GEK-SAT

Giant Earthquakes along the South-American Andean Trench


Talcahuano, Chile, 27-Feb-2010

Domain of the project : **Environmental risk**
Specific research field : **Seismic hazard**

1. PROJECT SUMMARY

To move ahead on the understanding of the mechanics of megathrust earthquakes, we propose to study the 2010 Mw8.8 Maule earthquake in every possible detail and to put it into the perspective of the geodynamics of the whole Andean margin. The Chilean subduction is one of the most active in the world, with 4 mega earthquakes in the last 120 years (1906, 1922, 1960 & 2010). The occurrence of these earthquakes poses a number of problems here addressed by a group working in Chile for more than 10 years, doing research that set the frame for a successful study of the 2010 event. This will be used as a starting point to improve our approach of active subduction: in the course of our study of the Maule earthquake, we will increasingly focus our attention to adjacent regions that are now approaching the end of their respective seismic "cycles" and entering into the early stage of the preparation of a mega-earthquake. There, we will extend and densify our existing GPS networks, make new measurements and acquire new data over the duration of the project.

For the specific study of the Maule earthquake we have acquired a substantial co- seismic data set: campaign GPS, high dynamic range accelerograms, classical strong motion instruments, 1 Hz continuous GPS records. In addition, we dispose of a long series of aftershock recordings obtained by a group of CNRS-INSU researchers to which we belong, as well as our foreign and Chilean colleagues. This unique data set will be used to study the rupture process of the earthquake. For example, we hope to explain why such a large event produced moderate strong motions. Is this a unique feature of this event, or is it typical of most large subduction zone mega-earthquakes? To answer this question we need to study the slip distribution of the main event. We need to understand why the aftershocks stretched over an area substantially longer than the rupture of the main event; why the aftershock series did not contain any events larger than Mw 7.1, a puzzling feature indeed. Finally, we need to understand why the largest aftershocks (excluding the Pichilemu crustal event of March 2010) occur in the epicentral area (February 2011, February 2012 and March 2012), an area where lesser slip associated to the main shock was observed.

No earthquake of magnitude larger than 8.5 had occurred in the last 40 years before the Sumatra 2004 event! With the 2011 Japan event, Maule 2010 is the first mega earthquake that occurs in a closely surveyed area. Our own published studies (Ruegg et al., PEPI, 2009) (published before the 2010 event) pointed out that the interplate zone was completely locked not just inside the so-called "Darwin gap" but well outside it, suggesting that historical earthquakes can serve to identify gaps, but not to determine their actual size. Our rupture model [*Vigny et al., Science, 2011*] supports this conclusion as the whole subduction plane broke for about 500km along strike, and from 40km depth to its very shallow parts near the trench. This latter finding, also reached for Japan, explains the generation of powerful and devastating Tsunamis but requires changes in our understanding of shallow rupture propagation and coupling. We also anticipate new advances on the comprehension of after slip that will be studied with a rich set of cGPS data: where does it occur and what are the properties of faults and bulk rheology that produce long episodes of silent deformation around earthquakes. On this topic, we build upon our long-term investment in Indonesia

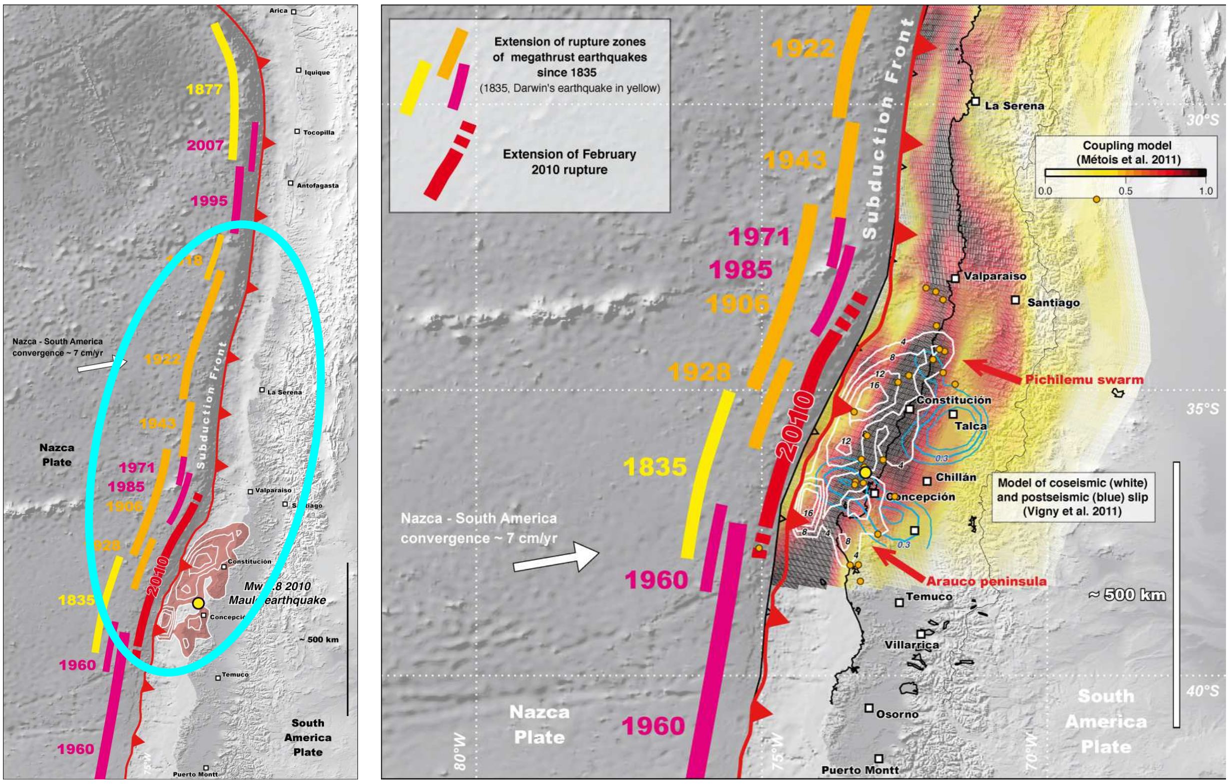


Figure 1. Historical earthquake segmentation and localization of the Maule earthquake of 27 February 2010 (Mw 8.8) on the larger Chilean subduction trench (left box). Area of interest of this proposal (blue ellipse). Coupling inverted from pre-seismic GPS data (Métois et al., 2012) and slip distribution inverted from co-seismic geodetic (GPS+INSAR) data (Vigny et al., 2011) (right box).

and our own work on the 2004 Sumatra giant earthquake and its post-seismic deformation: we showed that a very large scale subsidence is presently affecting the whole region of Thailand with dramatic consequences in terms of flooding.

Finally, inter-seismic accumulation of deformation reveals the segmentation of the subduction zone. Our own most recent work [*Métois et al., JGR, 2012*] shows that there is substantial evidence that the Chilean margin has long standing segments associated both with features of the oceanic plate (seamounts, ridges) and of the overriding plate (faults, uplifted terraces…). Do they actually play a role in stopping earthquakes or at least in fragmenting them? The Mejillones, Arauco, Talinay and many other peninsulas are long standing features where seismic ruptures seem to stop or slow down as they reach them. We plan to explore their role using the geodetic methods our group has been successfully implementing in Chile over the last decade and new seismic imaging we will perform.

The Maule earthquake is a rare event; the lessons to be learned from the study of this earthquake will most certainly have a lasting influence in the way geoscientists and engineers approach the problem of the occurrence of these events.

2. PROJECT JUSTIFICATION

2.1. SCIENTIFIC, SOCIAL & ECONOMIC ISSUES – IMPACTS & EXCHANGES WITH THE AXA COMMUNITY

Giant earthquakes (Mw close to 9 or larger) occurring on subduction zone mega-thrusts are amongst the deadliest natural hazards. During the last decade, such events took about 250 000 lives, the most devastating event being the 2004 Mw 9.2 Aceh earthquake in northern Sumatra, and the recent Mw 9 2011 Tohoku earthquake in northeastern Japan. In contrast to continental intraplate earthquakes, shallow subduction mega-events often have worldwide destructive impacts as the huge tsunami waves they generate propagate across oceans.

The most powerful earthquake ever recorded on Earth broke a 1000km long segment of the Nazca - South America subduction zone of south-central Chile in May 1960, just south of the 2010 Maule rupture which is the subject of this project. The earthquake and the Tsunami killed several thousand people, including about 200 in Hawaii and Japan where the waves reached 6m high. Its monetary cost has been estimated between 3 and 6 billion USD in 2011 dollars, adjusted for inflation. Costs of comparable disasters are now one order of magnitude larger in our 21st century world: according to the World Bank, estimates reach 15-30 billion USD for the 2010 Maule earthquake and perhaps over 230 billion USD for the 2011 Japan earthquake.

Understanding how mega-thrust ruptures initiate and propagate laterally and towards the surface is crucial to better forecast the hazards associated to the earthquake itself and to the trans-oceanic tsunamis. Undoubtedly, this knowledge is much needed to enhance the reliability of early-warning systems, which should help reduce human loss and economic costs. Additionally, educational outreach in vulnerable countries is crucial to explain the seismic, tectonic and tsunamic processes both to the politics and to the population. Only this ensures that people will react properly when the earthquake occurs. Fundamental research on densely instrumented sites, and publication of results in the best scientific journals, is necessary to reach these objectives. With Japan and Cascadia (northwest USA and Canada), Chile is one of the best places to perform such research. A segment we had identified broke recently; two other large segments approach the end of their respective seismic “cycles”.

We have been working actively on the Chilean subduction zone since the end of the 1980s. Over the last decade we have been developing a monitoring infrastructure based on arrays of many continuous GPS stations (~50) and repeated measurements on numerous geodetic benchmarks (>300). Based on those data, we had identified two seismic gaps with an extremely high seismic hazard and a third region of interest where “strange” things occurred in terms of upper plate deformation and seismicity. One of the identified seismic gaps – the Maule area – ruptured in 2010 with the 5th largest subduction earthquake in the instrumental era, just one year after we announced [*Ruegg et al., 2009*] its potential for an imminent magnitude 8+ earthquake (fig 1). The second one – The North Chile area – has experienced relatively large earthquakes (Mw 8.1 Antofagasta 1995, Mw 7.7 Tocopilla 2007, Tarapaca intraslab event 2005) but remains largely intact since 1877 and all calculations show that it is very mature. The third one – the Atacama segment - we now identify has a mature gap [*Métois et al., 2012*] produced a relatively unknown megathrust earthquake in 1928 and has been very poorly studied. Last, but not least, the whole central area produced what might have been the largest event on the Chilean trench ever in 1730 [*Udias et al., 2011]* and time might due for a repeat of this event.

2.2. POSITION OF THE PROJECT

One of the very important findings made immediately after the 27 February 2010 Maule event is that although its magnitude was 8.8, the destructions caused by the earthquake itself were moderate [*Madariaga et al., 2010*]. This might be related to the relatively low level of accelerations produced (significantly less than 1g everywhere). In addition, hardly any large aftershocks were recorded in the weeks and months following the main shock. Those a-priori surprising facts are related to the complex source (bi-lateral, slow initiation, etc…) of this event. Understanding the source of the Maule event will enhance our capacity of forecasting what might occur not only in other areas of Chile (i.e. the North Chile gap) but also on other subduction zones where major earthquakes are expected.

A second major finding based on our co-seismic data is that the Maule rupture propagated all the way from about 40 km depth up to the trench across the weak sediment layer usually considered un-capable of accumulating elastic deformation [*Vigny et al. 2011*]. The same conclusion was recently reached for the Tohoku-Oki earthquake in Japan [*e.g. Heki 2011*]. Is this a general feature of mega-thrust earthquakes that would be able to bypass mechanical barriers ? And does this relate to the generation of large Tsunamis by these earthquakes (similarly to Sumatra 2004 and Japan 2011) ?

A third important finding about the Maule earthquake is that it occurred precisely in the area where the coupling determined by our earlier GPS measurements was maximum [*Moreno et al., 2010; Vigny et al., 2011; Métois et al., 2012, Moreno et al., 2012*]. In particular, at the northern termination of the rupture, co-seismic slip decreases sharply where the rupture reaches a narrow area of low coupling (the San Antonio bay – 34°S), but the aftershock area extends up to at least 33°S. Do these observations mean that we should not expect a major earthquake north of the Maule event, since the coupling is lower (and seismicity is higher) in this area than it was in the Maule area prior to the earthquake? Does this mean we should expect a large earthquake north of 28°S, where sparse existing GPS measurements tend to indicate a higher coupling? Or on the contrary, was the 1835 gap the last highly coupled segment, inside this 1000 km long segment from 38°s to 28°S, now ready for one major mega-thrust event of magnitude significantly larger than 9 – a repeat of the 1730 megathrust event ?

This project takes place in the following National and International, very active context :

- We build it upon the post-seismic intervention that began in March 2010 just after the earthquake and during which we accumulated a very significant amount of data. Very rapidly after the earthquake we installed a network of seismographs, accelerometers and cGPS stations to monitor the aftershock activity and post-seismic deformations, reoccupied campaign GPS points and made geological observation along the coast. In the following weeks, different international groups also deployed networks of instruments (cGPS and seismographs) which makes this rare event extremely well monitored.

- The whole Franco-Chilean cooperation is operated under a specific umbrella, the International Associate Laboratory (LIA) "Montessus de Ballore", MOU signed between French CNRS and Chilean University of Chile at Santiago.
- Other international teams operate instrumental networks in different areas of Chile and conducted post-seismic interventions after the Maule earthquake:
  1. Caltech (Simons et al.) : ~15 cGPS in north Chile
  2. GFZ (Schurr et al.) : ~15 cGPS in north Chile + ~10 cGPS in South Chile + ~30 multisensor seismological stations in North Chile
  3. Ohio State Univ. (OSU) (Bevis et al.) : ~20 cGPS in South central Chile,
  4. University of Liverpool (Rietbrock et al.) : installed temporary seismographs and cGPS in Maule epicentral area

  We have a series of MOU and agreements with those groups and institutions. Data from all these networks are shared between participants and available for this project at no cost. We provide explicit letters of support from these groups.

  Finally, Argentinian (RAMSAC) and Brasilian (RBMC) cGPS networks also provide important data for the reference frame and the far field post-seismic deformations. These data are freely available (http://www.ign.gob.ar, http://www.ibge.gov.br) and already introduced in our data processing.

2.3. DETAILED OBJECTIVES

The 2010 Mw8.8 Maule earthquake raises challenging questions regarding the nucleation and the propagation of a megathrust earthquakes, the frequency contents associated to such large subduction events, the activation of crustal shallow splay faults and related seismic hazard, the segments of the subduction zone in Chile and the way large seismic gap eventually rupture. This project aims at providing new answers and perspectives to these questions, a better understanding of the seismic hazard along the Chilean subduction zone and its consequences, all in the light of the Maule Earthquake.

The first Challenge is to understand the Maule earthquake (a rare Mw 8.8 event) itself. Two years after the event, many important questions remain unsolved: Why did it generate only moderate accelerations, especially at high frequencies? Why aftershocks extend significantly longer than the rupture? Is that true? Did the low coupling area of San Antonio stop the northward rupture propagation? Did the rupture overlap the Valparaiso 1985 event (Mw 8) or was this older rupture mislocated? Why no large aftershock occurred until now? In addition, several findings based on our co-seismic data raised new questions: The GPS data revealed that the rupture propagated all the way up to the trench across the weak sediment layer usually considered un-capable of accumulating elastic stresses. Is this a general feature of mega-thrust earthquakes? And does this relate to the generation of large Tsunamis by these earthquakes (similarly to Sumatra 2004 and Japan 2011)?

The second objective is to improve our understanding of the patterns of earthquakes on the Chilean seismogenic zone. Small/moderate earthquakes represent failure of individual asperity while great earthquakes represent the collective failure of several to many asperities.

Maule 2010 is a great earthquake that ruptured the entire width of the subduction plane, implying along-dip and along-strike interaction of asperities and a complex bi-lateral source. Geodetic evidences of after-slip and post-seismic deformations also suggest the importance of seismic/aseismic interactions between asperities. We want to understand: the origin of asperities in relation with deep structures and variations of plate coupling; their interactions over various time and space scales; the implications for earthquake dynamics and radiation. All these studies require dense high-quality observations data sets integrating sGPS, cGPS, InSAR, seismographs, strong motion, and seismic imaging. Many observations will be available for our project, thanks to the rapid deployment of hundreds of instruments in the Maule area and around.

The third objective is to improve our understanding of the segmentation of the subduction zone. Understanding barriers between segments and their stability in space and time is an issue for mega-thrust earthquake seismic hazard assessment. Ruptures of the 1995 Antofagasta, 2007 Tocopilla, and probably the larger 1877 Iquique, earthquakes stopped where complex structural features are located under the Mejillones peninsula. The Arauco peninsula south of Concepcion acted as a barrier for the 1835, 1960 and 2010 earthquakes. Smaller structures like the Tallinay peninsula also acted as a barrier for past earthquakes. Like Mejillones, Arauco is marked with evidences of both quaternary and contemporary uplift. However, paleo-seismological information is still relatively scant, and most of our knowledge is biased by the brief span of historical data compared to seismic cycles of many centuries. Therefore we assume the most important/practical thing to be done at the moment is to quantify the coupling along the length of the trench so as to define the present day segmentation.

The fourth objective is to quantify the new seismic hazard generated by the Maule earthquake, since the subduction main shock triggered a new seismicity in the crust overriding the subduction plane. The majority of aftershocks following the Maule earthquake are located near the plate interface, and moderate to large aftershocks at the depth of the plate interface may not cause sufficiently strong ground motions to pose a hazard. However, any shallow aftershocks in the upper crust of the overriding plate may represent a significant seismic hazard because of small source-to-site distances and relatively strong ground motions in frequency ranges of concern to engineered structures. On 11 March 2010, two large aftershocks with magnitudes close to 7 and extensional mechanisms occurred within 15 minutes of each other near the town of Pichilemu. Damage to buildings was sustained locally and small tsunami waves were reported offshore. However, the ground and aerial reconnaissance efforts observed no evidence of surface rupture related to these events, indicating that the faults on which they occurred are blind and do not emerge at the surface. This has an important consequence: the earthquakes occurred on faults that were unknown and unmapped. Additionally, no crustal normal faulting events with M > 3 had ever occurred in the area during the 25 years prior to the Maule earthquake. Therefore, it is clear that the main shock triggered a perturbation of the background stress field, which presumably establishes a temporary tensile regime in the forearc, in the areas where the pre-earthquake regional tectonic stress was only weakly compressional. In those areas, this temporary regime will be responsible for a temporary seismicity of unknown size and duration. Similar mechanisms for triggered seismicity on previously unknown or poorly known shallow splay faults have been witnessed in Japan after the Tohoku earthquake

(Iwaki earthquake of 11 April 2011, Mw ~7), exactly analogous to the Pichilemu scenario. Therefore it is of great importance to map potential areas for triggered shallow crustal seismicity, regardless of current knowledge of active faults but rather by quantifying the pre-megathrust earthquake stress regime. This can be done with geodesy and seismic imaging.

Finally, one of the main lessons of the recent Tohoku earthquake in Japan is that there is a clear lack of offshore measurements to understand the properties of subduction fault planes in general. Slip models that include some of these offshore constraints, in particular sea-floor geodesy, are significantly different from models that were solely based on land data. The need for offshore measurements covers a wide range of geophysical measurements, the aim being to characterize the seismogenic zone at the exact location of maximum slip. We discuss here a particular type of measurements that can be made both before the earthquake and during the months that follow the event. This technique is based on the deployment at the sea-bottom of an array of Ocean Bottom Seismographs, or OBS. Such an array can be used in two modes: "active", i.e. artificial sources, or "passive", i.e. listening to earthquakes mode. During an "active" mode survey, OBS are used in combination with conventional wide-angle seismic to image major geological structures down to the friction plane. The source is made of a series of towed seismic guns tuned to deliver low-frequencies to allow for deep penetration. Recent results over the Alaska subduction zone suggest that the reflectivity in the region of the friction plane may vary as a function of the degree of locking of the plane. Such information would be highly valuable at other subduction zones, and in particular offshore Chile, to map areas that are fully locked and prone to future large-scale ruptures. One important output of the OBS processing is the mapping of seismic waves velocities down to the friction plane. Then, OBS arrays can also be used in a "passive" mode, in particular in the weeks and months that follow large earthquakes. The aim is to record and locate with high precision the events that follow the main shock (not only aftershocks, but also small-sized events that may have been triggered in the surrounding regions). Analysing the very first Maule post-seismic catalogues, we identify this is still an open issue with a blatant lack of off-shore records preventing accurate aftershock localization.

3. DETAILED WORK DESCRIPTION BY TASK

The GEK-SAT project is built upon the occurrence of the Mw8.8 Maule earthquake of 27 February 2010, the analysis of the data gathered at the occasion of the post-seismic intervention that was conducted immediately after in March 2010, and new data we will acquire in poorly known areas. Our program is based on the analysis of the existing dataset and on continued and renewed investigations outside of the rupture area to derive unprecedented information on how megathrust fault segments rupture and interact with each other, and possibly forecast the location and size of future major ruptures.

Our work program is built upon 4 tasks: **Task 1** will focus on the Maule mainshock and several of its aftershocks source and rupture process using all sorts of seismological data. Renewed source inversions will be conducted with static deformation (geodesy, tsunami), high-frequency GPS motograms and strong motion records and detailed study of the Maule aftershocks from the data of 142 seismic stations deployed just after the earthquake; **Task 2** will provide the quantification of the present-day upper plate deformation at different stages of the seismic cycle along different segments of the subduction using spatial geodesy (GPS); **Task 3** will focus on the analysis of the deformation throughout the whole seismic cycle (inter-seismic accumulation, co-seismic rebound, afterslip, post-seismic relaxation) and its modeling using a viscoelastic approach and 3D finite element coding. **Task 4** will foster the creation of a new network of scientists focusing their research on the friction plane at subduction zones, closing the gap between onshore studies (geodesy), remote studies (seismology) and in-situ studies (marine seismic surveys). The final goal here is to adjoin a group that has experienced massive deployment of ocean bottom seismometers (OBS) in a subduction context, so that this new technology can be brought to Chile. The networking will help shape the scientific objectives, raise funds for ship-time, define strategies for instruments deployment, data processing and quantitative scheme to combine land and sea data.

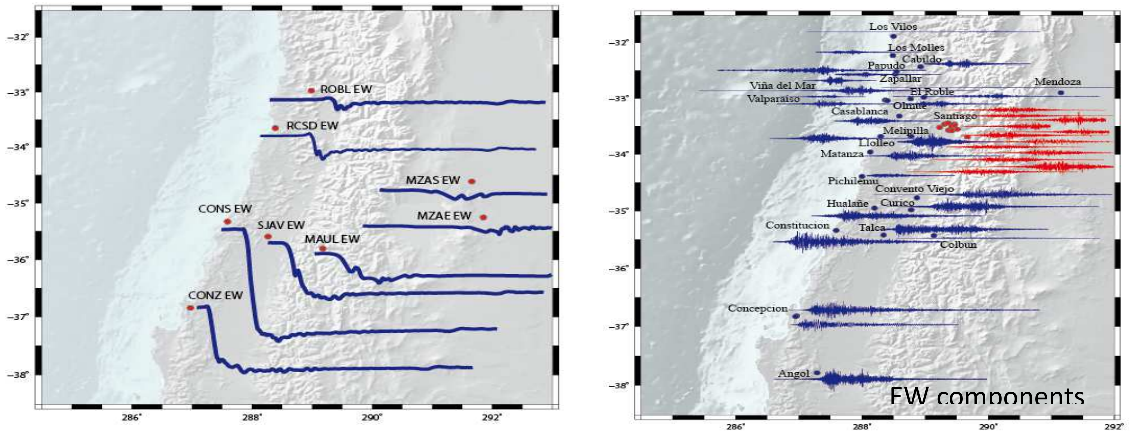
3.1. TASK 1 LOW AND HIGH FREQUENCY CHARACTERISTICS OF THE MAULE EARTHQUAKE AND SOME OF ITS MAJOR AFTERSHOCKS

Coordinator: R. Madariaga
Participants: R. Madariaga, professeur ENS; S. Ruiz PhD student U. Chile-ENS-IPGP;
Collaborations : J. Campos, Prof U. de Chile;

The 27 February 2010 Maule mega-earthquake was the fifth largest earthquake recorded since the beginning of the 20th century, yet it produced limited damage. One of the foremost questions in applied seismology is whether damage in large subduction zone earthquakes scales with the Moment (or equivalently Mw), or is due to some other characteristic of earthquakes that moment release does not account for ? The Maule earthquake was a major event with a large rupture zone of about 450-500 km length by roughly 140 km width; it produced a significant tsunami and large geodetic deformations in the near and intermediate field. Yet, from the point of view of damage in Central Chile it was an earthquake not much more destructive than the big Mw 7.8 event that hit Valparaiso on 3 March 1985. The zone of damage in 2010 is much longer than that of 1985 extending well below the Arauco peninsula, some 600 km south of Valparaiso. A possible explanation, advanced by some engineers is that the Maule event was smoother than what was expected, producing a low level of acceleration (less than 60 % of g); another is that Chilean construction practices have significantly improved in the last 20 years. Either way, and there may be other explanations not envisioned yet, we need to understand damage during large earthquakes better. This is important not just for Chile, but for all other areas of the world where mega earthquakes are expected, like the NW United States, Alaska, Kamchatka in Russia, Central Japan, Taiwan, Peru, Colombia, etc.

We propose to study the Maule event comparing high and low frequencies in a systematic manner. For that purpose we have three types of data: static deformation as observed by interferometry, GPS, and tsunami excitation [*Delouis et al, 2010*, *Tong et al, 2010*, *Lorito et al, 2011*, *Vigny et al, 2011*, etc]. We also dispose of data on low to intermediate frequency radiation in the near and far field from continuous GPS motograms and high frequency signals from some 15 high dynamic range accelerometers and some 30 more conventional engineering accelerograms.

Acelerograms of the Maule earthquake written in the Santiago metropolitan area all have durations of about 60 s and two strong pulses of acceleration with peaks of about 20-30 % g. This is strong motion, but much less than what was expected for such a large event (see the film by National geographic, 2010). A straightforward comparison of the accelerograms recorded in the Maipo valley (Melipilla, Santiago, Llolleo) shows that records of the Mw 8.8 event of 27 February 2010 look almost identical to those of the 1985 Valparaiso event [*Ruiz et al, 2011a, 2011b*].



High rate cGPS Vigny et al. (2010) **Strong Motion Data: Barrientos (2010), Boroschek**

Figure2. Available data for the study of the 27 February 2010 Maule earthquake. On the left we show the EW components of available motograms showing the clear crack-like slip at the very near field stations. At longer distance wave propagation phenomena requires corrections for the seismic structure of the upper mantle in Chile. On the right, we present a subset of all available EW accelerograms; they cover the area from Angol in the South to Los Vilos North of Valparaiso. There may be additional accelerograms owned by private companies that we are eagerly looking for. This is a unique collection of strong motion data, only available to us through agreements with the Chilean participants in this project.

Work program

We propose to study the source of the 27 February Maule earthquake at the broadest possible frequency band using all available data. We distinguish three steps in this work:

Subtask 1.1 Full kinematic inversion. We intend to carry out a full kinematic inversion that includes all the data already available. The main question is how far did the earthquake rupture extend in the trench direction. The inversion of the campaign GPS data acquired along the coast from Arauco to Llico by [*Vigny et al, 2011*] indicates that the rupture extended significantly close to the trench. Inversion of static data is very accurate near the coast but its resolution decreases with distance from the observers. For this reason we would like to invert the static data together with the intermediate field as recorded by continuous GPS instruments in the near and intermediate field. Inversion of this data cannot be done without processing because the static field is overwhelmingly dominant at the stations in Concepcion, Constitucion, San Javier and Maule. Comparison of the motograms with high rate accelerograms will be used a guide for data processing.

Subtask 1.2 High and intermediate frequency inversion. We dispose of close to 30 recordings of either acceleration from 16 bits accelerograms, high dynamic range 24 bit accelerograms and the motograms already mentioned earlier. From spectral analysis we know that this data has a common frequency band 0.02 to 0.16 Hz. Once inversion is done in this band we can extend the source to higher frequencies using the low dynamic range accelerometers. The goal will be not to determine a precise distribution of intermediate frequency sources, but to identify their approximate location. Identifying these sources from the high frequency data will be done only statistically using methods proposed by Ide and Aochi in recent publications.

Subtask 1.3 High and low frequency characteristics of the Maule earthquake. The ultimate goal of our project is to explain how a magnitude 8.8 earthquake produced accelerations that are similar to those produced by a Mw 8 event. This is a crucial question for future studies of seismic risk in those regions of the world where mega earthquakes are expected. Foremost, the Northern Chile gap from the Mejillones Peninsula to Southern Peru.

3.2. TASK 2 GPS MEASUREMENTS

Coordinator : Christophe Vigny
Participants : C. Vigny, DR CNRS-ENS, M. Métois, PhD student ENS-IPGP, Q. Bletery, future PhD student ENS, C.Rioux, field engineer ENS.
Collaborations : J. Campos, D. Carrizo (U de Chile)

The objective of this task is to use spatial geodesy tools (GPS) to measure pre-, co- and post-seismic deformation of the upper plate along the Chilean trench. Doing so, we will quantify the time and space variations of the coupling on different segments of the subduction interface. These segments being at different stages of their seismic cycle, we will measure post-seismic deformation in the Maule rupture area, inter-seismic deformation in central Chile and possibly pre-seismic deformation in a now mature gap : the Atacama segment and onward towards north.

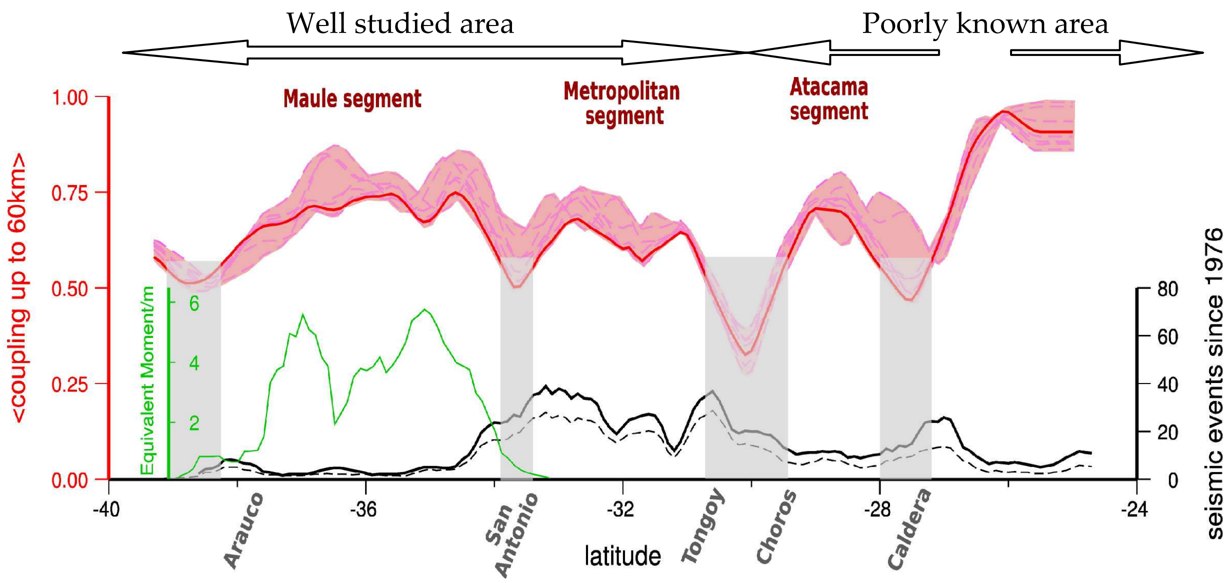


Figure 3. Average coupling between plates on the trench (red curve) as a function of latitude (after Métois et al., 2012). Grey shaded areas depict narrow zones where the coupling is lower than 60% which separate highly coupled segments. The 27-Feb 2010 event (green curve) rupture the Maule segment. The Metropolitan segment has more seimic activity (black curve) and is less coupled. The Atacama segment and its northern termination is very poorly studied and known, but seems highly coupled.

Inter- or pre-seismic. The Maule Earthquake showed that there was a strong correlation between inter-seismic coupling that prevailed prior to the earthquake and co-seismic slip (fig 4). Roughly speaking and on average, the slip is maximum where the coupling was maximum and the rupture is stopped by areas where coupling is low. Additionally, the coupling pattern seems to correlate well with past ruptures and therefore with the segmentation. Thus, although the physical mechanism for such correlation is not completely understood, quantifying inter-seismic coupling along the subduction, on segments which have not broken yet, is of primary importance to quantify seismic hazard along the trench.
Co-seismic. In the case of an earthquake during the 5 years of the project, we will capture the co-seismic deformation thanks to the cGPS networks, and complete these by immediate reoccupation of the survey sites.
Post-seismic. Post-seismic deformations generated by mega-thrust earthquakes like the Maule event are huge (cm/month), widespread (thousands of km), long lasting (decades), and allow to infer important parameters of the earth mantle (layering, viscosity, existence of asthenospheric wedges, …) similarly to Post-glacial rebound studies, as well as rheological properties of the fault zone itself where some after-slip occurs.

Models need data. Large portions of the Chilean trench remain where the amount of upper plate deformation is still poorly known. Additionally, we cannot push aside the fact that coupling may change with time, over long time scales. Therefore, the object of this task is to acquire those much-needed data by performing yearly GPS campaigns on a dense but large network covering the entire area of interest. For this purpose, we will **use, extend and densify** the existing networks in the Atacama region where we initiated measurements in 2010 on an initial sparse network (figure 4 right) [*Vigny et al., 2009*]. To keep a regular meshing with even spacing, we will be installing and measuring ~50 new survey markers and 10 permanent stations in this area.

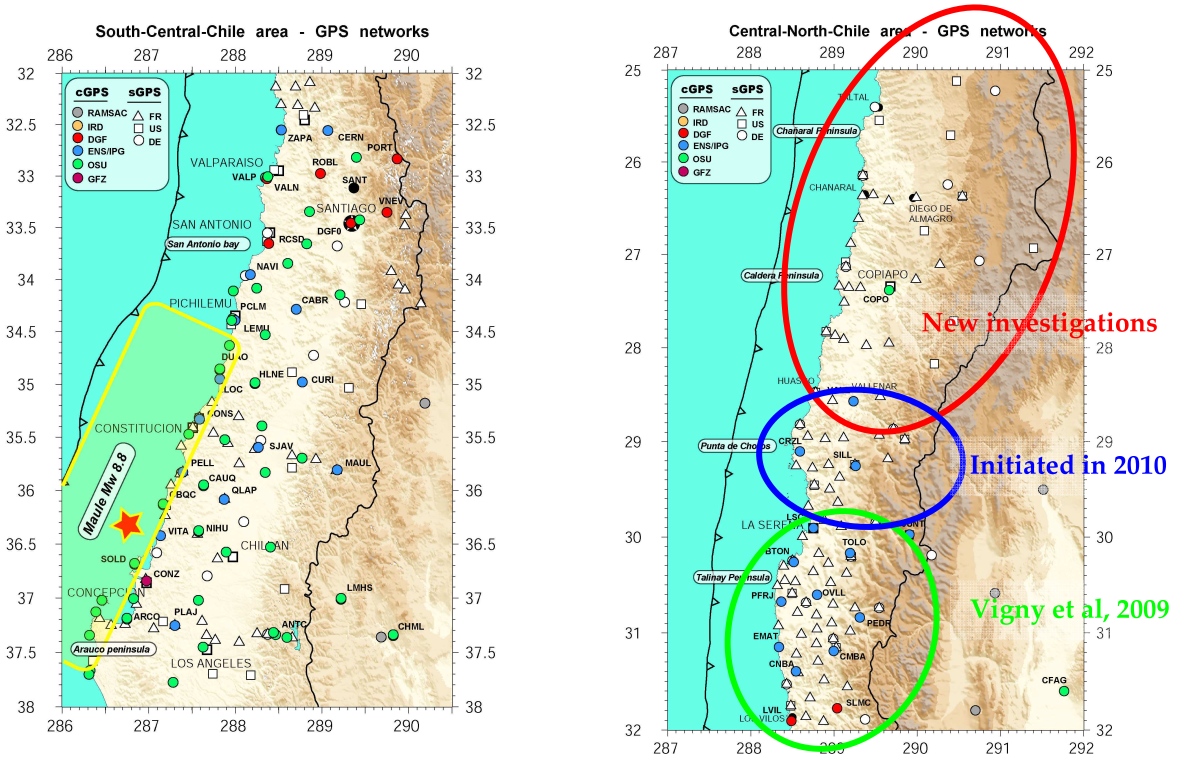


Figure 4. GPS networks (continuous and survey) in our area of interest in Chile. Maule Eq. area (left); Coquimbo/Atacama area (right). The red ellipse depicts the Atacama region with few survey benchmarks (white triangles installed by ourselves in 2011, with squares/circles corresponding to large scale CAP/SAGA networks) and almost no cGPS stations (blue, red and green dots). This shows especially well in comparison with our previous work in the Coquimbo region (Vigny et al., 2009), immediately south of Atacama (green ellipse. We initiated an extension to the north (unpublished yet) of our Coquimbo network in 2010 (blue ellipse).

For our work in Chile we designed special markers: stainless steel large bolts, sealed deep in the bedrock, on which the GPS antenna is directly screwed by means of an adaptor. This ensures precise measurements, both for the centering of the antenna and vertical measurements, guarantying quality results after few years of repeated campaigns only. We will install new cGPS stations to create a permanent network that does not exist at the moment along the Atacama segment (between 29°S and 23°S).We will extend and resurvey the entire benchmark network there every year, including large scale markers from other networks (CAP, SAGA) using state of the art instruments, techniques and methodologies. The GPS surveys will be performed at the same period of the year, each year in order to reduce seasonal artifacts. Each point is measured at least during two or three 24-hour sessions, with a 30 seconds sampling, using dual-frequency receivers and geodetic antennas ensuring high quality measurements. The survey will be conducted with a maximum number of receivers provided (at free cost) by the French INSU instrumental pool and by the LIA-MdB pool in Chile (~30 to 40 instruments in total) in order to directly measure a maximum of baselines between stations. This should guarantee a good consistency of the geodetic network. In addition, the numerous permanent GPS stations in the area will ensure a stable reference frame and help tying sites that could not be measured in a common time window.

3.3. TASK 3 SEISMIC CYCLE & POST-SEISMIC DEFORMATION MODELING WITH A 3D SPHERICAL FINITE ELEMENT CODE

Coordinator : L. Fleitout
Participants: L. Fleitout, DR CNRS-ENS, O. Trubienko, PhD student ENS, Q. Bletery, future PhD student ENS.
Collaborations: JD Garaud, chercheur ONERA, G. Cailletaud, professeur Mines-Paris-Tech

The process generating post-seismic deformation after large subduction earthquakes is still debated: Is it predominantly viscoelastic relaxation in the asthenosphere or aseismic afterslip on the subduction interface? This unsolved question affects our understanding of the whole seismic cycle, and has consequences on tectonic concepts (rigid plate and long term vs. short term velocities) and seismic hazard quantification [*Trubienko et al. 2012*]. In particular, far-fetch and long lasting viscous relaxation considerably alters what we used to call "inter-seismic" velocities and brings the need to view things in the complete seismic cycle context. Thanks to the three giant earthquakes which occurred since 2004, we now have the data to clarify this controversy. We propose here to analyze the deformations in Chile, taking advantage of the experience that we have acquired from a previous analysis of post-seismic deformation in South-East Asia following the Sumatran earthquakes: Aceh 2004 Mw 9.2, Nias 2005 Mw 8.5 and Benkulu 2007 Mw 8.7 [*Garaud et al. 2009, Fleitout et al. 2011, Garaud et al. 2012*].

With the help of a 3D finite element model, we have shown that the deformation related to relaxation in the asthenosphere can be distinguished from that due to slip on the fault plane because it is characterized by far-field (400 km to 2000km from the trench) post-seismic subsidence and by a relatively larger amplitude of far-field over near-field horizontal motions. A combination of the two mechanisms is required to fit the deformation in South-East Asia: Asthenospheric relaxation is more important for far-field deformation and explains the observed far-field subsidence. Sliding on the subduction interface generates most of the near-field (less than 150km from trench) deformation and relaxation in the low viscosity wedge generates the intermediate-field (150 to 400km from trench) deformations.

In the Sumatran case, there were very few cGPS stations monitoring the deformation since the first days after the 2004 and 2005 earthquakes. Morover, a large area over the Sunda plate is under sea so that the spatial coverage with GPS data is poor. This is also the case for Japan where only the 'intermediate-field' is very densely covered. Only in Chile we have both immediate measurements after the earthquake and a complete spatial coverage from 70 km to 3000 km away from the trench. Chile is also unique because there are data related to the long-term (50 years) response to the Valvidia earthquake of 1960 in addition to an accurate determination of the 'interseismic phase' before the Maule earthquake. Chile offers an exceptional opportunity to understand the whole seismic cycle at once.

Model and numerical methods

We will implement the same procedure than for South-East Asia deformation after the Aceh earthquake: We use the finite element code Zebulon (Ecole des Mines, ONERA, Northwest numerics). A region around the subduction zone corresponding to a portion of spherical shell extending over more than 40° in latitude and longitude and from the core-mantle boundary to the Earth's surface is discretized. The mesh is refined close to the subduction zone and includes a subduction interface with a realistic geometry. It is possible to choose the mechanical properties of each region of the mesh as well as the sliding properties over the subduction interface (with flat elements named 'éléments de zone cohésive'). We introduce elastic properties varying as a function of depth and regionally (oceans, continents, accretionary prism). We include a viscoelastic mantle (Maxwell or Burger models), a viscoelastic low viscosity wedge. We choose a finite element technique rather than 'spectral methods' because the lateral viscosity variations linked to the presence of the slab at depth or to a low viscosity wedge play an important role in the response of the model [*Pollitz et al. 2008, Trubienko et al. 2012*]. First, using the coseismic deformation (GPS and INSAR data), we invert for the coseismic sliding on the fault plane using the elastic response of our finite element model. We noticed that it was important for this coseismic slip determination to use an accurate 3D elastic structure. Then, the observed postseismic deformation is interpreted as the consequence of further slip on the subduction interface (dominant for near-field deformation) and of viscoelastic relaxation in the asthenosphere and the low viscosity wedge: The relaxation in the asthenosphere produces little motion on the stations close to the trench so that the two phenomena are rather easy to separate.

What we expect to learn from the modeling of Chile data

The general characteristics of the post-seismic deformation field (fig. 5) seem rather similar to what has been observed in South Asia after the Aceh earthquake, and a low viscosity asthenosphere will certainly be necessary to explain the far-field data. The dense near and intermediate-field data, the short-term data and also the longer-term post-seismic deformation linked to the Valvidia earthquake should allow elucidate several issues:

- It is rather difficult to distinguish relaxation in a low viscosity wedge from sliding in the deep part of the subduction interface. However, the ratio vertical over horizontal velocity in the middle-field is discriminant. The dense network of permanent GPS stations should provide pertinent data to determine the dominant mechanism.
- On a longer time-scale (several years), relaxation in the asthenosphere seems to be the dominant mechanism. However, over a short time-scale (a few months), the near-field signal is large and is usually a consequence of sliding on the fault plane [*Chlieh et al. 2007, Abstract AGU Simons*]. A short term relaxation phase (burger rheology) in the asthenosphere or in the low viscosity wedge would also induce sizable intermediate and far-field signal, perturbing the interpretation of the short-term signal, affecting in particular the depth range of the inferred slip. Because in Chile there is data in the near and intermediate-field just after the earthquake, the origin of this short-term surface deformation can be elucidated.
- The velocities just after the earthquake, 50 years after the earthquake and during the interseismic phase just before the next earthquake provide rheological constraints for various time scales. They are therefore sensitive to the various parameters of the viscoelastic (Burger or Maxwell) rheology [*Trubienko et al. 2011]*. While post-seismic data alone mainly constrain the 'short-term' viscosity. We will use post-seismic GPS data south of 38°S and pre-seismic GPS data north of 38°S to better constrain the mechanical properties of the asthenosphere.

3.4. TASK 4 SEISMIC IMAGING OF THE SUBDUCTION PLANE

Coordinator : N. Chamot-Rooke
Participants: N. Chamot-Rooke, CR CNRS-ENS, M. Delescluse, assistant professor ENS.

For the 3 mega thrust earthquakes (Sumatra, Chile, and Japan), the bulk of the data has been recorded from land stations. Yet, the fault plane that has broken is below water, and there is a clear lack of data collection right above the seismogenic zone. Preliminary deep-water observations, although scarce and spotted, have lead to question some of the concepts that seemed firmly established from the analysis of remote data. Rupture does not stop at some distance from the trench as generally inferred, but breaks all through, a surprising result that was difficult to reach using land geodetic and seismologic data. A new era has now opened for the study of these mega earthquakes at sea, both before they occur and after. Before the earthquake, pre-rupture benchmarks need to be settled, including mapping the seafloor above the seismic plane, and imaging the seismic plane at depth. Post-rupture surveys will allow quantifying where, how and how much the seafloor has been deforming during the co-seismic phase. Characterization of the friction plane before and after the earthquake, i.e. investigations through detailed imaging and local tomography using OBS (Ocean Bottom Seismometers), will open new windows on the physical processes at work at depth, such as mechanical, thermal, hydrogeological, petrographical properties of the surface break itself. Lateral variations in these fault plane properties as seen by local seismic tomography and long streamer reflection seismics may be proved crucial to understand and map locked (i.e. ready to break) versus unlocked portions of the trench.

Obtaining seismic velocities at proximity of the friction plane, i.e. immediately above and below is one of the key parameters. The technology for these studies exists, but has yet to be deployed over the major subduction planes. The strategy is to deploy a large number of OBS at the seafloor with a kilometric spacing, using a large and low frequency airgun array. Extreme pressure conditions at depth and unknown seafloor conditions at the trench are the first basic reason to deploy many instruments. Doing so, the odds to end up with dramatic acquisition gaps due to bad instrument recovery is minimized. The main reason to deploy a dense receiver array is however the new state of the art in velocity field imaging that is waveform tomography. This processing technique (discussed in the next section), recently applied to real data, is only possible with a kilometric spacing of receivers. The source spacing is always sufficient at sea because the standard has always been a maximum of 200 m.

Pools of instruments are available in a number of countries, including France, but only few groups are able to use the type of dense array that is needed here (about 100 instruments). The Japanese are pioneering in this type of deployment (“Waveform tomography imaging of a megasplay fault system in the seismogenic Nankai subduction zone”, Kamei et al., EPSL 2012). They used it in the Nankai subduction, producing for the first time a waveform tomography image that allows velocity to be mapped with a resolution of 700 m in the horizontal and 350 m in the vertical.

The standard acquisition strategy (about 20 instruments and a 10 to 15 km spacing) only allows for processing techniques involving travel times such as forward modelling (RAYINVR) or first arrival time tomography inversion (FAST, Tomo2D). Depending on the effective OBS spacing, a spatial resolution of 2 to 5 km can be reached, with a very smooth velocity field. Velocity inversions and low velocity zones at depth are usually not retrieved although they are evidences for fracturation and/or fluid circulation, as well as rocks phase change. Traveltime tomography only offers a limited resolution and is thus not sufficient to map seismic velocities around the friction plane and its neighbourhood.

Instead of traveltimes, one can use today the full-recorded seismic wavefield. The goal is to invert for phases and amplitudes of the dataset. A closely spaced receiver array is necessary to avoid aliasing, which is why the method cannot be seriously applied with less than 50 OBS. A sub-kilometric resolution can be obtained but the difficulty of the method is mainly due to the high non-linearity of the inversion. A very good traveltime tomography velocity model must thus be used as a starting model. Another way of managing the non-linearity of the waveform inversion is to use a frequency domain approach, starting with the inversion of the lowest frequency available (2Hz if a large source is used) and progressively including higher frequencies. These inversion methods are very well developed in the French community and only quality datasets are missing to fully benefit from it.

As it has been shown for Nankai, this method is able to retrieve a high-resolution velocity image of the subduction plane. It is now clear that the next step is to compare many of such profiles within a given subduction, but also between different subductions, which in both cases, has never been done. In particular, observing the difference between the high resolution velocity field of locked and unlocked portions of subductions would provide very important insights on the subduction processes leading to mega-earthquakes.

This proposal is the first step towards a new project that will ultimately lead to the deployment of about 100 OBS during a marine seismic survey.

The project schedule is the following:

1. Phase 1 (2013): establish contacts with groups that are able to deploy this new technology.
2. Phase 2 (2013-2014): choose the target with the partners (workshop)
3. Phase 3 (2014): September 2014, proposal for ship-time to the CNFE (French National Fleet Commission) / Complementary proposals by partners in their respective countries.
4. Phase 4 (2016-2017): shooting of the seismic survey if phase 3 is successful

Here we request funding only for phases 1 and 2. We need to meet the partners, choose the best target with them, evaluate the feasibility, and write the ship-time/instrumentation proposals. The identified partners so far are our Japanese and German colleagues (for the technology) and Chilean colleagues (for the target). At this stage, we seek funds to facilitate networking, meetings and workshops.

4. RÉFÉRENCES

Chlieh, M., J.P. Avouac, V. Hjorleifsdottir, et al., (2007), Coseismic Slip and Afterslip of the Great M_w 9.15 Sumatra–Andaman Earthquake of 2004, Bulletin of the Seismological Society of America January 2007 v. 97 no. 1A, [doi: 10.1785/0120050631]

Delouis, B., J.-M. Nocquet, and M. Vallée, (2010), Slip distribution of the February 27, 2010 Mw = 8. 8 Maule Earthquake , central Chile , from static and high rate GPS, InSAR, and broadband teleseismic data, *Geophys. Res. Lett*., 37, L17305, [doi:10.1029/2010GL043899].

Fleitout, L., J.D. Garaud, G. Cailletaud, C. Vigny, W. Simons, B. Ambrosius, I. Trisirisatayawong, and C. Satirapod, (2011), Modeling the post-seismic deformations of the Aceh, Nias and Benkulu earthquakes, Geophysical research abstracts vol 13, EGU 2011-6503

Garaud, J.D., L. Fleitout and G. Cailletaud, (2009), Simulation parallèle de la relaxation post-sismique dans la région de Sumatra, 9eme colloque en calcul de structures, Giens 2009, hal00399738, juin 2009 , 10pp

Garaud J.D., L. Fleitout, G. Cailletaud, C. Vigny, W. Simons, B. Ambrosius, C. Satirapod, A. Panumastrakul and I. Trisirisatayawong, (2012), Long term deformation in south-east Asia following the 2004 Sumatra earthquake, submitted to Nature

Heki, K., (2011), A tale of two earthquakes, *Science* 332, 1390 [doi: 10.1126/science,1206643]

Lorito, S., F. Romano, S. Aztori et al., (2011), Limited overlap between the seismic gap and coseismic slip of the great 2010 Chile earthquake, *Nature Geoscience*, 30 jan 2011, [doi: 10.1038/NGEO1073]

Madariaga, R., M. Métois, C. Vigny; J. Campos, (2010), Central Chile finally breaks, *Science*; 9 April 2010: 181-182. [DOI:10.1126/science.1189197].

Métois, M., A. Socquet and C. Vigny (2012), Interseismic coupling, segmentation and mechanical behavior of the central Chile subduction zone, *J. of Geophys. Res*., VOL. 117, B03406, [doi:10.1029/2011JB008736].

Moreno, M., M. Rosenau and O. Oncken,, (2010), 2010 Maule earthquake slip correlates with pre-seismic locking of Andean subduction zone, *Nature* 467, 198–202, [doi:10.1038/nature09349].

Moreno, M., D.Melnick, M.Rosenau, et al., (2012), Toward understanding tectonic control on the Mw 8.8 2010 Maule Chile earthquake, *EPSL,* 322, pp 152-165 [DOI:10.1016/j.epsl.201201.006]

Pollitz, F. F., B. Brooks, X. Tong, et al., (2011), Coseismic slip distribution of the February 27, 2010 Mw 8.8 Maule, Chile earthquake, *Geophys. Res. Lett*., 38, L09309, doi:10.1029/2011GL047065.

Ruegg, J.C., et al., 2009, Interseismic strain accumulation measured by GPS in the seismic gap between Constitucion and Concepcion in Chile, *PEPI,* 10.1016/j.pepi.2008.02.015.

Ruiz, S**.**, and R. Madariaga, (2011a). Determination of the friction law parameters of the Mw 6.7 Michilla earthquake in northern Chile by dynamic inversion. *Geophys. Res. Lett.,* 38, L09317, [doi:10.1029/2011GL047147].

Ruiz, S**.**, E. Kausel, J. Campos, et al., (2011b). Identification of High Frequency Pulses from Earthquake Asperities Along Chilean Subduction Zone Using Strong Motion. *Pure and Applied Geophysics*, *168, (1-2), 125-139.*

Tong, X., D. Sandwell, K. Luttrell et al., (2010), The 2010 Maule Chile earthquake: downdip rupture limit revealed by space geodesy, *Geophys. Res. Lett*, 37, L24311, [doi:10.1029/2010GL045805].

Trubienko, O., L. Fleitout, J.-D.Garaud et al., (2012), Interpretation of interseismic deformations and the seismic cycle associated with large subduction earthquakes, Submitted to *Tectonophysics*, 2012

Udias, A., R. Madariaga, E. Buforn et al., (2012), The large Chilean historical earthquakes of 1647, 1657, 1730 and 1751 from contemporary documents, *Bull. of Seismo. Soc. of Am.*, Vol 102, N°4, [doi: 10.1785/0120110289]

Vigny, C., A. Rudloff, J.C. Ruegg, et al., (2009), Upper plate deformation measured by GPS in the Coquimbo gap, Chile, *PEPI*, Vol 175, issue 1-2, June, 10.1016/j.pepi.2008.02.013.

Vigny, C., A. Socquet, S. Peyrat, et al., (2011), The 2010 (Mw 8.8) Earthquake of central Chile, monitored by GPS, *Science*, 332, 17 june 2011,pp 1417-1421 [DOI:10.1126/science.1204132].

5. TASKS SCHEDULE, DELIVERABLES AND MILESTONES

All tasks will be moving simultaneously: thanks to existing networks and surveys made in 2010/2011, initial data needed for the seismological studies and the numerical modeling are already available. Thus, methodological work concerning the 3D finite element model for example will start right away and tests will be conducted since the very first year of the project. Then, data produced every year by the GPS task will be assimilated yearly (for example: time series available for post-seismic series).

Deliverables & milestones

1. Data base of geodetic measurements in Chile. All GPS data acquired within this project will be archived and distributed by a centralized system at INSU/CNRS (GPSCOPE).
2. Combined solution with other international team's data (coordinates and velocity field over hundreds of points) in a common reference frame at the scale of the continent.
3. Precise quantification of the Nazca-South America convergence rate
4. Quantification of the amount of shortening available for the orogene of the Andes and current intra-plate fault motion.
5. Assessment of seismic hazard on distinct segments of the subduction and intra-plate faults
6. Global studies on the physics of the seismic cycle and mantle rheology
7. Publications in international research journals

6. PROJECT TEAM

6.1. ENS – PERMANENT POSITIONS

Monitoring crustal deformation along subductions (using GPS and seismology) is an identified project of the "laboratoire de Géologie de l'ENS" (ranked A+ by AERES) research plan, and of the IDEX PSL* Environment and Earth science component.

C. Vigny (project PI and coordinator of task 2), is a renown GPS geodesist, involved in long-term collaborations with DGF at U-Chile for the last decade. He is associate director of the "laboratoire de Géologie" at ENS and co-director of the Chilean-French international

Laboratory "Montessus de Ballore". He has been developing GPS activities (cGPS networks, benchmarks installation, measurement campaigns, data processing, teaching) in Chile since 2002.

Raul Madariaga (coordinator of task 1), is a renown seismologist (award of the Stephan Muller medal of the European geophysical Society – 1999 and the Harry F. Reid medal of the Seismological Society of America – 2004). His specific knowledge of subduction earthquakes and his joined theoretical and data approach of source mechanisms, his long time involvement with research projects in Chile, and his network of students in Chile are extremely valuable to the project. Madariaga is currently professor at ENS, and will have an Emeritus status for the coming 5 years.

Luce Fleitout (coordinator of task 3), works on thermo-mechanical modeling of the solid Earth (tectonic deformation, forces exerted on plates, Geoïd and mantle convection). In recent years, she has been interested in the viscoelastic response of the Earth due to loads (post-glacial rebond) or to large earthquakes. Through a collaboration with ONERA and Mines-Paritech, she has implemented a 3D finite element code able to tackle viscoelastic or non-linear responses with strong lateral mechanical heterogeneities.

Nicolas Chamot-Rooke (coordinator of task 4), has been heading a number of marine cruises using various geophysical tools to image active faults from surface (multibeam mapping, sonar and sub-bottom profilers) to depth (long-streamer seismic reflection and refraction). The project will be benefit from his experience at sea over other subduction zones (SE Asia and Mediterranean subductions).

6.2. ENS – TEMPORARY POSITIONS – JUSTIFICATION OF POSTDOC

2 PhD students will work on this project:

- O. Trubienko (Advisor L. Fleitout) is currently working on the modelling aspects, realizing finite-element 2D studies that will set the frame for this project's work. She will start the 3D work during her 3rd and last year.
- Q. Blettery is candidate for a PhD at ENS (Advisor C. Vigny). He should start October 2012, for 3 years, in line with this project schedule. He will contribute to tasks 2 and 3 by participating to the GPS field work, data processing and modelling.

We request a 36- month post doc (3 years) to contribute to the project essential goals. First, man power is needed to process, analyze and model the cGPS static data. This is not an easy task given the number of stations. Specific strategies will have to be defined. Second, since there are many earthquakes of magnitude 6-7 along the Chilean trench, we will have many opportunities to analyze co-seismic high rate GPS data. Methods will be improved (processing fine tuning, filtering, etc…). Therefore, ideally, the post-doc will be someone with dual expertise, on GPS data processing in general and on source seismology, to contribute to tasks 1 and 2 simultaneously. We expect much from this work direction, major brake-through are expected in this area.

The search for the Post-Doc candidates will start immediately at the initiation of the project, but the hiring will start at the beginning of the second year only, allowing us a full year for a successful search. The 3-year post doc will also end well ahead of the project termination (end of year 4) so that we will have a full year to incorporate his/her work in the project deliverable.

7. BUDGET DETAILS

Task 1 : Sismology

This task cost is essentially based on networking between France and Chile

• 1 yearly visit of 1 month to Chile for a French participant	4 300	x 5
• 1 yearly visit of 1 month to France for a Chilean participant	4 300	x 5
(Flight = 1300€ +Per diem (100€/day, x30 = 3000€)		
TOTAL for 5 years	43 000 Euros	

Task 2 : Spatial geodesy (GPS)

This task cost is based on field work (acquisition of campaign data, CNRS pool of mobile receivers accessible at no cost), acquisition and installation of equipment (new cGPS stations) and maintainance, and manpower (3 year post-doc).

• 1 yearly GPS campaign (4 teams x 2 persons – 15 days)	18 700	x 5
a. 4 Plane ticket (France – Chile) = 1300x4 = 5200€		
b. 4 car rentals (4x4 camionettas) = 1000x4 = 4000€		
c: gas (400l x 4 x 1E) = 1600€		
d: per diem (50E/day x 2 x 4 x 15) = 6000 €		
e: small consumables (batteries, tools, markers, glue, ...) = 1000€		
f: equipment transportation (freight, customs carnet ATA, taxi, etc…) = 900€		
• Acquisition of 10 GPS complete receivers (Unit price 5 750 €)	57 500	
Total for 5 years	151 000 Euros	

Task 3 : Geophysical modeling

• Computers, licence for the 'meshing' software and other small supplies	3 000	x 5
Total for 5 years	15 000 Euros	

Task 4 : seismic imaging

This task cost represents only networking and proposal building

• Yearly travels to and from Germany and Japan	3 000	x 2
• 1 international workshop of several days at ENS	10 000	
Total for 5 years	16 000 Euros	

All Tasks:

• 3 year post-doc (49 200 yearly salary based on French/CNRS standards)	147 600
• Publications : ~10 at 1000€ (based on 5 years of the group's publications, see Annex document)	10 000
• Congress participation: 1 person per task per year at AGU,EGU)	25 000
• Laboratories Overhead (4%)	15 000
Total for 5 years	197 600 Euros

Grand Total	**422 600 Euros**