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# Solid Earth

Concerning the Solid Earth's activity, one can note that over the last years the French scientific community has been deeply involved to exploit measurements from current space missions, efforts being made to using data from gravity missions as GOCE and GRACE, or from the high resolution SAR interferometry and optical missions. In addition, a noteworthy implication has been continued in geodetic, gravimetric and magnetic international services. A major event for the Solid Earth's observation was the launch of SWARM constellation, late 2013. The Solid Earth's observation program over the next years is stressed by the CNES Scientific Prospective Seminar (2014).

## GOCE and GRACE: surprising information from the gravity field

World Gravity Map denotes a set of three global anomaly maps of the Earth's gravity field realized by the Bureau Gravimétrique International (BGI), a service of the International Association of Geodesy (IAG). CNES was involved in realizing these first gravity anomaly maps computed in spherical geometry, that take into account a realistic Earth's model. The gravity anomaly maps (Bouguer, isostatic and surface free-air – see Fig. 1) are derived from available Earth's gravity models and include high resolution terrain corrections that consider the contribution of most surface masses [1].

The GOCE (Gravity and Ocean Circulation Explorer) satellite (Mars 2009 - November 2013) gathered unprecedented information on the subtle changes of the gravity field. Using data provided by this mission, gravity gradients maps have been published [2]. These maps reveal the structure of mass in the Earth's mantle and help to show how material moves up and down, driving a range of geological phenomena, including subduction zones, where the great tectonic slabs covering the Earth's surface dive under one another. Until nowadays imaging the Earth's mantle was conceivable from seismic data, only. The ability to have independent information from a new source should help in our understanding of mantle dynamics.

Apart from geodesic applications and the information gained from static gravity-field models, space gravimetry is also investigating temporal variations of the gravity field. GRACE CNES/GRGS geoid solutions make it possible to deduce the long-term variability of the gravity field [3]. A correlation was observed between the secular acceleration of the geomagnetic field and the gravity field. Besides, a common inter-annual variability was highlighted between these two observables with amplitudes compatible with an origin related to the core motions. The interpretation is straightforward for the magnetic field, however more challenging for the gravity field changes. Nevertheless, this is the first time that an anomaly of gravity field is associated to processes at the top of the core.

## SWARM: a must in observing of the geomagnetic field

Launched in November 2013, the third opportunity mission of the ESA *Earth Observation* program, SWARM, is the follow up to satellite missions such as ØRSTED and CHAMP. SWARM constellation measures the strength, direction and variations of the Earth's magnetic field and supplements these observations with those of the electrical field and the density and winds of the thermosphere. The mission main objectives are to improve our characterization and understanding of the core magnetic field and the dynamo mechanism that generates it, the dynamics of the core and the way it interacts with the mantle, the magnetic sources of the magnetic field in the lithosphere, the electrical currents circulating in the ionosphere and the magnetosphere and the way they are affected by the Sun, the role of the magnetic field and of the coupling between the ionosphere and the magnetosphere in injecting energy into the thermosphere.

In order to study the magnetic field thoroughly, each satellite carries two kinds of magnetometers: a Vector Field Magnetometer coupled with a startracker camera, to measure the directions of the magnetic field in space, and an Absolute Scalar Magnetometer, to measure its intensity. The CNES contribution to this mission consists in providing the six absolute magnetometers, two on each satellite boom. As an experimental project, these instruments also take vector field measurements in order to validate its ability to function as an autonomous, absolute vector field magnetometer in space, which is a world first.

## Space geodesy: a new mode to monitoring surface changes

Nowadays, the measurement and modeling of Earth's surface deformations related to some natural hazardous events, such as earthquake, volcano eruption, land subsidence, landslide are major challenges in geoscience. Global, remote sensing data are well adapted to survey such deformations, characterized by a wide variety of spatial wavelengths and temporal behaviors.

The recent evolution toward higher resolution and time series analysis in satellite imagery and space geodesy (SAR interferometry and optical satellite image correlation in particular, in which the French community has been pioneer) provides new key observations allowing to refine or even revise our views on the lithosphere response to tectonic loading variations. Space geodetic techniques such as InSAR and GPS, have demonstrated to be useful in mapping the displacement fields of large earthquakes, however the displacement fields of smaller earthquakes (< Mw 5.5), such as those that typically result from the collision of the European and African plates, are less

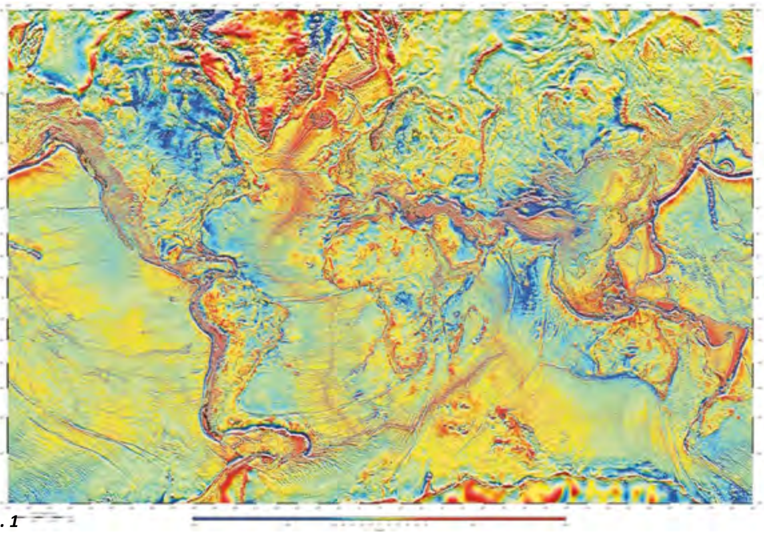
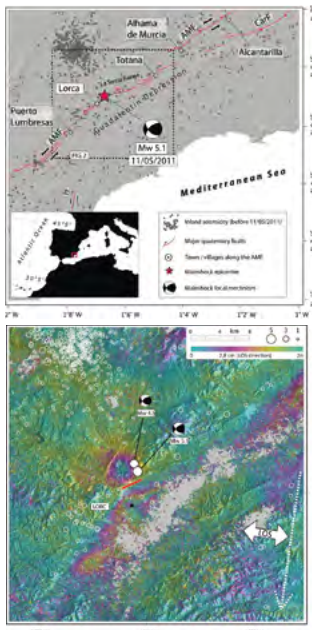


Fig. 1

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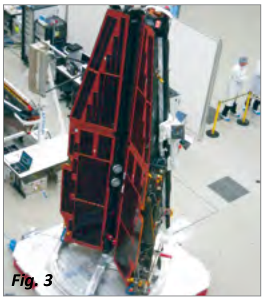

Fig. 3

Fig. 4

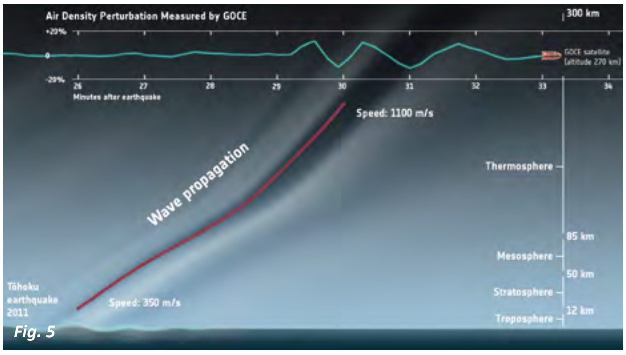


Fig. 5

often analyzed by these techniques [4]. Characterizing these displacements, in terms of slip along the fault plane at depth and focal depth location, is currently challenging (Fig. 2).

## International Services: contributions to the IAG's geodetic services

As it provides precise positions and velocities of ground stations and permits to compute well-referenced time series of positions of such stations and velocity fields, the International Terrestrial Reference Frame (ITRF) is essential for many applications in Earth sciences (precise orbitography, sea level monitoring, Earth's surface deformations, etc.). The fundamental geodetic services of the IAG produce the geodetic time series needed to compute and define the ITRF. They also provide the time series of Earth Orientation Parameters (EOP) used to compute the reference time series EOPC04. CNES and its partners in GRGS are heavily involved through a major contribution to the international DORIS service, but also through the provision of laser (Calern, Tahiti) and GNSS measurements, and analysis centers for these data. CNES also supports activities of BGI and ISGI.

*[Fig. 1]*
*Surface free-air gravity anomaly map computed in spherical geometry taking into account a realistic Earth model. This map is derived from available Earth gravity models (EGM2008, DTU10) and includes high resolution terrain corrections that consider the contribution of most surface masses. © From [1]*

*[Fig. 2]*
*Lorca earthquake (Spain, Mw 5.1, May 11, 2011) seen by InSAR (ENVISAT ASAR). The ground displacement generated by the earthquake (3 cm to the surface) is observed; the significant subsidence in the Guadalentin basin is due to sediment compaction related to water pumping. © From [4]*

*[Fig. 3]*
*SWARM satellites at ASTRIUM (2012). © Mioara MANDEA*

*[Fig. 4]*
*ESA's GOCE satellite reentered Earth's atmosphere on November 11, 2013 at 01:16 CET over the South Atlantic Ocean near the Falkland Islands, at an approximate altitude of 80 km. © ESA/Bill CHATER*

*[Fig. 5]*
*GOCE – the first space "seismometer" – detects sound waves from the massive earthquake that hit Japan on March 11. © From [5]*


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Laboratory contribution

# Solid Earth

## GOCE gradients: probing Earth's interior

## Gradients GOCE : une observation de la dynamique interne de la Terre

➔ **Abstract:** *From 2009 to 2013, ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE) Earth Explorer mission has been measuring the tiny variations of Earth's gravity vector in different directions of space with extreme accuracy and resolution. From these data, we have built maps of our planet's gravity in 3D, and we demonstrate their unexpected sensitivity to the lower mantle mass structure. Our results open new ways to investigate the deep geodynamics and its link with surface processes.*

➔ **Résumé :** De 2009 à 2013, la mission Gravity field and steady-state Ocean Circulation Explorer (Goce) du programme *Earth Explorer* de l'ESA a mesuré les variations fines du vecteur gravité de la Terre selon différentes directions, avec une précision et une résolution extrêmes. Nous avons montré la sensibilité inattendue des cartes 3D d'anomalies de gravité obtenues à la répartition des masses dans le manteau inférieur. Ces résultats ouvrent des voies nouvelles pour étudier la dynamique interne de notre planète.

Space measurements of the gravity field are of great importance for understanding our planet's interior and fluid envelopes. This invisible force indeed reflects the mass distribution within the geosphere, from core to atmosphere, and the associated dynamic processes in a wide range of spatial and temporal scales.

Gravity is a vector quantity, with a magnitude and a direction. Even if the measurement of the gravity vector variations between close points was put forward more than a century ago, most observations on the Earth's gravity field only inform on its magnitude. Yet, these subtle variations of the gravity vector, called the gravity gradients and measured by a technique named gradiometry, are much more sensitive to the geometry of the Earth's masses than observations on the intensity of gravity, as they are able to delimitate the edges of the structures if they are not too deep.

GOCE is a pioneering mission as it realizes, for the very first time in space and from an extremely low orbit, measurements of the full gravitational gradient tensor. For that, tiny differences of accelerations in three orthogonal directions have been sensed by three pairs of ultra-sensitive accelerometers constituting the GOCE gradiometer, with optimal accuracy for scales between 750 and 90 km.

These data picture our planet's gravity as never before. The gravity gradients are expressed in the local North-West-Up frame by the GOCE High-level Processing Facility by combining the gradiometric measurements with orbit-based data at larger scales [1]. From these data, we have computed global non-hydrostatic gravity gradient anomalies along the orbit [2]. For that, we have estimated and removed the contribution of a seismology-based reference Earth model, obtained from the hydrostatic equilibrium of a rotating spheroid, radially layered according to the PREM model [3]. The derived gravity gradient anomaly maps are shown in Fig. 1. The XX (resp. YY) gradients represent the variation rate of the Northern (resp. Western) component of the gravity vector in the Northern (resp. Western) direction, highlighting structures in the gravity field and mass distribution elongated in the orthogonal direction. In contrast, the ZZ gradients are isotropic.

At smaller scales, the signal from the lithosphere associated to mountain belts, subduction, oceanic ridges and plateaus is present, as can be seen over the Himalaya region in the ZZ-gradients map for instance, or as elongated patterns along the Marianna trench in the YY-gradients map. The analysis of these smaller scale variations brings new insights on the dynamics of the shallower layers of Earth, which was one of the main goals of the mission.

However, our maps also evidence strikingly clear large-scale anomalies whose strength was less expected and opens a new field of application of the GOCE data: deeper mantle dynamics. Our analysis indeed demonstrates the high sensitivity of these gravity gradients to mass anomalies associated to sinking tectonic plates and convective instabilities in the lower mantle [2]. The clear detection of this deep mantle mass signal arises from its small attenuation at the satellite altitude and from the symmetries between the gradiometric differentiation directions and the global North-South/East-West organization of the Earth's structure.

In the YY map, we thus show that the broad North-South elongated anomalies evidenced over Asia and America, following a belt of former tectonic plate boundaries, likely point

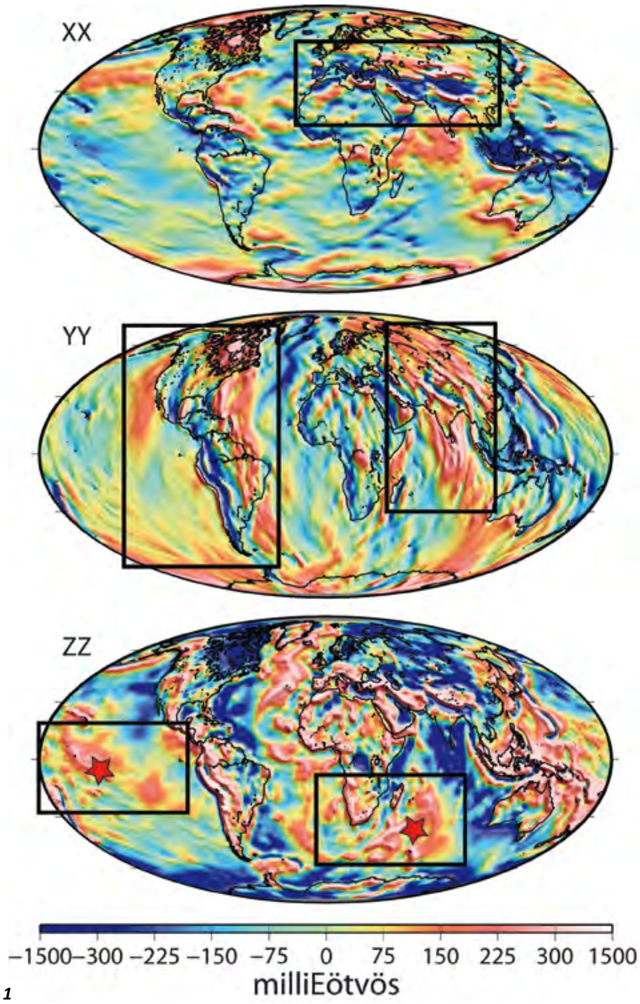


Fig. 1

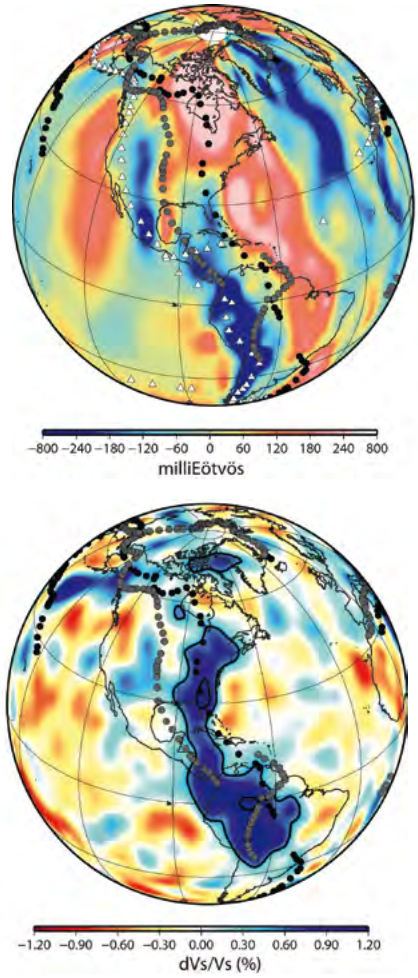


Fig. 2

to the buried remnants of these plates. How deep they sink is a matter of debate; our results suggest their presence between ~1 000 and 1 500 km depth below America, and in the mid-mantle below Asia. In the ZZ map, we find that the positive anomalies found in the South Central Pacific and south of Africa likely point towards deep mantle plumes, rising from more than 2 000 km depth. In the XX map, an East-West anomaly extending from the Mediterranean area to the Himalayas is interpreted as remnants of the former Tethys Ocean that existed before India collided with Asia.

Furthermore, the good geometric consistency we find between these anomalies and seismic velocity anomalies in the lower mantle as revealed by global tomography models (Fig. 2) shows that both kinds of datasets can be combined to decipher the mantle density structure and its links with internal temperature and composition variations, from global to regional scales. This is of major interest to understand our planet's deep dynamics, as these density variations drive the mantle flows and cannot be derived from seismic velocity nor gravity anomalies alone. These results thus call for a joint analysis of the gravity gradients with seismic data, mantle flow models, and tectonic plate history reconstructions, opening new avenues to unravel Earth's interior workings and their links with plate movements, and understand our planet history and evolution.

*[Fig. 1]*
*Spatial variations of Earth's non-hydrostatic gravity gradients (XX, YY and ZZ components). Reddish areas correspond to maxima; bluish areas indicate minima. They mark the presence of light or dense mass anomalies between 1 000 km and 2 500 km depths (in the black boxes).*
*© From [2]*

*[Fig. 2]*
*Top panel: Earth's non-hydrostatic YY gravity gradients over America (smoothed). Bottom panel: seismic shear-velocity anomalies from the S40RTS tomographic model at 1 100 km depth below America, illustrative of the 900–1 600 km depth range.*
*© From [2]*

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# Solid Earth

## *The (a)seismic behavior of active faults detected by SAR interferometry*

## Le comportement (a)sismique des failles détecté par interférométrie radar

➔ **Abstract:** *InSAR, using recent and forthcoming satellite data, represents an incredible potential for the study of active tectonic deformation. Since the 90's, InSAR has been routinely used to study earthquakes. During the last decade, InSAR started to be used to retrieve small, transient deformations. Interseismic loading of active faults can be monitored with unprecedented time space resolution. New satellites should enable mapping tiny deformations at the continental scale.*

➔ **Résumé :** L'InSAR représente un potentiel incroyable pour étudier la déformation tectonique active. Depuis 93, il a été régulièrement utilisé pour étudier les séismes. Durant la dernière décennie, il a été utilisé pour mesurer les petites déformations transitoires. Le chargement intersismique des failles peut maintenant être observé avec une résolution spatio-temporelle sans précédent. Les nouveaux satellites devraient permettre de cartographier les petites déformations à l'échelle continentale.

Synthetic Aperture Radar Interferometry (InSAR) using satellite images has proven very efficient to monitor ground movements generated by earthquakes, volcanic unrests or urban subsidence. The first SAR interferogram that imaged an earthquake was constructed using a pair of SAR images acquired by ERS-1 satellite [1]. It showed all the complexity of the ground displacement associated with an earthquake on a fault system, allowing the slip that occurred at depth on the different branches of the fault ruptured by the earthquake to be constrained. It was a huge improvement for earthquakes studies. Since then, InSAR has been routinely used to study earthquakes and offer a detailed spatial view of the seismic source that complements seismic data.

Thanks to the increasing amount of SAR satellite images, the community started during the last decade to evaluate the potential of InSAR to retrieve small or transient deformations that may occur on faults during the interseismic loading phase (*i.e.* between large earthquakes). Recent megathrust earthquakes in Japan and Chile (2011, 2010) have highlighted the need to address seismic hazard on active faults not only based on seismological information, but also on other type of information, such as the interseismic coupling derived from geodetic data. Determining the lateral variations of coupling allows coupled zones that should rebound into a future earthquake, and creeping zones that may act as barriers to the propagation of future earthquakes to be identified. Monitoring the deformation associated with interseismic loading on faults may be very challenging on a methodological point of view but it is a key issue. If we want to progress in our understanding of the mechanisms leading to the generation of large earthquakes it is mandatory to improve our ability to observe pre-earthquake phases in great details. For this purpose, the use of large SAR satellite data sets over a given area supplies piles of SAR interferograms, that can be derived into InSAR time series, and therefore describe with unprecedented resolution the time and space variations of ground displacement.

Most examples of faults monitoring during the interseismic period are mainly focused on continental faults. First results allowed the average interseismic deformation of moderate spatial wavelength to be mapped across strike-slip faults, such as the North Anatolian Fault, Altyn Tagh or Haiyuan Tibetan faults in Tibet (e.g., [2] and references therein) and more recently across the Himalayan main frontal thrust [3]. The faults' slip rates are then derived, as well as their locking versus creeping degree – a locked fault meaning that the system is accumulating elastic energy that should rebound into a future earthquake. On a few faults systems, dense data sets evidenced temporal variations of the deformation, that were interpreted as the surface expression of transient pulses of aseismic creep on faults [4-2] (Fig. 1). Until then, aseismic creep pulses on fault, also known as "silent earthquakes", had been detected thanks to continuous GPS monitoring on a few faults systems or subduction zones. The monitoring of these events with SAR interferometry allows the scientific community to reach unprecedented space resolution of the slip distributions on faults, allowing for new models of mechanism on the faults interface to arise.

A more challenging issue is to retrieve tiny deformation over a broad area, such as the one that is generated by slip on subduction zones, intracontinental deformation or even by the movement of tectonic plates. For these types of application a major issue with SAR interferometry is the correction of orbital errors that generates wide ramps across the interferograms, also known as flattening. By referencing their interferograms with local GPS networks or on stable rigid blocks, a

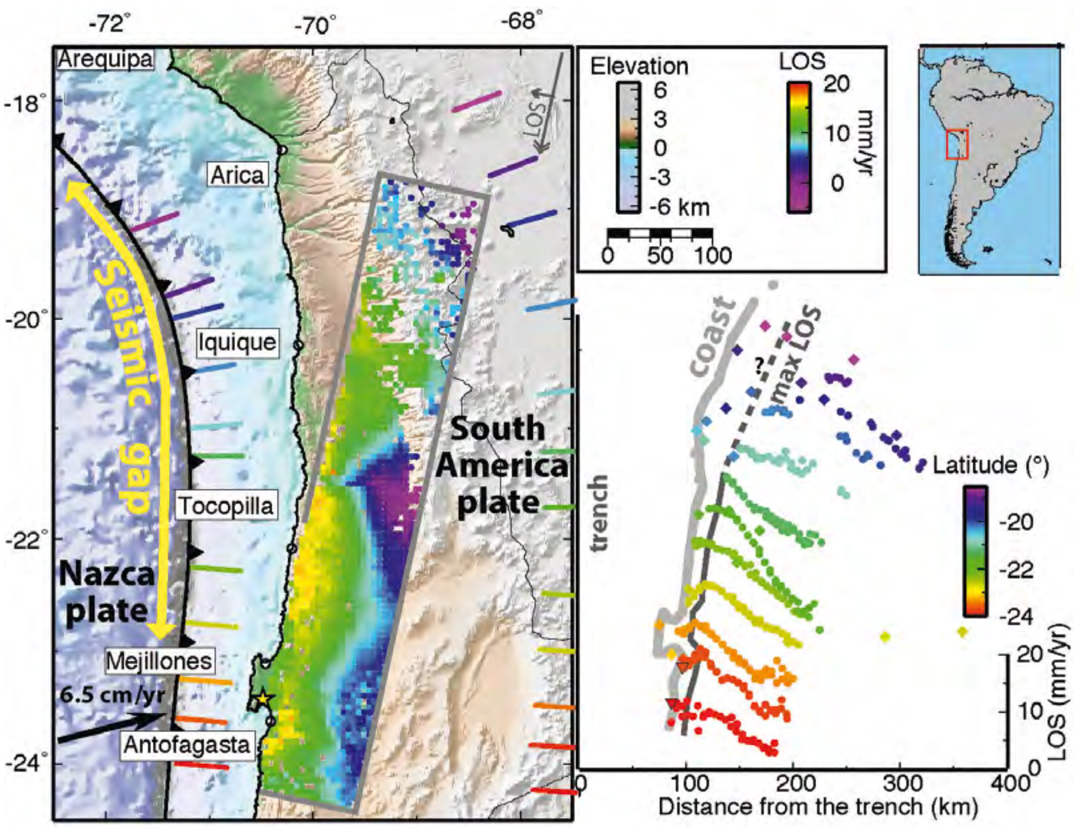


Fig. 1

few studies succeeded in retrieving the signal associated with interseismic or aseismic slip events on subduction zones in Chile [5] (Fig. 2) and Mexico [6], and with the rigid extrusion of Anatolia toward the west [7]. These new contributions offer new perspective in the range of application of InSAR studies, but are so far limited by the possibility of putting the InSAR images into a reference frame. So far, only GPS data allowed tackling large-scale deformation. ALOS2 and SENTINEL satellites should acquire a dense SAR data flow in ScanSAR mode, along long 400 km-wide strips and provide the opportunity to cover large zones affected by the seismic cycle over subduction zones, intracontinental deformation, or block tectonics. SAR data acquired by recent (e.g., ERS-1 & 2, ENVISAT, RADARSAT, ALOS-1) and forthcoming (e.g., SENTINEL-1, ALOS-2) satellite missions therefore represents an incredible potential for the study of active tectonic deformation, that should bring in the coming years major advances in the fields of active faults and mechanics of the lithosphere.

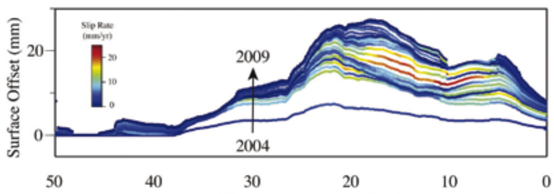


Fig. 2

*[Fig. 1]*
*Along-strike distribution of the fault parallel creep on Haiyuan fault (Tibet, China), derived from an InSAR time series between 2004 and 2009 (Envisat ascending track 240). Color indicates the velocity between two successive acquisitions.*
*© Adapted from [2]*

*[Fig. 2]*
*Interseismic strain above the Andean subduction, in the North Chile seismic gap, measured by Envisat SAR interferograms. Series of cross sections normal to the trench, sorted and color coded by latitude, represent InSAR velocities. Lines show the location of the coastline (light grey) and maximum in LOS displacement (dark grey).*
*© Adapted from [5]*

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