Nat. Hazards Earth Syst. Sci., 10, 1989–1993, 2010
www.nat-hazards-earth-syst-sci.net/10/1989/2010/
doi:10.5194/nhess-10-1989-2010


Natural Hazards and Earth System Sciences

# *Brief communication* "Report on the impact of the 27 February 2010 earthquake (Chile, $M_w$ 8.8) on rockfalls in the Las Cuevas valley, Argentina"

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Received: 22 April 2010 – Revised: 15 July 2010 – Accepted: 16 August 2010 – Published: 27 September 2010

**Abstract.** Numerous rockfalls were detected in the Las Cuevas valley, Argentina, after the 27 February 2010 earthquake in Chile. Live rockfalls were observed during aftershocks of 11 March 2010. Many rockfall source areas coincide with known thrust fault and some areas presented a rockfall activity even after the tremors. Some rockfalls crossed the National Road 7 but no damages to houses or vehicles were reported. This study illustrates how the 27 February 2010 earthquake impacted on unstable slopes in a valley far from the earthquakes epicentre. It is an interesting addition to previous studies on landslides caused by earthquakes because of the high magnitude of the event and of its aftershocks.

## 1 Introduction

The Chile earthquake of 27 February 2010 has triggered many rockfalls in the Mendoza Province, Argentina, at a distance of more than 400 km from the epicentre. As part of a multi-hazards susceptibility assessment study (Wick et al., 2010), many rockfalls and impacts caused by this earthquake and its aftershocks were observed by the authors or reported from inhabitants' testimonies during the three weeks that followed the event. The study area is located along the National Road 7, in the northwest sector of the Cordillera Principal (Fig. 1), between Punta de Vacas and Las Cuevas, near the Chilean Border and the Mount Aconcagua (6959 m). This road is the main corridor between the Atlantic and the Pacific South America and the studied stretch is used by more than 1900 vehicles daily (Vialidad Nacional, 2009).

The Las Cuevas valley relief is a result of fast uplift driven by tectonic of the Central Andes combined with glacial and fluvial incision. At present, the valley is mainly reshaped by fluvial action, mass movements and cryogenic processes. The steep valley slopes, fragile bedrocks cornices and the seasonal freeze and thaw contribute to the generation of mass movements (Baumann et al., 2005). This valley (between 32° S and 33° S) lies above the flat slab subduction segment (Ramos, 1988) which controls the seismic activity in the region.

The epicentre of the 27 February earthquake (Fig. 1; 03:34 LT) is located near Concepción (35°54′32″ S, 72°43′59″ W; depth 35 km), Chile, at about 420 km of the study area. Its magnitude of $M_w$=8.8 was felt very strongly in the Las Cuevas valley, according to testimonies. This event was an interplate subduction earthquake between the Nazca plate and the South American plate in the offshore Maule region (USGS, 2010a). Two high magnitude aftershocks ($M_w$=6.9 and 6.7) occurred on 11 March 2010 (11:39 and 11:55 LT) and were felt by the authors during the field survey. The epicentres of these earthquakes are located northeastward at about 235 km and 230 km of the study area (34°15′32″ S, 71°55′44″ W; depth 11 km and 34°16′55″, 71°50′14″; depth 18 km, respectively). They apparently occurred due to the change of regional stress caused by the 27 February earthquake, but these were generated by normal faulting within the subducting Nazca plate or the overriding South American plate (SSN, 2010; USGS, 2010b). Many others $M_w \geq 6$ aftershocks occurred during the hours or days following the $M_w$=8.8 earthquake, the highest one being the 28 February aftershock ($M_w$=6.2; 34°51′36″ S, 71°34′12″ W; USGS, 2010c). These direct new observations of rockfalls at a far distance from an earthquake epicentre or rupture zone are an opportunity to partially contribute to the relation between the maximum distance of landslides to the epicentre proposed by Keefer (1984) and Rodríguez et al. (1999).

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Published by Copernicus Publications on behalf of the European Geosciences Union.

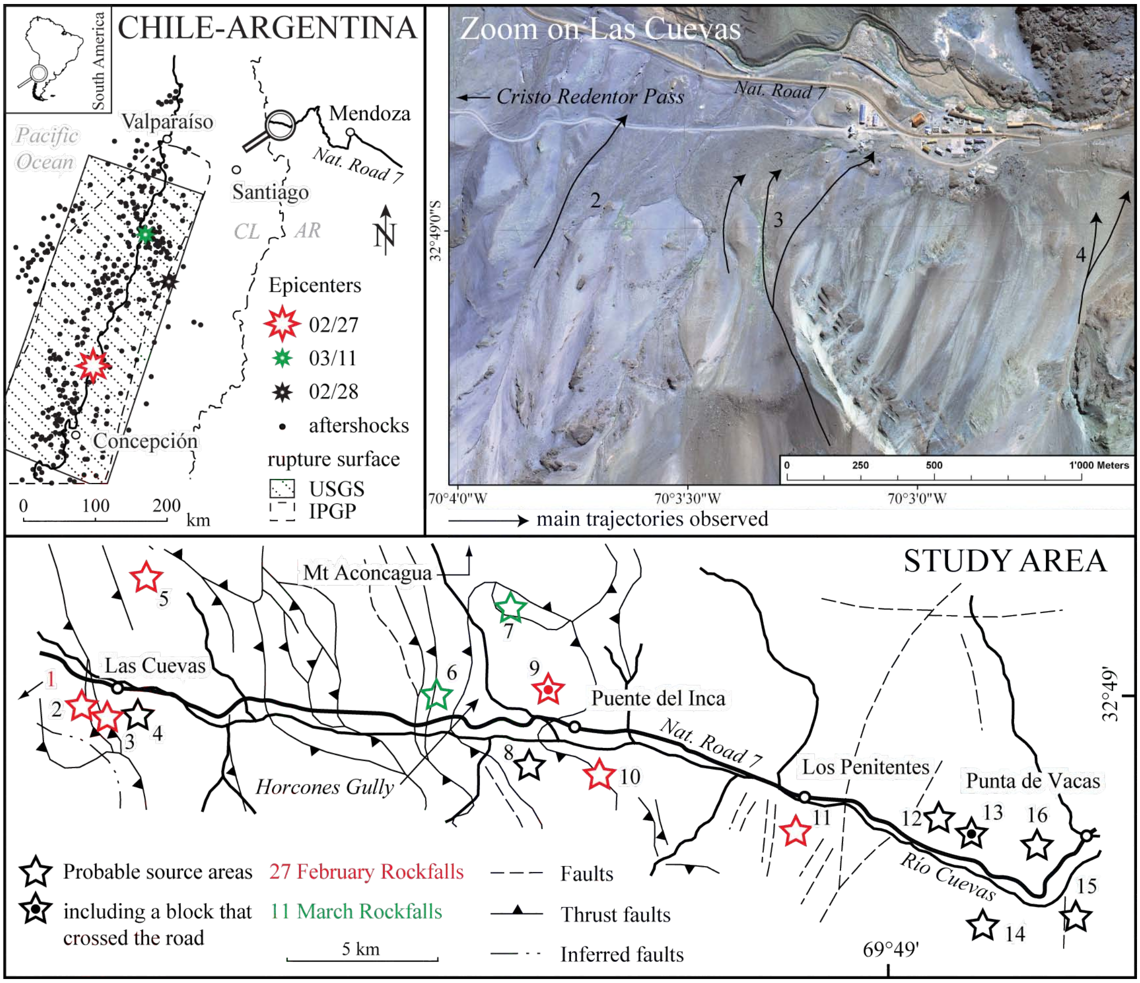


**Fig. 1.** Study area. Upper left: location of the study area and the epicentres of the 27 February earthquake, the 11 March and 28 February aftershocks, between Concepción and Santiago (Chile). Comparison of the projected rupture surfaces proposed by USGS (2010a) and IPGP (2010). Upper right: zoom on the main trajectories of rockfalls observed in Las Cuevas. Satellite imagery Ikonos. Bottom: location of probable source areas of observed rockfalls with faults, thrust faults and inferred faults determined by Ramos et al. (1996). Numbers correspond to the sites described in Table 1. Site no. 5: Paramillos Gully, regular rockfalls site since the 27 February earthquake. Site no. 10: Tordillo Formation outcrop, regular rockfalls site since 2009. Modified after USGS (2010a, 2010b, 2010c), IPGP (2010), Ramos et al. (1996), Google Earth and ESRI.

## 2 Report

Many testimonies of people living in the Las Cuevas valley were collected (Table 1). The 11 March aftershocks allowed the authors to observe live some rockfalls in Horcones, during and a few hours after the tremors. During the 27 February earthquake, people were woken up by the tremors and could hear the noise of blocks falling down, especially in the villages of Las Cuevas, Puente del Inca and Los Penitentes. No damage to houses were observed or related, but some of the Argentinean army buildings in Puente del Inca and an edifice in Las Cuevas were cracked due to the tremors. Also, new cracks in the Libertadores international tunnel appeared. On the following day, the entire valley was immersed in a powder cloud. On the field, numerous blocks and associated impact craters were observed at many places in the valley (Fig. 1). The trajectories of the blocks are visible by the impacts and sometimes from afar, due to the size and the number of the impacts on fans. Rockfalls were linked with the 27 February earthquake or its aftershocks using field evidence, such as fresh impact craters, new damages and fresh muddy material on the blocks. The size of the blocks ranges mainly between 1 and 3 $m^3$. Rockfall volumes were not determined because the source areas were difficult to access, but many recent blocks were observed over the entire path to the bottom of the valley. On a fan at the East of Las Cuevas (Fig. 1 and Table 1, site no. 4), 5 of 12 blocks $\geq 1\,m^3$ fell down probably because of the 27 February earthquake or the 28 February aftershock. At least two blocks (6.6 and 4.8 $m^3$)

**Table 1.** Rockfalls observations for each site presented on Fig. 1. The rockfalls in the sites without date of triggering probably occurred between 27 February and 19 March 2010, for example due to the 28 February aftershock.

| Site no. | Location | Authors' observation | Authors' observation date | Blocks' number | Blocks' size | Lithology | Date of triggering | Sources |
|---|---|---|---|---|---|---|---|---|
| 1 | Cristo Redentor | Blocks and impacts | 3 Mar 2010 | > 10 | $< 1\,m^3$ | Volcanic rocks | 27 Feb 2010 | Testimonies and authors |
| 2 | Las Cuevas | Blocks and impacts | 6 Mar 2010 | 1 | $4\,m^3$ | Volcanic breccia | * | Authors |
| 3 | Las Cuevas | Blocks and impacts | 7 Mar 2010 | min. 23 | $0.3–24\,m^3$ | Volcanic breccia | 27 Feb 2010 | Testimonies and authors |
| 4 | Sta Helena | Blocks and impacts | 8 Mar 2010 | min. 10 | $0.2– \geq 1\,m^3$ | Volcanic breccia | * | Authors |
| 5 | Paramillos | Powder cloud | 11 Mar 2010 | very high | – | – | 27 Feb 2010, 11 Mar 2010** | Testimonies and authors |
| 6 | West Horcones | Powder cloud and noise | 11 Mar 2010 | high | – | Sandstone | 11 Mar 2010 | Authors |
| 7 | Horcones | Rockfalls and powder cloud | 11 Mar 2010 | high | – | – | 11 Mar 2010 | Authors |
| 8 | Puente del Inca | Impacts | 12 Mar 2010 | – | – | – | *** | Far view |
| 9 | Puente del Inca | Blocks and impacts on the road | 12 Mar 2010 | 1 | $> 6\,m^3$ | Volcanic breccia | 27 Feb 2010 | Testimonies and authors |
| 10 | Puente del Inca | Impacts | 3 Mar 2010 | very high | – | Sandstone | 27 Feb 2010, 11 Mar 2010 | Far view |
| 11 | Los Penitentes | – | 17 Mar 2010 | – | – | Granite | 27 Feb 2010 | Testimonies |
| 12 | East Mundo Perdido | Blocks and impacts | 17 Mar 2010 | 1 | $5\,m^3$ | Rhyolitic tuff | * | Authors |
| 13 | West Punta de Vacas | Blocks and impacts on the road | 18 Mar 2010 | 2 | $4–5\,m^3$ | Volcanic breccia | * | Authors |
| 14 | West Punta de Vacas | Impacts | 12 Mar 2010 | – | – | – | *** | Far view |
| 15 | Punta de Vacas | Impacts | 7 Mar 2010 | – | – | – | *** | Far view |
| 16 | Punta de Vacas | Blocks and impacts | 19 Mar 2010 | 2 | $1–2\,m^3$ | Volcanic breccia | * | Authors |

* recent because of almost fresh damages and/or muddy material adhering on the blocks; ** almost every day at least until 19 March 2010;
*** recent rockfalls that could be caused (with reserve) by the tremors.

bounced onto the road between Horcones and Punta de Vacas. Rockfalls were mainly sourced from mesozoic volcanic and clastic outcrops that form cornices at the top or in the middle of the slopes along the Las Cuevas valley.

The most hazardous area of the valley is located in Las Cuevas and menaces some houses directly. On a transversal profile of about 300 m (Fig. 1, site no. 3), 23 different tracks of impacts ($\varnothing > 30$ cm) were detected. A block of $23.6\,m^3$ had stopped on a path (Fig. 1, site no. 3, second arrow from the left), a few meters before the village and another one of $1.9\,m^3$ had terminated its run out 30 m next to a house (Fig. 1, site no. 3, third arrow from the left). Furthermore, some of the fallen blocks hit and broke a water spring. Puente del Inca is another hotspot: a very active outcrop to the East does not endanger the village (Fig. 1, site no. 10), but a second one directly affects the military district and its surroundings. In

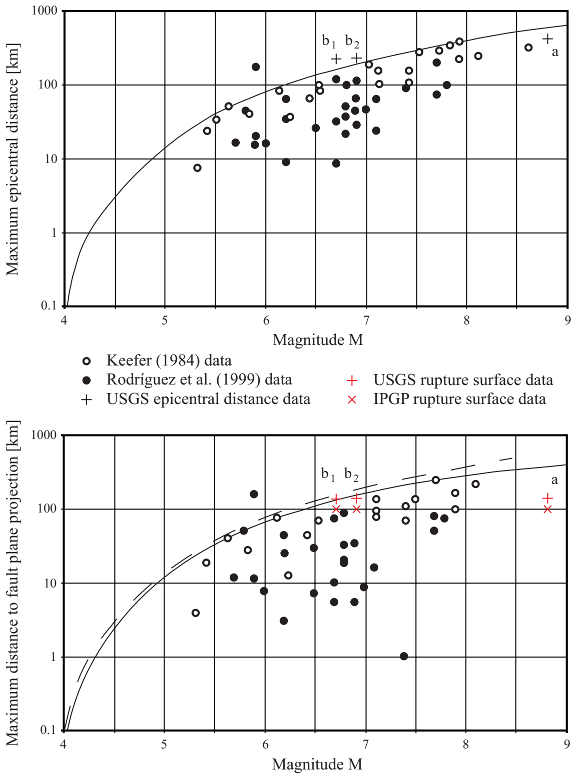


**Fig. 2.** Upper graph: maximum epicentral distance to disrupted landslides as a function of magnitude $M$. Bottom graph: maximum fault distance to disrupted landslides as a function of magnitude $M$. The magnitude used is the moment magnitude $M_w$, except for Keefer (1984) data ($M_w$, surface-wave magnitude $M_s$ and Richter local magnitude $M_L$). White points: data 1811–1980 from Keefer (1984). Black points: data 1980–1997 from Rodríguez et al. (1999). Solid line: upper bound proposed by Keefer (1984) in case of maximal epicentral distance (upper graph) or maximal fault distance (bottom graph). Dashed line: upper bound of Keefer (1984) for maximal epicentral distance, wrongly reported for maximal distance to fault by Rodriguez et al. (1999). a: 27 February earthquake; $b_1$ and $b_2$: 11 March aftershocks. Modified after Rodríguez et al. (1999) and Keefer (1984).

the Paramillos Gully (Fig. 1, site no. 5), rockfalls occur many times every day since the 27 February earthquake. A powder cloud is regularly visible from afar, but is hardly quantifiable because of the great distance.

## 3 Discussion

Some previous studies in the surrounding region include some data of landslides caused by earthquakes. Zavala et al. (2009) observed the damage of the 15 August 2007 earthquake ($M_w$=7.9), in Peru, on a large area up to 200 km of the epicentre. Sepulveda et al. (2008) focused on the effects of the 1958 earthquake at the latitude of Santiago, Chile, up to 60 km of the epicentre. Landslides are partially related to earthquakes along the Río Mendoza valley and several rockfalls were associated with $M>4$ earthquakes, according to Moreiras (2005).

Moreiras (2009) presented a landslide inventory map (1:500 000) including the present study area. The areas affected by the 27 February 2010 earthquake are identified as active and sometimes affected by complex slope processes. The Geological Survey of Argentina (SEGEMAR) published several maps focused on Puente del Inca. A geomorphological susceptibility map (1:7500) shows that all areas affected by the rockfalls (Fig. 1, site nos. 8–10) were described as not suitable for building construction. A simulation of rockfalls propagation (1:60 000 and 1:12 500) shows the same conclusions (SEGEMAR and MAP, 2007). To the best of our knowledge, such detailed studies do not exist for another village in the valley.

The last megathrust earthquake occurred in Chile in 1960 and had a magnitude of $M_w$=9.5. Prior to that, the last earthquake with an estimated magnitude of $M_s$=8.8 occurred in 1615 (SSN, 2010). The limited damages in the study area are mainly due to the poor population density in the valley. Furthermore, the hour of the event (03:34 LT) implies that people were sleeping and the road traffic was scarce. However, the current and future development will increase the risk in some places of the valley, especially in Las Cuevas and on the multiple skiing areas all along the road, where no detailed studies were done, unlike Puente del Inca.

It appears that many rockfall source areas along the valley coincided with the thrust faults mapped by Ramos et al. (1996, Fig. 1). One of the most relevant geological units is the red arenites outcrop of the Tordillo Formation located on the south slope of Puente del Inca (Fig. 1, site no. 10).

The 27 February earthquake and the 11 March aftershocks were outstanding and the resulting rockfalls distances to the epicentre are located near or above the superior limit of the curve determined by Keefer (1984, Fig. 2). This curve connects the magnitude of an earthquake (surface-wave magnitude $M_s$ and moment magnitude $M_w$) to the distance from the epicentre to the farthest landslide, based on data covering the period 1811–1980 that have been extended up until 1997 and discussed by Rodríguez et al. (1999). The resulting rockfalls distances to the projected rupture surface for the 11 March aftershocks are located on (Fig. 2; USGS, 2010a) or slightly below (Fig. 2; IPGP, 2010) the upper boundary determined by Keefer (1984), unlike the 27 February earthquake. The present study is very valuable because only two earthquake magnitudes higher than the present earthquake were noted by Keefer (1984) and none by Rodríguez et al. (1999). Although these observations are not systematic, i.e. they only focus on a small part of the area affected by the 27 February earthquake, unlike other studies for similar events (Sepulveda et al., 2008; Zavala et al., 2009). However, the present results are interesting regarding the upper bound of Keefer (1984) and could even be more impressive if rockfalls occurred farther away.

## 4 Conclusions

The 27 February earthquake was outstanding and consequently many rockfalls were observed. Following Keefer (1984), these are the most common landslides related to earthquakes. We did not observe any debris flows or other types of landslides due to the 27 February earthquake in the Las Cuevas valley. Nevertheless, the number and the size of the blocks discovered close to the edifices and the road illustrate the exposure of people living or transiting in this area. Many rockfall source areas coincide with known thrust fault and some areas presented a rockfall activity even after the tremors. These observations are an important contribution to earthquake-induced landslide hazard assessments and will complement the results of the ongoing research of other studies on the secondary effects of the 27 February earthquake focusing mainly on near epicentre effects in Chile.

**Supplementary material related to this article is available online at: http://www.nat-hazards-earth-syst-sci.net/10/1989/2010/nhess-10-1989-2010-supplement.pdf**.

*Acknowledgements.* The authors would like to gratefully acknowledge the assistance of Mario Rosas and Hugo Marengo, from the Geological Survey of Mendoza, for the help during the field survey. Many data and testimonies were collected thanks to the *Vialidad Nacional*, the Argentinean army section of Puente del Inca, the *guardaparques* of the Aconcagua Provincial Park, Mario Gonzales and Johnny. Reginald Hermanns and an anonymous referee permitted to substantially improve this paper.

Edited by: A. Günther
Reviewed by: R. Hermanns and another anonymous referee

## References

Baumann, V., Coppolecchia, M., González, M. A., Fauqué, L. E., Rosas, M., Altobelli, S., Wilson C., and Hermanns, R. L.: Landslide Processes in the Puente del Inca region, Mendoza, Argentina, in: Proceedings of the International Conference on Landslide Risk Management, edited by: Hungr, O., Fell, R., Couture, R., and Eberhardt, E., Vancouver, Canada, A.A. Balkema Publishers, London, 2005.

IPGP: Institut de Physique du Globe de Paris, Chile 2010 Earthquake, available at: http://www.ipgp.fr/~lacassin/Chile2010-7earthquake/Chile_2010_Earthquake.html (last access: 11 September 2010), 2010.

Keefer, D. K.: Landslides caused by earthquakes, Bull. Geol. Soc. Am., 95, 406–421, 1984.

Moreiras, S. M.: Landslide susceptibility zonation in the Rio Mendoza Valley, Argentina, Geomorphology, 60, 345–357, 2005.

Moreiras, S. M.: Análisis estadístico probabilistic de las variables que condicionan la inestabilidad de las laderas en los valles de los Ríos Las Cuevas y Mendoza, Rev. Asoc. Geol. Argent., 65(4), 780–790, 2009 (in Spanish).

Ramos, V. A.: The tectonics of the Central Andes; 30° to 33° S latitude, in: Processes in Continental Lithospheric Deformation, edited by: Clark, S. and Burchfiel, D., Geol. S. Am. S., 218, 31–54, 1988.

Ramos, V. A., Aguirre Urreta, M. B., Alvarez, P. P., Cegarra, M., Cristallini, E. O., Kay, S. M., Lo Forte, G. L., Pereyra, F., and Perez, D.: Geología de la región del Aconcagua: Provincias de San Juan y Mendoza, República Argentina, Dirección Nacional del Servicio Geológico, Subsecretaría de Minería de la Nación, Buenos Aires, Anales, 24(14), 387–422, 1996 (in Spanish).

Rodríguez, C. E., Bommer, J. J., and Chandler, R. J.: Earthquake-induced landslides: 1980–1997, Soil Dyn. Earthq. Eng., 18, 325–346, 1999.

SEGEMAR and MAP. authors: Baumann, V., Cegarra, M., Coppolecchia, M., Fauqué, L., González, M. A., Hermanns, R., Lo Forte, G., Rosas, M., Tchilinguirian, P., Videla, A., and Wilson, C.: Estudio geoscientífico aplicado al ordenamiento territorial en Puente del Inca, Provincia de Mendoza, Argentina, Unpublished report, SEGEMAR (Servicio Geológico y Minero Argentino) and MAP (Multinational Andean Project), Buenos Aires, 39 pp., 2007 (in Spanish).

Sepulveda, S. A., Astroza, M., Kausel, E., Campos, J., Casas, E. A., Rebolledo, S., and Verdugo, R.: New Findings on the 1958 Las Melosas Earthquake Sequence, Central Chile: Implication for Seismic Hazard Related to Shallow Crustal Earthquake in Subduction Zone, J. Earthq. Eng., 12(3), 432–455, 2008.

SSN: Servicio sísmico Universidad de Chile, http://ssn.dgf.uchile.cl/dbox/seismo.html, (last access: 8 April 2010), 2010 (in Spanish).

USGS: Magnitude 8.8 – Offshore Maule, Chile, National Earthquake Information Center, available at: http://earthquake.usgs.gov/earthquakes/recenteqsww/Quakes/us2010tfan.php, (last access: 11 September 2010), 2010a.

USGS: Magnitude 6.9 – Libertador O'Higgins, Chile, National Earthquake Information Center, available at: http://earthquake.usgs.gov/earthquakes/recenteqsww/Quakes/us2010tsa6.php, (last access: 11 September 2010), 2010.

USGS: Pager - M 6.2 - Libertador OHiggins, Chile, available at: http://earthquake.usgs.gov/earthquakes/pager/events/us/2010tgcz/index.html (last access: 11 September 2010), 2010c.

Vialidad Nacional: Tránsito Medio Diario Anual Proyectado Año 2009, Tramo acceso Puente del Inca – Las Cuevas, Dirección Nacional de Vialidad, División Tránsito, available at: http://transito.vialidad.gov.ar:8080/SelCE_WEB/intro.html (last access: 24 June 2010), 2009 (in Spanish).

Wick, E., Baumann, V., Michoud, C., Derron, M.-H., Jaboyedoff, M., Lauknes, T. R., Marengo, H., and Rosas, M.: Multirisk analysis along the Road 7, Mendoza Province, Argentina, EGU General Assembly Vienna, Austria, 2–7 May 2010, Vol. 12, EGU2010-4747-1, 2010.

Zavala, B., Hermanns, R., Valderrama, P., Costa, C., and Rosado, M.: Procesos geológicos e intensidad macrosísmica inqua del sismo de Pisco del 15/08/2007, Perú, Rev. Asoc. Geol. Argent., 65(4), 760–779, 2009 (in Spanish).