station-to-station paths, even some of them are in short-term deployments. The Japanese Fnet broad-band stations YNGF, IGKF are also adopted in this study to examine the coherence of noise propagating between island and OBS stations. The hydrophone series recorded simultaneously with these OBS machines provide further information for the acoustic propagation in water column and the in-situ ground motion. Our preliminary result reveals an extreme low velocity at the top layers of oceanic crust. This may reflect a strong dispersion generated by bathymetric scattering or variable thickness sediments. The Rayleigh wave Green functions show the distinct characters for the oceanic crusts separately in southwest offshore Taiwan, the Nanao Basin, and the Okinawa trough. It should not be caused by the varied seismometer capability but probably the difference of tectonic settings. Further comparisons among these different oceanic geological settings will reveal more information about the complexity of the seismotectonic frame in Taiwan convergence.

## Robustness to noise in active shear wave elasticity imaging

*Thomas Deffieux, Jean-Luc Gennisson, Benoit Larrat, Mathias Fink, Mickael Tanter*

The recent development of quantitative elastography techniques is a highly promising step toward improved clinical diagnosis. Those techniques are based on the imaging of shear waves propagating in soft tissues. Those shear waves can be either natural vibrations (in passive elastography imaging) or induced by a mechanical vibrator or acoustic radiation force (in active elastography imaging like Supersonic Shear Imaging). In supersonic shear imaging, a transient plane shear wave is generated using acoustic radiation force and is tracked using ultrafast ultrasound imaging. The local shear velocity can then be estimated using a simple time of flight algorithm to deduce the shear modulus locally. In this work we investigate the robustness of this approach when considering the electronic noise of the acquisition system. Using the Cramer-Rao lower bound both for the estimation of the velocity field variance from the radio frequency (RF) data signal to noise ratio (SNR) and for the estimation of the shear wave travel time from the velocity field SNR, we can derive the analytical formulation of the shear modulus standard deviation based on the physical parameters of the shear wave such as its center frequency or bandwidth and the ultrasonic system parameters. We found a good correlation between analytical, numerical and experimental results, which indicates that this formulation is well suited for the estimation of the shear modulus standard deviation in the Supersonic Shear Imaging approach.

## Ground motion prediction using the ambient seismic field

*Marine Denolle, Gregory Beroza, Eric Dunham, German Prieto*

Earthquake strong ground motion estimation is traditionally based on empirical prediction equations. To overcome the scarcity of large event ground motion records, seismologists increasingly turn to physics-based ground motion simulations. To accurately reproduce earthquake ground motions, these simulations must take into account source complexity, elastic and anelastic structure of the crust as it affects wave propagation and local site effects. Incomplete knowledge of the subsurface translates into uncertainty in the simulated amplification, so it is important to validate ground motion predictions against data. For many areas, we lack earthquake records to test simulations. In these cases the ambient seismic field can be used for validation because it is subject to the same elastic and anelastic propagation effects as earthquakes. We have shown that to first order, for a period range of 4-15s, station-to-station impulse responses from ambient noise show very similar amplification effects to earthquake records for moderate earthquakes in southern California. To achieve more accurate ground motion predictions, we have to correct for the difference in wave excitation for earthquakes, which have double-couple focal mechanisms at depth over a finite source, and ambient noise impulse responses, which are for a point source at the Earth's surface. We compute the depth-dependence of the fundamental mode surface waves by calculating the eigenmodes using Chebyshev spectral collocation methods. We take advantage of the 3D wavefield and simulate the radiation pattern of a double couple. Finally, we show the potential of this method to represent an extended source using a temporary deployment on the San Andreas Fault.

## Cross-correlating ambient ocean noise along arrays

*Stephanie Fried, Shane Walker, William Kuperman*

By cross-correlating time aligned recordings of ambient noise, it is possible to extract time-of-arrival information of the acoustic ray path between the sensors which recorded the data, even with no a priori knowledge of the sound field which contributed to the noise recording. Due to the nature of the ocean noise field and the fluctuations of the environment itself, difficulties arise in extracting the time of arrival information quickly and accurately before environmental changes corrupt the correlation result. The use of arrays of sensors incorporating standard array processing techniques into the noise correlation function and the effects of the directionality of the noise field are examined.

## Low Frequency Passive Seismic Tomography using Valhall LoFS

*Aurelien Mordret, N.M. Shapiro, S. Singh*

We used 6 hours of vertical component continuous data recorded from more than 2400 receivers of the Valhall LoFS for passive seismic interferometry. The Correlation Functions contain symmetrical Scholte waves in the 0.1-2 Hz frequency range and we showed by beamforming that the sources of these waves were homogeneously distributed around the array. We constructed group velocity dispersion curves of the extracted Scholte-waves and inverted them to produce a group velocity map of the Valhall field subsurface. We found that seismic velocities were higher in the center of the array than at its edge. It is in good agreement with geomechanical models based on the sea-floor subsidence due to the reservoir production.

## **Preliminary results on seismicity and fault zone structure along the North Anatolian fault**

*Yaman Ozakin, Yehuda Ben-Zion, Mustafa Aktar, Hayrullah Karabulut, Zhigang Pe*

We analyze seismic data recorded over ~2.5 yr by a line of 6-11 seismometers that cross the North Anatolian fault east of Ismetpasa on the 1944 rupture zone. The main goals are to image the local velocity structure, with a focus on lithology contrast across the fault, and to clarify the local seismicity patterns. Earthquake detection is done by manual inspection of automatic identification of candidate events. So far we detected only ~250 events in the magnitude range -1 to 2.5 within a radius of 45 km from the center of the network. The imaging studies done to date involve efforts to detect head waves that propagate along the fault interface and analysis of arrival times from teleseismic events. The preliminary results indicate ~10% contrast of P wave velocities across the fault with faster velocity on the north side. The continuing studies will also employ receiver function analysis and noise-based imaging.

## **Determination of Subsurface Velocity Structure and Precise Hypo**

*David Sahara, Sri Widiyantoro, Andri D. Nugraha, Rachmat Sule, Birger G Luehr*

High-resolution subsurface seismic velocity structure image beneath onshore and offshore of Central Java by using Double Difference Tomography method (TomoDD) is presented. This study is conducted in order to understand the mechanism effect of the subduction process to the surface seismicity and volcanic activity in Central Java. The data set was collected by a temporary seismic network called MERapi AMphibious EXperiment (MERAMEX), which was deployed for 150 days in May-August 2004. The network consists of 134 seismographic stations (106 short-period stations, 14 broadband stations, 8 ocean bottom hydrophones, 6 ocean bottom seismometers), which were installed onshore and offshore of Central Java. 210 events were selected for this research.

From the preliminary results, the joint inversion of the event locations and seismic velocity structure considerably improves the resolution of the subsurface image. The final locations of the sources after the inversion show a narrow region of the double seismic zone, which correlated with the subducting slab. The dip angle of the slab increases gradually from almost horizontal beneath offshore to 65°-80° beneath the northern part of Central Java. The seismic gap at depths of 140-185 km is also imaged clearly. It is showed that the subduction plays an important role in causing the volcanism in this study area. The strong negative velocity anomalies under the Merapi Complex Volcano are interpreted as the upward migration of fluids rejected from the slab because of the phase transition. These fluids may have caused decreasing viscosity, and possibly, partial melting. The partially molten materials are soft and less rigid, thus the velocity decreases.

## **Geoacoustic characterization with an horizontal array by the image source method**

*Samuel Pinson, Laurent Guillon*

Complementary to the direct geophysics measurements, remote sensing by acoustics has proved its ability to get the geometry and the physical parameters of the seabed. Recently, a technique has been developed: the image source method. This technique is based on the analysis of the reflected acoustic wave by the seafloor as a collection of image sources which positions are connected to the thickness and the sound speed of the sediment stack. In this communication, we present the result obtained with data acquired by the NURC in 2009 during the CLUTTER'09 experiment. The equipment used was an AUV towing a 1500-3500Hz frequency band source and a 32 m horizontal line array of 32 hydrophones at 12~m above the seafloor. Because of its low computational cost, the image source method with this measurement configuration is promising in term of real time analysis of sound speed profiles or to deal with a high number of measurement to map the seabed structure of large areas.

## **Lateral structure of the subducting Pacific plate beneath the K**

*Simanchal Padhy, Takuto Maeda, Takashi Furumura*

We studied the detailed lateral structure of the subducting Pacific plate near Honshu by analyzing waveforms from deep earthquakes recorded at fore-arc Hi-net and F-net stations in Japan. The results confirm most of the earlier observations, such as distorted body waves in 0.5-5 Hz, dominance of low-frequency precursor followed by high-frequency arrivals due to the stochastic waveguide effect of the heterogeneous subducting plate, proposed earlier by Furumura and Kennett (2005). Among large number of seismograms we found in particular source-receiver paths the waveform exhibit loss of high frequency energy in P-coda, loss of low-frequency precursor and presence of converted phases in P-coda, probably due to the strong lateral heterogeneities in the subducting plate. Recent tomography and waveform analysis revealed low velocity anomaly of the Pacific slab beneath Honshu and the observations of slab tear or thinning in the Pacific plate (Obayashi et al., 2009, Kennett and Furumura, 2010). The subducting plate geometry, together with small-scale inhomogeneity, strongly affects the high-frequency seismic waves that pass through the slab. Such complexities in the observed waveforms are difficult to explain by existing simple slab model, indicating sudden lateral change in the wave guiding properties of the subducting slab, such as caused by the thinning or tearing the slab in deeper part. To explain the observations, we employ two-dimensional finite-difference method

(FDM) simulations of complete high-frequency P-SV wave propagation taking thinning of Pacific slab into account. We expect that the observed guided wave energy must decouple from waveguide where the slab is deformed or thin. Low frequency energy leaks out of the slab and travels to the receivers along paths in the low velocity mantle surrounding the slab, while high frequency signal of shorter wavelength can travel through thin plate. The results of this study, along with seismic tomography and other studies

### **Ambient seismic noise tomography in the Lake Toba region.**

*J. Stankiewicz, T. Ryberg, C. Haberland*

An array of 50 seismic stations deployed for 6 months in 2008 around Lake Toba in Sumatra was used to continuously record three-component short period seismic data. Daily recordings were cross-correlated for all existing station pairs to extract the Rayleigh wave components of the Green's function. The daily cross-correlations were stacked in order to improve the signal to noise ratio. As group velocities of Rayleigh waves are frequency dependent, the resulting stacks were filtered with different band pass filters. Coherent Rayleigh wave arrivals between station pairs were observed at periods varying from 2.5 to 12 seconds. These arrival times were picked for 5 different periods, and two-dimensional travel time tomography was performed with each set of arrival times. A number of features in our velocity model are consistent with the known geological record, like a low velocity zone underneath the volcanic Samosir Island.

### **Seismic radial anisotropy from ocean bottom seismometer data**

*Akiko Takeo, K. Nishida, H. Kawakatsu, T. Isse, H. Shiobara, T. Kanazawa, and H. Sugioka*

In order to constrain the one-dimensional radially anisotropic structure of the oceanic upper-most mantle, we analyze surface waves in a broadband frequency range, 0.01-0.15 Hz (7-200 sec), using data by broadband ocean bottom seismometers operated in the Shikoku Basin, the western-most part of the Pacific Ocean. For the first step of analyses, we measure average phase velocities of Love and Rayleigh waves in the Shikoku Basin area using two methods: seismic interferometry at frequencies higher than 0.035 Hz (30 sec), and conventional array analysis of earthquake waveforms at lower frequencies. For the case of ambient noise interferometry method, we can observe the waveforms corresponding to the fundamental and first overtone of the Rayleigh wave, and the fundamental mode of the Love wave, using three-component data. Obtained phase velocities are consistent between two methods at an intermediate frequency band around 0.035 Hz. We then search for the optimal 1-D radially anisotropic structure that fits observed and theoretical waveforms by simulated annealing. As a result, there are two types of structures, RAS1 and RAS2, that can similarly explain the observation. For both types of structures, SH-wave is faster ( $V_{SH} > V_{SV}$ ), the intensity of radial anisotropy ( $(V_{SH} - V_{SV})/V_{mean}$ ) is 5-10 % at a depth range of 50-80 km, and smaller than 5 % at depth shallower than 30 km. This result is not affected by scaling laws that constrain parameters, such as the intensity of P-wave radial anisotropy. The depth of the largest anisotropy is deeper than the top of low velocity zone (LVZ) for RAS1, and is same as the top of LVZ for RAS2. RAS1 implies that the intensity of radial anisotropy is decreased at shallower depth by some mechanism. RAS2 implies that radial anisotropy is intensified at the top of LVZ due to strain accumulation or the melt-layering structure in the asthenosphere.

### **Preliminary results of the noise tomography of Lebanon**

*C. Voisin, R. Jomaa, A. Mariscal, A. Surssock, M. Brax, D. Youss*

A seismic survey of Lebanon is currently operating since last November 2010. About 30 stations are deployed over the country and continuously record the ground motion for a period of 2 years. We present here preliminary results based on the records of the 7 permanent stations of the Lebanese network (GRAL), operated by the Centre de Recherches Geophysiques over more than 7 years. On the side, we will present the preliminary results based on the 25 survey stations (SISMOB).

### **Seismic velocity contrast across the San Jacinto fault, California**

*Wei Wang, Greg Hillers, Yehuda Ben Zion*

We analyze 2 years continuous ambient noise data recorded at 24 broadband stations around the San Jacinto Fault Zone (SJFZ), California. Using similar techniques as Roux et al. (2005), we obtain noise-based cross-correlations in the frequency range 0.1-1.3 Hz in +/-50 seconds time windows across >200 station pairs with distances ranging from 2 to 130 km. To study the effect of seasonally varying noise sources on the resulting cross-correlations, we stack 3-month data from winter and summer periods separately. The following two main arrivals are resolved independent of season: (1) a Rayleigh wave travelling at ~3.2 km/s and (2) an arrival around  $t=0$  likely resulting from teleseismic P-phase with near-vertical incidents. In addition, two phases travelling roughly at 6 km/s and 12 km/s appear during winter, and are also attributed to teleseismic P-phases with high apparent velocities.

Amplitudes in winter are stronger than in summer, reflecting the seasonally dependent energy content of noise in the microseisms frequency band. An approximate 3-4% velocity contrast across the SJFZ can be resolved from our analysis. Updated results will be presented in the meeting.

## Analysis of the high-frequency noise field recorded by a vertical borehole array in Taiwan

*G. Hillers, M. Campillo, Y.-Y. Lin, K.-F. Ma*

We performed a comprehensive analysis of the high-frequency noise field recorded by a vertical borehole array consisting of 7 sensors sampling at 200 sps between 950 and 1280 m depth situated in the formation hosting the Chelungpu fault zone, Taiwan. Spectrograms reveal the anthropogenic character of noise amplitude pattern in the frequency range between 1 and 20 Hz. Spectral analysis of daily sampled minimum noise amplitudes around 5 Hz constructed from the 2 years of continuous records yields a distinguished 7-day periodicity, which is also preserved in the frequency content of daily constructed cross correlation functions (C1) computed between individual sensor pairs. In contrast to the cultural components of the noise field, significant increases in the noise level between 5 and 40 Hz coincide with strong rainfall recorded in the vicinity of the borehole. The main arrival of the C1 functions shows an upward propagation of the direct wave. We find, however, that the C3pp function exposes the downgoing direct wave. This indicates that information on the coherent downward propagating energy is contained in the positive-lag coda of the C1 function, but that this energy is small compared to the upgoing wave field that dominates C1. A similar conclusion is reached by measuring wave speed and incidence angle using beamforming techniques, confirming that the dominant part of the coherent wave energy at 1-5 Hz arrives from below. We analyze the coda of C1 functions obtained from all useful correlation pairs to measure relative arrival time changes (dt/t). Measurements are carried out using a constant and a moving reference stack, leading to 12 independent measures of temporal subsurface property changes, all stacks are improved by iteratively discarding traces with a low similarity to the resulting average. Two types of robust signals emerge in all measured dt/t functions. First, the low frequency component displays a distinguished seasonal variation over the course of the analysis period (2008-2009), with a stronger contrast during the first year. Time delays during the summer months are decreased with respect to winter months, i.e., relative wave speed is increased. Second, short-duration positive dt/t transients or decreased velocities are superimposed on the seasonal variations. We assess physical mechanisms responsible for the observed signals considering meteorological and seismological explanations.

## Microseism and microbarom source location

*Matthieu Landès, A. Le Pichon, N.M. Shapiro, M. Campillo*

It is now well established that passive imaging is a reliable approach in seismology to infer the Earth structure from the seismic noise. However the main assumption of ambient noise as a homogeneous random wavefield is not always justified. If the noise wavefield is away from a spatial and temporal homogeneous distribution, the Green's Function extracted from cross-correlations can be biased with systematic errors. This behaviour may have an important effect on tomography or volcano monitoring studies at regions where the noise source distribution has a strong seasonal behaviour. Information on ambient noise source distribution is therefore important to understand the effect of an inhomogeneous wavefield in Earth studies and will allow the estimation of uncertainties in cross-correlation measurements.

Ambient seismic noise is dominated by the secondary microseism peak (5-7s) generated by non-linear interaction of oceanic waves. But this source mechanism also has an infrasonic component composed of the emission of a low frequency signal (near 5s) called microbaroms detected at all infrasound stations. The aim of this study is to provide monthly a global and quantitative observation of the microseism and microbarom source location. These maps provide a first attempt to describe both microseism and microbarom sources. The comparison highlights well-constrained locations and clear seasonal trends. However, good understanding of the differences is far from being explained and leads to interesting questions, regarding for example the coupling between seismology and infrasound and better description of the ambient noise whether infrasonic or seismic.

## Observation and Scaling of Microearthquakes from TCDP Borehole

*Yen-Yu Lin, Kuo-Fong Ma, Volker Oye*

Microearthquakes with magnitude down to 0.5 were detected by the Taiwan Chelungpu-fault Drilling Project Borehole Seismometers (TCDPBHS). A location software (MIMO) was used to determine P- and S-wave onset times, incidence and azimuth angles for the locations of the microevents. Regardless of the large co-seismic slip of 12 m at the drill site during the 1999 Chi-Chi earthquake, our studies show very less seismicity near the drill site from the TCDPBHS recording. The microevents clustered at a depth of 8-10 km, where the 30 degree dipping of the Chelungpu thrust fault becomes flat to a decollement of the Taiwan fold-and-thrust tectonic structure. As a continuous GPS survey did not observe post-slip at the large slip region, and as no seismicity was observed near the drill site, we suggest that the thrust belt above the decollement during the interseismic period is locked. We also

examined the scaling of the source parameters of the small earthquakes in stress drops and seismic moments. The source parameters of 150 microevents were examined from the source spectra using Brune  $\omega^{-2}$  model for a constant Q model. The scaling of the magnitude to the Brune stress drop is a significant positive correlation. However, there has been a debate that this positive relationship might be biased for without Q correction. Fortunately, we had observed 65 clusters showing similar waveforms. The path effect can be removed by Projected Landweber Deconvolution (PLD) method from the events in clusters. The PLD method analyzed source time function from larger event and smaller event by iteration technique, and the source dimension and stress drop of larger event with Q correction could be estimated.

### **Observing and modeling microseism variations over the year.**

*E. Stutzmann, M. Schimmel, F. Ardhuin and A. Mangeney*

Ocean gravity waves travelling in opposite directions create second order pressure fluctuations which are the sources of secondary microseisms. These microseisms are mainly of Rayleigh waves and they have the double of the frequency of the incident ocean waves. The ocean regions where these microseisms are generated are not well known. We consider both amplitude spectra and polarization spectra of seismic data to identify the strongest sources and we combine back azimuths recorded by stations in and around a given ocean to determine likely source positions. Ocean wave directional and frequency spectra are then used to determine the wave-wave interactions as a function of frequency and the corresponding second order pressure fluctuations at the ocean surface. We observe a good agreement between the seismic source likelihood maps and the source locations computed with the ocean wave model. The location of the most abundant sources is changing over the year.

Following Longuet-Higgins (1950) and Kedar et al. (2007) we further compute synthetic seismic spectra. The IOWAGA ocean wave model enables to take into account coastal reflection and we compare data with synthetic spectra considering different coastal reflection coefficients. In many cases, we observe less than 20% difference between synthetic seismic amplitude spectra with and without coastal reflection and an excellent correlation with the real spectra.

## SESSION 2 (Thursday to Friday)

### Surface Wave Study at Laboratory Scale

*B. de Cacqueray, P. Roux, M. Campillo, S. Catheline, P. Boué*

The mix of body waves and surface waves is a recurrent problem for deep exploration in geophysical contexts. As they represent up to 70% of the recorded energy, surface waves hide a large part of the information coming from the sub-surface through body waves. Effort has been done in the past to better filter or remove them. But their impact is always far to be neglected, especially with strong backscattering contribution.

In parallel, taking advantage of an always growing number of channels, geophysical explorations face new opportunities to enhance the quality of earth imaging. For example, a better spatial sampling is a way to better use or remove the surface waves. There are compromises to find between higher spatial sampling and operational costs, even for on-field tests.

In this context, surface waves studies at laboratory scale is a flexible way to evaluate new acquisition designs and processing. This presentation shows how gel-based phantom can be successfully used to study wave mixing in the context of geophysics prospecting. Small-scale experiments provide the record of thousands of traces which enables wave identification and extraction with the goal to adapt recent array processing algorithms to geophysical-like designs.

### Double-beam analysis in the context of a seismic prospecting data

*Pierre Boué, Philippe Roux, Benoit De Cacqueray, Michel Campillo*

The use of seismic arrays is growing world wide both at large continental scale for deep-structure seismology purpose and at small scale with exploration geophysics goals. Seismic arrays require array processing from which new type of observables can be extracted that allow a better understanding of the wave propagation complexity. Among these array processing techniques, this study focus on a way to select and identify different phases based on double beamforming processing method. At the exploration geophysics scale, the goal is to study each body wave and surface wave separately. Synthetic data-set from finite-difference simulation is first used to validate the processing. Then real seismic prospecting data from Shell-Petroleum Development Oman are investigated. This data-set is a high resolution survey which provides a perfect control on source and receiver arrays geometry. From additional directional information obtained from double beamforming on both source and receiver arrays, it is demonstrated that surface and body waves can be extracted with a higher efficacy compared to classical point-to-point analysis.

### One channel spatio-temporal inversion of acoustic wave in reverberant cavities

*Matthieu Rupin*

It has been recently shown that it was possible to optimally recover the green's functions from a complex wave field despite of a non-isotropic distribution of the noise sources. The method used is based on a particular use of the Inverse Filter's (IF) formalism which is called the passive IF. Based on this formalism we have investigated the possibility to control the spatio-temporal degrees of freedom in a reverberant cavity for the focusing of waves (active processes). The understanding of this phenomenon can be very useful in a lot of different applications like in acoustical imaging, seismology, or telecommunications. In the present work, the spatio-temporal focalization of ultrasounds in reverberant cavities is studied using medical arrays and water tanks. Through experiments, a complete spatio-temporal inversion is realized to synthesize optimized emitting signals. The result generalizes the focalization's control over a spatial vector and during an arbitrary time window.

### Multi-disciplinary continuous monitoring of Kawah Ijen volcano,

*Corentin Caudron, Thierry Camelbeeck, Alain Bernard*

Kawah Ijen volcano (East Java, Indonesia) has been equipped since June 2010 with three broadband seismometers. In addition, different temperature and leveling divers have been immersed in the extremely acidic crater lake (pH~0) that can be considered as a calorimeter. While finding instruments capable of resisting in such extreme conditions has been particularly challenging, these provide us a data every hour. The coupling of lake monitoring techniques with seismic data improves the understanding and monitoring of the volcanic-hydrothermal system. Kawah Ijen seismic activity portrays a wide variety of events. These events have been daily compared with Real time Seismic Amplitude Monitoring (RSAM) technique in different spectral bands ranging from 0.001 to 40 Hz. We are currently working on the implementation of the approach developed by Brenguier et al. (2007) to detect small velocity changes by using ambient seismic noise. Since October 2010, an anemometer and a pluviometer have been installed to better assess environmental and volcanic interactions.

Indeed during the rainy season several Indonesian volcanoes usually experience an increase in seismic activity leading authorities to raise the alert status. A meteoric water recharge of the hydrothermal system enhances the movements of fluids triggering tremor and/or low frequency events which are not related to an increase in magmatic activity. Three low cost iButton temperature divers have been installed with different acid protection in Kawah Ijen crater lake. A winsitu level/temperature diver with a better resolution and precision was placed nearby. This allowed us to compare data of both instruments. Since meteorological equipments have been installed, it allows the calculation of the thermal flux of the lake and facilitates the interpretation of temperature fluctuations. While it was previously observed that temperature divers need to be at high depth (20 m) in neutral lakes (Rinjani, Kelud, Indonesia) to limit

### **Instantaneous Phase Variation estimation. New tool to measure weak velocity variations at exploration scale using ambient noise correlations.**

*Margherita Corciulo, P. Roux, M. Campillo and Dubucq D.*

The use of noise correlation to passive monitoring exploration fields is still debated despite the successfully results obtained at greater scale of analysis. In diffusive regime, it is possible to consider scatters as secondary sources randomizing the spatial distribution. Scattered waves are sensitive to weak velocity variations thus their phase variations can be used to perform a passive monitoring even at exploration scale. An innovative technique based on the computation of the instantaneous phase variations (IPV) was developed and applied to a real dataset acquired in an exploration context. The IPV works in the frequency domain and permits to estimate the phase shift all over the signal length without any assumption on the medium velocity. The phase difference at each instant of the signal is computed using the Hilbert transform and the corresponding phase difference function is fitted by a first-order polynomial function which slope corresponds to the velocity variation measured for the signal used. As inferred by numerical tests the IPV is the faster technique compared to the existing Doublet and Stretching techniques. This makes the IPV a useful procedure, which efficiently can be used on large data sets. Data used were acquired at an exploration field by 397 stations laid out on a 1-km side square seismic network. As the data set was continuously acquired over five days, for each couple of stations about 700 files were processed to perform a complete temporal analysis corresponding to about 80000 files analyzed at each window time. The huge amount of data allowed performing a statistical analysis that improved on the results obtained. Results showed a good coherence with micro-seismic event rate known for the area making the IPV a very useful tool to passive monitoring exploration field.

### **Temporal seismic wave speed changes associated with the May 12, 2008 Mw7.9 Wenchuan earthquake**

*Bérénice Froment, Jiu Hui Chen, Michel Campillo and Qi Yuan Liu*

We used continuous recordings of ambient seismic noise in Sichuan, China to track the temporal evolution of the seismic wave speed at a regional scale in a 2-year period, which includes the great Wenchuan earthquake. The data were recorded by a temporary network of 156 broadband seismographs ran by the China Earthquake Administration, in a 200 km x 200km region that covers the southern 2/3 of the fault system activated during the Wenchuan event. We computed cross correlation functions of continuous vertical records for all pairs of stations and we investigated temporal velocity changes with respect to a reference correlation. We carried out this analysis in different period bands. We first considered signals in the 1-3-s period band. We found clear evidence of a co-seismic velocity drop (up to 0.08% in the fault region after the Wenchuan earthquake while the velocity fluctuates within 0.02% in the months before the earthquake). We compared the measurements in different sub-arrays to get a spatial distribution of the velocity change. We observed that the co-seismic velocity drop is observable in a wide zone around the fault and that at regional scale, the velocity drop exhibits a better spatial correlation with the volumetric strain change during the Wenchuan earthquake than with the surface geology. In order to investigate deeper processes in the crust, we performed the same analysis on longer-period signals (around 15 s). We discuss observations obtained from this analysis and possible interpretations concerning deep crust behaviour in response to the Wenchuan earthquake.

### **Understanding the dynamics of a geyser from seismic record**

*Estelle Cros, Philippe Roux, Jean Vandemeulebrouck*

Old Faithful Geyser is the most popular geyser in Yellowstone National Park. The predictability, the repeatability and the short time lag, ~1 hour, between two eruptions make its study very convenient to apprehend its cycle and to make progress in the understanding of geyser's dynamics. In 1992, Sharon Kedar deployed 96 geophones around the geyser vent in order to continuously record seismic signals during several eruptive cycles. The signal recorded at Old Faithful is characterized by small impulsive

events, with durations of  $\sim 1$ s, related to bubble collapse in the boiling water column. We revisited the seismic signals recorded by Sharon Kedar in order to invert the locations of the source of these events and to determine the temporal variation of the velocity with the objective to monitor the temporal evolution of the system during an entire cycle.

## **Influence of a localized defect on acoustic field correlation**

*E. Moulin, N. Abou Leyla, J. Assaad*

The work presented here is concerned with the study of a damage detection principle in a reverberant medium, based on ambient acoustic noise correlation. The aim is to establish a theoretical relationship between the relative positions of the noise source, the sensor(s) and the defect, and the sensitivity of the detection. The acoustic reverberation in the medium is modeled by a random process and the (localized) defect is considered as a secondary random source with unidirectional radiation properties. The influence of the defect's presence on the correlation functions is quantified by the energy of the difference between the correlations in the medium with and without the defect, normalized by the energy of the defect-free correlation. The theoretical expression of this energy ratio is experimentally validated in a particular 2D-case (metallic plate) and then used to define the detection range and the optimal placements of the sensors.

## **Spatial and temporal imaging of fluid migration through the crust in the W-Bohemia/Vogtland earthquake swarm region with seismic methods based on ambient noise**

*Mohammad Javad, Michael Korn, Christoph Sens-Schönfelder*

The W-Bohemia/Vogtland region at the border between Germany and Czech republic is a place of presently ongoing geodynamic processes in the intra-continental lithosphere, which result in the occurrence of repeated earthquake swarms, mantle-derived fluid exhalations, mofettes, mineral springs and enhanced heat flow. It is a key site to study the mantle-crust interaction in an active magmatic environment, and has been proposed as a site for scientific drilling. Fluid reservoirs have been proposed for the upper crust as well as for the crust-mantle transition zone, but their direct observation is still missing. We attempt to image spatial and temporal crustal seismic structures and fluid dynamics by employing passive seismic methods based on ambient noise. Using the ambient noise cross-correlation technique, we derive Green's functions of Rayleigh waves from the continuous recordings of dense local networks. The derived Green's functions will be carefully examined, and only quality results will be used for the tomographic inversion. Furthermore, passive seismic interferometry is used to detect possible temporal variations in structure and/or seismic velocities due to stress changes, crack openings/closings, or groundwater level changes during an earthquake cycle.

## **Passive monitoring of temporal, coseismic, velocity variations**

*Pierre Gouédard, John A Collins, Jeffrey J McGuire, Robert D van der Hilst*

Passive techniques are now widely used for seismic imaging, for example ambient noise tomography. A recent development of passive techniques, namely the Passive Image Interferometry, allows the monitoring of temporal variations of seismic velocities from the continuous recording of ambient noise. The sensitivity of the method is as high as 0.01% in relative velocity changes. Such a high sensitivity is reached by using the (multiply-) scattered waves reconstructed in the noise cross-correlation functions in the surface-wave coda. In our study we utilized passive image interferometry to detect changes in velocity before/after a Mw 6.0 earthquake at the Gofar transform fault at the East Pacific Rise. The data set consists of a year of continuous recording at 15 ocean bottom seismometers (OBS) located in the vicinity of the fault. A velocity drop of 0.1% is measured at the time of the earthquake. Preliminary results suggest that the temporal variation is localized within the fault zone. Coseismic variations are usually interpreted as a consequence of the stress release on the fault. Multi-component analysis (3 components seismometers plus accelerometers) allows making independent measurements of the velocity variations, and further improving the resolution. We note that the method is insensitive to clock errors, which is of particular interest when working with OBS, and can also be used to measure and correct for clock errors, if any. The sensitivity of the method, along with its low cost and its continuous and real time nature, make it a promising tool for monitoring geological structures at different scales.

## **Extracting Green functions from seismic noise on andesitic volcanoes**

*Philippe Lesage*

I present some preliminary calculations of correlation function of seismic noise recorded on several andesitic volcanoes and attempts of detecting velocity variations in the structure related with volcanic activity.

## Variation of S-wave velocity as an indicator for predicting soil destabilization

*Guenole Mainsant, Eric Larose, Denis Jongmans, Laurent Baillet, Clement Michoud, Michel Jaboyedoff, Cornelia Brönnimann*

Clay landslides pose critical problems to the risk management because the slide velocity can vary dramatically (cm/y to m/s), with earthslide evolving to earthflow, depending on the meteorological conditions (rainfall, snowmelt) and water infiltration in the mass. The Pont Bourquin landslide (Swiss Alps) is a small but active clayey earthslide-earthflow which is threatening a cantonal road. Its small dimensions, 250 m in length, 35 m to 65 m wide and about 10 m deep, makes it easy to investigate and to instrument. The landslide has accelerated at the end of the spring of 2010, with displacement rates reaching a few m/month in the feeding zone. An earthflow of a few hundred of m<sup>3</sup> was triggered in summer 2010, between the 17<sup>th</sup> and the 19<sup>th</sup> of August, after two heavy rainfalls that occurred on the 12<sup>th</sup> and 15<sup>th</sup> of August. In order to detect medium changes in the feeding zone, two short-period 3C seismometers were installed in stable ground on both sides of the landslide in January 2010. Those were connected to the same seismic station operated in continuous acquisition mode. Passive seismic data were processed using the crosscorrelation technique to evince Rayleigh wave velocity (VR) variations, which are linked to shear wave velocity changes, in the sliding medium. In the frequency range 10-12 Hz (corresponding to penetration depth of about 10 m), the relative variation of VR exhibits a slight and continuous increase of about 1% between January and July 2010. After the 23<sup>rd</sup> of July, VR values show a significant decrease (7%) to the 17<sup>th</sup> of August when measurements stopped because of the damage caused by the earthflow. A higher decrease rate in VR was observed from the 13<sup>th</sup> of August, 5 days before the earthflow. These results suggest that the evolution of Rayleigh wave velocity (and the shear wave velocity) with time could be a valuable precursor for earthflow events and changes in clay rheology.

## On the Rayleigh-wave response from multi-component noise correlations

*Dylan Mikesell, Kasper van Wijk, Matthew Haney, Vera Schulte-Pelkum, Josh Stachnik and Thomas Blum*

The development of ambient noise tomography has provided a powerful tool to investigate the Earth's subsurface with increased resolution. Most commonly, tomography is performed on interstation estimates from vertical component ambient noise correlations. We present estimates of the crossterms of the Rayleigh wave Green tensor and show this is less sensitive to ghosts from the non-isotropic noise field. We do this using a spatial correlation framework and illustrate advantages to using the crossterms of the Green tensor. With passive three-component seismic data, we show that estimating the crossterms of the Green tensor leads to improved Rayleigh-wave phase-velocity dispersion curves when compared to the standard vertical-vertical crosscorrelations. This approach provides the opportunity for more reliable ambient noise crosscorrelations over shorter time windows.

## Relation between slow slip event, non-volcanic tremors and seismic velocity changes in the Guerrero Gap

*Diane Rivet, M. Campillo, N. M. Shapiro, V. Cruz-Atienza, M. Radiguet, N. C*

Slow slip events (SSEs) recently discovered in the seismic gap of Guerrero (Mexico) are considered as a very significant component of both the strain release process and the seismic cycle. Since SSEs can affect the recurrence of large thrust earthquakes, understanding the complex mechanical behavior of the subduction in this region is a key issue for the seismic risk assessment. Here we present a study of the relation between the deformation induced by the 2006 SSE, non-volcanic tremors (NVTs) and seismic velocity change within the overriding continental crust in the Guerrero region. On the one hand we measure a long-term seismic velocity change associated with the 2006 SSE in the Guerrero segment of the Middle-America subduction zone from repeated cross-correlations of ambient seismic noise. The perturbation observed maximized at periods between 7 s and 17 s, which correspond to surface waves with sensitivity to the middle crust. Besides, from a slip model that describes the slip evolution during the SSE (Radiguet et al., 2010), we performed numerical modeling of the deformation within the crust induced by the 2006 SSE. The temporal and spatial relation between the velocity perturbation and the strain due to the SSE suggests that the deformation of the overlying crust shows significant nonlinear elastic behavior. On the other hand we compare the distribution of the NVTs activity during the SSE period (Kostoglodov et al. 2010) with the deformation produced by the SSE. We observe that NVTs seem to occur in areas of the overriding plate where the dilation increases. This combination of seismological observations, inversion of geodetic data and numerical modeling enlighten the complex mechanical behavior of the subduction.

## Imaging in heterogeneous media with LOCADIFF: ultrasound in concrete

*Vincent Rossetto, Eric Larose, Ludovic Margerin, Thomas Planès*

A technique for monitoring the differences in a heterogeneous medium between two measurements is presented. We show how correlations of waveforms are modified by these changes and how the processing of these correlations yields an image of the inside of the medium. Concrete is a heterogeneous medium allowing laboratory experiments that we use to illustrate our results.

## Seismic velocity change after the 2008 Iwate-Miyagi Nairiku EQ.

*Ryota Takagi, Tomomi Okada, Hisashi Nakahara, Norihito Umino, Akira Hasegawa*

In this study, we performed two different analyses to detect temporal change in seismic velocity associated with the 2008 Iwate-Miyagi Nairiku earthquake. First, we performed ambient noise cross-correlation analysis to detect temporal change in Rayleigh wave speed at 2-4 s. Rayleigh wave speed suddenly dropped by 0.1~0.5 % at the occurrence of the main shock. Secondly, we performed cross-correlation analysis for earthquake records observed at vertical array to determine shear velocity change in superficial layer. Average shear wave velocity decreased by 5 % in superficial layer shallower than 250 m. In order to check relationship between the two results, we calculated theoretical phase velocity change of Rayleigh wave as the shear velocity decrease in the superficial layer. If we assume certain model, phase velocity at 2-4 s is expected to decrease by 0.1~0.3 %. Therefore, velocity decrease might occur mainly in the superficial layer due to strong ground motion.

## Using back projection to image earthquake source complexity

*Claudio Satriano, Viviana Dionicio, Jean-Pierre Vilotte*

In recent years a new approach to earthquake rupture imaging has emerged, based on the exploitation of the coherency of the seismic signal recorded at modern, dense seismic networks (e.g. Ishii et al., 2005). A dense station deployment can be used as an antenna to track the energy radiated by the propagating rupture along the fault. This energy, coherently recorded at the stations, is back propagated to its most likely position in the source region. The result is a time-evolving image of the rupture as it starts from the epicenter and propagates on the fault. The back-projection method (BPM) has been initially proposed as a tool for rapid assessment of extended source characteristics after a large earthquake. It has however subsequently proven to be an effective approach in constraining some key source parameters (slip geometry, rupture velocity) and in retrieving "hidden", features of the rupture process, like secondary events embedded in the main shock (Allmann and Shearer, 2007). The full potential of the BPM has however still to be exploited. The strength of this methodology is in its capacity of directly image the radiation emitted from the source, providing a natural framework for studying the radiation in time, space and frequency. The ideas and the methodologies behind BPM are rooted in a variety of disciplines, including seismic exploration for oil industry, medical imaging, and astronomy. We think that BPM can be brought to the next level, by taking advance from the most recent progresses in the multi-disciplinary fields of waveform migration, dynamic deconvolution, time-frequency analysis and understanding of heterogeneous media.

## Cross correlation and deconvolution of noise signals in random media

*Knut Solna, Josselin Garnier*

We consider a three-dimensional small-scale randomly fluctuating medium with also macroscopic variations. We consider a framework for analysis of cross correlations of waves generated by noise sources and propagating in such a medium, moreover, use this framework to design estimators for macroscale medium features. The analysis is carried out in the asymptotic framework where the typical wavelength is small compared to the scale of the macroscopic variations of the background medium and large compared to the decoherence length of the random fluctuations of the medium.

## Computing Green function by simulating seismic ambient noise

*Laurent Stehly, Paul Cupillard, Barbara Romanowicz*

The long-term goal of this work is to improve tomographic images resulting from noise correlations. More specifically we address two questions that relate to each other: 1) Is it possible to compute noise correlation by simulating ambient noise using the Spectral Element Method and 2) is it possible to "denoise" noise correlations using auto adaptive filters. Indeed seismic ambient noise correlations have been successfully used to develop tomographic models of the crust. However this method is still limited since correlations are inverted 1) using ray theory and 2) assuming that the noise sources are evenly distributed in the medium so that the correlations contain the Green function of the medium, which is not true in practice.

To go beyond these two limitations we investigate the possibility to simulate seismic ambient noise in a 3D medium using the Spectral Element Method. This would be useful to 1) compute synthetic correlations in a 3D starting model and 2) to take into account the uneven distribution of noise sources when inverting the correlations.

To that end we use RegSEM to simulate seismic noise sources and to compute synthetic correlations at the regional scale in the 20-50s period band. We study the convergence time of the correlation towards the Green function and the best way to denoise noise correlations.

### **Development of Hard- and Software of Microseismic for Geothermal exploration**

*Mohammad Rachmat Sule, D. P. Sahara, Y. Kusnadi, A. W. Kusumo, A. D. Nugraha, T. Setia*

The Ministry of Research and Technology (RISTEK) of Republic Indonesia launched a so-called RISTEK, since 2005. This allows Indonesian researchers to be active in research activities, which its funding is higher than other research funding available in Indonesia for small group of researchers. We received this kind of funding for the year of 2010 with its theme is development of hard- and software of microseismic for geothermal exploration and monitoring. This paper describes the first achievements after the funding is granted to us eight months ago. This research theme is grouped into 3 main activities, namely development of borehole seismometer by using MEMS, development of precise microseismic relocation technique, and development of first arrival travel time tomography software. The overall current achievements are beyond the target of first year, so that the funding will be extended for the 2nd year.

### **Velocity time variations from seismic noise cross-correlations**

*Lucia Zaccarelli, N M Shapiro*

The crustal velocity variations may be retrieved through the analysis of the seismic noise cross-correlations. We applied the Multi Window Cross-Spectral technique to more than 2 years of continuous seismic records from the area of the Mw 6.3 L'Aquila earthquake (Italy), and more than 10 years of recordings on the Kliuchevskoi volcano (Kamchatka). The first data set includes the occurrence of the L'Aquila mainshock. On the other hand, the Kliuchevskoi volcano experiences an almost constant volcanic activity. We performed the analysis for different frequency bands between 0.1 and 1 Hz, and then we try to relate the velocity temporal variations to the co-seismic effects of the mainshock or to the eruption occurrences, respectively.