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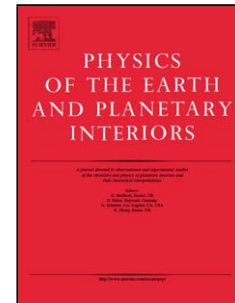
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# Interseismic strain accumulation measured by GPS in the seismic gap between Constitución and Concepción in Chile

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## Abstract

The Concepción-Constitución area [35-37°S] in South Central Chile is very likely a mature seismic gap, since no large subduction earthquake has occurred there since 1835. Three campaigns of Global Positioning System (GPS) measurements were carried out in this area in 1996, 1999 and 2002. We observed a network of about 40 sites, including two East-West transects ranging from the coastal area to the Argentina border and one North-South profile along the coast. Our measurements are consistent with the Nazca/South America relative angular velocity (55.9°N, 95.2°W, 0.610 °/Ma) discussed by Vigny et al., 2008 (this issue) which predicts a convergence of 68 mm/yr oriented 79°N at the Chilean trench near 36°S. With respect to stable South America, horizontal velocities decrease from 45 mm/yr on the coast to 10 mm/yr in the Cordillera. Vertical velocities exhibit a coherent pattern with negative values of about 10 mm/yr on the coast and slightly positive or near zero in the Central Valley or the Cordillera. Horizontal velocities have formal uncertainties in the range of 1-3 mm/yr and vertical velocities around 3 to 6 mm/yr. Surface deformation in this area of South Central Chile is consistent with a fully coupled elastic loading on the subduction interface at depth. The best fit to our data is obtained with a dip of 16° +/- 3°, a locking depth of 55 +/- 5 km and a dislocation corresponding to 67 mm/yr oriented N78°. However in the Northern area of our network the fit is improved locally by using a lower dip around 13°. Finally a convergence motion of about 68 mm/yr represents more than 10 m of displacement accumulated since the last big interplate subduction event in this area over 170 years ago (1835 earthquake described by Darwin). Therefore, in a worst case scenario, the area already has a potential for an earthquake of magnitude as large as 8 to 8.5, should it happen in the near future.

34

35 **Introduction**

36 The coastal ranges of Chile are among the most seismically active zones in the world. On  
 37 average, one major earthquake of magnitude 8 has occurred every 10 years in historical times,  
 38 and most of the individual segments of the coastal ranges have been the site of at least one  
 39 magnitude 8 during the last 130 years [Lomnitz, 1971, Kelleher, 1972, Nishenko, 1985]. One  
 40 exception is the South-Central Chile region, between 35°S and 37°S, which experienced its  
 41 last large subduction earthquake on 20 February 1835 [Darwin, 1851] with an estimated  
 42 magnitude close to 8.5 [Lomnitz, 1971, Beck *et al.*, 1998] (Figure 1). This area lies  
 43 immediately to the north of the rupture zone associated with the great 1960 earthquake, of  
 44 magnitude 9.5 [Plafker and Savage, 1970, Cifuentes, 1989] and south of the rupture zones  
 45 corresponding to the 1928 Talca earthquake [Beck *et al.*, 1998] and the 1906 and 1985  
 46 Valparaíso earthquakes [Barrientos, 1995]. Part of the region was affected by the 1939  
 47 Chillán earthquake (magnitude 7.9). Recent studies have demonstrated that this event was not  
 48 a typical subduction earthquake, but was a slab-pull event due to the release of tensional  
 49 stresses within the downgoing slab [Campos and Kausel, 1990, Beck *et al.*, 1998]. Further  
 50 North, the Talca earthquake of December 1, 1928, was interpreted as a shallow dipping thrust  
 51 event, [Lomnitz, 1971, Beck *et al.*, 1998]. Despite the uncertainties that remain on the  
 52 importance of the 1928 and 1939 earthquakes and their impact on the seismic cycle, the  
 53 region from 35°S -37°S is a likely spot for a major subduction earthquake in the coming  
 54 decades. In any case, it is the longest standing gap in Chile, the better known Northern Chile  
 55 gap was affected by large earthquakes in 1868 and 1877 [Lomnitz, 1971, Kelleher, 1972].  
 56 The area located immediately south of the city of Concepción between 37°S and 38°S is  
 57 particularly interesting. The Arauco peninsula is an elevated terrace with respect to the mean  
 58 coastal line. It shows evidences of both quaternary and contemporary uplift. Darwin [1851]  
 59 reported 3 m of uplift at Santa Maria Island due to the 1835 earthquake. On the other hand,  
 60 this area constitutes the limit between the rupture zones of the 1835 and 1960 earthquakes. As  
 61 such, it might play an important role in the segmentation of the subducting slab. This tectonic  
 62 situation is similar to that of the Mejillones Peninsula which seems to have acted as a limit to  
 63 southward propagation for the 1877 large earthquake in Northern Chile, and to northward  
 64 propagation during the 1995 Antofagasta earthquake [Armijo and Thiele, 1990; Ruegg *et al.*,  
 65 1996].

66 The seismicity of the region remained largely unknown and imprecise because of the lack of a  
 67 dense seismic network until a seismic field experiment that was carried out in 1996. The  
 68 results of this experiment reveal the distribution of the current seismicity, focal mechanism  
 69 solutions, and geometry of the subduction [*Campos et al.*, 2002].

70 What is the potential for a future earthquake? How is the current plate motion accommodated  
 71 by crustal strain in this area? In order to study the current deformation in this region, a GPS  
 72 network was installed in 1996, densified in 1999 with nine new points between the Andes  
 73 mountains and the Arauco peninsula, and finally resurveyed entirely in 2002. A first  
 74 estimation of the interseismic velocities in this area was done using the first two campaigns of  
 75 1996 and 1999 [*Ruegg et al.*, 2002]. We report here on the GPS measurements carried out in  
 76 1996, 1999 and 2002, and the interseismic velocities at 36 points sampling the upper plate  
 77 deformation.

78

## 79 **GPS measurements and data analysis**

80 The GPS experiments began in 1996 with the installation of geodetic monuments at thirty  
 81 three sites distributed in 3 profiles and five other scattered points covering the so-called South  
 82 Central Chile seismic gap between Concepción to the South and Constitución to the North.  
 83 The Northern transect, oriented 110°N, includes 8 sites between the Pacific coast and the  
 84 Chile-Argentina border (CO1, CT2, CT3, CT4 COLB, CT6, CT7, CT8) (Figure 1). A coastal  
 85 profile includes 11 sites between PTU north of the city of Constitución city and Concepción  
 86 in the South. A southern profile, roughly oriented W-E was initiated between the Arauco  
 87 peninsula, south of Concepción (2 sites, RMN, LTA and 4 sites between the foothills of the  
 88 Andes and the Chile-Argentina border MRC, MIR, CLP, LLA). Five additional points were  
 89 located in the Central Valley area (BAT, PUN, QLA, NIN, CHL). During the first  
 90 measurement campaign in December 1996 we used 9 Ashtech Z12 with geodetic L1/L2 P  
 91 antennas (ASHP12) and 3 Trimble SSE receivers with geodetic L1/L2 SSE antennas.

92 Eight new sites were installed during the March 1999 measurement campaign in the southern  
 93 part of the 1996 network in order to complete the southern profile between the Arauco  
 94 peninsula and the foothills of the Andes (LLI, RAQ, CAP, PUL, LAJ, SLT, SGE) (Figure 1). We  
 95 used 7 Ashtech Z12 equipped with choke-ring antennas. At the same time, 13 points of the  
 96 1996 network were measured again, providing a first estimation of the interseismic velocity  
 97 field (*Ruegg et al.*, 2002). Most of the sites were equipped with brass benchmarks sealed in

98 bedrock outcrops, but the measurements were done using tripods and optical tribrachs which  
 99 enable centering with only sub-centimeter accuracy. However, most of the sites were  
 100 equipped with 3 auxiliary points allowing a better permanency.

101 Finally almost the entire network was resurveyed in March 2002 using Ashtech Z12  
 102 equipped with choke-ring antennas. During all campaigns each site were measured for 12 to  
 103 24 hours per day over 2 to 4 days, while three points (QLA, PUN, CO6) were measured  
 104 continuously in 24-hour sessions during one week.

105 The current solution gives velocities at 36 sites determined over the 6 years period. We  
 106 analyse the GPS data in 24-hour sessions to give daily estimates of station position using the  
 107 GAMIT software [King and Bock, 2000], choosing the ionosphere-free combination, and  
 108 fixing the ambiguities to integer values. We use precise orbits from the International GPS  
 109 Service for Geodynamics (IGS) [Beutler *et al.*, 1993]. We also use IGS Tables to describe the  
 110 phase centers of the antennae. We estimate one tropospheric vertical delay parameter per  
 111 station every 3 hours. The horizontal components of the calculated relative position vectors  
 112 (Table 1) are accurate to within a few millimetres for pairs of stations less than 300 km apart,  
 113 as measured by the root mean square (RMS) scatter about the mean (the so-called baseline  
 114 repeatability). Daily solutions were recalculated for the three epochs including tracking data  
 115 from a selection of permanent stations (11 for the 2002 experiment) in South America, some  
 116 of them belonging to the International GPS Service (IGS) [Neilan, 1995]. Two stations are  
 117 close to the deformation area, 7 more span the South-American craton in Brazil, Guyana and  
 118 Argentina, and the remaining 2 sample the Nazca plate.

119 In the second step, we combine the daily solutions using the GLOBK Kalman filter software  
 120 [Herring *et al.*, 1990] in a “regional stabilization” approach. We combine daily solutions  
 121 using Helmert-like transformations to estimate translation, rotation, scale and Earth  
 122 orientation parameters (polar motion and UT1 rotation). This “stabilization” procedure  
 123 defines a reference frame by minimizing, in the least-square sense, the departure from the  
 124 prior values determined in the International Terrestrial Reference Frame (ITRF) 2000  
 125 [Altamimi *et al.*, 2002]. This procedure, described in more details in Vigny *et al.*, 2008 (this  
 126 issue), estimates the positions and velocities for a set of 9 well-determined fiducial stations in  
 127 and around our study area (AREQ, BRAZ, EISL, GALA, KOUR, LPGS, OHIG, RIOG,  
 128 SANT) . The misfit to these “stabilization” stations is 2.8 mm in position and 1.6 mm/yr in  
 129 velocity.

130 It is long recognized that without adding a proper noise model to GPS data processing we  
 131 obtain unrealistic very low uncertainties on rates determined over long periods of time. This  
 132 does not mean that the rate inferred from the time series is in error, but that its uncertainty is  
 133 not correct. When using continuous measurements and daily time series, robust mathematical  
 134 models of different kinds of noise (white noise, random-walk noise, flicker noise) can be  
 135 tested and applied to the data (for a complete discussion see e.g. [Williams *et al.*, 2004]).  
 136 Unfortunately, for survey mode measurements it is an impossible task to infer the noise model  
 137 from the data themselves and we have to use a-priori assumption on the noise nature. In our  
 138 processing, this is done by adding a moderate random-walk type noise ( $2 \text{ mm/yr}^{1/2}$ ) to the  
 139 coordinates of stations when combining the daily solutions, following the procedures  
 140 described in [Herring *et al.*, 1990] and [Herring, 1999]. Applying this strategy leads to the  
 141 estimation of more realistic velocity uncertainties (1-2 mm/yr instead of the formal a-priori  
 142 value of 0.1-0.2 mm/yr). However, although velocities don't change by more than  $\pm 1 \text{ mm/yr}$   
 143 at all sites, this procedure degrades the realization of the reference frame and the combination  
 144 with subsets of stations measured at different epochs: It simply also adds noise to the velocity  
 145 field. Therefore we choose to estimate the velocity uncertainties with added random walk  
 146 noise, but to keep the velocities estimated without adding this noise model.

147

## 148 **Velocity field**

149 This procedure leads to horizontal velocities with respect to ITRF2000 (Table 2). Here we  
 150 present our results both in the ITRF2000 reference frame, and relative to the South-American  
 151 plate by using the angular velocity of this plate ( $25.4^\circ\text{S}$ ,  $124.6^\circ\text{W}$ ,  $0.11^\circ/\text{Myr}$ ) given by the  
 152 Nuvel-1A model [Demets *et al.*, 1994]. Our data set is consistent with that of Vigny *et al.*,  
 153 2008 (this issue). First of all, far field stations spanning the South American craton show that  
 154 the latter is not affected by any significant internal deformation and that its present day  
 155 angular velocity does not differ significantly from the Nuvel-1A estimate. Second, stations on  
 156 the Nazca plate (EISL and GALA) are also consistent with their reduced Nazca/South  
 157 America angular velocity, which predicts  $68 \text{ mm/yr}$  of convergence oriented  $78^\circ\text{N}$  on the  
 158 trench at the latitude of our network.

# 159 *South Central Chile velocities*

160 Figure 2 depicts the velocity field with respect to the stable South America reference frame.  
 161 Observed velocities decrease rapidly from the Pacific coast to the Chile Argentina border, 200  
 162 km inland. Coastal stations move inland with velocities close to 35-40 mm/yr while Andean  
 163 stations move with a velocity closer to 10-20 mm/yr. Accordingly, velocity directions rotate  
 164 from their initial strike of 70°N +/- 1° along the coast (LLI, UCO, CO6, PTU), to 75°N +/-  
 165 2° in the central valley (SLT, CHL, QLA, CT4), and almost purely East trending in the Andes  
 166 (LLA and CT8).

167 Because it is the longest profile and because it starts closer to the trench, the southern profile  
 168 between the Arauco peninsula and the Andes is particularly interesting. The nearest point to  
 169 the trench (LLI) show a velocity of  $46 \pm 2.3$  mm/yr, while the last point in the Andes (LLA),  
 170 presents a velocity of  $15 \pm 1.3$  mm/yr (Figure 3). This implies an accumulation of 30 mm/yr  
 171 over this 200 km long distance, or an integrated strain rate of  $1.5 \cdot 10^{-6}$  per year.

173 The northern profile between Constitución and the Andes shows slightly less compression: 37  
 174  $\pm 1.6$  mm/yr at CO2 or CO4 and  $10 \pm 1.2$  mm/yr at Laguna Maule (CT8) on the top of  
 175 Andes near the Chile-Argentina border (Figure 3). Along this northern profile, stations lying  
 176 at the same distance from the trench have a velocity 10-25 % larger than along the southern  
 177 profile (Figure 3). Accordingly, northern transect stations show a different crustal strain than  
 178 southern stations: weaker in the first half (100-200 km from the trench) and stronger in the  
 179 second half in the foothills of the Andes (200-300 km from trench) (Figure 3). These patterns  
 180 are consistent with the accumulation of elastic strain in the upper plate due to locking on the  
 181 subduction interface with latitude-dependent dip angle (see elastic modelling section).

182 Although less precisely determined, the vertical velocities exhibit a coherent pattern which,  
 183 like the horizontal ones, is consistent with what is expected from standard elastic modelling.  
 184 Vertical velocities of the coastal stations are negative (indicating subsidence) when those of  
 185 the Central Valley are positive (indicating uplift) and those of the Andean range are  
 186 essentially near zero (Figure 4a). This is particularly true around the Arauco peninsula where  
 187 distance to the trench is lower than 100 km, and where vertical velocities are negative and less  
 188 than -10 mm/yr, accordingly with the modelled curve (Figure 4b).



## 189 Elastic modeling

190 To model the upper plate deformation during the interseismic stage, we make the usual  
 191 assumption that the interface between the Nazca and South American plates is locked down to  
 192 to a certain depth (the locking depth or coupling depth), while the deeper part is slipping  
 193 continuously at the relative plate velocities. This corresponds to the “seismically coupled  
 194 zone”, portion of the upper plate interface which might be the site of a future major thrust  
 195 earthquake in the BioBío and Maule regions of Chile. We model this deformation using a  
 196 simple back-slip assumption (Savage, 1983) for which the inter-seismic accumulation  
 197 correspond exactly to the released co-seismic deformation (with reversed sign), and we use  
 198 Okada's elastic model to relate the surface deformation to the dislocation buried at depth  
 199 [Okada, 1985]. We define the geometry of the fault plane model by considering the  
 200 distribution of earthquakes (Campos et al., 20021) and the slab geometry as given by Cahill  
 201 and Isacks (1992). The fault plane model is simply defined by 9 parameters: 3 for the location  
 202 of the fault's center, azimuth (strike), dip, width along the dip and length of the fault plane,  
 203 and finally the slip dislocation vector, (slip modulus and rake angle). A strike angle of about  
 204 N19°E is chosen in agreement with the average direction of both the trench axis and the coast  
 205 line between 33°S and 38°S. A dip angle of 20° is taken for our first trial model but our final  
 206 model uses a dip of 17°. The up-dip limit of our fault plane is taken to be at the trench, at a  
 207 depth of 6 km. The centre of the fault model is taken at the average latitude of the observed  
 208 sites (37 °S) and the length of the model extends for a distance of 1000 km along the coast to  
 209 avoid edge effects. We used the parameters defining the convergence at the trench, 68 mm/yr  
 210 in the direction 78°N, to define the slip vector of the model and the corresponding rake (here -  
 211 59° for a back slip model).

212 In our trial models, we fixed 6 parameters of the well known geometry of the subduction and  
 213 left only free the dip, the width along the dip, and the slip modulus. The goodness of fit of the  
 214 model is estimated by calculation of the mean residual (mean absolute error) between  
 215 observed and modeled vectors. We explored the dip angle between 12 and 22°, the width (W)  
 216 between 150 and 250 km, and the slip between 35 and 67 mm/yr, i.e. the range 50-100%  
 217 coupling.

218 Considering the whole set of observed points, the best fit is obtained with a fault plane of 17°  
 219 +/- 2° dip, and a locking depth of 58 km +/- 6 km located at a distance of 180 km eastwards  
 220 from the trench and a slip of 67 mm/yr. In this case the mean residual is 3.4 +/- 0.2 mm/a.

221 One point NIN0 shows an anomalous residual vector of about 10 mm/yr, because a shift on  
222 the direction of the observed vector probably due to a movement of the monument.

223 If we consider separately the Southern area, south of the city of Chillan ( $36.5^{\circ}\text{S}$ ) and the  
224 Northern one ( $35^{\circ}\text{S} - 36^{\circ}\text{S}$ ), we obtain the following results:

225 - Southern area: dip  $18^{\circ} \pm 2$ , a width of 180 km, a locking depth : 61 km  $\pm 3$ , a mean  
226 residual: 2.1  $\pm 0.4$  mm/a, and a 100% coupling, i.e. values very near from those of the  
227 whole set of points.

228 - For the Northern area we found two minimum: one with values very near from those of the  
229 whole set of points: dip  $17^{\circ} \pm 2$ , width 180 km, locking depth : 61 km  $\pm 9$ , mean  
230 residual: 4.0  $\pm 0.4$  mm/a, and a 100% coupling; but a second solution and slightly better  
231 solution is obtained with a slip of about 54 mm/yr (78% coupling): dip  $13^{\circ} \pm 1$ , width 250  
232 km, locking depth : 62 km  $\pm 1$ , which fits with a mean residual of 2.8  $\pm 0.1$  mm/a.

233 These results mean that at the first order the interface is fully locked, or in other words that  
234 the coupling between the two plates is 100%. This result is in agreement with those of  
235 Khazaradze and Klotz (2003) who find a similar locking depth and full coupling (100%).

236

237 The worse fit observed in the Northern area of our study could be due to either a different dip  
238 angle of the subduction interface, a variation in the dip with distance from the trench, or a  
239 change in the locking depth. Indeed, the fit can be improved locally by using a slightly  
240 reduced dip angle of  $13^{\circ}$ , which generates a longer slab before it reaches the depths at which  
241 it starts to slip freely. The usage of a shallower and longer slab generates an eastward shift of  
242 the deformation gradient, such as the one observed in our data (Figure 3).

## 243 **Conclusion**

244 In this paper we extend the finding of preliminary results obtained with only two GPS  
245 campaigns and a lower number of observed sites (*Ruegg et al.*, 2002). Interseismic velocities  
246 (horizontal and vertical components) have been determined at 36 sites (against 13 in *Ruegg et al.*  
247 *et al.*, 2002), with better uncertainties (formal uncertainties in the range 1-3 mm/yr and vertical  
248 velocities around 3 to 5 mm/yr). The velocities on the northern transect vary from 36 mm/yr  
249 at the coast and 10 mm/yr at the Chile-Argentina border, with a particularly high gradient of  
250 velocity from the foothills of the Andes to their top ( $0.5 \cdot 10^{-6}$  linear strain per year at 220-320  
251 km from trench). The southern transect exhibits very high geodetic speed in the coastal region  
252 of Arauco (45 mm/yr) which decrease to 15 mm/yr at the top of the Andes which implies a

strong strain accumulation of  $1.5 \cdot 10^{-6}$  per y over this 200 km long distance between the coast and the top of the Andes. Vertical velocities are negative at the coast, while those measured in the Central Valley have positive values and those on the Andean range are close to zero. This deformation pattern is very well explained by the elastic loading of the seismogenic zone of the plate interface by continuous slip at depth, using as slip vector the convergence rate between the two plates (68mm/yr at 78°N). Thus, it appears that at first order the plates are fully coupled with a locking depth situated at  $60 \pm 5$  km depth at a distance of 180 km from trench. We do not know whether the plate interface has slipped episodically in the past, or whether it has remained fully locked since the last big earthquake 1835. In the worst case scenario, that strains have not been relieved at all since 1835, at a convergence rate of 68 mm/yr more than 10 m of slip deficit will have accumulated since 1835. It is possible that the northern part of the plate interface between Constitución and Concepción was affected by the earthquakes of 1851, 1928 and 1939, but it is unlikely that this was the case near the city of Concepción. We would then conclude that the southern part of the Concepción-Constitución gap has accumulated a slip deficit that is large enough to produce a very large earthquake of about  $M_w = 8.0-8.5$ . This is of course a worst case scenario that needs to be refined by additional work.

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## References

- Altamimi, Z., P. Sillard, and C. Boucher (2002), ITRF2000: A new release of the International Terrestrial Reference frame for earth science applications, *J. Geophys. Res.*, SA 107 (B10): art. no. 2214.
- Angermann, D., J.Klotz, and C.Reigber, (1999), Space geodetic estimation of the Nazca-South America Euler vector, *Earth Planet. Sci. Lett.* 171, 329-334.

- 284 Armijo, R.; Thiele, R. (1990), Active faulting in northern Chile: ramp stacking and lateral  
285 decoupling along a subduction plate boundary? *Earth and Planetary Science Letters*, Vol. 98,  
286 p. 40-61.
- 287 Barrientos, S. E. (1995), Dual seismogenic behavior: the 1985 Central Chile earthquake.  
288 *Geophys. Res. Lett.* **22**, 3541–3544 .
- 289 Beck, S., S. Barrientos, E. Kausel and M. Reyes (1998), Source characteristics of historic  
290 earthquakes along the central Chile subduction zone, *J. South. American Earth Sci.*, 11,  
291 115-129.
- 292 Beutler, G., J. Kouba, and T. Springer (1993), Combining the orbits of the IGS processing  
293 centers, in proceedings of IGS analysis center workshop, *edited by J. Kouba*, 20-56.
- 294 Cahill, T and B. Isacks (1992), Seismicity and shape of the subducted Nazca plate, *Jour.*  
295 *Geophys. Res.* **97**, 17503-17529.
- 296 Campos J. and E. Kausel (1990), The large 1939 Intraplate earthquake of Southern Chile, *Seis.*  
297 *Res. Lett.*, 61.
- 298 Campos, J., D. Hatzfeld, R. Madariaga, G. López, E. Kausel, A. Zollo, G. Iannaccone, R.  
299 Fromm, S. Barrientos, et H. Lyon-Caen (2002), A Seismological study of the 1835  
300 Seismic gap in South Central Chile. *Phys. Earth Planet. Int.*, **132**, 177-195.
- 301 Cifuentes, I.L, The 1960 Chilean earthquake, *J. Geophys. Res.*, 94, 665-680, 1989.  
302 Darwin, C. , Geological observations on coral reefs, volcanic islands and on South  
303 America, 768 pp., Londres, Smith, Elder and Co., 1851.
- 304 DeMets, C., et al. (1994), Effect of the recent revisions to the geomagnetic reversal time scale  
305 on estimates of current plate motions, *Geophys. Res. Lett.*, **21**, 2191-2194.
- 306 Herring, T. A., Davis, and Shapiro, Geodesy by radio Interferometry : the application of  
307 Kalman filtering to the analysis of very long baseline interferometry data, *J. Geophys.*  
308 *Res.*, 95, 12561-12581, 1990.
- 309 Herring, T. A., Documentation for the GLOBK software version 5.01, *Mass. Inst. of Technol.*,  
310 *Cambridge*, 1999.
- 311 Kelleher, J. (1972) Rupture zones of large South American earthquakes and some predictions,  
312 *J. Geophys. Res.* **77**, 2087-2103.
- 313 Khazaradze, G., and J. Klotz (2003), Short and long-term effects of GPS measured crustal  
314 deformation rates along the South-Central Andes. *J. of Geophys. Res.*, 108, n°B4, 1-13

- 315 King, R. W., and Y. Bock (2000) Documentation for the GAMIT GPS software analysis  
316 version 9.9, *Mass. Inst. of Technol.*, Cambridge.
- 317 Larson, K., J.T. Freymueller, and S. Philipsen (1997), Global plate velocities from the GPS, *J.*  
318 *Geophys. Res.*, 102, 9961-9981.
- 319 Lomnitz C., Grandes terremotos y tsunamis en Chile durante el periodo 1535-1955, *Geofis.*  
320 *Panamericana*, 1, 151-178, 1971.
- 321 Neilan, R. (1995), The evolution of the IGS global network, current status and future aspects,  
322 in IGS annual report, edited by J.F. Zumberge et al., *JPL Publ.*, 95-18, 25-34.
- 323 Nishenko, R. (1985), Seismic potential for large and great intraplate earthquakes along the  
324 Chilean and Southern Peruvian margins of South America: a quantitative reappraisal., *J.*  
325 *Geophys. Res.*, 90, 3589-3615.
- 326 Okada, Y. (1985), Surface deformation due to shear and tensile faults in a half-space, *Bull.*  
327 *Seism. Soc. Am.*, 75, 1135-1154.
- 328 Plafker, G. and J.C. Savage (1970), Mechanism of the Chilean earthquake of May 21 and 22,  
329 1960, *Geol. Soc. Am. Bull.*, 81, 1001-1030.
- 330 Ruegg J.C., J. Campos, R. Armijo, S. Barrientos, P. Briole, R. Thiele, M. Arancibia, J.  
331 Canuta, T. Duquesnoy, M. Chang, D. Lazo, H. Lyon-Caen, L. Ortlieb, J.C. Rossignol and  
332 L. Serrurier (1996), The Mw=8.1 Antofagasta earthquake of July 30, 1995 : First results  
333 from teleseismic and geodetic data, *Geophysical Res. Letters*, vol.23, no 9, 917-920.
- 334 Ruegg J.C., J. Campos, R. Madariaga, E. Kausel, J.B. DeChabaliér , R. Armijo, D. Dimitrov,  
335 I. Georgiev, S. Barrientos (2002), Interseismic strain accumulation in south central Chile  
336 from GPS measurements, 1996-1999, *Geophys. Res. Lett.*, 29, no 11,  
337 10.1029/2001GL013438.
- 338 Savage J.C. (1983) A dislocation model of strain accumulation and release at a subduction  
339 zone, *J. Geophys. Res.* 88 pp. 4948-4996.
- 340 Williams, S. D. P., Y. Bock, P. Fang, P. Jamason, R. M. Nikolaidis, L. Prawirodirdjo, M.  
341 Miller and D. J. Johnson (2004), Error analysis of continuous GPS position Time Series, *J.*  
342 *Geophys. Res.*, 109, B03412, doi:10.1029/2003JB0022741.

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348 **Table 1:** Average short (< 300km) baseline repeatabilities (Root Mean Square scatter about the mean) for each  
349 of the 3 campaigns. Values are in mm.

|               | Dec.1996 | March 1999 | April 2002 |
|---------------|----------|------------|------------|
| North rep     | 3.8      | 2.4        | 2.5        |
| East rep.     | 4.5      | 2.5        | 3.0        |
| Vertical rep. | 14.8     | 12.6       | 9.7        |

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**Table 2:** Site positions and velocities, in ITRF2000 and relative to South-America plate. Latitude and longitude are in decimal degrees. All velocities and velocity uncertainties are in mm/yr.

| Site            | Position  |          | Velocity/ITRF2000 |       | Velocity / SOAM |        | Uncertainties |       |        |
|-----------------|-----------|----------|-------------------|-------|-----------------|--------|---------------|-------|--------|
|                 | Longitude | Latitude | Vlon              | Vlat  | Vlon            | Vlat   | s_lon         | s_lat | corr,  |
| BAT             | -71.962   | -35.307  | 32.56             | 19.62 | 33.21           | 9.24   | 1.28          | 1.17  | 0.025  |
| CAP             | -73.272   | -37.245  | 34.47             | 27.41 | 34.74           | 17.15  | 2.83          | 1.79  | 0.093  |
| CHL             | -72.205   | -36.639  | 26.65             | 18.89 | 27.11           | 8.53   | 1.58          | 1.22  | 0.013  |
| CLM             | -72.812   | -36.236  | 33.08             | 23.02 | 33.53           | 12.72  | 1.54          | 1.21  | 0.003  |
| CLP             | -71.625   | -37.336  | 16.77             | 11.50 | 17.21           | 1.09   | 1.30          | 1.19  | 0.026  |
| CO1             | -72.415   | -35.318  | 36.41             | 21.55 | 37.01           | 11.21  | 1.49          | 1.19  | 0.002  |
| CO2             | -72.491   | -35.412  | 34.65             | 22.97 | 35.23           | 12.64  | 1.61          | 1.25  | 0.025  |
| CO4             | -72.626   | -35.586  | 34.70             | 23.97 | 35.25           | 13.65  | 1.47          | 1.22  | 0.019  |
| CO6             | -72.606   | -35.828  | 34.32             | 23.24 | 34.84           | 12.92  | 1.24          | 1.15  | 0.022  |
| CO7             | -72.639   | -35.843  | 35.48             | 23.13 | 36.00           | 12.81  | 1.60          | 1.24  | 0.048  |
| CO8             | -72.744   | -35.949  | 35.46             | 23.61 | 35.95           | 13.30  | 1.75          | 1.27  | 0.052  |
| COLB            | -71.347   | -35.677  | 27.21             | 15.83 | 27.88           | 5.39   | 1.23          | 1.16  | 0.019  |
| CT2             | -72.255   | -35.464  | 34.76             | 20.56 | 35.36           | 10.20  | 1.62          | 1.22  | 0.014  |
| CT3             | -72.086   | -35.558  | 33.04             | 20.26 | 33.65           | 9.89   | 1.42          | 1.21  | 0.013  |
| CT4             | -71.777   | -35.616  | 30.08             | 17.46 | 30.71           | 7.06   | 1.40          | 1.25  | 0.004  |
| CT6             | -71.069   | -35.709  | 22.49             | 17.56 | 23.19           | 7.09   | 1.27          | 1.17  | 0.015  |
| CT7             | -70.834   | -35.815  | 17.86             | 13.48 | 18.57           | 2.99   | 1.41          | 1.18  | -0.002 |
| CT8             | -70.399   | -35.991  | 9.84              | 11.34 | 10.58           | 0.81   | 1.23          | 1.10  | 0.033  |
| GUA             | -72.333   | -37.346  | 22.92             | 16.56 | 23.28           | 6.21   | 2.60          | 1.97  | 0.232  |
| LAJ             | -72.697   | -37.255  | 25.86             | 20.55 | 26.19           | 10.24  | 1.62          | 1.45  | 0.024  |
| LLA             | -71.344   | -37.369  | 14.79             | 10.95 | 15.26           | 0.51   | 1.31          | 1.20  | 0.025  |
| LLI             | -73.569   | -37.192  | 42.29             | 24.92 | 42.54           | 14.69  | 2.28          | 1.65  | 0.090  |
| LTA             | -73.142   | -37.059  | 30.95             | 23.87 | 31.26           | 13.60  | 1.60          | 1.24  | -0.003 |
| MIR             | -71.75    | -37.330  | 16.54             | 12.60 | 16.97           | 2.20   | 1.41          | 1.22  | 0.033  |
| MRC             | -71.955   | -37.411  | 18.62             | 14.02 | 19.01           | 3.64   | 1.30          | 1.19  | 0.026  |
| NIN             | -72.437   | -36.410  | 34.76             | 15.56 | 35.23           | 5.22   | 1.28          | 1.17  | 0.020  |
| PTU             | -72.269   | -35.172  | 32.02             | 22.88 | 32.66           | 12.53  | 1.37          | 1.18  | 0.032  |
| PUL             | -72.942   | -37.285  | 30.16             | 21.03 | 30.46           | 10.74  | 1.62          | 1.45  | 0.027  |
| PUN             | -71.957   | -35.750  | 31.30             | 19.90 | 31.90           | 9.52   | 1.24          | 1.16  | 0.021  |
| QLA             | -72.125   | -36.085  | 29.87             | 18.28 | 30.41           | 7.91   | 1.23          | 1.15  | 0.021  |
| RAQ             | -73.436   | -37.256  | 36.44             | 24.51 | 36.69           | 14.27  | 2.43          | 1.65  | 0.087  |
| SGE             | -72.231   | -37.393  | 23.90             | 16.81 | 24.27           | 6.45   | 2.14          | 1.60  | 0.088  |
| SLT             | -72.384   | -37.216  | 27.66             | 18.28 | 28.03           | 7.94   | 1.63          | 1.47  | 0.021  |
| UCO             | -73.035   | -36.829  | 33.77             | 23.05 | 34.12           | 12.77  | 2.16          | 1.67  | 0.045  |
| DGF             | -70.664   | -33.457  | 22.93             | 18.36 | 23.94           | 7.86   | 2.27          | 1.58  | 0.018  |
| Permanent sites |           |          |                   |       |                 |        |               |       |        |
| SANT            | -70.669   | -33.150  | 19.39             | 16.64 | 20.44           | 6.14   | 0.79          | 0.76  | 0.013  |
| AREQ            | -71.493   | -16.466  | 14.20             | 14.89 | 17.12           | 4.46   | 4.50          | 2.80  | 0.075  |
| BRAZ            | -47.878   | -15.947  | -4.32             | 12.31 | -0.08           | 0.64   | 1.00          | 1.00  | 0.000  |
| EISL            | -109.383  | -27.148  | 66.00             | -7.72 | 65.27           | -12.70 | 0.92          | 0.89  | -0.007 |
| GALA            | -90.304   | -0.743   | 51.76             | 12.15 | 56.26           | 3.99   | 0.92          | 0.93  | -0.012 |
| KOUR            | -52.806   | 5.252    | -4.68             | 12.05 | 0.06            | 0.48   | 0.88          | 0.90  | 0.037  |
| LPGS            | -57.932   | -34.907  | -1.99             | 11.10 | -1.99           | 11.10  | 0.83          | 0.81  | -0.014 |
| OHIG            | -57.9     | -63.321  | 14.58             | 9.71  | 14.58           | 9.71   | 0.98          | 0.98  | 0.008  |
| RIOG            | -67.751   | -53.785  | 3.27              | 11.59 | 3.27            | 11.59  | 0.88          | 0.90  | -0.001 |

354 *Interseismic strain accumulation in South Central Chile*  
 355 *PEPI 2008*

356 **Figure caption**

357 **Figure 1.** - Location of stations of the South Central Chile GPS experiment with respect to  
 358 the seismotectonics context: open circles show location of GPS stations implanted in  
 359 December 1996 and black triangles in March 1999. All stations were remeasured in April  
 360 2002. Black stars show the epicentres of the 1928, 1939, 1960 and 1985 earthquakes and large  
 361 ellipses delimit the corresponding rupture zones. Dashed lines show the approximate  
 362 extension of 1835 and 1906 earthquake ruptures. Plate convergence is from Nuvel-1A model  
 363 (De Mets et al., 1994). Inset shows the location of the studied area in South America.

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366 **Figure 2.** Central South Central Chile experiment: GPS velocities relative to stable South  
 367 America. Dots show locations of GPS stations. Arrows depict their horizontal velocities with  
 368 respect to a reference frame fixed on the South-America plate. Bold numbers aside the arrows  
 369 indicate the velocity in mm/yr. Ellipses depict the region of 99% confidence using the  
 370 uncertainties in Table 2.

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373 **Figure 3.** Parallel velocity: cross section of the velocity parallel to the convergence direction  
 374 versus the distance to the trench. Black diamonds are for northern area points. Black dots are  
 375 for southern transect and open square for other distributed points between the two transects.  
 376 The grey line shows the horizontal parallel velocity predict by our best model described in  
 377 fig.5.

378

379 **Figure 4.** Vertical component of the displacement. (a) map of vertical velocities, (b) vertical  
 380 velocities in mm/yr versus the distance to the trench of each station. The grey line shows the  
 381 vertical component of the model described in fig.5.

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384 **Figure 5.** Elastic modeling of the upper plate deformation in the South Central Chile gap.

385 **(a):** GPS observations (brown arrows) and model predictions (white arrows) are shown. Inset  
 386 describes the characteristics of the model. **(b):** residual (i.e. observations-model) velocities  
 387 are shown (black arrow). In both boxes, the grey contour line and shaded pattern draw the  
 388 subduction plane buried at depth and the white arrows depict the dislocation applied on this  
 389 plane.

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