Acronym of the proposal	**PEPS - Chile**
Title of the proposal in French	Physique des mécanismes de Tremblements de Terre de la Subduction Andine au Chili
Title of the proposal in English	Physics of Earthquake processes on the Andean Subduction in Chile
Theme (principal)[1]	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☑ 6 ☐ 7 ☐ 8 ☐ 9
Theme (secondary)	☐ 1 ☐ 2 ☐ 3 ☑ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9
Type of research	☑ Basic Research ☐ Industrial Research ☐ Experimental Development
International Cooperation	Agency : CONYCIT Country : Chile

Total requested funding **ANR** **CONICYT**	 **376 781 €** **218 200 €**	**Project Duration**	36 months

1 Voir comité scientifique disciplinaire en annexe 7.4

1. Context and relevance to the call

1.1. Context, economic and societal issues

Chile is located over an extended and very active subduction zone, with a Mw 8 earthquake every ten years in average along the coast, and at least one multi-segments Mw>8.7 earthquake per century, as a result of the rapidly forcing of the Nazca plate beneath the South American plate. Subduction zones are regions of high seismic and tsunami hazards. The largest earthquake ever recorded is the 1960 Chiloé mega earthquake (Mw 9.5) in Southern Chile, which put the entire Pacific basin in jeopardy.

Seismicity in Chile is characterized by at least three conspicuous features: a) diversity of tectonic environments, this is, tectonic forces give rise to several type of seismic sources, underthrusting under the coast, compressional fields at shallow depths close to the Andes, down-dip tension and compression along the subducting plate, strike-slip along the Liquiñe-Ofqui and Magallanes fault zones; b) it is unique in terms of a high earthquake productivity -i.e., the number of earthquakes per unit time- large size and c) This region has been the site of the largest earthquakes in the last 150 years. Apart from the 1960 southern Chile earthquake, the 1868 (southern Peru) and 1877 (northern Chile), both magnitude around 9, and the 1922 Copiapó-Vallenar event rank amongst the largest in seismological history.

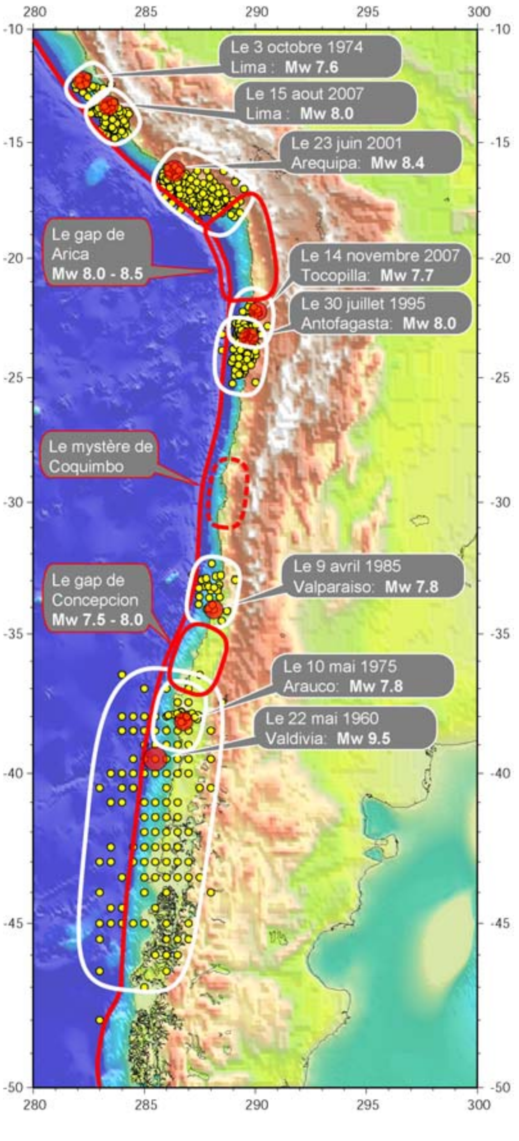


***Fig 1** : large earthquakes in Chile since 1960. Epicenters (red dots), aftershocks (yellow dots). Gaps circled in red.*

The level of exposure and vulnerability in Chile, related to earthquakes and tsunamis, is quite high. Almost all of the cities along the subduction coast in Chile have experienced in the last century a mega or large subduction earthquake. Seismic risk in Chile is also related to inland large intermediate depth earthquakes and fewer shallow crustal events along the active western front of the Andes. In the realm of seismic hazard mitigation, it is well to recall that despite continued progress in building code development, the economical cost associated with these earthquakes is quite high, for instance, the 1985 Central Chile (M=7.8) produced an economic negative impact estimated in 1.5%-2% of the GNP. Reliable assessment and mitigation of seismic hazards in active subduction zones is therefore a challenging problem in Chile with significant economic and social implications.

Accumulation of deformation at convergent margins is recently identified to be highly discontinuous and transient in nature. Silent slip events, non-volcanic tremors, afterslip following major earthquakes, stress transfer and fault coupling as well as complex response patterns occurring in the upper plate during the seismic cycle of subduction earthquakes all constitute novel observations. This first identification at the Cascadia and Japan margins during the past decade has significantly stimulated research on active deformation and seismic processes at convergent margins. While the above processes are only poorly understood to date, they have substantial consequences for understanding the physical mechanisms underlying active deformation at convergent plate margins as well as for the time dependence of hazard requiring new hazard prediction techniques. Modern space-based observation technologies that have triggered these observations and their integration with seismological and field-based techniques are opening new challenges.

A critical step is to improve our physical understanding and monitoring of the active subduction-zone processes generating earthquakes, as well as the characterization of the strong motion associated with large subduction and intermediate depth earthquakes. Another important issue is to improve our understanding of seismic activity in relation with the spatio-temporal deformation and the along-strike variations of coupling of the Chilean subduction zone. In relation with the latter we also need a better understanding in space and time of the segmentation of the subduction and of the segment interactions. This can only be achieved by integrating state-of-the-art seismology, geodesy, and geology observations that are becoming available in Chile thanks to the modern, multi-parameter networks including digital seismometers and accelerometers, continuous GPS (cGPS), tiltmeters and radar interferometry (InSAR) images data bases, built by the University of Chile and several French-Chilean collaborative programs.

1.2. RELEVANCE OF THE PROPOSAL

The West coast of South America is one of the most seismically active regions of the world. In the past it has been the site of some of the largest earthquakes that pose a significant threat not only to Chile and Peru but also to many countries around the Pacific because of possible triggering of giant tsunamis that have crossed the entire Pacific Ocean. Chile covers about half of this region and it hosted the largest earthquake ever recorded, the May 1960 earthquakes in Southern Chile that produced widespread damage to Chile and and the Pacific. This seismic activity is due to subduction of the Nazca plate under South America, but the actual process that lead to such large destructive events are still barely understood.

We believe that there is no other better place than Chile for understanding the seismic hazard due to subduction. There are several reasons for this: (1) The country is an excellent natural laboratory with exceptional conditions for the deployment of instruments and (2) The very long subduction zone stretches over more than 3000 km with different areas of Chile currently in different steps in their seismic cycle. (3) Recent economic development of Chile subjects many regions that were barely affected by “medium sized” earthquakes of Magnitude close to 8 in the past, in serious seismic hazard that needs to be carefully studied and understood.

The research we propose is important from the point of view of the physics of convergent plate margins and the mechanical and thermodynamic origin of earthquakes. Subduction is the ultimate cause of earthquakes, but the process that leads to a particular earthquake needs to be carefully studied. Recently, an entire new realm of deformation process has been discovered in well instrumented subduction zones, like those of Japan, Mexico and Cascadia in NW US and Canada. The instrumentation of the Chilean active margin has seen a fantastic development in the last fifteen years with the deployment a wealth of new instruments deployed by Chilean, French, German and American researchers both in North and South Central Chile. These instruments will become even denser with the deployment of a new National seismic and geodetic network by the Chilean government. In order to analyse the entire spectrum of transient motions that occur in Chile we have to develop an integrated approach to the subduction process combining geodetic, seismic, paleoseismic and tectonic studies. The recent earthquake in Tocopilla on 14 November 2007 poses a number of geophysical questions related to concept of “seismic gap”, first proposed by Kelleher et al for Northern Chile as a long-term forecast of major earthquakes. Long-standing discussions ensued as to whether those gaps are semi-permanent features of the subduction zone limited by barriers or simply reflect the largest events in recent history. The Tocopilla earthquake lends strong support to the observation first made in Southern Chile by Cisternas et al (2005) that Chile is the different size earthquakes, with very rare tsunamigenic events and more frequent events of magnitude close to 8. A scenario that has support from the historical seismicity of Central Chile and new paleoseismic studies in the Mejillones peninsula.

The present proposal builds upon a long history of collaboration between the French and Chilean research teams, supported through time by a number of CNRS-CONYCIT PICS projects, of ECOS-Sud and EEC projects and the Nucleo Millenio program of Mideplan, the Chilean Minister of Economic Planning. More recently, French instrumentation in Chile has been supported by two ANR-CATNATTEL projects, e.g. ANR-05-CATT-014 (ended in December 2008) and ANR-06-CATT-01001 (ending in December 2009). The aim of these ANR projects was to improve the instrumentation in two major identified gaps of the Chilean subduction zone, e.g. in Central Chile between La Serena (30°S) and Concepción (37°S) with the gaps of Coquimbo and Constitución-Concepción, including the Metropolitan area, and in Northern Chile (18°S-27°S) between Antofagasta and Arica with the Iquique gap. Some of these gaps, identified in the 1970s and the 1980s by seismologists (Montessus de Ballore, 1911-1916; Lomnitz, 1972; Comte and Pardo, 1991) on the base of historical studies by Chilean authors, are reaching the end of the seismic cycle with a high seismic risk for the 21st century.

In 2006, an International Associated Laboratory (LIA) "Montessus de Ballore" was created. The LIA associates the CNRS/INSU with the University of Chile (departments of geophysics and geology) and structures the collaborative efforts between French and Chilean teams. This proposal is part of the LIA "Montessus de Ballore".

Together with the LIA, collaborations with the GFZ Potsdam have been organized through a collaborative agreement (MOU) leading to the creation and the operation of the multi-parameter IPOC network in Northern Chile. IPOC is integrated to the monitoring effort of the Servicio Sismologico at the University of Chile. In the last years, these collaborations lead a number of joint publications and communications in international meetings like the AGU and EGU.

The major instrumental results of these collaborative efforts are:

- cGPS networks operate in Northern Chile, between Arica and Antofagasta (18°S-27°S), in Central Chile, between Constitución and Concepción (35°S-37°S) and between La Serena and Los Villos (30ºS-32°S). The cGPS networks, currently consists in 37 continuously recording receivers, 27 of them record at 1 Hz and 21 stations are on line. In parallel, networks of GPS temporary points have been increased and repeatedly measured in the last years. Finally, in North Chile a long base tiltmeter was installed for the first time in 2007.
- In the Northern Chile gap we deployed the permanent, continuously recording multi-parameter network IPOC, a join venture of CNRS/INSU, GFZ and DGF. The network consists presently of 15 sites (+2 in 2009) combining broadband, strong motion receivers and two tiltmeter components, with a mean spatial spacing of 80 km. This network is completed by the permanent stations at LVC, CPO and PEL. Thanks to this instrumental effort, the 14 November 2007 Tocopilla earthquake is the best recorded in Chile.

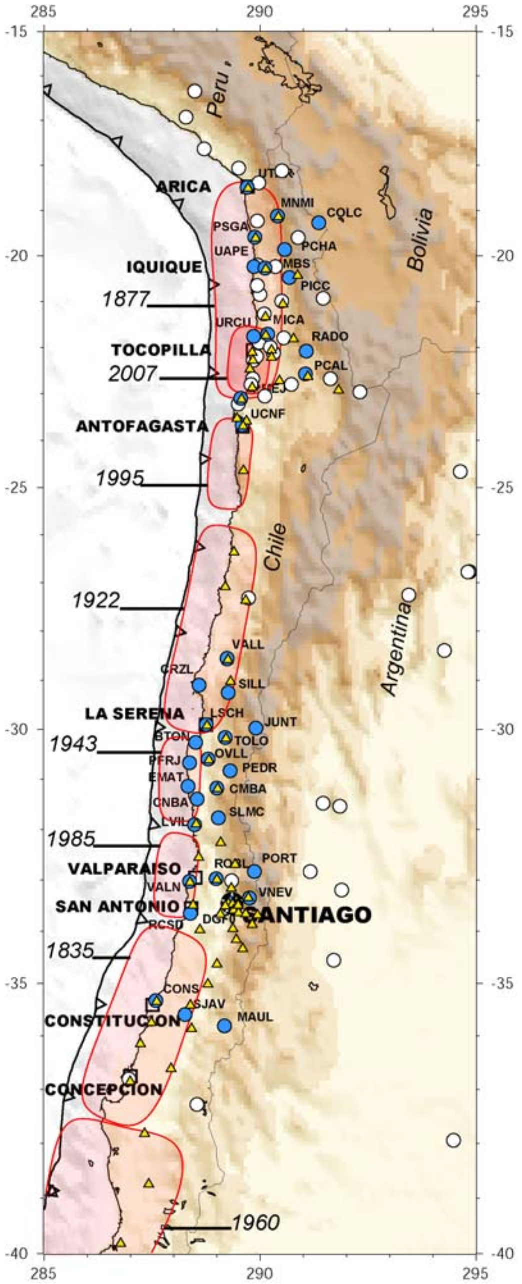


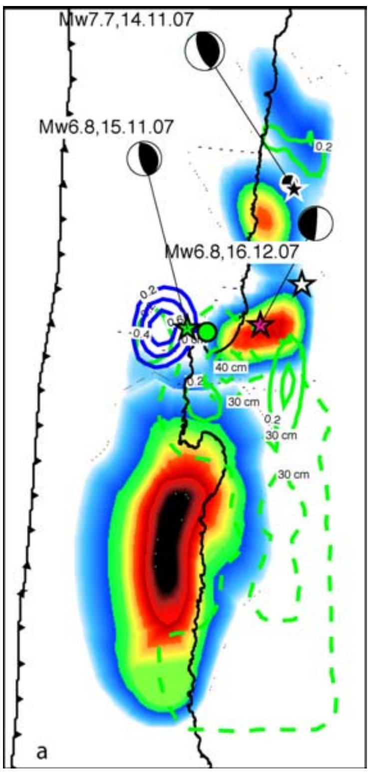
Fig 2 : major earthquakes in Chile(red areas) and existing monitoring networks:cGPS (blue dots), seismic stations (yellow triangles)

- The cGPS data are archived in Chile (http://www.dgf.uchile.cl) and in France (http://gpscope.dt.insu.fr) where they are made available to the community.
- The transmitted seismological data of the IPOC network are archived in the University of Chile (Santiago), the GFZ Potsdam and IPG Paris. They are distributed through the Geofon data centre (http://geofon.gfz-potsdam.de/geofon//status/index.html) and soon, in April 2009, the Geoscope data centre (http://geoscope.ipgp.jussieu.fr/).

The French-Chilean teams, in close coordination with the GFZ Potsdam, have collaborated in several field activities during recent seismo-volcanic crises.

- Aysen – January-May 2007: on April 21, 2007 at 5:35 pm TU a Mw 6.2 earthquake occurred in the area of Aysen in Southern Chile (45°S). This earthquake triggered giant landslides around the Aysen Fjord, which produced a local tsunami devastating the Fjord coasts within a radius of few km
- Tocopilla – December 2007-March 2008 : November 14, 2007 at 3:40 pm TU, a Mw 7.6 earthquake ruptured a long and narrow zone at the base of the coupled zone of the Northern Chile gap between Tocopilla and Mejillones (22°S-23°S). This ebevnt was recorded by the IPOC network and, in addition, a post-seismic field study was carried out by University of Chile, French CNRS and the Task Force of the GFZ Potsdam. A temporary network of 25 short-period, 6 broad-band and 5 strong motion instruments was deployed in the area. This network operated until March 2008 and recorded a large volume of data. In parallel, a network of 21 temporary points was measured three times since the earthquake.

These collaborations, together with the continuous instrumental efforts deployed by the Servicio Sismologico Nacional of University of Chile, have significantly improved the monitoring in Central and in Northern Chile. These networks record routinely produce a large volume of high quality observations that we propose to model in order to improve our understanding of the segmentation of the subduction one, the slow phenomena that precedes large earthquakes, the rupture process of large earthquakes and their geologic and tectonic settings. We also plan to extend our research to the small shallow earthquakes that are generated in the Andes, from Santiago to Aysen. Their origin and role in the build up of the Andes and slip portioning is a new research subject that we plan to explore in this proposal



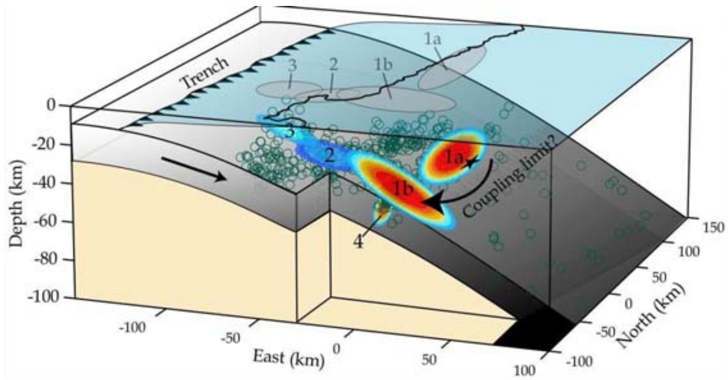


Fig 3: Composite Tocopilla and Antofagasta slip models (left). Coloured contours depict co-seismic slip. Contour line depicts post-seismic (green Antofagasta, blue Tocopilla). Tocopilla 2 patches interactions top.

We believe that this research is a critical step to improve the assessment and the mitigation of seismic hazard in Chile. Strong motion data available in Chile concerns mainly the Central Chile earthquake of March 3, 1985; and the Northern Chile events of Antofagasta and Tocopilla. The study and full exploitation of the strong motion data is an absolute need in order to understand why M 8 subduction zone earthquakes produce moderate ground accelerations. A thesis has already started on this subject with the participation of both the Geophysics and Civil engineering departments at University of Chile. Our current hypothesis is that these events are dominated by a few asperities whose strength is weak. Will this be the case for a mega earthquake of magnitude close to 9? May be those events occur only when the stronger asperities break. The answer to this question is not known of course, but it interests not only Chilean engineers but also Japanese, Mexican and North American colleagues.

This proposal, par of the LIA "Montessus de Ballore" will foster the scientific collaborations between Chilean and French teams for improving our knowledge of the physical processes of the active margin in Chile and for improving physically based evaluation of the seismic hazard in Chile.

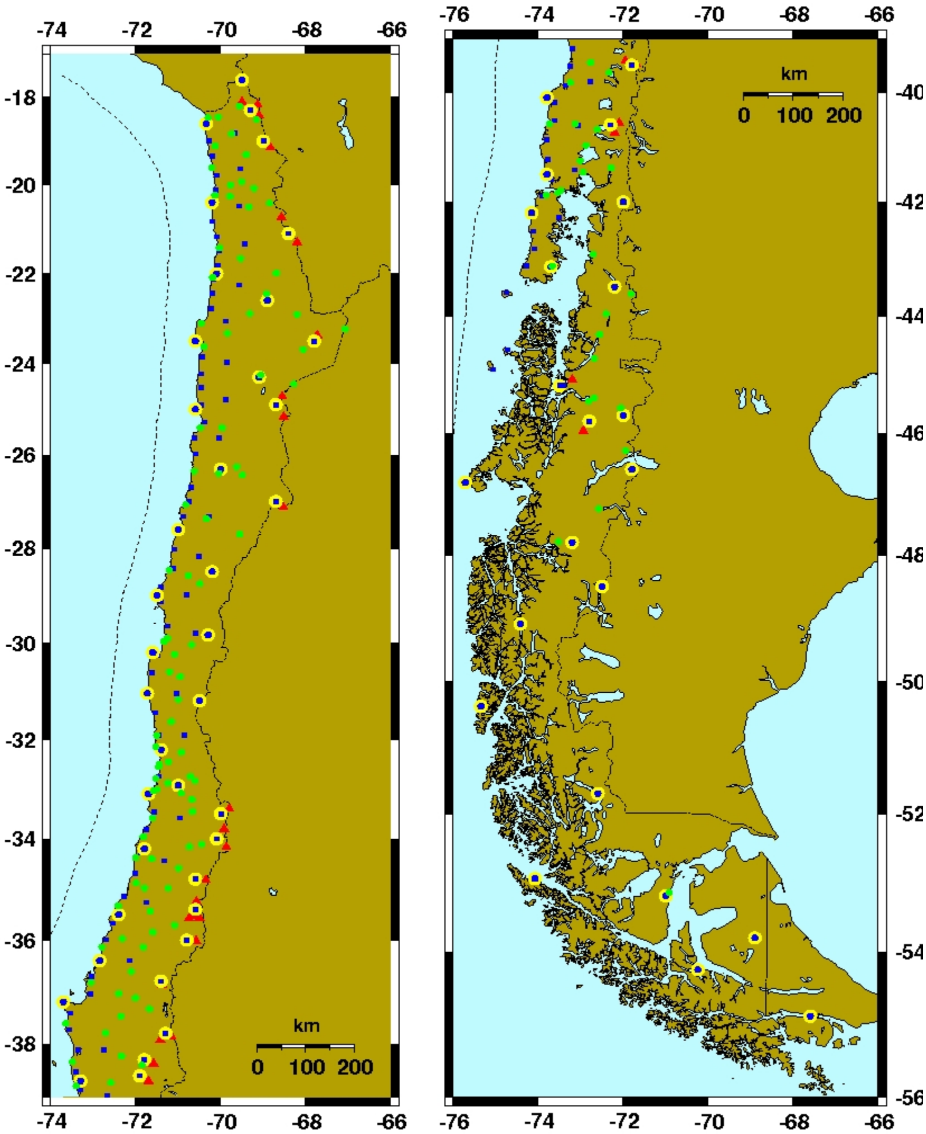


***Fig 4** : project "red nacional" in Chile. Multiparameter (broabdband, strong motion and cGPS) stations ((yellow circle), cGPS (blue dots), strong motion (green dots)*

With the new Chilean "red nacional" project being launched we believe this proposal to be timely. The existing cGPS and seismological networks operated in collaboration between Chile, the French CNRS and the GFZ-Potsdam, as well as the results of this new collaborative project will provide new scientific results that will help to guide the design of the Chilean "red nacional" project. Furthermore, if considered adequate by the Chilean authorities, these existing networks can be incorporated into the "red nacional" as an international contribution.

2. SCIENTIFIC AND TECHNICAL DESCRIPTION

2.1. STATE OF THE ART

In Chile, several studies have shown an along strike variation in the dip angle of the subduction. The fast convergence (~ 7 cm/yr) is accommodated by large thrust earthquakes and occasional intermediate depth earthquakes, inside the Nazca plate below the coupled interface, together with shallow crustal earthquakes associated with intra-continental fault systems in the Andes cordillera and the Altiplano-Puna.

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 earthquake and occasionally produce mega thrust earthquake when the rupture can 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 were great earthquakes of very long lengths occur and regions where only moderate large earthquakes occur. Seismic gaps were defined as regions that had not experience a large earthquake for the last 30 years. In hindsight this period of time is too short to characterize the seismicity 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 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. the Central Chile (Constitución and Concepción 35°S-37°S and Coquimpo-Illapel 30°S-32°S) and the 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 and the CNRS-CONYCIT projects as above-mentioned. Two of these segments are identified as major gaps, e.g. Constitución-Concepción and Antogasta-Arica, as reaching the end of their rupture cycles. The last known large earthquakes occurred in 1835 in Concepción and 1877 in Iquique. The third segment of Illapel presents a slightly different situation: the last subduction earthquake there was in 1943 ("only" 65 years ago), but has been the locus of an increasing seismicity (with a dozen of significant earthquakes of magnitude between 6 and 7), over the last decade. 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 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.

Central Chile is currently very active with magnitude Mw 8 events occurring at regular intervals of about 80 years (Comte et al., 1986; Beck et al., 1998). The gap of the Coquimpo-Illapel area between La Serena (30°S) and Los Villos (32°S) was the site of a major earthquake (at least 600 km of rupture) in 1730, and two large earthquakes in 1880 and 1943 (Nishenko, 1985, Beck et al., 1998). Several studies by researchers of the DGF (Barrientos et al., 2004; Pardo et al, 2002a,b) have delimited the main structures and the geometry of the subduction zone in this area, as well as the distribution of seismicity. The last major event in this area occurred on the 15 October 1997 at a depth of 55 km under the city of Punitaqui. This intermediate depth slab-push event of Mw 7.3, followed with a series of four shallow M>6 thrust earthquakes, was studied in details by Lemoine et al. (2001) and Gardi et al. (2006). This puzzling seismicity could be either the herald of a major earthquake initiation and/or the manifestation of slow aseismic transient slip on the subduction interface. Surface deformation in this area, studied with high precision GPS over more than 5 years is compatible with an elastic loading due to the partial locking on the subduction interface at depth, with 60-55% of the convergence rate being dissipated by free or aseismic slip. The deformation accumulation seems to decrease drastically northward to reach almost zero around 30°S (La Serena-Tongoy), e.g. see Vigny et al. (2009) and Klotz et al. (2001). Whether this is a steady state or only a transient pattern is not yet understood due to the lack of long enough time series. Another striking feature is the bay of La Serena between the two peninsulas of Lingua de Vaca in front of Tongoy (30°S) and Punta de Choros (29°S) which may be identified as a potential barrier similar – but erversed in topography - to the Mejillones peninsula in North Chile. The gap of Constitución-Concepción (35°S-37°S) is identified as a very mature gap. The last great subduction earthquake (M ~ 8.5, Darwin, 1851) occurred in February 1835 (Lomnitz, 1971,; Beck et al., 1998). This area lies immediately North of the rupture zone of the great 1960 earthquake (Cifuentes, 1989) and South of the rupture zone of the 1906 and 1985 Valparaiso earthquakes (Barrientos, 1995). Part of the region was affected by the intermediate slab-pull earthquake of Chillan (Mw 7.9, 1939). This region was extensively studied since 1996 with temporary seismological networks (Campos et al., 2002) and recurrent campaign of geodetic surveys (Ruegg et al., 2002, 2008). From geodetic studies, the surface deformation there is showed to be consistent with a fully coupled elastic loading on the subduction interface at depth, in contrast with the more complex situation of the Coquimbo-Illapel segment. This clearly raises the question of the variations of coupling at the interface in space. A striking feature in this area is the Arauco peninsula immediately South of Concepción (37°S-38°S) which acted as a barrier for the 1835 and 1960 earthquakes, with evidences of both quaternary and contemporary uplift. This barrier is quite similar to that of the Mejillones Peninsula in North Chile (Armijo and Thiele, 1990; Ruegg et al., 1996). In between these two segments, the Metropolitan region of Santiago, shallow depths earthquakes, associated with the deformation of the Andes, are recognized as a potential threat, e.g. the earthquake of Las Melosas (1958, Ms=6.9). This seismic risk pointed out by recent studies of active faulting along the western front of the Andes, is still poorly understood. It might related to North-South striking crustal fault, accommodating either or both a small component of shortening not accommodated by the subduction and contributing to the building up of the Andes, and a small component of strike-slip partitioning due to the obliquity of the trench in this area.

The Northern Chile gap, between Antofagasta and Arica (18°S-27°S), is quite interesting and can be considered as a proxy for the scientific problems addressed in this proposal. Information about historical earthquakes in Northern Chile, is scan since this region was very lightly inhabited until the beginning of the last century. Two mega thrust earthquakes have affected the Northern Chile Southern Peru region: in August 1868 (Mw > 8.7) and in May 1877 (Mw 8.9). The epicental are of the 1877 earthquake was located near Iquique and the rupture area of the 1877 is relatively well known (Comte and Pardo, 1991, Kausel, 1986). A recent paleo-seismological study of the Mejillones Peninsula (Vargas et al., 2005) evidenced at least 2 mega-thrust events in the period 1409-1449 and 1754-1789, but no trace of the 1877 event in the Mejillones Peninsula. Several studies (Comte et al., 1994,; Rietbrock,and Haberland, 2001; ANCORP Working group, 2003, Husen et al., 1999) have delimited the main structures and the geometry of the subduction zone in this area, as well as the distribution of seismicity. The region is bounded in the North by the Arequipa earthquake (Mw 8.4, 2001), that partly filled the rupture zone of 1868 earthquake (Giovanni et al., 2002), and in the South by the Antofagasta earthquake (Mw 8, 1995). This earthquake was very well studied from seismological and geodetic point of views (Ruegg et al., 1996, Delouis et al., 1996; Chlieh et al., 2004; Klotz et al., 2005). Co-seismic slip initiated near the Mejillones Peninsula and propagated southwards with little co-seismic slip below the peninsula. Recent study of Pritchard and Simons (2006) revealed that the average rate of fault slip beneath the Mejillones Peninsula was nearly twice the plate convergence rate between

1995-2000 and conclude that the peninsula was not likely to rupture soon. This study revealed also complex spatio-temporal seismic/aseismic coupling with an aseismic slip pulse that may have triggered the deep Mw 7.1 aftershock in 1998. The Mejillones Peninsula appears therefore as a natural barrier for this segment in the South. In the last century, the seismicity linked to the coupled subduction interface in Northern Chile has been very weak with the exception of of the 1967 Tocopilla earthquake (Mw 7.4, Kelleher et al., 1973, Malgrange and Madariaga, 1983), and no large shallow earthquake (Mw > 7.4) have been recorded during this period. On the other hand, geodetic studies indicate that in this region the Nazca and South American plates are fully coupled leading to the conclusion that this area is under considerable tectonic loading. In contrast, and similarly to other segments of the Chilean subduction zone, a significant seismic activity occurs at intermediate depth (Rietbrock and Waldhauser, 2004; Comte and Suarez, 1994) with two large slab-pull earthquakes in 1950 (Mw 9) East of Tocopilla (Kausel and Campos, 1992) and in 2005 (Mw 7.7) near Tarapaca (Peyrat et al., 2006, Delouis and Legrand, 2007; Peyrat and Favreau, 2009) which was interpreted as the reactivation of a horizontal oceanic lithospheric fault due to dehydration embrittlement processes.

The 14 November 2007, a large Mw 7.6 subduction earthquake occurred in Northern Chile near the city of Tocopilla. The earthquake produces a small tsunami (Hebert et al., 2008) and was followed by several aftershocks. On the 16 December 2007 a slab-pushed aftershock occurred near the southern end of the rupture zone close to the Mejillones peninsula (Peyrat et al., 2009). The rupture of the Tocopilla earthquake (Delouis et al., 2009,; Peyrat et al., 2009) is shown to propagate North to South along 130 km, and to have activated in time two main asperities localised at a depth between 30 to 50 km at the base of the coupled zone: a first long narrow one along the coast from Tocopilla to Michilla, an 20s later a second one shallower and more intense furter south near the northern end of Mejillones Peninsula. These two asperities have been independently confirmed by a detailed study of the GPS data and the InSar images (Bejar et al., 2008, 2009). South, the slip is limited by the northern end of 1995 Antofagasta rupture; North, the slip is limited by the southern end of the 1967 Tocopilla earthquake. The slip zone of the Tocopilla earthquake remains localized in the deep part of the coupled zone, right below the coast line with no evidence of slip below the Mejillones peninsula. In contrast with the Antofagasta earthquake, the off-shore superficial part of the contact zone, between 10-30 km, remains most probably locked. The Tocopilla earthquake did not break the entire plate interface relieving only partially the stress accumulated since the 1877 mega thrust event. Preliminary results from geodetic study of the post-seismic deformation, immediately after the Tocopilla earthquake, identified two post-seismic slipping asperity. One is located North-West of the Mejillones Peninsula at relatively shallow depth and associated to the aftershocks in this region, Another one is identified in depth East of the peninsula, a zone where few aftershocks have been recorded and where 50 cm of post-seismic slip was identified in the 3 years following the 1995 Antofagasta earthquake.

If one can't exclude the possibility that the Tocopilla can be a precursor of a mega-earthquake, is the seismic risk today be that of a mega earthquake encompassing all the Northern Chile or that of recurring earthquakes in the Mw 8 ranges like in Central Chile? Will those earthquakes migrate along strike toward North or will they continue to break the South part of the segment migrating along dip toward the surface ?

2.2. S & T OBJECTIVES, PROGRESS BEYOND THE STATE OF THE ART

The Tocopilla earthquake raises recently new and challenging questions related to the understanding of the segments of the subduction zone in Chile and the way large seismic gap eventually rupture. It raises also important issues on how to improve the monitoring of a gap as it comes up to activity. This project aims at providing new scientific contributions to these questions.

Paleo-seismological informations along the coast of Chile is still relatively scant, and most of our knowledge of the seismic activity is based on historical data gathered by Chilean historians and seismologists. With probably the exception of Central Chile, these informations is biased by the scarcity of early settlements, the difficulty to interpret old documents and, most important, and by the relative shortness of this record versus a seismic cycle of possibly many centuries.

Although one can not exclude that the Tocopilla event is a large foreshock of a future mega-thrust event, a more likely explanation, suggested by the recent studies of Delouis et al. (2009) and Peyrat et al. (2009), is that the awakening seismic activity in North Chile provide further evidence that rupture length and coseismic slip vary between successive earthquake cycles within the same segment of the Andean subduction zones (Kanamori and McNally, 1982; Collot et al. 2004). This type of seismic activity is evidenced in the Ecuado-Colombia region where inferred rupture area of the very large 1906 mega-thrust event (Mw 8.8) was the site of three thrust events in 1942 (Mw 7.8), 1958 (Mw 7.7) and 1979 (Mw 8.2). A similar activity is also suggested in Central Chile where the inferred rupture area of the very large 1730 tsunamigenic earthquake, has then ruptured repeatedly with magnitude 8 events in 1921, 1906, 1971 and 1985 (Comte et al., 1986, Vargas et al., 2005). The best known example in the world of such seismic activity is probably that of the Nankai through (Ando, 1975) in Japan.

A first challenging scientific objective of this project is to improve our understanding of the complex patterns of earthquake in the Northern and Central Chile. The asperity model proposed by Kanamori and McNally (1982) and Ruff (1992) is probably the simplest self-consistent paradigm to start with. Small earthquakes represent failure of individual asperity while great earthquake represent the collective failure of several asperities depending on the asperity interactions and the seismic history. The Tocopilla earthquake suggests that the asperity sizes have to be smaller than the inter-plate width implying along-dip and along-strike asperity interactions. Geodetic evidences of after-slip and postseismic 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 in a segment. Scientific issues are related here to identify the seismogenic asperities, and their distribution; to understand the asperity origin in relation with the deep structures and variations of the plates coupling, to understand the seismic and aseismic asperity interactions over various time and space scales, to understand the implications for earthquake dynamics and radiation and for earthquake and deformation activity patterns. All these studies require dense high quality observations data sets integrating cGPS, broadband, strong motion, as well as spatial radar interferometry (InSAR) in a segment. Recent seismic observations must also be extended in time by paleo-seismologic studies. These observations are becoming available today in Northern Chile, and in a less extent in Central Chile, as a result of the Chilean-French efforts of the LIA “Montessus de Ballore” in close collaborations with the GFZ Potsdam, the efforts of the Servicio Sismologico Nacional of University of Chile. This problem can now be tackled with state-of-the-art methodologies at the time and space scales of one Mw 8 earthquake and its aftershocks, and at the scale of a whole segment.

A second challenging objective of this project is to improve our understanding of the segmentation of the subduction zone in Chile. Tears in the slab, indentation of fossil structures of the oceanic plate in the continental plate, asperities, define the segment boundaries or barriers. However, segments do interact with each other because of strain and stress transfer: Rupture on a given segment can promote failure of the adjacent segments, overpassing those barriers and generating much larger earthquakes than expected, like was the case for the 26 December event of Sumatra. Stable structural barriers correspond very often to regions of structural and geometrical complexity in the fault zone (the coupled region of the subduction interface in this case), with possible variation of the subduction interface coupling. Such regions appear to be characterised by specific deformation features, which can accumulate over the long-term and propagate to the surface. If the barrier is important and long-lived, the cumulative deformation is strong and it can be identified as a singularity along the coastal morphology. Understanding these barriers and their relative stability in space and time is a challenging issue for mega-thrust earthquake seismic hazard assessment. Rupture of both, the 1995 Antofagasta earthquake (Mw 8.1) and the 2007 Tocopilla earthquake (Mw 7.8) has probably been arrested by structural complexity under the Mejillones peninsula. The same is possible for the rupture of the larger 1877 Iquique (M~8.5) earthquake. South of Concepción (37°S-38°S) acted as a barrier for the 1835 and 1960 earthquakes, with evidences of both quaternary and contemporary uplift. In order to tackle this problem one must integrate geology and geomorphology observations, geodesy informations and seismic profiles together with paleo-seismologic informations. All these informations are becoming available from the French-Chilean collaborations, and the GFZ-Potsdam experiments.

A third challenging objective of this project is to better understand shallow depth seismicity along Chile in relation with the volcanic activity and the active surface faults. Recently it has been proposed that the San Ramón Fault, critical for the seismic hazard in the city of Santiago, is at the tip of a large active fault-propagation fold system affecting the whole Andean cover behind along most Chilean Andes (at least from 18°S to 38°S), of the propagating West Andean Front, interpreted as the tip of the crustal-scale West Andean Thrust (WAT). The recent deployment of instruments by the Chilean Servicio Sismológico Nacional (with good resolution near Santiago, between 33°S-35°S) provides new image of the 2000-2005 shallow seismicity under the Principal Cordillera which will allow a better understanding and quantification of this problem. Further South, the interplay between active surface faults and volcanic activity has been dramatically illustrated during the Aysén crisis. In This region,the Liquine-Ofqui Fault Zone (LOFZ) in Southern Chile, provides a unique natural laboratory to examine the deformation of the continental margin where oblique subduction of a young oceanic plate occurs. However the short-term deformation is affected by different processes, as the ones related to the seismic and volcanic cycles for each segment, the interaction of fluids within weak zones of the crust and its heterogeneities, among others. Improving our understanding of the strain partitioning in this region has strong implications on seismic hazard assessment.

All these objectives need to integrate observations which cover the whole space and time spectrum of the subduction processes based on long term collaborative instrumentation projects. The French-Chilean teams, together with our GFZ colleagues, integrate the multi-disciplinary skills to achieve those objectives and have a long history of productive collaborations.

A important scientific outcome of this project will be a better understanding of the seismic hazard along the Chilean subduction zone, as well as new operational tools for monitoring and data analysis integrating the entire spectrum of transient motions and seismicity, from depth to surface, related to the seismic cycle of subduction earthquakes. This will reinforce the international visibility of the French and Chilean teams already interacting within the LIA “Montessus de Ballore”

Finally an important outcome of this project will be in terms of education and training of young researchers in Chile and France at various levels: Master, PhD and PostDocs. This will be achieved by promoting the circulation of these young researchers between the different groups, and the training to advanced state-of-the-art methods in seismology, geodesy, geology and paleo-seismology.

3. SCIENTIFIC AND TECHNICAL OBJECTIVES / PROJECT DESCRIPTION

3.1. SCIENTIFIC PROGRAMME, PROJECT STRUCTURE

The project is structured along three main tasks that cover the different aspects of the research to be carried out in the framework of the proposal. These tasks are:

TASK 1 ANALYSIS OF THE CO- AND POST-SEISMIC PHASES OF THE TOCOPILLA EARTHQUAKE

TASK 2 SEGMENTATION, SPATIO-TEMPORAL VARIATION OF THE DEFORMATION AND OF THE COUPLING

TASK 3 SHALLOW DEPTH SEISMICITY, DEFORMATION PARTITIONING AND ACTIVE FAULTS AT THE SURFACE

These tasks reflect the main objective of our proposal which is to work on top of existing observational facilities in order to characterize and explore the subduction zone of Chile from a geophysical and geological perspective. Our ultimate goal is to contribute to the evaluation of seismic hazard in a subduction context and to help Civil engineers and deciders integrate seismic risk in their work. Our observational work so far has addressed the problem of active seismicity, particularly the large to very large earthquakes that frequently affect Chile along the subduction interface between the Nazca and South American plate. Task 1 has as its main immediate goal to study the large M 7.7 earthquake that occurred in Northern Chile on 14 November 2007 and that affected the region between the city of Tocopilla and the Mejillones Peninsula. This is one of the big mining regions of Chile and it is possible that the Tocopilla earthquake be the first of a series of M~8 earthquakes that will strike the region in the future. Its careful study will then permit to build realistic scenarios about the strong motion hat such earthquakes will generate in the future, not only in this particular stretch of Chile but also in other regions of the country and in other subduction zones. This research will address most important aspects of earthquake studies and their application to earthquake engineering.

The second task is devised to exploit the information we have been gathering over the last 18 years on the deformation of Chile. At present a substantial effort is in progress concerning the observation of deformation using continuous and campaign mode GPS receivers. Some very important results are starting to emerge from these observations, namely, the segmentation of the subduction zone with regions that fully locked as is the case with Northern Chile and regions that appear only partially locked (La Serena) where strain is relieved by mechanisms that we would like to elucidate. We do not know whether this is due to slow continuous or episodic slip, for instance.

The third task is in many ways a new problem: until recently the main geophysical risks studied in Chile were large subduction earthquakes and volcanoes. Recent activity in Curico, Aysen and earlier earthquakes in the Cordillera near Santiago put into evidence that there is also a less dramatic seismic activity that can put Chilean citizens in jeopardy: these are shallow of medium sized magnitudes that occur at shallow depths very close to civil structures, bridges, tunnels, fish farms, etc. The activity on these shallow faults was shown dramatically in Aysen where a shallow intraplate earthquake produced a small tsunami on the Fjord of Aysen. Less dramatic, but equally damaging was the 1958 earthquake in Las Melosas a few km from the edge of the city of Santiago. This event destroyed several abduction tunnels of the electrical plant of Las Melosas and produced extended damage I the are of Cajon de Maipo. Its vicinity to the main Copper production mines of the areas is also a reason for concern. These shallow faults are related to two different process occurring in the Andes, the general west oriented motion of the Cordillera along shallow inverse ramp faults (WAT) and shallow strike slip faults that are produced by slip partitioning between a subduction that occurs at an angle with respect to the Chilean coast and the shallow earthquakes that occur on the subduction zone. Evidence for this partition is clear in several areas of Southern Chile, but it seems to be active in South Central Chile too.

These three projects are obviously connected since many of the participants participate in at least two of the tasks. The teams that participated in the study of the Aysen mini-tsunami were largely the same that study the deformation of North Central Chile and the seismologists that study the Tocopilla earthquake will also work in the study of the Central Chile seismic crustal zone.

Task 4 will provide the technical support for data base management and operation together with the networking activity (external web site and managing distribution of the information)

Task 5 will be coordinated by the coordinators of the project in order to insure connections between the different tasks and the dissemination and valorization of the project.

3.2. Project management

This project management of this project will be part of the LIA "Montessus de Ballore" in which a coordination structure already exists. The management will benefit from a support of the LIA. The management will imply specifically include

Kick-off meeting

It will be held in Santiago, will all the partners and our GFZ colleagues, immediately after the beginning of the project.

Creation of a project website integrated within the LIA website

A website of the project will be integrated within the LIA website. This website will have a public section and an internal sections. The website will be designed to be a cooperative space for diffusing informations, discussions, results, activity technical reports.

Project reports

The different tasks of the project will produce contractual reports every 6 months, addressing progress and problems.

Tasks 2.3, 3.1 and 3.2 which involve field work, will produce mission reports.

Task 2.1 which will involve campaigns of repeating measurements, will produce reports after each campaign.

Technical reports will be produced during this project.

Yearly meetings

Contractual meeting will be organized every year alternatively in Chile and in France. At these meetings, on going progress and scientific results ill be addressed. These meetings will involve the French and Chilean participants, as well as the GFZ participants.
External scientists will be invited in order to foster the collaborations and the coordination between other projects on subduction zones.

Tasks coordinators

Each task has a coordinator, in charge of focused meetings and communication within the task activity, and coordination with the project coordinators and to other group.

Progress meetings

Every two month, progress meetings will be organized on each side. These progress meetings will foster interdisciplinary discussions between the different tasks of the project. These progress meetings will involve also the GFZ scientists participating in the project. It will also help the integration of the young researchers within the project.

Circulation of young researchers

During the project special attention will be paid to provide the possibility for the young scientists to spend time in the French and the Chilean teams, in order to actively collaborate with the different component of this collaboration.

Link to other project

External scientists will be regularly invited at the yearly and progress meetings in order to beter coordinate this project to other ongoing projects on subduction zones in France, Chili but also abroad like in the US and in Japan.

3.3. DESCRIPTION OF THE TASKS

3.3.1 TASK 1 ANALYSIS OF THE CO- AND POST-SEISMIC PHASES OF THE TOCOPILLA EARTHQUAKE

Coordinator: R. Madariaga (ENS Paris) and J. Campos (DGF, U. Chile)

The Tocopilla earthquake (Mw 7.6, 14 November 2007) has been very well recorded, as a result of the Chilean, French, German collaborative efforts. **Never before has so much data been available to study a large Chilean earthquake.**

We propose to use these data together with modern, stat-of-the art methodologies to analyze the seismic and geodetic data, extract information about the earthquake and its aftershocks, extract information about the after-slip and post-seismic spatio-temporal deformation. Another important objective is to analyze these data with the goal of understanding strong ground motion for large earthquake in Chile and similar subduction zones.

What is interesting about the Tocopilla earthquake and its aftershocks is that it shows that large subduction zone earthquakes in the magnitude range of 7.5 to 8. are much more complex than proposed in the past. First of all, it seems that ruptures of this Mw 8 class earthquakes do not actually break the entire plate interface. This was thought to be already the case for the 1971-1985 pair of earthquakes in Valparaiso, but near field data available at the time were not good enough to fully identify the rupture process. In the case of Tocopilla, slip models inverted from seismic and geodetic data demonstrate very coherently that the rupture is confined to intermediate depths (right bellow the coast line) and didn't reach the surface. Second, in the case of Tocopilla, the earthquake broke in two parts: a first long narrow zone along the Coast from Tocopilla to about Michilla , then a second part broke about 20 s after the main shock further south near the northern edge of Mejillones peninsula (Delouis et al, 2009, Peyrat et al., 2009)). This second patch of rupture is more intense and larger, reaching shallower depth near its southern tip.

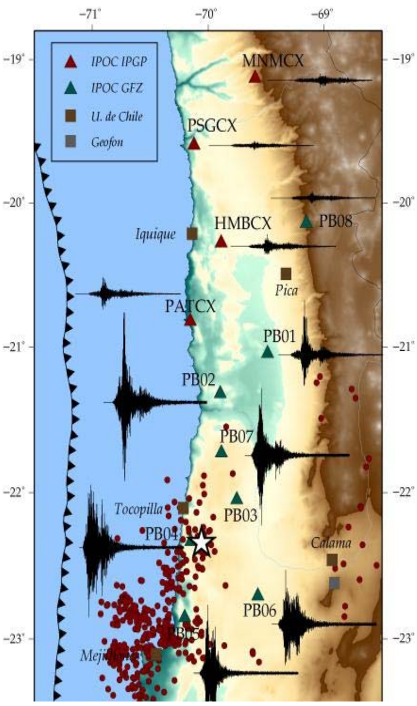


Fig 5 : Tocopilla available data

Available data for the study

Data for the study of the November 14, 2007 earthquake is available from many sources: (1) The global network of stations distributed by the IRIS data center in the USA. (2) A network of 10 accelerometers run jointly by the Department of Civil Engineering and the Department of Geophysics (DGF) of Universidad de Chile. They recorded the main event and the largest aftershocks with excellent signal to noise ratio, but they could not record smaller aftershock because they have a trigger that only records data for the very largest events. (3) About two weeks after the earthquake, a temporary post-seismic network has been deployed by the University of Chile, the French CNRS and the Task Force of the GFZ Potsdam in the area to record the aftershocks. The network was composed of 25 short-periods, 6 broadbands and 5 strong motions. The network has been operating until March 2008 and recorded a large volume of data. The postseismic network reoccupy sites of the Task force post-seismic network deplyed after the 1995 Antofagasta earthquake. (4) The Integrated Plate Boundary Observatory in Chile (IPOC) network, a joint international effort between Geoforschung Zentrum Potsdam (GFZ), Institute de Physique du Globe de Paris (IPGP), and the Universidad de Chile and Universidad Catolica del Norte as Chilean counterparts. This network is one of the main projects of the Montessus de Ballore International Laboratory of CNRS-DGF and Conicyt (Chilean National Science Foundation). (5) Co- and post-seismic Interferometric images have been obtained by a joint work between IPG Paris, GFZ Germany and DGF in Santiago. (6) Several permanent cGPS stations were deployed in the earthquake area in the 90s and early 2000s by IPG Paris, DGF Santiago and Caltech. (7) Additional cGPS stations were installed by IPGP and GFZ in the weeks following the earthquake to monitor post-seismic deformations. (8) Campaign style GPS measurements were made immediately after the earthquake on a network of 21 pre-existing benchmarks and repeated every 6 months. These data are presently available for research in a data base created at DGF in Santiago, in Germany and Paris.

Data sources (1) and (2) were used by Delouis et al (2009) in a preliminary study of the Tocopilla earthquake. Data sources (1-2-4) were used in a more detailed study of the main event and its aftershocks by Peyrat et al (2009). Data sources (6) and (7) and (8) are the subject of a paper in preparation by Bejar-Pizarro et al (2009). We propose now to study the complete set of data in order to make a complete model of the rupture process of the event.

Task 1.1 - Teleseismic body wave analysis, main event and aftershocks

Team: R. Madariaga (ENS Paris), A. Fuenzalida (Master, ENS Paris)
J. Campos (U. Chile), S. Ruiz (PhD., U. Chile), G. Meneses (Master, U. Chile)

More than one hundred eighty VBB stations of the IRIS and Geoscope networks have been used for wave-form modeling the main shock and the five larger aftershocks. The modeling obtained so far by Delouis et al (2008) and Peyrat et al (2008) is excellent. We propose to continue this work by inverting simultaneously the near field and far field data available for the main event and its main aftershocks. We also intend to model all the aftershocks greater than 6 in the area since digital data became available in the early 1990s.

Task 1.2 - Near field broad band data

Team: R. Madariaga (ENS Paris)
S. Ruiz (PhD, U. Chile), F. Leyton (U. de Talca)

We developed a new method for the kinematic and dynamic inversion of near field records. We use all available broad band data in the near field. The digital accelerograms acquired in Chile both by the IPOC and the University of Chile networks record the real GPS time, they can be used to determine arrival times that allow us to carefully relocate the sub-events of large earthquakes. We propose now to invert simultaneously the seismic and geodetic data in order to get the best possible model for the main event of Tocopilla. A model determined by Peyrat et al (2009) using the accelerometer data is shown in Figure X. We propose to improve this preliminary inversion with broader band data filtered down to 1 Hz. This will bring unprecedented detail about the slip distribution of any previous large subduction earthquake.

Task 1.3 - Co-seismic perturbation of the velocity medium

Team: P. Bernard (IPG Paris), J.-P. Vilotte (IPG Paris), F. Brenguier (IPG Paris), N. Shapiro (IPG Paris)

A large stress fluctuation (dynamic) and stress drop (static) has affected the crustal volume above the activated fault plane. As a consequence, one could expect a significant change in the seismic velocities, at least in the shallow crust, due to a perturbation (increase?) of the crack density. We will investigate this with two tools. First, empirical Green's functions will be generated by cross-correlating the continuous noise records of the IPOC stations. EGF surface waves will then be compared at different epochs, before and after the earthquake, for detecting possible delays of propagation. Second, S wave polarization from local events, recorded at the IPOC sites, will be analysed for detecting crustal shear-wave splitting, and changes of directions and/or fast-to-slow S delay will be tracked in space (sites) and time. The comparison of both methods will help to separate dynamic from static perturbation.

Task 1.4 - Relocation and space-time characteristics of the aftershock series

Team: P. Bernard (IPG paris), R. Madariaga (ENS Paris) , M. Lancieri (PostDoc, ENS Paris)
J. Campos (U. Chile), A. Perez (U. Chile), G. Meneses (Master, U. Chili)

External collaborators: M Sobiesak (GFZ Potsdam), S. Eggert (Ph.D. Potsdam)

We propose to determine the location of all possible aftershocks using the data acquired during the event. For this purpose we have explored the data from all Chilean stations installed after the main event and the extensive data set available from the IPOC stations. Preliminary work for the first two days of the event show that aftershock data clearly delineates the two patches of the main event found by previous studies. Our determinations show that the the second part of the rupture broke the region of Mejillones on November 14. This is different from the models produced by earlier works (Delouis et al , 2009 and Perat et al, 2009). The locations reported by USGS using data from the international network are very different from those obtained from the IPOC data, specially that we can now determine close to a 100 evens on the afternoon of the main event.

We propose to improve the location of late aftershocks, starting from November 20, reading carefully all the data available in High and Low gain channels of the IPOC network and the data read from the 46 temporary stations deployed by the DGF (U. de Chile), the GFZ Potsdam and IPG Paris which are being merged in a single data base. This post-seismic network reoccupies part of the sites of the post-seismic network deployed by the Task Force of the GFZ after the 1995 Antofagasta earthquake.

The accurate relocation of the aftershock sequence, with double-difference techniques, will provide first order insights of the possible irregularities of the interplate seismogenic contact geometry. They may also reveal seismic activity and faulting away from this contact, possibly related to old structure (in the subducting plate) or to fluid migration (in the overriding plate).

The temporal characteristics of this seismicity will also be investigated. A global overview can be provided by plotting activity rates versus time, and distribution of inter-event time delays, in different areas of interest: within the two main co-seismic asperities, around them, at shallow depth, below the Mejillones Peninsula, close or far to the main aftershocks.. The fit of a gamma law to the selected distribution should provide the degree of dependence or "cross-triggering" between the events, and possibly define areas of different mechanical behaviour.

The systematic detection and classification of multiplets in the aftershock sequence, if any, will be used to refine their relocation (using time differences calculated from cross-correlations). For non-overlapping events in a given multiplet, the dip of the deduced fine structure will be analysed and interpreted in terms of interplate or intraplate structure, at the scale of the multiplet. For overlapping events (repeaters), the modelling may involve forcing creep around them, and their inter-event time delay would then be diagnostic of the creeping rate; cumulative slip would also be estimated (through seismic moment and size/corner frequency), and should constrain the creeping rate.

The study of aftershock location is essential for the determination of slip distribution of the main event and a better characterization of the co-seismic asperities and post-seismic asperities involved in the

Tocopilla earthquake. The aim is to contribute to localize and characterize patches of creeping areas, which would surround locked seismogenic areas.

Task 1.5 - Foreshock activity

Team: P. Bernard (IPG Paris), J.P. Vilotte (IPG Paris)
J. Campos (U. Chile), G. Meneses (U. Chile)

The same space-time analysis as above will be conducted on the foreshock sequence which was well developed at least one day before the mainshock. They will be relocated together with the aftershocks, in order to benefit for the better absolute location of the latter. The space-time organization of the foreshock sequence, and its spatial relationship with the coseismic hypocentral asperity, will help to constrain the nucleation process of the earthquake.

Task 1.6 - Analysis of accelerograms

Team: R. Madariaga (ENS Paris), P. Bernard (IPG Paris), J.-P. Vilotte (IPG Paris), A. Fuenzalida (Master, ENS Paris)
J. Campos (U. Chile) , S. Ruiz (Ph.D. U. Chile), F. Leyton (U. de Talca)

The accelerograms data set available at DGF in Santiago contains 100s of well recorded accelerograms for all the aftershocks and a few foreshocks of the November 14 event. These data will be studied in detail in order to obtain information about the rupture process of the main shocks, in particular in order to understand very carefully the wave propagation processes at lower frequency. Our goal is to determine the frequency limit within which we can consider deterministic models of the source. Current know-how about accelerograms is mainly established from shallow earthquakes in the US Europe and Japan. Few of these events are large subduction earthquakes. We expect to contribute with new insight about wave propagation near a shallow dipping seismic source in a subduction context. Recent work by Ruiz and Saragoni (2008) has shown that accelerograms up to a few Hz carry information about rupture process at the source and that random effects like scattering and multi-pathing merge in at a few Hz. In the framework of the Ph D thesis being prepared by Sergio Ruiz at the University of Chile and Ecole Centrale in France, we will:
a) Select small events that can be used as Green functions for larger events. This work is already well in progress by S. Ruiz. It is astonishing to see that near field terms for an earthquake of M 6.8 can be recovered from small events of magnitudes close to 4.
b) Study the radiated spectrum of aftershocks of different size determining moment, corner frequency and energy radiation in order to establish a scaling law of the earthquake spectrum in Chile.
c) Model small and large events using spectral methods calibrated by empirical Green functions as suggested by Irikura and colleagues Our hope is that we can provide physically based spectra for earthquake resistant design in Chile.

Task 1.7- Early warning

Team: R. Madariaga (ENS Paris), C. Vigny (ENS Paris), M. Lancieri (PostDoc, ENS Paris)

There is a major debate in seismology regarding the use of magnitudes determined from a few seconds of P wave recording in early warning. So far data are inconclusive, some authors believe this is possible, others believe that the magnitude of large earthquakes can not be determined from short time series. The same debate animates the Geodesy community. Numerous papers have been published after the 26 December 2004 mega-thrust earthquake of Sumatra to investigate the possibility of determining roughly but accurately the localization and magnitude of a large earthquake, using early GPS displacements (eg. Bock et al, 2004; Blewitt et al., 2006; Sobolev et al., 2007; Song et al., 2007, Blewitt et al., 2009). Because we have data provided by cGPS stations in near and far field, including high sampling rate stations (5 Hz), we can apply and test those methods (rapid static or kinematic) to this earthquake. We will also analyse the data (using both temporal and sideral filtering) before the earthquake to check for possible precursors.

The Chilean data set being uniform, we will attempt to test early warning for these events. The conclusions of this study will be very important for several projects currently in progress in Europe, Japan, Mexico of the US because we are the only ones.

Task 1.8 - Post-seismic deformations

Team: A. Socquet (IPG Paris), M. Bejar (PostDoc, IPG Paris)
D. Carrizo (U. Chile), S. Barrientos (U. Chile)

The release of deformation accumulated during the inter-seismic period is not purely instantaneous. Following the earthquake, a post-seismic period of unknown duration starts, during which deformation is released silently and continuously. Post-seismic deformation results from a combination of different phenomena each of which has a characteristic time-scale. Deformation occurring over a month period represents mostly immediate after-slip due to either a-seismic slip in the poorly consolidated sediment layer overlying the fault or co-seismic slip associated to the aftershock sequences. Deformation occurring over a year period might be dominated by poro-elasticity, and thereafter by visco-elastic or plastic flow from low-viscosity shallow earth layers. An increasing amount of evidence indicates that after-slip follows the majority of earthquakes, particularly in subduction zones (eg. Heki et al., 1997; Ruegg et al., 2001; Marquez-Azua et al., 2002, Perfettini et al., 2005). The size and duration of the post-seismic deformation also depends on the magnitude of the earthquake, the depth of the rupture, and many other parameters. One of the important things to understand about these post-seismic deformations is whether they contribute significantly to the seismic cycle. In other words, do they dissipate “silently” a significant amount of elastic deformation accumulated before the earthquake. Should this be the case, then the amount of deformation available for the seismic events is reduced. We will monitor Tocopilla event post-seismic deformations with InSAR (with monthly SAR images stacked into time series) and GPS measurements (both cGPS and repeated campaigns on dense benchmarks network). These data will allow to model slip distribution on the subduction interface, and in particular constrain its amplitude, localization and depth.

Task 1.9- Mechanics of the Tocopilla earthquake

Team: P. Favreau (IPG Paris), J.-P. Vilotte (IPG Paris)
J. Campos (U. Chile)

The main earthquake of November 14 was followed by a large M=6.8 aftershock that occurred near the southern end of the rupture zone of the main event. This aftershock had a very rare fault plane solution: along the slab compression with slip on a sub vertical that is such that the subducted plate **shortened** instead of extending as is usually the case with the very frequent intra-slab seismicity in Chile, for instance, the 1939 Chillan, the 1950 Antofagasta or the recent 13 June 2005 Tarapaca earthquake. The 16 December event is similar to the Punitaqui earthquake of October 15, 1997 that occurred 3 months a series of magnitude 6-7 that occurred on the plate interface between Ovalle and Tongoy in the Coquimbo region of North Central Chile. An interesting hypothesis about the nature of intraplate earthquakes was proposed by Astiz and Kanamori (1986) is that they are due to the relaxation of internal stress inside the subducted plate with cycles of tensional and compressional events. They proposed that preceding large earthquakes are tensional and compressional after the main event. This simple model clearly applies to the 2007 earthquakes. A more detailed model based on Coulomb stress was proposed by Gardi et al (2004) that we will carefully test. In order to build a more detailed model of stress transfer we have to do all the previous work: improve locations, obtain a better slip distribution, compute vertical distribution of seismicity and compute Coulomb stress transfer for different models of slip distribution.

3.3.2 TASK 2 SEGMENTATION, SPATIO-TEMPORAL VARIATION OF THE DEFORMATION AND OF THE COUPLING

Coordinator: C. Vigny (ENS Paris), G. Vargas (U. Chile)

Like other subductions in the world, the Chilean subduction is segmented in several sections of different length, geometrical characteristics and physical properties which lead to different behavior. Varying obliquity, changing dip angles, different locking depths, define the segment properties, and in particular the coupling between the two converging plates. Tears in the slab, indentation of fossile structures of the oceanic plate in the continental plate, asperities, define the segment boundaries or barriers. Each segment will accumulate elastic deformation in its own way, live different seismic cycle and produce different earthquakes. However, segments do interact with each other: because of strain and stress transfer, a rupture on a given segment will promote failure of the adjacent segments. Also, even if ruptures usually occur on individual segments and stop at their boundaries, some ruptures seem to pass those barriers and generate much larger earthquakes than expected, like was the case for the 26 December event of Sumatra. On the opposite, several successive ruptures may stop short of reaching the barriers and give the impression of smaller segments... until a larger rupture happens. In Chile, the historic record begins around 1570 with the first accounts provided by the Spanish settlers. Its analysis gives a lot of information on segments behavior and patterns of seismicity on the trench since then, but is biased by the scarcity of early settlements, the difficulty to interpret old documents and, most important, by the relative shortness of this record versus a seismic cycle of possibly many centuries (eg. Lomnitz 1971; Beck et al., 1998). Several sections of the subduction could produce magnitude 8+ earthquakes similar to those of Concepcion (1835), Valparaiso (1906, 1985), La Serena (1880, 1943), Vallenar (1819, 1922), Arica (1877); or rupture several segments continuously in one larger magnitude 9 earthquake like the mega event of 1730 which seemed to have ruptured the whole central part Chile, from Concepcion to LaSerena. The recent earthquake of Tocopilla (2007) could be an indication of the preparation of a larger rupture on this particular section of the fault (the gap of Arica). It could also be that the intra-plate events (Chillan 1939 ~35°S, Punitaqui 1997 ~30°S, Tarapaca 2005 ~20°S) are an indication of the preparation of the subduction interface for a major rupture.

Task 2.1 Spatio-temporal variation of the coupling along subduction segments

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Over the last 15 years, different groups have been doing GPS measurements along the Chilean and Peruvian subduction zone to quantify the surface deformation of the continental plate during the inter-seismic part of the cycle (SAGA Klotz et al., CAP Beavis et al., SNAP Norabuena et al.). This elastic deformation is controlled by the plate tectonics velocity, the geometry of the slab (dip angle, width of locked zone) and finally the amount of coupling on the interface. This deformation affects a very wide area including all Chile and penetrating deep into Argentina on the other side of the Andes, Up to now, all studies concentrate on the geometry and assumed full coupling, or complete locking, of the interface (eg. Khazaradze et al., 2003, Brooks et al., 2003; Chlieh et al., 2006)

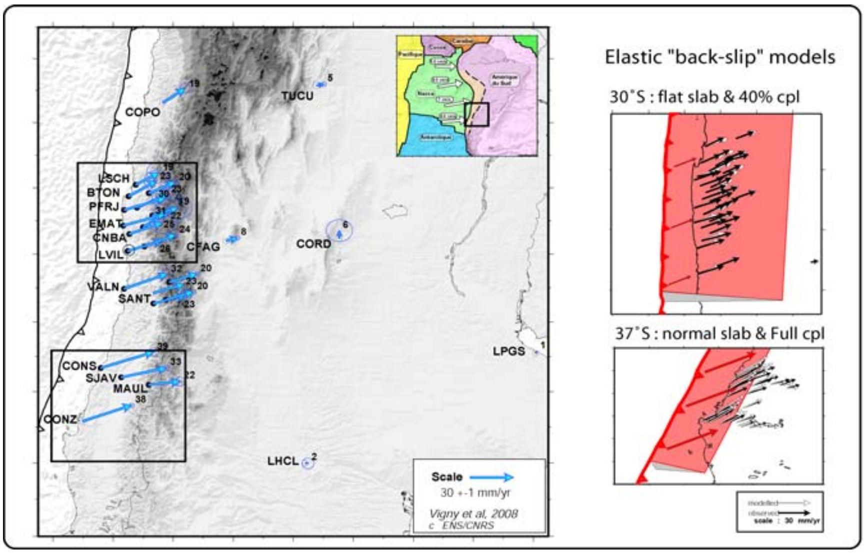

***Fig 6** : Gps measurements in central Chile(left), and models (right): Fully coupled in Concepcion gap (bottom), partially locked in Illapel gap (top)*

Recent more detailed studies based on small scale networks (Ruegg et al., 2009; Vigny et al., 2009) show that if this model applies well in the Concepcion are (35°S-37°S), there is a clear change of trend in the Coquimbo region between 30°S and 32°S, and that this region is itself different from what is expected from the standard elastic modelling. Coastal stations lying approximately at the same distance from the trench have decreasing velocities as their latitude increase: stations at corresponding latitudes have approximately the same velocities: Therefore, it is the amount of compression that is changing (decreasing) with latitude. This decrease is so intense, that North of 30.3°S (Tongoy) the compression is essentially zero. All stations in this area from the coast to the Andes have roughly the same velocity. Profiles of compression with distance to trench sorted by latitude depict this tendency very clearly: strain in the Coquimbo area is on average two-times lower than the average strain rate corresponding to the profiles measured between 35°S and 37°S. Moreover, a steady decrease of strain rates with latitude seems to emerge from the picture.Thus, the most important finding of these studies is that to model these patterns with a full coupling on the trench is not possible. Following Norabuena et al. (1999), and contrary to Khazaradze et al. (2003) and Brooks et al (2003), we conclude that coupling must be varying on the interface, both with depth and along strike, and can reach value as low as 40% regionally and even less locally. A very important question remains: whether this diminished coupling is a permanent feature or transient. We noted the presence of an active seismic swarm over the last decade in the area, triggered by the intraplate “slab-push” earthquake of Punitaqui in 1997 (Gardi et al, 2006, Vigny et al, 2009).. In principle, the cumulative co-seismic deformation from the swarm might explain the relatively low slip deficit we observe but the cumulative moment over the last 15 years (1992-2007), only accounts for a small (~1/4th) part of the slip deficit. Therefore we conclude that the bulk of the slip deficit (~3/4th) comes from the modification of the friction properties of the interface, triggered by the intra-plate event of 1997, but not from co-seismic slip.

This task is two-fold:

For spatial variations, we want to:

- Compile all existing inter-seismic GPS velocities in the Chilean trench, and merge them in an homogeneous set of vectors (which poses an acute problem of rotating all these solutions in a common reference frame. Some reprocessing may be needed.
- Re-analyse this data set without a-priori ideas on the locking, inverting for the amount of coupling as well as the geometric properties of the interface.

- Complete the data set by acquiring new measurements where needed, more specifically in gaps between existing small scale benchmark networks. In the metropolitan area, between La Serena and Copiapo, between Tocopilla and Aricca.
- Merge the GPS data with InSAR data, systematically acquired and processed

For time variations, we want to:

- Complete the existing data base with the daily data flow provided by the existing cGPS network of ~60 stations for the duration of this project, and the data provided by the tiltmeter. For this purpose, we need to maintain the network, decrease data loss, improve automatic procedures of data transfer and data processing.
- Reprocess all the existing cGPS data in an homogeneous way to produce accurate time series.
- Re-analyse those time series using recent atmospheric and oceanic loading models, filtering out seasonal effects like the hydrology and geodetic monument noise using appropriate models.
- Produce InSAR time series by stacking all available SAR images on selected areas
- Merge these times series with those provided by the long base tilt-meter in Iquique. The tilt-meter is an extremely sensitive instrument, which records very small deformation on a very broad spectrum. However, the long term drift of the instrument is not very well known, but could be calibrated using the GPS data.
- Analyse of the long base tiltmeter signal using corrections from yearly cycle, from earth and sea tide, and atmospheric pressure. The residual, having drift less than 10^{-7} per year, will be interpreted as coseismic effect and transient deformation, or change in the tectonic loading rate. Transient signal will be compared with space-time changes microseismicity rates, and to GPS displacement sequences, from interfering their causative processes.
- Look for transient variations with spatial coherence which could be associated to deep processes occurring on the subduction interface like silent slip or non-volcanic tremors
- Systematically associate these transient motions to the seismicity, whether it occurs on the subduction interface and/or is triggered by an intraplate intermediate depth earthquake (like was the case for the Punitaqui earthquake of 1997 in the Coquimbo area).

Deliverables: velocities data base and time series

Success indicators:

- Establisment of a data base of velocities in a common reference frame
- Decrease of data loss: currently (test year = 2007, 15 stations in central Chile) we suffer 13% of data loss, due to all kind of reasons, from power failure to full memory buffer. We want to reach at least 10%, possibly 5%.
- Decrease final product (stations daily position, and hourly atmospherical delays) latency: currently, the process is semi-automatic and ends 31 December 2008, implying a varying latency of at least 3 to 6 months. We want to reach a stable latency of at least 3 months, possibly 1.

Methodology

<u>GPS Equipment</u>

- **cGPS**: Trimble Net-RS + Zephyr Antennas. These Geodetic dual-frequency receivers allow to acquire data at high sampling rate (up to 10Hz - useful in case of earthquake) and geodetic sampling rate (30s) simultaneously. Their capacity to internally store data up to 1 Gb is precious in case of local computer failure or data transmission rupture. The Net-Rs has also been chosen by Caltech, Nucleo millenio, Argentina and Brasil groups for their projects in South America. We have accumulated a lot of experience with this equipment over the last 4 years.
- **Campaigns**: we use specially designed bolts sealed in bedrock outcrops. These sites enable direct antenna centering with sub-millimeter accuracy. One campaign is 2-3 teams deploying

~15 receivers simultaneously and moving them every 4-5 days from one site to the next ones. 2 to 3 weeks of measurements allow to survey 40 to 60 sites with the millimetric precision provided by 24 hours long sessions repeated at least 4 times on every site. We will use the Ashtech ZX-treme pool of receivers made available to us by the LIA “Montessus de Balore” (6 receivers) and the French INSU (30 receivers) at no cost. We will repeat campaigns every year in order to get velocities constrained by 3 points over 2 years of time span at the end of the project duration.

Tilmeter Equipment

- Tiltmeter: a long base tiltmeter has been installed in August 2007 10 km NNE of Iquique in a tunnel of the Neuquen mine. The instrument has been developed by F. Boudin during his thesis at IPGP. This instrument isbased upon the hydrostatic level principle, with silicium floats and LVDT displacement sensors. It has a resolution 100 to 1000 times more accurate than cGPS. On the other hand, this resolution makes the instrument quite sensitive to meteorological perturbations requiring a well controlled and isolated underground installation.

Software

- **GPS data processing** : GAMIT
  We will implement the GAMIT/GLOBK package (*King and Bock*, 2000; *Herring et al.*, 1990) at DGF to process all acquired data. Standard procedure (repeated sessions of 24hours of measurements, the use of IGS precise orbits, the modeling of Ionosphere and troposphere effects using the GPS data themselves, the resolution of ambiguities, mapping in precise ITRF2005 reference frame using Helmert transformation) will allow to reach a precision of 2-3 mm/yr on most points surveyed with these methods in no more than 2 years of measurements.
- **InSAR data processing** : ROI_PAC
  We will process automatically all existing data on our selected target areas, using the well known ROI_PAC package developed at JPL. One of us (A. Socquet) is expert in using this software after a 2 year postdoc with one of its co-developer (G. Peltzer).
- **Elastic modeling** : RNGCHN, DEFNODE
  In this project, we will use only “simple” elastic equations developed by Okada in the 1980’s (*Okada*, 1985). In a first step we will do forward modelling using dislocations on simple rectangular planes with the RNGCHN software (*Feigl and Dupré,* 1999). In a second step, we will do a complete description of the slab and plausible continental faults geometry and a full inversion of slip deficit on these structures using the DEFNODE software (*McCaffrey*, 1995)

Data flow
Data are acquired by the GPS receivers at different sampling rates (1Hz or 30s). Daily files are generated and stored in the receiver memory (RAM or flash card). Those files are transmitted through modem, DSL or internet when available, or downloaded manually and occasionally otherwise. Those files are collected, checked and archived at DGF. They are ultimately sent to processing centers (IPGP and ENS at the moment), where they are merged with global data (IGS) and processed. Daily estimates of station positions are computed, time series and velocities over given periods of time are generated. In this project, we want to decrease the loss of data, and raise the rate of data collection to 100%. We want to improve the efficiency of the data streaming so that daily positions and time series are computed faster and broadcasted earlier.

- **1. in situ** : We need to decrease the probability of data loss by increasing the size of the buffers and the number of back-ups.
- **2. Data transfer** : We need to increase the number of stations connected to internet, or to high speed mobile telephone data transfer technology (EON)
- **3. Data quality check** : We need to implement automatic routines of data collection, automatic quality check, alarm sending. This implies in particular a continuous effort and a maintained link with all the institutions hosting our instruments within their internet network and behind their firewalls.

- **4. Automatic data processing** : We need to implement existing routines for automatic data processing at all processing centers.

Sub-Tasks 2 and 3 in particular, require qualified man power in Chile. This task is strongly interconnected with Task 2.2 and Task 1.8.

Task 2.2 - Spatio-temporal signatures of seismogenic asperities of the subduction interface in Northern Chile

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External Collaborators: M. Sobiesiak (DGF Potsdam), S. Eggert (Ph.D. Potsdam)

Spatio-temporal monitoring and analysis of the seismic activity along the subduction zone of Chile, in relation with the main structures and geometry of the subduction interface,together with pressure and temperature dependent dehydration processes, should provide important informations for understanding the structuration and the dynamics processes in seismogenic segments of a subduction zone.

Previous Studies in The Andean subduction zones have found evidences that rupture length and coseismic slip vary between successive earthquake cycles in the same segment of the subduction zone (Kanamori and McNally, 1982; Collot et al., 2004), more over interactions between adjoining segments along the subduction zone remain poorly understood. It has been recently prosed (Peyrat et al., 2009), based on the rupture history suggested by the recent Tocopilla earthquake (Mw 7.6, 2007), that Norther Chile could be reminiscent of the Ecuador-Colombia region where inferred rupture area of the very large 1906 mega-thrust event (Mw 8.8) was the site of three thrust events in 1942 (Mw 7.8), 1958 (Mw 7.7) and 1979 (Mw 8.2). The best known example of such regime of seismic activity is probably that of the Nankai trough (Ando, 1975). A crucial question today is whether Northern Chile will break in the future with a single rupture encompassing all the Northern Chile, or whether Northern Chile will enter in a regime similar to that of Central Chile.

A simple paradigm, to understand these complex spatio-temporal patterns of earthquake in subduction zone, is the asperity model proposed by Kanamori and McNally (1982) and Ruff (1992) in which small earthquakes represent failure of individual asperity while great earthquake represent the collective failure of several asperities depending on the asperity interactions and the history. The Tocopilla earthquake suggests that the asperity sizes have to be smaller than the interplate width implying along-dip and along-strike asperity interactions. Furthermore, non-volcanic tremors (Roggers and Dragert, 2003; Obara et al., 2004; Shelly et al., 2006), extended duration episodic seismic signals observed along major subduction interface in Japan, Cascadia and Mexico, often in conjunction with slow slip events, strongly suggest the importance of seismic/aseismic interactions between asperities.

A critical step issue is to better identify and characterize sismogenic asperities in Northern Chile based on high quality observations of recent seismic activity, and to assess whether these asperities are persistent both in space and time. Another issue is to understand how asperities are generated.

Recent studies recently pointed out potential relations between seismogenic asperities on the subduction interface and geologic, tectonic and topographic features. Correlations between deep sea terraces and sedimentary basin structures and seismogenic slip asperities, along convergent margins, have been proposed as a proxy for the identification of variations of coupling and the state of stress on the plate interface (Song and Simons, 2003). Geometry, surface topography and tectonics features of the subducting plate, e.g. seamounts, ridges, weak transverse faults, have long been identified to leave seismic signatures, like aligned seismic activity and clusters, in relation with the segmentation and the variation of coupling along subduction zones.

Northern Chile has be shown (Comte et al., 2003, Riedbrock and Waldhauser, 2004) to be characterized by a strong intermediate depth seismicity which delineates, like in Japan, a double seismic zone and can produce large intermediate depth earthquake. Wave form analysis of records from the 1950 Mw 8 Calama earthquake, the 2005 Mw 7.6 Tarapacá earthquake, and the Mw 6.8 December 2007 aftershock of the Tocopilla earthquake have shown that these events are of slab-push or slab-pull nature , associated with nearly vertical fault or sub-horizontal rupture plane within the subducting plate and high stress drop. Intermediate depth earthquakes are though to be enabled by dehydration embrittlement processes (Kirby, 1995; Jung et al., 2004). High precision relocations of intermediate-depth earthquakes studies (Riedbrock and Waldhauser, 2004) suggest that this seismicity might be related to repeated rupturing of a low-permeability seal, at the interface between the oceanic crust and the continental mantle, triggered by pore-pressure increase due to dehydration processes in the down-going mantle and crust. Space and time variations of the intermediate depth seismic activity could provide new informations of the dehydration processes and their potential link with slow-slip and tremor events at the base of the coupled zone.

Up to now a detailed analysis and understanding of these asperities in Northern Chile is missing. The aim here is therefore to improve our understanding of:

- the signature of the seismogenic asperities in the spatio-temporal seismic activity patterns and in potential variations of seismological parameters ;
- the origin of these asperities in relation with the segmentation of the subduction zone and their spatio-temporal stability during seismic cycles ;
- the seismic and aseismic asperity interactions along-stirke and along-dip of the seismogenic portion of the subduction interface ;
- the potential relation between asperities, tremors and slip transients.

This task is therefore closely interconnected with tasks 2.1 and 2.3 together with tasks 1.4 and 3.1. It will be primarily focused in Northern Chile region where we have high quality data sets to start with, as detailed below. This task will be performed in close collaborations with our colleagues at the GFZ Potsdam.

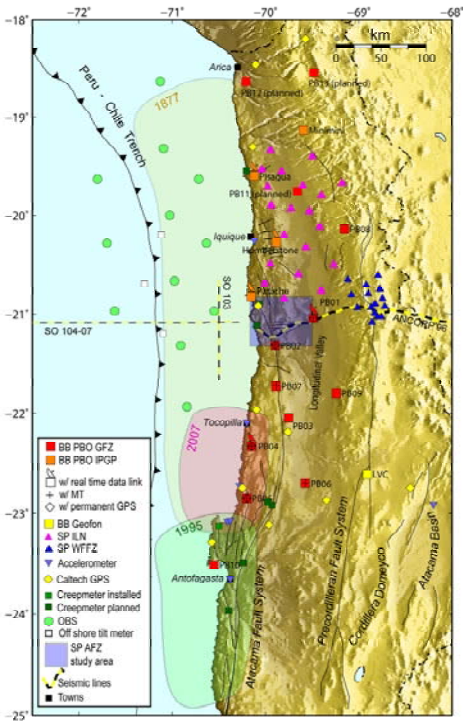

Fig 7: Networks monitoring Tocopilla earthquake (dots), and asperity (grey patch)

The main objectives in this task will be to investigate various indicators of asperities:

- seismic repeaters based on clusters of repeating earthquakes or doublets,
- seismic scatterers based on differential seismograms analysis and coda wave interferometry,
- temporal changes in seismic velocities based on coda wave interferometry and cross-correlation noise analysis,
- ES/M0 and energy spectrum variation analysis
- statistical analysis of the seismic activity in space and time and b-value distribution
- short term transients like tremors and low frequency events in connection with potential slow slip events detection of task 2.1.

For tremor analysis, a first step detection will be based on envelope analysis, adaptative filtering and moving window analysis of the existing IPOC stations; a second step, provide transient signals can be detected, will make use of seismic antenna techniques (some ILN stations), and investigate energy envelop and phase inter-station correlations to improve detection and locate these events.

Available data for the study

In Northern Chile, the IPOC (DGF/GFZ/IPGP) network, integrating broadband, strong motion and cGPS in continuous mode, has been operating for three years now and has already recorded a large volume of high quality data. This IPOC data set will allow to start with and to investigate the seismicity activity in this segment just after the Tarapaca earthquake (2005).

In 2009, the Iquique Local Network (GFZ) (20 seismogical stations: 14 broadband, 6 short period stations) will be integrated to the IPOC network. All together IPOC and ILN will provide a very dense array in the area of Iquique, with a wide combination sensor bandwidths. Merged into the IPOC data set, this additional network will provide during the project unique observations for improving the monitoring and the analysis of the seismic activity, in space and time, as well as for the detection of potential transient signals like tremors in the next three years. Temporary seismic antenna experiments will be performed using stations of the ILN network and permanent IPOC stations, based on preliminary transient signal analysis.

A German Geomar project (H. Kopp) should install, in coordination with IPOC, 12 OBS stations in this area. When installed and the data merged with the IPOC data base, this will have a major impact on the precision of the hypocenter determinations. The OBS network should be operated for at least 3 to 5 years.

Informations on the deep structure of the Northern Chile segment exist from previous previous large geophysical and seismological experiments (ANCORP Working Group, 2002) and a high quality catalogue of over 14000 events could be gathered from the PUNA'94 and ANCORP'96 temporary short period experiments (Haberland and Rietbrock, 2001; Martin et al., 2003). Aftershocks catalog from the postseismic temporary networks of the 1995 Antofagasta and the 2007 Tocopilla will be merged.

These analysis will require the constitution and the management of

- high quality event and multiplets data bases
- automatic detection and signal analysis tools

Routine tools have to be developed and implemented to continuously perform basic data processing and include new incoming data in an event based data base. Standard data processing will include the use of relative hypocenter relocation methods.

The multiplet data base will be generated automatically, based on the results of standard automatic location: The continuous seedlink data flow from the stations is first analysed for triggers, which are associated in time for defining events: each new event is compared to the entire multiplet data base (singlets and representant of each mutiplet), by cross-correlation, and it is itself put in the data base, either as singlet, or as an additional event of some already existing multplet. This procedure is presently being developed by S. Lambotte and H. Lyon-Caen at ENS, for the Corinth data base (CRL), and the tools will be transferred and adapted to the Chilean data.

Success indicators: Event based and multiplets data bases with automatic routine tools
Analysis of repeaters and scatterers in Northern Chile
Analysis of intermediate-depth seismic activity
Tremors analysis

Task 2.3 Origin and spatio-temporal stability of the barriers

Team : R. Armijo (IPG Paris), R. Lacassin (IPG Paris), A. Coudurier-Curver (PhD., IPG Paris)
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Stable structural barriers correspond very often to regions of structural and geometrical complexity in the fault zone (the coupled region of the subduction interface in this case). Such regions appear to be characterised by specific deformation features, which can accumulate over the long-term and propagate to the surface. If the barrier is important and long-lived, the cumulative deformation is strong and it can be identified as a singularity along the coastal morphology. It has been suggested that the upper plate structure underlying large peninsulas like the Mejillones and the Lengua de Vaca peninsulas (north of Antofagasta and south of La Serena, respectively, see Armijo & Thiele 1990; Ruegg et al., 1996) is a direct result of long-term deformation associated with specific structural barriers in the subduction interface. Rupture of both, the 1995 Antofagasta earthquake (Mw 8.1) and the 2007 Tocopilla earthquake (Mw 7.8) has probably been arrested by structural complexity under the Mejillones peninsula. The same is possible for the rupture of the larger 1877 Iquique (M~8.5) earthquake. For the well-documented 1995 and 2007 events, both the aftershock seismicity and the post-seismic deformation show clearly specific patterns under Mejillones (Delouis et al., 1997; Chlieh et al., 2004; Pritchard & Simons, 2006; Sobiesak et al., 2008; Béjar-Pizarro et al., 2008; 2009 in prep.; Delouis et al., 2009). The strongest (southern) subevent during the 2007 main shock appears rupturing partly into the region of structural complexity and also the two large aftershocks that occurred just the day after the main shock have ruptured close to that area (Peyrat et al.,2009).

Recent work focused on the study of sedimentary records off the Central Andes provides new perspectives about the problem of the occurrence of large earthquakes in the Andean subduction margin. The narrow shelf off Northern Chile is characterized by low sediment accumulation. However, Holocene series can be found in small shallow basins protected from coastal hydrodynamic as well as from oceanic currents. This is the case of the Mejillones Bay, where relatively high sedimentation rates, derived from detailed ^{210}Pb and ^{14}C down-core data (0.13-0.15 cm a^{-1}; Vargas et al., 2004; 2005; 2007), are associated to the accumulation of pelagic sediments derived mostly from organic material close to intense up-welling centres (Ortlieb et al., 2000; Valdés et al., 2004; Vargas et al., 2004). Anomalous sedimentary structures in this kind of sediments, as slumps and discontinuities, have been associated with large historic earthquakes in the area (Vargas et al., 2005). In fact, in this hyper-arid environment, characterized by mean annual rainfall of. 4 mm/yr, sporadic heavy rainfalls produce debris flows that cause a localized impact along the coastal fringe (Vargas et al., 2000; 2006). Thus, slump deposits of 10-40cm thick within the pelagic sedimentary sequences in the shallow marine basin, can be interpreted as the direct effect of large seismic events, as those occurred in 1877 and in 1768 off Northern Chile, which can be precisely dated through ^{210}Pb and AMS ^{14}C geochronology (Vargas et al., 2005; Villaseñor et al., 2008). The ongoing study of short sediment cores from this bay (1 m and 5 m long), have revealed the occurrence of other slumps and discontinuities that can be interpreted as previous seismic events of probably similar characteristics in the last ca. 2000 years (Vargas et al., 2008). Large slump deposits of ca. 5 m thick, observed from high resolution 12 kHz seismic data within the Holocene sedimentary infill of the Mejillones Bay, are associated to stratigraphic horizons affected by submarine fault scarps, indicating reactivations of faults during recent time, which provide crucial information about recent crustal earthquakes (Vargas et al., 2005; Becerra, 2007).

Beside the Mejillones Peninsula, other barriers will be investigated in Central Chile in relation with the segmentation of the subduction in Chile and their implications for great earthquakes. In particular in the bay of La Sereana between the two peninsulas of Lingua de Vaca in front of Tongoy (30°S) and Punta de Choros (29°S) which may be identified as a potential barrier similar – but reversed in topography - to the Mejillones peninsula barrier in North Chile, and in the he Arauco peninsula immediately South of Concepción (37°S-38°S) which acted as a barrier for the 1835 and 1960 earthquakes, with evidences of both quaternary and contemporary uplift.

During the project, we intend to characterize the surface long-term deformation and the palaeo-seismicity associated with the structural complexity under the Mejillones peninsula and surrounding areas of the subduction zone.

- For the first purpose, we will study in detail the geology and the morphology of surface features to deduce a set of deformation models kinematically consistent with seismological and geodetic observations (A. Coudurier-Curveur thesis). We will use high-resolution DEM's and precise geologic field-work, including 40Ar-39Ar dating of volcanic ash embedded in the most critical stratigraphic markers.

- For the second purpose, we will pursue exploratory studies of past large seismic events, as those that occurred in 1877 and in 1868, which appear recorded by slump deposits within the pelagic sedimentary sequences in shallow marine basins along the shelf, north of Mejillones. We will use a shallow-penetrating 3.5 kHz sounder combined with sediment coring and precise AMS 14C geochronology to date the events (see Vargas et al., 2005), in an attempt to establish a reliable paleo-seismological catalogue.
- Another exploratory study using the same approach will be performed north of Lengua de Vaca peninsula, in the bay of Tongoy and the Arauco peninsula in Central Chile

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Methods:

a) Analysis of DEM's for various morphological parameters, compiling geological observations with field-work, sample collection, ash sample dating with Ar-Ar technique, numerical modelling.
b) Collection of 3.5 kHz sounder profiles, collection of short sediment cores, dating of cores with AMS 14C technique, data analysis and compilation in catalogue.

This task will is interacting with tasks 2.1 and 2.2.

3.3.3 TASK 3 SHALLOW DEPTH SEISMICITY, DEFORMATION PARTITIONING AND ACTIVE FAULTS AT THE SURFACE

Coordinator: S. Barrientos (U. Chile), R. Armijo (IPG Paris)

It has been almost two decades now that GPS has been used to measure plate tectonics and quantify plate deformation. In South America, the debate rapidly focused on the motion of the Nazca plate relative to the South America plate. Since the initial work of (*Larson et al., 1997*) which found similar rates, it is well known now (eg*: Norabuena et al, 1998; Norabuena et al, 1999; Angermann et al., 1999; Altamimi et al., 2002; Kendrick et al, 2003; Vigny et al, 2009*) that in fact the present day motion of the Nazca plate is around 15% slower than its Nuvel-1A estimate. This finding has the important consequence that along the South American margin, instead of nearing 8 cm/yr, today's subduction rate ranges from 5.5 cm/yr in Equator to 7 cm/yr in central Chile, before it decreases again to 6.5 cm/yr in southern Chile. Up to now, two different families of models have been presented. Based on campaign measurements over a network of hundreds of geodetic benchmarks spanning the whole continent (SAGA), Klotz and co-authors (*Klotz et al., 2001; Khazaradze et al., 2003*) use a 2-plate (Naza and South America) model, where the slab geometry varies with latitude and depth. Kendrick and co-authors (*Kendrick et al., 2003; Brooks et al, 2003)* also use a comprehensive network of benchmarks (CAP), but reach a different conclusion: Claiming they have a better definition of the Nazca plate (thanks to measurements at San Felix and Robinson Crusöe islands), they find a motion reduced by 5 mm/yr for this plate, and then re-assign this motion to an Andean rigid block between Nazca and South America. The seismic hazards generated by the two models are somehow different: in the first case it is maximized on the subduction and essentially zero everywhere else; in the second case it is slightly reduced on the subduction, at the cost of generating a new at-risk area on the eastern margin of their Andean block. Therefore, kinematic studies using GPS should address this important issue of assessing if enough shortening - not accommodated by the subduction - remains across the mountain ranges to generate seismic hazard on localized faults on both sides of the Andes. If such faults exist they could also accommodate strike-slip motion, similarly to the Liquine-Ofqui fault zone in the South of Chile. In this part of Chile this fault exists to accommodate the strike-slip component generated by the obliquity of the subducion, similarly to other oblique subductions in the world like Sumatra for example. Everywhere else in Chile, the subduction motion is itself oblique. It should be noted that it will be very difficult, if not impossible, to characterize a motion of 1-5 mm/yr on these continental structures if the knowledge of the deformation generated by the subduction remains at this level of uncertainty. However, if these shallow crustal faults exist and accommodate deformation, they clearly pose a serious problem in terms of seismic hazards for major cities like Santiago, built at the foot of the Andes, precisely where they might be located. Therefore, assessing their existence and quantifying their motion could reveal quite important, even if it is only at the mm/yr level. In this case, GPS measurements carried out during this project may not evidence this small signal, but precise geodetic measurements should start as early as possible anyways to provide the longer time span needed by future studies.

Task 3.1- Shallow seismicity and active faults in Central and North Chile

Team: R. Armijo (IPG paris), R. Lacassin (IPG Paris), R. Madariaga (ENS Paris),
C. Vigny (ENS Paris), M. Métois (Ph.D., ENS Paris)
G. Vargas (U. Chile), G. González (U. Católica Norte), S. Barrientos (U. Chile),
J. Campos (U. Chile), A. Perez (U. Chile)

The importance of active west-verging structures at the western flank of the Andes, parallel to the subduction zone, appears currently high-lighted by the increasing collection of seismicity data (*Barrientos et al.,* 2004) and by recent studies of the West Andean Front, particularly of the Ran Ramón Fault located immediately east of Santiago (Armijo et al., 2008). It has been shown that the San Ramón Fault, which is critical for the seismic hazard in the city of Santiago, is at the tip of a large active fault-propagation fold system affecting the whole Andean cover behind. The study of the San Ramón Fault uncovers the primary importance, probably along most of the Chilean Andes (at least from 18°S to 38°S), of the propagating West Andean Front, interpreted as the tip of the crustal-scale West Andean Thrust (WAT).

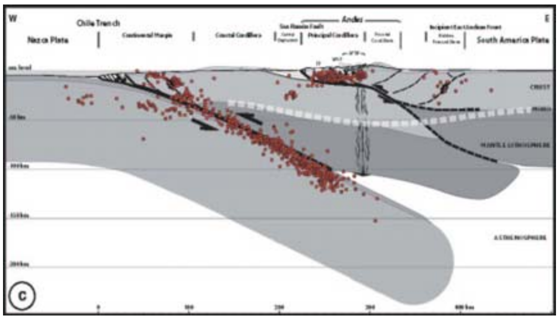


***Fig. 8**: Tectonic model of WAT at 33°S (San Ramon fault). Seismicity from the Chilean network (red dots).*

The shallow seismicity associated with the western flank of the Andes and the WAT is poorly known, mainly because of its poor record by local networks [*Barrientos et al.,* 2004]. The recent deployment of instruments in the region of the present study by the Chilean Servicio Sismológico Nacional (with good resolution near Santiago, between 33°S-35°S) provides the image of the 2000-2005 seismicity with local magnitude Ml > 4.0 illustrated in Fig. 8. Beside the seismicity associated with the subduction zone, there is significant shallow seismicity (depth of < 20 km) under the Principal Cordillera, which is mostly concentrated ahead of the Frontal Cordillera ramp anticline and apparently above the basal detachment. It may thus be associated with deformation of the Andean Basin cover, and more precisely, with the westward fault-propagating fold structure behind the San Ramón Fault.

The Principal Cordillera region has been the site of significant shallow earthquakes with M > 6.0, like the 1958 Las Melosas sequence [*Barrientos,* 2007; *Alvarado et al.,* 2008]. All these events occurred beneath the zone of west-verging folds described by Armijo et al. (2008), thus probably associated with the ramp system beneath the Frontal Cordillera anticline. Fault plane solutions obtained for six M ≥ 5.0 events are consistent with P axes oriented NE-SW to NW-SE [*Barrientos et al.,* 2004; *Barrientos,* 2007; *Alvarado et al.,* 2008]. The three (or four) larger events discussed by *Barrientos* [2007] and by *Alvarado et al.* [2008] are strike-slip events. All but one of these events are consistent with EW compression, thus with the Andean shortening. The remaining one is the Las Melosas main shock, indicating NW-SE compression, which is inconsistent with the right-lateral component of the Nazca - South America plate motion. The complex kinematics of events occurring in this region may be due to the complexity expected for the basement-involved structures that have propagated beneath [*Narr and Suppe,* 1994]. In particular, the steep front of the basement wedge appears a likely place for lateral decoupling (Fig. 8).

The San Ramón Fault, mapped in great detail, is a thrust ramp at the front of a basal detachment with average slip rate of ~0.4 mm/yr. Young scarps have been characterized at various scales and seismic events with magnitude of up to Mw 7.4 appear plausible. However, the specific relation of mapped faults with seismicity observed in the region is not well established and we will make a detailed analysis of the seismicity records available at the Chilean Servicio Sismológico Nacional with that seismotectonic aim (A. Pérez Franco thesis). We will also make a palaeo-seismological study of the San Ramón Fault with the aim of determining when the last large earthquake has ruptured that fault. (Fig. 9)

One important question is to determine how active is the rest of the WAT and specifically its seismic potential in northern Chile, where the structure of the Cordillera Domeyko (Precordillera between 18°S – 24°S) appears similar to that of the San Ramón Fault. Our working hypothesis is that a fundamental partitioning of deformation operates between the subduction zone and the WAT, and we wish to determine the ratio of this partitioning for the long-term deformation as well as in terms of seismic release.

Another important question concerns the deep Andean structure. The analysis by *Gilbert et al.* (2006) of broadband data and receiver functions provides a complex image of the deep Andean structure, revealing possible interruptions of Moho arrivals. A possible interpretation is superposition by the West Andean Thrust of crustal-scale units and involvement of the lithospheric mantle in an embryonic intra-continental subduction. We plan to re-analyze the all the available broadband data and receiver functions to document precisely the possible interruptions of the Moho beneath the Andes and use them to constrain the deep Andean structure (post-doc project to be proposed at DGF).

Task 3.2 Shallow seismicity and strain partitioning in South Chile – Aysen

Team: G. Vargas (U. Chile), G. González (U. Católica Norte)
S. Barrientos (U. Chile), K. Bataille (U. Concepción), S. Rebolledo (U. Chile),
S. Sepúlveda (U. Chile), A. Serey (Ms.Sc. U. Chile), V. Naquira (Ms.Sc. U. Chile).

On January 23, 2007, an intensity IV earthquake was felt in Puerto Aysén, a city of twenty thousand people located nearly 200 km north-east of the Nazca-South America-Antarctica triple junction. This event marked the initiation of a spatially concentrated earthquake sequence that developed for more than five months in the Aysen Fiord. Several magnitude 5+events took place being the 21 April, with magnitude Mw 6.3 the largest of the sequence. This strike-slip event (most likely oriented north-south, along one of the branches of the Liquiñe-Ofqui Fault System) produced rockfalls and landslides that generated a local tsunami causing death and destruction along the Aysén Fiord. A permanent seismic station located close to Coyhaique, about 80 km East of the epicentral region, which recorded the whole sequence of events, reveals an unusual pattern of decay of number of earthquakes as a function of time. Five more seismic stations were installed in the areas within one week of the initiation of the activity. The seismic activity, together with the observed GPS derived displacements, are interpreted as a consequence of the role of movement of fluids in magmatic conduits in the region superimposed on the tectonic framework of the Liquiñe-Ofque Fault System. Precise earthquake locations well define the source of the seismic activity. In addition, a number of GPS measurements pre and post 21 April evidence significant co-seismic displacements consistent with the seismicity.

The Liquine-Ofqui Fault Zone (LOFZ) in Southern Chile, provides a unique natural laboratory to examine the deformation of the continental margin where oblique subduction of a young oceanic plate occurs. The long-term deformation surrounding the LOFZ is mainly due to the oblique convergence, where the normal component is accommodated at the thrust zone and the right-lateral component is accommodated through the LOFZ. The short-term deformation is affected by different processes, as the ones related to the seismic and volcanic cycles for each segment, the interaction of fluids within weak zones of the crust and its heterogeneities, among others. Furthermore, different segments of this natural laboratory have become very active within the last three years, through episodes of seismic and volcanic activity: BioBio 2007, Llaima 2008 (Jan. and Jun.), Aysen 2007, Chaiten 2008, Hornopiren 2008 (http://www.sismologia.cl), providing a great opportunity to study active processes within the LOFZ.

The aim is to improve our understanding of the strain partition and of the seismic activity in this region by integrating observations from geodesy, seismology, geology and paleo-seismology. The main difficulty is the relative slow motion along the LOFZ. Understanding the origin and the relative importance of the strain partitioning between the active convergent margin and the Liquine-Ofqui Fault Zone in relation with the plates coupling in Southern Chile is a challenging scientific problem with has strong implications for the seismic hazard in this region and other subduction zone like the Sumatra subduction zone. Strain partitioning have been often advocated as a result of a change in obliqueness of the direction of convergence. This clearly can not be advocated in Southern Chile.

cGPS studies

We propose to complement the existing GPS network in the area in two more continuous recorder GPS stations in order to quantify the present day deformation of the region surrounding the LOFZ combining mainly two observational tools: precise GPS observations and seismic data. Another tool, InSAR will be used in case we recognize significant signal in GPS time series. These observations will be compared with detailed numerical modelling considering different sources of deformation distributed throughout the region.

There are already 14 cGPS instruments spread along the LOFZ from which we are currently collecting data. The processing of these data is providing a static picture of the broad deformation. Only three sites have been operating almost continuously for more than 3 years. Current cGPS stations distribution is not appropriate for determining the spatial variation of deformation, since most sites are distributed along the LOFZ and only in few areas, across. We plan to

- increase this number with 6 new cGPS sites, realize campaign GPS measurements,
- distribute 30 corner reflectors,
- acquire sufficient radar images to determine eventual deformation within last years including the first period of the project,
- strengthen our collaboration with two foreign groups working on similar problems: Bevis from Ohio State University, US and Klotz from the GFZ, Germany. Both groups have GPS campaign data from the area since 1990.

Since background displacement rate in the area is of the order of 2 cm/yr, and the estimated precision (for periods over three years) 0.2 cm/yr, it is necessary to observe at least three yeas in order to have a clear signal, and therefore a sound conclusion. During this project, the main task will be therefore to increase these observations and merge them in a data-base.

Previous geodetic studies (Klotz et al. 2006, Wang et al. 2007) have emphasized their analysis on horizontal displacements, while in this project we will include the vertical component in our analysis. The resolution of the vertical component is not as good as horizontal ones. We estimate the time series long enough (> 6 years) at some sites (Punta Arenas, Coyhaique, Puerto Montt, Antuco, Concepción, and Los Angeles) to contribute with critical informations for reducing the number of possible scenarios.

Seismic studies

Three temporal passive experiments have been conducted in this region since 2004, which will be analysed to determine detailed crustal properties (P and S wave velocities, and attenuation parameters), and their lateral variations. The data from these seismic networks in the LOFZ region - in total up to 138 stations in operation during 2005 - will provide the data set required to perform a surface wave phase-velocity dispersion, receiver-function and attenuation studies to determine the velocity and attenuation structure in the top 100 km of the crust and upper mantle, including the depth of the crust/mantle boundary, for the southernmost part of the LOFZ. This data will be incorporated as a constraint into the source model for the displacement field. Crustal lateral variations are important properties to relate with models of present day deformation because it affects the strength or the degree of coupling across the LOFZ.

Once a clear deformation field is determined for the region, forward and inverse schemes will be tried for the retrieval of the best source model for different periods and segments. Models will be based on a layered half-space geometry to characterize more realistically the media. We will determine the spatial and temporal evolution of the source, important to understand the style of deformation in this region and potentially other subduction region in the world. Understanding the deformation style surrounding the LOFZ is important also for improving the knowledge of the geological hazard in this region and therefore improve future human developments in Southern Chile.

Paleoseismology of the LOFZ fault from submarine studies

In the Aysén region of southern Chile, the acquisition of sub-bottom profile data using a 3.5 kHz source in the area of the last seismic crisis in 2007 (Barrientos et al., 2007), revealed fresh fault scarps along the Liquiñe-Ofqui Fault Zone (LOFZ) that can be interpreted as the result of the last large (M_w 6.2) earthquake in the area, and possible of previous events during the last hundreds or thousands of years (Vargas et al., in prep). Some of the fresh fault scarps that have been observed in the area of the LOFZ, can be directly associated to the activity of faults limiting the flanks of active volcanoes (Vargas et al.,in prep.). This kind of information, together with the cartography of recent potential active fault in this zone, have greatly improved our knowledge about the link between shallow (crustal) seismicity, active faults and active volcanism, in a region characterized by high stress partitioning, as the triple junction of the Nazca, South American and Antarctic Plates (Cembrano et al., 1996; 2002).

In this project, we propose to continue the exploration of the oceanic and inner branches of the LOFZ close to the area of the last seismic crisis, to evaluate the activity of the different fault segments, in an area where the deformation appears to be highly partitioned.

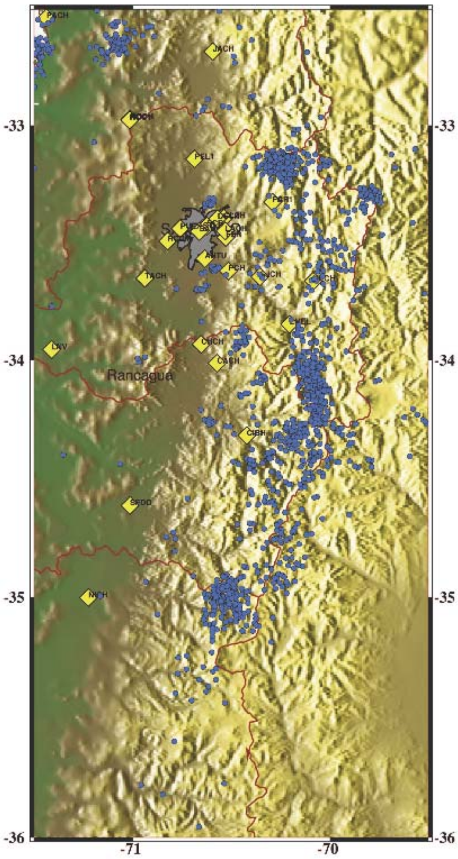


Fig 9 : Shallow crustal seismicity (blue dots) and Chilean network (yellow diamonds)

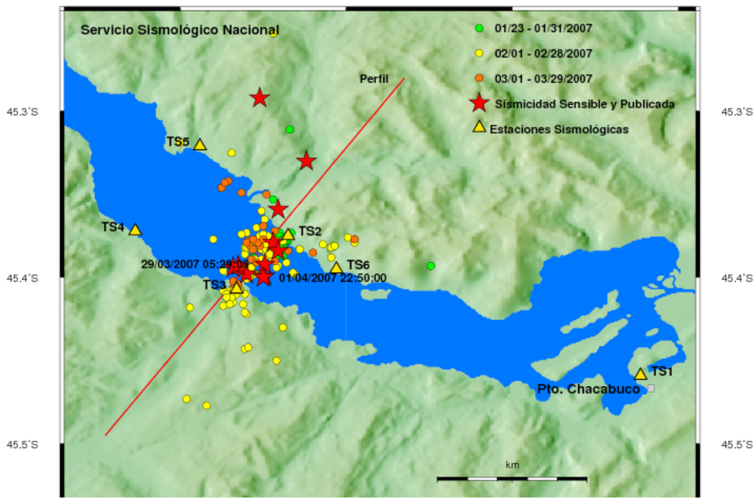


Fig 10 Aysen area, seismicity with time (green, yellow and orange dots)/

Landslide hazard in Fjord coasts along the Liquiñe-Ofqui Fault Zone.

Current research by the CIIT of the 2007 earthquake in the Aysen fjord is providing information on the seismic response of rock and soil slopes along fjord shores in areas close to the active LOFZ. The goal of this research is to characterize the hazard of landsliding in case of future seismic events along the LOFZ, particularly on fjord slopes, where landsliding may trigger tsunamis (as observed in 2007) that may impact populated areas and infrastructure such as salmon farms and roads.

The areas that may be studied are the Reloncavi, Comau, Reñihue, Puyuhuapi and Quitralco fjords. Research activities include field landslide mapping, geomorphological analysis and geotechnical investigations, and susceptibility analyses based on geotechnical models and/or statistical analyses.

This research will also be part of a current collaboration scheme with the International Center of Geohazards, the Norwegian Geological Survey and Sernageomin.

3.3.4 Task 4 Data bases and Networking activities

Coordinator: G. Moguilny (IPG Paris), C. Aranda (U. Chile)

Team: M. el Assaoui (IPG Paris), S. Morvan (ENS Paris), A. Delorme (IPG Paris), A. Nercessian(IPG Paris)
M.C. Valderas-Bermejo (U. Chile), I. Ortega (U. Chile)

Task 4.1: Data bases and data analysis tools

During this project above the operation of the existing observational facilities (cGPS and seismological network) we will build new data bases: event based and multiplet data bases integrating IPOC data, the post-seismic networks data and the ILN network data.

Automatic data processing will be implemented in order to operate these data bases.

Integration of other kinds of data: InSAR images and GPS time series.

These data bases will be shared through the different tasks of the project and will be opened to the scientific community.

Task 4.2: networking activities

Provide technical support for the information dissemination and valorisation. This include building and running an internal and external Web site, managing the distribution of information (reports, publications, etc ..)

3.3.5 Task 5 Dissemination and Valorisation

Coordinator: J.-P. Vilotte (IPG paris), J. Campos (U. Chile)

This important task of the project will operate on top of all the other tasks and is linked to all the other tasks.

A - Scientific Dissemination

- The results of this project will be published in per-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. Thesis, co-supervised by a Chilean and a French supervisor. The Ph.D positions will allow students to be trained in sate-of-the-art monitoring and data analysis technologies, as well as in an unique interdisciplinary approach of active subduction processes, integrating seismology, geodesy, geology and paleo-seismology, and in the evaluation of physically based seismic hazard. The student will spend time in Chile and French research laboratories.
- This project will offer non permanent positions, at the Research assistant level, to young international scientists who will have the opportunity to develop innovative and interdisciplinary research on top of state-of-the-art existing observational facilities.
- During the project, training courses will be organized both in Chile and France on new and innovative Instrumentation, data analysis and modelling methods in seismology and geodesy. These courses will be open to a larger audience than the active participants of the project at a Master and Ph.D. Level.

C – International collaborations

- This project is directly linked to the existing Associated International Laboratory “Montessus de Ballore” between the CNRS/INSU and the Universitad de Chile.
- This project is based on existing and structured collaboration between the LIA “Montessus de Ballore” and the GFZ Potsdam with whom many tasks will be performed and with whom we operate today many of the existing observational facilities in Northern 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 Norway (Norvegian Geological Survey) and Japan (Tokyo Earthquake Research Institute, and Japan Geological Survey).
- These International collaborations will also benefit to the Master, PhD and young researchers involved in this project.

C – Reports for end-users

During the project, reports will be produced and disseminated through the web-site of the LIA « Montessus de Ballore » to all the participants of the project, as well as to a broader audience. This reports will provide documentation on data analysis techniques, modelling methods as well as technical issues on instrumentation and transmission

D – General public conferences

The project will participate and organize in close collaboration with the Servicio Sismologico Nacional of the Universidad de Chile, general public conferences, especially in the town halls and schools in the area where our observational facilities are installed.

E – Data distribution and availability

This project, as detailed above, will produce new integrated data bases in France and Chile, e.g. GPS and InSAR, event based and multiplets data base, that will be made available to the national and international scientific community

3.4. TASKS SCHEDULE, DELIVERABLES AND MILESTONE

3.4.1 TASK 1 ANALYSIS OF THE CO- AND POST-SEISMIC PHASES OF THE TOCOPILLA EARTHQUAKE

Coordinators: R. Madariaga (ENS Paris) and J. Campos (DGF, U. Chile)

Task 1.1 - Teleseismic body wave analysis, main event and aftershocks
R. Madariaga (ENS Paris), A. Fuenzalida (Master, ENS Paris)
J. Campos (U. Chile), S. Ruiz (PhD., U. Chile), G. Meneses (Master, U. Chile)
Task 1.2 - Near field broad band data
R. Madariaga (ENS Paris)
S. Ruiz (PhD, U. Chile), F. Leyton (U. de Talca)
Task 1.3 - Co-seismic perturbation of the velocity medium
P. Bernard (IPG Paris), J.-P. Vilotte (IPG Paris), F. Brenguier (IPG Paris), N. Shapiro (IPG Paris)
Task 1.4 - Relocation and space-time characteristics of the aftershock series
P. Bernard (IPG paris), R. Madariaga (ENS Paris) , M. Lancieri (PostDoc, ENS Paris)
J. Campos (U. Chile), A. Perez (U. Chile), G. Meneses (Master, U. Chili)
Ext : M Sobiesak (GFZ Potsdam), S. Eggert (Ph.D. Potsdam)
Task 1.5 - Foreshock activity
P. Bernard (IPG Paris), J.P. Vilotte (IPG Paris)
J. Campos (U. Chile), G. Meneses (U. Chile)
Task 1.6 - Analysis of accelerograms
R. Madariaga (ENS Paris), P. Bernard (IPG Paris), J.-P. Vilotte (IPG Paris), A. Fuenzalida (Master, ENS Paris)
J. Campos (U. Chile) , S. Ruiz (Ph.D. U. Chile), F. Leyton (U. de Talca)
Task 1.7- Early warning
R. Madariaga (ENS Paris), C. Vigny (ENS Paris), M. Lancieri (PostDoc, ENS Paris)
Task 1.8 - Post-seismic deformations
A. Socquet (IPG Paris), M. Bejar (PostDoc, IPG Paris)
D. Carrizo (U. Chile), S. Barrientos (U. Chile)
Task 1.9- Mechanics of the Tocopilla earthquake
P. Favreau (IPG Paris), J.-P. Vilotte (IPG Paris)
J. Campos (U. Chile)

3.4.2 TASK 2 SEGMENTATION, SPATIO-TEMPORAL VARIATION OF THE DEFORMATION AND OF THE COUPLING

Coordinators: C. Vigny (ENS Paris), G. Vargas (U. Chile)

Task 2.1 Spatio-temporal variation of the coupling along subduction segments
C. Vigny (ENS), A. Socquet (IPGP), P. Bernard (IPG Paris), F. Boudin (U. Montpellier)
S. Barrientos (U. Chile), D. Carrizo (U. Chile), M. Métois (Ph.D. ENS/IPGP)
Task 2.2 - Spatio-temporal signatures of seismogenic asperities of the subduction interface in Northern Chile
R. Madariaga (ENS Paris), P. Bernard (IPG Paris), J.P. Vilotte (IPG Paris), N. Shapiro (IPG Paris), F. Brenguier (IPG paris)
J. Campos (U. Chile), S. Barrientos (U. Chile), F. Leyton (U. Talca), A. Perrez (U. Chile)
Ext : M. Sobiesiak (DGF Potsdam), S. Eggert (Ph.D. Potsdam)

Task 2.3 Origin and spatio-temporal stability of the barriers

R. Armijo (IPG Paris), R. Lacassin (IPG Paris), A. Coudurier-Curver (PhD., IPG Paris)
G. Vargas (U. Chile), G. González (U. Católica Norte)

3.4.3 TASK 3 SHALLOW DEPTH SEISMICITY, DEFORMATION PARTITIONING AND ACTIVE FAULTS AT THE SURFACE

Coordinators: S. Barrientos (U. Chile), R. Armijo (IPG Paris)

Task 3.1- Shallow seismicity and active faults in Central and North Chile

R. Armijo (IPG paris), R. Lacassin (IPG Paris), R. Madariaga (ENS Paris), C. Vigny (ENS Paris)
G. Vargas (U. Chile), G. González (U. Católica Norte), S. Barrientos (U. Chile), Campos (U. Chile), A. Perez (U. Chile)

Task 3.2 Shallow seismicity and strain partitioning in South Chile – Aysen

G. Vargas (U. Chile), G. González (U. Católica Norte), S. Barrientos (U. Chile), K. Bataille (U. Concepción), S. Rebolledo (U. Chile), S. Sepúlveda (U. Chile), A. Serey (Ms.Sc. U. Chile), V. Naquira (Ms.Sc. U. Chile).

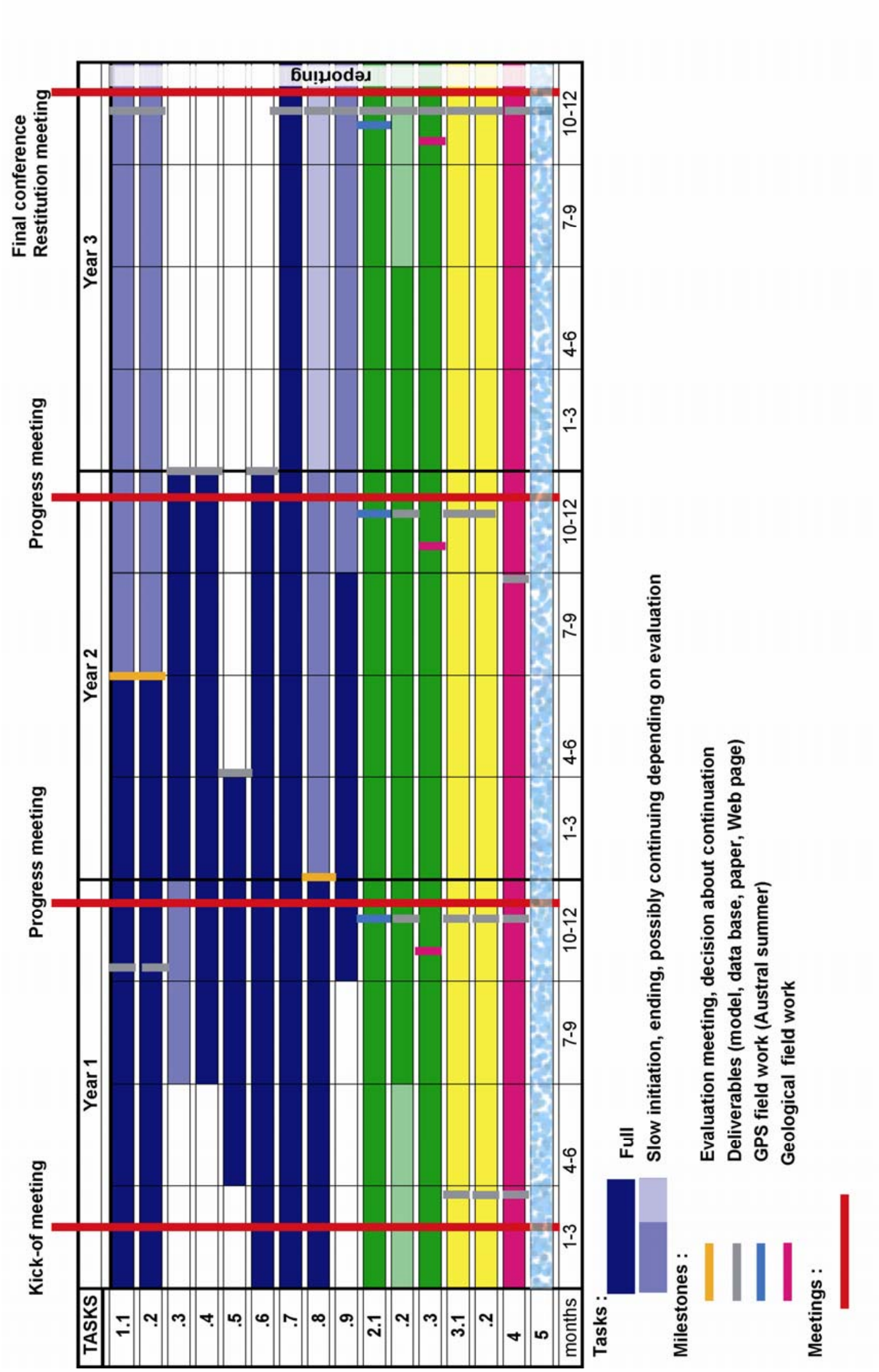
3.4.4 TASK 4 DATA BASES AND NETWORKING COMMUNICATION

Coordinators : G. Moguilny (IPG Paris), C. Aranda (U. Chile)

M. el Assaoui (IPG Paris), S. Morvan (ENS Paris), A. Delorme (IPG Paris), A. Nercessian (IPG Paris)
M.C. Valderas-Bermejo (U. Chile), I. Ortega (U. Chile)

3.4.5 TASK 5 DISSEMINATION AND VALORISATION

Coordinators: J.-P. Vilotte (IPG Paris), J. Campos (U. Chile)


Kick-of meeting
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Progress meeting
Final conference
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Tasks :
Full
Slow initiation, ending, possibly continuing depending on evaluation
Milestones :
Evaluation meeting, decision about continuation
Deliverables (model, data base, paper, Web page)
GPS field work (Austral summer)
Geological field work
Meetings :

4. DISSEMINATION AND EXPLOITATION OF RESULTS. MANAGEMENT OF INTELLECTUAL PROPERTY

This project involves academic partners in Chile and France who are already coordinated within the Chilean-French Associated International Laboratory « Montessus de Ballore », which was officially created November 2006. The LIA « Montessus de Ballore » involve the **Universitad de Chile**, the French **CNRS**, the **Institut de Physique du Globe de Paris**, and the **Ecole Normale Supérieure Paris**. Moreover a Memorandum of Understanding (MOU) has been signed with the **GeoForschungsZentrum Postdam.**

Valorization of the results to the various en-users is listed below, and is in continuation of the Task 5.

Science and Research

- Scientific papers and international conferences
- PhD thesis: the project developments and deliverables will lead to to new PhD projects, during and after the projects especially in the domain of great earthquake accelerogram analysis, probabilistic models of seismic activity, inter and intra-plate earthquake attenuation laws, monitoring and modelling of transient slip events, slow earthquakes and tremors, dynamics of complex rupture, seismic activity and segmentation along subduction zones.
- The operation of the international observational facilities in Chile will continue after the end of the project and contribute to the Servicio Sismologico Nacional and the LIA "Montessus de Ballore" data bases (open to the scientific community).
- GPS campaigns will be repeated every year, for reducing the position uncertainties and tracking transient slip
- The GPS and seismological networks, and the results of this project, will guide the selection of future sites of the Chilean RED Nacional project.

Hazard and Risk

- Data bases of accelerograms for large and great subduction and intermediate depth earthquakes in the subduction zone in Chile
- Attenuation laws for great subduction and intermediate depth earthquakes
- Stochastic models for earthquake seismic activity and high-frequency radiation
- Scaling laws for seismicity and rupture dynamics
- end-users: contact will be maintained with local public authorities to improve communications between scientists, engineers, public and authorities
- end-users: if relevant continuous and almost real time monitoring of tremors and seismic activity

International Collaborations

- coordination with other international projects on active margins in Peru, Mexico and Japan
- coordination with EELA Grid initiatives in Latin America

Communication to various public

- communications for engineering community: international conferences and Chilean association of earthquake engineering
- conferences for general publication web sites pages for general publication

5. CONSORTIUM DESCRIPTION

5.1. PARTNERS DESCRIPTION & RELEVANCE, COMPLEMENTARITY

The partners in this project, i.e. Universidad de Chile, Institut de Physique du Globe de Paris and Ecole Normale Supérieure de Paris, have a long history of active and productive collaboration. Since 2006 this collaboration has been formally recognized and structured with the Laboratoire International Associé (LIA) "Montessus de Ballore", a formal collaborative structure between CNRS and Universidad de Chile.
Lately, this collaboration has been enriched and integrates other national and international partners: Universidad Catolica del Norde (UCN), Universidad de Concepcion (UdC), GFZ-Potsdam, Germany. UCN contribute with complementary expertise in tectonics and paleo-seismology, UdC contribute with GPS and theoretical seismology expertise.

- *Institut de Physique du Globe de Paris (IPGP)*

Two scientific teams of IPGP are contributing to this project: the seismology team (4 researchers, 2 engineers), the tectonic and geodesy team (3 researchers, 1 engineer).

The coordinator has already coordinated several French-Chilean projects. He is one the four co-directors of the LIA Montessus de Ballore and coordinates the collaboration between the GFZ Potsdam and the CNRS/INSU in Chile.

The seismology team will provide expertise on:
Strong motion and wave form analysis;
Analysis of microseismicity and transient deformation
Kinematic modelling and statistical analysis;
Source inversion;
Dynamic rupture and mechanical models;
Noise cross-correlation techniques and tomography.

The tectonic and geodesy team will provide expertise on:
Geomorphology and active tectonics;
Paleo-seismology
Mechanical modelling;
GPS analysis and inversion, InSAR techniques and inversion.

- *Ecole Normale Supérieure de Paris*

The geological laboratory (2 researchers, 1 PostDoc, and 1 engineer) is participating to the project.

The coordinator has already coordinated an ANR project in Chile.

The geological team will provide expertise on:
Strong motion and wave form analysis;
Seismic engineering;
Dynamic and kinematic source inversion;
Coulomb stress transfer modeling;
Early warning thechniques;
GPS analysis and modeling;
Geodynamic modeling;

- *Universitad de Chile*

Two departments of "faculdad de Ciencias Fisicas y Matématicas" of the Universidad de Chile, the department of geophysics and the department of Geology, are directly involved in this proposal.
Four faculty members from department of Geology will bring expertise in:
Tectonics,
Paleo seismology,
Geological hazards, in particular landlsides.
A similar number of faculty members of the department of Geophysics will bring expertise in:
Seismic source processes and wave form analysis,
Seismo-tectonics,
Seismic hazards.

5.2. RELEVANT EXPERIENCE OF THE PROJECT COORDINATOR

(0,5 page maximum)

Fournir les éléments permettant de juger la capacité du coordinateur à coordonner le projet.

CHILEAN COORDINATOR : JAIME CAMPOS , Associate Professor Dept. Of Geophysics, Faculty of Physics and Mathematicas Sciences, University of Chile ; Director of National Seismological Network of University of Chile (1997-2006) ; Director of Millenium Nucleous of Sismotectonic and Seismic Hazard 2004-2007 (ICM-Mideplan Ministery, Chile) ; Director of Internationa Earthquake Reserach Center M.B., 2008-2010 (ICM-Mideplan Ministery, Chile) ; Director (Chilean) of Seismological International Associated Laboratory Montessus de Ballore (C.N.R.S.-French / University of Chile) ; Coordinator of Seismological group at Dept. Of Geophysics of University of Chile ; Co-PI of Seismic Hazard for Metropolitain Region, Central Chile (2004-2007, FONDEF projet) ; PI of scientifical project in seismology (Fondecyt ; ECOS).

FRENCH COORDINATOR : JEAN-PIERRE VILOTTE, Physicien des Observatoires, Dept. Of Seismology, Institut de Physique du Globe de Paris : Director of the Parallel Computer and Data Processing Center of IPGP ; Director of the IPGP seismo laboratory (2003-2007) ; Director (French) of the International Associated Laboratory Montessus de Ballore (CNRS-France / University of Chile), Coordinator (French) of the International Plate Boundary Observatory in Chile (IPOC) CNRS/GFZ Potsdam/University of Chile ; PI of the ANR-06-CATT-01001 SubChile (ending in December 2009), Coordinator of the French Earth Sciences in the European EGEE and EELA (Europe/Latin America) Grid projects.

5.3. RELEVANT EXPERIENCE AND ROLE OF INDIVIDUAL PARTNERS

Partner **U-Chile**	Surname	First Name	Position	Domain*	Person-months	Role/Responsability in Projet 4 lignes max
Exemple	*LATIFI*	*Fatima*	*Professeur*			*Caractérisation des facteurs de transcription recombinants en système in vitro …*
Co-ordinator	Vargas	Gabriel	Professor	Tectonics and paleo-seismology	9	Research and coordinator tectonics and paleoseismology
Other members	Barrientos	Sergio	Professor	Seismology	9	Research and coordinator in seismology
	Kausel	Edgar	Professor	Seismology	3.6	Research in seismic hazard

	Carrizo	Daniel	PostDoc	Geodesy	18	Research in GPS
	Rauld	Rodrigo	PhD	Tectonics	18	Research in tectonics in Central Chile
	Gonzalez	Gabriel	Professor	Tectonics and paleo-seismology	9	Research in tectonics and paleoseismology
	Leyton	Felipe	Professor	Seismology	9	Research seismic source / strong motion analysys
	Foncea	Claudio	Professor	Seismic hazard	3.6	Research in seismic hazard in Central Chile
	Gonzalez	Lenart	Professor	Seismic hazards	3.6	Research in seismic hazard
	Ruiz	Sergio	Ph.D.	Seismology	18	Research strong motion analysis, dynamic of the seismic rupture.
	Sepúlveda	Sergio	Professor	Tectonics and Geo-Hazards	9	Research in Tectonics and landslide modelling.
	Perez	Adriana	Ph.D.	Seismology	18	Research in seismotectonics and seismic hazard in Central Chile
	Valderas	Carolina	Technician	Geodesy	36	GPS maintennce and analysis
	Aranda	Carlos	Technician	Seismology	3.6	Seismology mannagement
	Meneses	Gianina	MsSc.	Seismology	18	Research in aftershock location for Tocopilla earthquake
	Rebolledo	Sofía	Professor	Seismotectonics	3.6	Research in seismotectonics in Central Chile and Aysen areas
	Thiele	Ricardo	Professor	Seismotectonics	3.6	Research in seismotectonics and Tectonics in Central Chile
	Bataille	Klaus	Professor	Seismology and Geodesy	3.6	GPS analysis in Aysén region
	Silva	Natalia	Ms.Sc.	Seismic risk	18	Research in risk and seismic hazard
	Serey	Alejandra	Ms.Sc.	Geohazards	18	Research in landslide in Aysén region
	Naquira	Verónica	Ms.Sc.	Geohazards	18	Research in landslide and seismic hazard in Central Chile
	Astroza	Maximiliano	Professor	Seismic-hazard	3.6	Research in seismic hazard Central Chile
	Cisternas Palacios	Armando Carlos	Professor Professor	Seismology Tectonics	3.6 3.6	Research in rupture dynamic in the seismic source Research in tectonics and in Northern Chile

Partner : **IPG Paris**	Surname	First Name	Position	Domain*	Person-months	Role/Responsability in Projet 4 lignes max
Co-ordinator	VILOTTE	Jean-Pierre	Physicien des observatoires	Sismologie Computational seismology	18 months	Coordinator of the project Dynamic and mechanical modeling Strong motion analysis and stochastic modeling
Other members	BERNARD	Pascal	Physicien des observatoire	Sismologie Inclinomtry	9 months	Strong motion and wave form analysis, Kinematic modeling Multiplet analysis
	ARMIJO	Rolando	Physicien des observatoires	Tectonics	20 months	Seismo-tectonics, geomorphology, paleo-seismology
	BRENGUIER	Florant	Physicien des observatoires	Sismologie	Expert	Cross-correlation noise analysis, tremors
	FAVREAU	Pascal	Assistant Professor	Sismologie	15 months	Dynamic modelling and source inversion Mechanical modeling
	LACASSIN	Robin	DR CNRS	Tectonics	15 months	Sismo-tectonics, geomorphology
	SHAPIRO	Nikolai	DR CNRS	Seismologie	Expert	Noise correlation analysis, tomography and tremors
	NERCESSIAN	Alex	Physicien adjoint	Sismologie	9 months	Network design maintenance, data transmission, data analysis, noise analysis
	SOCQUET	Anne	Physicien adjoint	Geodesy	15 months	Network design and maintenance, GPS and InSAR analysis
	DELORME	Alain	IE CNRS	Geodesy	9 months	Data transmission, GPS instruments
	El ASSAOUI	Mamadi	IE MEN	Seismologie	24 months	Network design and management, data analysis, data flow and data analysis
	MOGUILNY	Geneviève	IR CNRS	Computer science	6 months	Networking, Web, Data base

Partner : **ENS**	Surname	First Name	Position	Domain*	Person-months	Role/Responsability in Projet 4 lignes max
Co-ordinator	Vigny	Christophe	Directeur de recherches	Geodesy	24	GPS task coordination network design, maintainance, data processing, modellisation, publications
Other members	Madariaga	Raul	Professeur	Seismology	24	Seismology task coordination Strong motion analysis, Earthquake source modelling, Seismicity analysis
	Lancieri	Maria	PostDoc	Seismology	24	Relocation of aftershocks
	Métois	Marianne	Ph.D.	Geodesy	36	GPS data processing and modelling
	Fuenzalida	Amaya	Master	Seismology	6	Analysis of accelerograms
	Morvan	Sylvain	Ingenieur	GPS data	36	Participate to field work, network maintainance, tele communications, GPS data base, automatic data processing

6. Scientific justification for the mobilisation of the resources

This proposal is part of the LIA “Montessus de Ballore” which as a formal structure has specifics funding to support scientific exchange and collaboration. As such, the LIA will be financially supporting this project for the coordination and the regular progress meetings to a total amount of 8000 E /year.

6.1. Partner 1 : Universidad de Chile

1. *Equipment*

No funding is requested here for this proposal

2. *Personnel costs*

Technical and support staff 120 000 E

A massive amount of data has been collected in the past few years by seismic and GPS observational facilities funded by ANR (France) and Millenium (U-Chile) with Universidad Catolica del Norde and Universidad de Concepcion.
Extracting new scientific information from these data requires high quality data bases and data analysis tools.
Today there are of the order of 10 Tb of GPS and Seismological data and meta-data. During the period of the project, priority will be given to :

1 computer engineer: for data bases construction and management.
1 GPS engineer for network maintainance, data transmission, quality check and preliminary processing
1 seismic engineer for implementing quality check and data analysis work flow.

Master students and young researchers 72 000 E

Two Ph.D. students will be involved in this project: Sergio Ruiz, in collaboration with ENS-Paris is studying strong motion of great subduction earthquakes (like Tocopilla), Rodrigo Rauld, in collaboration with IPG-Paris is finilazing his thesis on the SanRamon fault system in central Chile.
During this project support for 4 MSc thesis is needed in the following topics:-
- One in Paleo-sismology (very important to understand the seismic behaviour of tectonic problems in subduction environments)
- Two in GPS studies (essential tool to characterize active crustal deformation related to Earthquake occurrence)
- One in Seismic hazard studies in Andean subduction evironment

3. Subcontracting

No funding is requested here for this proposal

4. Travel (8000 E Year1, 8000 E Year 2, 10200 E Year 3)

Scientific coordination, regular scientific meetings, and circulation of young researchers within the project request specific travel expenses. The multi-disciplinary approach of this proposal must be confronted in a personnal manner to allow a constructive point of view and improve our understanding of earthquake processes.

5. Expenses for inward billing (Costs justified by internal procedures of invoicing)

No funding is requested here for this proposal

6. Other working costs

No funding is requested here for this proposal

6.2. PARTNER 2 : IPGP

1. Equipment

No funding is requested here for this proposal

2. Personnel costs

Young researcher: 163 988 €

During this project we request:
- One 18 month young-researcher position at the post-doc level in seismology: the research activity will be focused on Tocopilla aftershocks analysis, asperity studies, slow earthquakes and non-volcanic tremor analysis in relation with tasks 1 and tasks 2 in northern Chile.
- One 18 month young-researcher position at the post-doc level in InSAR geodesy: the research activity will be focused on active deformation and transients using InSAR and GPS techniques.

3. *Subcontracting*

No funding is requested here for this proposal

4. *Travel*

Tectonic field trips : 60 000 €

Specific financial support is requested for three tectonic field trips (on per year) in relation with task 2.3 and task 3.1in Chile. One trip includes travel allowance and 3-weeks costs for 3 scientists.

Coordination and scientific activity : 10 800 €

As coordinator of the project we request special funding for travel associated with :

- Activity coordination and progress meetings (scientific): **this will be explicitly supported by the LIA "Montessu de Ballore" up to 8000E/year**
- Circulation of the young French and Chilean researches of this projects between the different scientific groups and disciplines,
- Young researcher participation to international meetings.

5. *Expenses for inward billing (Costs justified by internal procedures of invoicing)*

No funding is requested here for this proposal

6. *Other working costs*

Other costs: 5 000 €

Support for acquiring new sets of RADAR images: ENVISAT (ASAR or ScanSAR) data covering north Chile. These images will be acquired at reduced cost (25E/image) through category 1 ESA projects:

100 ENVISAT ASAR images over North and central Chile

80 ScanSAR images over North and central Chile

For the image processing we request also the funding of a post-processing software licence (ENVI-IDL).

6.3. PARTNER 3 : ENS

1. *Equipment*

No funding is requested here for this proposal

2. *Personnel costs*

Young researcher: 81 994 €

During this project we request:

- One 18 month young-researcher position at the post-doc level in seismology: the research activity will be focused on strong motion analysis for seismic risk, early warning evaluation in the Chilean context, coupling between subduction and intra-plate earthquakes.

3. Subcontracting

No funding is requested here for this proposal

4. Travel

GPS measurement campaigns : 55 000 €

Specific financial support is requested for at least three (once a year) GPS campaigns and field work in relation with task 1, task 2.1 and task 3.1 in Chile. We will organize GPS field trips and coordinate french partners (ENS, IPGP) GPS activities over the different areas (North and central Chile).
We realized 2 GPS campaigns every year in the area of Illapel-Coquimbo since 2004, and participated to 2 campaigns in the area of Tocopilla since 2007. We are very much used to managing these campaigns and controlling field operations and expenses.
A campaign dedicated to measure a network of 50 points over an area of 400 km (North-South) and from the coast to the cordillera is:
- 15-20 receivers
- 20-30 batteries (re-usable for the whole duration of the project)
- 3 teams (of 2 people and 1 pick-up truck)
- 21 days of measurements
- 18,000 km in total (=> 1800l of gas)

They almost always costs 15-20 kEuro

5. Expenses for inward billing (Costs justified by internal procedures of invoicing)

No funding is requested here for this proposal

6. Other working costs

No funding is requested here for this proposal

7. ANNEXES

7.1. REFERENCE

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Ruegg, J.C., A. Rudloff, C. Vigny, R. Madariaga, J.B. DeChabalier, J. Campos, E. Kausel, et al., 2009, Interseismic strain accumulation measured by GPS in the seismic gap between Constitucion and Concepcion in Chile, *PEPI, in press*.Ruff, L.J., 1992, Asperity distribution and large earthquake occurrence in subduction zones, tectonophysics, 211 (1-4), 61-83.

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Shelly, D.R., Beroza, G.C., Ide, S., and Nakamula, S., 2006, Low frequency earthquakes in Shikoku, Japan, and their relationship to episodic tremor and slip, Nature, 442, 188-191.

Sobolev, SV; Babeyko, AY; Wang, R, et al., 2007, Tsunami early warning using GPS-Shield arrays, *J. Geophys. Res.*, 112, B8, B08415.

Song, Y.T., 2007, Detecting tsunami genesis and scales directly from coastal GPS stations *Geophys. Res. Let*., 34, L19602.

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Vigny, C., Rudloff, A., Ruegg, J.C., Madariaga, R.,Campos, J. and Alvarez, M., 2009, Upper plate deformation measured by GPS in the Coquimbo gap, Chile, Phs. Earth Planet. Int. in press.

Von Huene, R., and Ranero, C.R., 2002, Subduction erosion and basal friction along the sediment starved convergent off Antofagasta, Chile, J. geophys. Res., 108 (B2), 2079, doi:10.1029/2001JB001569.

7.2. BIOGRAPHIES

(1 page maximum par personne)

Cf. §5.3.

ROLANDO ARMIJO

BORN: December 14, 1950, at Santiago, Chile; Male.
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EDUCATION:
B.Sc. in Earth Sciences, University of Paris (1975).
Doctorat de 3ème cycle, Structural Geology, University of Paris (1977).
Doctorat d'Etat ès Sciences (Ph.D.), University of Paris (1986).
POSITIONS HELD:
Assistant, University of Paris (1977-78).
Research Fellow, CICESE, Mexico (1978-80).
Associate Professor, Institut de Physique du Globe de Paris, (1980-88).
Professor of Geophysics, Institut de Physique du Globe de Paris, (1988-present).
Headed Tectonics Laboratory from 1997-2001
HONORS:
"1994 Best Paper Award", Structural Geology and Tectonics Division, Geological Society of America.
Prize "Eugénie de Rosemont" (Sciences), Chancellerie des Universités de Paris, 1997.
Prize "Constantinos Ktena" (Geology), Academy of Athens, 1997.
SCIENTIFIC CONTRIBUTIONS:
(1) Pioneered interpretation methods in geomorphology and active continental tectonics, produced comprehensive studies in different regions as the Himalaya and Tibet, the Andes and the Perú-Chilean subduction zone, the East-African Rift (Afar-Djibouti), the Mediterranean region (Spain, France, Algeria, Tunisia, Italy, Greece, Bulgaria, Turkey. Contributed to studies of submarine deformation in the East-Pacific Rise (Easter microplate, Galápagos triple junction) and in Turkey.
(2) Mapped many major active faults using fieldwork, geophysical data and various remote-sensing techniques; studied the deformation associated to recent and past earthquakes; contributes to leading-edge current studies of deformation transients related to the seismic cycle using space geodesy (GPS and SAR interferometry), seismology and mechanical modelling.

(3) Leaded an international multi-disciplinary project on the seismic hazard in Turkey and the North Anatolian Fault, including studies on land and several oceanographic cruises to study the Sea of Marmara pull-apart.

SELECTED PUBLICATIONS:
(*out from more than 60 contributions published in international peer-review journals*)

Armijo, R., Meyer B., G. C. P. King, Rigo A., and Papanastassiou D. (1996), Quaternary evolution of the Corinth Rift and its implications for the late Cenozoic evolution of the Aegean, *Geophys. J. Int.*, *126*, 11-53.

Armijo, R, B. Meyer, A. Hubert, and A. Barka (1999), Westward propagation of the North Anatolian Fault into the Northern Aegean: Timing and kinematics, *Geology*, *27*, 267-270.

Armijo, R., B. Meyer, S. Navarro, G. King, and A. Barka (2002), Asymmetric slip partitioning in the Sea of Marmara pull-apart: A clue to propagation processes of the North Anatolian Fault ?, *Terra Nova*, *14*, 80-86.

Hubert-Ferrari, A., R. Armijo, G.C.P. King, B. Meyer and A. Barka (2002), Morphology, displacement and slip rates along the North Anatolian Fault (Turkey), *Jour. Geophys. Res.*, *107*, 0, doi: 10.1029/2001JB000393.

Çakir, Z., J.-B. de Chabalier, R. Armijo, B. Meyer, A. Barka, and G. Peltzer (2003), Coseismic and early postseismic slip associated with the 1999 Izmit earthquake (Turkey), from SAR interferometry and tectonic field observations, *Geophys. J. Int., 155*, 93-110.

Armijo, R., F. Flerit, G. King, and B. Meyer (2003), Linear Elastic Fracture Mechanics explains the past and present evolution of the Aegean, *Earth Planet. Sci. Lett.*, *207*, 85-95.

Armijo, R., et al. (2005), Submarine fault scarps in the Sea of Marmara pull-apart (North Anatolian Fault): Implications for seismic hazard in Istanbul, *Geochem. Geophys. Geosyst.*, *6*, Q06009, doi:10.1029/2004GC000896.

(*Contributions on the subject "Seismotectonics of Chile", published in international peer-review journals*)

Francheteau J., P. Patriat, J. Segoufin, R. Armijo, M. Doucouré, A. Yelles-Chaouche , J. Zukin, S. Calmant, D. Naar, and R. Searle (1988), Pito and Orongo fracture zones: the northern and southern boundaries of the Easter (Rapanui) microplate (S.E. Pacific), *Earth Planet. Sci. Lett.*, *89*, 363-374.

Armijo R. and R. Thiele (1990), Active Faulting in Northern Chile: Ramp Stacking and Lateral Decoupling Along a Subduction Plate Boundary ?, *Earth Planet. Sci. Lett.*, *98*, 40-61.

J.-P. Cogné, J. Francheteau, V. Courtillot, R. Armijo, M. Constantin, J. Girardeau, R. Hekinian, R. Hey, D.F. Naar, and R. Searle (1995), Large rotation of the Easter microplate as evidenced by oriented paleomagnetic samples of the ocean floor, *Earth Planet. Sci. Lett.*,*136*, 213-222.

Ruegg, J.C., J. Campos, R. Armijo, S. Barrientos, P. Briole, R. Thiele, M. Arancibia, J. Cañuta, T. Duquesnoy, M. Chang, D. Lazo, H. Lyon-Caen, L. Ortlieb, J.C. Rossignol, and L. Serrurier (1996), The M_W = 8.1 Antofagasta (North Chile) Earthquake of July 30, 1995: First results from teleseismic and geodetic data, *Geophys. Res. Lett., 23*, 917-929.

Ruegg, J.C., J. Campos, R. Madariaga, E. Kausel, J.B. de Chabalier, R. Armijo, D. Dimitrov, I. Georgiev, and S. Barrientos (2002), Interseismic strain accumulation in south central Chile from GPS measurements, 1996-1999, *Geophys. Res. Lett.*, 29, 11, 10.1029/2001GL013438.

Chlieh, M., J.-B. de Chabalier, J.-C. Ruegg, R. Armijo, R. Dmowska, J. Campos and K. Feigl (2004), Crustal deformation and fault slip during the seismic cycle in the North Chile subduction zone, from GPS and InSAR observations, *Geophys. J. Int., 158*, 695-711.

Searle, R. C., J. Francheteau, R. Armijo (2006), Compressional deformation north of the Easter microplate: A manned submersible and seafloor gravity investigation, *Geophys. J. Int.,* 164**,** 359–369, doi: 10.1111/j.1365-246X.2005.02812.x.

Armijo, R., R. Rauld, R. Thiele, G. Vargas, J. Campos, R. Lacassin, and E. Kausel (2008, *submitted to Tectonics*) The West Andean Thrust (WAT), the San Ramón Fault and the seismic hazard for Santiago (Chile).

Pascal BERNARD

Born 1958
Seismologist
Physicien du Globe, Equipe de Sismologie, Institut de Physique du Globe de Paris, IPGP, France
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Education :
1978 Ecole Normale Supérieure de St Cloud, Physique
1979 Maîtrise de Physique, Univ. Paris 6.
1981 Agrégation de Physique
1983 PhD Thesis - Thèse de 3ème Cycle, Univ. Paris 6.
1987 Doctorat d'Etat, Univ. Paris 6.

7.2.1.1.1Research : seismogenesis
7.2.1.1.2- Measure and modeling of strong ground motion
7.2.1.1.3- Observation and modeling of seismic source through a multidisciplinary approach
7.2.1.1.4- Research on crustal transients and on precursory phenomena
7.2.1.1.5- Development of geophysical observatories in Greece and Chile
7.2.1.1.6
7.2.1.1.7Main Scientific and Administrative responsabities
7.2.1.1.8- Advisor for 15 PhD thesis
7.2.1.1.9- Coordinator for 4 European projects on seismogenesis and seismic hazard
7.2.1.1.10 - Deputy director of IPGP 1999-2004
7.2.1.1.11 - Director of the seismogenesis group 1994-2005
7.2.1.1.12 - Elected member of Section 18 of CNRS - 2004-2008

since 1985, more than 50 publication in international journals with peer review.

Selected recent publications in international journal with peer review:

Bernard, P., F. Boudin, S. Sacks, A. Linde, P.-A. Blum, C. Courteille, M.-F. Esnoult, H. Castarède, S. Felekis, and H. Billiris, Continuous strain and tilt monitoring on the Trizonia island, Rift of Corinth, Greece, *C.R. Geoscience 336,* 313-324, 2004.

Lyon-Caen, H., P. Papadimitriou, A. Deschamps, P. Bernard, K. Makropoulos, F. Pacchiani, G. Patau, First results of CRLN seismic array in the western Corinth rift: evidence for old fault reactivation, *C.R. Geoscience 336,* 343-352, 2004.

Bernard, P., and D. Baumont, Shear *Mach* wave characterization for kinematic fault rupture models with constant supershear rupture velocity, *Geophys. J. Int. 162,* 431-447, 2005.

Cornet, F;, **P. Bernard,** and I. Moretti, The Corinth Rift Laboratory, *C.R. Geosciences* 336, 235-242, 2004.

Bernard, P, H. Lyon-Caen, P. Briole, A. Deschamps, F. Boudin, K. Makropoulos , P. Papadimitriou, F. Lemeille, G. Patau, H. Billiris, D. Paradissis, K. Papazissi, H. Castarède, O. Charade, A. Nercessian, A. Avallone, F. Pacchiani, J. Zahradnik, S. Sacks, and A. Linde, Seismicity, Deformation and seismic hazard in the western rift of Corinth : New insights from the Corinth Rift Laboratory (CRL), *Tectonophy. 426,* 7-30, doi:10.1016/j.tecto.2006.02.012, 2006.

Peyrat, S., J. Campos, J.-B. Dechaballier, A. Perez, S. Bonvalot, M.-P. Bouin, D. Legrand, A. Nercessian, O. Charade, G. Patau, E. Clévédé, **P. Bernard,** and J.-P. Vilotte, Source parameters of the Mw=7.7 Tarapaca intermediate-depth earthquake (June 13, 2005, Northern Chile) constrained from seismological and geodetic observations: A slab-pull event with a horizontal fault plane, *Geophys. Res. Lett.,* 33, L22308, doi:10.1029/2006GL027710, 2006

Bourouis, S., and P. Bernard, Evidence for coupled seismic and aseismic fault slip during water injection in the geothermal site of Soultz (France), and implications for seismogenic transients, Geophys J Int, 169, 723-732, doi 10.1111/j.1365-246X.2006.03325.x, 2007

Ruiz, J., D. Baumont, P. Bernard, and C. Berge, A new approach in the kinematic k-2 source model for generating physical slip velocity functions, *Geophys. J. Int.,* doi: 10.1111/j.1365-246X.2007.03503.x2007, 2007

Boudin, F., **P. Bernard**, L. Longuevergne, N. Florsch, C. Larmat, C. Courteille, P-A. Blum, A silica long base tiltmeter with high stability and resolution. Rev. of Sci. Inst., 79, 034502 , 2008.

Main Publication for general public:

Bernard, P., *Qu'est-ce qui fait trembler la terre*, Coll. Bulles de Sciences, Ed. EDP-Sciences, Paris, 2003.

Pascal Favreau

né le 02/10/1972 (37 ans)

Cursus :

Depuis Septembre 2002: Maître de Conférences à l'Institut de Physique du Globe de Paris.
2000-2002 : Post-doc à l'Université de Californie à Santa Barbara
1997-2000 : Doctorat à l'Université Joseph Fourier (Initiation et propagation de la rupture sismique:
instabilité de frottement en élastodynamique.)
1996-1997: Service National
1996 : DEA de Géophysique à l'Université Joseph Fourier
1992-1995 : élève à l'Ecole Normale Supérieure de Cachan (Génie Civil)

Cinq publications les plus significatives des cinq dernières années :

Favreau, P. and R.J. Archuleta (2003). Direct seismic energy modeling and application to the 1979 Imperial Valley earthquake Geophys. Res. Lett. 30, 2002GL15968

Dunham, E.M., P. Favreau and J. Carlson (2003). A supershear transition mechanisms for cracks. Science, 2999,11571159

Favreau, P. and S. Wolf (2007). Theoretical and numerical stress analysis at edges of interacting faults. Application to fault propagation modeling. Accepted to Geophys. J. Int.

Peyrat, S. and Favreau P. (2008). Kinematic and spontaneous rupture models of the 2005 Tarapaca intermediate depth earthquake. in revision in Geophysical Journal International.

S. Wolf, P. Favreau and I.R. Ionescu (2008). Hybrid unstructured FEM - FDM modeling of seismic wave propagation. Application to dynamic faulting. Submitted to Journal of Geophysical Research.

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Date and place of birth : March 29, 1944, Santiago (Chile)

Academic Degrees:
• University of Chile. 1961-1967, Civil Engineer degree (C.E.), August 1967.
• Massachusetts Institute of Technology 1967-1971, Ph.D. in Geophysics, June 1971.

Professional Experience:
Researcher, Department of Geophysics, University of Chile, 1971-1973
Research Associate, Massachusetts Institute of Technology, 1974-1976.
Physicien Adjoint, Institut de Physique du Globe de Paris, 1977-1979.
Associate Professor. Full Professor UniversitéParis VII, 1979-1991.
Professeur classe exceptionnelle, Université Paris VII, 1991-1998.
Professeur classe exceptionnelle. Ecole Normale Superieure, since 1998.

Academic and Administrative Responsabilities:
• Chairman, Laboratory of Geology, Ecole Normale Sup'erieure, 2000-2005.
• Director Seismological Laboratory, Institut de Physique du Globe de Paris, 1985-1996.

Awards:
Research fellow U.S. National Science Foundation, 1967-1971.
Green Scholar, IGPP, University of California, San Diego, 1981.
Fellow American Geophysical Union, 1991.
Senior Member Institut Universitaire de France, 1993-1998.
Grand medal of the Rector de la Universidad de Chile in Santiago, November 1998
Stephan Mueller Medal of the European Geophysical Society, 2000.
H.F. Reid Medal of the Seismological Society of America, 2004

Publications:
1 Book
Madariaga, R. and G. Perrier, Les Tremblements de Terre, 260 pp., Les Editions du CNRS, 1991.

More than 120 papers in reviewed journals, among the latest:
Madariaga, R., Dynamics of an expanding circular fault. Bull. Seismol. Soc. Am., 65, 163-182, 1976.
Madariaga, R., High frequency radiation from crack (stress drop) models of earthquake faulting. Geophys. J.R. Astr. Soc., 51, 525-651, 1977.
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Farra, V. R. Madariaga, Seismic waveform modeling in heterogeneous media by Ray Perturbation theory J. Geophys. Res., 92, 2697-2712, 1987
Fukuyama, E., and R. Madariaga, Integral equation method for a plane crack with arbitrary shape in 3D elastic media, Bull. Seismol. Soc. Am.,85, 614-628, 1995.
Cochard, A. and R. Madariaga, Complexity of seismicity due to highly rate dependent friction, J. Geophys. Res., 101, 25231-25336, 1996.
Campos, J., R. Madariaga and C. H. Scholz, Faulting process of the August 8, 1993 Guam earthquake. J. Geophys. Res., 101,17581-17596, 1996.
Olsen, K.B., R. Madariaga, R.J. Archuleta, Three-dimensional dynamic simulation of the 1992 Landers Earthquake, Science, 278, 834-838, 1997.
Fukuyama, E., R. Madariaga, Rupture dynamics of a planar fault in a 3D elasic medium: rate and slipweakening friction, Bull. Seismol. Soc. Am. , 88,1-17, 1998.
Madariaga, R., Olsen, K.B. and R.J. Archuleta, Modeling dynamic rupture in a 3D earthquake fault model, Bull. Seismol. Soc. Am., 88, 1182-1197, 1998.
Madariaga, R. & K.B. Olsen, Criticality of Rupture Dynamics in 3-D, Pageoph, 157, 1981-2001, 2000.

Lemoine, A., J. Campos & R. Madariaga, Evidence for earthquake interaction in the Illapel Gap of Central Chile, Geophys. Res. Lett,28, 2743-2746, 2001.
Peyrat, S., R. Madariaga & K.B. Olsen, Dynamic modelling of the 1992 Landers earthquake, J. Geophys. Res.,106, 25467-25482, 2001.
Lopez, G., Kausel, E., S. Barrientos, J. Campos, R. Madariaga, D. Hatzfeld, H. Lyon-Caen and A. Zollo, The 1835 seismic gap in South Central Chile, Phys. Earth Planet. Int., 132, 177-195, 2002.
Gardi, A., Lemoine, A.; Madariaga, R.; Campos, J., Modeling of stress transfer in the Coquimbo region of central Chile, J. Geophys. Res., 111, B04307, 10.1029/2004JB003440, 2006.
Madariaga, R.., Slippery when hot, Science, 316, 842, 2007.
Adda-Bedia, M. and R. Madariaga Seismic radiation from a kink on an antiplane fault, Bull.

Maria Lancieri

Personal Details

Date of birth: January 2, 1977
Place of birth: Castellammare di Stabia (Napoli), Italy
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Research Interests:

Earthquake Early Warning System
Real Time Magnitude Estimation
Statement of empirical correlation between final earthquake magnitude and strong motion parameters read in first seconds after P and S waves arrivals.
Evolutionary approach for real time magnitude estimation based on the Bayesian approach.

Analysis of strong motion data from regional catalogues
Analysis of European and Japanese strong motion database.
Analysis of Tocopilla (Chile), 2007 aftershocks sequence.
Design and implementation of software for the automatic analysis of large data-set.

Strong motion simulation
1D model of the seismic rupture process for complete wave field seismograms simulation.
Simulation of engineering parameters for deterministic scenario studies.
Deterministic hazard assessment.

Professional History:

February 2009 - January 2010:
Ecole Normale Superieure, Paris France:
Post-doc fellowship

November 2006 - January 2009 :
Istituto Nazionale di Geofisica e Vulcanologia, Italy
Research contract at the "Osservatorio Vesuviano" in Napoli, Italy.

February - March 2008:
Gender Awareness Participation Process (contract n° 042864)
Scientific consultant in "Pilot activities" as defined in project workpackage 3.2

April 2005 – October 2006:
AMRA scarl, Napoli, Italy
Scientific consultant for the design and development of the earthquake early warning system for the Campania region (southern Italy).

November 2005 – April 2005:
Università di Napoli Federico II, Italy
Fellowship: "*Study and analysis of a software for the simulation of the strong ground motion from complex seismic sources. Application to the southern Apennines area*".

February 2005 – September 2005:
Università di Napoli Federico II, Italy
Fellowship: "*Development of a numeric code for the simulation of a deterministic post-earthquake scenario*".

Education

February 2005:
PhD in Seismic Risk at the Università di Napoli Federico II
"*Shaking maps in the immediate post-event: How to account for complex source and propagation*" (Italian). Tutor: prof. A. Zollo.

October 2001:
Degree in physics summa cum laude at the Università di Napoli Federico II
“*Strong motion simulation using the empirical Green’s functions*”.
Supervisors: prof. A. Zollo and dott. A. Herrero.

Skills

Computing:
Operating Systems: Mac OS X, Solaris, Linux, Windows.
Programming Languages: MATLAB, Bash, Awk, FORTRAN77.
Seismological Software: SAC, Axitra (O. Coutant), PGA Pack (D. Lavine), GMT.

Languages:
Italian (mother tongue)
English (written and spoken)
French (written and spoken)

Teaching Activity

January 2005 December 2006
Degree thesis supervisor:
“Magnitude estimation from spectral analysis of first seconds of recording finalized to seismic early warning applications”

May 2004 and November 2006:
Early warning methodologies for the seismic risk mitigation: seismological aspects. (CRdC AMRA Scuola di alta formazione in “Analisi, monitoraggio e gestione del rischio ambientale”).

February 2004:
Seismology Fundamentals. (CSM Corso di formazione per tecnico di ricerca esperto nella conduzione di sistemi informatici e di telecomunicazione di monitoraggio strategico).

Most significant publications

A. Zollo, G. Iannaccone, **M. Lancieri**, L. Cantore, V. Convertito, A. Emolo G. Festa, F. Gallovic, M. Vassallo, C. Martino, C. Satriano, and P. Gasparini (2009) The Earthquake Early Warning System in Southern Italy : Methodologies and Performance Evaluation, *Geophys. Res. Lett* 36, L00B07, doi 10.1029/2008GL036689

G. Festa, A. Zollo and **M. Lancieri** (2008) What does an early seismic rupture know about its end? 2008 *Geophys. Res. Lett* 35, L22307, doi:10.1029/2008GL035576

M. Lancieri, A. Zollo (2008) A Bayesian Approach to the Real Time Estimation of Magnitude From the Early P- and S-wave Displacement Peaks. *Journ. Geophys. Res*. 113, B12302, doi:10.1029/2007JB005386

A. Zollo, **M. Lancieri** and S. Nielsen (2007) Peak Ground Displacement and Earthquake Magnitude: Reply. *Geophys. Res. Lett*, 34, L20303, doi:10.1029/2007GL030560

A. Zollo, **M. Lancieri** and S. Nielsen (2006) Predicting the Earthquake Magnitude From Peak Amplitudes of Very Early Seismic Signals,. *Geophys. Res. Lett*. , 33, L23312, doi : 10. 1029/2006GL027795.

SOCQUET Anne, 33, female, 2 children

Current situation: Associate Physicist at Institut de Physique du Globe de Paris since 2006

Research Thematic:
Space geodesy (InSAR + GPS) applied to seismotectonics and faults behavior during the earthquake cycle (Myanmar, Indonesia, North Tibet, Chile or Ethiopia).
Previous experience:

2000-2003	PhD in Geophysics at Ecole Normale Supérieure / Université Paris XI
2003-2004	Assistant professor (ATER) at Versailles University
2004	Postdoc fellow at Department of Earth Observation and Space Systems, Delft University of Technology, The Netherlands
2005-2006	Postdoc fellow at UCLA, Department of Earth and Space Sciences, Los Angeles, USA

Experiences on Project Management:
In charge of IPGP North Chilean continuous GPS array since 2007 (13 instruments over 120 000km^2)
- Management of GPS instrumentation campaigns in North Chile (so far March, Nov. 2007)
- Coordination of post-Tocopilla earthquake geodetic intervention in Dec. 2007 (GPS survey + installation of 3 additional temporary GPS stations)
- Maintenance/upgrade of stations, telemetry
- Supervision of data processing and analysis
- Coordination with Chilean, American and German colleagues

Co-adviser of 2 PhD theses since fall 2006 (R. Grandin and M. Bejar)
Responsible for D. Carrizo post-doctoral project since mid-2007
Organization of GPS survey campaign in Sulawesi (Indonesia, 2004)

5 most significant papers:
Anne Socquet, Gilles Peltzer, Cécile Lasserre. InSAR observations of interseismic strain along the central Altyn Tagh Fault accepted to GRL (Pending revision).
Julie Pietrzak, Anne Socquet, David Ham, Wim Simons, Christophe Vigny, Robert Jan Labeur, Ejo Schrama, Jurjen Battjes, Guus Stelling and Deepak Vatvani (2007), Tsunami modelling of the Sumatra-Andaman Earthquake helps to constrain co-seismic deformation derived from GPS data, EPSL, doi:10.1016/j.epsl.
Socquet, A., W. Simons, C. Vigny, R. McCaffrey, C. Subarya, D. Sarsito, B. Ambrosius, and W. Spakman (2006), Microblock rotations and fault coupling in SE Asia triple junction (Sulawesi, Indonesia) from GPS and earthquake slip vector data, J. Geophys. Res., 111, B08409, doi:10.1029/2005JB003963.
Socquet, A., C. Vigny, N. Chamot-Rooke, W. Simons, C. Rangin, and B. Ambrosius (2006), India and Sunda plates motion and deformation along their boundary in Myanmar determined by GPS, J. Geophys. Res., 111, B05406, doi:10.1029/2005JB003877.
Christophe Vigny, Wim Simons, S. Abu, Ronnachai Bamphenyu, Chalermchon Satirapod, M. Hashizume, C. Subarya, Anne Socquet, K.Omar, H.Z. Abidin, B.A.C. Ambrosius. GPS unveils actual impact of the mega-thrust earthquake in S.E. Asia. Nature, 436, 201-206, 2005.

10 publications in peer review journals since 2002. Complete list available at http://www.ipgp.jussieu.fr/~socquet/publication.html

Christophe VIGNY

Born 02 Mars 1964; Married, 3 children; now “Directeur de recherches” at CNRS

EDUCATION/DIPLOMAS

1987: Master of physics – option astronomy and fluid mechnics
1989: PhD in Earth Sciences entitled "Geoïd and internal dynamics of the Earth"
1990: PostDoc at ONERA “modeling of space gravimetric measurements: ARISTOTELES/GRADIO satellite project”
1991: PostDoc at MIT “Spatial Geodesy (GPS) and plate tectonics”
2006: H.D.R. entitled “GPS: from plate tectonics to seismology”

PROFESSIONAL EXPERIENCE

1999-2004 **Head of geophysics team of the "laboratoire de Géologie"** (8 full-time researchers – 1 administrative staff).
1999-2003 "**Chargé de mission" at INSU (**l'Institut National des Sciences de l'Univers**) -** for satellite observation of the Earth.
2002-2006 **Director of GDR « Géodesie-Géophysique »** a multi-institute cooperation implying CNRS, CNES, IGN, CEA, IRD, SHOM).
2007-2008 **Co-Director of International Laboratory (LIA) “Montessus de Ballore”** a joint-venture between French CNRS and Chilean U-Chile
2009- **Member** of the Scientific Advisory Board of the Earth Observatory of Singapore

Since 1991, I am at “Laboratoire de Géologie” at ENS, Paris, France, working on the measurement of the Earth crustal deformation associated to active faults with high seismic hazard. For this purpose, I use modern style space geodesy (GPS): I install arrays of permanent cGPS and networks of geodetic benchmarks which I survey regularly. These measurements allow to quantify the crustal deformation before, during and after an earthquake. My goal is to understand how major earthquake nucleate and I apply these methods on different faults around the world where seismic hazard is high: South-East Asia (Indonesia – Sumatra and Sulawesi, Malaysia, Thailand, Myanmar), Chile (from Patagonia to Atacama), Iran (Zagros, Alborz), Nepal (Himalayas), Djibouti (East African Rift), etc...My last work is a comprehensive study of the sequence of earthquakes since 2004 on the Sumatran trench.
Author of ~40 publications in international scientific journals, 45 communications in congress, (complete list on http://www.geologie.ens.fr/~vigny/biblio.html)

5 most significant publications:

1. Insight into the 2004 Sumatra-Andaman earthquake from GPS measurements in southeast Asia
   Vigny, C., W. Simons, S. Abu, R. Bamphenyu, et al.
   Nature, vol 436,14/07/05, pp201-206,doi:10.1038/nature03937, 2005
2. Confirmation of Arabia plate slow motion by new GPS data in Yemen.
   Vigny, C., P. Huchon, J.C. Ruegg, K. Khanbari, and L. Asfaw
   J. Geophys. Res., 111, B02402, doi:10.1029/2004JB003229, 2006.
3. GPS determination of the relative motion between India ands Sunda, and its accomodation in Myanmar
   Socquet, A., **C. Vigny**, W. Simons, N. Chamot-Rooke, et al.
   *J. Geophys. Res.,*111, B05406, doi:10.1029/2005JB003877, 2006.
4. A decade of GPS in SE Asia: Resolving Sundaland motion and boundaries
   Simons, W., A. Socquet, **C. Vigny**, B. Ambrosius, et al.
   J. Geophys. Res., 112, B06420, doi:10.1029/2005JB003868, 2007.
5. Upper plate deformation measured by GPS in the Coquimbo gap, Chile
   Vigny, C., A. Rudloff, J.C. Ruegg, R. Madariaga, J. Campos, M. Alvarez
   PEPI, doi, 2009.

Name	***Vilotte Jean-Pierre***
Birth date	22/02/55
Nationality	French
Address	Seismology Laboratory (IPGP-CNRS UMR7154) Institut de Physique du Globe de Paris 4 Place Jussieu , 75251 – Paris cedex 05

Education

1983 Thèse de Troisième cycle, Géophysique, Université de Montpellier

1989 Doctorat d'état, Géophysique, Université de Montpellier

Profession

Position Physicien des Observatoires, première Classe

Institute Institut de Physique du Globe de Paris (CNRS UMR 7580)

Research Topics
Mechanic and Dynamic earthquake modelling
Wave propagation in complex media
Earthquake processes in subduction zones
Granular physics
Parallel computing

Scientific Responsability
Director of the Parallel and Data Centre (IPGP)
Director of the seismology laboratory (IPGP-CNRS) 2003-2007
Director of the National Parallel Computing Centre in Earth Sciences 1994 – 1997

International experience
University College of Swansea, Civil Engineering Department, Royal Society fellowship (1982-1984)
Arizona State University, Department of Geology, visiting fellow, 1984 (4 mois)
Minesotta State University, Department of geology, visiting fellow 1989 (3 mois)
Brown University, Deparment of Engineering, NATO fellowship, 1990-1991 (1 an)
Minneapolis Army High Performance Computer Research Center, visiting fellow, 1991 (2 mois)
Tokyo University, Earthquake Research Institute, invited professor, 2007 (4 mois)
University California Berkeley, Department of Earth and Panetary Sciences, Miller resaerch Professor, 2007-2008 (1 an)

Publications Auteur et co-auteur de 80 publications internationales

Vilotte J.-P., Festa G. And Ampuero J.-P. (2009), « Earthquakes dynamic simulation using non-smooth Spectral Element method », Bull. Sosc. Seism. Am., submitted.

G. Festa and Vilotte J.P. (2009), Dynamic rupture propagation and radiation along kinked faults: in-plane numerical simulation using non smooth spectral element method, Geophys. J. Int, in press.

Chaljub E., Komatitsch D., Vilotte, J.-P., Capdeville, Y., Valette, B. and Festa G. (2007), "Spectral Element Analysis in Seismology, in Advances in Wave Propagation in Heterogeneous Media », edited by R-S Wu and Maupin V., "Advances in Geophysics" series, Elsevier, vol. 48, 365-419.

Mangeney A., Bouchut F., Thomas N., Vilotte J.-P. And Bristeau M.O. (2007), "Numerical modelling of chanelling granular flows and of the levées channel morphology of their deposits", J. Geophys. Res., 112, 02017,doi:10.1029/2006JF000469.

G. Festa and Vilotte J.P. (2006), « Influence of the rupture initiation on the intersonic transition: crack-like versus pulse-like modes », Geophys. Res. Lett., 33, L15320, doi:10.1029/2006GL026378.

Chaljub, E., Capdeville, Y. and Vilotte J.P. (2003), Solving elastodynamics in a fluid-solid heterogeneous sphere: a parallel Spectral Element approximation on non-conforming grids, J. Comp. Phys., 187(2), 457-491.

Chambon G., Schmittbuhl J., Corfdir A., Vilotte J.-P., Roux S. (2003), « Shear with commiution of a granular material : Microscopic deformation outside the shear band », Phys. Rev. E., 68, 011304.

J.-P. Ampuero, Vilotte J.-P. and Sanchez-Sesma F.J. (2002), Nucleation of rupture under slip-dependent friction law: simple models of fault zone, J. Geophys. Res., 107 B12, doi:10.1029/2001JB00452.

Capdeville Y., Larmat C., Vilotte J.-P. And montagner J.P. (2002), « A new coupled Spectral Element and Modal Solution method for global seismology: A first application to the scattering induced by a plume-like anomaly », Geophys. Res. Lett., 29, 1029.

Komatitsch, D. and Vilotte J.-P. (1998), The Spectral Element method: an efficient tool to simulate the seismic response of 2D and 3D geological structures, Bull. Seism. Soc. Am., 88, 368-392, 1998.

7.3. INVOLVEMENT OF INDIVIDUAL PARTNERS IN OTHER CONTRACTS

(un tableau par partenaire)

Cf. §5.3.

Mentionner ici les projets en cours d'évaluation soit au sein de programmes de l'ANR, soit auprès d'organismes, de fondations, à l'Union Européenne, etc. que ce soit comme coordinateur ou comme partenaire. Pour chacun, donner le nom de l'appel à projets, le titre du projet et le nom du coordinateur.

Part.	Name of project participant	Person-months	Programme Name Funding body Funding amount	Project Title	Name of co-ordinator	Start and Finish dates
#						
#						

7.4.

CSD1 Sciences et technologies de l'information et de la communication
CSD2 Sciences pour l'ingénieur
CSD3 Chimie
CSD4 Physique
CSD5 Mathématiques et interactions
CSD6 Sciences de l'univers et géo-environnement
CSD7 Sciences agronomiques et écologiques
CSD8 Biologie santé
CSD9 Sciences humaines et sociales