Analysis of postseismic deformations after the 2010 Maule earthquake based on GPS data

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INTRODUCTION

- The Chilean subduction zone is one of the most seismically active regions of the Earth. One of the most outstanding features of Chilean subduction zone was the Darwin seismic gap, which have been existed since 1835 and was finally interrupted by the Maule earthquake (Mw = 8.8) occurred on February 27, 2010. The earthquake source zone stretched for about 600 km, completely including the source zone of the Concepcion earthquake of 1835 and overlapping the southern segments of source zones of 1906 and 1985, as well as the northern segment of the source zone of the Great Chilean earthquake of 1960 (Fig. 1).
- According to the (Melnick et al., 2012), during the Maule earthquake, there was almost complete relaxation of tectonic stresses accumulated in the Darwin seismic gap for 175 years. Hence, we can conclude that the quick recurrence of such a strong earthquake in this zone is highly unlikely.
- Geological and seismological data in the Central Chile region favor the keyboard structure of the continental margin (Melnick et al., 2012; Geersen et al., 2011; Moreno et al., 2012; Jara-Munoz et al., 2015). According to these data, the source zone of Maule earthquake affected four seismogenic blocks (Fig. 1).

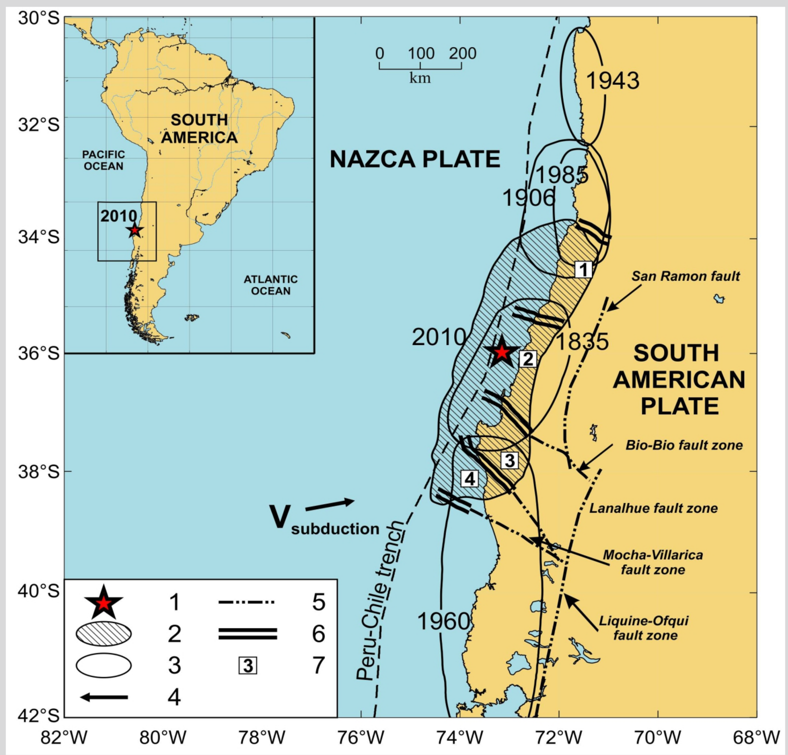

Figure 1. Maule earthquake against the seismic and tectonic background. 1 - main shock of the 2010 earthquake; 2 - source zone of the 2010 earthquake; 3 - source zones of historical earthquakes; 4 - subduction rate (66 mm/a; 5 - main tectonic faults; 6 - boundaries of seismogenic blocks; 7 - numbers of blocks.

KEYBOARD MODEL OF THE SEISMIC DEFORMATION CYCLE (SDC)

- According to the keyboard model (Lobkovsky et al., 1991) the frontal part of the island arc is divided on wedge-shaped blocks (keys - B), which are separated from each other by transcurrent vertical faults (C) that reach the surface of a subducting plate (D) (Fig. 2). The blocks are bounded from the ocean-side by deep-sea trench, and from the continental side by a longitudinal fracture zone, which separates them from the main arc massif (A).
- Due to interaction between the oceanic and continental lithospheric plates, the blocks accumulate stresses, which are released during the megathrust earthquakes. The stage of elastic energy accumulation within each block occupies the principal part of the periods between great earthquakes (Fig. 2).
- The block projection on the surface during the long-term energy-accumulated stage is identified with a seismic gap according to the given model. Release of the seismic energy of the whole seismogenic block occurs in the seismic stage, when a critical value of the tangential stress is achieved along the greater part of the contact surface between the block and the subducted plate. This leads to rupture of the contact surface accompanied by coseismic displacement and a great earthquake of the thrust type. As a result, unloading seismogenic blocks almost instantly shift towards the ocean.
- However, during a fast seismic stage, only a partial relaxation of accumulated stress occurs. The release of the remaining part of the elastic energy stored in the blocks takes place at the aftershock stage of the SDC during the final "straightening" of the system. The so-called aftershock stage can last several months or years and the end of it marks the beginning of a new SDC, when the seismogenic blocks are at a maximum distance from the islands.

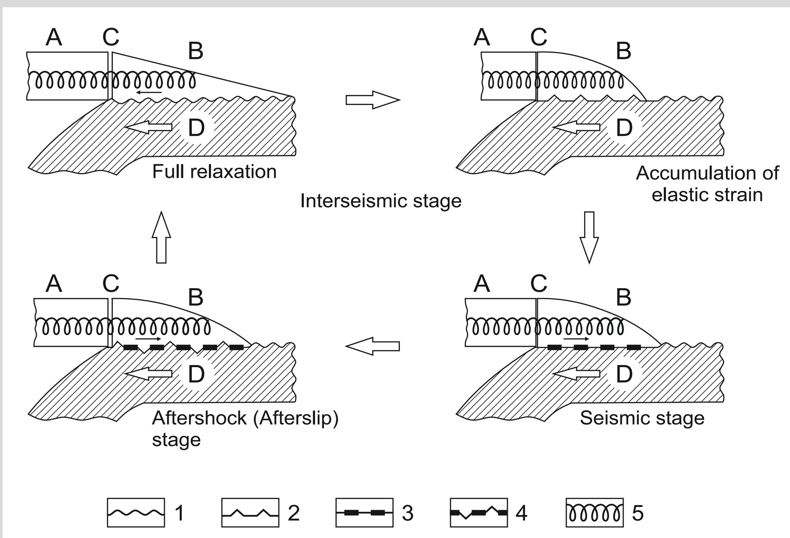

Figure 2. Scheme of successive stages of deformation (loading and relaxation) of the seismogenic blocks and the corresponding stages of the seismic cycle:
1 – Undisturbed "rough" contact zone structure (CZS) (stable stage of the cycle); 2 – elastic "smoothed" CZS (preseismic stage of the cycle); 3 – strongly fragmented and heterogeneous CZS (seismic stage of the cycle); 4 – partly restored CZS (aftershock stage of the cycle); 5 – spring imitating the elastic interaction between blocks [Lobkovsky et al., 1991].

PRESEISMIC AND COSEISMIC STAGES OF THE SDC

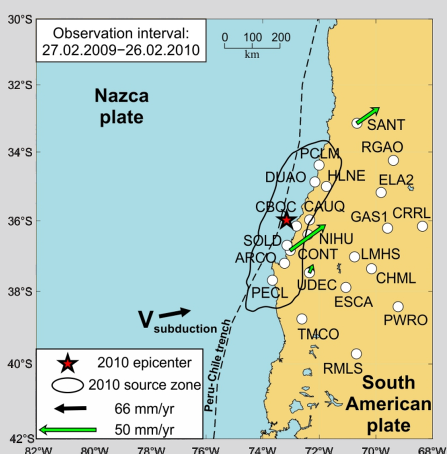

Figure 3. Preseismic displacement rates field near the source zone of Maule earthquake

- Since most of the GPS observation stations were deployed after the Maule earthquake, an estimate of the interseismic rate of deformation accumulation was achieved using only three points (Fig. 3).
- The directions of the movements of CONT and SANT stations (Fig. 3) are close to the direction of subduction, which reflects the compression of seismogenic blocks during the stable interseismic stage of the cycle.

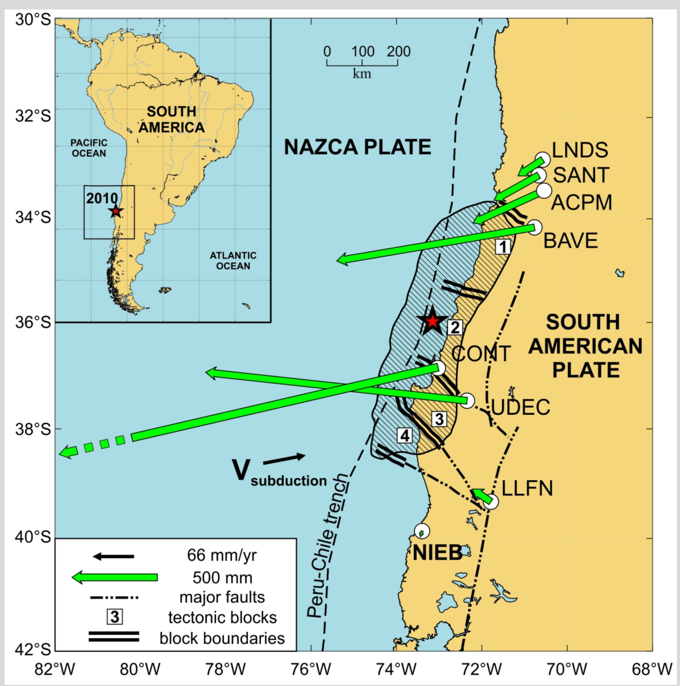

Figure 4. Coseismic displacements observed on GPS stations during the 2010 Maule earthquake

- At the same time, the motion of the UDEC station (Fig. 3), differs significantly from the motion of the other two stations. This suggests that the displacement of the UDEC station may reflect the motion of a rear block completely compressed before the earthquake.
- During the 2010 earthquake, the fast coseismic displacements directed against the vector of subduction were recorded on the GPS stations functioning at that time. According to the keyboard model, these displacements are due to the displacement of the unloading seismogenic blocks towards the ocean. Since some of the stations located immediately above the earthquake source, we can estimate the value of these rapid displacements, which were about 1 m at BAVE and UDEC, whereas exceeded 3 m at CONT (nearest to the epicenter); thus, these displacements were maximal at the boundaries of the blocks (Fig. 4).
- Coseismic displacements recorded by the stations of the Chilean network during the Maule earthquake were used to construct a model of distributed slip in the source zone of this earthquake using programming code STATIC1D by Fred Pollitz.
- The constructed model is in good agreement with the same models based on teleseismic, tsunami and InSAR data (Moreno et al., 2010; Lay et al., 2010; Lorito et al., 2011; Lin et al., 2013). In all these models, the zone of maximal slip in the source of Maule earthquake lays from about 33.5° to 38° S, completely encompassing the source zone of the Concepcion earthquake of 1835, and the northern segment of the source zone of the 1960 Great Chilean earthquake.

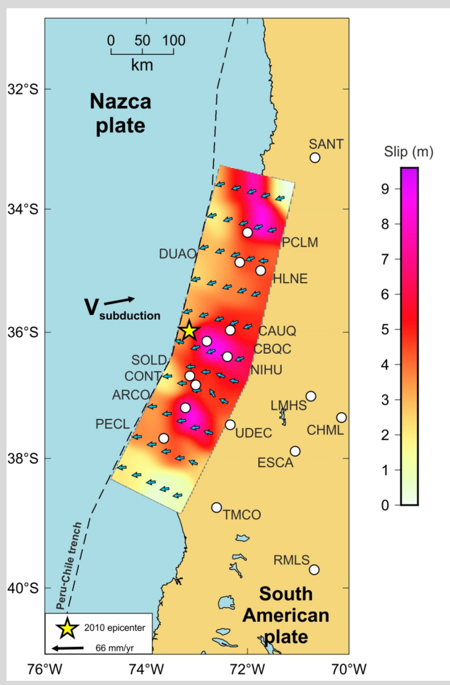

Figure 5. Model of slip distribution in the source zone of Maule earthquake based on inversion of GPS coseismic displacements [Vladimirova, 2012].

COSEISMIC STAGE OF THE SDC

- Displacements recorded at the GPS stations in the first two years after the Maule earthquake (Fig. 6A, B) are characterized by a consistent direction and high intensity decreasing with time. In addition, the values of the displacements noticeably decrease in the direction deeper into the continent. This type of displacement within the keyboard model can be caused by the continuing retreat of unloading seismogenic blocks and the rear blocks to the ocean, at the afterslip stage of the SDC.

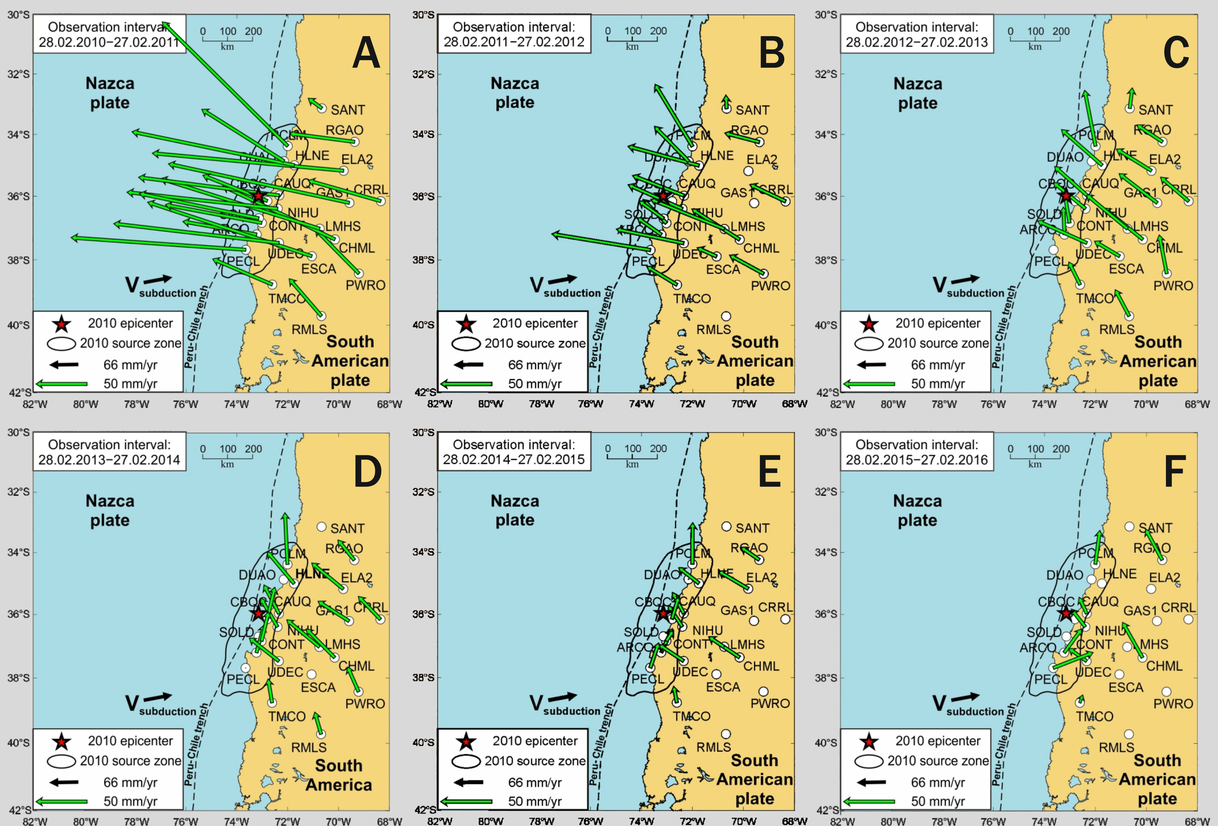

Figure 6. Postseismic displacement rates field after the 2010 Maule earthquake estimated from 1-year intervals, from A - 1 year after earthquake to F - 6 years after earthquake.

- To check this hypothesis and estimate the duration of the afterslip stage we performed a modeling of development of afterslip in the source zone of Maule earthquake on the basis of six months of GPS dispacements recorded after the event using programming code STATIC1D by F. Pollitz. As you can see on Fig. 7 the slip in the source zone affected adjacent seismogenic blocks and almost decreases to the end of the six months interval.

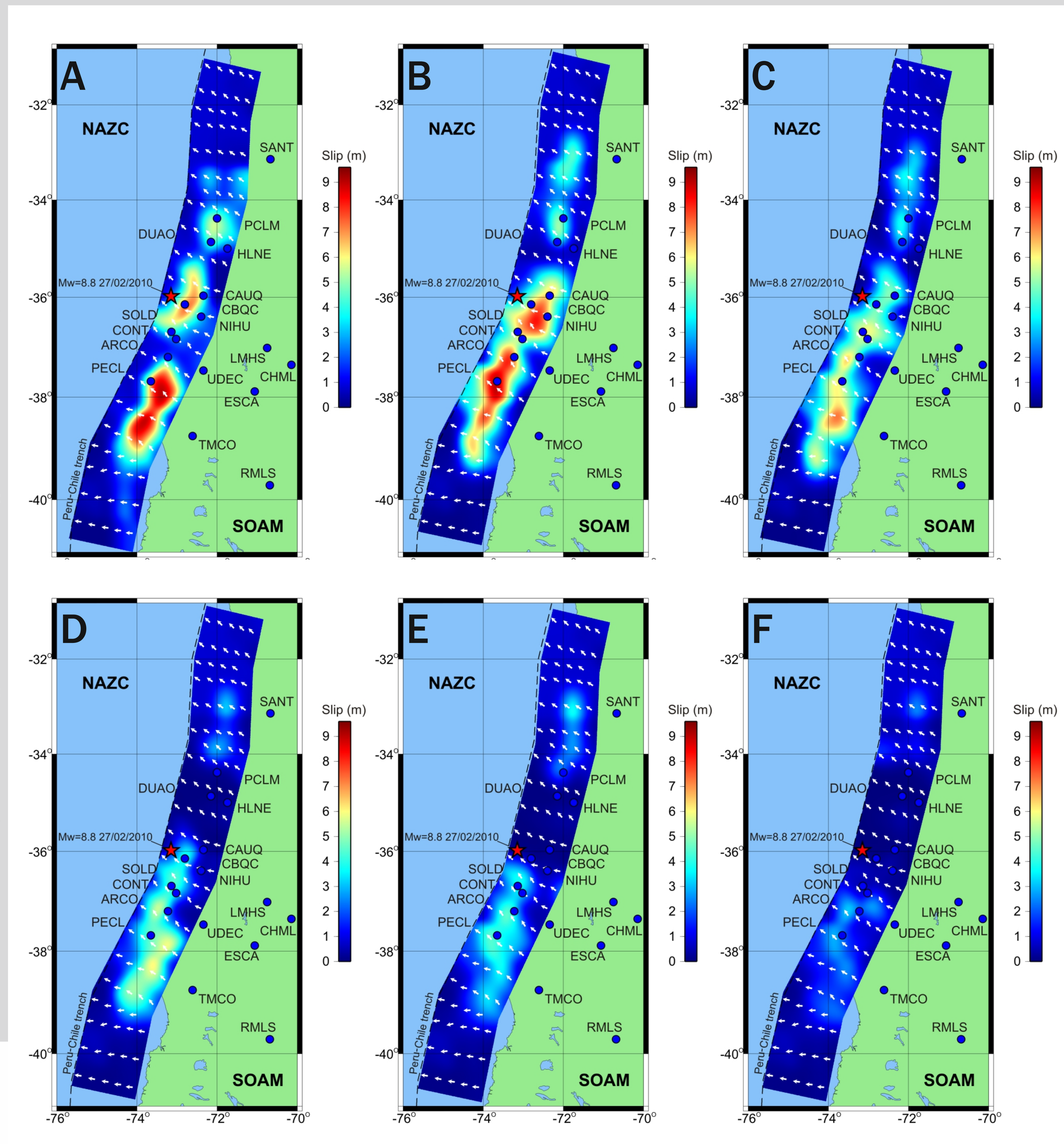

Figure 7. Modeling of afterslip process in the first 6 months after Maule earthquake based on 1-month data (Vladimirova and Steblov, 2015), from A - first month after earthquake to F - six month after earthquake.

- The completion of the aftershock stage is also favored by the characteristic pattern of displacement rates field obtained 3 years after 2010 earthquake (Fig. 7C), which is expressed as a beginning of rotation of rate vectors to the direction of subduction. At the same time, to the east of the source zone, the observed displacement vectors retain both their magnitude and direction, which also supports the hypothesis of the existence of a viscoelastic response in the asthenosphere.

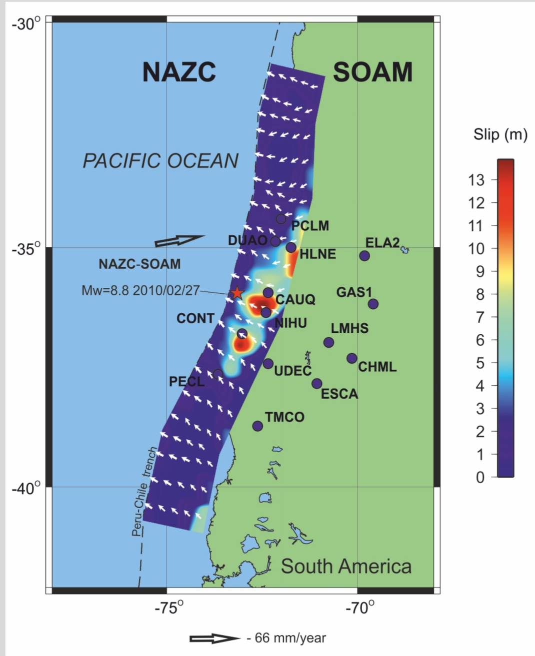

Figure 8. Model of slip distribution in the source zone of 2010 earthquake based on inversion of postseismic data (Vladimirova, 2012).

- To check this assumption, we constructed a model of viscoelastic relaxation in the asthenosphere near the source zone of Maule earthquake on the basis of two-year time series of 6 stations, using the program code VISCO1D by F. Pollitz.
- The models of the distributed slip in the source of the Maule earthquake obtained independently from the data on the coseismic (Fig. 5) and postseismic (Fig. 8) displacements agrees well in magnitude and localization of the maximum slip, however, a later model takes into account the development of the source zone as a result of motion of seismogenic blocks at the afterslip stage of SDC.
- According to the constructed model, the maximum decay time of anomalous movements is more than 20 years (Vladimirova and Steblov, 2015). This process can significantly affect the duration of the postseismic stage of seismic deformation cycle in Central Chile.

CONCLUSIONS

- Application of the keyboard model of the SDC, combined with the models of frictional afterslip and viscoelastic relaxation in the asthenosphere has allowed us to completely explain the displacements observed by satellite geodetic methods prior to, during, and after the 2010 Maule earthquake.
- A long–term postseismic stage, which exceeds 20 years, can significantly affect the peculiarities of the passage of the seismic cycle in the Chilean subduction zone, providing an explanation for such a long duration of the entire cycle.
- Tangential stresses due to oblique subduction in the Central Chile cause compression of seismogenic blocks at the interseismic stage, which results in very long source zones of megathrust eartquakes in this subduction zone.

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