Observatorio San Calixto – National Seismic, Infrasound and Strong Motion Network of Bolivia (Plurinational State of)

Mayra Nieto, Bastien Joly, Gonzalo A. Fernández M, Felipe Condori, Jonas Baldivieso, Teddy Griffiths, Walter Arce and Zulma Machaca

Observatorio San Calixto, La Paz

Bolivia (Plurinational State of)

Excerpt from the
Summary of the Bulletin of the International Seismological Centre:

Nieto, M., Joly, B., Fernández M, G.A., Condori, F., Baldivieso, J., Griffiths, T., Arce, W. and Machaca, Z. (2021), Observatorio San Calixto – National Seismic, Infrasound and Strong Motion Network of Bolivia (Plurinational State of), *Summ. Bull. Internatl. Seismol. Cent.*, July – December 2018, *55*(II), pp. 29–49, `https://doi.org/10.31905/THGTN1JD`.

5

Operational Procedures of Contributing Agencies

5.1 Observatorio San Calixto – National Seismic, Infrasound and Strong Motion Network of Bolivia (Plurinational State of)

Mayra Nieto[1], Bastien Joly[2], Gonzalo A. Fernández M [1], Felipe Condori [1], Jonas Baldivieso [1], Teddy Griffiths [1], Walter Arce [1] and Zulma Machaca [1]

(1) Observatorio San Calixto, La Paz, Bolivia (Plurinational State of)

(2) Commissariat à l'Energie Atomique / Département Analyse, Surveillance, Environnement, France

Team of Observatorio San Calixto in La Paz, Bolivia

The history of seismic studies at the Plurinational State of Bolivia begins around the first decade of the past century and is strongly related to the foundation of Observatorio San Calixto (OSC) which is the only institution committed to seismology in Bolivia since 1st May 1913. The Bolivian Jesuit Company took the responsibility to install and operate a seismic station at La Paz, Bolivia, after the suggestion was made by the Second Seismology General Assembly held in 1911.

Thanks to the commitment of the Jesuit Principals that ran our institution (Pierre M. Descotes SJ from 1913 to 1964, Ramon Cabré SJ from 1964 to 1993 and Lawrence Drake SJ from 1993 to 2000) long term agreements were made on behalf of seismology in our country. The first one is with the Air Force Technical Application Center (AFTAC) and United States Geological Survey (USGS) for contributing real time data to the World Wide Standard Seismological Network and to the Comprehensive Test Ban Treaty Organization (CTBTO). The second agreement is with formerly "Laboratoire de Geophysique" (LDG) that later became "Commissariat à l'Energie Atomique / Département Analyse, Surveillance, Environnement" (CEA/DASE) in France. Both agreements allowed us to improve the study of seismology in our country.

Nowadays, our seismic network is called "Red Sismologica Observatorio San Calixto" (RS-OSC) and is composed of our own stations as well as stations installed by collaborative partners such as CEA/DASE from France for stations BBOB, BBOD, BBOE, BBOJ (short period sensors), SIV (long period station) and an infrasound array (IS08). AFTAC from the U.S contributes one high gain borehole broadband seismic sensor, another high gain borehole short period (LPAZ and LPAZ1) and four short period sensors (SOEP, SOEH, SOEV, REDDE). Data from all of these stations is shared with the seismological community. The University of Sao Paulo (USP) from Brazil provides three broadband sensors (BBSD, BBRT, BBPS). Finally, our own seismic stations are four broadband stations (SOEJ, SOEO, SOEA, SOET) and three strong motion stations (AOEA, AOES, AOVT). Figure 5.6 shows our seismic network configuration with all stations contributing to the seismic and infrasound monitoring over the country.

In this document we would like to highlight the history of our seismic networks and the importance of each one that contributes to the geophysics, seismology and earthquake engineering sciences in our country.

5.1.1 Local Seismicity

The seismic activity in Bolivia is strongly related to the subduction process between the Nazca (oceanic) and South American (continental) plates, where the former subducts underneath the latter along the Peru – Chile trench in ENE-WSW direction with a rate of 78 mm/year (*DeMets et al.,* 1994), (see detailed explanations at e.g., *Ward et al.*, 2013; *Eichelberger et al.*, 2015; *Ryan et al.*, 2016; *Anderson et al.*, 2017).

Bolivia's seismicity is composed of inter-plate and shallow seismicity. Inter-plate seismicity is related to intermediate and deep earthquakes which are linked to the subduction process and can reach depths of 650 km. Below the central part of our country, seismicity caused by the subduction process occurs at depths from 100 to 350 km, and then continues at depths from 500 to 700 km.

The other seismic source, shallow seismicity, is related to crustal deformation and is located at the Bolivian Orocline that is composed of the Eastern and Sub Andes belt Cordillera. The crust from West to East shows a thickness variation from 60 to 45 km and a very complex variation from North to South (*Wigger et al.*, 1994). Moreover, more distant seismic sources (from Chile, Peru and Argentina) are also felt and represent a hazard for us. Figure 5.1 represents all seismological sources from our country.

5.1.2 History of Seismic, Strong Motion and Infrasound Network

First Generation

Seismic Station LPZ (1913-1964):

Installed in 1913, LPZ was the first seismic station of the Plurinational State of Bolivia, located at the San Calixto school crypt at the city of La Paz. The first mechanical equipment had two horizontal bifilar pendulums, the same as for the Mainka seismograph, and were built by Pierre M. Descotes SJ (first principal) and Tortosa and Lizarralde from the Jesuit Company (Fig. 5.2). The masses weighed 1500 kg (vertical component), 2000 kg (N-S component) and 3500 kg (E-W component). The station worked until 1964.

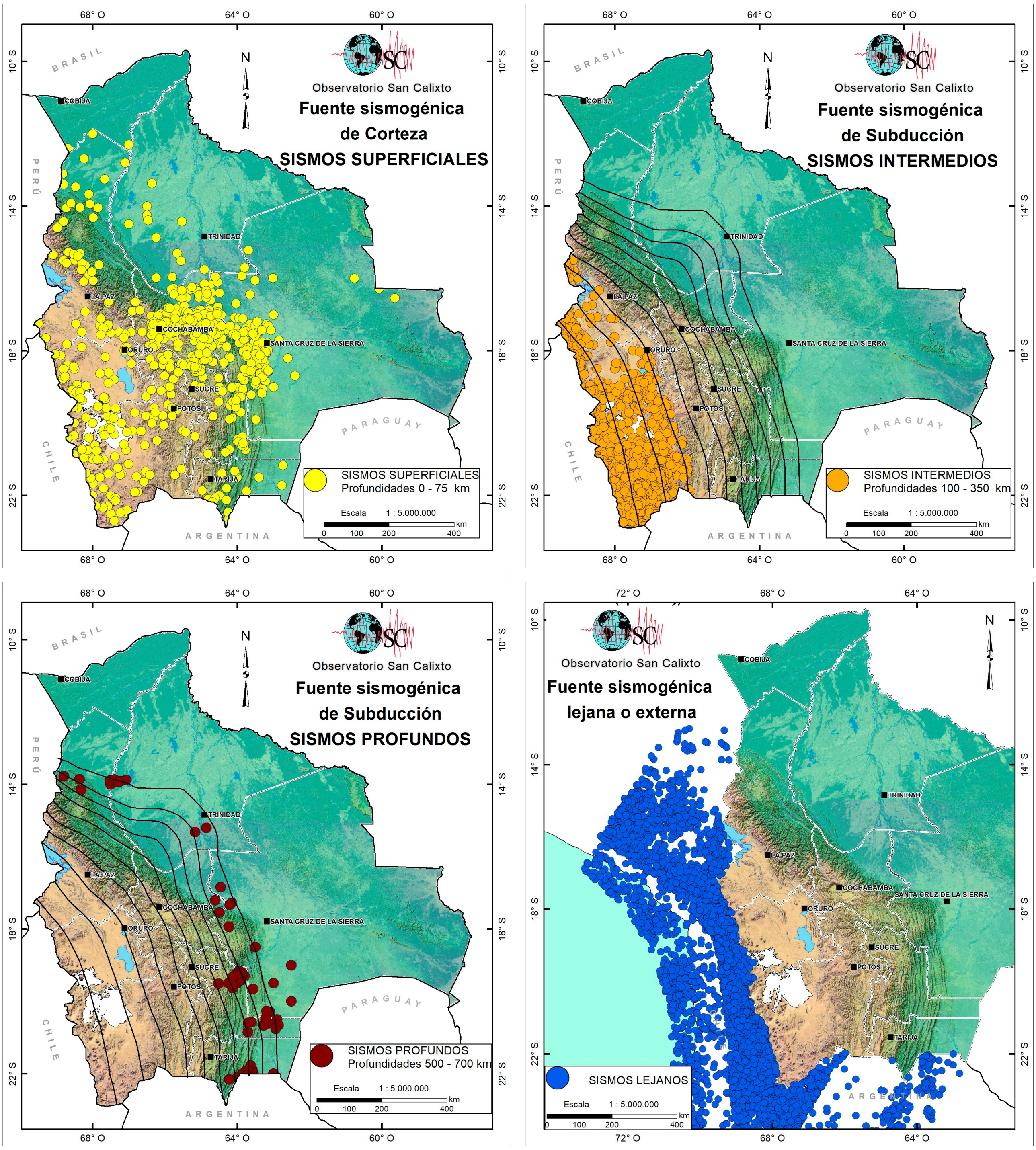
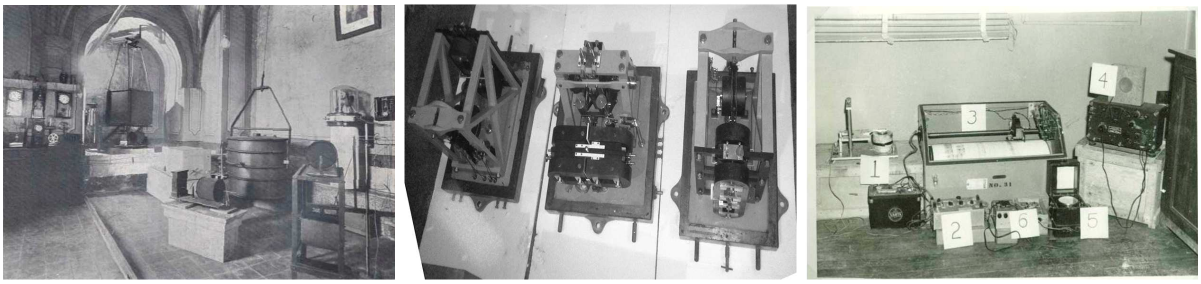


Figure 5.1: *Seismicity of Bolivia from 1650 to 2018 (Mw ≥ 4).* Top left: *Yellow circles are shallow seismicity (depths from 0 to 75 km),* top right: *orange circles are intermediate depth seismicity (depths from 100 to 350 km),* bottom left: *red circles are deep seismicity (depths from 500 to 700 km),* bottom right: *blue circles are distant seismic sources felt in our country.*



(a) Modified Maika seismometer (b) Galitzin-Wilip sensors (c) Spregnether seismic sensor

Figure 5.2: *Different sensors at LPZ seismic station. (*Minaya et al.*, 2013).*

The first Principal was devoted to reading the seismograms to create the seismic bulletins, which were shared with other Jesuit observatories in Spain and France, for that reason he was recognized by the international community. In 1930 a new seismic sensor "Galitzin and Wilip" was installed in the same place and a new helicorder drum was also set up to record the seismograms on film paper. Years later, Gutenberg and Richter assessed that LPZ was one of the best stations in the world and complimented the operators for their great work: "A further improvement followed the installation at La Paz (Bolivia) with reports beginning May 1, 1913. La Paz at once became, and still remains, the most important single seismological station of the world. This is a consequence of its isolated location, the sensitive instruments, and the great care with which records were interpreted and reports issued under the direction of Father Descotes." (*Gutenberg and Richter*, 1949). In 1958 the United States Coast and Geodetic Survey donated a short period vertical component sensor (Spregnether) that was installed in the same place (Fig. 5.2). In 1963 due to the increasing background noise of La Paz LPZ needed to be placed outside the city (*Cabre*, 1974; *Ayala*, 1997).

Estación Sísmica Sucre (1926 - 1948):

In 1926, the same seismic equipment as at LPZ was installed at the "Sagrado Corazón" school (Chuquisaca – Sucre) with the station code SUC. Unfortunately, the earthquake of 27th March 1948 with a magnitude of 6.1 destroyed the sensors when the roof collapsed and there was no solution to fix the mechanical parts of the seismograph (*Cabre and Vega*, 1995).

Second Generation

Seismic Station LPB (1962 - 1997):

In 1962, a new seismic station was installed with the code LPB, located at Seguencoma neighbourhood in La Paz city. This station was part of the World-Wide Standard Station Network (WWSSN) and was supported by the U.S. Coast and Geodetic Survey (*Cabre*, 1965). It was composed of a Benioff short period three component sensor and Spregnether long period three component sensors (Fig. 5.3). A helicorder was used to register the seismograms. LPB shared bulletin data with the international seismological community until 1997, when the station was closed due to the increased background noise of the city (*Ayala*, 2001).

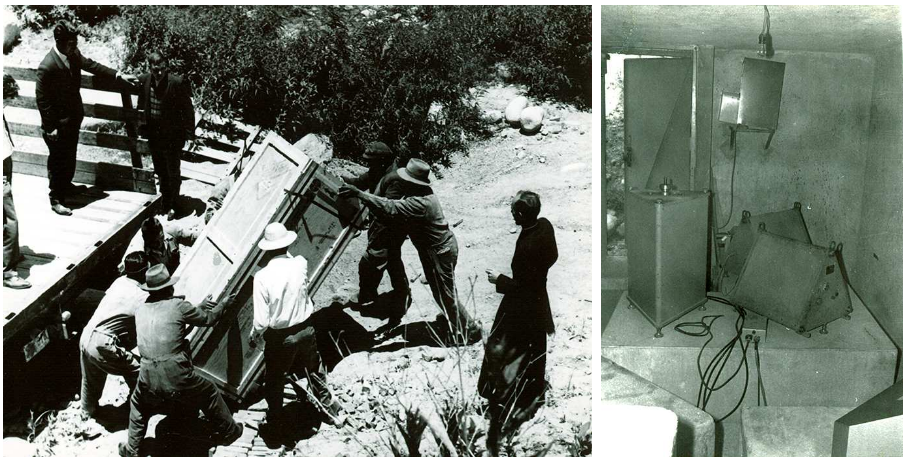


Figure 5.3: Left: *LPB installation at Seguencoma, La Paz - Department,* Right: *Benioff short period seismometer at Seguencoma. (*Minaya et al.*, 2013).*

Andina Seismic Network (1960-1976):

In 1960 within the framework of the International Geophysical year (1957 – 1958) the Earth Magnetism Carnegie Institution of Washington suggested to donate six semi portable seismic sensors to Bolivia. They were installed over the country until 1976. The aim was to gain a better knowledge of the seismicity in our country (*Cabre*, 1974; *Ayala*, 2001).

Geophysical Network of Peñas (1963-1975):

In 1965 the Observatorio San Calixto was in charge of operating and maintaining seven seismic stations (Geothech) financed by the Advanced Research Projects Agency (ARPA) from the U.S. They were installed in the town of Peñas (La Paz – Department). In 1966 an infrasound array was also installed that composed of four elements. In 1970 a set of three elements was added. The seismic network and the infrasound array registered the data on helicorder drums and film paper until 1975 (*Cabre, 1974; Ayala, 2001).*

Third Generation

Tupiza Seismic Station (1985 - 1987):

In 1985 cooperation between the Free University of Berlin and Yacimientos Petroliferos Fiscales Bolivianos allowed us to install a seismic station at Tupiza town (Potosi Department). The code was TZP and it worked until 1987 (*Ayala*, 2001).

Cochabamba Seismic Network (1998 - 1998):

In 1998 a set of three seismic stations was donated by the Japan International Cooperation Agency (JICA) to be installed at Cochabamba Department. The codes assigned to the stations were: BBBO (Bombeo), BAPC (Apacheta) and BIKK (C. Kollo). The waveforms were sent by VHF radio link to

Juan XXIII school located at the center of the city. Unfortunately, vandalism prevented the seismic network operating fully.

Seismic and Infrasound Network CEA/DASE (1975 – Recent):

In 1975, thanks to an agreement with the "Laboratoire de Geophysique" (LDG) in France and the Paris University a long term collaboration began. Years later, the "Commissariat à l'Energie Atomique / Département Analyse, Surveillance, Environnement" (CEA/DASE) assumed the responsibility to continue this project in coordination with our institution.

The same year, three seismic stations (short period, one component, high gain) were installed in Zongo valley (La Paz – Department) with the station codes: BBOA (Zongo), BBOB (Banderani) and BBOC (Huaylipaya). Data was sent in near real time by UHF radio links to our data center located at La Paz city. Years later, from 1982 to 1993, this network was expanded and four more stations were installed: BBOD (Gloria), BBOE (Chanca), BBOF (Collana) and BBOG (Alto Peñas). Moreover, a three-component high gain short period sensor was installed at San Ignacio de Velazco (SIV) at Santa Cruz Department.

In 1999, the CEA/DASE installed an infrasound array of four elements in Peñas town. This array is certified by CTBTO. The station code is IS08 and data is sent in near real time to our data center (La Paz City), the International Data Center (IDC) and the French national data center (CEA/DASE). Data from this station contributed a lot to atmospheric modelling (*Ayala*, 2001; *LePichon et al.*, 2005, 2006).

Fourth Generation

BID Seismic Network (2010-2014):

The "Banco Interamericano del Desarrollo (BID)" financed the installation of 18 seismic stations over the country in cooperation with the national telecom company (ENTEL). The data arrived at our data center through 3G mobile communication (*Minaya et al.*, 2012).

Figure 5.4: Left: *BBOI short period station,* Middle: *BBOK short period station,* Left: *BBOM short period station.*

Figure 5.5: Left: *ZOBO seismic station (Huayna Potosí mountain Tunnel),* Right: *LPAZ seismic station (Milluni). (*Minaya et al.*, 2013).*

Short Period Seismic Network CEA/DASE:

In order to expand the seismic network and to strengthen the agreement with CEA/DASE a new set of seismic stations were installed from 2006 to 2007: BBOI (Colquencha), BBOM (Mururata), BBOK (Pakuani) and BBOJ (Jacaque) (Fig. 5.4). However, due to some incidents (natural and man-made) only BBOJ remained part of the Short Period Seismic network.

Fifth Generation

High Gain Seismic Station LPAZ (1972 – Recent):

In 1972 the National Oceanic and Atmospheric Administration from the U.S supported the installation of a high gain long period seismic sensor (HGLP) around Zongo town (La Paz Department). A 70 m tunnel was built to get a good signal to noise ratio and high-quality waveforms. The tunnel was located at the foot of "Huayna Potosi Mountain". In 1976, this seismic station was upgraded to be part of the Advanced Seismological Research Observatory and the code changed to ZOBO. (*Cabré*, 1988).

In 1993, ZOBO was closed but a major upgrade was done and the station was reopened as LPAZ. A new place was found around Miluuni town (La Paz – Department) where two boreholes were drilled to install a three-component broadband sensor and a vertical component short period sensor (Figure 5.5). The station became part of the Global Telemetered Seismograph Network (GTSN) and data was exchanged with the U.S. National Data Center and AFTAC.

In 1999, this seismic station was certified by CTBTO under the code: PS06, (Primary Station 06). Since then, the data is passed to IDC and becomes open data through the Incorporated Research Institutions for Seismology (IRIS). The data is transmitted by a VSAT C – band in near real time to our data center (*Cabre*, 1974; *Ayala*, 2001).

Long Period Seismic Station – SIV:

In 1998 a lot of effort was made to install a seismic station in coordination with CEA/DASE in the Sub Andes region (Santa Cruz - Department). Initially it was composed of three short period sensors and installed in San Ignacio de Velazco. A central facility was also installed at the Santa Clara Monastery. The data were saved on floppy disk and then sent to our main data center. In 1998 a big upgrade was made at the station and three high gain long period sensors were installed. The data was transmitted from the station to the central facility in Santa Clara Monastery by UHF radio link and from there was sent to our data center and the French national data center through a VSAT C-band. The assigned station code was SIV. In 2008, this station was certified by CTBTO with the code AS08 (Auxiliary Station 08).

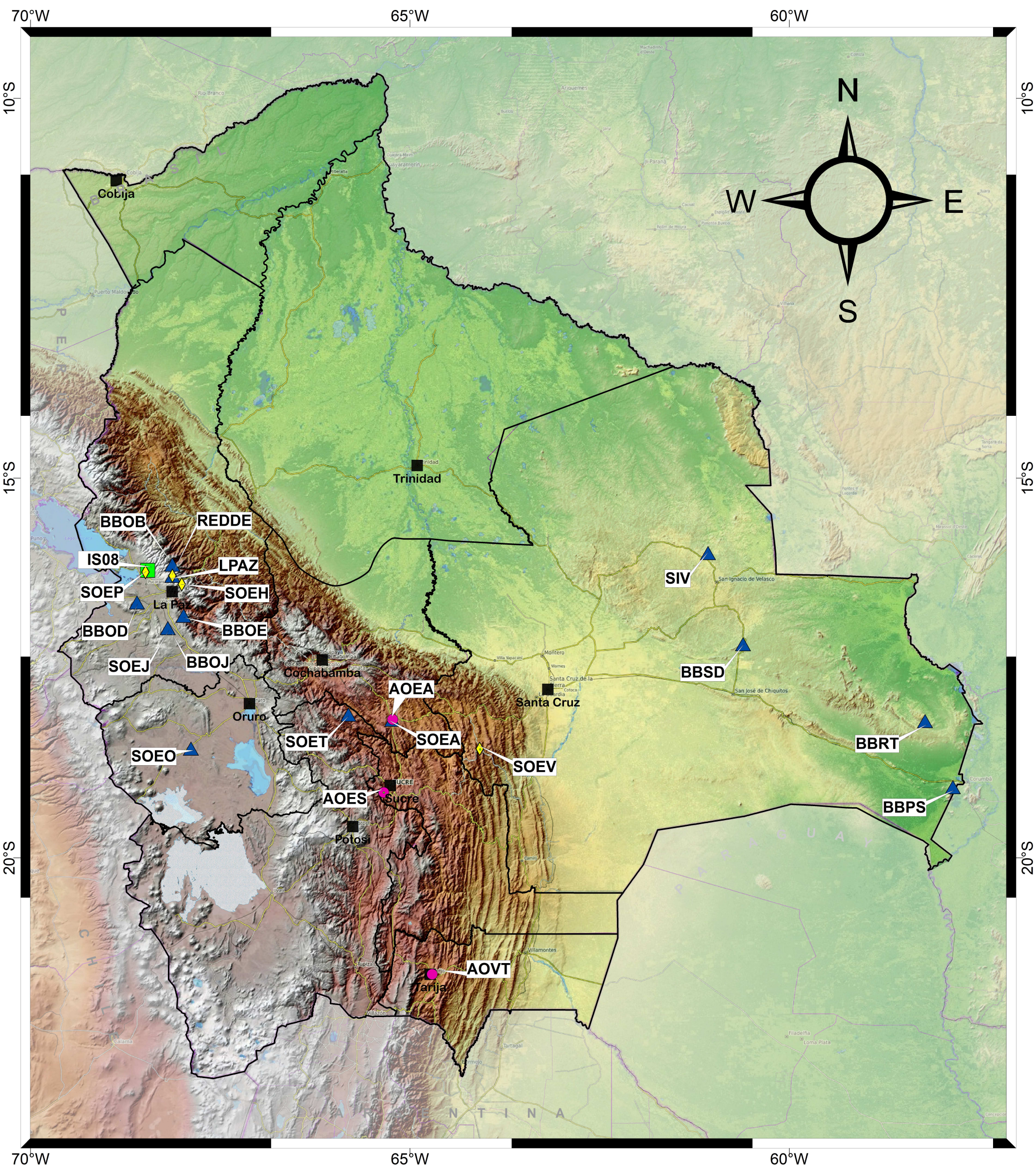


Figure 5.6: *Seismological Network Observatorio San Calixto (RS-OSC). Blue triangles are stations of the local seismic network, magenta circles are stations of the local accelerometer network and yellow diamonda are stations of the infrasound permanent network.*

Observatorio San Calixto Seismic Network (RS-OSC):

In order to improve the seismic location within our country and enhance the research in seismology we decided to install four broadband Guralp-6TD and three strong motion Guralp-5C sensors. With a Raspberry Pi board that functions as 3G data bridge data is sent in real time to our data center. The codes for the broadband sensors are SOEJ, SOET, SOEO and SOEA and are distributed over the country. The strong motion stations are AOVT, AOES and AOEA. This small seismic network is called "Red Sismologica Observatorio San Calixto" (RS-OSC) and is shown in Figure 5.6 (*Schamberger et al.*, 2016).

Table 5.1 summarises the seismic stations installed in Bolivia over time.

Table 5.1: *Current (Seismic station installed in Bolivia along the time supported by different projects (some temporary and others permanent). OSC = Observatorio San Calixto, IGB = Instituto Boliviano de Geofisica, WWSSN/USGS = World Wide Standardized Seismograph Network/ United States Geological Survey, ARPA = Advanced Research Projects Agency, CEA/DASE = Commissariat à l'Energie Atomique / Département Analyse, Surveillance, Environnement, RS-OSC = Red Sismica Observatorio San Calixto, JICA = Japan International Cooperation Agency, BID = Banco Interamericano de Desarrollo, AFTAC/USGS = Air Force Technical Application Center / United States Geological Survey, USP = Universidade de Sao Paulo*

	Name	Code	Operating Dates	Lat / deg	Lon / deg	Elev. / m	Geomorph. Region	Main Characteristics	Belongs to
1	Ciudad de La Paz	LPZ	1913-1964	-16.495	-68.133	3651	Eastern Cordillera	1913: San Calixto Seismograph 1500 kg (LP:Z)	OSC
2	Ciudad de La Paz	LPZ	1913-1964	-16.495	-68.133	3651	Eastern Cordillera	1913: Mainka Modified 2000 kg (LP:N)	OSC
3	Ciudad de La Paz	LPZ	1913-1964	-16.495	-68.133	3651	Eastern Cordillera	1913: Mainka Modified 3500 kg (LP:E)	OSC
4	Ciudad de La Paz	LPZ	1930-1958	-16.495	-68.133	3651	Eastern Cordillera	1930: Galitzin-Wilip Seismic Sensor (LP:ZNE)	OSC
5	Ciudad de La Paz	LPZ	1958-1964	-16.495	-68.133	3651	Eastern Cordillera	1958: Sprengnether Seismic Sensor (SP:Z)	OSC
6	Ciudad de Sucre	SUC	1926-1948	-19.047	-65.264	2796	Eastern Cordillera	1926: San Calixto Seismic Sensor 1500 kg (SP:Z)	OSC
7	Ciudad de Sucre	SUC	1926-1948	-19.047	-65.264	2796	Eastern Cordillera	1926: Mainka Modified 3000 kg (LP: NE)	OSC
8	Cochabamba	CCH	1960-1962	-17.458	-66.121	2634	Eastern Cordillera	1960: Wilson-Lamison Seismic Sensor (SP:Z)	IGB
9	Cochabamba	CCH	1963-1975	-17.458	-66.121	2634	Eastern Cordillera	1963. Wilson-Lamison Seismic Sensor (SP:Z)	IGB
10	Coroico	CRO	1961-1962	-16.183	-67.720	1422	Eastern Cordillera	1961: Wilson-Lamison Seismic Sensor (SP:Z)	IGB
11	Mallasilta	MLL	1961-1961	-16.554	-68.111	3407	Eastern Cordillera	1961: Wilson-Lamison Seismic Sensor (SP:Z)	IGB
12	Peñas	PNS	1961-1965	-16.232	-68.513	4057	Altiplano	1961: Wilson-Lamison Seismic Sensor (SP:Z)	IGB

Continued on next page

	Name	Code	Operating Dates	Lat / deg	Lon / deg	Elev. / m	Geomorph. Region	Main characteristics	Belongs to
13	Sicasica	SCS	1961-1967	-17.285	-67.815	3897	Altiplano	1961: Wilson-Lamison Seismic Sensor (SP:Z)	IGB
14	Desaguadero	DSG	1961-1965	-16.559	-69.025	3839	Altiplano	1961: Wilson-Lamison Seismic Sensor (SP:Z)	IGB
15	Tarija	TEU	1964-1968	-21.513	-64.776	2004	Eastern Cordillera	1964: Wilson-Lamison Seismic Sensor (SP:Z)	IGB
16	Samaipata	SMB	1964-1966	-18.181	-63.875	1643	Subandean zone	1964: Wilson-Lamison Seismic Sensor (SP:Z)	IGB
17	Riberalta	RTA	1965-1967	-11.007	-66.078	136	Chaco Beniana plain	1965: Wilson-Lamison Seismic Sensor (SP:Z)	IGB
18	Chacaltaya	CHA	1966-1967	-16.346	-68.125	5261	Eastern Cordillera	1966: Wilson-Lamison Seismic Sensor (SP:Z)	IGB
19	Harca	HAA	1970-1971	-16.083	-68.042	1757	Eastern Cordillera	1970: Wilson-Lamison Seismic Sensor (SP:Z)	IGB
20	Zongo	ZLPB	1970-1971	-16.269	-68.119	4439	Eastern Cordillera	1970: Wilson-Lamison Seismic Sensor (SP:Z)	IGB
21	Charaña	CHÑ	1976-1976	-17.555	-69.442	4097	Western Cordillera	1976: Wilson-Lamison Seismic Sensor (SP:Z)	IGB
22	Huachacalla	HUG	1976-1976	-18.770	-68.283	3814	Altiplano	1976: Wilson-Lamison Seismic Sensor (SP:Z)	IGB
23	Seguencoma	LPB	1962-1997	-16.533	-68.098	3294	Eastern Cordillera	Sprengnether Seismic sensor (LP:ZNE)	WWSSN/ USGS
24	Peñas	Z-1	1963-1975	-16.249	-68.494	4254	Altiplano	1963 - 1975: Johnson-Matheson SP:Z (Peñas Seismic Network)	ARPA
25	Peñas	Z-2	1963-1975	-16.249	-68.491	4159	Altiplano	1963 - 1975: Johnson-Matheson SP:Z (Peñas Seismic Network)	ARPA
26	Peñas	Z-3	1963-1975	-16.258	-68.480	3987	Altiplano	1963 - 1975: Johnson-Matheson SP:Z (Peñas Seismic Network)	ARPA
27	Peñas	Z-4	1963-1975	-16.268	-68.475	3978	Altiplano	1963 - 1975: Johnson-Matheson SP:Z (Peñas Seismic Network)	ARPA
28	Peñas	Z-5	1963-1975	-16.264	-68.491	4088	Altiplano	1963 - 1975: Johnson-Matheson SP:Z (Peñas Seismic Network)	ARPA
29	Peñas	Z-6	1963-1975	-16.266	-68.497	3964	Altiplano	1963 - 1975: Johnson-Matheson SP:Z (Peñas Seismic Network)	ARPA
30	Peñas	Z-7	1963-1975	-16.274	-68.508	3942	Altiplano	1963 - 1975: Johnson-Matheson SP:Z (Peñas Seismic Network)	ARPA
31	Zongo	BBOA	1975-1999	-16.269	-68.124	4361	Eastern Cordillera	1975 -2000: Seismic Sensor ZM 500 (SP:Z)	CEA/ DASE

Continued on next page

	Name	Code	Operating Dates	Lat / deg	Lon / deg	Elev. / m	Geomorph. Region	Main characteristics	Belongs to
32	Banderani	BBOB	1975 -	-16.144	-68.133	3733	Eastern Cordillera	Since 1976: Seismic Sensor ZM 500 (SP:Z)	CEA/ DASE
33	Huaylipaya	BBOC	1975-1993	-16.051	-68.004	1635	Eastern Cordillera	1977 -2000: Seismic Sensor ZM 500 (SP:Z)	CEA/ DASE
34	Chanca	CNCB	1982-1990	-16.813	-67.982	4305	Eastern Cordillera	1982-1990: Teledyne/Geotech S-13 SP:Z	CEA/ DASE
35	Chanca	BBOE	1988 -	-16.813	-67.982	4305	Eastern Cordillera	1975 -Keep working: Seismic Sensor ZM 500 (SP:Z)	CEA/ DASE
36	Gloria	BBOD	1986 -	-16.637	-68.598	4190	Altiplano	1975 – Keep working: Seismic Sensor ZM 500 (SP:Z)	CEA/ DASE
37	Collana	BBOF	1993-2000	-16.954	-68.338	4285	Altiplano	1975 – 2000: Seismic Sensor ZM 500 (SP:Z)	CEA/ DASE
38	Alto Peñas	BBOG	1999-2000	-16.266	-68.472	3966	Altiplano	1975 - 2000: Seismic Sensor ZM 500 (SP:Z)	CEA/ DASE
39	San Ignacio	SIV	1988-1998	-16.413	-60.984	590	Brazilian shield	1988 – 1998: Seismic Sensor ZM 500 (SP:ZNE)	CEA/ DASE
40	San Ignacio	SIV	1991-. . .	-15.991	-61.072	555	Brazilian shield	1991 – Keep working (certified CTBTO) :ZM 500 (SP:ZNE) and LP 500 (LP:ZNE)	CEA/ DASE
41	Tupiza	TPZ	1985-1987	-21.465	-65.711	2982	Eastern Cordillera	1985-1987: Seismic Sensor Portacofder (SP:Z)	RS-OSC
42	Cochabamba	CCH	1985-1998	-17.384	-66.134	2838	Eastern Cordillera	1985 – 1998: Seismic Sensor Spreagaether MEQ-200 (SP:Z)	JICA
43	Bombeo	BBBO	1998-1999	-17.658	-66.438	3210	Eastern Cordillera	1998 - 1999: Seismic Sensor Lennartz (SP:ZNE)	JICA
44	Apacheta	BAPC	1998-1999	-17.359	-66.025	3598	Eastern Cordillera	1998 – 1999: Seismic Sensor Lennartz (SP:ZNE)	JICA
45	Cr, Ichu, Kkollu	BIKK	1998-1999	-17.251	-66.326	4577	Eastern Cordillera	1998 – 1999: Seismic Sensor Lennartz (SP:ZNE)	JICA
46	Col Juan XXIII	CJX	1998-1999	-17.375	-66.193	2569	Eastern Cordillera	1998 – 1999: Seismic Sensor Lennartz (SP:ZNE)	JICA
47	Zongo	ZLP	1972-1976	-16.270	-68.118	4511	Eastern Cordillera	1972 – 1976: Seismic Sensor HGLP:LP:ZNE	AFTAC/ USGS
48	Zongo	ZOBO	1976-1993	-16.269	-68.124	4361	Eastern Cordillera	1976 – 1993: Seismic Sensor type ASRO:ZNE	AFTAC/ USGS
49	Zongo	LPAZ	1973 -	-16.288	-68.131	4772	Eastern Cordillera	1976 -1993: Seismic Sensor type ASRO:ZNE	AFTAC/ USGS
50	Montecillos	BB01	2011-2012	-18.070	-65.260	2297	Eastern Cordillera	2011 – 2012: GURALP – 6TD (ZNE)	BID - OSC

Continued on next page

	Name	Code	Operating Dates	Lat / deg	Lon / deg	Elev. / m	Geomorph. Region	Main characteristics	Belongs to
51	La Guardia	BB02	2011-2012	-17.900	-63.320	524	Subandean zone	2011 – 2012: GURALP – 6TD (ZNE)	BID - OSC
52	San Juaquin	BB03	2011-2012	-17.030	-64.880	229	Chaco Beniana plain	2011 – 2012: GURALP – 6TD (ZNE)	BID - OSC
53	Tambo Quemado	BB04	2012-2012	-18.280	-69.010	4379	Western Cordillera	2011 – 2012: GURALP – 6TD (ZNE)	BID - OSC
54	Carapari	BB05	2012-2012	-21.830	-63.740	831	Subandean zone	2011 – 2012: GURALP – 6TD (ZNE)	BID - OSC
55	Yocalla	BB06	2012-2012	-19.390	-65.910	3420	Eastern Cordillera	2011 – 2012: GURALP – 6TD (ZNE)	BID - OSC
56	Casarave	BB07	2012-2012	-14.861	-64.493	164	Chaco Beniana plain	2011 – 2012: GURALP – 6TD (ZNE)	BID - OSC
57	Balcon	SIX 01	2011-2012	-20.730	-65.190	2816	Eastern Cordillera	2011 – 2012: SIXAOLA (SP:ZNE)	BID - OSC
58	Patallajta	SIX02	2011-2012	-19.110	-65.070	2807	Eastern Cordillera	2011 – 2012: SIXAOLA (SP:ZNE)	BID - OSC
59	Mojotorillo	SIX03	2011-2012	-19.320	-64.380	2667	Eastern Cordillera	2011 – 2012: SIXAOLA (SP:ZNE)	BID - OSC
60	Villa Nueva	SIX04	2011-2012	-20.060	-65.340	3313	Eastern Cordillera	2011 – 2012: SIXAOLA (SP:ZNE)	BID - OSC
61	Cuyupaya	SIX05	2011-2012	-17.010	-65.940	1806	Eastern Cordillera	2011 – 2012: SIXAOLA (SP:ZNE)	BID - OSC
62	Camiri	SIX06	2012-2012	-20.020	-63.530	795	Subandean zone	2011 – 2012: SIXAOLA (SP:ZNE)	BID - OSC
63	San Felipe	SIX07	2012-2012	-17.970	-67.130	3900	Altiplano	2011 – 2012: SIXAOLA (SP:ZNE)	BID - OSC
64	Vallegrande	SIX08	2011-2012	-18.500	-64.110	2112	Eastern Cordillera	2011 – 2012: SIXAOLA (SP:ZNE)	BID - OSC
65	Huarina	SIX09	2012-2012	-16.189	-68.609	3833	Altiplano	2011 – 2012: SIXAOLA (SP:ZNE)	BID - OSC
66	Tuti	SIX10	2011-2012	-17.460	-65.860	4018	Eastern Cordillera	2011 – 2012: SIXAOLA (SP:ZNE)	BID - OSC
67	Colquencha	BBOI	2006-2008	-16.956	-68.338	4308	Altiplano	2006 – 2008: Seismic Sensor ZM 500 (SP:Z)	CEA/ DASE
68	Jacaque	BBOJ	2007 -	-16.980	-68.190	4016	Altiplano	Since 2007: Seismic Sensor ZM 500 (SP:Z)	CEA/ DASE
69	Pacuani	BBOK	2007-2008	-16.579	-67.874	4584	Eastern Cordillera	2007 – 2008: Seismic Sensor ZM 500 (SP:Z)	CEA/ DASE
70	Mururata	BBOM	2008-2010	-16.499	-67.854	4792	Eastern Cordillera	2007 – 2010: Seismic Sensor ZM 500 (SP:Z)	CEA/ DASE
71	Ciudad de Tarija	AOVT	2016 -	-21.330	-64.410	2056	Eastern Cordillera	Since 2016: Guralp 5TD.	RS-OSC
72	Roboré	BBRB	2016-2018	-18.278	-59.809	348	Chaco Beniana plain	2016 – 2018: Nanometrics Trillium 360GSN (ZNE)	USP

Continued on next page

	Name	Code	Operating Dates	Lat / deg	Lon / deg	Elev. / m	Geomorph. Region	Main characteristics	Belongs to
73	Cerro San Diablo	BBSD	2016 -	-17.188	-60.611	374	Brazilian shield	Since 2016: Nanometrics Trillium 360GSN (ZNE)	USP
74	Santa Ana	BBLB	2016-2018	-18.665	-58.800	193	Brazilian shield	2016 – 2018: Nanometrics Trillium 360GSN (ZNE)	USP
75	Jacaque	SOEJ	2016 -	-16.975	-68.192	4076	Altiplano	Since 2016: GURALP – 6TD (ZNE)	RS-OSC
76	Toro Toro	SOET	2016 -	-18.115	-65.811	2846	Eastern Cordillera	Since 2016: GURALP – 6TD (ZNE)	RS-OSC
77	Opoqueri	SOEO	2017 -	-18.563	-67.887	3836	Altiplano	Since 2017: GURALP – 6TD (ZNE)	RS-OSC
78	Incahuasi	SOTI	2017 -	-19.831	-63.662	1130	Subandean zone	Since 2017: GURALP – 6TD (ZNE)	RS-OSC
79	Aiquile	SOEA	2017 -	-18.180	-65.233	2552	Eastern Cordillera	Since 2017: GURALP – 6TD (ZNE)	RS-OSC
80	Aiquile	AOEA	2017 -	-18.180	-65.233	2552	Eastern Cordillera	Since 2017: GURALP – 5TD (ZNE)	RS-OSC
81	Puerto Suarez	BBPS	2018 -	-19.069	-57.843	214	Brazilian shield	Since 2018: Nanometrics Trillium 360GSN (ZNE)	USP
82	Rincón del Tigre	BBRT	2018 -	-18.200	-58.211	196	Brazilian shield	Since 2018: Nanometrics Trillium 360GSN (ZNE)	USP
83	Sucre	AOES	2019 -	-19.140	-65.344	3198	Eastern Cordillera	Since 2019: GURALP – 5TD (ZNE)	RS-OSC

5.1.3 Temporary Seismic Stations with Contribution from OSC

BANJO / SEDA (1994-1995):

A collaboration of the Carnegie Institution of Washington, the Lawrence Livermore National Laboratory, the University of Arizona, the ORSTROM Institute, the University of Chile, the University of Mayor de San Andres and our institution installed 23 broadband seismic stations in Bolivia and Chile to enhance the knowledge of the tectonics of the Central Andes, especially the Altiplano. The project “Broadband Andean Joint Experiment” (BANJO) installed 16 broadband seismometers between 19°S and 20°S, from Chile to the Chaco basin in Bolivia. The project “Seismic Exploration of the Deep Altiplano” (SEDA) installed 7 broadband stations from North to South within the Altiplano region, which registered the then largest deep focus (636 km) Mw 8.3 earthquake of 9th June 1994 (*Silver*, 1994; *Polet et al.*, 1996).

ANCORP Seismic Network (1996–1997):

Between 1996 and 1997 the German Research Centre for Geosciences (GFZ) installed 39 seismic stations at the Altiplano region with the aim of increasing knowledge of the seismicity at the back arc region (*Haberland et al.*, 1996).

Puna Altiplano Volcanic Complex Project (1996-1997):

From 1996 to 1997 the Natural Environment Research Council, UK (NERC) installed 33 seismic sensors at Uturuncu Volcano in collaboration with us to enhance the knowledge about volcanos in the Altiplano region (*Zandt*, 1996).

REFUCA Project (2002 - 2004):

From 2002 to 2004, 60 seismic stations (45 short period and 15 broadband) were installed around 21°S from 70°W to 64°W. The aim of this project was to monitor all seismicity of the Central Andes (*Asch et al.*, 2002).

Volcano Project (2009-2013):

The University of Cornell in collaboration with our institution installed 41 seismic stations distributed at the Uturuncu volcano and volcanos at the border between Chile and Bolivia. The project started in 2009 and finished in 2013 (*Pritchard*, 2009).

Central Andes Uplift and Geodynamic High Topography "CAUGHT" (2010-2012):

Between 2010 and 2012 the University of Arizona and our institution installed a set of 50 temporary broadband seismic stations to enhance the results obtained by the BANJO/SEDA project with a high-resolution tomography of the Altiplano and part of the Eastern Cordillera. The data is openly available through IRIS (*Beck*, 2010; *Ward et al.*, 2013, 2016; *Ryan et al.*, 2016; *Scire et al.*, 2016; *Scire et al.*, 2017; *Garzione et al.*, 2017.)

GPS and Seismic Network PLUTONS Project:

From 2010 to 2013 a set of broadband seismic stations and GPS stations were installed at the Andes volcanos with the main attention focused on Uturuncu (Bolivia) and Lazufre (Argentina). This project involved national (Observatorio San Calixto, Universidad Mayor de San Andes, Universidad Tomas Frias and Servicio Geologico Minero) and international agencies (Universidad de Chile, Cornell University). An extension of this project was done in 2018 but the participation of institutions was reduced to New Mexico University and Cornell University and our institution (*Pritchard et al.*, 2018).

Figure 5.7: *Temporary seismic network installed along our country in 108 years of operations.*

Cuencas Pantanal - Chaco - Paraná (PCPB) Project:

The university of Sao Paulo installed 50 broadband seismic stations in collaboration with different entities from different countries at South America. In our case, 3 broadband seismic stations were installed at the Sub Andes with the main objective to obtain a high resolution of the crust. The project will run until 2022 (*Assumpção et al.*, 2016).

An overview of the temporary seismic networks is displayed in Figure 5.7.

5.1.4 Acquisition and Data Processing

During the first 20 years of our institution the data were recorded on smoked and film paper. Pierre M. Descotes SJ – the first principal - manually picked the seismic phases and wrote the first bulletins, which are safely stored at our library. Over the years and with the help of donations and collaboration with international agencies we improved data acquisition and processing and nowadays use Seiscomp3 (`https://www.seiscomp.de/seiscomp3/`), Seisan (*Havskov and Ottemoller*, 1999; *Havskov, Voss and Ottemoller*, 2020) and Earthworm (`http://www.earthwormcentral.org/`).

Around 1990, the CEA/DASE and AFTAC collaboration migrated the helicorders drums to digital data bases and digital display with graphical user interfaces, the data protocols used were FONYX (CEA/DASE protocol), SAC, CD10 and CD11.

In 2010 a big jump forward was made due to the availability of the Internet and free open access source codes dedicated to seismology. Data integration from open seismic networks was applied at our institution when we initially started to work with Earthworm and open data from Seedlink servers such as IPOC (Integrated Plate Observations Chile), INPRES (Instituto de Prevención Sísmica - Argentina) and USP (Universidade de Sao Paulo – Brazil). Later, we switched to SEISAN for data analysis (*Havskov and Ottemoller*, 1999; *Havskov, Voss and Ottemoller*, 2020). In 2011 CTBTO made alternative software available to state signatories for hypocenter location and waveform analysis. (GEOTOOL). We use it especially for teleseismic earthquakes.

In 2016 CTBTO provided us with a Seiscomp3 (modified) server for state signatories which was integrated to our daily routine as the main software of acquisition. We keep using SEISAN for data analysis, the velocity model is based on the research of *Ryan et al.* (2016). The same year with collaboration with CEA/DASE the software Progressive Multi Correlation Channel (PMCC) was installed to analyse infrasound data from the IS08 station.

Earthquakes Magnitudes Reported Over Time

Over time we calculated different types of magnitudes depending on what procedures were available at certain times.

We began determining body wave magnitudes (mb) when data analysis was still done manually on paper seismograms. m_b is calculated with the following equation for regional and teleseismic events:

$$m_b = \log(A/T) + Q(\Delta, h), \tag{5.1}$$

where A is the amplitude in mm, T period in s and Q a correction term dependant on epicentral distance Δ and focal depth h (*Gutenberg and Richter*, 1956).

OPALES System (CEA/DASE):

The local Magnitude (M_L) is defined by:

$$M_L = \log(A) + 0.84\,\log(R) + 0.00102 - 1.85, \tag{5.2}$$

where A is the amplitude of the maximum peak measured in nanometres and R is the hypocentral distance in km.

GEOTOOL (CTBTO):

For local Magnitude (M_L) on a Wood-Anderson filtered seismogram the equation is:

$$M_L = \log(A) - \log(A_0\,R), \tag{5.3}$$

where A is the amplitude in mm, R is the hypocentral distance in km. A_0 is defined by the following Equation 5.4 where C_1 to C_3 are constants.

$$-\log(A_0) = C_1\log(R/100) + C_2(R - 100) + C_3, \tag{5.4}$$

The equation with constants for Southern California is:

$$-\log(A_0) = 1.11\,\log(R/100) + 0.00189\,(R - 100) + 3, \tag{5.5}$$

SEISAN:

For local earthquakes we use the M_L magnitude expressed by:

$$M_L = \log(A) + 1.11\,\log(D) + 0.00189 - 2.09, \tag{5.6}$$

where A is the amplitude in mm measured on a Wood-Anderson filtered seismogram and D is the distance in km.

For magnitudes larger than M_L 6.0 we apply the following empirical relations to convert to M_W, for shallow (5.7) and intermediate earthquakes (5.8):

$$M_W = 0.8021\,M_L + 0.8883, \tag{5.7}$$
$$M_W = 1.0325\,M_L + 0.0106. \tag{5.8}$$

SeisComp3 (CTBTO modified):

M_{LV} is automatically calculated with the following equation based on *Richter* (1935):

$$M_{LV} = \log(A) - \log(A_0(\delta)), \tag{5.9}$$

where A is the amplitude on a Wood-Anderson filtered seismogram and A_0 is a distance (δ) dependent calibration function.

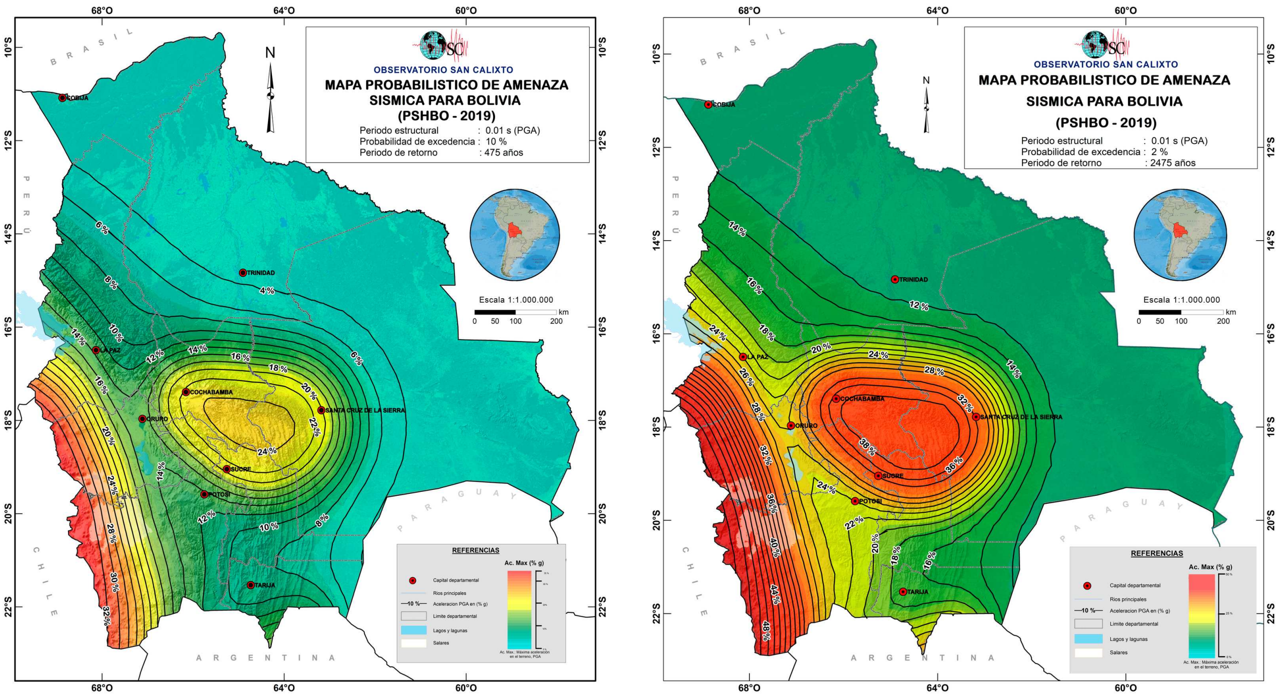


Figure 5.8: *Probabilistic Seismic Hazard Map for Bolivia, an application of our seismic bulletins reported over time.* Left: *475 years return period,* right: *2475 years return period.*

5.1.5 A Product of the Seismic Bulletins: a Probabilistic Hazard Map for Bolivia (Plurinational State of)

Based on our bulletins we decided to provide our country with a probabilistic hazard map for 475 and 2475 years return period. This map is the basis for a new national building code "GBDS-2020". It is not a finalised norm yet and is still being developed.

Figure 5.8 (left) shows the seismic hazard map of Bolivia: PGA for shallow earthquakes (depth < 70 km) located at the central part of Bolivia can reach 26% g while for the intermediate earthquakes (depths from 100 to 350 km), mostly located at the Western part of our country, PGA can reach 32% g. For deep earthquakes (depth from 500 to 700 km) there are no ground motion prediction equations and no PGA was computed. Figure 5.8 (right) shows higher values of PGA due to the higher return period of 2475 years. In general this map is applied for high buildings, dams, hospitals and / or structures that need more resistance to earthquakes.

5.1.6 Data Availability

Our local and regional seismic bulletins are shared with the International Seismological Centre (ISC) under the agency code SCB, formerly LPZ. Moreover, regional agreements made within CERESIS (Centro Regional de Sismologia para America del Sur) allow member states (South American countries) to have our bulletins for regional research. Good examples of homogenising shared regional data were the following projects:

- SISAN* (Sismicidad Andina) from 1976 to 1982

- SISRA* (Programa de Mitagacion de los Terremotos en la Region Andida) from 1980 to 1986
- CERESIS-91* (Centro Regional de Sismicidad para America del Sur) from 1987 to 1995
- SARA – GEM (South America Risk Assessment* Global Earthquake Modelling) from 2013 to 2016

* report available under the document "Peligro Sismico en Latinoamerica y el Caribe" hosted by the Instituto Panamericano de Geografía e Historia (IPGH) (https://idl-bnc-idrc.dspacedirect.org/bitstream/handle/10625/36057/107805_v4.pdf?sequence=1).

Our bulletins for local seismicity are shared via the web page http://www.osc.org.bo. Since February 2021 we are starting to share near real time data through IRIS, where a set of three short period three components sensors under the code BV (https://doi.org/10.7914/SN/BV) will be available for the research community.

References

Ayala Sánchez, R. (1997), Sismotectonique des andes de bolivie et role de l'orocline bolivien, PhD thesis, École et Observatoire de Physique du Globe, Strasbourg, France.

Ayala Sánchez, R. (2001), La Historia del Observatorio San Calixto de La Paz y su Contribucion al Desarrollo de la Ciencia y la Sismologia en Bolivia, *Revista Geofísica*, *101*.

Anderson, R.B., S.P. Long, B.K. Horton, A.Z. Calle and V. Ramirez (2017), Shortening and structural architecture of the Andean fold-thrust belt of southern Bolivia (21°S): implications for kinematic development and crustal thickening of the central Andes, *Geosphere*, *13*(2), 538–558, https://doi.org/10.1130/GES01433.1.

Assumpção, M., F. Dias, I. Zevallos, and J. Naliboff (2016), Intraplate stress field in South America from earthquake focal mechanisms, *J. South. Am. Earth. Sci.*, *71*, 278–295, https://doi.org/10.1016/j.jsames.2016.07.005.

Asch, G., B. Heit and X. Yuan (2002), The ReFuCA project: Receiver Functions Central Andes, Deutsches Geo Forschungs Zentrum (GFZ), Other/Seismic Network, https://doi.org/10.14470/MN7557778612.

Beck, S., G.Z. (2010), Central Andean Uplift and the Geodynamics of the High Topography, International Federation of Digital Seismograph Networks, https://doi.org/10.7914/SN/ZG_2010.

Cabre, R (1965), Historia Sismica de Boliva, *Bol. del Insti. Boliviano del Petroleo*, La Paz.

Cabre, R. (1974), Conocimientos sobre el Riesgo Sismico en Bolivia, *Rev. de Geofisica*.

Cabré, S.J. (1988), 75 Años a la vanguardia de la sismología, Observatorio San Calixto (internal publication).

Cabré, R. and A. Vega (1995), Sismo boliviano del 9 de junio de 1994, *Revista Técnica de YPFB (Yacimientos Petrolíferos Fiscales Bolivia)*, *16*(1-2), 5-8.

DeMets, C., R. Gordon, D. Argus and S. Stein (1994), Effect of recent revision to the geomagnetic reversal time scale on estimates of current plate motion, *Geophys. Res. Lett.*,*21*(20), 2191–2194, https://doi.org/10.1029/94GL02118.

Eichelberger, N., N. McQuarrie, J. Ryan, B. Karimi, S. Beck and G. Zandt (2015), Evolution of crustal thickening in the central Andes, Bolivia, *Earth. Planet. Sci. Lett.*, *426*, 191–203, https://doi.org/10.1016/j.epsl.2015.06.035.

Garzione, C.N., N. McQuarrie, N. D. Perez, T.A. Ehlers, S. L. Beck, N. Kar, N. Eichelberger, A. D. Chapman, K. M. Ward, M. N. Ducea, R. O. Lease, C. J. Poulsen, L. S. Wagner, J. E. Saylor, G. Zandt and B.K. Horton (2017), Tectonic Evolution of the Central Andean Plateau and Implications for the Growth of Plateaus, *Ann. Rev. Earth. Planet. Sci.*, *45*(1), https://doi.org/10.1146/annurev-earth-063016-020612.

Gutenberg, B and C. F. Richter (1949), Seismicity of the Earth and associated Phenomena, Princeton Univ. Press, Princeton, New Jersey, 273 pp.

Gutenberg, B., and C. F. Richter (1956), Magnitude and Energy of earthquakes, *Ann. Geof.*, *9*, 1–5.

Haberland, C., A. Rietbrock, G. Asch and G. Chong (1996), The ANCORP Seismic Network, GFZ Data Services, Other/Seismic Network, https://doi.org/10.14470/MR6441682066.

Havskov, J. and L. Ottemoller (1999), SeisAn Earthquake analysis software, *Seis. Res. Lett.*, *70*(5), 532–534, https://doi.org/10.1785/gssrl.70.5.532.

Havskov, J., P.H. Voss and L. Ottemoller (2020), Seismological Observatory Software: 30 Yr of SEISAN. *Seismol. Res. Lett.*, *91*(3), 1846–1852, https://doi.org/10.1785/0220190313.

Le Pichon, A., E. Blanc, D.P. Drob, S. Lambotte, J. Dessa, M. Lardy, P. Bani and S. Vergniolle (2005), Infrasound monitoring of volcanoes to probe high-altitude winds, *J. Geophys. Res. Solid Earth*, *110*, https://doi.org/10.1029/2004JD005587.

Le Pichon, A., P. Mialle, J. Guilbert and J. Vergoz (2006), Multistation infrasonic observations of the Chilean earthquake of 2005 June 13, *Geophys. J. Int.*, *167*(2), 838–844, https://doi.org/10.1111/j.1365-246X.2006.03190.x.

Minaya, E., J. Illanes and G. Fernández (2013), Memoria 100 años OSC, Observatorio San Calixto (internal publication).

Pritchard, M. (2009), The life cycle of Andean volcanoes: Combining space-based and field studies, International Federation of Digital Seismograph Networks. https://doi.org/10.7914/SN/YS_2009.

Pritchard, M., S. de Silva, G. Michelfelder, G. Zandt,S. Mcnutt, J. Gottsmann, M.E. West, J. Blundy, D.H. Christensen, N.J. Finnegan, E. Minaya, R.S.J. Sparks, M. Sunagua, M. Unsworth, C. Alvizuri, M. Comeau, R. del Potro, D. Diaz, M. Diez and K.M. Ward (2018), Synthesis: PLUTONS: Investigating the relationship between pluton growth and volcanism in the Central Andes, *Geosphere*, *14*, https://doi.org/10.1130/GES01578.1.

Polet J. , P. Silver, G. Zandt, S. Ruppert, R. Kind, G. Bock, G. Asch, S. Beck and T. Wallace (1996), Shear wave anisotropy beneath the central Andes from the BANJO, SEDA and PISCO experiments, *Géodynamique andine : résumés étendus = Andean geodynamics : extended abstracts*, Paris :

ORSTOM, 97-98 (Colloques et Séminaires), ISAG 96 : Symposium International sur la Géodynamique Andine, 3., Saint-Malo (FRA), 1996/09/17-19. ISBN 2-7099-1332-1.

Richter, C.F. (1935), An instrumental earthquake magnitude scale, *Bull. Seismol. Soc. Am.*, *25*(1), 1–32.

Ryan, J., S.L. Beck, G. Zandt, L. Wagner, E. Minaya and H. Tavera (2016), Central Andean crustal structure from receiver function analysis, *Tectonophysics*, *682*, 120–133, `https://doi.org/10.1016/j.tecto.2016.04.048`.

Schamberger, P., G.A. Fernandez, F. Condori and M. Nieto (2016), Reporte Interno del OSC sobre el diseño de uns sistema de transmision de datos por red celular 3G (internal publication).

Scire, A., G. Zandt, S.L. Beck, M.D. Long, L.S. Wagner, E. Minaya and H. Tavera (2016), Imaging the transition from flat to normal subduction: Variations in the structure of the Nazca slab and upper mantle under southern Peru and northwestern Bolivia, *Geophys. J. Int.*, *204*(1), 457-479, `https://doi.org/10.1093/gji/ggv452`.

Scire, A., G. Zandt, S. Beck, M. Long and L.S. Wagner (2017), The deforming Nazca slab in the mantle transition zone and lower mantle: Constraints from teleseismic tomography on the deeply subducted slab between 6°S and 32°S, *Geosphere*, *13*(3), 665–680, `https://doi.org/10.1130/GES01436.1`.

Silver, P., S. B. (1994), Broadband Study of the Altiplano and Central Andes, International Federation of Digital Seismograph Networks, `https://doi.org/10.7914/SN/XE_1994`.

Ward, K.M., R. Porter, G. Zandt, S.L. Beck, L.S. Wagner, E. Minaya and H. Tavera (2013), Ambient noise tomography across the Central Andes, *Geophys. J. Int.*, *194*(3), 1559-1573, `https://doi.org/10.1093/gji/ggt166`.

Ward, K., G. Zandt, S. Beck, L. Wagner and H. Tavera (2016), Lithospheric Structure Beneath the Northern Central Andean Plateau from the Joint Inversion of Ambient Noise and Earthquake Generated Surface Waves, *J. Geophys. Res. Solid Earth*, *121*, `https://doi.org/10.1002/2016JB013237`.

Wigger, P.J., M. Schmitz, M. Araneda, G. Asch, S. Baldzuhn, P. Giese,W.-D. Heinsohn, E. Martínez, E. Ricaldi, P. Röwer and J. Viramonte (1994), Variation in the Crustal Structure of the Southern Central Andes Deduced from Seismic Refraction Investigations, *Tectonics of the Southern Central Andes*, Springer, Berlin, Heidelberg, `https://doi.org/10.1007/978-3-642-77353-2_2`.

Zandt, G. (1996), Altiplano-Puna Volcanic Complex Seismic Experiment, International Federation of Digital Seismograph Networks, `https://doi.org/10.7914/SN/XH_1996`.