



HAL
open science

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

J.C. Ruegg, A. Rudloff, C. Vigny, R. Madariaga, J.B. de Chabalier, J. Campos, E. Kausel, S. Barrientos, D. Dimitrov

► **To cite this version:**

J.C. Ruegg, A. Rudloff, C. Vigny, R. Madariaga, J.B. de Chabalier, et al.. Interseismic strain accumulation measured by GPS in the seismic gap between Constitución and Concepción in Chile. *Physics of the Earth and Planetary Interiors*, 2009, 175 (1-2), pp.78. 10.1016/j.pepi.2008.02.015 . hal-00533423

HAL Id: hal-00533423

<https://hal.science/hal-00533423v1>

Submitted on 6 Nov 2010

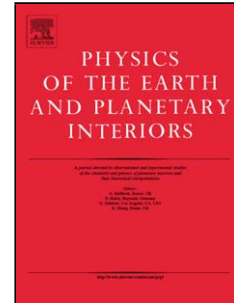
HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Accepted Manuscript

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

Authors: J.C. Ruegg, A. Rudloff, C. Vigny, R. Madariaga, J.B. de Chabaliér, J. Campos, E. Kausel, S. Barrientos, D. Dimitrov



PII: S0031-9201(09)00039-9
DOI: doi:10.1016/j.pepi.2008.02.015
Reference: PEPI 5140

To appear in: *Physics of the Earth and Planetary Interiors*

Received date: 30-3-2007
Accepted date: 10-2-2008

Please cite this article as: Ruegg, J.C., Rudloff, A., Vigny, C., Madariaga, R., de Chabaliér, J.B., Campos, J., Kausel, E., Barrientos, S., Dimitrov, D., Interseismic strain accumulation measured by GPS in the seismic gap between Constitución and Concepción in Chile, *Physics of the Earth and Planetary Interiors* (2008), doi:10.1016/j.pepi.2008.02.015

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

1 **Interseismic strain accumulation measured by GPS**
2 **in the seismic gap between Constitución and Concepción in Chile**
3

4 J.C. Ruegg¹, A. Rudloff², C. Vigny², R. Madariaga², J.B. de Chabaliér¹, J. Campos³,
5 E. Kausel³, S. Barrientos³, D. Dimitrov⁴
6

7 ¹Institut de Physique du Globe (IPGP), Paris, France

8 ²Laboratoire de Géologie, Ecole Normale Supérieure (ENS), CNRS, Paris, France

9 ³Departamento de Geofísica (DGF), Universidad de Chile, Santiago, Chile

10 ⁴Bulgarian Academy of Sciences, Sofia, Bulgaria

11 **Abstract**

12 The Concepción-Constitución area [35-37°S] in South Central Chile is very likely a mature
13 seismic gap, since no large subduction earthquake has occurred there since 1835. Three
14 campaigns of Global Positioning System (GPS) measurements were carried out in this area in
15 1996, 1999 and 2002. We observed a network of about 40 sites, including two East-West
16 transects ranging from the coastal area to the Argentina border and one North-South profile
17 along the coast. Our measurements are consistent with the Nazca/South America relative
18 angular velocity (55.9°N, 95.2°W, 0.610 °/Ma) discussed by Vigny et al., 2008 (this issue)
19 which predicts a convergence of 68 mm/yr oriented 79°N at the Chilean trench near 36°S.
20 With respect to stable South America, horizontal velocities decrease from 45 mm/yr on the
21 coast to 10 mm/yr in the Cordillera. Vertical velocities exhibit a coherent pattern with
22 negative values of about 10 mm/yr on the coast and slightly positive or near zero in the
23 Central Valley or the Cordillera. Horizontal velocities have formal uncertainties in the range
24 of 1-3 mm/yr and vertical velocities around 3 to 6 mm/yr. Surface deformation in this area of
25 South Central Chile is consistent with a fully coupled elastic loading on the subduction
26 interface at depth. The best fit to our data is obtained with a dip of 16° +/- 3°, a locking depth
27 of 55 +/- 5 km and a dislocation corresponding to 67 mm/yr oriented N78°. However in the
28 Northern area of our network the fit is improved locally by using a lower dip around 13°.
29 Finally a convergence motion of about 68 mm/yr represents more than 10 m of displacement
30 accumulated since the last big interplate subduction event in this area over 170 years ago
31 (1835 earthquake described by Darwin). Therefore, in a worst case scenario, the area already
32 has a potential for an earthquake of magnitude as large as 8 to 8.5, should it happen in the
33 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 Valparaiso 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 +/- 1mm/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°S , 124.6°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 mm/yr of convergence oriented 78°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 ± 2.3 mm/yr, while the last point in the Andes (LLA),
170 presents a velocity of 15 ± 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.

172

173 The northern profile between Constitución and the Andes shows slightly less compression: 37
174 ± 1.6 mm/yr at CO2 or CO4 and 10 ± 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°S) and the
224 Northern one (35°S – 36°S), we obtain the following results:

225 - Southern area: dip 18° +/- 2, a width of 180 km, a locking depth : 61 km +/- 3, a mean
226 residual: 2.1 +/- 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° +/- 2, width 180 km, locking depth : 61 km +/- 9, mean
230 residual: 4.0 +/- 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° +/- 1, width 250
232 km, locking depth : 62 km +/- 1, which fits with a mean residual of 2.8 +/- 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°, 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*
247 *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

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

270

271 **Acknowledgments.** This work is part of a cooperative project between Universidad de Chile,
272 Santiago, Institut de Physique du Globe de Paris and Ecole Normale Supérieure, Paris. It was
273 initiated by a European Community contract CII-CT94-0109 and supported by the French
274 Ministère des Affaires Etrangères (comité ECOS), by CNRS/INSU programs (ACI CatNat)
275 and by "Nucleo Milenio en Sismotectonica y Peligro Sismico". We are grateful to many
276 people who participated in measurement campaigns, and particularly our colleagues H. Lyon-
277 Caen, E.Clevede and T.Montfret, as well as students from DGF and ENS.

278 **References**

- 279 Altamimi, Z., P. Sillard, and C. Boucher (2002), ITRF2000: A new release of the
280 International Terrestrial Reference frame for earth science applications, *J. Geophys. Res.*,
281 SA 107 (B10): art. no. 2214.
- 282 Angermann, D., J.Klotz, and C.Reigber, (1999), Space geodetic estimation of the Nazca-
283 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. Iannacone, 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. DeChabalier , 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.

343

344

345

346

347

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

350

Accepted Manuscript

350 **Table 2:** Site positions and velocities, in ITRF2000 and relative to South-America plate. Latitude and longitude
 351 are in decimal degrees. All velocities and velocity uncertainties are in mm/yr.
 352

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

353

1

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.

364

365

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.

371

372

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.

382

383

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.

390

