Analysis of surface deformations related to the 2010 Maule earthquake based on GPS data

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Photography encouraged

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 1835 Concepcion earthquake and overlapping the southern segments of source zones of 1906 and 1985 earthquakes, as well as the northern segment of the source zone of the 1960 Great Chilean earthquake (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 (Geersen et al., 2011; Melnick et al., 2012; 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).

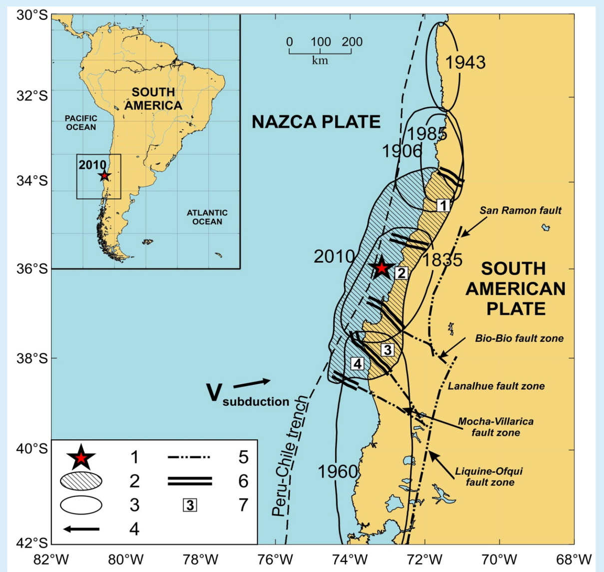

Figure 1. Maule earthquake against the seismic and tectonic background. 1 – main shock of the 2010 earthquake; 2 – source zone of the 2010 earthquake; 3 – source zones of historical earthquakes; 4 – subduction rate (66 mm/a); 5 – main tectonic faults; 6 – boundaries of seismogenic blocks; 7 – numbers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

- We analyze the data of long-term continuous observations at GPS stations deployed in the vicinity of the source zone of the 2010 Maule earthquake. GPS stations are located on continental margin both along the source zone and across its strike, which makes it possible to study the deformations of the earth surface both in the immediate vicinity of the source of the Maule earthquake and at a considerable distance from it (Fig. 3).
- The processing of raw GPS observations was performed using GAMIT/GLOBK software package (Herring et al., 2018). The analysis of variations in surface deformation fields is based on displacement rates fields of GPS stations estimated over 1-year intervals. All observations are in stable South American reference frame.

KEYBOARD MODEL OF THE SEISMIC DEFORMATION CYCLE (SDC)

- Modern satellite geodetic methods allow us to perform high-precision registration of the earth surface displacements observed in subduction regions at all stages of the seismic deformation cycle (SDC). Thus, high-quality geodetic observations can provide a "snapshot" of evolution of the SDC in a particular subduction zone. We use long-term space geodetic observations to reveal the patterns of the SDC in Chilean subduction zone in terms of the mechanical keyboard model of SDCs (Lobkovsky et al., 1991).
- According to the keyboard model 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 consequent great earthquakes (Fig. 2).

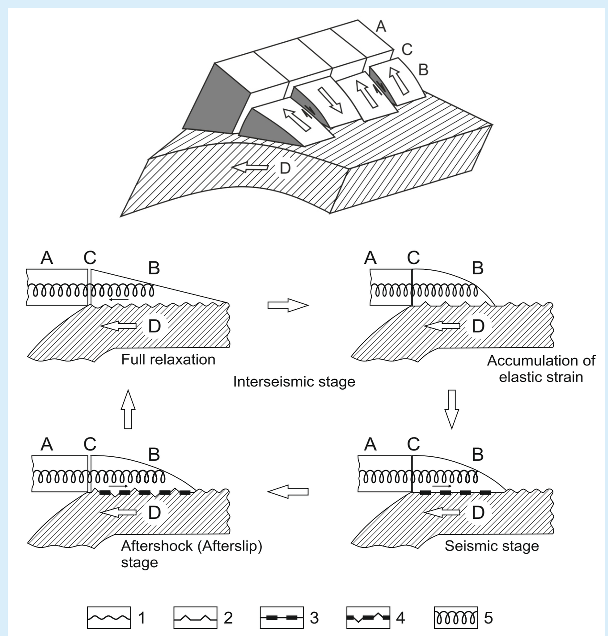

Figure 2. Scheme of successive stages of deformation (loading and relaxation) of the seismogenic blocks and the corresponding stages of the seismic cycle: 1 – Undisturbed "rough" contact zone structure (CZS) (stable stage of the cycle); 2 – elastic "smoothed" CZS (preseismic stage of the cycle); 3 – 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].

- 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. Conditions for the block motion towards the ocean trench at the aftershock stage are formed by sediments filling the negative forms of the ocean floor relief. During the subduction of oceanic plate these sediments are pulled into the contact zone of lithospheric plates and forming a thin contact high-plastic layer between the bottom of the island arc and the downgoing plate. During the main shock of the large earthquake the material of the contact zone is destroyed, that leads to significant decrease in its effective viscosity from interseismic 10^{19} Pa·s down to 10^{18} Pa·s. As a result, at the aftershock stage of the SDC, the block fairly rapidly shifts towards the ocean trench. This shift is accompanied by destruction of local inhomogeneities of the contact zone together with healing of the sedimentary rock defects.
- 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.

PRESEISMIC AND COSEISMIC STAGES OF THE SDC

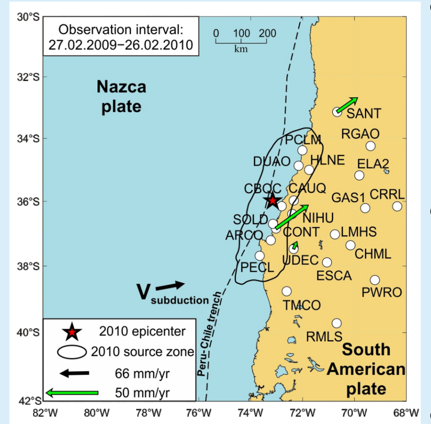

Figure 3. Preseismic displacement rates field near the source zone of Maule earthquake

- 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 motions 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.
- 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 massif completely compressed before the earthquake. Such pattern may serve as an indicator of passing of a preseismic stage of the SDC.

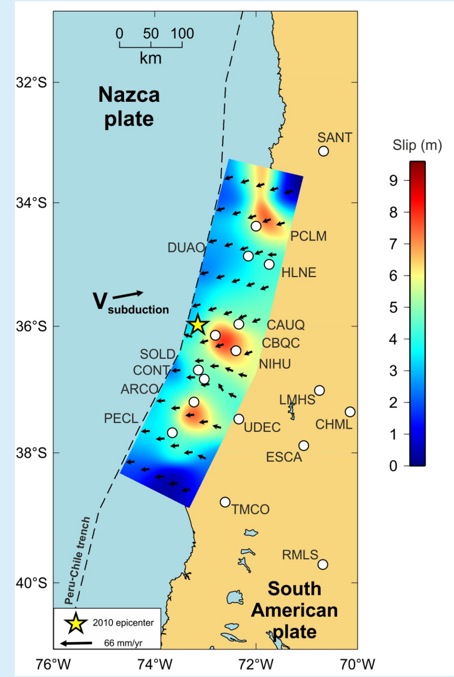

Figure 5. Model of slip distribution in the source zone of Maule earthquake based on inversion of GPS coseismic displacements

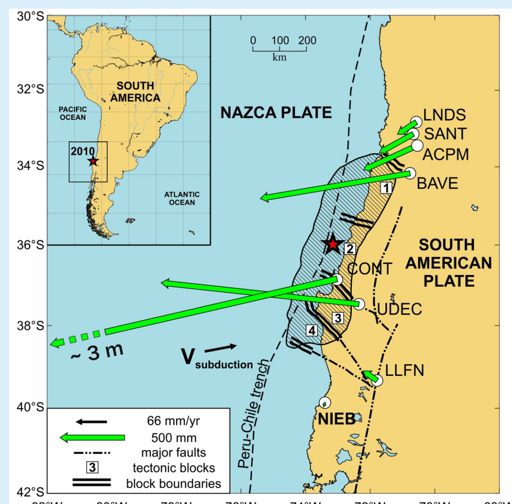

Figure 4. Coseismic displacements observed at GPS stations during the 2010 Maule earthquake

- During the 2010 earthquake, fast coseismic displacements directed opposite 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 are located immediately above the earthquake source, we can estimate the value of these rapid displacements, which were about 1 m at BAVE and UDEC, and exceeded 3 m at CONT (nearest to the epicenter). The 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 (Pollitz, 1996). This program allowed as to calculate instant deformation in the elastic layered spherical medium caused by buried complex-shaped dislocation.
- 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.

POSTSEISMIC STAGE OF THE SDC

- According to the GPS vertical displacements, we observe a significant subsidence of the earth surface (up to 60 mm) in the first 6 months after the Maule earthquake (Fig. 6A). These observations are in good agreement with the afterslip model data (Fig. 6B) and contradict the data of viscoelastic relaxation model (Fig. 6C).
- At the same time, analysis of geodetic data on vertical displacements for the next 2 years suggest that a process of viscoelastic relaxation instead of afterslip might be predominant (Fig 6. D-E).

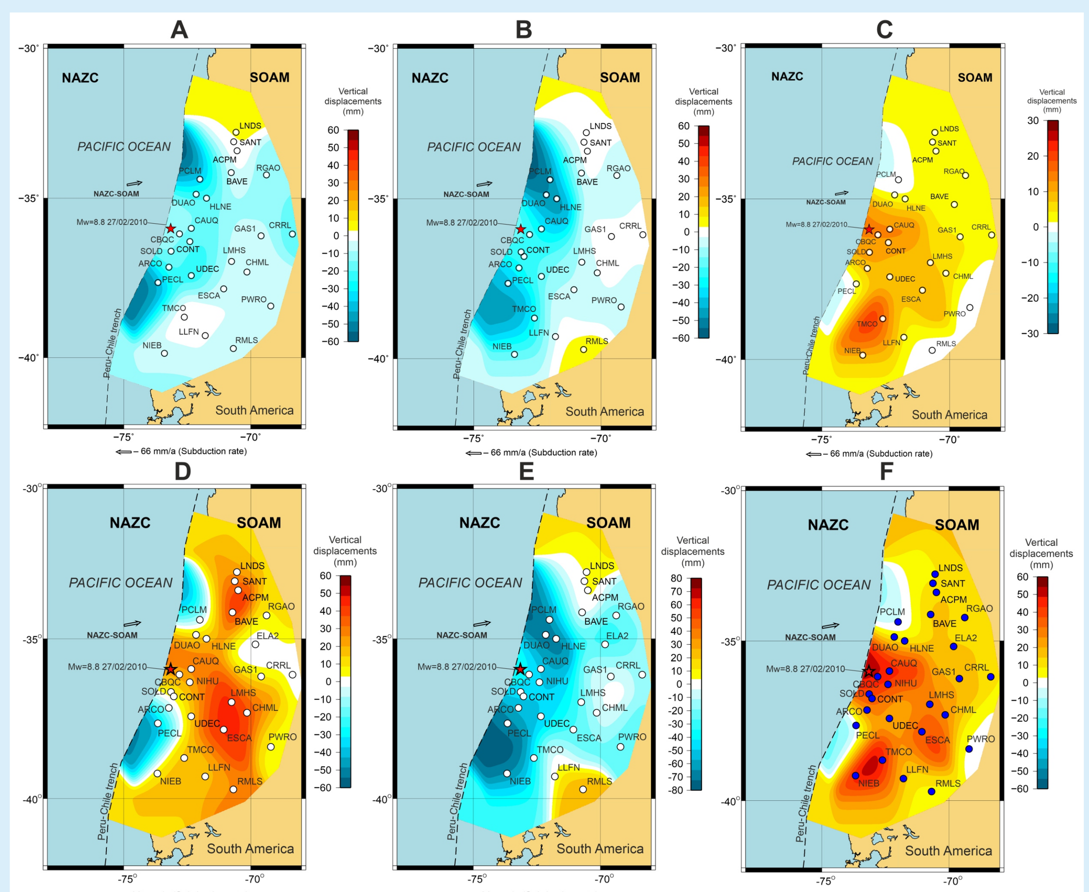

Figure 6. Vertical displacement field calculated over the interval 28/02/2010 – 27/08/2010: (A) – observed, (B) – afterslip model, (C) – viscoelastic relaxation model, and 28/08/2010 – 21/04/2012: (D) – observed, (E) – afterslip model, (F) – viscoelastic relaxation model.

- 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.
- According to the analysis of vertical displacements the duration of afterslip stage must be at least half a year.

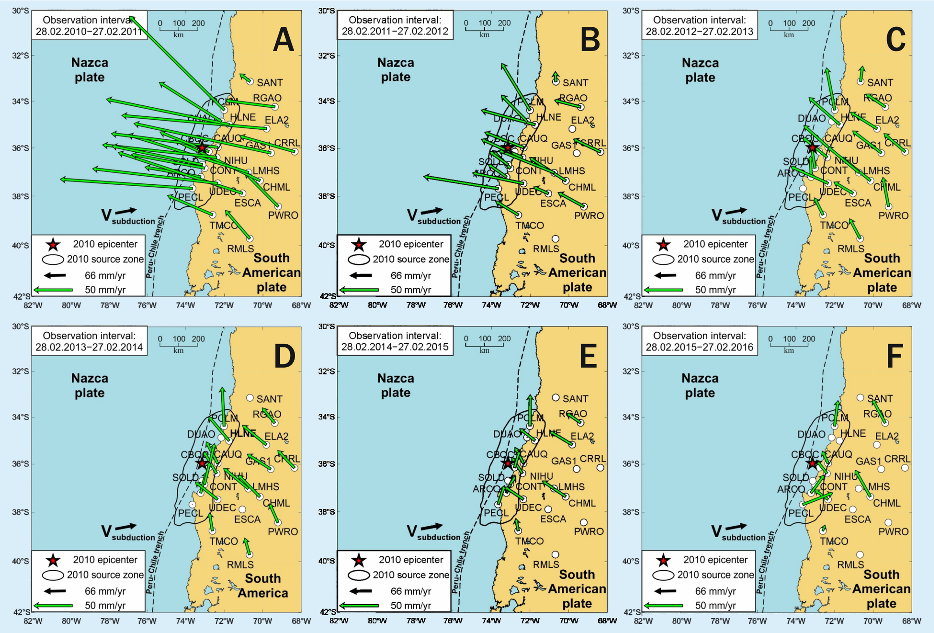

Figure 7. Postseismic displacement rates field after the 2010 Maule earthquake estimated from 1-year intervals, from A – 1 year after earthquake to F – 6 years after earthquake.

- To check the hypothesis of existence of afterslip and estimate its duration we performed a modeling of development of afterslip in the source zone of Maule earthquake. We use data of six subsequent monthly GPS dispacements recorded after the event and perform calculations using programming code STATIC1D (Pollitz, 1996). We have searched for the slip distribution in the extended source zone due to its possible expansion at the afterslip stage.
- As you can see on Fig. 8 the slip in the source zone affected adjacent seismogenic blocks and almost decreases to the end of the six months interval.

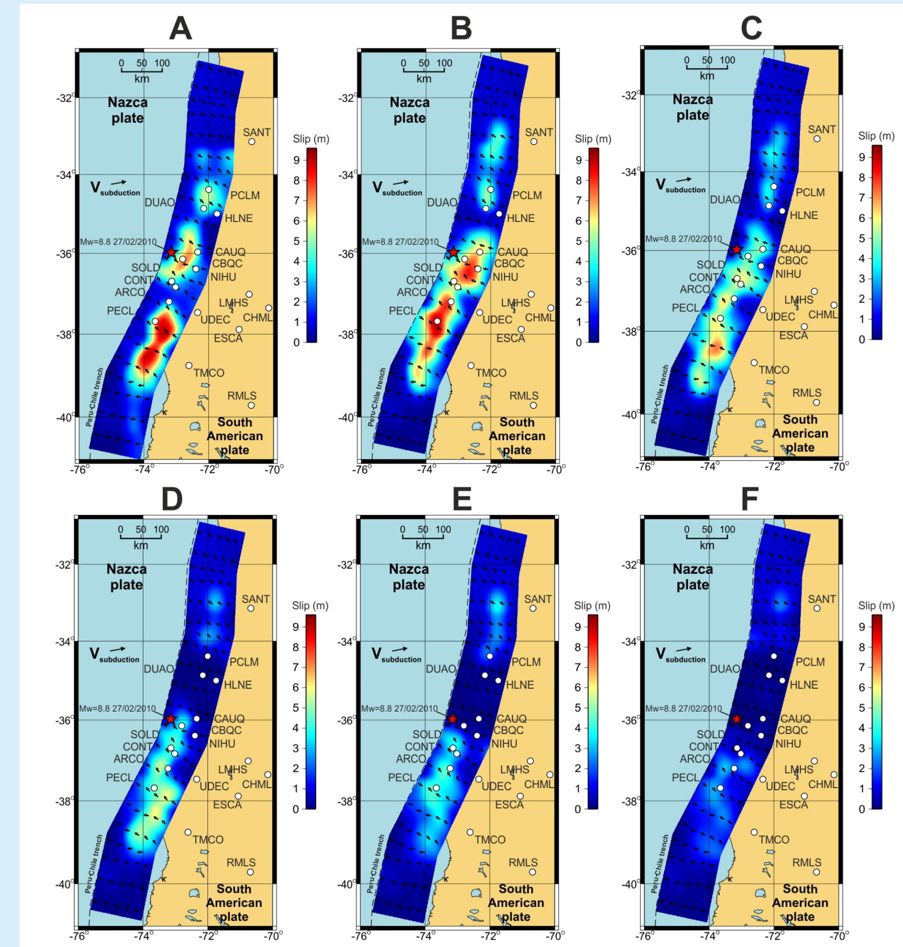

Figure 8. Modeling of afterslip process in the first 6 months after Maule earthquake based on 1-month data (Vladimirova and Steblov, 2015), from A – first month after earthquake to F – sixth month after earthquake.

- 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, previously suggested on the basis of vertical displacements data.
- To check this assumption, we constructed a model of viscoelastic relaxation in the asthenosphere near the source zone of Maule earthquake using the program code VISCO1D by F. Pollitz (Pollitz, 2006). During the modeling, the rheology of the asthenosphere was represented by biviscous Burgers solid, comprising both Maxwell (6×10^{17} Pa·s) and Kelvin (5×10^{17} Pa·s) viscosities (Vladimirova and Steblov, 2015).

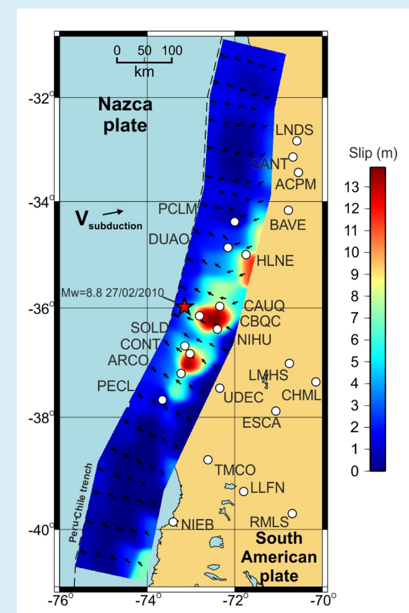

Figure 9. Model of slip distribution in the source zone of 2010 earthquake based on inversion of postseismic data (Vladimirova, 2012).

- We searched for an effective slip distribution in the source zone of Maule earthquake, taking into account the expansion of the boundaries of the initial source zone due to its development in the first six months during afterslip stage. The search zone in this formulation is expanded to 1100 km and the effective source is limited to the region of nonzero slip in the obtained distribution.
- Cumulative postseismic displacements are simulated using data from 17 continuous stations, which are 100 km or more remote from the earthquake epicenter, for the period 2010.2–2012.3. Such a choice of the spatial location of observation points suggests that the postseismic displacements recorded by these points are mainly due to the viscoelastic relaxation process in the asthenosphere accompanying the Maule earthquake. The effective distribution of the slips in the source of the Maule earthquake found as a result of solving the inverse problem is shown in Fig. 9.
- The models of the slip distribution in the source of the Maule earthquake obtained independently from the data on the coseismic (Fig. 5) and postseismic (Fig. 9) 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.

FORECAST OF THE TIME OF TRANSITION TO INTERSEISMIC STAGE

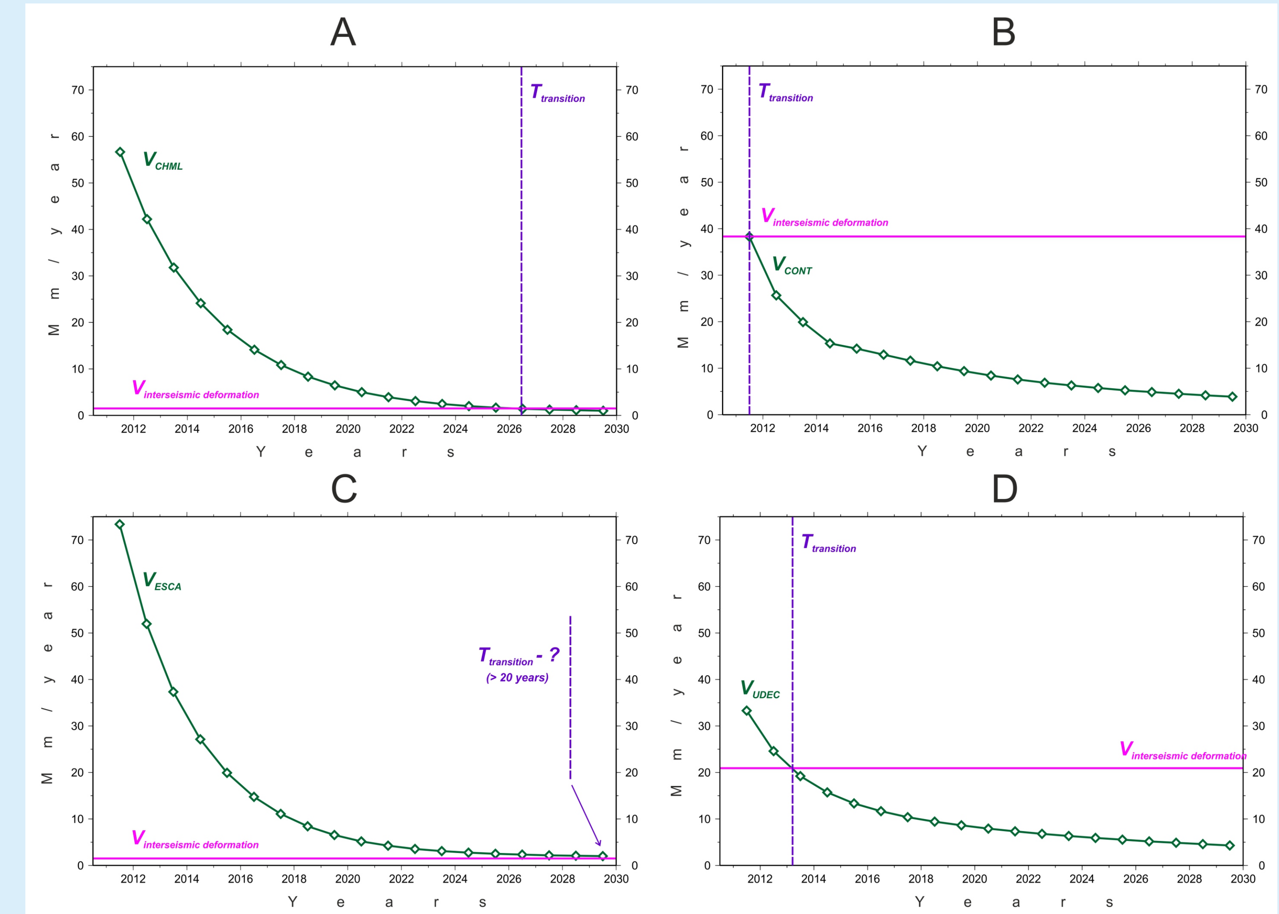

Figure 10. Forecast of attenuation of anomalous postseismic velocities (Vladimirova and Steblov, 2015) and, therefore, the time of transition of the SDC to the interseismic stage for (A) – CHML GPS station (far-field), (B) – CONT GPS station (near-field), (C) – ESCA GPS station (far-field), (D) – UDEC GPS station (near-field).

- The obtained distribution of the effective slip (Fig. 9) in the source of the Maule earthquake allowed us to predict the intensity of attenuation of viscoelastic stresses in the asthenosphere, which, in turn, led to estimation of the time of transition of the seismogenic zone to a stationary state of stress accumulation (Fig. 10).
- Estimates of the transition time were made taking into account the average interseismic horizontal velocities in the central part of the Chilean subduction zone relative to the South American plate. These rates range from 38 mm/a in the near-field (<100 km to the Peru-Chile trench), to 2 mm/a at points in the far-field (>250 km).
- Based on the results of the simulations, we can conclude that the calculated attenuation time of viscoelastic relaxation is about 3 years in the near-field and can exceed 20 years for stations in the far-field.

CONCLUSIONS

- Application of the keyboard model of the SDC, combined with the models of frictional afterslip and viscoelastic relaxation in the asthenosphere allowed us to completely explain the displacements observed by satellite geodetic methods prior to, during, and after the 2010 Maule earthquake.
- Afterslip was a predominating postseismic process in the first 6 months after the 2010 earthquake. The released scalar moment during the afterslip stage slightly exceeded the coseismic one, The nonlinear motion of GPS station in the next 6 years is explained by viscoelastic relaxation in the asthenosphere. The effective postseismic source costructed on the basis of the long-term postseismic timeseries showed that only 41% of summury scalar moment caused the observed viscous response.
- 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.

Table 1. Comparison of seismic and geodetic scalar moments and magnitudes

Source	Scalar moment (N x m)	Magnitude
Seismic (Global CMT catalog)	1.86×10^{22}	8.78
Geodetic coseismic source	2.38×10^{22}	8.85
Geodetic cumulative afterslip	3.03×10^{22}	8.92
Postseismic effective source	2.24×10^{22}	8.83

REFERENCES

Geersen J., Behrmann J.H., Volker D., Krastel S., Ranero C.R., Diaz-Naveas J., and Weinrebe W.. (2010) Active tectonics of the South Chilean marine fore arc (35°S-40°S). Tectonics. 30 (Tc3006).

Herring T.A., King R.W., Floyd M.A., McClusky S.C. (2018) GAMIT Reference Manual, Release 10.7. – Cambridge: MIT. – 171 p.

Jara-Munoz J., Melnick D., Brill D., and Strecker M.R. (2015) Segmentation of the 2010 Maule Chile earthquake rupture from a joint analysis of uplifted marine terraces andseismic-cycle deformation patterns. Quat. Sci. Rev. V. 113, P. 171–192.

Lay T., Ammon C.J., Kanamori H., Koper K.D., Sufri O. and Hutko A.R. (2010) Teleseismic inversion for rupture process of the 27 February 2010 Chile (Mw 8.8) earthquake. Geophys. Res. Lett. V. 37. L13301.

Lin Y.N., Sladen A., Ortega-Culaciati F., Simons M., Avouac J.-P., Fielding E.J., Brooks B.A., Bevis M., Genrich J., Rietbrock A., Vigny C., Smalley R. and Socquet A. (2013) Coseismic and postseismic slip associated with the 2010 Maule Earthquake, Chile: Characterizing the Arauco Peninsula barrier effect. J. Geophys. Res. V. 118. P. 3142–3159.

Lobkovsky L.I., Baranov B.V., Pristavakina E.I. and Kerchman V.I (1991) Analysis of seismotectonic processes in subduction zones from the standpoint of a keyboard model of great eartquakes. Tectonophysics. V. 199. I. 2–4. P. 211–236.

Lorito S., Romano F., Atzori S., Tong X., Avallone A., McCloskey J., Cocco M., Boschi E. and Piatanesi A. (2011) Limited overlap between the seismic gap and coseismic slip of the great 2010 Chile earthquake. Nature Geoscience. V. 4. N. 3. P. 173–177.

Melnick D. and Echtler H.P., (2006) Morphotectonic and Geologic Digital Map Compilations of the South-Central Andes (36° –42°S) in The Andes. Active Subduction Orogeny (Springer, Berlin, 2006), Chap. 30, pp. 565–568.

Moreno M, Rosenau M. and Oncken O. (2010) 2010 Maule earthquake slip correlates with pre-seismic locking of Andean subduction zone. Nature. V. 467. P. 198–204.

Moreno M., Melnick D., Rosenau M., Baez J., Klotz J., Oncken O., Tassara A., Chen J., Bataille K., Bevis M., Socquet A., Bolte J., Vigny C., Brooks B., Ryder I., Grund V., Smalley B., Carrizo D., Bartsch M. and Hase H. (2012) Toward understanding tectonic control on the Mw 8.8 2010 Maule Chile earthquake. EPSL. N. 321–322. P. 152–165.

Pollitz F.F. (1996) Coseismic deformation from earthquake faulting on a layered spherical Earth. Geophys. J. Int. V. 125. P. 1–14.

Pollitz F.F. (2006) VISCO1D. Version 3. Tutorial. Reston: USGS. – 36 p.

Vladimirova I.S. (2012) Modelling of postseismic processes in subduction regions. Geodynamics & Tectonophysics. V. 3. N. 2. P. 167–178.

Vladimirova I.S. and Steblov G.M. (2015) Postseismic development of source zones of the strongest earthquakes. Geofiz. Issled. V. 16(2), P. 27–38.

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