Appel d'offre pour la labellisation par l'Insu de « Sites instrumentés » en Terre Interne

Sites instrumentés pour l'étude des processus sismogéniques et de l'aléa sismique des zones de subduction : Chili et Mexique

Understanding plate boundary processes and assessing the seismic and tsunami hazards associated with large earthquakes in active subduction zones is a challenging problem in Earth Sciences with important societal implications. The world's greatest earthquakes occur in subduction zones, as in the past the 1960 Chile (Mw 9.5, 22 May 1960), the 1964 Alaska (Mw 9.2, 28 March 1964), the Sumatra-Andaman (Mw 9.3, 26 December, 2004) earthquakes.

Scientific context

The last Sumatra-Andaman earthquake was an important reminder that although the potential of great earthquakes in subduction zone has been known for a few decades, complex systems like great earthquakes, where seismic and a-seismic interactions between different segments could cause the triggering of rupture over an extended area, can significantly deviate from simple empirical relationships. Variability of seismic activity, and earthquake expectation, in a given subduction segment is difficult to test along a single subduction zone, owing to the small number and the uncertainties of great historical earthquakes, the limited time periods of the records, and the lack of extended paleo-seismological observations.

Several studies have evidenced cycle-to-cycle variability in rupture length and co-seismic slip along a given segment of a subduction boundary. The best known examples are perhaps that of the Nankai trough of southwest Japan, the subduction zone off the coast of Colombia and Ecuador and the Kurile trench off the coast of Hokkaido, Japan. Seismic variability has been evidenced in Central Chile, where the inferred rupture area of the giant 1730 Valparaiso earthquake (M 8.5-9) has since been ruptured repeatedly with magnitude 8 events, and in southern Chile, where the rupture area of the 1960 mega-thrust earthquake was prepared by two large earthquakes in 1737 and 1837 and several magnitude 8 precursors. The same picture emerges today in northern Chile, where the recent Tocopilla earthquake (Mw 7.7) ruptured only the lower part of a small portion of the inferred rupture area of the giant 1877 Iquique earthquake (M > 8).

The cause of such variability include subduction segments. A paradigm is provided by the asperity model proposed by Kanamori, McNally and Ruff, in which small earthquake results from the rupture of a single asperity while great earthquakes represents rupture of multiple asperities as a result of seismic and a-seismic interactions and of the dynamic heterogeneities distribution left by the recurrence history of the smaller events. How seismic variability helped the triggering of great earthquakes is a challenging question that require the integration of extended instrumental recordings and field paleo-seismological studies.

Recently, new and exciting observations revealed a wide variety of transient phenomena in the deformation processes along densely instrumented subduction zones, e.g. Japan, Cascadia, Mexico. In large part, these observations have been triggered by long-term baseline of measurements integrating

modern space-based technology, e.g. InSAR, and dense arrays of seismic and geodetic instrumentation, that allow to resolve the broad space and time spectrum of the subduction processes.

Episodic slow slip events (ETS) lasting days to months, non-volcanic tremors (NVT) and low-frequency earthquakes (LFE) all constitute new observations that have stimulated in the last years active research activities and challenge our understanding of plate boundary processes with important implications in terms of seismic hazard assessment and monitoring. One important finding is certainly the wide variety and variability of these transient phenomena, e.g. energy spectrum scaling laws, duration and recurrence time, across different subduction contexts. This strongly suggests that any attempt to physically understand these phenomena must include more accurate depth localization and extensive comparative studies based on standardized analysis tools and collection data from different subduction contexts.

Understanding the seismic and a-seismic activity in subduction zones must today include observations covering the whole space and time spectrum of the plate boundary processes involved in the seismic cycle, taking into account their subduction dependent intrinsic variability and different origin. This is the only path that can lead to physically based scenarios for seismic hazard estimation along active subduction zones.

The main scientific challenges are to:

- develop new monitoring techniques, e.g. such as targeted seismic antenna, and new signal analysis methods, in the whole time and space spectrum of the plate boundary processes, taking advantage of dense arrays of continuously recording instruments in seismology and geodesy, together with the space-based InSAR observations.
- improve observation and analysis of the seismic activity - and its space and time variability - along and across segment boundaries in relation to different subduction contexts.
- improve observation analysis of broadband strong ground motion, and frequency scaling relations, of large subduction, intermediate-depth and shallow earthquakes which have significant impact on modern infrastructures.
- improve observation and analysis of space and time variations of the deformation and of the inter-plate coupling in relation with subduction geometries and segmentation - e.g. the stability of the barriers and/or asperities – including strain partitioning along active surface faults.
- Develop innovative detection, localization and frequency analysis methods of the wide variety of slow transient events during the seismic cycle – and their space and time variability - along and across different subduction zones.

These challenges have to be addressed across different subduction environments to understand the variability of these plate boundary processes and their underlying physical mechanisms.

This requires to establish or build upon long-term baseline capacity, and capability, of continuous observations in different well targeted subduction zones. This must integrate state-to-the-art arrays of instrumentation in seismology (continuous broadband and strong motion) and geodesy (cGPS, InSAR, long base inclinometry), with field studies in tectonics, geomorphology and paleo-seismology. The most interesting phenomena recur over time scales of years at least, from the ~ 14 months ETS cycle in Cascadia to the > 100 years repeat time of most great earthquakes.

This requires also to increase our capability in the development and the mutualization of innovative

instrumental techniques and data analysis methods which can data mine large volume collection and perform cross comparative analysis between different subduction environments.

National context

In the last years, the French research teams have been quite active in instrumenting subduction sites, built on long-term international collaborations, in different contexts. With the support of the CNRS-INSU and the ANR, well instrumented sites have now emerged along the Andean subduction in Chile and the Central Mexico subduction.

This proposal is a first attempt to actually coordinate two international CNRS-INSU instrumented sites in complementary subduction zones, and to define the necessary layer for weaving together long-term collection data and for developing cross collaborative studies and innovative data analysis methods.

With the support of IRD and the ANR, well instrumented sites have also emerged along the Andean subduction zone in Peru, Ecuador and South Colombia. Extending the coordination to these instrumented sites would be of great importance. Moving toward such a coordination requires official discussions between the CNRS-INSU and the IRD to define an actual framework. We call today for such an initiative that will empower these instrumented sites efforts of both Research Institutes with a unique scientific visibility and productivity.

Clearly here there is much interest nationally on the problem of mega-thrust earthquakes and transient phenomena in subduction zones. All these long-term investments could allow the French community to play a leading role if initiatives to foster coordination between these sites get supported.

International context

Several international efforts are underway at the international level. Of course, Japan play a leading role and will be always the best monitored subduction zone on the planet, with fantastic arrays of borehole instruments (broadband, strong motion, strain meters), permanent cGPS with high sampling rates, and soon permanent off-shore instrumentation. The U.S. MARGINS program developed several programs focus on subduction zones at Central America and Nankai, where the NanTroSEIZE major drilling is underway. The U.S. National Science Foundation has recently launched a $10M upgrade program to long-term seismic and geodetic monitoring of Cascadia, onshore and offshore.

U.S. initiatives strongly supported cross comparative studies. Perhaps the most exciting emerging results of such a politics is the evidence of the wide variety of the NVT and LFE observed along Cascadia and the subduction boundaries in Japan which is not yet physically understood.

Toward coordinating instrumented subduction sites

In the last years, research teams in LGIT Grenoble, IPG Paris and ENS Paris have actively invested, with the support of the INSU and the ANR, in establishing well instrumented sites in two targeted subduction zones: the Andean subduction zone in Chile, and the Central Mexico subduction zone.

Both instrumented sites are built upon long-term history of scientific collaborations with research teams and institutions in Chile and Mexico:

- The ENS and IPGP groups have been working for decades with geodesists and seismologists in

Chile with a long track record of collaborative publications and young researcher education. More recently, active collaborations have been structured with the GFZ Potsdam also involved on long-term projects in this part of South America, e.g. the IPOC project in North Chile is a joint project CNRS-INSU, GFZ Potsdam, University of Chile.

- The partnership between LGIT and UNAM (Mexico) has also a long and highly productive scientific record of collaborative publications and young researcher education. Recently, with the move to Paris of Nikolai Shapiro, actively involved in these collaborations, IPGP involvement in the Mexico project seems quite natural.

Both sites involve also active collaborations and data sharing with Caltech:

- in Chile, with the geodesy group (M. Simons and J.Ph. Avouac) leading long term cGPS projects in North Chile and South Peru;
- in Mexico, the seismology group (D. Helmberger and R. Clayton) who conducted large footprint experiments.

We feel that the time is ripe to coordinate the Chile and Mexico instrumented sites in a long-term collaborative effort. This would be a first step toward the coordination of CNRS-INSU instrumented sites in subduction zones.

This collaborative proposal has therefore two objectives:

- **an INSU label recognition of both the Chile and the Central Mexico instrumented sites,**
- **beyond this first step, the recognition of a higher level research coordination to weave together collection data from the two sites, to share innovative data analysis tools and instrumentation techniques, to stimulate new collaborative studies across the two different subduction contexts.**

The INSU label for the CNRS-INSU instrumented sites in Chile and Central Mexico will provide a national recognition for

- the long-term instrumental and scientific efforts of these teams,
- the long-term collaborations developed between France and Chile and Mexico.

The coordination initiative of this proposal will provide the appropriate and necessary level to

- Build and provide long-term integrated data collection (seismology, geodesy, long base inclinometry, InSAR, tectonics) in two different high-activity subduction areas, a critical thing to do if plate boundary processes, and their variability, are to be better understood.
- Develop and share innovative instrumental techniques that can be used in both sites and therefore assessed in different subduction contexts.
- Develop and share innovative modelling methods and data analysis tools, allowing collaborative comparative studies of plate boundary processes, and their variability, across different subduction contexts.
- Improve our understanding of the seismic cycle, over the wide range of space and time spectrum of plate boundary processes, in different subduction contexts in relation with the seismic hazard assessment.
- Increase the international visibility of the INSU research activities and instrumentation efforts on the problem of mega-thrust earthquakes and transient phenomena in active subduction zones.

Complementarity and specificity of the North Chile and Central Mexico sites

Chile and Central Mexico are both young oceanic crust subduction zones with high rates of subduction. As such they are classically identified as potential sites of large subduction earthquakes following the early classification of Ruff and Kanamori in the 1980's. The 2004 Sumatra-Andaman earthquake actually spurred a reappraisal of such age and rate-dependence among the mega-thrust earthquakes. North Chile and Central Mexico represent quite different types – almost two end members - of young and fast subduction zones.

- In Mexico, at the Guerrero gap, the flat slab subduction of the Cocos plate beneath the Mexican Pacific margin, with weak dip angle of about 23°E, becomes at the Mexican coast almost flat under the continental Mexican plate (North America plate). Recent data from the UNAM-Caltech temporary experiment evidence an under-plating of the Cocos plate beneath the Mexico plate up to the central volcanic arc where it starts dipping into the mantle almost vertically. The seismic activity of the Cocos plate has been quite weak, with no large earthquakes south of the M8 1985 Michoacan earthquake, since at least the last 80 years which leads to identify the Guerrero zone as a seismic gap.
- In North Chile, the "normal" subduction of the Nazca plate beneath the South America margin extends up to Argentina, with a dip angle from 23°E to 30°E, far behind the seismogenic zone. The seismic activity of the Nazca plate is quite continuous at least down to 300 km depth. After the great tsunami earthquake of 1877 (M>8.7), North Chile has been very quiet until the end of the 1990's. Awakening of the seismic activity in North Chile started in 1995 with the Antofagasta (Mw 8) earthquake, and recently the 2007 Tocopilla (Mw 7.6) earthquake.

Probably the main interesting difference between the two subduction zones is the presence of a weak frictional plate boundary contact in central Mexico, while in Northe Chili the contact zone appears to be locked.

- In Mexico, slow episodic transient slip events have been detected eight years ago, although their actual periodicity are still debated, thanks to the UNAM cGPS arrays and long base tiltmeter instrumentation. The partial observations available today suggest a localization of these slip events at the low dip angle contact plate boundary, although this remains to be confirmed. In the same zone, the UNAM-Caltech temporary seismology experiments allowed the detection of non-volcanic tremors, a phenomenon associated in some subduction zones like Cascadia to the episodic transient slip events. The localization of these events, their actual relation to the slow slip events and the fluids at the plate contact boundary are not yet fully understood.
- In North Chile no dense seismology and cGPS arrays were available until the recent IPOC network (CNRS-INSU, U. Chile, GFZ Potsdam) leaving open the question of the existence and of the characteristics of slow events in this region. Extensive InSAR studies, by IPGP and Caltech groups, have evidenced slow continuous accumulation of deformation, in support of a fully coupled plate boundary contact, and potential propagating slow slip pulse following the Antofagasta earthquake. The main uncertainty being today the actual depth of the transition zone. Two quite different models have been proposed by Chlieh et al. and Pritchard et al., both fitting equally well the observations. Another feature is an active intermediate-depth seismic activity in the subducting oceanic slab which can lead to large and damaging earthquakes, e.g. The Tarapaca (2005, Mw 7.7). The origin of this activity, and its potential relation with dehydration processes at the base of the transition zone, is still debated.

These sites are quite complementary.

- In Chile, real time monitoring of the seismicity - and seismicity variability - with a network of more than 20 stations, e.g. integrating broadband, strong motion and cGPS instruments, complementing a strong motion network in triggered mode operated by the University of Chile, is an important objective in North Chile where the Tocopilla earthquake raised questions in terms of seismic variability and seismic awakening of a gap with implications in terms of great earthquake preparation and of seismic and tsunami hazard in this region. The IPOC network provides also a unique opportunity to study the active intermediate-depth seismicity in this region – both in time and space – in relation to dehydration processes and to the seismic cycle. At the same time, this dense instrumentation, which is going to be complemented in collaboration with the GFZ Potsdam by seismic antenna in the area of Iquique, open new perspectives for the detection and the analysis of slow transient events which will clearly benefit from the expertise developed in the Central Mexico project.

- In central Mexico, access to a densely instrumented site, e.g. with the UNAM and LGIT networks, complemented by well designed seismic antenna experiments, will actually allow to improve our understanding of the origin and the location of slow transient events, e.g. slow slip events, non volcanic tremors and potentially low frequency events, and their implication within the seismic cycle in a region with only weak seismicity. Another important issue is to improve our physical understanding of the slow event processes in relation to the subduction geometry - flat slab subduction – and to the dehydration and thermal processes associated with the under-plating of the Mexico plate. How specific are those processes will be assess by cross analysis between central Mexico and North Chile.

Understanding these processes and their variability between North Chile and central Mexico is a unique and exciting challenge that the coordination of these two sites will allow to tackle.

Coordination Level

At this stage, the necessary coordination scheme must be kept simple and manageable, especially with no clear perspective for additional financial support. This coordination scheme must also take into account the specificity and the constrains of international instrumented sites involving convention and collaborative schemes specific to each in-country partners, as a result of the in-country - Chile and Mexico - science organization. Without an open-minded flexibility, long-term bi-lateral collaborations can not be operational.

The aim of the coordinating layer is to foster the synergies between the two sites, preserving each site long-term dynamics and collaboration scheme, so as to weave together long-term collection data, to stimulate active scientific collaborations in the development of innovative data analysis methods and cross studies.

The coordination committee should include:

- Michel Campillo (LGIT Grenoble)
- Andrea Walpersdorf (LGIT Grenoble)
- Nikolai Shapiro (IPG Paris)

- Jean-Pierre Vilotte (IPG Paris)
- Christophe Vigny (ENS Paris)
- Sergio Barrientos (U. Chile)
- Vladimir Kostoglodov (UNAM, Mexico)
- Martin Vallée (Geosciences Azur) – external expert
- Luis Rivera (EOST Strasbourg)

The committee will be in charge of the coordination level. At the same time, each instrumented site will still require the existing scientific committee, as the result of each specific international collaboration schemes and operation of the networks with the in-country partners. These committees will be extended so as to each include a French and in-Country leader of the other site.

Finally French teams will organize regular meetings to coordinate and manage a shared specific shared collection data; to actually develop shared innovative data analysis and instrumentation techniques.

Data management and data policy

At the level of each instrumented site, the policy of the data management and data distribution reflect the specificity and the constrains of each in-country partners. Another important constrain is the abroad network operation and integration within the in-country facilities and organizations. This is explicitly detailed in the following Chile and central Mexico sections.

Chile

Data distribution

Seismology:

The IPOC (CNRS-INSU, GFZ Potsdam, U. Chile) network has today 17 sites (broadband and strong motion) continuously operating with the same mode in North Chile. Ten sites are continuously transmitting, and the data stream is received in GFZ Potsdam and IPGP. Each institute is in charge of correcting and validating the data of their respective sites.

- Data distribution: The seismological data (broadband and strong motion) are distributed to the community by official seismological data centers, part of the Digital Seismological Network and of the IRIS consortium: in France, the Geoscope data center (integrated to the Fosfore portal, and IRIS and tomorrow the RESIF data center); in Chile, the data center of the Servicio Sismologico Nacional, at the University of Chile; in Germany, the Geofon data center at the GFZ Potsdam.
- Data policy: For France, all the broadband and strong continuous data (4 sites) are made available immediately. For Germany, broadband and strong motion continuous data of part of the continuously transmitted German sites (4 sites) of the IPOC network are made immediately available. The remaining broadband and strong motion continuous data (9 sites) are made available immediately available within the project, and is open to all the community after 16 months delay. During this period, these part of the data is available to the community upon request and agreement of the stakeholders. Temporary seismological networks data (post-seismic arrays, others) are made available, following the SISMOB and PASCAL policy, after 16

months delay to the all community.

Geodesy:

The French cGPS networks in Chile involve today 37 stations in central and north Chile, 21 of these stations are daily transmitting. In north Chile, 8 stations of the Caltech group are also operating.

- Data distribution: The raw and the processed data of all the French cGPS stations are distributed in France, the GPScope data center at the DT INSU. All these data are also integrated in Chile, at the University of Chile, together with the Chilean cGPS stations, and they are by the data center of the Servicio Sismologico Nacional at the University of Chile. The raw cGPS data (1 Hz) of the Caltech group are also integrated to the French and Chilean data in Chile. These data are open to access within the project and distributed by the Caltech group.
- Data policy: For France, the raw data are made available immediately, and the processed data as soon as they have been processed. For Chile, same data policy.

Data archive

Mirrored data archives are being operated between IPGP and University of Chile. The archive data are

- Today, all the seismological continuous seismological data (broad band and strong motion) of the French and German sites of the IPOC project since 2006.
- soon by the end of 2009, all the cGPS continuous records of the French and Chilean stations of the project (raw data and processed data), and the long base tiltmeter records.
- In 2010, the archive will also contents an event data archive for North Chile since 2006 for North Chile, and all InSAR tracks and processed interferometry images.

The cGPS data of the French, Chilean and Caltech stations in Chile are also archived at the University of Chile in a single archive system.

The IPGP/ENS archive system is integrated in IPGP within a e-infrastructure including hierarchical data storage and computing resources to allow standardized data processing, and data analysis of these data in a robust and efficient way.

Central Mexico

Seismology:

- The data acquired by the Mexican seismological network are indeed under the only responsibility of the Mexican partners but the data are actually available to the community.
- The data acquired with the French networks in collaboration with our Mexican colleagues will be shared among the participant institutions immediately.

Indeed we need to include the data in a data base to make the access easier. This will be done on the French side with BDSis in Grenoble with access through the Fosfore portal. We have a project (ANR International, under review) to build a facility in Mexico that would allow to share the data and the developed tools amongst the participants of the present joint project.

Our goal with the ‘site instrumenté’ proposal is to evolve towards an effective open access to our data. This is both a practical issue from the French side and a political issue with our partners. In Mexico, like everywhere, we have to comply with national rules.

Geodesy:

- The GPS data of French stations will be distributed to the community in France by GPScope (http://gpscope.dt.insu.fr <http://gpscope.dt.insu.fr/>_).
- Today, because of the competition between the Mexican and American teams, only part of the Mexican GPS data are published on the UNAVCO site (http://facility.unavco.org).
- Within the collaboration scheme between the French and Mexican teams, all the Mexican GPS data are available within the ANR G-GAP.

La publication des données des stations mexicaines financées dans le cadre des projets ANR et 3F sur GPSCOPE nous permettra de rester cohérent avec l'effort d'instrumentation de nos collaborateurs mexicains, par une distribution sur demande, ce qui est tout à fait une option d'intégration dans la base de données GPSCOPE. De plus, une réussite du projet ANR pour l'ensemble des partenaires impliqués nous permettra éventuellement de compléter la base de données disponible en France avec un certain nombre de stations additionnelles qui sont actuellement sous responsabilité exclusive de nos collègues mexicains.

L’objectif à terme est de rendre toutes les données des stations françaises et d’un maximum de stations locales disponibles à la communauté.

Chantier Subduction Chili

Coordinators

Jean-Pierre Vilotte & Christophe Vigny
Institut de Physique du Globe de Paris (CNRS-UMR 7154)
Laboratoire de Géologie (CNRS-UMR 8531), ENS Paris

Academia Partners

Institut de Physique du Globe de Paris (CNRS-UMR 7154) :
seismology, tectonic and geodesy teams
Laboratoire de Géologie (CNRS-UMR 8531), École Normale Supérieure de Paris :
seismology and geodesy teams

The Chile site is from the beginning open to all the French researchers and French laboratory involved in Chile and willing to participate.

International Partners

Universidad de Chile (Santiago) : departments of de geophysics and geology
GFZ Potsdam : departments of seismology, geodynamic and geodesy
Universidad Catholica del Norte (Antofagasta, Chile)
Universidad Arturo Prat (Iquique, Chile)

Scientific management and direction

The scientific committee is the scientific committee of the Laboratoire International (LIA) Montessus de Ballore, created in 2006 between te CNRS-INSU and the Universidad de Chile.

Scientific committee:
Francisco Brieva (Dean of the Universidad de Chile)
Bruno Goffé (DSA Earth Sciences, INSU, CNRS)
Gerardo *Suárez (UNAM, Mexico): President of the scientific committee, external expert*
Hélène Lyon-Caen (ENS Paris) : external expert
Tony Monfret (Geosciences Azur, CNRS-IRD, Nice): external expert
Jean-Paul Montagner (IPG Paris): external expert
Onno Oncken (GFZ Potsdam): external expert
Miguel Angel Parada (geology department, Univsersidad de Chile)
Mario Pardo (geophysics department, Universidad de Chile)

The scientific committee will be extended to have cross leadership between the Chile and the central Mexico project:
Michel Campillo (LGIT, Grenoble)
Vladimir Kostoglodov (UNAM Mexico)

Scientific direction:
Jaime Campos (geophysics department, Universidad de Chile)
Gabriel Vargas (geology department, Universidad de Chile)
Christophe Vigny (ENS Paris)
Jean-Pierre Vilotte (IPG Paris)

Proposed time duration

10 years long-term duration

Support to International Collaboration

One ANR project (Subchile-II 2006-2009)
The Laboratoire International Associé (LIA) Montessus de Ballore (2006-2010)
One International ANR proposal (PEPS) in review process

Scientific proposal

The West coast of South America is one of the most seismically active regions of the world. It has been the site of some of the largest earthquakes.

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. This activity is the result of the fast convergence (~ 7 cm/yr) of the Nazca plate subducting under the American plate. The subduction zone in Chile is segmented, each segment can produce large earthquakes and eventually mega-thrust earthquakes when interactions allow the rupture to propagate through multiple segments.The largest earthquake ever recorded is the 1960 Chile mega-thrust earthquake (Mw 9.5) in Southern Chile, which put the entire Pacific basin in jeopardy. 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. The level of exposure and vulnerability in Chile, related to earthquakes and tsunamis. 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.

Chile is a natural laboratory for understanding and developing monitoring techniques of seismic hazard in subduction zones: (1) It provides exceptional conditions for the deployment of field instruments and InSAR; (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 seismicity in Chile is characterized by major inter-plate earthquakes as well as intermediate depth earthquakes together with moderate shallow earthquakes along active surface faults of the Andes. Based on parsimonious historical data, several gaps have been identified and classically used to identify potential zones of large earthquakes. Three seismic gaps in North and Central Chile were identified by the French and Chilean teams as close to rupture: In two of these gaps, no major earthquakes has been recorded since the last 130 years.

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/aseismic activity in relation with the spatio-temporal deformation and the along-strike variations of the subduction zone coupling. 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. Analyzing the entire spectrum of transient motions in Chile, can only be achieved by integrating, and operating, over a long period of time, state-of-the-art seismology, geodesy, and geology observations that are becoming available thanks to modern multi-parameter networks including digital seismometers and accelerometers, continuous GPS (cGPS), long base inclinometry and strain meters, as well as radar interferometry (InSAR).

The main scientific objectives in Chile are:

- The spatio-temporal analysis of the seismicity – and seismicity variability- in subduction segments in relation with the subduction structures and the dehydration processes ;
- The analysis of the co- and post-seismic phase of large subduction earthquakes , together with strong motion prediction and potential early warning methodologies ;
- The analysis of intermediate-depth seismicity in relation with dehydration processes and seismic/aseismic coupling ;
- The detection and analysis of transient slip events, non-volcanic tremors, low frequency earthquakes in Chile - together with their spatio-temporal variability - to improve the understanding of their origin and mechanisms as well their their implications in the maturation of large subduction earthquakes ;
- The analysis of the segmentation and the spatio-temporal variations of the deformation and seismic coupling along the subduction zone ;

- The analysis of the shallow depth seismicity in relation with the deformation partitioning and the active faults at the surface.

  The instrumentation of the Chilean active margin has seen a significant development in the last decade with the deployment of a wealth of new instruments by Chilean, French, German researchers both in North and Central Chile. These instruments will become even denser with the deployment of a new National seismic and geodetic network (RedNat) by the Chilean government.

  The recent earthquake in Tocopilla on 14 November 2007, one of the best recorded large subduction earthquakes tanks to this international instrument efforts, raises a number of important questions related to concept of “seismic gap” and to the long-standing discussions whether those gaps are semi-permanent features of the subduction zone limited by barriers or simply reflect the largest events in recent history. If one can't exclude the possibility that the Tocopilla earthquake 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 earthquakes migrate along strike toward North or will they continue to break the South part of the segment migrating along dip toward the surface ? All these questions are rooted in the understanding of seismic variability in a given segments, and of how such seismic variability actually enhance the probability of a mega-thrus earthquake.

  The present proposal builds upon a long history of collaboration between the French and Chilean research teams, supported through time by the: CNRS-CONYCIT (PICS), ECOS-Sud, EEC, Mideplan (Nucleo Millenio program), e.g. the Chilean Minister of Economic Planning. More recently, the IPGP-ENS 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.

  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). The LIA structures the collaborative efforts between French and Chilean teams.

  Collaborations with the GFZ Potsdam have been structured through a collaborative agreement (MOU), between the GFZ and the CNRS-INSU,for the operation of the multi-parameter IPOC network in Northern Chile and the scientific analysis of these observations. In the last years, these collaborations lead to a number of joint publications and communications in international meetings like the AGU and EGU.

  We believe that this long-term instrumentation and research efforts are critical to improve observations and data analysis methodologies for the assessment and the mitigation of seismic hazard in subduction zones. The availability and the analysis of strong motion data is an absolute need to understand large subduction zone earthquakes ground accelerations. This has strong implications for other subduction zones like in Central Mexico and the French Antilles.

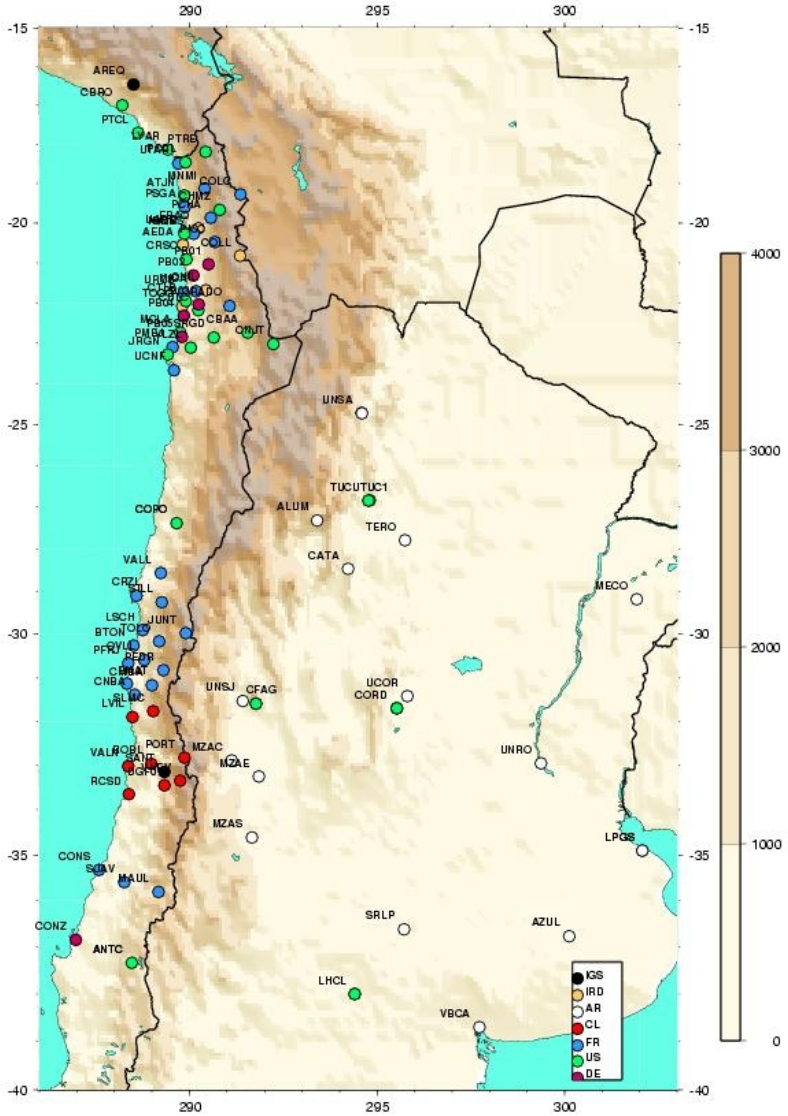
  The Chile site is quite complementary to the Central Mexico site. A coordination between this two sites is advocated here by IPGP, ENS and LGIT. Other complementary efforts are those developed by IRD teams on the Andean subduction zone in Peru and Ecuador. A coordination between INSU and IRD would also be very timely.

Instrument site description

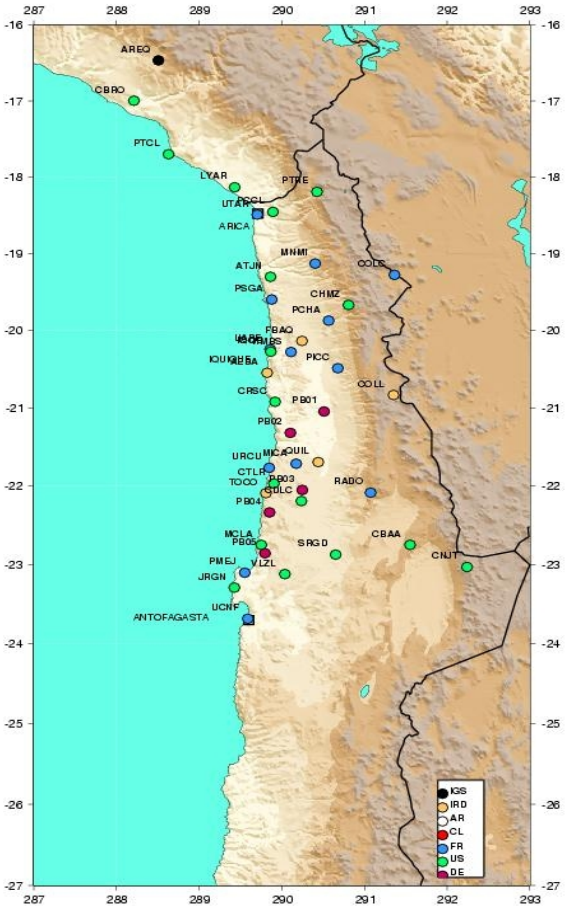
GPS networks

The cGPS networks density has been significantly improved in North Chile, between Arica and Antofagasta (18°S-27°S), Central Chili, between Constitución and Concepción (35°S-37°S) and between La Serena et Los Villos (30ºS-32°S). The cGPS networks, initially composed of 16 stations (6 in North Chile and 10 in Central Chile) integrate now 37 stations, other stations have been upgraded to improve the coherence and the quality of the network. Today, 27 stations are recording at 1 Hz, and 21 stations are daily transmitting. In North Chili, the network is coordinated in a complementary way with the cCGPS network of Caltech and GFZ Potsdam. In parallel, networks of GPS temporary points have been increased and repeatedly measured several times during the project. Finally, in North Chile a fist long base inclinometre has been installed in 2007.

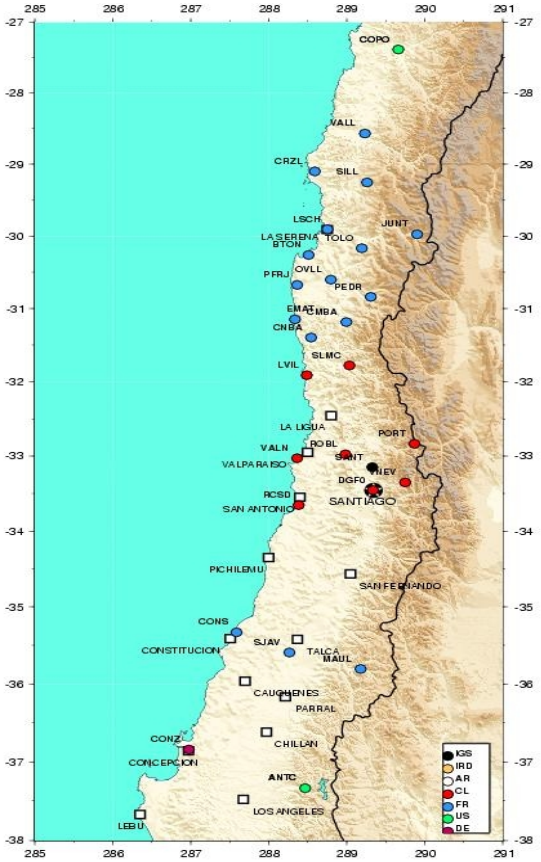
cGPS networks



Chile-Argentina-Bolivia GPS sites: 15°S – 40°S

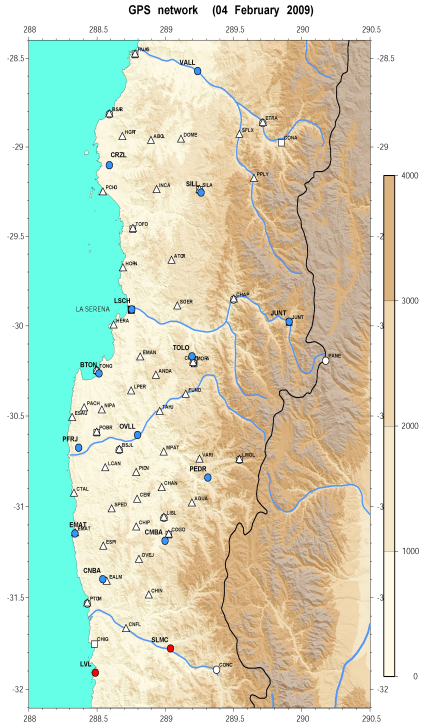


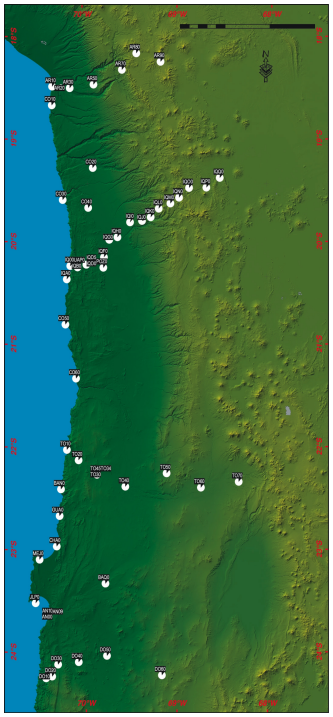
Arica-Antofagaasta region: cGPS stations



Concepcion-Copiapo region: cGPS stations

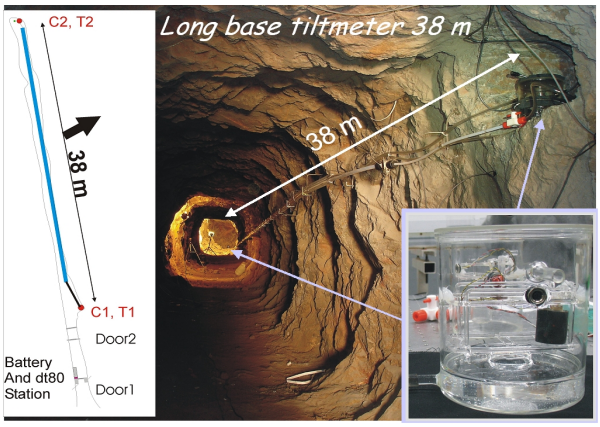
Repeated GPS points

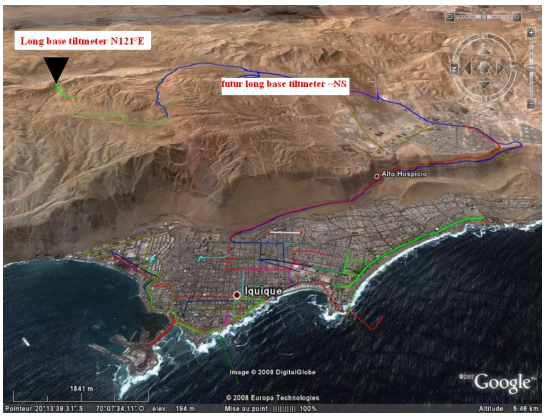




« Coquimbo » – 32°S-28°S	Antofagasta-Iquique-Arica 23°S-18°S

Long base inclinometer





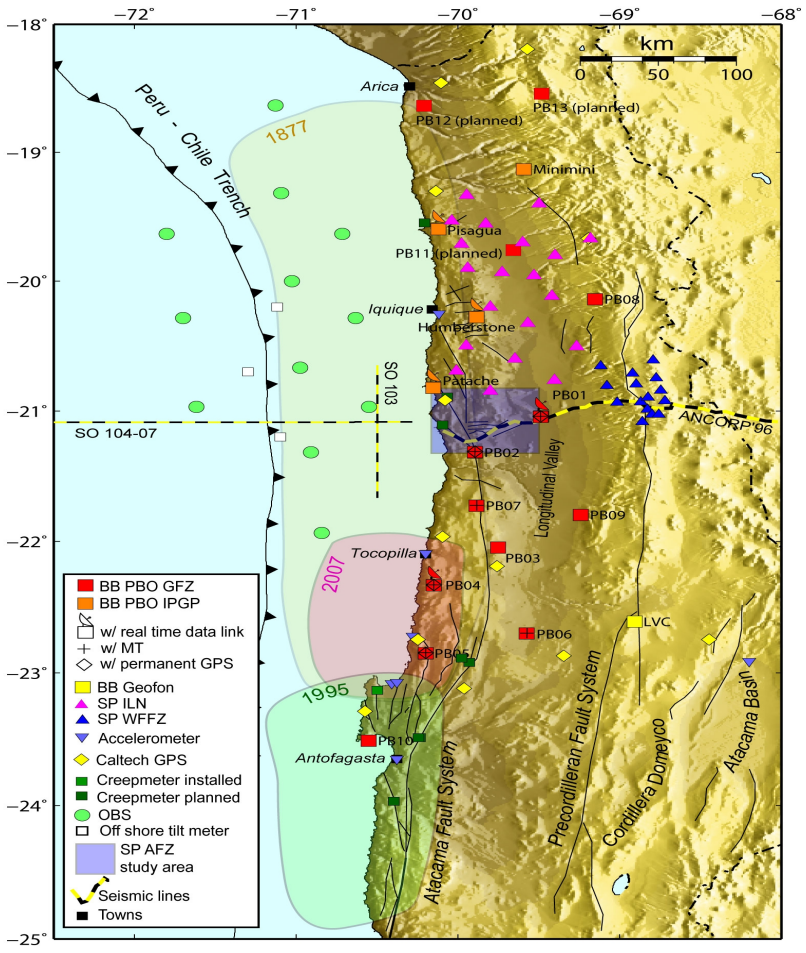
One component of a long base inclinometer has been installed in August 2007 in a tunnel of the Neuquen mine 10 km NNE of Iquique. The instrument was developed by F. Boudin (IR Geosciences Montpellier). A second component will be installed by the end of this year.

Seismological network

In collaboration with the GFZ Potsdam and the University of Chile (Santiago), the North Chile gap has been instrumented with the continuously recording permanent seismological network IPOC (CNRS/INSU, GFZ, DGF). The network integrates today 15 sites (+2 in 2009) combining broadband and strong motion receivers and two tiltmetres components, with a mean spatial spacing of 80 km. Four French sites were financed by the ANR projects. Eight sites - four French sites - are equipped with a continuous satellite transmission system. This network is completed by the IRIS/Geofon station of Limon Verde. Thanks to this instrumentation effort,

the Tocopilla earthquake has been very well recorded and is probably one the best subduction earthquake ever recorded in Chile.

IPOC network



nstallation type d'un site

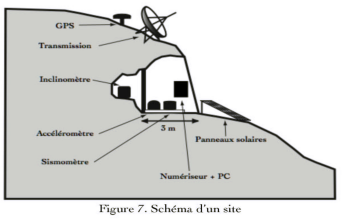
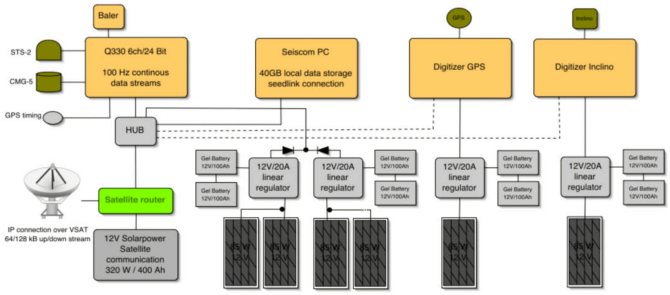


Figure 7. Schéma d'un site

Figure 8. Site de Miñiminiñi (MNMCX)



IPOC network (CNRS/INSU-GFZ-U. Chile) (broad-band, strong motions) in North-Chile. New ongoing GFZ instrumentation projects are also indicated (OBS and ILN network deployed March 2009).

The French sites of the IPOC network are equipped with: one broad band (STS 2), one strong motion (CMG5), a Q330 digitizer (+ Bailer) and a seiscomp PC. The IPOC sites, in continuous

mode, are completed by 10 Chilean strong motions stations (in triggered mode) operated by the University of Chile. Eight IPOC sites (4 French and 4 German sites) have a continuous satellite transmission using seed-link to the DGF (Chile), Potsdam (Germany) and IPG Paris.

Data distribution and data policy

Data Policy

The data policy of an international instrumented site must take into account the specificity and the constrains of the in-country partners science and data organization and policy. Another important specificity is to keep in mind that the networks must be operated abroad in collaboration and in good integration with the in-country networks organization and management. Without a certain flexibility and an open-minded understanding of the in-country specificity, there is possible long-term bi-lateral collaboration.

The CNRS-INSU and the Universidad de Chile have agreed today on a data policy built on:
a common management of long-term data collection with mirrored data archives ;

- a data distribution to the scientific community through community data centres: in France, Geoscope (and tomorrow RESIF) data centre integrated in the IRIS consortium and with the Fosfore web portal; in Chile, the Servicio Sismologico Nacional data centre localized at the Universidad de Chile.
- A system of mirrored data archives between France and Chile

The CNRS-INSU and Universidad de Chile data policy today is:

- Immediate availability to the community of the French-Chilean seismological networks and temporary experiment networks in Chile (broadband, and strong motion) through existing seismological data centres.
- Availability to the community of the Servicio Sismologica Nacional networks data
- Availability to the Chile project partners and upon request to the community of the triggered strong motion array operated by the Universidad de Chile (geophysics and seismic engineering departments).
- Immediate availability of the French-Chilean cGPS data (raw and processed) through existing community data centres.
- Availability to the Chile project partners, and upon request to the community, of the cGPS data of the Servico Sismologico Nacional networks.

The CNRS-INSU, The Universidad de Chile and the Caltech group have agreed to day on:

- integration of the Caltech cGPS 1Hz data with the French and Chilean cGPS data into a single mirrored archive at the Universidad de Chile, open immediately to the partners.
- Distribution of the cGPS raw data of the Caltech group immediately by Caltech.
- The cGPS 5Hz data of the Caltech group is available to the partners upon request, and to the community after a delay time fixed by Caltech.

The CNRS-INSU and the GFZ Potsdam and the Universidad de Chile have agreed today on:

- immediate availability to all partners of the IPOC project of all the German seismological sites data (broadband, strong motion) of the IPOC network, and of temporary experiment networks.
- Immediate availability to the community of all French sites data (broadband andstrong motion) of the IPOC network, distribution by existing community data centres.
- Immediate availability to the community of four transmitting sites data (broadband and strong motion) of the IPOC network, distribution by existing community data centres.
- Availability of the remaining data (9 German sites) after a 2 year delay, and immediately upon request after agreement of the stakeholders.

Data distribution

The cGPS data (raw and processed) are today archived and distributed today by the dgf of the Universidad de Chilei (http://www.dgf.uchile.cl), and in France by GPScope at the DT INSU (http://gpscope.dt.insu.fr). All these data are immediately available to the scientific community.

The IPOC seismological data are today archived in mirrored archives at IPGP, GFZ Potsdam and the Servicio Sismologico (U. Chile). They are distributed through the Geofon data centre (http://geofon.gfz-potsdam.de/geofon//status/index.html), the Geoscope data centre (http://geoscope.ipgp.jussieu.fr/). Both centres are part of the IRIS consortium.

Toward a single data archive

A complete archive, of all the collection data (cGPS, InSAR, tiltmeter, broadband, strongmotion, inclinometry) of the Chilean project, is being developed at IPG Paris, and will be mirrored at the DGF in the Universidad de Chile. This archive system is integrated in a e-infrastructure (hierarchical data storage, computing resources) which constitutes a platform for standardized data processing and data analysis of large volume of data. These processing and analysis tools are interfaced to the archive system using data base services.

A web site, operated by the LIA Montessus de Ballore, is under construction and will provide informations on the scientific activity of the Chilean project and on the available data.

Moyens financiers disponibles ou envisagés

- Un projet ANR SubChile2 a été déposé, et accepté, au programme CATTEL-2006 en complément du premier projet CATTEL-2005 (budget 200 000 euros, fin du projet Décembre 2009).
- Un projet ANR blanc international (France-Chili) a été déposé (projet PEPS) lors du premier appel d'offre en 2009 (durée 3 ans) (450 000 euros demandé partie française).
- Un demande d'action de suivi a été déposée en 2008 (budget demandé 45 000 euros).
- Une demande BQR IPGP 2009 a été financée, faisant suite à une précédente demande financée en 2008 (35 000 euros 2009 ; 20 000 euros 2008).
- Un Laboratoire International Associé (LIA) « Montessus de Ballore » a été créé par le CNRS(DRI) associant le CNRS/INSU et l'Université du Chili (départements de géophysique et de géologie) en 2006. (durée 4 ans, renouvelable une fois) (budget 15 000 euros/an). Un élargissement du LIA en direction du GFZ Potsdam est en cours d'étude entre l'INSU et la DRI du CNRS.
- Un accord cadre (MOU) a été signé entre l'INSU d'une part et le GFZ-Potsdam d'autre part afin de structurer la collaboration scientifique entre ces deux instituts au Chili, ainsi que l'opération et la maintenance du réseau IPOC (CNRS/GFZ/DGF).

Moyens humains disponibles ou envisagés

Partner : **IPGP**	Surname	First name	Position	Domain	Person - months	Role/Responsability
Co-ordinator	VILOTTE	Jean-Pierre	Physicien des observatoires	Sismologie Computational seismology	40.00%	Coordinator of the project Dynamic and mechanical modeling Strong motion analysis and stochastic modeling
Members	BERNARD	Pascal	Physicien des observatoire	Sismologie Inclinomtry	10.00%	Strong motion and wave form analysis, Kinematic modeling Multiplet analysis
	ARMIJO	Rolando	Physicien des observatoires	Tectonics	20.00%	Seismo-tectonics, geomorphology, paleo-seismology
	BRENGUIER	Florant	Physicien des observatoires	Sismologie	Expert	Cross-correlation noise analysis, tremors
	FAVREAU	Pascal	Assistant Professor	Sismologie	15.00%	Dynamic modelling and source inversion Mechanical modeling
	LACASSIN	Robin	DR CNRS	Tectonics	15.00%	Sismo-tectonics, geomorphology
	SHAPIRO	Nikolai	DR CNRS	Seismologie	Expert	Noise correlation analysis, tomography and tremors
	NERCESSIAN	Alex	Physicien adjoint	Sismologie	10.00%	Network design maintenance, data transmission, data analysis, noise analysis
	SOCQUET	Anne	Physicien adjoint	Geodesy	20.00%	Network design and maintenance, GPS and InSAR analysis
	DELORME	Alain	IE CNRS	Geodesy	10.00%	Data transmission, GPS instruments
	El ASSAOUI	Mamadi	IE MEN	Seismologie	70.00%	Network design and management, data analysis, data flow and data analysis
	MOGUILNY	Geneviève	IR CNRS	Computer science	10.00%	Networking, Web, Data base

Partner : **ENS**	Surname	First name	Position	Domain*	Person-months	Role/Responsability
Co-ordinator	Vigny	Christophe	Directeur de recherches	Geodesy	60%	GPS task coordination network design, maintainance, data processing, modellisation, publications
Members	Madariaga	Raul	Professeur	Seismology	35%	Seismology task coordination Strong motion analysis, Earthquake source modelling, Seismicity analysis
	Lancieri	Maria	PostDoc	Seismology	100.00%	Relocation of aftershocks, early warning
	Métois	Marianne	Ph.D.	Geodesy	100.00%	GPS data processing and modelling
	Fuenzalida	Amaya	Master	Seismology	100.00%	Analysis of accelerograms
	Morvan	Sylvain	Ingenieur	GPS data	60%	Participate to field work, network maintainance, tele communications, GPS data base, automatic data processing

Bibliographie relative au site instrumenté

Recent Publications

1. Tarapaca intermediate depth earthquake (Mw7.7, 2005, northern Chile): a slab pull event with horizontal fault plane constrained from seismologic and geodetic observations
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   Geophys. Res. Let., V33, DOI 10.1029/2006GL027710, 2006.

2. 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 in press, 2008.

3. Interseismic strain accumulation measured by GPS in the seismic gap between Constitucion and Concepcion in Chile
   Ruegg, J.C., A. Rudloff, C. Vigny, R. Madariaga, J.B. DeChabalier, J. Campos, E. Kausel, S. Barrientos, D. Dimitrov
   PEPI in press, 2008

4. The West Andean Thrust (WAT), the San Ramon Fault and the Seismic Hazard for Santiago (Chile)
   Armijo, R., R. Rauld, R. Thiele, G. Vargas, J. Campos, R. Lacassin and E. Kausel
   submitted to Tectonics, 2008

5. Site effect evaluation in the basin of Santiago de Chile using ambient noise measurements,
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6. Kinematic and spontaneous rupture models of the 2005 Tarapaca earthquake,
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   Geophys. J. Int. in press, 2009

7. Kinematic rupture process of the Tocopilla Earthquake and its main aftershoks from teleseismic and strong motion data
   Peyrat, S., R. Madariaga, E. Bufforn, J. Campos, G. Asch and J.-P. Vilotte
   submitted to Geophysical Journal International, 2009-02-16

Recent Communications

1. The Mw=7.7 Tocopilla Earthquake (North Chile) of November 14, 2007: First results from space geodesy (InSAR).
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   VII Congreso Geológico de España, 2008.
2. The Mw 7.7 Tocopilla, Chile, Earthquake of 14 November 2007: A Comprehensive Study Using Teleseismic, Local and InSAR data
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   Eos Trans. AGU, 89(23), Jt. Assem. Suppl., Abstract S24A-01, may 2008
3. Rupture Geometry and Slip Associated With the 2007 November 14 Mw = 7.7 Tocopilla (Chile) Earthquake, as Preliminary Determined by InSAR and GPS

Observations
Béjar-Pizarro, M., D. Carrizo, A. Socquet, R. Armijo, J.-B. DeChabalier, A. Nercessian, O. Charade, J.-C. Ruegg, S. Barrientos, and J. Campos
Eos Trans. AGU, 89(23), Jt. Assem. Suppl., Abstract S24-A02, may 2008

4. Detailed source process of the 2007 Tocopilla earthquake.
   Peyrat, S ., R. Madariaga, J. Campos, G. Asch, P. Favreau, P. Bernard, J.-P. Vilotte
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   D. Carrizo, Bejar-Pizarro, M., Socquet, A., Armijo, R., Ruegg, J-C., de Chabalier, J-B., Nercessian, A., Charade, O., Barrientos, S., Campos, J.
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2. Rapport_cGPS_IV Rapport sur l'installation de stations GPS permanentes dans la lacune du Coquimbo. **[Christophe Vigny, période 2006-2007]**.

3. GPS: Intervention séisme Tocopilla 1 Rapport sur l'installation de stations GPS permanentes et semi-permanentes pour la crise sismique de Tocopilla. **[Anne Socquet, Nov-Dec. 2007]**.
4. Rapport_cGPS_IV_CB1 Rapport sur la maintenance des stations GPS permanentes dans la lacune du Coquimbo. **[Carolina Valderas-Bermejo, février 2008]**.
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6. CR-missionsGPSavrmai2008.pdf Rapport sur la campagne de mesures GPS dans la région du Coquimbo **[Christophe Vigny, avril/mai 2008]**.
7. CR-mission_Tocopilla_Chaiten_mai08.pdf Rapport sur la maintenance des stations GPS/sismo Nord Chili et Tocopilla et intervention sur la crise du volcan Chaiten **[Alexandre Nercessian & Sophie Peyrat, mai 2008]**.
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9. Profils topo pour transmissions radio Etude de faisabilité des transmissions radio pour les stations cGPS**[Arthur Delorme, Octobre 2008]**.
10. Inclinomètre longue base d'Iquique (Nord Chili) Rapport sur l'installation et la première année de mesure de l'inclinomètre LBT**[Frédéric Boudin & Pascal Bernard, période 2007-2008].**

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Chantier Subduction Mexique-Guerrero

Coordinateurs : Michel Campillo et Nathalie Cotte (LGIT),
Nicolas Shapiro (IPGP)

Partenaires du monde académique

Laboratoire de Géophysique Interne et Tectonophysique(CNRS-UMR5559), Observatoire de Grenoble
Institut de Physique du Globe de Paris (CNRS-UMR 7154) : équipes de sismologie, de tectonique et géodésie

Partenaires étrangers

UNAM Mexico
Caltech

Structure de pilotage

La structure de pilotage proposée serait cadrée par le Memorandum Of Understanding signé en 2006 entre les partenaires français et mexicains. Les membres de ce comité seraient ceux du comité scientifique actuel : Michel Campillo (LGIT), Nathalie Cotte (LGIT), Nikolai Shapiro (IPG Paris), F.J. Sanchez-Sesma (UNAM, Mexico), Shri Krisna Singh (IG-UNAM, Mexico), Vladimir Kostoglodov (IG-UNAM, Mexico) et Victor Cruz Atienza (IG-UNAM, Mexico). Nous proposons que ce conseil soit élargi à trois autres membres : C. Vigny (ENS Paris) OU J.-M. Nocquet (Géosciences Azur) pour le volet GPS, J.-P. Vilotte (IPG Paris) et un membre de CALTECH pour le volet sismologique, et un membre de la commission des observatoires de l'INSU.

Durée proposée

Une durée de 10 ans.

Soutien à la collaboration internationale

Le chantier Mexique est soutenu par :

- un projet ANR (G-GAP 2008-2012 : Nouvelles perspectives sur le risque sismique associé à la subduction : transitoires, tremors, monitoring passif, tectonique et scénarios.),
- un projet ECOS-*Nord* 2006-2010 (Etude des trémors non volcaniques et du bruit sismique dans les zones de subduction)
- un PICS CNRS 2009-2011 (Nature et rôle des séismes lents dans le cycle sismique : cas de la lacune de Guerrero, Mexique)
- une demande ANR internationale Mexique en cours d'évaluation

Résumé en français

Les grands séismes des zones de subduction sont une menace majeure à l'échelle globale et pour le territoire français. Toute politique de prise en compte de ces phénomènes repose sur une évaluation rationnelle de la probabilité d'occurrence d'un mouvement du sol, et des niveaux d'incertitude, dans l'attente de la mise en évidence de phénomènes précurseurs. Ce projet est centré autour de changements radicaux de perspective pour la compréhension des

séismes et du cycle sismique d'une part, et sur l'évaluation de l'aléa d'autre part. Ces changements sont liés d'une part à des découvertes nouvelles: grands séismes lents, qui remettent en cause notre vision du cycle sismique et tremors non-volcaniques qui sont une expression encore mal comprise de l'évolution des zones de failles. Nous proposons donc d'acquérir des données nouvelles sur ces phénomènes dans une zone de subduction dont la géométrie et l'amplitude des phénomènes est particulièrement favorable à ces études. Il s'agit de la zone de subduction du Mexique où nous disposons d'importantes collaborations locales, où nous avons une longue tradition de travail et avec lequel des accords formels ont été signés. C'est de surcroît une région où se posent une série de questions sur les mouvements forts : lois d'atténuation, effets des grands bassins et durées des signaux. Les nouvelles perspectives viennent aussi de l'évolution récente des méthodes d'analyse. Il s'agit d'abord des progrès constants réalisés dans les mesures géodésiques (traitement GPS et interférométrie répétée) mais aussi de l'émergence de nouvelles méthodes sismologiques. Nous avons montré que le bruit sismique était utile pour imager la structure en ondes S de la croûte supérieure. Nos plus récents résultats montrent le potentiel de cette approche pour le suivi continu de faibles variations des vitesses sismiques en profondeur ce qui en fait un outil de surveillance dont les performances vont encore être améliorées. Notre projet a plusieurs volets : 1- Il faut acquérir plus de données géodésiques continues. Nous allons installer 8 nouvelles stations permanentes en 2009 pour compléter le réseau actuel, composé de 18 stations dont nous avons accès aux données. Nous améliorerons le traitement actuel de ces données et testerons l'apport des données INSAR. Nous développerons les outils d'inversion et de modélisation des glissements lents. 2- Nous installerons des antennes sismiques dans la région où les tremors ont été détectés. Nous améliorerons les outils de localisation des tremors à partir de traitement d'antennes.

The working plan:

Choice of studied region: Central Mexican subduction zone, a natural laboratory for studying of transient deformation events and their relation to the seismic cycle

While ETS were discovered in the Cascadia and the Nankai subduction zones where dense geodetic and seismic networks exist, there are other regions providing very favorable geological conditions for studying this phenomena. Among important factors to consider are: the subduction convergence rate and coupling that determine the intensity of the seismic cycle, the subduction geometry that affects the size of the area where the ETS occur and the accessibility of land-based observations, and existence of good instrumental and historical records of past earthquakes and transient events. Combination of these factors makes the Pacific coast of central Mexico an almost ideal natural laboratory where we can advance our understanding of slow earthquakes and non-volcanic tremors and their relation to the seismic cycle. A fast subduction (~6cm/year) of a young Cocos plate gives rise to very active thrust fault seismicity with several $M \geq 8$ earthquakes per century. Another particular feature of this subduction zone is its flat geometry that results in a very favorable observational setting with a ~200 km long portion of the subduction interface lying at depths ≤ 40 km and is well exposed to land based geodetic and seismic stations (Figure 1). Recent observations revealed that slow earthquakes and non-volcanic tremors occur on the more than 100 km wide flat segment of the subduction interface (e.g., Lowry et al., 2001, Kostoglodov et al., 2003; Payero et al., 2008). The size (equivalent to magnitudes between 6.5 and 7.5) and the duration (several months) combined with a very favorable observational setting makes them a particularly attractive object to study. Another important aspect is that these slow slip events are located in the Guerrero seismic gap where no large subduction earthquake occurred since the 19th century making it prone to occurrence of a catastrophic event in a near future. Therefore Central Mexico is a very suitable location to study the relationship between the slow transient events and the evolution of seismic gap.

Crustal, upper plate deformation and back-arc seismicity

Strong, crustal normal faulting earthquakes affect the upper plate, as attested by the large 1912 Acambay earhquake (M ≈7; Langridge et al., 2000) which occurred nearby the highly populated Mexico City. Most of those earthquakes occur within the so-called Transmexican Belt (Suter et al., 1996, Zuniga et al., 2003), an easterly-striking zone of active normal and strike-slip faulting associated to active volcanism, which offsets the upper plate a few hundred kilometers away from the coast. Because Mexico City and many other large towns are located within that belt of active faulting, it is necessary to assess the seismic risk related to the crustal, seismogenic faults. We thus plan to perform a tectonic analysis of the upper plate, dedicated to identify and characterize (distribution, hierarchy, geometry, slip modes and rates, etc…) the major active faults which offset it. Most of the faults identified so far from a preliminary work that we have conducted bound large and likely deep basins. To recover the at-depth geometry of the bounding faults, as the thickness of the sediments accumulated in the basins (information requested for site effect assessment), we will produce accurate crustal models. Those will be done by using the recently developed noise based tomography. Detailed geophysical surveys (seismic, electric, GPR) will also be performed to more precisely determine the position and geometry of the active faults bounding the major basins, as the Acambay one.

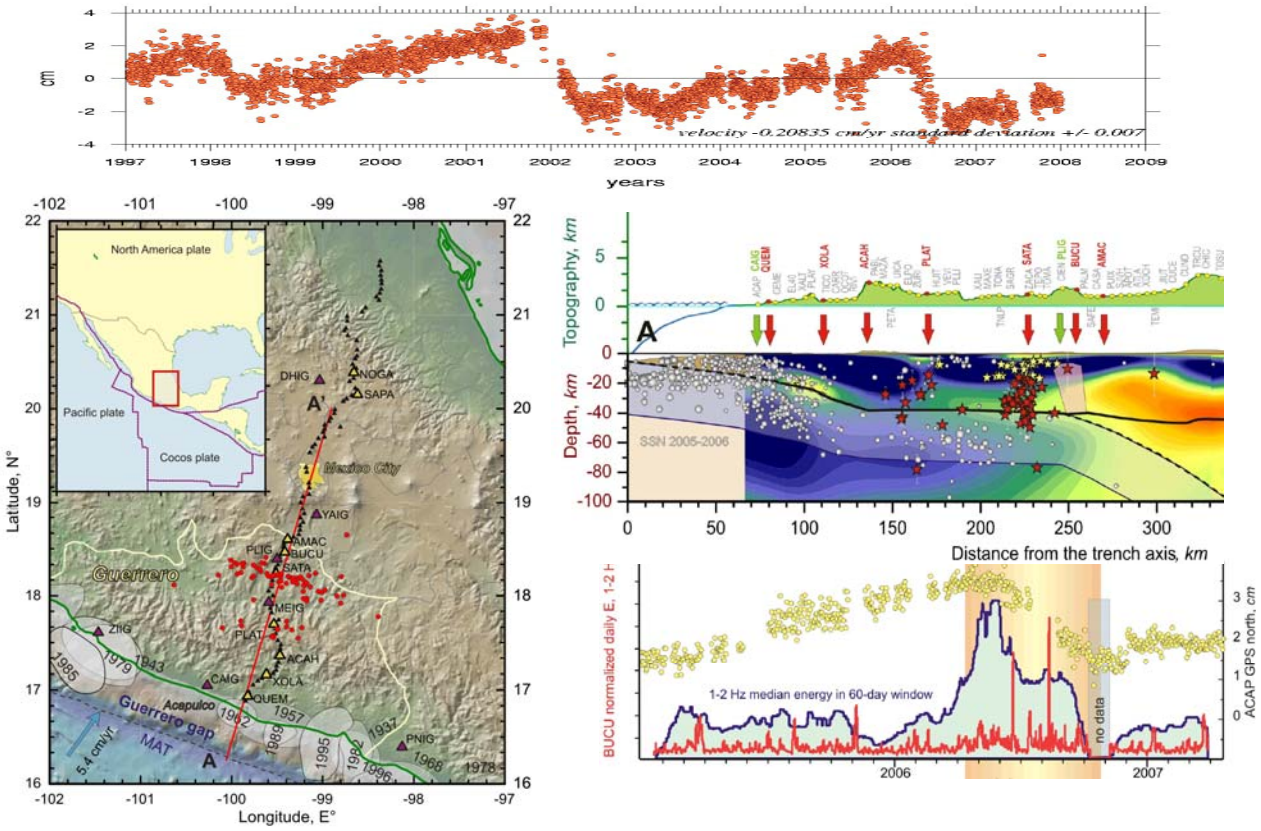

Figure 1.. Observation of slow slip events and non-volcanic tremors in Central Mexico. (A) North-South displacement measured during 12 years by the GPS station CAIG (shown in B). (B) Map of the studied area (light-filled rectangle) and plate boundaries. Seismotectonic setting, seismic network configuration and NVT locations. Red circles are epicenters of NVT bursts estimated from the analysis of MASE data (small black triangles indicate the positions of broad band seismic stations) by Payero et al., 2008. Large dark triangles show locations of the SSN broad band stations. Line A-A' denotes a location of profile presented in (C). Shaded areas along the coastline annotated with the years are approximate rupture areas of the most recent major thrust earthquakes (M≥6.5) in the Guerrero segment of the Mexican subduction zone. MAT is the Middle American trench. Arrow indicates NUVEL1-A relative Cocos-North America plate motion vector (*DeMets et al.*, 1994). (C) A-A' transect that shows locations of MASE and SSN stations on the topography profile. Solid and dashed lines in the bottom graph illustrate the Cocos-North America tectonic plates interface and Moho [*Clayton et al.*, 2007]. Red and yellow stars are the NVT hypocenters projected on the A-A' vertical cross-section plane. White circles are the projection of the earthquake (M > 4) hypocenters from the SSN catalog for 2005-2006 epoch.

Shaded polygon area located in the continental crust, above the tip of the mantle wedge (~250 km from the trench) stands for a probable mega-intrusion of lower density and high magnetization which can explain the gravity and magnetic anomalies shown in the upper chart. Background image is a resistivity model [*Jödicke et al.*, 2006] (digital image is a courtesy of A. Jording). (D) NVT activity during latest 2006 Guerrero slow slip event (GPS displacement is shown with yellow dots). A median filter is applied to 1-2 Hz band-passed record at BUCU station, and then the resulting signal is integrates to obtain a daily normalized "energy" (red curve). 60-day window smoothing is applied to obtain the final (blue) curve.

Methodological developments

Geodesy

During the last two decades, the development of satellite based geodetic methods revolutionized geophysical observation by continuously monitoring the Earth surface. As we mentioned it, this led to several important discoveries that brought to light complex time-dependent and space-variable behavior underlying solid Earth deformation in response to tectonic and volcanic forcing and to environmental changes.

Improving the processing of available GPS data to better determine the time evolution of the slow earthquakes

The surface displacements produced by the slow earthquakes have small amplitudes (a few cm cumulated over a few days to months), that additionally vary in space and time. Measuring their cumulated displacements can be achieved with standard GPS analysis strategies, but precisely determining the start and end of the slow events, as their precise temporal evolution, requires implementing most sophisticated approaches. Our objective is to contribute to the improvement of the positioning precision, so that we may properly document the time evolution of the slow slip (amplitude and direction). For the 24 hr static analysis, we process the standard data (i.e., 30 sec. sampling) with a classical double-differenced strategy using the GAMIT/GLOBK softwares. We integrate the most recent models or estimations of antenna phase centers, oceanic, atmospheric and hydrological loading, and meteorological model-based mapping functions. We perform tests to identify the most appropriate models and strategies to reduce the instrumental and non-tectonic geophysical noise affecting the measurements, mainly their vertical component. We also test the impact of the definition of the reference frame on the position time series. We have actually started to process some of the data.

The development of a 1Hz GPS network in Guerrero is particularly important to be prepared for recording the future large 'normal' earthquake that may soon occur in that zone and to record the early postseimic relaxation, thereby closing the frequency gap that exists between seismological and classical geodetic observations. We are transforming existing permanent GPS stations into high frequency stations. All receivers are technically high frequency transformable.

Further improvement of our understanding of the transient slip events requires information about time-dependent process occurring at depth. In the following we consider the in-situ seismic speed as a proxy for the mechanical state of the rocks, since speed is known to change with strain in complex medium containing cracks or fluids. Monitoring the seismic speed is one of the goal of the project of long term observation. We will also investigate the possibility of using such parameters as the attenuation coefficient or anisotropy.

Imaging and monitoring based on ambient seismic noise

Seismologists have long considered the Earth as a complex but unchanging body. It was due to the fact that slight transient changes are difficult to detect with standard techniques. Several attempts to monitor temporal changes were proposed using repeated artificial sources (e.g. Karageorgi et al., 1997) or repeated earthquakes (e.g., Poupinet et al., 1984). Repeated imaging is in use for objects with relatively large mechanical changes (reservoir in the oil industry, the so-called 4D seismics, or volcanoes (e.g., Patane et al., 2006) It is nevertheless almost impossible to monitor continuously

transient changes in mechanical conditions that are now detected by geodesy in several places with traditional seismological methods.
An important breakthrough that should help us to overcome these limitations is a recent development of methods based on correlation of ambient seismic noise (e.g., Shapiro and Campillo 2004; Shapiro et al., 2005; Sabra et al., 2005). The background signal is composed of waves that continuously sample the earth interior and, therefore, contain information about transient processes. Using seismic noise for imaging and monitoring is a completely new and very promising research direction (e.g., Shapiro et al., 2005 for the first tomographic application or Brenguier et al., 2008 for forecasting volcanic eruptions). We will apply those new techniques to two different objectives:

- to improve the models of the crust, with a particular interest to the Central Mexican belts and its series of sedimentary basins whose geometry is required both for a better characterization of the active faults which bound them, and for a determination of the sediment-filling thickness and distribution whose knowledge is needed to make numerical quantitative prediction of strong ground motions.

- to study transient processes related to tectonic activity through continuously measuring mechanical changes in deep parts of the Earth by developing and applying new noise-based methods of seismological analysis.

Activities of observations

1- Geodesy

A first critical unknown is the exact location, extent, and space-time evolution of the detected slow events. That knowledge being a prerequisite to any further understanding of the slow earthquakes, we put a strong emphasis to address it properly. For that, we propose to follow complementary axes improving the observation network, optimizing the GPS analysis, filling the frequency gap with respect to seismological measurements by implementing high rate GPS measurements (1Hz), exploiting the complementarities between GPS and InSAR, resolving the slow slip history from our high resolution geodetic observations, and finally inferring the impact of slow events on the earthquake clock

In the zone of the Guerrero gap, the GPS network consists of 26 permanents stations, from which 8 are directly the contribution from the French side. All data are shared between Mexican and French researchers. The processing is done in Grenoble.

The GPS network is designed to monitor the slow slip event activity. With a repetition time that seems to be of the order of 4 years and moment magnitude reaching 7.5, the Guerrero region is one of the best places to study these phenomena. The slip occurs at relatively small depth 30-40 km. The development of the rupture can therefore be reliably study with an inland network.

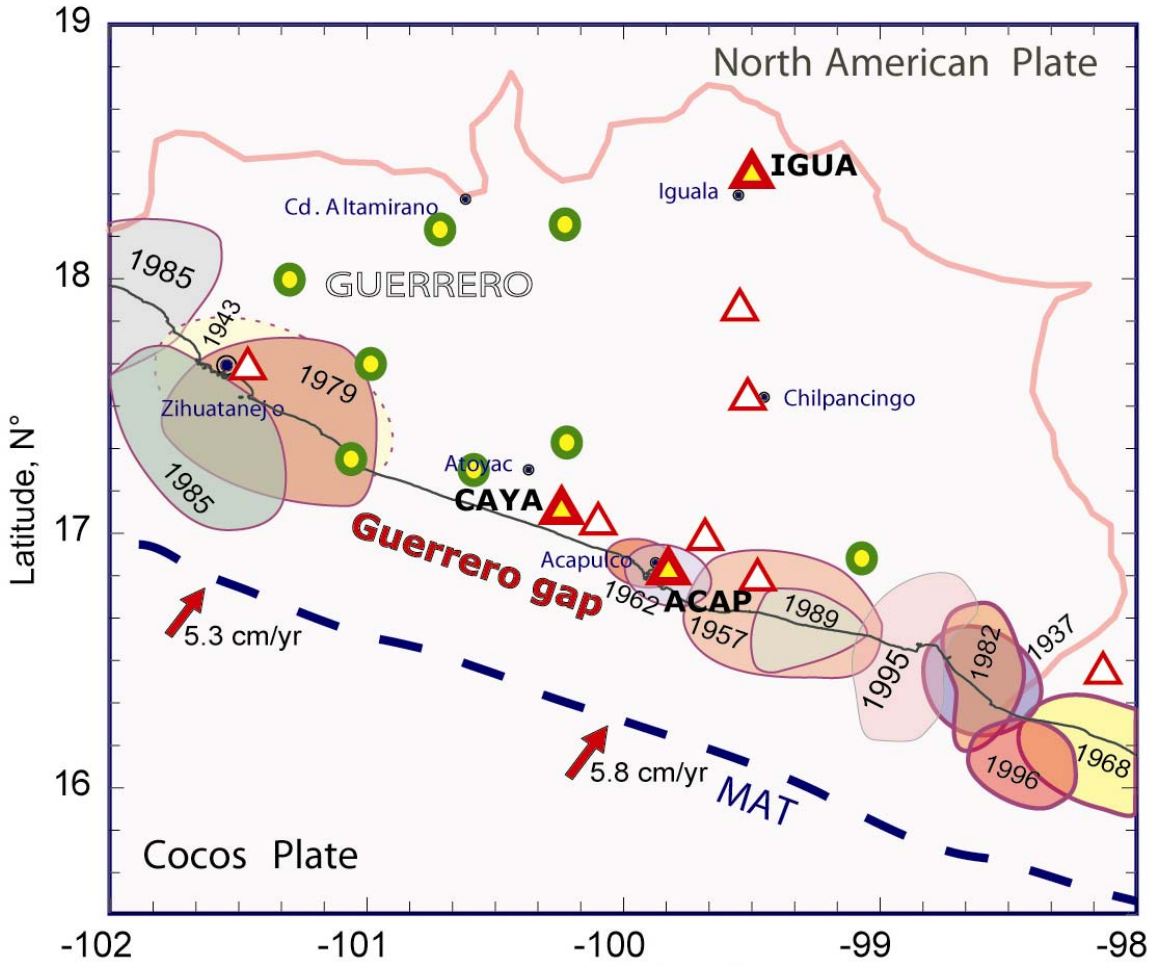

Figure 2: Location of permanent GPS stations. Triangles indicate the Mexican permanent stations. The circles indicate the newly installed continuous GPS sites

2-Seismological arrays.

The region is monitored by the broad band network run by the Instituto de Geofisica of UNAM (18 stations). Jointly with our Mexican colleagues, we are installing a network of arrays specifically devoted to the recording of tremors. At 9 new sites, we install a broad band seismometer and a small aperture array of 6 short period seismometers. Very shortly, 6 mini arrays installed by our colleagues will also be in operation. Overall 99 channels will be collecting data in the region where tremors have been detecting. With this density of observation, this site will offer the opportunity to develop new approaches in the characterization, the location and the quantification of tremors. The presence of both geodetic and seismological coverage is required to understand the relationship between slow slip events and tremors. This network also offers new opportunity to study the relation of seismicity with transient deformation.

3-Data availability

The data will be made available through the national data centers : fosfore for seismic data and GPScope pour GPS data.

G-GAP arrays

I.Geof. arrays

BB stations

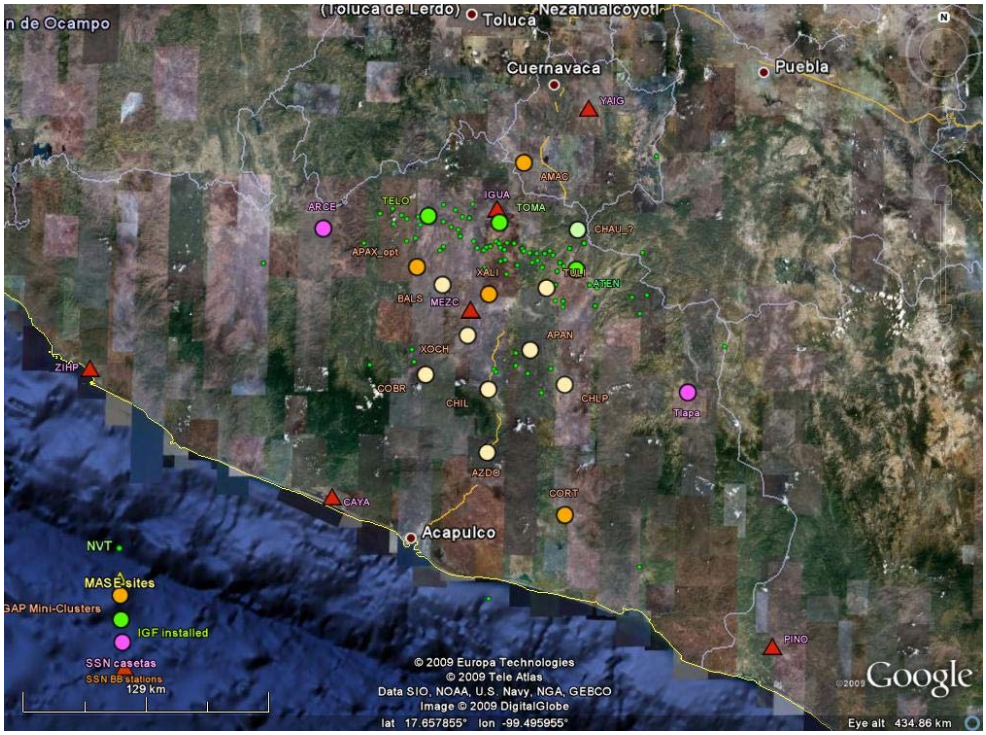

Figure 3: Location of the arrays (orange-yellow: new 'French' sites)

The monitoring of ETS in Guerrero is completed by the construction of SAR interferogram (Pathier et al., 2009).

4-Participants

Correspondants Mexicains

UNAM:

L'Universidad Nacional Autonoma de Mexico is a central institution in geophysics and earthquake engineering in Latin America (**F.J. Sanchez-Sesma**-theory,modelling-, **V. Kostoglodov**, -GPS, tremors-, **S.K. Singh**-earthquake source, seismic hazard analysis-, **V**. **Atienza-Cruz**-numerical simulation-).

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Publications résultant de la collaboration du groupe LGIT-IPGP avec l'UNAM

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Fait à Santiago, 26 Juin 2009

Lettre adressée à la
Commission des observatoires, CNRS - INSU

Chers Collègues,

Nous souhaitons exprimer par cette lettre notre soutien au projet commun de labélisation des sites instrumentés au Chili et Central Mexico, ainsi qu'apporter quelques précisions.

Les collaborations entre la France et le Chili ont une longue histoire, attestée par de nombreuses publications scientifiques communes et la formation conjointe de jeunes chercheurs.

En 2006, cette collaboration s'est structuré à travers de la création d'un Laboratoire International Associé (LIA) Montessus de Ballore, entre l'Université du Chili (Départements de Géologie - DGL et de Géophysique -DGF) et les équipes du CNRS-INSU de l'Institut de Physique du Globe de Paris (Sismologie, Géodésie et Tectonique) et de l'Ecole Normale Supérieure de Paris (Sismologie et Géodésie). Le LIA, CNRS-INSU - Université du Chili, est structuré depuis son origine comme ouvert à tous les chercheurs et laboratoires français impliqués au Chili ou souhaitant s'y impliquer.

Le LIA a déjà permis de structurer et de renforcer des collaborations avec d'autres universités Chiliennes, i.e., Universidad de Concepcion, Universidad Catholica del Norte, Universidad Arturo Prat d'Iquique, ainsi qu'avec les équipes de sismologie, géodésie et géodynamique du GFZ Potsdam au sein du projet IPOC (Integrated Plate Boundary Observatory in North Chile) associant le CNRS-INSU, l'Universidad de Chile et le GFZ Potsdam qui opèrent conjointement ce réseau d'instrumentation sismologique et géodésique. Par ailleurs, le LIA a également développé des collaborations avec le Caltech, en particulier par la coordination et l'intégration des données des réseaux cGPS au Nord Chili.

La priorité et la volonté de renforcement de la collaboration Franco-Chilienne, au travers du LIA Montessus de Ballore, dans les domaines de l'étude physique des mécanismes des tremblements de Terre de la subduction Andine au Chili, ont été récemment réaffirmées officiellement par le Chili, lors de la visite de la Présidente du Chili en France.

Ajourd'hui le LIA coordonne les projets scientifiques et instrumentaux des équipes français et chiliens, financés au niveau français par l'ANR et au niveau chilien par la CONYCIT et le programme Nucleo Millenio du Ministère MIDEPLAN qui siège au DGF. Par ailleurs, le LIA est aujourd'hui étroitement associé au Servicio Sismologico Nacional (SSN) de l'Université du Chili en charge de la surveillance et l'alerte sismologique au Chili. Les efforts instrumentaux français ont permis de compléter et de renforcer significativement les réseaux de surveillance sismologique et géodésique Chilien opérés par l'Université du Chili à travers de le Servicio Sismologico Nacional. L'ensemble de ces données sont archivées également au Chili et ouvertes à la communauté scientifique.

Au Sud et au Nord de la région du Centre du Chili, les réseaux cGPS permanents français ont permis de compléter et de densifier les réseaux d'instrumentation Chiliens, et d'avoir aujourd'hui

des réseaux opérationnels transmettant les données au Servicio Sismologico Nacional localisé à l'Université du Chili.

Au Nord Chili, une région encore peu couverte par les réseaux Chiliens, le réseau IPOC (CNRS-INSU, GFZ Potsdam et Université du Chili), constitue une contribution importante à la surveillance sismologique et géodésique de cette région. Ce réseau, de plus de 15 sites multi-instrumentés (large bande, accéléromètre, cGPS), en acquisition et transmission continues, est aujourd'hui intégré dans les réseaux de surveillance du Servicio Sismologico Nacional. Un résultat majeur de cet effort, a été l'enregistrement du séisme de Tocopilla (2007, Mw 7.6) est un de grands séismes de subduction les mieux enregistrés du Chili. Les données accélérométriques du réseau IPOC ont ainsi stimulé une forte activité de recherche associant, sismologues, géodésiens et ingénieurs sismiques, avec des avancées importantes dans les domaines de la compréhension et de la prévision des mouvements forts associées aux grands séismes de subduction, ainsi que le développement de méthodes d'alerte en temps réel.

Aujourd'hui, le réseau IPOC doit permettre répondre à la question de savoir s'il existe des évènements lents au Nord Chili, et de caractériser leur récurrence, leur localisation et leurs caractéristiques (durée, contenu fréquentiel). Il permet également de mieux comprendre la variabilité sismique qui émerge dans ce segment, ainsi que l'activité sismique de profondeur intermédiaire particulièrement active dans cette région.

Les études à long-terme, et le renforcement de ces réseaux, est aujourd'hui d'une importance majeure pour le Chili, et s'intègre complètement au nouveau projet de réseau national sismologique et géodésique chilien financé récemment par le gouvernement.

Nous souhaitons par ailleurs, exprimer tout notre soutien et notre volonté de participer à l'effort de coordination entre les sites Chiliens et Mexicains. Il existe une longue tradition de collaboration scientifique entre UNAM et l'Université du Chile dans les domaines de la sismologie et de l'aléa sismique des zones de subduction active. L'intervention scientifique conjointe pour l'étude du séisme de Valparaiso en 1985 et les travaux menés par les collègues Mexicains et Chiliens au Nord du Chili en 1991 sont un exemple de cela. Les zones de subduction Nord Chili et Central Mexico constituent deux cas exceptionnelles de zones de subduction de plaques océaniques jeunes avec une vitesse de convergence rapide.

La zone de subduction Central Mexico, est une subduction de type "flat slab", est aujourd'hui active sismiquement. La zone de contact est partiellement découplée avec des mécanismes particuliers de type « underplating ». Nos collègues de UNAM et du LGIT ont mis en évidence dans a zone central de Mexico des événements lents, transitoires de glissement lent et des trémors non-volcaniques. Les développements méthodologiques et instrumentaux dans le cadre de ce projet devraient apporter un éclairage nouveau sur ces phénomènes. Nous sommes particulièrement intéressés à pouvoir, au travers de cette coordination, collaborer à ces développements et ainsi faire émerger une base d'expertise, de techniques instrumentales, et de méthodes d'analyse communes qui aura d'importantes implications au Chili dans le cadre des collaborations franco-chiliennes.

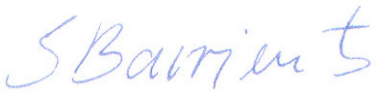
La zone de subduction Nord Chili, est une subduction de type normal avec une activité sismique continue sur plus de 300 km. Si aujourd'hui la zone de contact est bloquée, la profondeur de la zone de transition est encore assez mal déterminée. Depuis le séisme d'Antofagasta (1995), une nouvelle activité sismique émerge dans cette région. Comprendre sa variabilité est aujourd'hui un enjeu majeur. Il existe au Nord Chili, une forte activité sismique de profondeur intermédiaire,

attestée récemment parle séisme de Tarapaca (2005, Mw 7.7). Le Nord Chili est un lieu unique pour mieux comprendre cette activité sismique et sa relation avec les mécanismes des processus de charge et décharge sismique et de déshydratation au sein de l'appareil de subduction. Une question ouverte aujourd'hui est celle de l'existence, et de la nature de possibles événements lents.

Il nous parait donc particulièrement important de coordonner scientifiquement et techniquement ces deux projets, et nous souhaitons nous associer à cette coordination.

Nous espérons que ces projets et leur coordination puissent recevoir un avis favorable de la commission et nous nous engageons à participer activement à ces efforts de coordination et d'exploitation de données communes.

À l'expression de toute ma considération.



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INSTITUTO DE GEOFISICA

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CODIGO 04510 MEXICO, D.F.

GEOFISICA UNAM

Departamento de Sismología

June 28, 2009. Mexico City.

Dear Michel and Jean-Pierre,

This letter is in support of your project of “Site Instrumenté” in the Mexican and the Chilean subduction zones. Increasing collaboration with French research institutions is very important both for the scientific research and for the seismic risk mitigation in Mexico. During the last decades this collaboration was very fruitful. It comprised a bilateral exchange of students and postdocs as well as joint field experiments, which provided us with very valuable information and helped to improve significantly our understanding of seismic wave propagation and site amplification in central Mexico and our ability to evaluate strong ground motion during future large Mexican earthquakes.

More recently, French-Mexican collaboration was focused on understanding a seismic cycle in subduction zones in scope of recent discoveries of “silent earthquakes”. This challenging scientific problem is of the high priority in the international Earth Science community, in particular because of its apparent importance in the evaluation of seismic risk. We have discovered in Mexico a number of very large asesimic slow slip events and a high activity of the non-volcanic tremor correlated in time to these events. The origin and these new phenomena and their possible relation with the occurrence of large subduction earthquakes are not yet well understood and require further monitoring of the crustal deformation and seismic events with continuous records by dense geodetic and seismic networks.

Recent French-Mexican collaboration projects have permitted us to densify notably the existing GPS network in central Mexico and significantly improve a data processing technique. In a frame of our new mutual projects we are preparing now an installation of large cluster of seismic mini-arrays. New observations which will be obtained using these GPS and seismic networks should improve significantly our ability to monitor seismic and slow transient events in Mexican subduction zone. Considering the time scale of the studied phenomena, it is important to carry out the observations for sufficiently long periods of time that should be longer than a typical duration of temporary seismic experiments. Therefore, a recognition of the “Site Instrumenté” project by the Institut national des sciences de l'Univers would be very important act to maintain our long-term partnership in the area of seismic and geodetic observations, the studies of seismic cycle and related seismic hazard in the subduction zones.

Sincerely yours,

Vladimir Kostoglodov