Important
Ce document ne doit pas dépasser 30 pages, dans la mise en page et la typographie fournies par l'ANR. Ce point constitue un critère de recevabilité de la proposition de projet. Les propositions de projet ne satisfaisant pas aux critères de recevabilité ne seront pas évaluées.

Acronyme / Acronym	**MEGA-CHILE**		
Titre du projet	Mega-séismes au Chili: Exemple de Maule en 2010 (Mw 8.8) et implications sismo-tectoniques		
Proposal title	Megathrust earthquakes in Chile: 2010 Maule Earthquake (Mw 8.8) and sismo-tectonic implications		
Comité d'évaluation/Evaluation Committee	SIMI-6		
Type de recherche / Type of research	☒ Recherche Fondamentale / Basic Research ☐ Recherche Industrielle / Industrial Research ☐ Développement Expérimental / Experimental Development		
Coopération internationale (si applicable) / International cooperation (if applicable)	☒ OUI ☐ NON		
Aide totale demandée / Grant requested	257 546 €	**Durée du projet / Projet duration**	36 mois

8. ANNEXES (DEPOSEES SUR LE SITE DE L'ANR) :

1. RESUME DE LA PROPOSITION DE PROJET / EXECUTIVE SUMMARY

During the last decade, the Aceh (2004, Mw>9.1), Maule (2010, Mw 8.8) and Tohoku-Oki (2011, Mw 9) earthquakes dramatically shed light on the seismogenic and tsunamigenic hazard due to subduction megathrusts. The recent Japan event revealed fundamental misunderstandings on the mechanics of the subduction and on the way mega-events may repeat in time and space, leading to a failure in correctly assessing and forecasting hazards. To significantly move ahead on the understanding of the mechanics of megathrust earthquakes at different time scales we propose to study the Mw 8.8 Maule mega earthquake of February 2010 in every possible detail and to put it into the perspective of the geodynamics of the Andean margin. This project, submitted to "ANR blanche" in January 2011, was positively evaluated and selected by the comittee, but remained on the complementary list. Here, we submit an updated version of the project, taking into account the advances made since one year and the few recommendations transmitted by ANR.

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 20 years, doing research that helped to set the frame for a successful study the 2010 event. This will be used as a starting point to improve our approach of active subduction: as we conduct our study of the Maule earthquake in south-central Chile, we will increasingly focus our attention to adjacent regions that are now approaching the end of their respective seismic "cycles". Foremost of them are the "N-Chile gap" and the Coquimbo region in earlier stage in the preparation of a mega-earthquake. These observations will be translated into models of deformation of the active margin to understand how short term strain due to the seismic cycle combines with finite strain, and what are the implications in term of segmentation.

For the specific study of the Maule earthquake we have acquired a substantial coseismic data: campaign GPS, high dynamic range accelerograms, classical strong motion instruments, 1Hz continuously recording GPS antennas. This unique data set will be used to study the rupture process of the earthquake. We hope to explain why such a large event produced moderate strong motion. Is this a unique feature of this event, or is it typical of most megathrust earthquakes? We need to study the slip distribution of the main event and understand why the aftershocks stretched over an area substantially longer than the main rupture. The aftershock series did not contain any events larger than Mw 7.1, a puzzling feature indeed. We dispose of aftershock recordings obtained by the CNRS-INSU researchers and our foreign and Chilean colleagues. Are these aftershock uniformly distributed or highly concentrated in a few asperities as preliminary results seem to suggest?

With the 2011 Japan event, Maule 2010 is the only mega-earthquake that occurs in a closely surveyed area. Published studies pointed out that the interplate zone was completely locked not only in 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 and shows that the whole subduction plane broke for about 500km along strike, and from 40km depth to its very

shallow parts near the trench. A conclusion also reached for Japan, which 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. This problem is closely related to that of segmentation; 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 and Talinay peninsulas are long standing features where earthquakes seem to stop or slow down as they reach them. We plan to explore their role using tectonic, geological and geodetic methods.

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. CONTEXTE, POSITIONNEMENT ET OBJECTIFS DE LA PROPOSITION / CONTEXT, POSITION AND OBJECTIVES OF THE PROPOSAL

2.1. CONTEXTE ET ENJEUX ECONOMIQUES ET SOCIETAUX / CONTEXT, SOCIAL AND ECONOMIC ISSUES

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 astonishing ones being the 2004 Mw 9.2 Aceh earthquake in northern Sumatra, and the recent Mw 9 2011 earthquake in northeastern Japan. At the difference of 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. Several thousands of people were killed by the earthquake and the tsunami, 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 the way 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. Finally, 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 identified recently broke, two other large segments approach the end of their respective seismic "cycles".

2.2. POSITIONNEMENT DU PROJET / POSITION OF THE PROJECT

Since the end of the 1980s we have been working actively on the Chilean subduction zone. Over the last decade we have been developing a monitoring infrastructure based on arrays of many continuous GPS stations (~50), seismological stations (broad band, accelerometers), tilt meters, and repeated measurements on numerous geodetic benchmarks (>300). Thanks to all these studies, 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 and all calculations show that it is very mature.

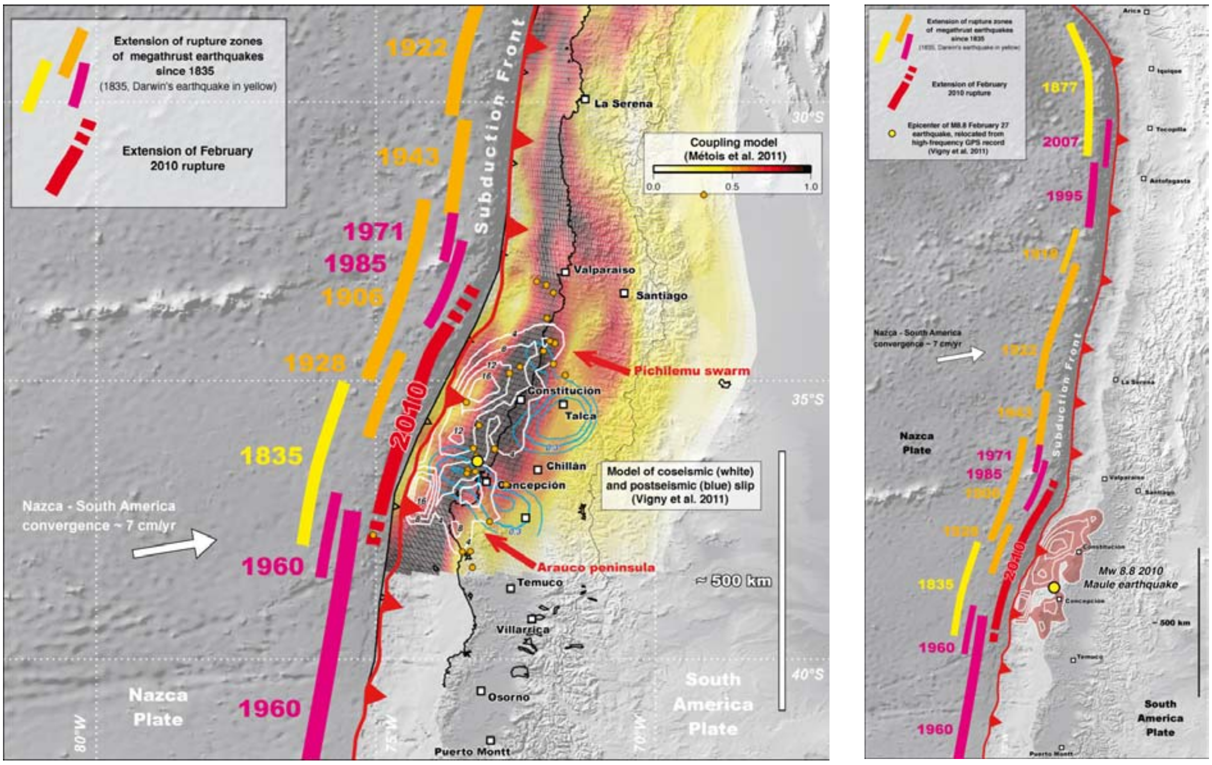

Figure 1. :Left box: The Maule earthquake of 27 february 2010. Coupling inverted from pre-seismic GPS data (Métois et al. 2011), slip distribution inverted from co-seismic geodetic (GPS+INSAR) data (Vigny et al. 2011). Historical earthquake segmentation compiled by R.Lacassin. Right box: the localization of the earthquake on the larger Chilean subduction trench.

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., 2011; Vigny et al., 2011; Métois 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. The LIA operates and

maintains the permanent networks (cGPS, multi-sensor seismological stations) with CNRS & U-Chile funding (https://www.lia-mb.net).

- 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
  5. IRIS (Beck et al.) : installed ~60 seismographs in Maule epicentral area.

  We have a serie 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 groups 1-4 in the "annexe" documentation.
- 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. ÉTAT DE L'ART / STATE OF THE ART

Despite little paleo-seismological information, the seismicity in Chile is relatively well-known, based on historical data gathered by historians and seismologists (Montessus de Ballore, 1911-1916, Lomnitz, 1972, Comte and Pardo, 1991). From these works, the Chilean subduction appears as fragmented in a number of segments (~ 100-200 km long and 50-100 km wide) which can host repeated great earthquakes and occasionally produce megathrust earthquakes when the rupture manages to propagate between different segments. The segments along the subduction zone in Chile are at different stages of their seismic cycle along the coast and have their own geometrical and mechanical characteristics. In the early 1970s and 1980s, several authors (Kelleher et al., 1973; McCann et al., 1979) divided the subduction zone into regions where great earthquakes of very long lengths occur and regions where only moderate large earthquakes occur. Seismic gaps were defined as regions that had not experienced a large earthquake for the last 30 years. In hindsight this period of time is too short to characterise the seismic activity produced by the Chilean subduction (Cisternas, 2005). The seismic gap concept was originally proposed as a long-term forecast of major earthquakes (see, e.g. McNally 1983; Nishinko, 1985). A long-standing discussion ensued as to whether those gaps are semi-permanent features of the subduction limited by barriers well attested in the surface geology and geomorphology, or simply reflect the largest events in recent history (Comte et al., 1986; Madariaga, 1998): An important issue with regard to seismic hazard assessment in Chile.

Three segments in Chile, e.g. Central Chile (Constitución and Concepción 35°S-37°S and Coquimpo-Illapel 30°S-32°S) and Northern Chile (Antogasta and Arica 18°S-27°S), were identified and instrumented in collaboration between the Chilean and the French teams, e.g. with the support of French ANR-CATT projects, Chilean CONYCIT projects, and the CNRS/U-Chile association through the international associated laboratory (LIA) "Montessus de ballore".

In previous proposals, two of these segments were identified as major and mature gaps: Constitución-Concepción and Antogasta-Arica.

- The first one ruptured on 27 February 2010 with a Mw 8.8 earthquake, 175 years after the 1835 earthquake described by Darwin and Fitzroy in the area, and several decades after it had been surrounded by subduction and intraplate earthquakes (1960, 1985, 1937). It is now experiencing after-slip and post-seismic relaxation.
- The second one did not experience any large rupture since the 1877 Iquique earthquake, but has been surrounded again by subduction and intraplate events over the last decade (1995, 2001, 2005, 2007). It is still going under inter-seismic accumulation, but for how long ?

A third segment (Coquimbo-Illapel) was identified in a slightly different situation: the last subduction earthquake there was in 1943 ("only" 65 years ago), but it had been the locus of an increasing seismicity (with a dozen of significant earthquakes of magnitude between 6 and 7), over the last decade, again after an intraplate earthquake (Punitaqui, 1997, Mw 7.3).

The fact that the three segments are at different stages of their evolution (post-seismic for Maule, pre-seismic for N-Chile, probably in-between for Coquimbo-Illapel) should allow us to calibrate the visco-elastic models of the subduction taking into account the full earthquake cycle with all its components and spatio-temporal interactions. In this proposal, we propose to focus our studies in these regions where a huge amount of high quality observations have been and are continuously recorded allowing us to improve our physical understanding of the spatio-temporal seismic activity and deformation of subduction segments, in relation with their geometry and structure, as well as their stability.

2.4. OBJECTIFS ET CARACTERE AMBITIEUX/NOVATEUR DU PROJET / OBJECTIVES, ORIGINALITY AND NOVELTY OF THE PROJECT

The 2010 Mw8.8 Maule earthquake raises challenging questions related to the nucleation and the propagation of a megathrust earthquakes, the frequency contents associated to such large subduction events, 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 deformation. 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)?

A second objective is to improve our understanding of the patterns of earthquakes on the Chilean trench. The asperity model proposed by Kanamori and McNally (1982) and Ruff (1992) is probably the simplest self-consistent paradigm to start with. Small/moderate earthquakes represent failure of individual asperity while great earthquake represent the collective failure of several asperities. The Valparaiso (1985) or Tocopilla (2007) earthquakes suggest that the asperity sizes may be smaller than the inter-plate width. Maule 2010 is a great earthquake which 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 in Chile, as well as non-volcanic tremors (Roggers and Dragert, 2003; Obara et al., 2004; Shelly et al., 2006), observed in Japan, Cascadia and Mexico, often in conjunction with slow slip events, strongly suggest the importance of seismic/aseismic interactions between asperities. We want to understand: the asperity origin in relation with deep structures and variations of plates 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 cGPS, seismographs, strong motion, and InSAR. Such observations will be available for our project, thanks to the rapid deployment of hundreds of instruments in the Maule area and around. For InSAR, to extract the best inter-seismic information, new methodologies will have to be developed. We are confident that recent developments to which we contributed (Cavalié et al. 2007, 2008; Doin et al. 2009, Jolivet et al., 2011), will allow us to overcome the difficult technical issues like correction of topographic or tropospheric effects and the flattening of large images in the context of large-scale deformation.

A third objective is to improve our understanding of the segmentation of the subduction zone in Chile. Understanding barriers between segments and their stability in space and time is a challenging issue for mega-thrust earthquake seismic hazard assessment. Ruptures of the 1995 Antofagasta (Ruegg et al.), 2007 Tocopilla (Bejar et al.), and probably the larger 1877 Iquique, earthquakes have been stopped by structural complexity 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 (1922 Mw 8.4 and 1943 Mw 7.9). Like Mejillones, Arauco is marked with evidences of both quaternary and contemporary uplift, Tallinay – like many other smaller peninsulas in Chile, has not been studied yet. However, paleo-seismological information is still relatively scant, and most of our knowledge is biased by the relative shortness of the historical data versus a seismic cycle of many centuries. In order to tackle this problem one must integrate geology, geomorphology, geodesy and seismic profiles together with paleo-seismology. All these are now available in central and North Chile.

3. PROGRAMME SCIENTIFIQUE ET TECHNIQUE, ORGANISATION DU PROJET / SCIENTIFIC AND TECHNICAL PROGRAMME, PROJECT ORGANISATION

3.1. PROGRAMME SCIENTIFIQUE ET STRUCTURATION DU PROJET / SCIENTIFIC PROGRAMME, PROJECT STRUCTURE

The MEGA-Chile project is built upon the occurrence of the Mw8.8 Maule earthquake of 27 February 2010 and the analysis of the data gathered at the occasion of the post-seismic intervention that was conducted immediately after in March 2010. This mega-thrust event broke one of the two seismic gaps we identified on the Chilean subduction, one in central Chile (that finally ruptured), one in North-Chile (still waiting for a mega-event), both instrumented by our team since several years. Just after the Maule event, we installed a seismological network, an array of cGPS stations, and made geological field work in and around the epicentre area. A huge dataset have been, and will continue, to be collected with the support of CNRS-INSU through the LIA "Montessus de Ballore" and in the framework of an intense international cooperation (GFZ, Caltech, OSU, U-Liverpool, IRIS, UNAVCO). Our program is based on the analysis of this 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 earthquake 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 and InSAR); Task 3 will document and model deformation of the upper-plate, due to structural complexities at the subduction interface, and their relation with segmentation and coupling; Task 4 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.

3.2. MANAGEMENT DU PROJET / PROJECT MANAGEMENT

As we are already acquiring most of the data, their analysis and modeling will thus begin without delay at the onset of the project. Therefore, we will be able to obtain and publish results very rapidly in peer-review international journals in seismology, geophysics, tectonics and earthquake engineering. These results will also be presented every year in international meetings in Geophysics like the EGU and the AGU, as well as in Latin American meetings. Attention will be paid to send Chilean and French young researchers and students participating to this project at those meetings and we will also have strong interaction with Chilean colleagues collaborating to the project.

3.3. DESCRIPTION DES TRAVAUX PAR TACHE / DESCRIPTION BY TASK

3.3.1 TÂCHE 1 / TASK 1 SEISMOGNEISIS AND MULTI-SCALE, MUTLI-FREQUENCY SLIP PROCESSES ON THE INTERPLATE SURFACE IN THE REGION OF THE MAULE 2010 MEGATHRUST EARTHQUAKE

Coordinator: J.-P. Vilotte
Participants: C. Satriano, N. Poieta, E. Kirany, P. Bernard, N. Shapiro, S. Peyrat, J. Ruiz
Collaborations : L. Rivera (IPG Strasbourg), T. Monfret (Geoazur), J. Campos (DGF)

For seismologist, the rare occurrence of destructive megathrust earthquake raises two major questions: how big can an earthquake grow during a dynamic rupture; and how will its destructive effects scale with this growth. The first relates to the ability of major locked asperities of the interplate to interact and trigger each other in a cascade rupture process. The second, at the lowest frequencies (periods > 10s) is linked to major shallow slip aperities (~ 10 – 100 km) and tsunami hazard; at the highest frequencies (< 1s) is linked to the interaction between small-scale (< 5km) geometry or strength heterogeneities and to the generation of strong ground acceleration. Precise location of major slip asperities and small-scale high-frequency sources on the plate interface during major ruptures is of primary importance for a better understanding of these processes. This must also be complemented by post-seismic (afterslip, aftershocks) and inter-seismic analysis (plate coupling and lithospheric rheology), combining geodesy, seismology and 3D structural/thermal models.

In this project, we plan to work along two lines: (1) investigation of the along-dip and down-dip segmentation of the low frequency slip and high frequency radiation during the Maule rupture; (2) investigation of the northern termination of the Maule earthquake, and its potential overlapping of the Valparaiso (7.9, 1985) ruptured zone. The main objective is to better understand the physical and geometrical parameters controlling the seismogenic processes of mega-thrust faults, and of their coseismic radiation.

This task is built upon previous works in that direction obtained within the LIA Montessus de Ballore and the international post-seismic teams. In summary:

1. The static part of the 2010 Maule rupture, constrained by geodesy (eg Vigny et al., 2011) defines two main asperities, mostly offshore, cumulating most of the moment, and extending far towards the trench. Teleseismic inversion studies suffer from a lack of resolution, due to the complexity of the kinematic rupture pattern (bilateral rupture,

variable velocity...). Presently no reliable large-scale, low frequency (LF) image of the rupture is available and the precise limits of the main asperities still remain uncertain.

2. Back-projection of high frequency (HF) waves radiated during the main shock, using beam-forming techniques on large-scale teleseismic array (USArray) (e.g., Satriano et al., EGU 2011, AGU 2011; Kiser and Ishii, 2011)) show a dominance of high frequency sources at the down dip limit of the large slip asperities. This remains to be confirmed - and refined by the use of other teleseismic arrays – and analysed together with the after-slip distribution. The method of back-projection – embedded in the coherent interferometry techniques - remains to be carefully calibrated using well located aftershocks, and improved with a better physical understanding of the far-field coherent radiation in terms of fault rupture processes.
3. The earthquake appears to be rather depleted from high-frequency radiation, (eg. Ruiz et al, 2012) with little destructions and "moderate" reported acceleration levels (0.2-0.3 g), typical of a magnitude 8.0 (and not 8.8) especially in the northern termination of the rupture. The radiation capabilities of the various areas of the 2010 surface rupture remains to be more precisely defined.
4. Our analysis of the 2007 Tocopilla (Chile) (Peyrat et al., 2010) and 2011 Tohoku (Japan) (Satriano et al., 2011) thrust earthquakes brings some insight for the Maule event: the different locations of the HF and LF radiation sources for the Tohoku event may reflect a different role of the interplate surface, possibly due to the presence of a strong mantle wedge at these depths. For Tohoku, the rupture of the deeper part, corresponding to the HF sources, has triggered the rupture of the shallower, low frequency major asperity offshore - associated to more than 90% of the total moment release and to the tsunami source. Historical interplate earthquakes (M=7 to 8) located at depth near the area of HF radiation from the Tohoku earthquake may be seen as equivalent to the Tocopilla and eventually the Valparaiso earthquakes, having failed to propagate upwards towards the trench. The relevance of such a model to the Maule 2010 earthquake remains to be analyzed.
5. Recent studies of the first months aftershocks of the Maule (Rietbrock et al., 2011; Lange et al., 2011, Fig A1), provide interesting results of the location and the distribution of these aftershocks along the ruptured segment and have identified clusters and repeated earthquakes associated in particular to the northern part of the ruptured zone. The locations and the patterns of these aftershocks remain to be refined and will allow calibration of the back-projection and relocalisation of the Valparaiso earthquake.
6. The rupture area of the Valparaiso earthquake (1985, M=7.9) remains uncertain as well as the exact northern extension of 2010 Maule ruptured area, and may be overlapping. Potential locked asperities, or a possible weakly coupled interface between the two ruptures zones, remain to be investigated. The 1985 rupture area could thus be an isolated asperity – in which case the next large earthquake may take one more century to build up – or could be limited to the deepest part of an area locked towards the trench (similarly to the Tocopilla 2007 event) – in which case this region would be under the threat of a large mega-thrust in the coming decades. This area thus deserves a particular attention, owing to its vicinity to large cities (San Antonio, Valparaiso, and Santiago).

Large Seismological databases are available today for this study:

- Teleseismic waveforms of the USArray and of the VEBSN array, for application of the back-projection techniques on the Maule 2010 main shock and for their calibration using well located aftershocks.
- Post-seismic database - with continuous waveforms and triggered events from the 142 stations of the post-seismic field survey, - deployed by Chilean, French, USA, and German institutions making The Maule aftershocks sequence one of the best-observed mega-thrust aftershock sequence to date. In particular this unique data set will be used to develop coherent interferometry techniques – array and array of array techniques - for the analysis of the broadband postseismic events.
- Existing catalogues of aftershocks (simple and double difference) will be available for this study through collaboration with the University of Liverpool (A. Rietbrock) and the GFZ (D. Lange and F. Tillman)
- Local and teleseismic records for the 1985 Valparaiso earthquake, and its main aftershocks (see for example Mendoza et al., 1994), as well as of other events in the Valparaiso area, will be available for this study, in particular through collaboration with T. Monfret (Geoazur, Nice) and the DGF team (Universidad de Chile).

Based on all these elements we define 2 main subtasks, divided in several items

Subtask 1.1 Analysis of the main rupture zone of 2010 (from co- and post-seismic records)

Part 1 - Coseismic records

HF source imaging (C. Satriano, E. Kirany, J. Ruiz; S. Peyrat, J.P. Vilotte and P. Bernard): We will use jointly the USArray and the European stations for applying the back-projection technique. Based on the Maule data, we will improve the methodology by several means: calibrating the method with moderate magnitude events; frequency dependent resolution analysis; methods for deconvolving the image from the array geometrical imprint; probabilistic quantification of the radiated energy. We will also test the method with direct modeling and inversion of synthetic, stochastic extended sources (for example from k-square source models). Direct modeling of high frequency generation will also allow to test the consistency of the back-projected sources of Maule with the few relevant local strong motion records (free field, rock sites).

LF source imaging (E. Kirany, V. Dionicio, J.P. Vilotte, P. Bernard): We will improve the location of the low frequency sources, by using the HF space-time locations from back-projection as a proxy for the rupture front propagation (following Satriano et al., AGU 2011). This will stabilize the standard teleseismic bodywave inversion methods, and hopefully help them to converge towards a more constrained kinematic, low-frequency solution.

High-rate GPS and strong motion (S. Peyrat, P. Bernard, C. Vigny): We propose to use data on low to intermediate frequency radiation in the near and regional field from continuous GPS motograms (Fig A2) and high frequency signals from some high dynamic range accelerometers, to invert the complete space and time fault displacement of the Maule earthquake and to study the dynamic behaviour of the rupture.

Part 2 - Postseismic and Interseismic versus Coseismic records

We will investigate a possible link between the aftershocks characteristics (GR distribution, space-time clustering, interaction and diffusion, multiplets …), and the various modes of slip or activation on the interplate surface.

Aftershocks and the 2010 coseismic radiation (E. Kirany, N. Poieta, C. Satriano, P. Bernard): The sources of HF and LF radiation, as well as the non-radiative ones, will define various areas, off shore or at depth, which could be correlated with different aftershock populations. Identified area of post-seismic slip may also define different classes of aftershocks. In this context, the search for multiplets and their characterisation for characterizing the interface properties and state will bring valuable information.

Integration of the results (E. Kirany, C. Satriano, J.P. Vilotte, P. Bernard, C. Vigny): The seismological – HF/LF radiation segmentation, aftershocks - and the geodetic results – co-seismic and after-slip - will be integrated within a global analysis including the geometry and rheology of the interface, for proposing a qualitative model of the interface properties and of its spatial variations in relation with the subduction structures.

Subtask 1.2 Analysis of the rupture northern area (of Valparaiso) and the 1985 rupture

The 1985 rupture area revisited (E. Kirany, N. Poieta, J.P. Vilotte, P. Bernard): We will relocate the centroid of the 1985 event using well located aftershocks of the Maule 2010 event. We will also attempt to invert the W-phase of this event, in collaboration with L. Rivera (IPG Strasbourg) to better constrain its low frequency content. We will relocate similarly other large earthquakes of the area.

Study of 2010 aftershocks and background seismicity in the northern region (N. Poieta, C. Satriano, J.P. Vilotte, P. Bernard): We will look in particular for multiplets, which could be indicative of surfaces of stable slip, and hence of low coupling.

Search for tremors and LFEs with the regional post-seismic antenna (N. Poieta, C. Satriano, P. Bernard, N. Shapiro, J.P. Vilotte): The two subarrays will be used as antennas for identifying and analyzing possible weak or emergent seismic events like tremors and LFEs (low frequency earthquakes). These could be diagnostic of transient creep in the deeper part of the interplate contact.

3.3.2 TÂCHE 2 / TASK 2 SPATIAL GEODESY

Coordinator : Christophe Vigny
Participants : C. Vigny, DR CNRS-ENS, M.P. Doin, CR CNRS-ENS, M. Métois, PhD student ENS-IPGP, R. Grandin, PostDoc, Ducret G., PhD student, C.Rioux, field engineer ENS, A. Delorme, GIS engineer IPGP
Collaborations : J. Campos, D. Carrizo (U de Chile); A. Socquet (Isterre)

The objective of this task is to use spatial geodesy tools (GPS and InSAR) 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 the now most mature gap of the entire South American subduction: the North-Chile gap.

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 1). 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. trench and to make the link with the geometry of long-term segmentation and structural complexities, subject addressed in Task 3.

Co-seismic. In the case of an earthquake during the 3 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:

a) performing yearly GPS campaigns on a dense but large network covering the entire area of interest
b) systematically processing SAR images over long period of times in specific areas

Those two processes are complementary: GPS gives the ultimate precision, InSAR (when available and coherent) provides the spatial resolution. Both will take advantage of the existence of a large scale cGPS network, which will provide an accurate reference frame for GPS campaign measurements and reference points -possibly ionospheric and tropospheric corrections- for InSAR.

Subtask 2.1 : GPS measurements

We will use the existing networks (~170 markers – Fig A6-8) made of:

- the original networks installed in north Chile (1st and 2nd regions of Chile, Arica and Antofagasta) in the early 1990's (~40 markers), complemented over the years (~20 markers)
- the network installed/measured in the 4th region of Chile (Coquimbo) in the years 2004-2011 (~60 markers),
- new markers we installed/measured in the 3rd region of Chile (Atacama) in 2010/2011 where almost no measurements had ever been done (~30 markers),
- the newest markers we installed/measured in the 1st region of Chile (Arica) in June 2010 (~20 markers).

These numerous markers design a small scale network, within the large scale cGPS network operated by the LIA "Montessus de Ballore" (50 cGPS stations), over most of the northern part of the Chilean trench that has not ruptured yet: from Santiago to Arica. All new markers since 2000 are special bolts, sealed in the bedrock, on which the GPS antenna is directly screwed. This ensures precise measurements, both for the centering of the antenna and vertical measurements, guarantying quality results after a few years of repeated campaigns only.

We will resurvey the entire network 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.

Subtask 2.2 : InSAR time series

Multi-temporal InSAR studies have shown the potential of InSAR to detect interseismic deformation across strike-slip faults (Wright et al., 2001, 2004, Taylor et al., 2006, Cavalié et al., 2008) and, more rarely, of the overlying plate of subduction (Chlieh et al., 2004; Bejar Phd Thesis). To increase the signal to noise ratio while detecting small signals (a few mm/yr) with large spatial wavelength, the InSAR data were averaged both in time and space, leading to an average interseismic signal. One obtains an average slip-rate on a fault below a locking depth, the physical meaning of which remains poorly understood. One challenge consists in the measurement of spatial (along-strike) and temporal variations of the surface strain, optimizing the use of the available SAR data archive. The second challenge is to extend multi-temporal InSAR analysis to non optimal conditions (vegetated area, large relief, sparse data set). Recent methodological advances, specifically addressing these challenges, have been assembled in the evolving NSBAS processing chain (Doin et al., 2011, ANR-EFIDIR project). The chain includes corrections of stratified atmospheric delays based on empirical phase versus elevation relationships (Cavalié et al., 2007) or on global atmospheric models

(Doin et al., 2009, Jolivet et al., 2011a) and corrections of local DEM errors (Ducret et al., 2011). Filtering and unwrapping modules have also been adapted to areas with low coherence, yielding surprisingly good results on the quantification of interseismic uplift across the Himalayan chain (Grandin et al., 2011). Finally, the time series inversion of all interferograms, weighted by each SAR image noise, allows to separate the deformation signal from residual noise (Lopez-Quiroz et al., 2009, Jolivet et al., 2011b) and extract spatio-temporal deformation patterns (Cavalié et al., 2007, Jolivet et al., 2011c).
All these specificities are essential for the systematic exploitation of the Envisat and ERS SAR archive in Chile from 40S to 25S (freely available through the ESA project AOE720, PIs : A. Socquet, MP. Doin & JB de Chabalier), characterized by a large Andean relief, low coherence in the South and uneven data sampling. Further development will consist in using cGPS data for atmospheric corrections and interferogram flattening (M. Bejar, PhD thesis).
We will exploit the data available (heterogeneously distributed) between 25S and 34S (3 descending tracks, 325, 53, 282) to constrain lateral variations in interseismic coupling between 1992 and Oct 2010, taking into account the effect of seismic activity (Copiapo swarm, Maule EQ). A preliminary stack by G. Ducret (PhD thesis) shows N-S variations in uplift rates of several mm/yr that could be related to a low coupling along la Serena Bay for example. We will also attempt the mapping of the interseismic deformation from 39S to 34S before Maule earthquake (descending tracks 52, 282, ascending track 261).
The early Maule post-seismic deformation can be captured by some ALOS data (once corrected from ionospheric delays) and by a few ERS and Envisat interferograms. More interestingly, a systematic Envisat acquisition campaign, in ascending I6 geometry, with a cycle every 30 days, crosses the Maule area since Dec. 2010 and will last until the end of 2013. Despite progressive de-orbiting, these data should be suitable for time series analysis. We will process the data across long tracks crossing the Andes to capture the large-wavelength signal (a few cm/yr) associated with visco-elastic relaxation in the mantle.
Furthermore, we will process the data acquired by the future Sentinel-1 pair of satellites (Sentinel-1A to be launched in May 2013 and Sentinel-1B in 2014). Both satellites will acquire continuous SAR data with a TopSAR ScanSAR acquisition mode, with a swath of 250km and every 6-12 days. Integration of this huge data set along the Chilean coast will require automatization of the processing routines. We expect from these data the measurement of the spatio-temporal deformation pattern in two independent directions with a 1-3 mm/yr accuracy after 2-3 years of acquisitions.

3.3.3 TÂCHE 3 / TASK 3 STRUCTURAL COMPLEXITY AT THE PLATE INTERFACE VS. COUPLING & SEGMENTATION

Coordinator : R. Lacassin
Participants: R. Lacassin, DR CNRS-IPGP - R. Armijo, Physicien - M. Simoes, CR CNRS-IPGP, R. Grandin PostDoc CNES-ENS, P. Sternai, Post-doc IPGP, A. Coudurier-Curveur, PhD student + On PhD student to be recruited, A. Delorme, GIS engineer IPGP.
Collaborations: G. Vargas and D. Carrizo (U. Chile Santiago), G. Gonzalez (U. Antofagasta), A. Socquet (Isterre)

The subduction zone at the W margin of S-America is the living paradigm for the Chilean-type subduction, which is the geodynamic system that generates the largest earthquakes (e.g. 1960 Valdivia Mw 9.5, 2010 Maule Mw 8.8), as well as the Andes, one of the largest mountain belt -high-plateau- of our planet. At the subduction interface, a fundamental interaction between mechanisms leading to these two processes. However, it is now clear (contrary to expectations ascribed to C. Darwin) that crustal deformation associated with subduction earthquakes leaves no significant contribution to mountain building. It is also clear that crustal deformation and uplift involve the whole forearc region from the continental margin, above the seismogenic subduction interface, to the volcanic arc at more than 4000m of elevation (Armijo et al., 2000). How those two fundamental processes interact is unknown and no current geodynamic model explains satisfactorily both the generation of the large earthquakes and the topographic relief generated by some combination of accretion and tectonic shortening, thus necessarily by structural complexity at the subduction interface. Current models of the subduction interface based solely on seismologic or geodetic data do not resolve that complexity. Here we make the hypothesis that crustal deformation in the Chilean forearc (and more specifically the deformation identified from geology and morphology in some spots along the Chilean coastline) is associated with specific geometric/mechanical complexities at the subduction interface, which appear persistent over the geological time scale (~10^5-10^6 yrs) and can thus be defined from the geology. Examples are the peninsular regions of Arauco (secondary splay thrusts, e.g. Melnick et al. 2006, 2009) and of Mejillones (secondary normal faulting, e.g. Armijo and Thiele 1990, Allmendinger and Gonzalez 2009). As a consequence, variations of the mode and degree of complexity at the subduction interface should govern along-strike variations of mechanical parameters (i.e., friction, coupling), location of persistent asperities and barriers, and ultimately segmentation. We will focus on 3 sub-tasks (Fig.1 for geographical location): One targeting features of the 2010 Mw 8.8 rupture zone in Central Chile; two aiming at understanding features of complexity variation: one just north of the Maule rupture zone, up to La Serena; and the last one in the rupture area of the 1995 Mw 8.1 Antofagasta (e.g. Ruegg et al. 1996, Chlieh et al. 2004) and the 2007 Mw 7.7 Tocopilla earthquakes in N Chile (Delouis et al. 2009, Peyrat et al. 2010, Béjar-Pizarro et al. 2010, Fig. A3).

Sub-Task 3.1 Study of crustal deformations above S and N tips of the Mw8.8 rupture. We shall study secondary deformations in the region of Arauco (S) and in Pichilemu (N) region. We will attempt to characterize the residual deformation on the Arauco peninsula, possibly accommodated by thrust splaying, once the first-order model main subduction interface rupture has been removed. We plan to assess whether the Mw 7.1 Araucanía of Jan. 2, 2011 occurred on the subduction interface or on a splay fault. Source location and mechanism of the March 11, 2010 Mw 6.9 Pichilemu earthquake clearly indicates extension of the upper plate just above the N end region of the 2010 rupture (eg. Farias et al, 2011). This is the first time the occurrence of a relatively large event of this type, comparable to faulting in Mejillones, can be precisely documented. Comparable crustal ruptures occurred in Japan a few days after the 2011 Mw9 earthquake. We shall combine available seismologic (Task 1) and geodetic (GPS and InSAR, Task 2) data with our geological evidence collected in the field, and with the analysis of comparable strain in N-Chile (where morphology and quaternary evolution of crustal structures is easier to decipher, Sub-Task 3.3), to explore how the crustal strain field is activated and how it is related to segmentation at the plate interface.

Sub-Task 3.2 Evaluation of geological constraints (active structures in the upper plate, uplift deduced from geomorphology) in the region between the Gulfs of San Antonio and La Serena, north of the 2010 Mw 8.8 rupture. The coupling in this region is already well constrained by GPS data (Fig. 1), and will be studied further in Task2. Our aim is to determine if the observed low coupling in the smaller regions beneath the Gulfs of San Antonio and La Serena are persistent features. With the hypothesis that crustal strain and surface relief evolution are related to the geometry and mechanics of the underlying plate interface, and to derive constraints on long-term variations of geometry and coupling, we shall study and date geological and geomorphic markers of vertical uplift.

Sub-Task 3.3 Kinematic and mechanical modeling of the structural complexity variation associated with the S end of the seismic gap in N Chile: mega-earthquake pending since the 1877 Mw 8.5 earthquake (Fig. A3). The region is well documented by data of the 1995 Mw 8.1 Antofagasta and the 2007 Mw 7.7 Tocopilla earthquakes (Béjar-Pizarro et al. 2010). Recent results on the mechanical coupling at the plate interface (M. Béjar-Pizarro, thesis 2011) suggest a intimate link between the geometry of the down-dip limit of the coupled zone and surface geomorphology. Using very constraining geological/morphological data collected in the Atacama desert (A. Coudurier, Phd thesis 2012), new dating of the plio-quaternary sediments and geomorphic markers, we plan to produce a series of generic models of mechanical complexities and complexity variation consistent with the earthquake data and explaining explicitly the development of the main geological features, such as the normal faulting, the Coastal Scarp, the wholesale uplift of the forearc region and the Mejillones peninsula. Using this test of N Chile, where we have enough data of excellent quality to build such models, we will be able to derive implications for the other part of the Chilean subduction, and specifically the Maule area (Sub-Task 3.1 above).

3.3.4 TÂCHE 4 / TASK 4 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.
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 (Hu et al. 2004) 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. A4) 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. 2012). 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. CALENDRIER DES TACHES, LIVRABLES ET JALONS / TASKS SCHEDULE, DELIVERABLES AND MILESTONES

Since the bulk of the data (GPS, seismology) already exist, all tasks will be moving forward simultaneously. No task will be waiting for a particular achievement of another task (ie. modeling can start with existing deformation data), but their results will enhance mutual interactions (ie. new GPS/InSAR data or refined subduction geometries coming from seismological studies will be regularly introduced in the modeling). To promote such scientific interaction and integration of data, monthly meeting will be scheduled

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

4. STRATEGIE DE VALORISATION, DE PROTECTION ET D'EXPLOITATION DES RESULTATS / DISSEMINATION AND EXPLOITATION OF RESULTS. INTELLECTUAL PROPERTY

A - Scientific Dissemination

- The results of this project will be published in peer-Review International journals in seismology, geophysics, tectonics and earthquake engineering. These papers will foster the international visibility of the French and Chilean teams as well as their collaborative efforts.
- The results of this project will also be regularly presented in International meetings in Geophysics like the EGU and the AGU meetings, as well as in Latin American meetings. Attention will be paid to send Chilean and French young researchers and students participating to this project at those meetings.
- The project will also foster special sessions, co-chaired by Chilean and French scientists at these international meetings.

B – Scientific training and teaching

- This project will lead to a number of Chilean and French Ph.D. Theses, co-supervised by a Chilean and a French supervisor. The Ph.D positions allow students to be trained in state-of-the-art data analysis technologies and modeling. Students will spend time both in Chile and French research laboratories.

C – International collaborations

- This project is supported by the existing Associated International Laboratory "Montessus de Ballore" between the CNRS/INSU and the Universidad de Chile.
- Beside these existing collaborations, the project will allow to reinforce or foster new collaborations with other international partners, e.g. in the United States (Caltech,

Ohio State University), in UK (University of Liverpool) and in Germany (GFZ-Potsdam).

- These International collaborations will also benefit to the Master, PhD and young researchers involved in this project.

D – Data distribution and availability

This project will produce new integrated data bases in France and Chile (GPS, InSAR, and seismological) that will be made available to the national and international scientific community

5. Description du partenariat / Consortium description

5.1. Description, adequation et complementarite des partenaires / Partners description & relevance, complementarity

5.1.1 ENS

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 (coordinator of the project, responsible of partner ENS 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 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.

Luce Fleitout (coordinator of task 4), 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.

Marie-Pierre Doin (associated to Task 2), coordinates all InSAR activites at "laboratoire de Géologie". She is at the origin of several technical and methodological decisive progress made over the last years in the fine processing of SAR images and InSAR products applied to the detection of small crustal deformations.

Raul Madariaga (expert associated to 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.

Hélène Lyon-Caen (expert associated to task 2), has been involved in many large earthquakes studies. As an active participant to the Corinth Rift Laboratory European project since 2000, she is responsible for the data analysis of the seismological network CRLNET. She thus has a good experience of managing large amount of data and is familiar with up to date processing techniques.

5.1.2 IPGP

IPGP is a single CNRS research unit, made of thirteen scientific teams all been ranked A+ by AERES. The objective of studying active subductions is part of the LABEX UnivEarth led by IPGP The present project involves two IPGP teams:

- Team "Tectonics and Mechanics of the Lithosphere" work on transient and finite strain of the lithosphere, from the earthquake cycle to mountain-building time-scales.
- Team "Seismology" pursue research such as imaging and tomography of the Earth's interior, studies of earthquakes and of seismic cycle, developing theoretical and numerical approaches for modeling seismic rupture and seismic wave propagation, and mitigation of seismic and other natural hazards.

Jean-Pierre Vilotte (coordinator of task 1), seismologist, has been extremely active over the last 5 years for the development of the Chilean-French cooperation, and with the international ties and collaboration of this structure with other groups. As co-director of the LIA "Montessus de Ballore" he organized the French post-seismic intervention after the Maule earthquake. He also fostered and organized the relations between the LIA and other groups working in Chile, namely Caltech, GFZ-Potsdam, IRIS, Univ. of Liverpool.

Robin Lacassin (coordinator of task 3, and responsible of partner IPGP), is a geologist, specialist of large-scale tectonics, mountain building processes, fault and shear zone evolution. He works on large-earthquakes in relation with fault mechanics, geomorphic and geological evolutions at different time and space scales. He is leading the Tectonics and Mechanics of the Lithosphere team of IPGP.

Rolando Armijo (associated to task 3) is one the few french geoscientists listed in ISI highly-cited scientists. He is a world-leader in seismotectonics. He developed pioneering interpretation methods in geomorphology and active tectonics in regions like Tibet, the Andes and the Mediterranean. He studied the deformation associated to recent and past earthquakes; contributes to leading-edge current studies of deformation transients using space geodesy (GPS and SAR interferometry), seismology and mechanical modeling.

Martine Simoes (associated to task 3) is a specialist of tectonic geomorphology and more specifically of studies of erosion, rock exhumation, and fluvial incision above active thrusts. She has also produced kinematic and thermo-kinematic modeling of accretion on active thrust systems and on the Sumatran subduction zone.

The two partners (ENS and IPGP) have a long history of collaboration in general and in particular in Chile. Those joined efforts leaded to the creation in 2007 of the international laboratory (LIA) "Montessus de Ballore" by CNRS and U-chile, where the French side is represented by ENS and IPGP.

5.2. QUALIFICATION DU COORDINATEUR DU PROJET / QUALIFICATION OF THE PROJECT COORDINATOR

Christophe Vigny at ENS has a long experience of GPS data acquisition/processing (both survey and cGPS) in many areas of the world. Over the last 20 years he designed, installed and measured networks in Indonesia, Thailand, Myanmar, Nepal, Iran, Afar, Antarctica, the Alps, Greece and Chile. His work has been subject to ~50 publications in peer reviewed international newspaper, and high visibility journals like Nature (Sumatra Earthquake and Tsunami of 2004) and Science (Chile earthquake of 2010). Vigny is also one of the key actors in the "GPS applied to geodynamics" French CNRS/INSU community, having signed or co-signed a very significant part of this group's publications.

Since 2000, Vigny has been one of the key actors of GPS geodesy in Chile: he is one of the co-author of the GPS article in PEPI, 1999 which declared the Maule gap mature with a high probability of an imminent 8 to 8.5 earthquake. He was also responsible for the installation of 3 cGPS stations in the epicentral area as early as 2003 (CONS, SJAV, MAUL), which produced critical data. Finally, he was appointed coordinator of the geodetic part of the CNRS post-seismic intervention that took place immediately after the earthquake in March 2010. Post-seismic campaign measurements were carried out and an additional 12 cGPS stations were installed on the occasion, no later than 5 days after the earthquake.

Finally, Vigny also as had some experience in managing projects or subprojects aimed at acquiring, processing and modeling GPS data (both survey and cGPS) funded by EC and ANR.

- GEODYSSEA (EC) 1994-1997: GPS measurements all over SE-Asia (Indonesia, Malaysia, Thailand, Vietnam, Philippines, Singapore, Brunei) and follow on projects (SEMERGES 98-01, GEOTEC-DI 02-05, GEOTEC-DIsong 06-09,…)
- SUB-CHILI (ANR) 2005-2008: GPS measurements in Chile
- OPOSSUM (ANR) 2006-2009: deformation in Sumatra

5.3. QUALIFICATION, ROLE ET IMPLICATION DES PARTICIPANTS / QUALIFICATION AND CONTRIBUTION OF EACH PARTNER

Partenaire / partner	Nom / Name	Prénom / First name	Emploi actuel / Position	Discipline* / Field of research	Personne.mois** / PM	Rôle/Responsabilité dans le projet / Contribution to the project 4 lignes max.
ENS						
Coordinateur / responsable	VIGNY	Christophe	DR-CNRS		30	Overall coordinator – coordinator pf partner ENS and coordinator of Task2 « geodesy » GPS data acquisition & processing
Autres membres	FLEITOUT	Luce	DR-CNRS		12	Coordinator of task 4 « modeling » 3D finite element computations
	DOIN	Marie-Pierr	CR-CNRS		12	InSAR data processing

	MADARIAGA	Raul	Prof.		- na-	Associated Expert : Seismology
	LYON-CAEN	Hélène	DR-CNRS		- na -	Associated Expert : Seismology
	GRANDIN	Raphaël	Post-doc		15	InSAR. Post-doc support not requested
	RIOUX	Cyrille	I.E.		12	Field engineer GPS acquisition, data base
	METOIS	Marianne	PhD student		12	GPS acquisition & processing (finish. 2012)
	DUCRET	Gabriel	PhD student		6	InSAR data processing (finish 2013)
	TRUBIENKO	Olga	PhD student		6	Finite element modeling (finish 2015)
Associated external						
	GARAUD	JeanDidier	ONERA		3	Finite element modeling, meshing

Institut de Physique du Globe de Paris						
Coordinateur / responsable	LACASSIN	Robin	DR CNRS		15	Coordinator of partner IPG and Task4 «structural complexity» Forearc long term tectonics, mechanical modeling supervisation
Autres membres	ARMIJO	Rolando	Phys CE		15	Seismotectonics. Link between short-term and long term geological, geomorphic and geodetic observations
	VILOTTE	Jean Pierre	Phys		12	Seismology. Coord. of Task1. Link with the national/International framework
	SIMOES	Martine	CR CNRS		10	Geomorphology. Fluvial incision in relation with uplift and segmentation
	DELORME	Arthur	IE		5	GIS engineer, geodesy
	SHAPIRO	Nikolai	DR-CNRS		- na -	Associated Expert : Seismology
	BERNARD	Pascal	Phys		- na -	Associated Expert : Seismology
	SATRIANO	Claudio	Post-Doc		12	Seismology – coherent interferometry - back projection. Post-doc not requested in project
	POIETA	Natalia	Post-doc		12	Seismology – aftershocks – antennas. Post-doc not requested in project
	STERNAI	Pietro	Post-doc		12	Tectonics, modeling - Post-doc support not requested in project
	COUDURIER	Aurélie	PhD/ATER		6	Tectonics – Geomorphology
	XXX	XXX	Post-Doc		12	Seismology 12 month post doc REQUESTED by this project
	XXX	Xxx	PhD		18	Tectonics - PhD student to be recruited
	Kiraly	Eszter	PhD		18	Seismology – Valparaiso relocalisation PhD student to be recruited

Associated external						
Isterre	SOCQUET	Anne	Phys Ad		3	Geodesy.
Geosc - Montpellier	PEYRAT	Sophie	MdC		9	Source seismology

* à renseigner uniquement pour les Sciences Humaines et Sociales
** à renseigner par rapport à la durée totale du projet

	Nom de la personne participant au projet / name	Personne . Mois / PM	Intitulé de l'appel à projets, source de financement, montant attribué / Project name, financing institution, grant allocated	Titre du projet : Project title	Nom du coordinateur / coordinator name	Date début & Date fin / Start and end dates
N°1	Luce Fleitout	4	ANR Flash Japon 100 kE	DYNTOHOKU	Madariaga	2012 - 2013
N°1	Marie-Pierre Doin	12	ANR « jeune »	LONGRIBA	deSigoyer	2011 - 2014
N°1	Marie-Pierre Doin	16	INSU-PNTS	Methodo INSAR multi-temporel	Doin	2011 - 2012
N°1	Christophe Vigny		-	-	-	-
N°2	Robin Lacassin	8	Marie-Curie ITN	PLATECLIM	Lacassin	2012 - 2016
N°2	Rolando Armijo	8	Marie-Curie ITN	PLATECLIM	Lacassin	2012 - 2016
N°2	Jean-Pierre Vilotte	6	ANR blanc	MEME	Capdeville	2011 – 2014

6. JUSTIFICATION SCIENTIFIQUE DES MOYENS DEMANDES / SCIENTIFIC JUSTIFICATION OF REQUESTED RESSOURCES

Actions/Budget per task

Task 1 : Sismology

- 12 month post-doc (4083€/month TTC) 48 996
- 4 visits to Liverpool, 2 persons for 3 days 4 400
  Flight = 250x8= 2000€ +Per diem (100€/day, 2x3x4)=24x100

TOTAL for 3 years 53 396 Euros

Task 2 : Spatial geodesy

- 1 yearly GPS campaign (4 teams x 2 persons – 15 days) **x3** 18 800
  - 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…) = 1000€
- InSAR & GPS processing
  InSAR images will be provided at no cost by ESA through project AOE720, but our participation to the Fringe meeting organized by ESA is required.
  To process the InSAR and GPS data sets, we will need a dedicated server at ENS with high processing and storage capacities. We also request here funding for a new acquisition of SARScape license and ENVI/IDL softwares, needed for TopSAR & ScanSAR Sentinel data processing.
  - Data servers (Storage bay + applicative servers) 4 000
  - 20To of storage capacity 2 000
  - Renewal SARScape licence + 3 years = 3 x 2175 € 6 525
  - ENVI / IDL yearly licences renewal 2 x 510 € 1 020
  - Mandatory participation to Fringe meetings 10 000

Total for 3 years 79 945 Euros

Task 3 : Structural complexity

- 1 yearly Geological field trip (4 persons – 20 days) **x3** 14 000
  - a) air fares (international + domestic flights) =1500€ x 4 = 6000€
  - b) car rental (1 large 4x4 vehicle) = 2400€
  - c) field expanses (gas, per diem, etc, 70€ x 4 x 20) = 5600€
- Sampling and analytical costs for dating of geomorphic markers 16 000
  - a) transport of samples from Chile to France = 1000€
  - b) analytical costs (Ar-Ar or OSL) : 25 analyses x 600€ = 15 000€

Total for 3 years 58 000 Euros

Task 4 : Geophysical modeling

- Computers, licence for the 'meshing' software and other small furnitures 3 000

Total for 3 years 9 000 Euros

All Tasks:

- Publications : ~10 at 1500€ (based on 3 years of the group’s publications, see Annex document) 15 000
- Congress participation: 1 person per task per year at AGU,EGU) 25 000
- Laboratories Overhead (4%) 7 300

Total for 3 years 47 300 Euros

Grand Total	**247 641,00 Euros**
Aide demandée *(incluant frais de gestion/structure calculés par ANR)*	**257 546,64 Euros**

6.1. PARTENAIRE 1 / PARTNER 1 : ENS — 112 945 €

- *Équipement / Equipment*

No equipment (unit cost > 4000 Euros) is requested for this project

- *Personnel / Staff*

No personnel is requested by this partner

- *Prestation de service externe / Subcontracting*

No subcontracting

- *Missions / Travel* — *78 900 €*

Field work	56 400
Congress (FRINGE/EGU/AGU)	22 500

- *Dépenses justifiées sur une procédure de facturation interne / Costs justified by internal procedures of invoicing*

None

- *Autres dépenses de fonctionnement / Other expenses* — *34 045 €*

Computer consumables (data storage, CPU, …)	15 000
Licensing	7 545
Publication fees	7 500
Laboratory overhead (4%)	4 000

6.2. PARTENAIRE 2 / PARTNER 2 : IPGP 134 696 €

- *Équipement / Equipment*

No equipment (unit cost > 4000 Euros) is requested for this project

- *Personnel / Staff* *48 996 €*

We request a 12 month post doc, attributed to Task 1 « seismological studies ».
Under the supervision of Jean-Pierre Vilotte (coordinator of the task) and Andreas Rietbrock at Univ. of Liverpool, the post-doc will manage the whole data base for relocation, providing the general framework for focussed studies in which he will participate.

- *Prestation de service externe / Subcontracting*

No subcontracting

- *Missions / Travel* *58 900 €*

Field work	42 000
Congress (EGU/AGU)	12 500
Trip to Liverpool	4 400

- *Dépenses justifiées sur une procédure de facturation interne / Costs justified by internal procedures of invoicing*

None

- *Autres dépenses de fonctionnement / Other expenses* *26 800 €*

Sampling & dating	16 000
Publication fees	7 500
Laboratory overhead (4%)	3 300

7. REFERENCES BIBLIOGRAPHIQUES / REFERENCES

For convenience, references, figures and support letters are in separate documents deposited on the ANR electronic submission system

Figures list :
- Fig. A1 : Maule 2010 Eq aftershoks localisation (A. Rietbrock)
- Fig A2 : High rate cGPS (motograms) & particle motion at selected sites.
- Fig A3 : North Chile gap detail and significant earthquakes there since 1995
- Fig A4 : One year of large scale cGPS post-seismic deformations (horizontal and vertical)
- Fig A5 : Comparison of far field cGPS time series at 3 sites (Aceh 2004, Chile 2010, Japan 2011)
- Fig A6-A9 :Networks (cGPS, sGPS, seismological) maps