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# CRUSTAL DEFORMATION CAUSED BY THE 1960 EARTHQUAKES IN THE SOUTH OF CHILE

**Felipe Villalobos**[1]

## ABSTRACT

Large earthquakes can cause significant subsidence and uplifts of one or two meters. In the case of subsidence, coastal and fluvial retaining structures may therefore no longer be useful, for instance, against flooding caused by a tsunami. However, tectonic subsidence caused by large earthquakes is normally not considered in geotechnical designs. This paper describes and analyses the 1960 earthquakes that occurred in the south of Chile, along almost 1000 km between Concepción and the Taitao peninsula. Attention is paid to the 9.5 moment magnitude earthquake aftermath in the city of Valdivia, where a tsunami occurred followed by the overflow of the Riñihue Lake. Valdivia and its surrounding meadows were flooded due to a subsidence of approximately 2 m. The paper presents hypotheses which would explain why today the city is not flooded anymore. Answers can be found in the crustal deformation process occurring as a result of the subduction thrust. Various hypotheses show that the subduction mechanism in the south of Chile is different from that in the north. It is believed that there is also an elastic short-term effect which may explain an initial recovery and a viscoelastic long-term effect which may explain later recovery. Furthermore, measurements of crustal deformation suggest that a process of stress relaxation is still occurring almost 50 years after the main seismic event.

Keywords: tectonic subsidence, 1960 earthquakes, Valdivia, crustal deformation, stress relaxation

## INTRODUCTION

Tectonic subsidence or uplift is not considered in any design of onshore or near shore structures. For instance, tectonic subsidence can reduce drastically the protection role of sea wall structures against tsunami. Even if the sea wall resists strong shake motions and tsunami drag forces, it can be seriously limited due to a partial or complete inundation, say by a subsidence of 1 or 2 m.

In the case of the city of Valdivia, the inundation has not been attributed only to tectonic subsidence. Other reasons, such as soil compaction due to severe shaking during the 1960 earthquakes have been formulated. Furthermore, inundation by the overflow of impounded water was caused by earthquake-triggered landslides, which made difficult to separate the inundation caused by the tectonic subsidence itself. Then the question is why Valdivia nowadays is not flooded? This article presents explanations and answers to this question.

Despite the geological, geophysical and geotechnical studies carried out some years after the 1960 seismic events (Duke and Leeds, 1963; Weischet, 1963), there are only few available publications compared with the ones for the north area of Chile. Research has been focused mostly on the Arauco zone, rather than further south (Tichelaar and Ruff, 1991; Bhom *et al*., 2002; Krawczyk *et al*., 2003; Lüth *et al*., 2003). The article describes the 1960 earthquake, mainly in terms of land subsidence and uplift observed, then

[1] Lecturer, Dept. of Civil Engineering, Catholic University of Concepción, Chile, avillalobos@ucsc.cl

explains the subduction mechanisms and finally presents results of land displacements obtained from GPS techniques by Klotz *et al*. (2001).

## GENERAL DESCRIPTION

The earthquake of 22nd May 1960 remains the largest seismic event ever recorded by seismological instruments. The main earthquake of moment magnitude of 9.5 Richter generated 20 minutes later a devastating tsunami, which not only hit the Chilean coast, but also reached countries as far as Japan, Hawaii, Russia and New Zealand.

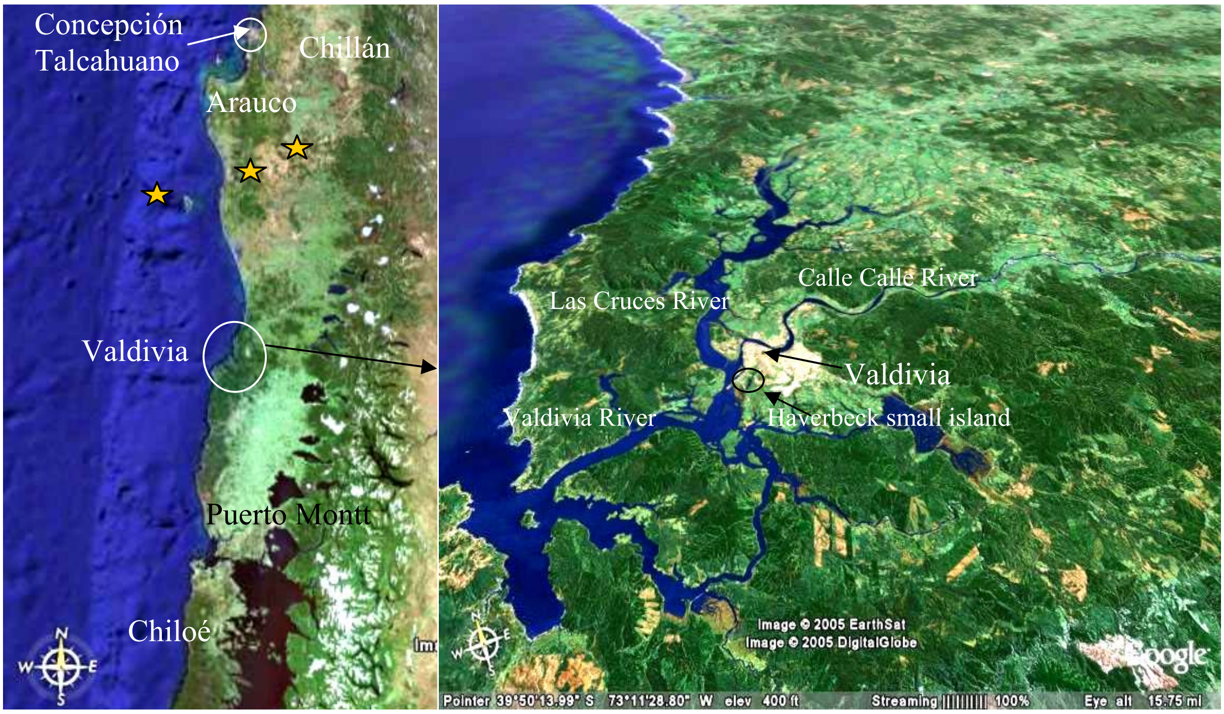
The interest for studying this seismic event after fifty years becomes even more relevant after the 8.8 moment magnitude Chilean earthquake of 27 February 2010. Understanding the 1960 earthquakes can ease answering questions arising from this new big event. The 1960 earthquakes shook the planet earth, changed some parts of the Chilean south geography. Islands disappeared and appeared, sea level changed, river' mouths shifted, large landslides in the Andes dammed rivers and volcanoes erupted. These processes, which normally take time and several factors to develop, occurred suddenly and developed in short time.

On early morning of May 21st at 4.03 (local time) an earthquake of 7.5 Richter magnitude was followed by a series of aftershocks in Concepción and Arauco. The four largest of these aftershocks occurred during the next day and had magnitudes of 6.5, 7.5, 7.8 and 7.5, respectively. Later, at 15.11 (local time) of May 22nd the strongest earthquake ever recorded struck the south of Chile. Initially, a magnitude Richter of 8.5 with the epicentre located at latitude 38ºS and longitude 73.5º was determined. Aftershocks were recorded to propagate from the hypocenter up to Chiloé. According to Kanamori (1977) the main shock was actually a sum of two event, which made up an earthquake of moment magnitude $M_w$ = 9.5. This type of magnitude started to be used for large earthquakes, since local magnitudes $M_L$, body magnitudes $M_b$ and surface wave magnitudes $M_s$, reach a limit. This limit is referred to as saturation, where $M_L$ and $M_b$ saturate around 6 and 7 and $M_s$ around 8. The moment magnitude scale does not saturate because is a function of parameters involved along the fault rupture, *i.e.*, material rupture strength along the fault, rupture area and amount of slip.

Unfortunately, no acceleration records are available; however, Weischet (1963) mentioned estimations about 0.25g and 0.3g according to a Mercalli intensity of X. These values are obviously not accurate and hence arguable.

### Area affected

The further north city seriously affected was Chillán with around 20% of buildings severely damaged. Figure 1 shows the area affected and main cities and a close up to Valdivia. A description of structural damage in Talcahuano, Concepción and Puerto Montt, with special attention in Valdivia can be found in Steinbrugge and Flores (1963). A geotechnical description of failures can be found in Duke and Leeds (1963). Although the damages propagated from Concepción to Chiloé in the bottom south, the city most drastically affected was Valdivia and for that reason this earthquake is called the Valdivia Earthquake. Figures 2a and 2b show almost the same place of the Valdivia promenade before and after the earthquake. The river floods the promenade, which is equivalent of at least 2 m of subsidence. Figures 3a and 3b show pictures taken by Karl Steinbrugge on 19th June 1960 further upstream, where it is clear to observe the promenade sinking of around 2 m due to subsidence.




(a) South of Chile (b) Valdivia and surroundings

Figure 1: (a) View of the whole area affected (stars represent possible epicentre locations) and (b) view of Valdivia city and surroundings


Figure 2: (a) Valdivia promenade before the earthquakes and (b) after the earthquakes (Steinbrugge and Flores, 1963)


Figure 3: Road along the promenade showing concrete pavement distorted, broken and tilted towards the river (a) under Pedro de Valdivia Bridge and (b) passing the bridge upstream (Steinbrugge and Flores, 1963)

**Geological and geomorphological changes**

Weischet (1963) presented a geologic and geomorphologic study of the region, where he compared similar features before and after the earthquake because he had collected data just before the earthquake. Evidences of changes in the land level as well as tsunami effects were observed. Weischet (1963) pointed out that from his observations the most significant damage did not occurred close to the epicentre in Arauco, but 200 km south, in the area of Valdivia. This area is located in a tectonically depressed basin with unfavourable geological and geotechnical conditions, from the civil engineering point of view. A similar case occurred in the Mexico earthquake of September 1985, when the epicentre was located 350 km away from Mexico City, the most seriously damaged region.

Valdivia lies on a low area without the rock basement of the coastal mountains along Chile, but instead on deep alluvial sedimentary deposits of around 40 m thick, which overlay gravel deposits before reaching the bedrock. In Valdivia there is also a stiffer soil material called *cancagua*. This material was responsible for diminishing the damage of structures founded on it.

During the first hours after the main earthquake, wetlands and low lands along streams between Imperial River and the south of Chiloé were flooded. Figure 4 shows the Haverbeck small island almost disappeared under water, only top of houses and trees are possible to distinguish. Weischet (1963) observed around 17:00 (local time) the Calle Calle River not only flowing upstream but also at a higher rate than when it flows downstream (see Figure 5b). Some days later, 30 km upstream of the river mouth marine fish and salty water were found. It took a couple of months to have freshwater again. The flood covered 15000 hectares of sowing land only around Valdivia (Figure 5a).

On one hand, land subsidence can be in part attributed to the compaction of sediments of approximately 40 m thickness in Valdivia. On the other hand, it can be attributed to movements of the earth crust or actually to a combination of both. It has been difficult to evaluate separately both processes due to the lack of fixed reference points and scarce geological and geotechnical information. However, Weischet (1963) was one of the first in pointing out the earth crust deformation as the main cause of subsidence.

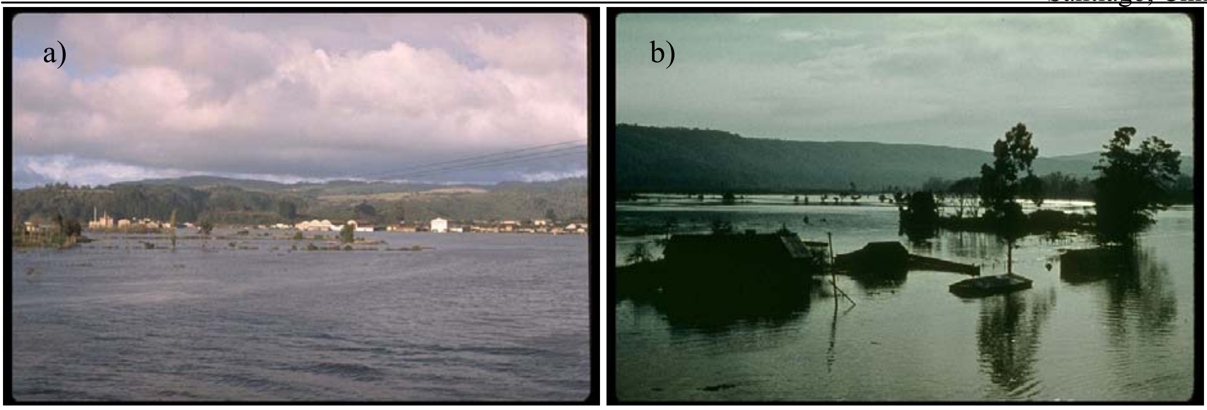



Figure 4: (a) View from the Valdivia River towards Miraflores showing the Haverbeck Islet under water and (b) closer view of Haverbeck Islet from Miraflores (Steinbrugge and Flores, 1963)

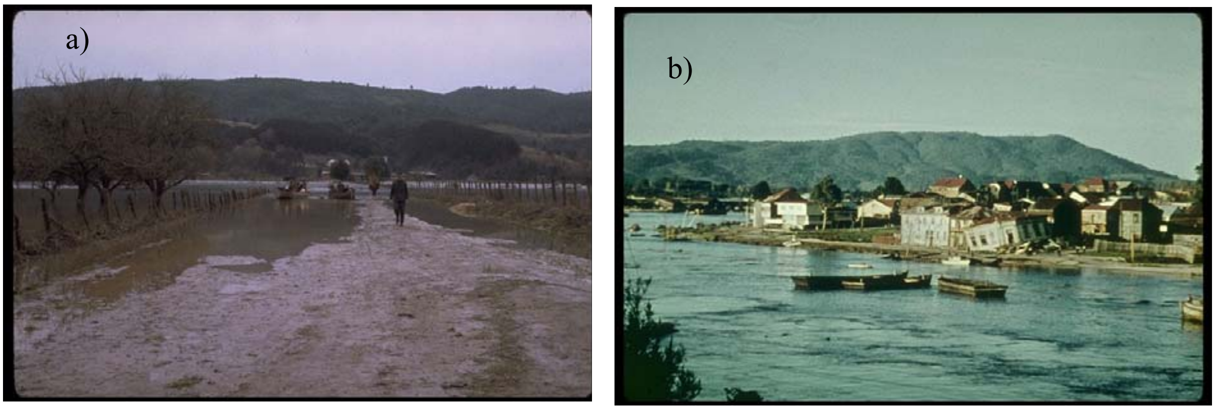



Figure 5: (a) Inundation of the country side around Valdivia and (b) drifted boats flowing upstream after passing the Pedro de Valdivia Bridge half an hour after the main earthquake (Steinbrugge and Flores, 1963)

The dynamic compression of soft and loose sediment deposits represents a local effect and counts only for a few centimetres. In contrast, subsidence of the land between 1 and 1.5 m occurred along an area of 600 km long by 30 km wide with an inclination towards the sea. Evidence of subsidence was found on the coast and inland along rivers such as Maullín, Bueno, Calle Calle and Cruces. It is important to mention that whilst subsidence occurred in the above areas, no subsidence effects were found for example in Puerto Montt. Moreover, in the Arauco Peninsula, the land suffered 1.2 m uplift and in the south of Chiloé, the Guafo Island uplifted between 1 and 3 m. The small island Guafito was joined to the Guafo Island by means of a new beach, which did not disappear even with high tide. The bathymetry in the port of Corral and Valdivia River and in other navigable paths changed significantly. Sand banks which were between 1 and 2 m high were afterwards below water level. This, added to the erosion of the stream bottom due to stronger currents, allowed vessels to enter with less trouble into Valdivia because of an increment of vessel keel.

Related to the tsunami, five waves were reported (Weischet, 1963). The first wave reached the shore at 15:30 (Chilean time), the first destructive wave arrived at 16:20 and the last wave came at 21:30. The wave height varies with the shape of the coast, bathymetry and distance from the source. Determinations of absolute height of tsunami waves have given values of 11.5 m south of Puerto Saavedra Bay, 8 m in Mahuín and Corral, 7.5 m in Bahía Mansa and 5 m in Ancud.

In addition to the earthquake and tsunami direct damages, in the Andes mountains landslides were detected. Large landslides blocked the beginning of the San Pedro River just at the exit of the Riñihue Lake. This lake is the end of a series of seven lakes interconnected, draining into the San Pedro River which flows to the sea passing by different towns before reaching Valdivia. A similar phenomenon had occurred for the earthquake of 16 December 1575, when the exit of the Riñihue Lake was blocked too. But in April 1576 the dam formed breached, flooding disastrously a large area downstream (Davis and Karzulovic, 1963). Fortunately, this situation did not occur again since a work force removed slowly the 24 m height plug to allow the flow of millions of cubic meters without breaching. The lake water level started to reduce after 23 days of hard work.

**Questions**

From the facts described and evidences given by researchers who witnessed and studied the phenomena of subsidence and uplift caused by the 1960 earthquake, it is possible to raise some questions. A question is about the causes of flooding in Valdivia. Tsunami waves, heavy rain and controlled overflow of the Riñihue Lake occurred after the entrance of seawater in Valdivia around half an hour after the main quake, as can be seen in Figures 4a and 5b. Therefore, the causes of this flooding can be attributed to dynamic compaction of thick layers of sedimentary deposits and tectonic subsidence as pointed out by Weischet (1963). But even accepting these explanations remains the question about why Valdivia is today after 50 years not flooded. Figure 6 shows a sequence of pictures of Valdivia before the 1960 earthquake, immediately after the quake and today.


Figure 6: View of Valdivia from the Teja Island (a) before the 1960 earthquake, (b) immediately after (Steinbrugge and Flores, 1963) and (c) nowadays

## SUBDUCTION AND FAILURE MECHANISMS

The subduction mechanism is not the same along the Chilean trench. The decreasing altitude towards the south of the coastal and Andes Mountains is an intuitive form of perceiving this. Gutscher (2002) has proposed a hypothesis about the subduction mechanism, establishing for the north of Chile a flat slab subduction and for the south a steep slab subduction. Figure 7a shows the Wadati Benioff zone, where a steep slab is associated to the south of Chile and a flat slab or plateau is associated to the north of Chile according to Gutscher (2002).

Geological evidences related to fault displacements such as orientation and sense of slip, have not been found (Álvarez, 1963). Additionally, the seismological information was limited and not complete enough to determine accurately the focal region (Plafker and Savage, 1970). When the first seismic waves from the main quake arrived, waves from the previous earthquakes were still propagating. This wave overlapping has affected the interpretation of seismographic data making difficult the fault plane determination (Cifuentes, 1989). For the same reason it has been complicated to localised the hypocentre of the main earthquake. Figure 1a shows three stars representing three locations of the epicentre. The star on the left hand side is located 60 km west from the Mocha Island (38.3ºS, 74.3ºW), representing the epicentre according to information provided by the US Coast and Geodetic Survey. The star in the middle is the epicentre determined by Cifuentes (1989) using the master-event technique where the earthquake sequence is relocated (38.05ºS, 72.34ºW and 38.16ºS, 72.20ºW for the two shocks assumed). The third star corresponds to the epicentre proposed by Krawczyk *et al.* (2003) at 38ºS and 73.08ºW, who, for the first time, presented the slab geometry of this area based on near-vertical seismic reflection tests.

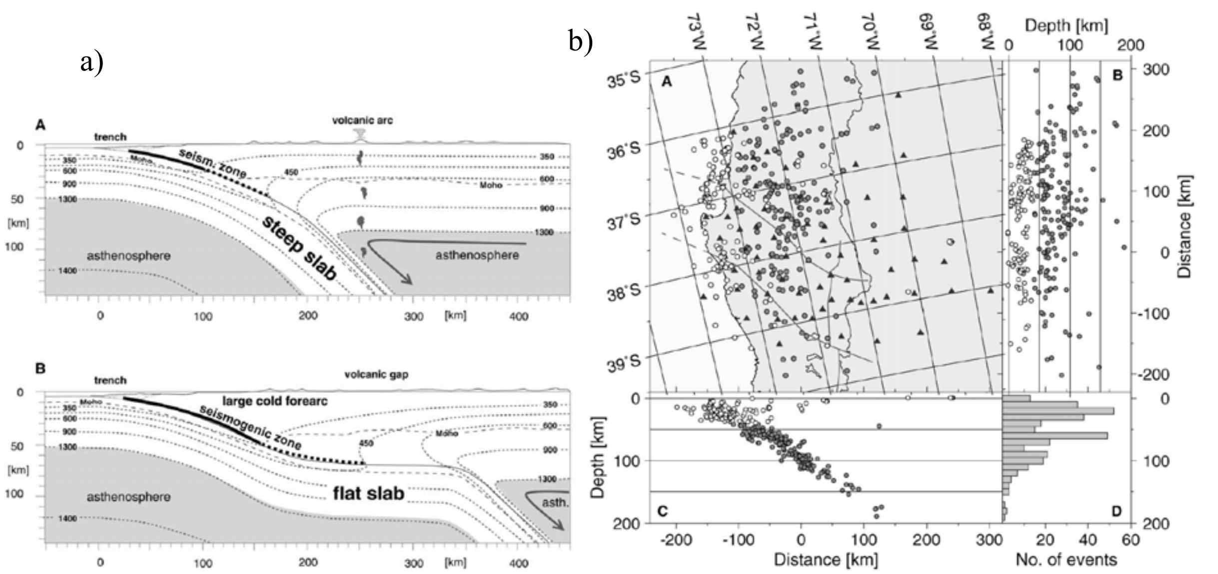



Figure 7: a) Wadati Benioff zone showing type of subduction A: steep slab in the south of the Andes and type of subduction B: flat slab in the north of the Andes (Gutscher, 2002) and b) results from a seismic recording campaign, white circles are events up to 40 km deep and black triangles are the recording stations. A: epicentres, B: hypocentres projected in the longitudinal direction, C: hypocentres showing the Benioff zone and D: depth frequency distribution of the seismic events (taken from Bohm *et al.*, 2002)

Figure 7b shows the Benioff zone delineated from a seismic recording work carried out in the Bío Bío and Araucanía Regions by Bohm *et al.* (2002). Despite the dispersion, it is possible to define an initial inclination of around 15º for the first 40 km followed by an inclination of around 36º for depths up to 180 km. However, the subduction zone around Valdivia and further south are not yet sufficiently studied. One option is to assume the same subduction configuration shown in Figure 7b for the Valdivia area. From this and knowing the aftershocks depths Cifuentes (1989) estimated the width of the rupture zone in 140 km.

The rupture length of the main earthquake has been difficult to determine due to the lack of recordings further south of Chiloé. Benioff *et al.* (1961) estimated a fault length between 960 and 1200 km from instrumental data. Cifuentes (1989) determined 930 km from the distribution of the aftershocks during the first month. The furthest south vertical displacement measured was at 45.21ºS (Aisén) by Plafker and Savage (1970), however, uplift in the Taitao peninsula has been reported (~47ºS).

The co-seismic slip on the rupture zone have been estimated in average between 20 and 40 m. Plafker and Savage (1970) and Plafker (1972) suggested an average fault slip of 20 m. Kanamori and Cipar (1974) determined an average dislocation of 24 m from seismographic long-period analysis. Further studies using surface deformation data in more than 300 points have indicated several slip peaks of 40 m (Barrientos and Ward, 1990). However, according to a convergence rate of 7.5 cm/year and a recurrence period of 130 years a slip of no more than 10 m should be expected.

## RECENT DEFORMATION OF THE EARTH CRUST

The technology of Global Positioning System GPS has dramatically changed the way to study the earth kinematics and dynamics. Since the middle of the 90s and increasingly during the beginning of the 21$^{st}$ century research groups have been using space geodetic techniques to analyse the deformation of the Central Andes. These studies have focused mainly on Perú, Bolivia and the north of Chile (Norabuena *et al.*, 1998; Bevis *et al.*, 1999). This satellite technology has allowed the measurement of accurate velocity fields of the earth crust. However, as Bevis *et al.* (1999) have pointed out, using 12 geodetic stations around Arica (22ºS), there are some difficulties in interpreting the data. Klotz *et al.* (2001) presented a velocity field around Antofagasta (22ºS and 26ºS), which allowed the analysis after the 1995 Antofagasta earthquake.

The work of Klotz *et al.* (2001) included also the centre and part of the south of Chile, which allows the analysis of the area affected by the 1960 earthquakes. Figure 8a shows a velocity field, by means of velocity vectors, between the latitudes 22ºS and 42ºS. In the central area between Taltal and Concepción (26ºS and 37ºS), the velocity vectors magnitude on the coast are relatively larger than the others (~35 mm/year). These vectors tend to follow the direction of convergence of the Nazca and South American plates. Looking at the top north and bottom south there are only some vectors closer to the trench which follow the convergence direction, the others seems to follow random directions.

These two observations might be explained by the hypothesis of a sequence of stages as part of a deformation cycle generated by large earthquakes (Thatcher, 1986; Bourgeois, 2006). Bourgeois (2006) suggests the existence of four stages related to subsidence and uplifts, which may explain deformations on the land close to the shore. First a co-seismic subsidence occurs due to a massive earthquake, then a relatively fast and significant post-seismic uplift recovers the land elevation followed by an inter-seismic slower and less pronounced uplift. The fourth stage corresponds to a pre-seismic subsidence, which does not have a proof yet (measurements of the 27 February 2010 earthquake gives the opportunity to validate or discard this hypothesis). This sequence should change inversely for the case of initial uplift followed by subsidence for the 1960 earthquake.

The random orientation of the measured velocity vectors in the north and south of Chile shown in Figure 8a is a consequence of the previous large earthquakes in 1995 and 1960 respectively. Figure 8b shows a more regular orientation when elastic inter-seismic velocities are eliminated.

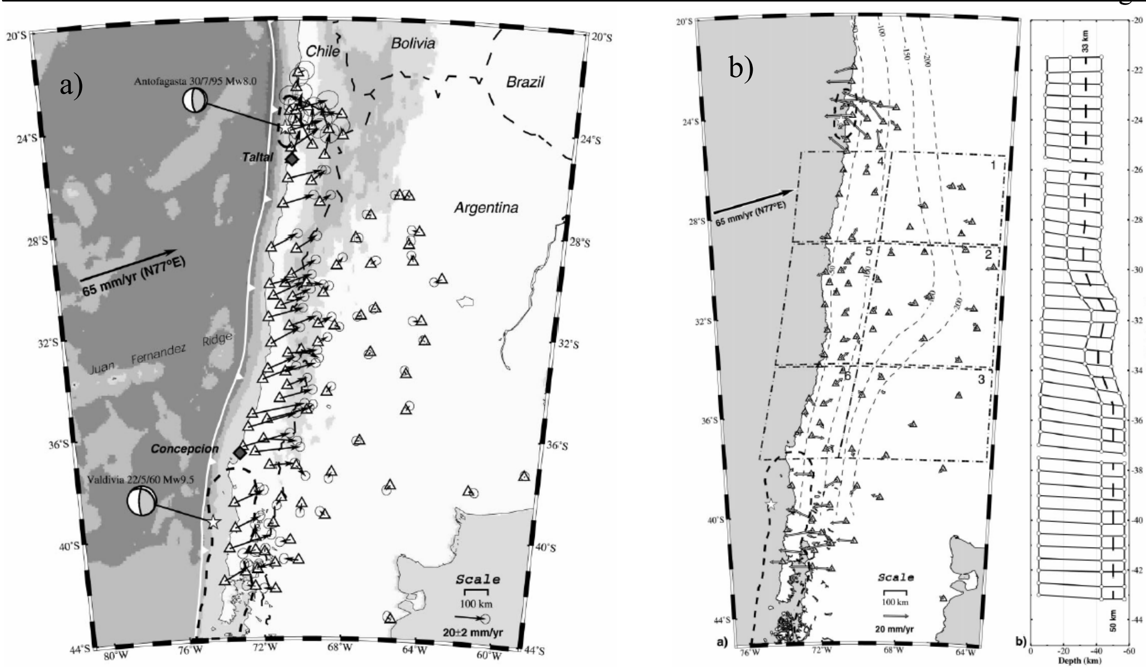



Figure 8: a) Velocity map obtained from of the GPS network SAGA in 1994 and 1996 campaigns. Two stars represent epicentres of the 1960 and 1995 earthquakes and dashed lines their rupture areas and b) resultant velocity fields obtained from removing the elastic part of the measured velocity vectors shown in a). Contour lines depict the Nazca plate depth in km and 6 areas delineated by straight lines, in between the two rupture zones in Antofagasta and south of Arauco, represent an inactive zone. Cross section of the seismogenic zone showing with a bold dash line an estimated average coupling depth (taken from Klotz *et al.*, 2001)

Klotz *et al.* (2001) estimated a resultant velocity field showed in Figure 8b, which is determined by removing the elastic part of the displacement rates obtained instrumentally. For details of elastic dislocation models see Klotz *et al.* (2001) and Hu *et al.* (2004). It can be observed in Figure 8b that the majority of the resultant velocity vectors on the two rupture zones are oriented towards the trench, *i.e.* in opposite direction of the Nazca plate convergence. These post-seismic movements are obviously associated to the previous seismic events, clearly for the more recent 1995 Antofagasta earthquake of $M_w$ = 8.0 and incredibly for the 1960 Valdivia earthquake of $M_w$ = 9.5. Since the measurement campaign was carried out in 1994 and 1996, it would be extremely valuable to verify the current state of movement in the south area.

A possible explanation for these post-seismic displacements can be found in assuming further movement of the overriding plate due to slips along the rupture surface. Another hypothesis is attributed to processes of viscoelastic relaxation taking place in the lower crust and upper mantle. Klotz *et al.* (2001) associate the first hypothesis to a short-term effect, whereas the second is associated to a long-term effect. Separation of both effects from the total deformation rate in terms of percentage of influence is still a matter of study. It can be concluded that the deformation rate in the north of Chile should represent the effect of slips occurring one year after the main shock, whereas the deformation rate in the south of Chile should be attributed to mostly viscoelastic relaxation effects. It is worth realising that several years after the 1960 earthquake the earth crust deforms almost comparatively with the recent 1995 earthquake. However, accurate displacements measured by GPS techniques allow only analyses of horizontal movements. Vertical displacements to account for subsidence and uplift are not yet accurate enough. Measurement of vertical movements is still taken with respect to the sea for example, which also varies.

Other observation from Figure 8b is that the velocity vectors in the middle have a considerably reduced magnitude and they seem not to have a preferred direction. This apparent inactivity is actually indicating strain accumulation. This observation results in the 27 February 2010 earthquake. Therefore, GPS technology can assist in identifying potential areas where a major seismic event might occur.

## FINAL REMARKS

The earthquakes of 1960 has been described and analysed focusing on subsidence and uplift phenomena. The main shock on 22nd May affected strongly the city and surroundings of Valdivia. Flooding of the area as evidence of subsidence has been presented, originating the question of why Valdivia is nowadays not flooded any more. Explanation of different subduction mechanisms along the Chilean trench gives insight to answer this question.

Recently GPS techniques have allowed accurate measurements of horizontal displacement of the earth surface. Results from the work carried out by Klotz *et al.* (2001) showed that the area affected by the 1960 earthquake is moving towards the trench at rates as high as 20 mm/year. Valdivia is not flooded nowadays because the land has recovered from the subsidence. This can be explained by the relaxation of stresses, *i.e.* the earth crust deforms in order to return to its previous level. The hypothesis of subsidence and uplift sequences should be verified using this advanced measurement technique. To this end GPS techniques should allow accurate measurement of vertical displacements. Nowadays measurements of subsidence and uplift are made manually by comparing the level of body waters such as lakes and the sea. This has the inconvenient of a reference that moves within certain ranges. Another important aspect of GPS measurements is that areas with low resultant velocity fields are likely to undergo an earthquake. However, it is not possible yet to estimate exactly when it will occur.

## REFERENCES

Álvarez, L. (1963). Studies made between Arauco and Valdivia with respect to the earthquake of 21 and 22 May 1960. *Bulletin of the Seismological Society of America* **53**(6), 1315–1330

Barrientos, S.E. and Ward, S.N. (1990). The 1960 Chile earthquake: inversion for slip distribution from surface deformation. *Geophysical Journal International* **103**, 589-598

Benioff, H., Press, F. and Smith, S. (1961). Excitation of the free oscillations of the earth by Earthquakes. *Journal of Geophysical Research* **66**, 605-619

Bevis, M., Kendrick, E.C., Smalley, R., Herring, T., Godoy, J. and Galban, F. (1999). Crustal motion north and south of the Arica deflection; comparing recent geodetic results from the Central Andes. Geochemistry Geophysics Geosystems 1, 1-12

Bohm, M., Lüth, S., Echtler, H., Asch, G., Bataille, K., Bruhn, C., Rietbrock, A. and Wigger, P. (2002). The Southern Andes between 36º and 40ºS latitude: seismicity and average seismic velocities. *Tectonophysics* **356,** 275–289

Bourgeois, J. (2006). A movement in four parts? *Nature* **440** (23), March, 430-431

Cifuentes, I.L. (1989). The 1960 Chilean Earthquakes. *Journal of Geophysical Research* **94**, 665–680

Davis, S.D. and Karzulovic, K. (1963). Landslides at Lago Riñihue, Chile. *Bulletin of the Seismological Society of America* **53**(6), 1403-1414

Duke, M. and Leeds, D. (1963). Response of soils, foundations and earth structures to the Chilean earthquakes of 1960. *Bulletin of the Seismological Society of America* **53**(2), 309-357

Gutscher, M.A. (2002). Andean subduction styles and their effect on thermal structure and interplate coupling. *Journal of South American Earth Sciences* 15, 3-10

Hu, Y., Wang, K., He, J., Klotz, J. and Khazaradze, G. (2004), Three-dimensional viscoelastic finite element model for postseismic deformation of the great 1960 Chile earthquake. *Journal of Geophysical Research* **109**, B12403

Kanamori, H. (1977). The energy released in great earthquakes. *Journal of Geophysics Research* **82**(20), 2981-2987

Kanamori, H. and Cipar, J.J. (1974). Focal process of the great Chilean earthquake May 22, 1960. *Physics of the Earth and Planetary Interiors* **9**, 128-136

Klotz, J., Khazaradze, G., Angermann, D., Reigber, C., Perdomo, R. and Cifuentes, O. (2001). Earthquake cycle dominates contemporary crustal deformation in Central and Southern Andes. *Earth and Planetary Science Letters* **193**, 437-446

Krawczyk, C. and the SPOC team (2003). Amphibious seismic survey images plate interface at 1960 Chile earthquake, *EOS, Trans.,* **84**(32), 301–312

Lüth, S.,Wigger, P. and the ISSA Research Group (2003).A crustal model along 39°S from a seismic refraction profile- ISSA 2000, *Rev. geol. Chile,* **30**(1), 83–101

Norabuena, E., Leffler-Griffin, L., Mao, A., Dixon, T., Stein, S., Sacks, I.S., Ocola, L. and Ellis, M. (1998). Space geodetic observations of Nazca-South America convergence across the central Andes. *Science* **279**(22), 358-362

Plafker, G. (1972). Alaskan earthquake of 1964 and Chilean earthquake of 1960: implications for arc tectonics. *Journal of Geophysical Research* **77**(20), 901-925

Plafker, G. and Savage, J.C. (1970). Mechanism of the Chilean earthquakes of May 21 and 22, 1960. *Geol. Soc. Am. Bull*. **81**, 1001–1030

Steinbrugge, K.V. and Flores, R. (1963). The Chilean earthquake of May, 1960: a structural engineering viewpoint. *Bulletin of the Seismological Society of America* **53**(2), 225-307

Thatcher, W. (1986). Cyclic deformation related to great earthquakes at plate boundaries. *Bulletin of the Royal Society of New Zealand* **24**, 245-272

Tichelaar, B.W. and Ruff, L.J. (1993). Depth of seismic coupling along subduction. *Journal of Geophysical Research* **98**, 2017-2037

Weischet, W. (1963). Further observations of geologic and geomorphic changes resulting from the catastrophic earthquake of May 1960, in Chile. *Bulletin of the Seismological Society of America* **53**(6), 1237-1257