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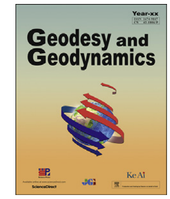

Goce derived geoid changes before the Pisagua 2014 earthquake

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A B S T R A C T

The analysis of space – time surface deformation during earthquakes reveals the variable state of stress that occurs at deep crustal levels, and this information can be used to better understand the seismic cycle. Understanding the possible mechanisms that produce earthquake precursors is a key issue for earthquake prediction. In the last years, modern geodesy can map the degree of seismic coupling during the interseismic period, as well as the coseismic and postseismic slip for great earthquakes along subduction zones. Earthquakes usually occur due to mass transfer and consequent gravity variations, where these changes have been monitored for intraplate earthquakes by means of terrestrial gravity measurements. When stresses and correspondent rupture areas are large, affecting hundreds of thousands of square kilometres (as occurs in some segments along plate interface zones), satellite gravimetry data become relevant. This is due to the higher spatial resolution of this type of data when compared to terrestrial data, and also due to their homogeneous precision and availability across the whole Earth. Satellite gravity missions as GOCE can map the Earth gravity field with unprecedented precision and resolution. We mapped geoid changes from two GOCE satellite models obtained by the direct approach, which combines data from other gravity missions as GRACE and LAGEOS regarding their best characteristics. The results show that the geoid height diminished from a year to five months before the main seismic event in the region where maximum slip occurred after the Pisagua $Mw = 8.2$ great megathrust earthquake. This diminution is interpreted as accelerated inland-directed interseismic mass transfer before the earthquake, coinciding with the intermediate degree of seismic coupling reported in the region. We highlight the advantage of satellite data for modelling surficial deformation related to pre-seismic displacements. This deformation, combined to geodetical and seismological data, could be useful for delimiting and monitoring areas of higher seismic hazard potential.
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1. Introduction

The convergence of the Nazca and South American Plates (65 mm/y rate and N75°E azimuth [1]) explains long-term deformational patterns along the Peru–Chile margin. The western edge of South America undergoes partly elastic deformation during the interseismic period [2]. Gradual accumulation of crustal deformation (mainly fore- and intra-arc shortening) occurs during the interseismic stage, considering seismic cycle deformation as explained within the framework of the purely elastic rebound theory [3]. The study of the deformational field over seismic regions (e.g. interplate) is a key issue for understanding the mechanical

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processes that occur during crustal strain accumulation and sudden relaxation from inter-to co-seismic stages along the seismic cycle.

Determination of surficial displacements at regional scale in subduction zones requires quantification of centimetre displacements over large areas, the ocean and high mountainous areas. During the interseismic period, the interplate contact remains coupled and blocked, accumulating strain and elastic energy between plates along the subduction zone. As the interplate contact continues locked, converging plates are brittle-ductile and also elastically deformed (prior to the main shock) driving tectonic uplift of the upper plate in the forearc region. Prior to rupture, a period of accelerated deformation develops, in which precursor signals may occur (e.g. absence or increase of seismicity, variations of seismic wave propagation parameters, fluid chemical composition and pressure, electrical resistivity, radon levels, etc. [4]. Additionally, gradual crustal uplift or subsidence, depending on the observation point location with respect to the epicentre and the mechanism of the future earthquake, are among long-term precursors. During the interseismic period the upper plate undergoes ductile deformation in the lower part and brittle deformation in the upper part. Furthermore, it has been observed in the north-central Chilean margin that shallow crustal seismicity in the upper plate of the marine forearc is characterized by contractional shallow events [5].

Modern geodesy as Global Positioning System (GPS), Synthetic Aperture Radar interferometry (InSAR)and satellite gravimetry (GRACE, GOCE), allows to precisely quantify surface displacements associated with both interseismic strain build up and coseismic strain release along plate boundaries [6]. Modelling deformation at a regional scale facilitates the characterization of the short-term seismic cycle behaviour and its relation to the long-term tectonic evolution [7]. Models based on geodetical data (GPS, InSar) allowed determining slip models, stress and strain behaviour, seismic coupling degree, convergence rate, etc. [6,8–12]. On the other hand, gravity field variations allowed inferring mass transfer before and after earthquake occurrence [13–18]. Geoid changes are useful for quantifying crustal deformation that could be related to tectonic mechanisms as well as deeper causes as viscoelastic behaviour of the mantle.

In this work, we used the gravity signal from GOCE (Gravity Field and Steady State Ocean Circulation Explorer) satellite in order to model preseismic deformation along plate interface expressed by means of geoid heights variations. GOCE models from Ref. [19] GO_CONS_GCF_2_DIR_R4 (Nov. 1, 2009–Aug. 1, 2012) and GO_CONS_GCF_2_DIR_R5 (Nov. 1, 2009–Oct. 20, 2013) cover a data span between Aug. 2012 and Oct. 2013 allowing to model gravity variations prior to the Pisagua $Mw = 8.2$ great megathrust earthquake on April 24 2014, the greatest earthquake after GOCE mission ending.

2. Gravity variations and earthquake monitoring

Gravity variations are presently considered of great importance for understanding the development and occurrence of earthquakes [20]. Terrestrial gravity variations provide information about crustal mass transfer [21,22] and have proved to be useful in predicting occurrence and particularly locations of medium to large intraplate earthquakes [20,23,24]. These regional gravity anomaly variations and high gravity gradients along the related active faults before earthquakes can be used as seismic precursors. Local positive gravity variations near the epicentre and occurrence of high-gravity-gradient zones across the epicentre prior to intraplate earthquakes were reported in several cases [20,25].

Different studies have shown the usefulness of gravity satellite derived data for studying both coseismic and postseismic deformation, and consequent gravity changes from major earthquakes [13–16,26–29]. These results, based on satellite gravity data, are consistent with other geodetic measurements [30]. The long wavelength characteristic of satellite derived gravity field models allows comparison and analysis of the rupture zones of great megathrust earthquakes that occur along the plate interfaces. In these regions, where subducting and upper plates are in a close contact, after slip and viscoelastic relaxation involve the lower crust and upper mantle.

Earthquake interseismic and postseismic deformations influence broad areas including the offshore, where terrestrial gravity measurements are scarce and their changes is difficult to be monitored. In these regions, the distribution of satellite derived gravity anomalies and gravity gradients present a close relation to rupture zones [31–33]. Recent works focused on the Peruvian-Chilean convergent margin [17,18] have shown gravity variations after the Maule and before the Iquique-Pisagua earthquakes based on GOCE TIM models. Similarly, Fuchs, M.J. et al. [16] found that gravity changes detected by GOCE gradient trends were related to coseismic slip for the Tohoku earthquake, through analysing GOCE gravity gradiometry raw data.

3. Data and method

GOCE models present homogeneous data quality (precision) as no terrestrial data enter into their computation, avoiding consequent induced errors or sampling biases typical of terrestrial gravity measurements. One of the main problems of terrestrial data is the non-uniformity of the database (different campaigns) and lack of coverage in regions with difficult access (high mountains) or no availability (offshore). This is well solved by satellite missions as satellite data present homogeneous precision and quality, although with lower spatial resolution than achieved by terrestrial data or combined models as EGM2008 [34] (a spatially heterogeneous combination of data). Even though satellite models only provide information on the long wavelength part of the spectrum [35], spatial resolution is not a major problem when analysing great megathrust rupture zones, since involved areas are in the range of hundreds of km^2 according to the last GOCE derived models. Half wavelength spatial resolutions ranging from 60 to 80 km are achieved with the GO_CONS_GCF_2_TIM_R4/R5 [36]and the GO_CONS_GCF_2_DIR_R4/R5 [19,37] satellite GOCE models. The smallest resolvable feature of the gravity field or spatial resolution is given by $\lambda/2 = \pi R/N$, where R is the Earth radius and N is the degree/order of the model [38].

The geoid is expressed as a first approximation by Bruns' formula [39]:

$$N(\lambda,\phi) = T(0,\lambda,\phi)/\gamma(0,\phi) \tag{1}$$

It is obtained from the anomalous potential (T) regarding the normal gravity (γ) (see Ref. [38] for a detailed explanation). It can be directly calculated from the Earth gravity field model expressed as a series of spherical harmonic coefficients [38,40].

Geoid is representative of a hypothetical equipotential surface of the Earth following the mean level of the oceans at rest that is prolonged under the continents. Geoid changes show a variation of this equipotential surface and are related either to exogenous forces (topographic erosion) or to endogenic forces (mass redistributions inside the Earth interior). However, large variations on one-year time-scale mainly represent the crustal response to accelerated mass redistributions inside the Earth.

In the present work, we calculated geoid heights from the GOCE models GO_CONS_GCF_2_DIR_R4 and R5 [19,37]. These models are based on the direct approach combining kinematic GOCE orbit data,

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