Erratum: Seismic hazard reappraisal from combined structural geology, geomorphology and cosmic ray exposure dating analyses: The Eastern Precordillera thrust system (NW Argentina) (Geophys. J. Int. vol. 150 (241-260))

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Corrigendum

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INTRODUCTION

In Siame *et al.* (2002) we integrated a combination of structural geology, geomorphology, and exposure dating approaches in order to improve earthquake source characterization and seismic hazard assessments of a major regional active reverse structure, the Villicùm-Pedernal thrust (San Juan region, NW Argentina). This approach allowed us to (1) constrain the Quaternary stress regime by inversion of geologically-determined slip vectors on minor or major fault planes; (2) analyse the geometry and the geomorphic characteristics of the Villicùm-Pedernal thrust; and (3) estimate uplift and shortening rates through the determination of *in situ* produced ^{10}Be cosmic ray exposure ages of abandoned and uplifted alluvial terraces. Along the studied fault zone, our results showed that the development of the Argentine Eastern Precordillera between 31°S and 32°S latitude is dominated by a reverse faulting stress regime characterized by a N110° ± 10° E trending σ_1-axis. The geomorphic study conducted along the Las Tapias fault segment, associated with cosmic ray exposure ages, showed that the minimum shortening rate calculated over the last ~20 kyr is at least on the order of 1 mm yr^{-1}. To compare this 20 kyr time-spanned tectonic deformation rate with the regional shortening rate caused by seismic deformation, an earthquake moment tensor sum was also calculated. Unfortunately, the published values for the moment tensor sum were erroneous resulting in an underestimation of the regional shortening rate produced by seismogenic deformation. The aim of this Corrigendum is thus to correct this erroneous value, and propose an additional value based on a longer time-window and larger volume of integration.

NEW SHORTENING RATE FORM THE SEISMIC MOMENT TENSOR SUM

In our previous paper, 12 shallow focal mechanism solutions (Table 1) were used over a time-period of about 23 yr. These events are located within a 45 × 100 × 30 km^3 volume centred on the Bermejo Valley between the Sierra Pie de Palo and Sierra Valle Fértil (Fig. 1), with a regional seismogenic depth of about 30 km (Smalley *et al.* 1993). Within this volume, the value of the horizontal component of the maximum compressional strain rate ($\dot{\varepsilon}_{ij}$Hmax) is 1.0×10^{-6} yr^{-1} instead of 6.47×10^{-7} yr^{-1} as reported in our previous paper due to an error in the calculation. Following the methodology defined by Súarez *et al.* (1983), a ~46 mm yr^{-1} rate of crustal deformation is thus calculated (and not 3 mm yr^{-1} as published in our paper) by multiplying the $\dot{\varepsilon}_{ij}$Hmax value times the width of the deformed area, measured in the direction of $\dot{\varepsilon}_{ij}$Hmax(N93°E) (Table 2).

Since the publication of our paper, several focal mechanism solutions have been published allowing us to calculate a new moment tensor sum (Table 3) on a slightly longer time span (27 yr instead of 23 yr). Moreover, a reevaluation of the volume where this moment tensor sum should be integrated to estimate a shortening rate lead us to consider a volume of 93 × 123 × 30 km^3 which is more representative of the deforming region. Within this volume, the $\dot{\varepsilon}_{ij}$Hmax value is 3.4×10^{-7} yr^{-1} and oriented N93°E (Table 3). In terms of orientation, this result is quite similar to the previous one and still consistent with the N110° ± 10° E-trending σ_1 compressive axis determined from fault slip kinematics (Siame *et al.* 2002) as well as the N107°E-trending σ_1 axis calculated by Régnier *et al.* (1992) using Sierra Pie de Palo crustal microseismicity. In terms of shortening rate the new value that can be calculated from above following the methodology defined by Súarez *et al.* (1983), is ~32 mm yr^{-1} rate, which is of the same order of magnitude as the corrected value above.

Table 1. List of the focal mechanism solutions used for the calculation.

#	Date	Lat	Lon	Depth	Scalar Moment	*Mw*	Nodal Plane 1			Nodal Plane 2			T axis	
		(°S)	(°W)	(km)	(Nm)		strike	dip	slip	strike	dip	slip	az	pl
1	11/23/77*	31.0	67.8	13	1.86E+20	7.4	183	44	90	4	46	90	289	89
2	12/6/77*	31.2	67.7	19	7.95E+17	5.9	181	37	82	11	54	96	306	80
3	12/10/77*	31.2	67.6	39	1.92E+17	5.5	199	29	117	348	65	76	232	67
4	11/24/77*	31.3	67.6	33	2.81E+17	5.6	190	34	91	8	56	89	275	79
5	11/28/77*	31.7	67.8	36	2.84E+17	5.6	150	52	27	43	69	139	0	43
6	11/28/77*	31.6	67.5	16	2.02E+18	6.1	182	21	106	345	70	84	246	64
7	01/17/78*	31.3	67.9	24	1.07E+18	6.0	142	66	12	47	79	156	2	25
8	08/21/78*	31.3	67.8	10	1.16E+17	5.3	218	9	79	49	81	92	321	54
9	08/30/79*	31.4	67.6	32	2.03E+17	5.5	354	31	35	233	73	116	176	55
10	04/9/80*	31.7	67.5	10	1.28E+17	5.3	340	37	136	108	65	61	336	59
11	11/10/80*	31.6	67.5	21	3.60E+17	5.6	133	31	49	358	67	111	301	62
12	08/11/86*	30.9	67.7	27	1.33E+17	5.4	187	49	167	285	80	41	155	35
13	03/25/88	31.4	68.0	24	7.95E+16	5.2	360	65.8	51	243	45	144	224	52
14	07/2/02	31.1	67.8	27	2.17E+17	5.5	156	40	15	54	81	129	1	41
15	04/27/02	30.9	67.4	33	8.02E+16	5.2	341	41	31	227	71	127	178	50

All focal mechanism solutions are Harvard CMT solutions except #13 from Régnier *et al.* (1992). * indicates CMT solutions used by Siame *et al.* (2002). Keys: az, azimuth; pl, plunge.

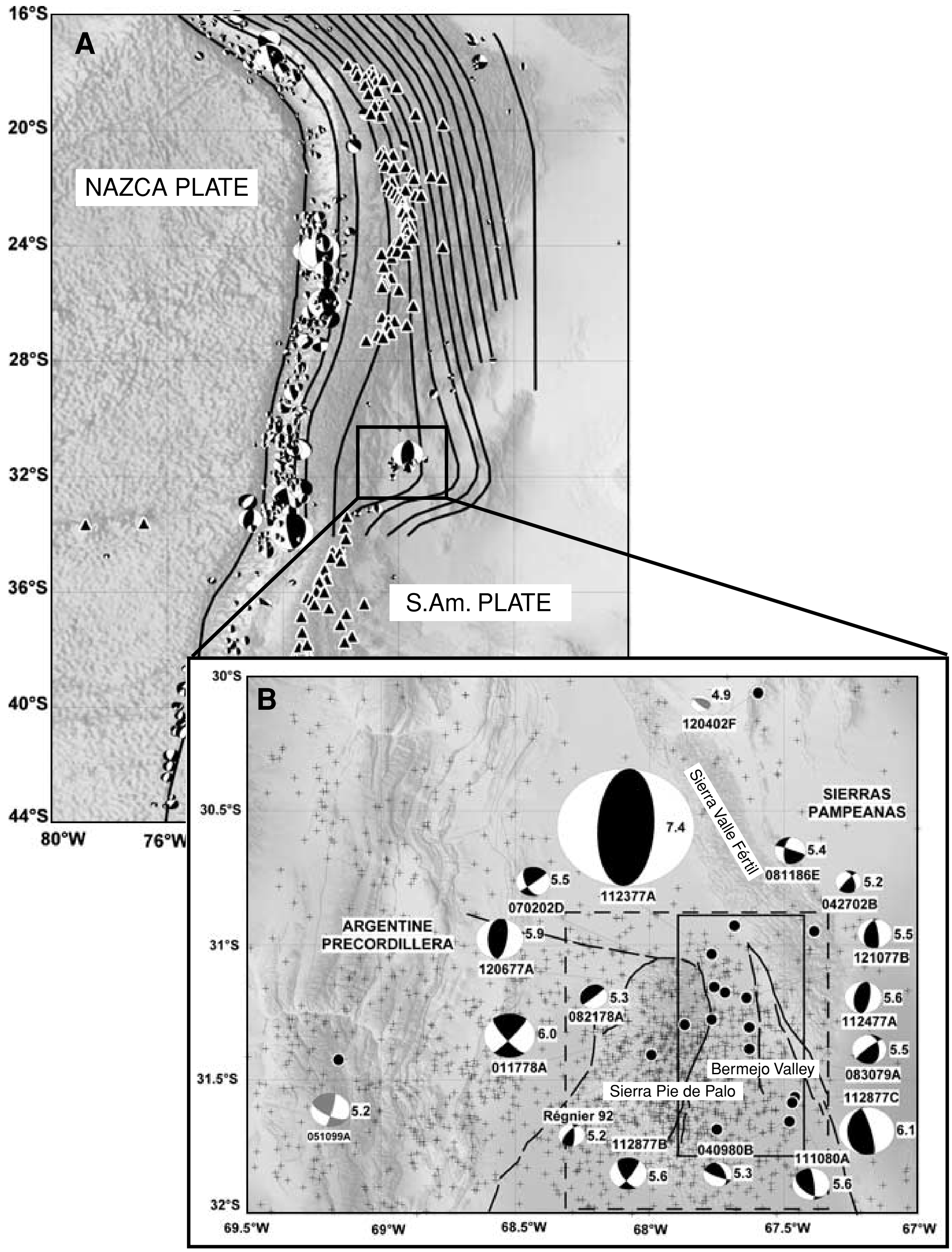

Figure 1. A: Map of the Central Andes using SRTM30 (Shuttle Radar Topography Mission; 30 arcsec/1 km resolution; US Geological Survey; EROS data center) topographic data and showing Harvard centroid moment tensor (Hcmt) solutions of shallow events (<70 km; $Mw > 5.0$) as well as the isodepths of the Nazca slab (after Cahill & Isacks 1992). B: Map of the San Juan region using SRTM90 (Shuttle Radar Topography Mission; 3 arcsec/90 m resolution; US Geological Survey; EROS data center) topographic data and showing the Hcmt solutions (black beachballs) used for the moment tensor sum calculation, NEIC (National Earthquake Information Center, US Geological Survey) preliminary determination events (<70 km; black crosses), and the trend of the main active tectonic structures in the Sierra Pie de Palo area (black solid lines). Solid and dotted boxes delineate respectively, the Siame *et al.* (2002) and the area used in this note, where the moment tensor sum calculation is integrated to estimate a regional shortening rate due to seismic contribution.

Table 2. Numerical results for the moment tensor sum in the Pie de Palo area.

	P-axis			*N*-axis			*T*-axis		
	m_P value (Nm)	az	pl	m_N value (Nm)	az	pl	m_T value (Nm)	az	pl
Siame *et al.* (2002)	-1.9×10^{20}	93	1.3	1.1×10^{18}	183	0.5	1.9×10^{20}	295	88.5
This Corrigendum	-1.9×10^{20}	93	1.3	1.1×10^{18}	183	0.5	1.9×10^{20}	295	88.5

P, *N*, and *T* axes are the compressional, neutral and tensional principal axes of the moment tensor. The orientation of these axes coincides with the orientation of the eigenvectors of the moment tensor. *P* coincides with the eigenvector with the smallest value (i.e. m_P), N to the eigenvector with the intermediate value (i.e. m_N), and *T* with the eigenvector with the largest value (i.e. m_T). Keys: az, azimuth; pl, plunge. Note: no difference is evidenced when adding focal mechanism solutions 13, 14 and 15 to those used by Siame *et al.* (2002).

Table 3. Numerical results for the regional deformation rate due to seismic contribution.

	Seismic moment sum value (Nm)	Deformed volume (km^3)	Time span (yr)	$\dot{\varepsilon}_{ij}$Hmax (yr^{-1})	Shortening rate (mm yr^{-1})
Siame *et al.* (2002)	1.9×10^{20}	45 × 100 × 30	23	$1.0 \times 10^{-6*}$	45.9**
This Corrigendum	1.9×10^{20}	93 × 123 × 30	27	3.4×10^{-7}	31.8

*$\dot{\varepsilon}_{ij} H_{\max}$ corrected value (compared to 6.47×10^{-7} yr^{-1} in Siame *et al.* 2002).
**Shortening rate corrected value (compared to 3 mm:yr in Siame *et al.* 2002).

CONCLUSIONS

In this Corrigendum, we corrected the $\dot{\varepsilon}_{ij}$Hmax value published in our previous paper and proposed a reevaluated value, integrated over a larger volume and time span. The corrected $\dot{\varepsilon}_{ij}$Hmax value implies a reevaluation of the seismic rate of deformation which is one order of magnitude greater than the previously published value (∼32 mm yr^{-1} instead of ∼3 mm yr^{-1}). This estimate has to be considered as a lower bound since fault creep, visco-elasticity deformation, and contribution due to earthquakes with magnitude lower than Mw 5.0 are neglected.

When compared to the shortening rate derived from our geomorphic study (Siame *et al.* 2002) along the active front of Eastern Precordillera (0.8 ± 0.5 mm yr^{-1}), interestingly the shortening rates calculated from the seismic moment sums are one order of magnitude greater. On a longer time scale, previous geological studies have shown that the deformation front of the Argentine Precordillera has experienced a total shortening of about 40 km and 90 km during the last 5 Ma and 20 Ma, respectively (Jordan *et al.* 1993; Allmendinger *et al.* 1990), implying mean geological slip rates ranging from 5 to 10 mm yr^{-1}. When comparing these slip rates, integrated over different time and space scales, discrepancies may be reconciled by arguing that mean geological slip rates have to be taken up by several individual thrusts that may act simultaneously or individually during the last 20–5 Ma, whereas the slip rate determined on the Eastern Precordillera is taken up on one single thrust. Even if one argued that the available time window may not be representative, the analysis of the focal solutions available for the last 27 yr shows that the seismic contribution may be one order of magnitude greater than that shown by both geological and geomorphic rates (Siame *et al.* 2002). Considering the historical seismicity, the San Juan region has experienced four earthquakes with $M \approx 7$ during the last 60 yr. Thus, considering one $M \approx 7$ in 27 yr is probably realistic to evaluate the seismic strain released in the San Juan Basin during the second half of the 20th century. The high crustal seismic rate of deformation may reflect that the San Juan region has experienced a cluster of events, i.e. a seismic crisis during the last century resulting in active deformation around the Sierra Pie de Palo.

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REFERENCES

Allmendinger, R.W., Figueroa, D., Snyder, D., Beer, J., Mpodozis, C. & Isacks, B.L., 1990. Foreland shortening and crustal balancing in the Andes at 30°S latitude, *Tectonics,* **9,** 789–809.

Cahill, T. & Isacks, B.L., 1992. Seismicity and shape of the Nazca Plate, *J. geophys. Res.,* **97,** 17 503–17 529.

Jordan, T.E., Allmendinger, R.W., Damanti, J.F. & Drake, R., 1993. Chronology of motion in a complete thrust belt: the Precordillera, 30–31°S, Andes Mountains, *J. Geol.,* **101,** 135–156.

Régnier, M., Chatelain, J.-L., Smalley, R., Jr, Chiu, J.-M., Isacks, B.L. & Araujo, M., 1992. Seismotectonics of the Sierra Pie de Palo, a basement block uplift in the Andean foreland, *Bull. seism. Soc. Am.,* **82,** 2549–2571.

Siame, L.L., Bellier, O., Sébrier, M., Bourlès, D.L., Leturmy, P., Perez M. & Araujo, M., 2002. Seismic hazard reappraisal from combined structural geology, geomorphology and cosmic ray exposure analyses: the Eastern Precordillera thrust system (NW Argentina), *Geophys. J. Int.,* **150,** 241–260.

Smalley, R., Jr, Pujol, J., Régnier, M., Chiu, J.-M., Chatelain, J.-L., Isacks, B.L., Araujo, M. & Puebla, N., 1993. Basement seismicity beneath the Andean Precordillera thin-skinned thrust and fold belt and implications for crustal and lithospheric behavior, *Tectonics,* **12,** 63–76.

Súarez, G., Molnar, P. & Burchfield B.C., 1983. Seismicity, fault plane solutions, depth of faulting and active tectonics in the Andes of Peru, Ecuador and Southern Colombia, *J. geophys. Res.,* **88,** 403–428.