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Post-seismic deformation of the 1960 Chile earthquake or a silent-slip?

G. Khazaradze [1], J. Klotz [2], K. Wang [3,4], & Y. Hu [4]

1. Universitat de Barcelona, Faculty of Geology, 08028 Barcelona, Spain (gkhazar@ub.edu)
2. GeoForschungsZentrum Potsdam, Section 1.1: Geoprocesses and GPS-Technology, Potsdam, Germany
3. Pacific Geoscience Centre, Geological Survey of Canada, Sidney, British Columbia, Canada
4. School of Earth and Ocean Sciences, University of Victoria, British Columbia, Canada

Introduction

Large plate boundary earthquakes are known to induce time-dependent post-seismic crustal deformation. For timescales of months to a few years, the deformation is commonly attributed to the continuing aseismic slip of the co-seismically ruptured fault segment [e.g., Heki et al., 1997] and/or its downdip extension [e.g., Barrientos and Ward, 1990]. The afterslip model is simple to use: usually the Earth is represented as an elastic half-space; but the viscoelastic rheology of the earth cannot always be ignored. For example, postglacial rebound analysis by James et al. [2000] indicates that the mantle viscosity in a forearc/backarc environment can be of the order of 10^{19} Pa s. Regardless of the presence or absence of afterslip, a viscosity of this magnitude will give rise to mantle stress relaxation that may cause post-seismic deformation, particularly for time-scales of decades or longer.

In the proximity of the rupture zone and very shortly after the earthquake, it is usually difficult to distinguish between the contributions to post-seismic deformation from fault afterslip and mantle relaxation [Pollitz et al., 1998]. However, very large earthquakes, such as great subduction earthquakes of $M > 9$, may induce large stress in the mantle over a very broad region, and the relaxation of this stress may cause prolonged crustal deformation far away from the coseismic rupture zone. Not including the recent great Sumatra earthquake of 16/12/2005, there have been only two earthquakes of this type recorded in the past century, and in both cases, seaward crustal motion has been observed landward of the rupture region several decades after the occurrence of the events. Freymueller et al. [2000] reported similar motions for sites on the western Kenai Peninsula on Alaska, located 300 to 400 km from the trench. Freymueller et al. [2000] and Zweck et al. [2002] attributed these unusual velocities to the continued post-seismic response to the 1964 Mw9.2 Alaska earthquake and the absence of a shallow locked interface. Another example of trenchward oriented crustal motion was reported by Klotz et al. [2001] for the stations located landward of the 1960 Mw9.5 Chile earthquake rupture area. In the previous papers we have utilized the 3-D FEM models to explain these motions in terms of mantle stress relaxation, and estimate the mantle viscosity of the Chilean forearc/backarc.

GPS Observations

The GPS data used in this study have been obtained under the ongoing South American Geodynamic Activities (SAGA) project initiated in 1993 by the GeoForschungsZentrum (GFZ) Potsdam. Data from 29 stations between 35°S and 43°S latitudes were obtained during two GPS campaigns in 1994 and 1996. Detailed descriptions of data processing procedure for these stations and a table of GPS velocities can be found in Klotz et al. [2001].

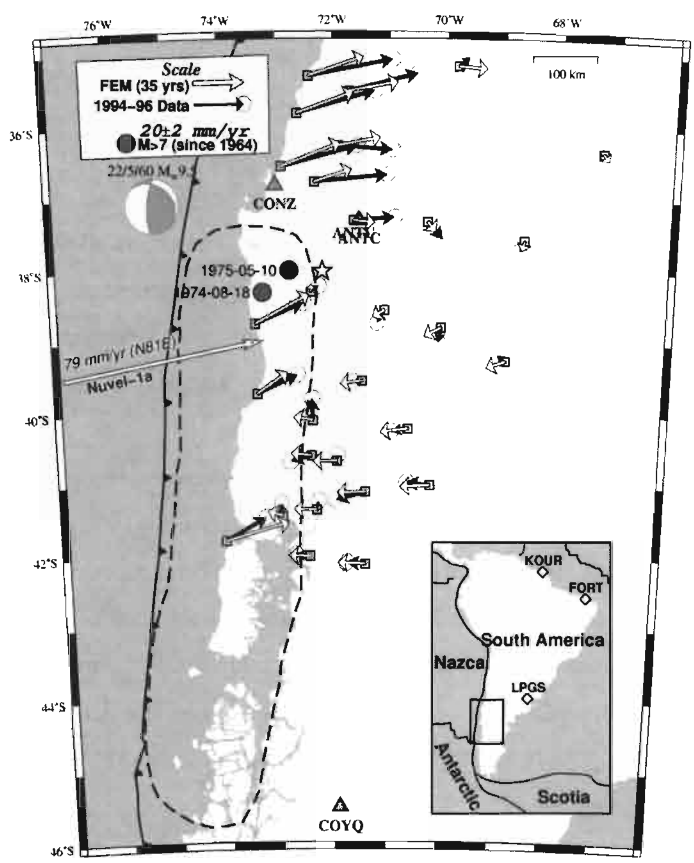

Figure 1. GPS velocities relative to the stable South America defined by the IGS stations shown as diamonds in the inset. Thick dashed line outlines the area of geodetically measured coseismic crustal uplift and subsidence associated with the 1960 Chile earthquake [Plafker, 1972]. The epicenter of the main event determined by Cifuentes [1989] is shown as a star. Filled circles show earthquakes with M>7 that occurred in the past 30 years in this region. Triangles depict existing continuous GPS stations.

In this study we also include data from the permanent GPS stations located in the vicinity of the rupture area of the 1960 Chile earthquake. The closest three continuous GPS stations shown as triangles in Figure 1 are operated by the University of Hawaii (ANTC, COYQ) [Brooks et al., 2003] and the Observatorio Geodesico TIGO of the University of Concepción (CONZ) [*http://www.tigo.cl*].

The velocity vectors presented in Figure 1 are characteristic of inter-seismic forearc deformation due to a locked subduction fault. The GPS sites are moving landward in the direction of plate convergence with their rates decreasing gradually away from the trench. However, the velocity field near the area affected by the 1960 Chile earthquake exhibits an unusual behavior. Inland sites 300-400 km from the trench are moving seaward in a coherent fashion, opposite to the type of motion expected for the inter-seismic phase of the earthquake deformation cycle (Figure 1). This motion can not be an artifact due to the choice of reference frame. GPS data from all sites along the margin were processed using the same procedure and referenced to the same nominal stable SA as explained above. The motion is not caused by recent large local earthquakes, as no events of M >7 have been registered in this area since 1975 (Figure 1). We are led to the hypothesis that this seaward motion represents post-seismic crustal deformation in response to the 1960 great earthquake by the following facts: 1) the area of the seaward motion spatially correlates with the region affected during the 1960 great earthquake 2) a contiguous set of GPS sites move in a coherent fashion, and 3) the sense of motion is exactly opposite of the direction of plate subduction, hence in the direction of the co-seismic slip during the 1960 earthquake.

3-D FEM Visco-Elastic Model

We have developed a 3-D linear Maxwell viscoelastic model to study the postseismic deformation following the 1960 Chile earthquake. The model consists of elastic converging plates and viscoelastic mantle. The earthquake is modeled using a forward slip over the rupture zone. The slip is allowed to decrease to zero over a downdip transition zone to account for the effects of afterslip or preslip downdip of the rupture zone. Because of this approximation, the model results cannot be directly compared with observations made near the coseismic rupture shortly after the earthquake. Fault locking is modeled by assigning a back slip rate to the locked zone, with back slip at the plate convergence rate representing full locking.

With a continental mantle viscosity of 2.5×10^{19} Pa s, model predicted surface velocities reproduce the first-order pattern of the GPS observations at the Chile margin 35 years after the 1960 earthquake, including landward motion of all coastal sites, smaller landward coastal velocities in the 1960 rupture region as compared to those to the north, and the seaward motion of inland GPS sites. The model shows that at a given time after the earthquake, two competing processes control the direction and magnitude of crustal velocities of the inland area. Relaxation of the earthquake induced stresses causes seaward velocities that decrease with time. On-going plate convergence with the subduction fault locked leads to landward velocities. Not too long after the earthquake, such as 35 years, velocities in the inland area are dominated by the earthquake effect and are in the seaward direction. At later stages, the effect of fault locking becomes predominant, the velocities decrease and eventually change to the landward direction. The model predicts that the seaward motion would disappear into the noise of the surface deformation data 70 years after the earthquake. Further details of the model are given in Khazaradze et al. [2002] and Hu et al. [2004].

Discussion and Conclusions

The 3-D FEM model described above enabled us to attribute the unusual seaward motion of the inland sites to a prolonged crustal deformation due to mantle stress relaxation following the 1960 great earthquake. However, due to the limited availability of the GPS data, we were not able to exclude an alternative possibility that the seaward motion is caused by a silent slip event on the plate interface at large depths. Dragert et al. [2001] and Rogers and Dragert [2003] reported a silent slip event on the plate interface of the Cascadia subduction zone downdip from its currently locked seismogenic portion. A cluster of continuously monitoring GPS stations about 100 to 250 km from the trench was observed to briefly reverse their direction of motion. Similar transient motions have been reported for a few other subduction zones [Lowry et al., 2001]. Our area of seaward motion is farther away from the trench (200 to 400 km) than that reported for Cascadia. If the motion was due to a silent slip on the plate interface, the slip had to take place in the 50 to 150 km depth range. It had to be quite a coincidence that a transient motion occurred at the time of our 1994 and 1996 campaign surveys and only in the region of the 1960 earthquake. Nevertheless, we cannot completely exclude the possibility of a silent slip. Our model predicts that the seaward motion of those inland sites should continue for the next few decades with decreasing rates. The present work attempts to incorporate additional GPS data in order to support or invalidate this hypothesis.

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