PANAM: PAn-AMerican geodetic study of active deformation

I. Pre-proposal's context, positioning and objective(s)

The western margin of South America where the oceanic Nazca plate converges toward the South American continent, is among the most seismically active area of our planet and is one of the places where new quantitative information about the earthquake cycle can and will be gained in the next few years. Since the arrival of the Spanish conquistador during the 16th century, almost the entire 6000 km of subduction from northern Colombia to Chile has been broken by at least one great (Mw>8.5) earthquake (Bilek, 2010) and several segments are thought to be ready for a new great earthquake (Chlieh et al. 2011, Villegas et al. 2016). Instrumental seismicity dates back to the beginning of the XXth century and every new large earthquake can now be put in the context of the history of the previous ruptures and slip deficit rate determined from GPS data, making the basis for the discussion of persistency of subduction interface frictional anatomy through several earthquakes and moment budget (e.g. Metois et al., 2012,2016; Moreno et al., 2010; Nocquet et al., 2017). The post-seismic deformation triggered by the largest earthquakes (eg. Valdivia, 1960 Mw 9.6; Maule, 2010 Mw 8.8) has also started to be investigated, providing insights into the rheology of the mantle and the lower crust, as well as the frictional properties of the subduction interface (e.g. Klein et al., 2016). Similarly to the Sumatran trench that ruptured in a rapid succession of megathrust earthquakes between 2000 and 2011, the South American trench, with already 5 large earthquakes close to or larger than 8 over the last decade offers the opportunity to study the remote interaction between large ruptures (e.g. Klein et al., 2017), the preparation of large earthquakes (Jara et al., 2017, Socquet et al., 2017) and the origin of abnormally large sequences of earthquakes (Nocquet et al., 2017).

The present proposal focuses on a key information required for understanding the earthquake cycle, namely the slip deficit currently accumulating at the megathrust. With different segments presently at different stages of their seismic cycle, now is the right time to integrate the results at the whole plate boundary scale.

Aside from megathrust earthquakes, the subduction induces continental deformation of the south American continent. Numerous crustal earthquakes occurred within the Andes and east of them in the sub-andean domain. Some of them have been particularly devastating like for instance the 1949 Mw 6.8 Ambato earthquake that killed ~5000 people in central Ecuador or the San Juan 1977 Mw 7.4 that left > 10 000 people homeless. During the last decade, GPS results led to an important finding: along the entire length of the Nazca/south America plate boundary, continental slivers (continental pieces squeezed between the Nazca and South America plates) have been identified (see figure). The motion of the slivers is consistent with a partitioning of the oblique subduction, but the level of partitioning appears to be highly variable along strike and involves internal deformation of the slivers (e.g. Alvarado et al., 2016, Villegas-Lanza et al., 2016). Although different kinematics models have been proposed, both the eastern and lateral extent of the slivers are usually not constrained and no kinematics model consistent at the scale of the plate boundary has been determined so far. Uncertainties on the slivers motions have important consequences on great subduction earthquakes hazard assessment: the amount of locking inferred on the subduction interface depends on the long-term slip rate at the subduction interface, hence the relative motion between the slivers and the Nazca plate. In the absence of data, large trade-offs exist between the level and spatial extent of interseismic coupling and the motion and deformation of continental slivers. Another major outcome of a better quantification of continental deformation in the Andes is an evaluation of the seismic potential for the sub-andean domain east of the Andes. Brooks et al. (2010) proposed a provocative conjecture that can be summarized as follows: the sub-andean deformation is the consequence of a >100 km large and long decollement at shallow (10-15 km) depth, where friction laws expect stick-slip behavior. Their GPS data in Bolivia are consistent with the decollement being locked over a distance of 100 km, therefore potentially able to host an extremely large earthquake (Mw 8.7-8.9), similar to subduction events, and to be expected soon given the long duration of strain accumulation. We will challenge this conclusion based on a better understanding of the sliver tectonics in this region.

The core of our proposal is to derive a key observation to quantify both the strain accumulation at the megathrust and continental deformation. We propose to reprocess and combine two decades of GPS measurements in the Andes from Colombia to southern Chile and extend our networks to reach the stable part of the south America plate. The result will be a single, homogeneous and consistent velocity field at the Nazca/South America plate boundary scale. Our initiative builds upon a well-established collaboration developed by the team members since the 1990's.

Finally, we propose a new methodology potentially leading to a new geodetic observable for active tectonics. The geodetic data used so far are based on static high precision GPS measurements providing discrete measurements of surface displacements, mostly restricted to the horizontal components. We propose here to realize an unprecedented integration of all data sets and long time series to derive a unified vertical velocity field over the whole continent. This vertical continental scale reference will be most useful not only for tectonic studies but also for the analysis of non-tectonic signals like seasonal hydrological loads. We also propose to move one step forward and will develop a kinematic GPS approach to determine a reference geodetic line all along the entire south America coast: a rover based profile along the PanAmerican Highway over ~5000 km. Such a reference line could be then re-measured after any large earthquake and subsequent post-seismic period to derive a continuous change of vertical motion, providing a new geodetic observable to modelling.

The novelty of our project is that it integrates and analyzes results at the scale of the plate boundary by rigorously merging a great wealth of geodetic data in a single homogeneous data set. The second novel aspect is that the analyzing of coupling and continental active deformation will be made for the first time at the scale of south America. The third novel aspect is a prototype of a new type of geodetic observable for tectonics through the determination of a vertical reference line along the coast.

II. Project organization and means implemented

a. Scientific coordinator

C. Vigny, is a renown GPS geodesist, involved in long-term collaborations with U-Chile at Santiago. He is director of the "laboratoire de Géologie" at ENS and of the Chilean-French International Laboratory "Montessus de Ballore". He has been developing GPS activities in Chile since 2002. His work has been subject to ~100 communications in congress, ~70 publications in peer reviewed international journals including Nature and Science. Vigny has successfully lead 3 ANR research projects and is co-PI of an ongoing European ITN (ZIP).

b. Consortium

The consortium involves French scientists together with scientists in charge of the GPS activities in Colombia, Ecuador, Peru, Bolivia and Chile. From north to south: **In Ecuador/Colombia**, the main partners are P. Jarrin and P. Mothes from the Instituto Geofisico de la Escuela Politecnica Nacional (IG-EPN, Quito, Ecuador). The IG-EPN operates a network of ~80 CGPS in Ecuador jointly with the IRD (Mothes et al., 2013) under the frame of the Joint International Laboratory "Earthquakes & Volcanoes in the Northern Andes", funded until 2021. The IG-EPN and the IRD have agreement with the Instituto Geografico Militar (IGM, Quito, Ecuador) and the Geored/Servicio Geologico Colombiano (SGC, PI H. Mora) for sharing data. **In Peru**, the main partners will be the Instituto Geofisico del Peru (IGP) with J.-C. Villegas (head of the geodesy department) and E. Norabuena. The IGP develops a new campaign network in Peru including 70 campaign sites and ~20 CGPS sites jointly operated with IRD. Additionally, IRD has an agreement with the Instituto Geografico Nacional (IGN) operating a ~50 CGPS network that will be made available to the project. **In Chile,** the main partners will be the departamento de geofisica (DGF) of the University of Chile at Santiago (J. Campos, S. Ruiz, D. Carrizo) and the new Centro Sismologico Nacional (CSN) (S. Barrientos) who is in charge of a backbone network of ~100 cGPS stations across Chile. ENS and IPGP partners also operate a network of ~40 cGPS stations in Chile. Additional data from GFZ (~15 stations) and Caltech (~15 stations) are available through the IPOC agreement. Campaign network data (250+

benchmarks) measured intensively (~40 campaigns over the last two decades) are also available with the French partners.

From the French side, aside from the PI, the team will include the geodesists involved in GPS activities in the Andes (**J.-M. Nocquet, F. Rolandone, A. Socquet, S. Bonvalot, M. Metois, J.-B. De Chabalier, C. Vigny, M. Vergnolle**), modelers (**L. Fleitout, E. Klein, K. Chanard, M. Chlieh**) and experts in active tectonics of the Andes (**L. Audin, P. Baby, R. Lacassin, Y. Klinger**).

c. Work plan

I. Nazca Plate kinematics

The kinematics of the Nazca plate is a fundamental parameter for all studies along the Andean margin. So far, values determined either from the global IGS network using only two sites in the Galapagos island offshore of Ecuador and the Easter Islands (e.g. Altamimi et al., 2012, 2016) or campaign data (Kendrick et al., 2003) have been used. New GPS sites operating at the Juan Fernandez, San Felix and Robinson Crusoe islands offshore Chile and at San Cristobal west of the Galapagos and potential new measurement at the Malpelo island (offshore Colombia) will allow a new robust calculation of the Nazca motion. We will use 100+ stations available through the RAMSAC (Argentina) and RBMC (Brazil) networks operated by the national geographic agencies which will also contribute to a better South America kinematics determination. Funding is asked to organize a joint seminar involving the colleagues from Chile, Ecuador and Colombia to derive a new solution and publication.

II. New GPS observations East of the Andes

Our observation plan consists in densifying existing geodetic networks along 5-6 selected profiles crossing main active structures and reaching the stable part of South America plate. Anticipated locations of profiles are based on our existing networks in Ecuador, Peru, Bolivia and Chile/Argentina. These new observations will allow us to resolve (1) the width of the Andean active continental deformation by defining its easternmost boundary (2) the geometry and kinematics of the sliver. We will test the possible fragmentation of the large slivers identified so far into smaller blocks and/or distributed deformation. GPS network implementation will be developed in close collaboration with the geologists & tectonicians involved in the project and will benefit from existing seismic imaging of active structures in Ecuador, Peru and Bolivia (Baby et al., 2013, Eude et al., 2015, Calderon et al., 2017).

III. A combined velocity field for the Nazca/South America plate boundary

We will combine our results for the different areas into a single consistent solution. The methodology used will be similar to other projects in the Geodesy community (e.g. IGS, EUREF, EPOS, PBO). Each group will provide daily free (or loosely constrained) solutions following standard guidelines. Then the daily solutions will be combined and expressed in the ITRF2014 reference frame to derive daily time series. At this step, analysis problems, discrepancy among solutions will be flagged and discussed within our group. Then time series will be analyzed to derive velocities, together with their uncertainties based on the time correlated noise analysis. Several products can be considered. One will be the interseismic velocity field, using only data before the major earthquakes that have occurred recently. Another product could be the current “instantaneous” velocity field and some information related to the duration and spatial extent expected for transient post-seismic signal. This velocity field will include an unprecedented vertical reference (positions and velocities) at the scale of the whole continent. Vertical displacements relate to plate tectonics (elastic loading, Andes orogene) but also to non-tectonic signals like seasonal hydrological loading, particularly obvious in relation with the Amazonian basin (+/- 6 cm oscillations at a cGPS station located in a loop of the Madeira river). Time series will allow to analyze these signals, improve the modelling of the seasonal loads, compare them to the GRACE (satellite gravity) measurements and finally filter them to grant access to the purely tectonic signal.

IV. Plate-boundary scale deformation modelling

Several approaches will be carried out. We will first use classical elastic block models where sliver motion and internal deformation is simultaneously solved together with locking at the megathrust. Including vertical velocities will be tested. Effects of geometry change of the slivers, internal deformation and geometry of the plate interface will be evaluated. In a second step, visco-elastic models will be tested (e.g. Klein et al., 2016). The result will be interpreted in terms of segmentation of the subduction interface and more generally in terms of the earthquake cycle and the relation to the past large ruptures.

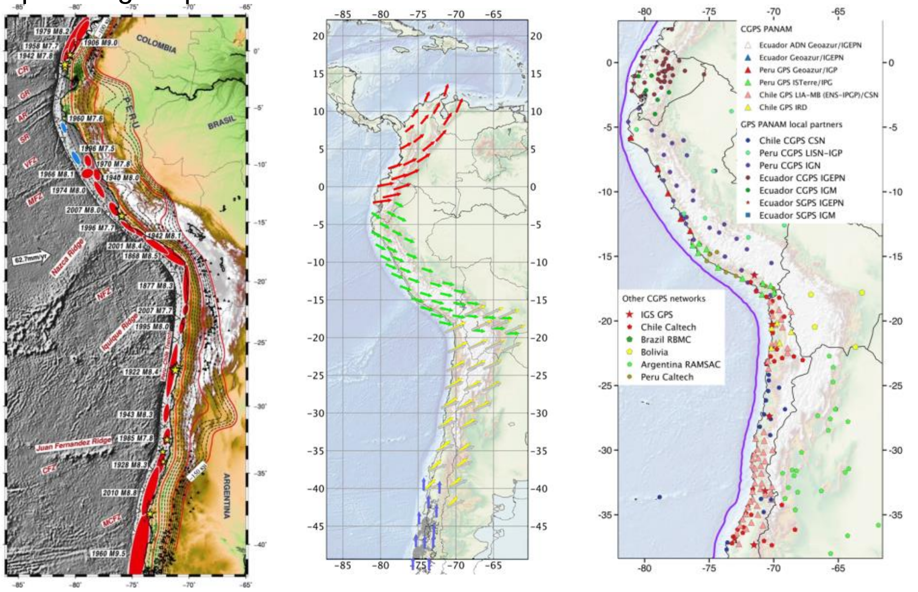

Figure: **left**: Approximate rupture areas of large subduction earthquakes (M ≥ 7.5) between 1868 and 2015 (from Villegas-Lanza et al., 2016). **middle**: Sliver kinematics estimates with respect to Stable South America along the Andes. From north to south: red and green arrows: North Andean and Inca slivers (Nocquet et al., 2014) ; grey and yellow arrows : Central Andes sliver from Metois et al., (2012) and Brooks et al. (2003). blue arrows: Chiloe sliver (Wang et al., 2008). **right**: Summary of cGPS data available for the PANAM project in the Andean domain.

V. A continuous vertical reference line: a new observable for tectonic studies

The availability of new GNSS satellites, improvement of kinematics algorithms and developments of CGPS networks recording at high rate might define the infrastructure enabling a new geodetic observable for tectonics studies. We will develop a light and versatile system to be adapted to a car in order to record (1) the trajectory of an antenna attached to a car (2) a rapid measurement of a high density of points. The system will consist of a high-performance multi-GNSS antenna-receiver system, linked to a laser system to monitor the antenna–ground distance and an ultra-rapid centering system for rapid-static measurement. A prototype will be developed and implemented along the Panamerican Highway from Ecuador to Chile. In case of any earthquake, we will re-measure a relevant section and get a continuous vertical profile of displacement.

VI. Budget: 290 k€

- Field work (GPS surveys, cGPS maintenance and PanAm kinematic profile, UC 10 k€ x 1 /yr /area of interest).	200 k€
- Common work sessions in France, meetings (AGU, EGU),	25 k€
- specific visits and meetings in South America	25 k€
- consumables (markers, tools, prototypes…)	10 k€
- publication fees (mostly open-access)	10 k€
- Overhead (8%)	20 k€

III. Impact and benefits of the project

The main benefits of the projects will be:

- An integrated view at the scale of the Andes for the segmentation and earthquake cycle at the subduction interface
- A new picture of the continental present-day deformation of the Andes
- A quantitative data set ready to be used for Probabilistic Seismic Hazard Assessment for the Andean countries
- A quantitative data set for understanding the current dynamics of the Andes orogen
- A potentially new geodetic methodology and observable for active tectonics studies

IV. References related to the project

References are available at http://www.geologie.ens.fr/~vigny/panam.html