Operational Procedures of Agencies Contributing to the ISC

The Brazilian Seismographic Network: Historical Overview and Current Status

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Brazil

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Operational Procedures of Contributing Agencies

7.1 The Brazilian Seismographic Network: Historical Overview and Current Status

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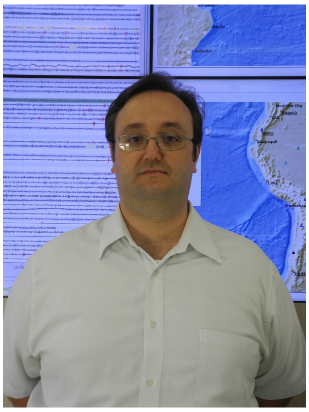

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7.1.1 Introduction

Brazil occupies more than 47% of South American territory and is about three times the area of Argentina, which is the second largest country in the continent. Although Brazil has significant area, Brazilian intraplate seismicity is almost negligible compared to that in neighbouring countries. Intraplate seismicity in Brazil results from a complex interaction of more stable and less seismic cratonic areas with relatively more active surrounding Neoproterozoic foldbelts, where stresses from plate-boundary forces are more likely to be in effect (Assumpção *et al.*, 2014; Agurto *et al.*, 2015).

Efforts to study Brazilian seismicity nevertheless date back to the 1860's when Emperor Don Pedro II ordered a survey of felt reports for past Brazilian earthquakes. The first seismograph installation, with a German Rebeur-Ehlert triple pendulum at the National Observatory in Rio de Janeiro, was in 1899. Despite a promising start in the early 20th century, following the establishment of the RDJ station in 1905, further development was discontinued and no instruments were operational in the 1940's. In 1955, when the two largest earthquakes of magnitude mb 6.2 and mb 6.1 occurred in Brazil, no seismic stations were in operation in Brazil. The RDJ station was then reactivated in 1957.

In the latter part of the 20th century, several institutions in Brazil, from north to south, operated seismic stations and studied different aspects of Brazilian seismicity. In the late 1960's and early 1970's interest in Brazilian seismicity was renewed, spurred by studies of seismic hazard at the nuclear power plants and the occurrence of dam-induced seismicity. The Universities of São Paulo (USP), Brasília (UnB) and Rio Grande do Norte (UFRN) and the National Observatory (ON) then started to deploy their own seismic stations. At the start of the 21st century, six institutions (USP, UnB, UFRN and ON, together with the Institute of Technological Research, São Paulo, and the State University of São Paulo, Rio Claro) were involved in seismology, operating permanent and temporary network stations, but without a unifying central organization.

The Brazilian Seismographic Network (RSBR) was created in this context through a coordinated effort of all Brazilian seismology groups. Its main purposes are a) to monitor in real-time the national territory and b) to provide a reference network for research projects on earth structure and national seismicity. The network is made up of four sub-networks (FDSN network codes BL, BR, ON and NB), each with varying sets of instrumentation and technologies. In total there are 80 broad-band stations.

The vast majority of stations transmit real-time data that are relayed to all institutions using SeisComP3 SeedLink protocols. A few stations are still not online but should be incorporated in the near future. Each sub-network covers a specific region of the country, as shown in Figure 7.1. While the main purpose of RSBR is to improve earthquake monitoring in Brazil, it also significantly improves detection and locations of seismic events in this part of South America previously covered by only five permanent stations in global networks: BDFB (network GT), PTGA, RCBR and SAML (IU), and SPB (G).

RSBR is the result of a long process of development of Brazilian seismology, dating back to the regular bulletins for RDJ station published by the National Observatory between 1906 and 1944. Seismology grew mainly in universities deploying several temporary and a few permanent stations and then exchanging picks to publish the joint Brazilian Seismic Bulletin (BSB). With support from Petrobras (a Brazilian oil company), the implementation of RSBR, started in 2009, is the first jointly coordinated major project of all Brazilian universities and research institutions working in seismology.

7.1.2 Historical Overview

We present now a brief historical summary of seismographic stations installed in Brazil, some successfully accomplished and others not so well. In the first half of the 20th century, several attempts were made to install stations soon after the occurrences of large felt events. However, as often happens, practical and financial difficulties usually beset the scientific interests.

1899: Rebeur-Ehlert Triple Pendulum at the National Observatory

This instrument was brought from Germany by Luiz Cruls, an astronomer and one of the early directors of the National Observatory (ON), to be installed in Rio de Janeiro. It was installed by Henrique Moritze, who would later succeed Cruls as ON director. Apparently the seismograph worked for a few months but then operation ceased. Nevertheless, it can be regarded as the first operational seismic station in South America.

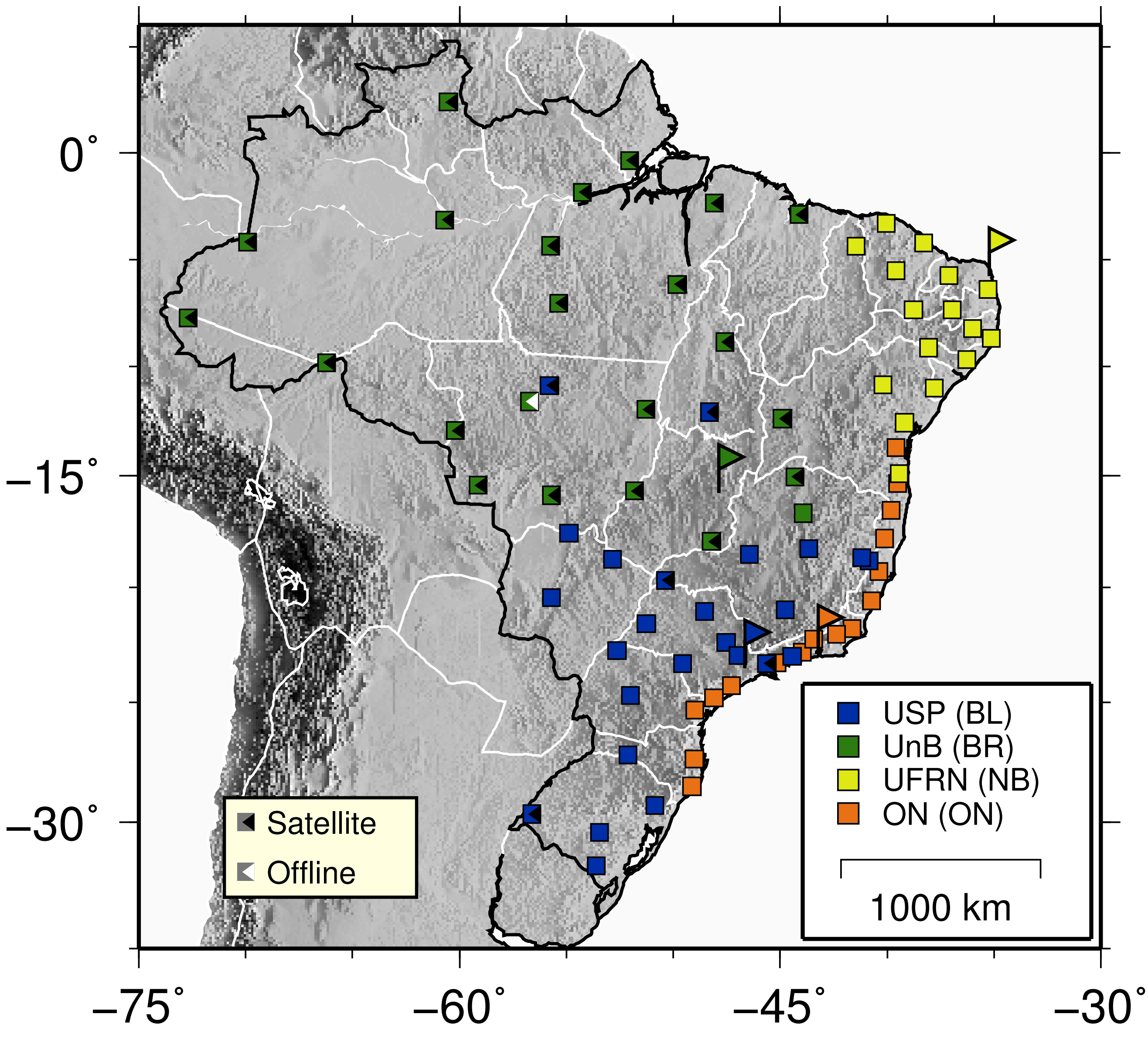


Figure 7.1: *Map of seismic stations (squares) and institutions (flags) participating in the RSBR initiative. Sub-networks and host institutions are coded by color. Further annotations indicate stations that are currently offline or using satellite technology for data links.*

1906-1944: National Observatory, Rio de Janeiro

Following the initial start with the Rebeur-Ehlert triple pendulum, other instruments were used by the National Observatory, sometimes in simultaneous operation. There are early reports of Wiechert (1909-1912), Bosch-Omori (1912-1922), Mainka (1921-1922) and Milne-Shaw (1923-1944) instruments in operation.

A Bosch-Omori seismograph with horizontal components and smoked-paper recording was installed at ON in 1905. It recorded the 1906 San Francisco earthquake and seems to have been in operation until 1922. From 1909 until 1912, a Wiechert seismograph was also in operation at ON (Pérez, 1984).

In June 1921 a Mainka seismograph was started in operation at Rio de Janeiro. On 27 January 1922 it recorded, 400 km away, the mb 5.1 São Paulo earthquake, which was felt across São Paulo and Rio de Janeiro states. Later that year, a more modern Milne-Shaw seismograph was installed and was operated there reliably for two decades, enabling ON to produce regular seismic bulletins until 1944.

1908, 1920: Porto Alegre, Rio Grande do Sul

An attempt was made in 1908 to install a seismograph at the recently created (1907) Astronomical and Meteorological Observatory of Porto Alegre, Rio Grande do Sul state, in southern Brazil, though without much success. A second attempt occurred around 1920 when ON sent a Wiechert seismograph to Porto Alegre. That installation seems to have recorded a few events but was discontinued after 1923.

1910: Fernando de Noronha Island

John Milne included Fernando de Noronha Island, near the equatorial region off northeast Brazil, as a site in the global Milne network (Turner *et al.*, 1911). The instrument was there from March 1910 to 1915 and recorded the $M7$ Avezzano earthquake, which killed 30,000 people in Italy.

1920: Bom Sucesso, Minas Gerais State, SE Brazil

After a series of small earthquakes up to magnitude 4 in 1919-1920 that caused panic and great concern in the local population, a Wiechert seismograph (200kg, two horizontal components) was deployed by ON. It seems to have been in operation there until 1932 but the local seismicity died down and no local events were recorded. Further, it seems to have recorded the São Paulo 1922 earthquake, but the seismograms were lost. In 1935, when local activity occurred in Bom Sucesso, no instruments were in operation.

≈1947: São Paulo

Despite the motivation prompted by the São Paulo earthquake of 1922, and several promises and attempts to get a seismographic station, it was only in the 1940's that the "São Paulo Observatory" (later to become the "Institute of Astronomy and Geophysics" of the University of São Paulo) installed two Wiechert-type seismographs, one vertical and one horizontal pendulum (Santos, 2005). However, it seems they never worked properly and their operation was discontinued. USP resumed its seismological activity in 1975 by deploying a temporary local network in collaboration with the Global Seismology Unit (Edinburgh) of the British Geological Survey.

1957: Lamont-Doherty at the National Observatory

As part of the 1957 International Geophysical Year, the Lamont-Doherty Geological Observatory (now Lamont-Doherty Earth Observatory) installed a complete seismographic station with Press-Ewing horizontal-components and Sprengnether vertical-component. Long-period and short-period seismometers were installed but only the long-period instruments remained operational until the early 1980's.

1965: WWSSN Station in Natal – NAT

As part of the USGS-organized World Wide Standard Seismographic Network, a station was installed near the city of Natal, northeast Brazil, in cooperation with the Brazilian Navy. NAT recorded several important earthquake sequences in northeast Brazil. The operation and maintenance of NAT was transferred from the Navy to the Federal University of Rio Grande do Norte in the late 1970's, when a seismology research group was established in the UFRN Physics Department. This motivated the development of the seismology group at UFRN.

1966-1971: Brasilia Array Station

With the creation of CERESIS (South American Regional Seismological Center) in 1963, a high-sensitivity array station (in T-format with up to 18 short-period seismometers and 2.5 km spacing) was proposed to be installed near the middle of the continent. In 1966, with support from the British Geological Survey, the Brazilian National Research Council and the University of Brasilia (UnB), initial field work and temporary installations were carried out near Brasilia. The SAAS (South American Array System) started operation in 1971 in its finalized form. In addition to the international and national support, the creation of a seismology group at UnB was essential to sustain the development of seismological studies in Brasilia.

1970-2000: Pre-RSBR Aspects

Seismology in Brazil advanced in the 1970's through the formation of the seismology groups in the universities and the National Observatory. Because of a growing importance of seismic hazard studies related to nuclear plants and of monitoring dam-induced seismicity, several permanent stations (with analogue recording) were installed, such as at BDF (the WWSSN station in Brasilia), the VAO network (USP), the CAI station (transferred from NAT by UFRN) and at BEB (Belém, UFPA).

In the 1980's, UnB started operating a network of stations in the Amazon, and IPT (Institute of Technological Research, São Paulo) installed several stations monitoring induced seismicity near dams in southern Brazil. In the 1990's digital stations in the new global networks were installed (BDFB, PTGA, SAML, SPB and RCBR), all of them successfully operating within international programs and backed by local support from the seismology groups at UnB, USP and UFRN.

Despite efforts of astronomers at several observatories early in the 20th century, Brazilian seismology could only be firmly established when full-time seismologists took an academic interest in research. In a country with low seismicity levels, only scientific research was able to sustain the long-time operation of seismic stations when there was normally only ephemeral interest and support after notable regional earthquakes.

During 1990-2010, all seismology groups in Brazil developed several independent research programs using temporary deployments to study earth structure or local seismicity. Cooperation and data exchange enabled the regular preparation of the joint BSB. However, it is only now with the establishment of the RSBR that there is an integrated effort to operate a national seismic network.

7.1.3 Current Status

RSBR network configuration and operational practice has been developed in the last four years and is still evolving. The RSBR is a single network composed of four sub-networks, each operated by a different institution and with various instruments but all following a minimum agreed standard. Because of the vast area, Brazil was geographically divided into four regions and local centers were chosen in each region to operate an independent set of stations. Table 7.1 lists the participant institutions, the areas of operations and the main instrumentations used in each sub-network.

While each institution is responsible for its own sub-network, ON was chosen as the main RSBR aggregator institution in the long term, responsible for archiving and distributing ground-motion and parametric data generated by all sub-networks. Furthermore, ON runs the main website (http://www.rsbr.gov.br) for the project. Please consult the RSBR website for updates.

Table 7.1: *Institutions, regions and technologies used in RSBR network operation*

Acronym	Institution	Net	Attributed Region	Sensor	Datalogger
ON	National Observatory	ON	South to central coastline	Streckeisen, STS-2	Quanterra, Q330
UFRN	Rio Grande do Norte Federal University	NB	Northeast Brazil	Reftek, RT151 + RT131B	Reftek, RT130
UnB	University of Brasília	BR	Central and north Brazil	Nanometrics, Trillium 120PA	Nanometrics, Trident/Taurus*
USP	University of São Paulo	BL	Central and southeast Brazil	Nanometrics, Trillium 120PA	Nanometrics, Trident/Taurus*

* Trident dataloggers are in many cases used instead of Taurus for stations transmitting over satellite links (Table 7.2).

Station Distribution

As shown in Table 7.1, all stations operate with broad-band sensors (120s to 50Hz). Stations in the UFRN network have additionally an accelerometer installed at each site as northeast Brazil is historically the most seismic area of the country, presenting recurrent intraplate swarms with magnitudes up to *mb* 5.0 at upper-crustal depths. Important historical events there include the 1986 João Câmara earthquake sequence, with the largest earthquake of magnitude *mb* 5.1, and over 50.000 events struck this region between 1986 and 1990.

Each sub-network of the RSBR network has a main target region with the station site locations determined by the responsible institution. Figure 7.1 shows the location map of the 80 stations currently operated in the RSBR network. In general, most of the country has been covered by stations, but with a lower density in the Amazon region mainly due to accessibility and logistic problems. Complementing Figure 7.1, Table 7.2 lists the detailed information of station codes, coordinates, altitude, closest city and transmission technology used for on-line data acquisition.

Table 7.2: *RSBR station parameters by sub-network: Tr, the transmission method, has "S" for Satellite, "W" for Wireless link, "2G" for GSM mobile network and "-" for offline status.*

i	Code	Longitude	Latitude	Alt.(m)	Closest City/State Name	Tr.
			BL network			
1	AQDB	-55.6997	-20.4758	158	Aquidauana, Mato Grosso do Sul	2G
2	BB19B	-48.5279	-21.0662	571	Bebedouro 19, São Paulo	2G
3	BSCB	-44.7635	-20.9984	935	Bom Sucesso, Minas Gerais	2G
4	BSFB	-40.8465	-18.8313	185	Barra do são francisco, Espírito Santo	2G
5	C2SB	-52.8377	-18.7688	757	Chapadão do Sul, Mato Grosso do Sul	W
6	CLDB	-55.7965	-10.8732	298	Colíder, Mato Grosso	S
7	CNLB	-50.8533	-29.3148	712	Canela, Rio Grande do Sul	2G
8	CPSB	-53.4432	-30.4123	290	Caçapava do Sul, Rio Grande do Sul	2G
9	DIAM	-43.6648	-18.2952	1280	Diamantina, Minas Gerais	W
10	ESAR	-44.4403	-23.0207	7	Angra dos Reis, Rio de Janeiro	W
11	FRTB	-49.5640	-23.3439	518	Fartura, São Paulo	2G
12	ITAB	-52.1313	-27.2349	459	Itá, Santa Catarina	W
13	ITQB	-56.6275	-29.6638	95	Itaqui, Rio Grande do Sul	S
14	ITRB	-50.3590	-19.7042	426	Iturama, Minas Gerais	S
15	PARB	-45.6246	-23.3421	777	Paraibuna, São Paulo	S
16	PCMB	-51.2619	-21.6074	346	Pacaembu, São Paulo	2G
17	PEXB	-48.3008	-12.1058	346	Peixes, Tocantins	S
18	PLTB	-53.6044	-31.7637	412	Pelotas/Pedras Altas, Rio Grande do Sul	2G
19	PMNB	-46.4400	-18.5400	950	Patos de Minas, Minas Gerais	2G
20	PP1B	-54.8796	-17.6003	368	Sonora, Mato Grosso do Sul	2G
21	PTGB	-52.0118	-24.7209	981	Pitanga, Paraná	W
22	RCLB	-47.5310	-22.4191	650	Rio Claro, São Paulo	2G
23	SJMB	-41.1847	-18.7029	243	São João de Manteninha, Minas Gerais	W
24	TRCB	-52.6357	-22.7946	490	Terra Rica, Paraná	2G
25	VABB	-46.9657	-23.0021	866	Valinhos, São Paulo	2G
			BR network			

Table 7.2: Continued.

i	Code	Longitude	Latitude	Alt.(m)	Closest City/State Name	Tr.
1	ARAG	-51.8120	-15.7060	237	Araguaiana, Mato Grosso	S
2	BOAV	-60.5225	2.3953	114	Boa Vista, Roraima	S
3	CZSB	-72.7049	-7.7299	196	Cruzeiro do Sul, Acre	S
4	ETMB	-66.2137	-9.8168	196	Extrema, Roraima	S
5	IPMB	-48.2117	-17.9830	706	Ipameri, Goias	S
6	ITTB	-55.7343	-4.3672	118	Itaituba, Pará	S
7	JANB	-44.3112	-15.0581	693	Januária, Minas Gerais	S
8	MACA	-60.6838	-3.1615	75	Manacapuru, Amazonas	S
9	MALB	-54.2649	-1.8529	27	Monte Alegre, Para	S
10	MC01	-43.9417	-16.7074	740	Montes Claros, Minas Gerais	2G
11	MCPB	-52.0567	-0.3602	127	Macapá, Amapá	S
12	NPGB	-55.3579	-7.0454	266	Novo Progresso, Pará	S
13	PDRB	-56.7296	-11.6123	322	Porto dos Gaúchos, Mato Grosso	-
14	PRPB	-49.8150	-6.1724	265	Parauapebas, Pará	S
15	PTLB	-59.1368	-15.4487	72	Pontes e Lacerda, Mato Grosso	S
16	ROSB	-44.1246	-2.8967	60	Rosário, Maranhão	S
17	SALV	-55.6936	-15.9012	213	Santo Antônio do Leverger, Mato Grosso	S
18	SDBA	-44.9030	-12.4085	623	São Desidério, Bahia	S
19	SMTB	-47.5886	-8.8617	292	Santa Maria do Tocantins, Tocantins	S
20	SNDB	-51.2943	-11.9742	252	Serra Nova Dourada, Mato Grosso	S
21	TBTG	-69.9090	-4.1868	91	Tabatinga, Amazonas	S
22	TMAB	-48.0957	-2.3704	26	Tome-Acu,Pará	S
23	VILB	-60.2002	-12.9528	434	Vilhena, Roraima	S
					NB network	
1	NBAN	-36.2746	-9.6686	260	Anadia, Alagoas	2G
2	NBCA	-36.0130	-8.2256	613	Caruaru, Pernambuco	2G
3	NBCL	-38.2910	-4.2243	27	Cascavel, Ceará	2G
4	NBCP	-39.1820	-12.5937	232	Cabeceiras do Paraguaçu, Bahia	2G
5	NBIT	-39.4345	-14.9307	183	Itapé, Bahia	2G
6	NBLA	-37.7890	-10.9925	192	Lagarto, Sergipe	2G
7	NBLI	-36.9498	-7.3645	624	Livramento, Pernambuco	2G
8	NBMA	-38.7641	-7.3654	437	Mauriti, Ceará	2G
9	NBMO	-40.0414	-3.3108	95	Morrinhos, Ceará	2G
10	NBPA	-37.1121	-5.7503	92	Paraú, Rio Grande do Norte	2G
11	NBPB	-39.5837	-5.5432	263	Pedra Branca, Ceará	2G
12	NBPN	-40.1988	-10.8468	386	Ponto Novo, Bahia	2G
13	NBPS	-41.4457	-4.3940	713	Pedro Segundo, Piauí	2G
14	NBPV	-35.2905	-6.4175	91	Pedro Velho, Rio Grande do Norte	2G
15	NBRF	-35.1272	-8.6794	56	Rio Formoso, Pernambuco	2G
16	NBTA	-38.0633	-9.1220	348	Tacaratú, Pernambuco	2G
					ON network	
1	ALF01	-40.7252	-20.6169	22	Guarapari, Espírito Santo	2G
2	CAM01	-41.6574	-21.8257	31	Campos, Rio de Janeiro	2G
3	CMC01	-39.5191	-15.3601	169	Camacan, Bahia	2G
4	DUB01	-42.3742	-22.0810	623	Duas Barras, Rio de Janeiro	2G

Table 7.2: *Continued.*

i	Code	Longitude	Latitude	Alt.(m)	Closest City/State Name	Tr.
5	GDU01	-39.5753	-13.7200	251	Guandu, Bahia	2G
6	GUA01	-39.8053	-16.5835	198	Guaratinga, Bahia	2G
7	JAC01	-48.1024	-24.8114	297	Jacupiranga, São Paulo	2G
8	MAJ01	-49.0118	-27.3972	344	Major Gercino, Santa Catarina	2G
9	MAN01	-43.9641	-22.8652	617	Mangaratiba, Rio de Janeiro	2G
10	NAN01	-40.1257	-17.8442	206	Guarapari, Espírito Santo	2G
11	PET01	-47.2753	-24.2901	150	Pedro de Toledo, São Paulo	2G
12	RIB01	-40.3944	-19.3142	216	Rio Bananal, Espírito Santo	2G
13	SLP01	-45.1559	-23.3243	1117	São Luis do Paraitinga, São Paulo	2G
14	TER01	-49.1291	-28.5318	315	Treze de Maio, Santa Catarina	2G
15	TIJ01	-49.0046	-25.3235	1049	Tijucas do Sul, Paraná	2G
16	VAS01	-43.4426	-22.2801	402	Vassouras, Rio de Janeiro	2G

Detectability of Regional Events

In this report, we use the Brazilian regional magnitude scale, m_R, determined by the maximum particle velocity in the whole P-wave train using the following equation (Assumpção, 1983):

$$m_R = log(V) + 2.3log(D) - 2.28 \tag{7.1}$$

where V is the ground velocity in μm/s and D is the distance in km in the range 200−1500 km.

This regional magnitude scale is consistent with the teleseismic mb scale in the range $3.5 < m_R < 5.5$ (Assumpção *et al.*, 2014). A preliminary relationship with Mw is given by (Druet, 2014):

$$Mw = 1.12m_R - 0.76 \tag{7.2}$$

In addition to the indicated m_R values, we also use M values, which do not relate to any specific scale but can be taken as an average magnitude as in the case of SeisComP3 practice, which averages all available magnitude types for the event.

An attempt to quantify the current detectability of the RSBR network is presented in Figures 7.2 and 7.3, which indicate the distribution of the “Number of Stations” and “Maximum Azimuth Gap” for given magnitudes. As a rule of thumb we assumed that an earthquake with magnitude m_R 2.5 ($Mw = 2.0$) is recorded to a maximum distance of 150 km, m_R 3.5 ($Mw = 3.0$) to 500 km and finally that an earthquake with magnitude m_R 4.0 ($Mw = 3.5$) can be detected out to a distance of 1200 km.

For an indication of the regional monitoring thresholds, Figure 7.2 was prepared by counting the number of stations within the indicated distance from each grid-position. For earthquakes of m_R 2.5 (Figure 7.2a) only events near the coast and along part of the northeast region would be detected by more than two stations, but earthquakes there of that magnitude would not normally be located automatically

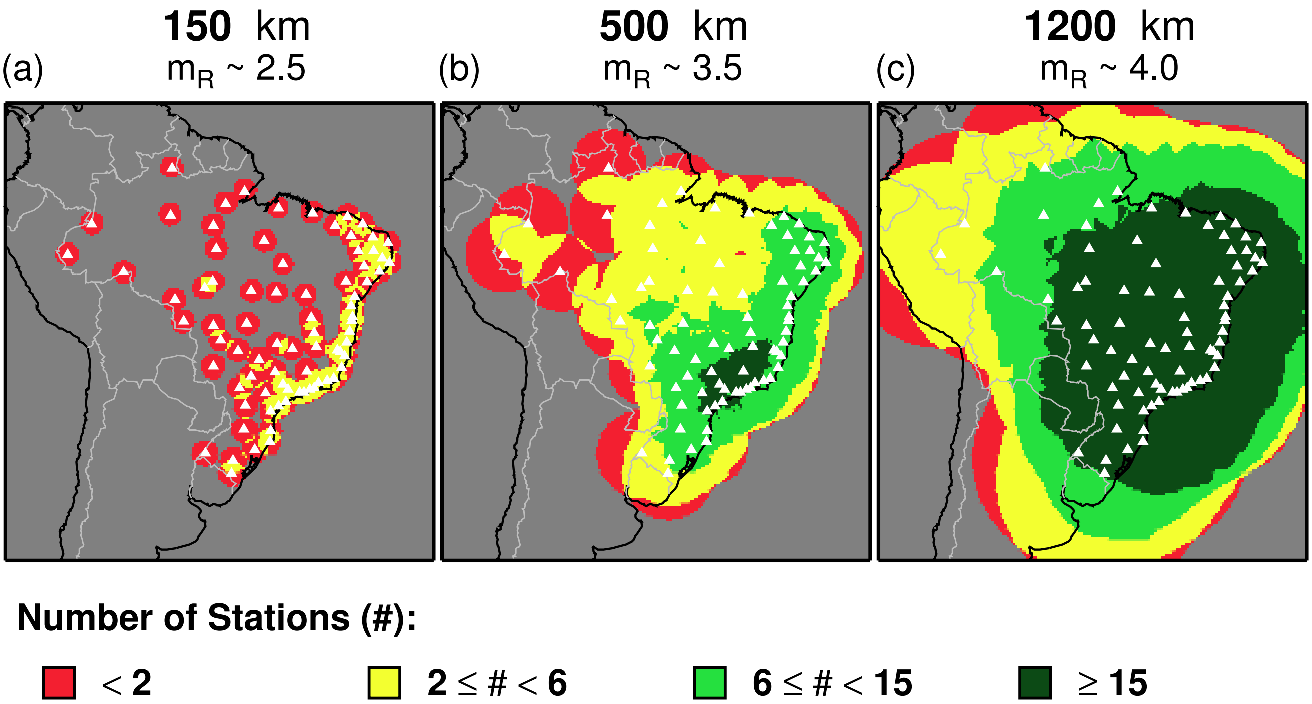


Figure 7.2: *Expected station detections for specified regional magnitudes. The number of detecting stations within the indicated distance for the specified regional magnitude is coded by color.*

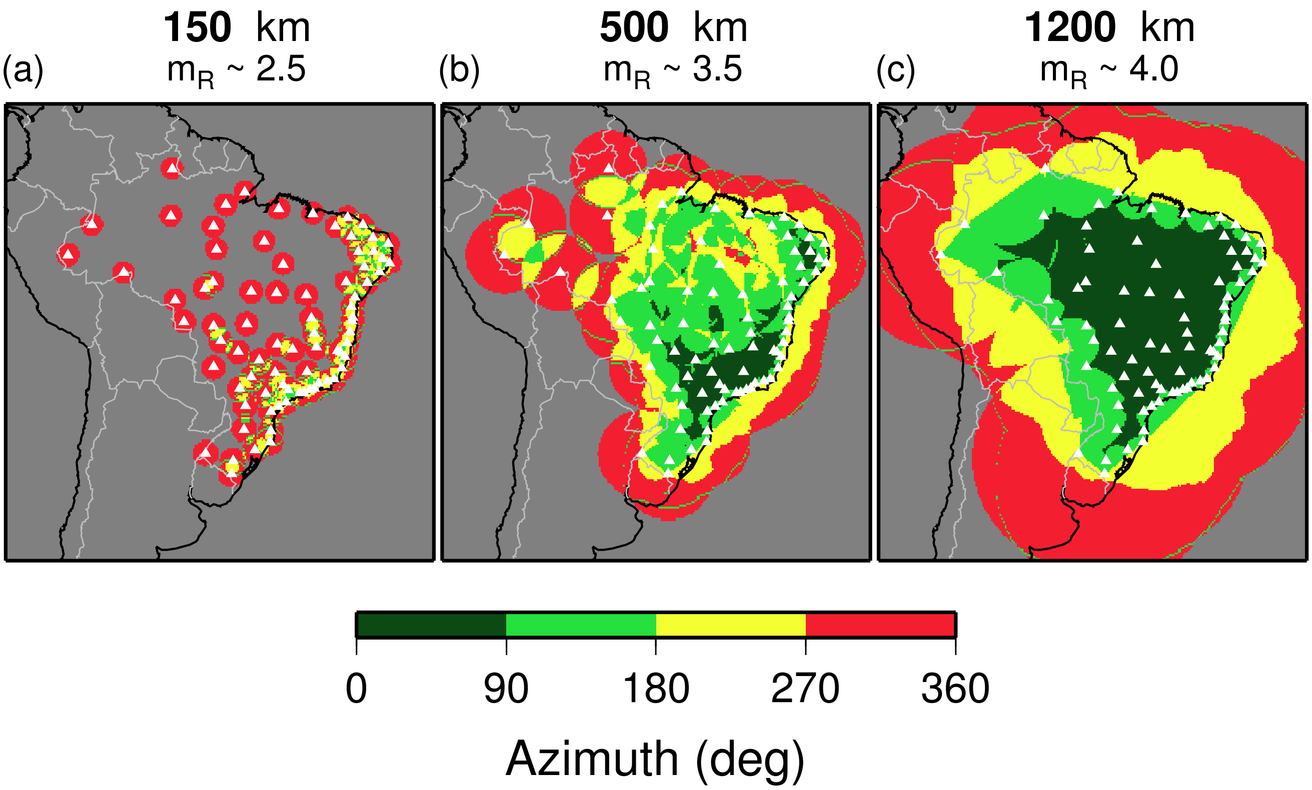


Figure 7.3: *Expected maximum azimuthal gap for the detecting station distribution. The maximum azimuthal gap is coded by color for the cases indicated by the specified regional magnitude and detecting station distance.*

as a minimum of six detections is required by the automatic system. A better result is achieved for earthquakes of m_R 3.5 (Figure 7.2b). In this case sufficient stations for an automatic location (6 - 15) are obtained along the coast in the middle and southeast regions, where sub-networks BL and ON partly overlap. Furthermore, São Paulo and Rio de Janeiro cities (Brazil's most densely populated areas) are monitored with an optimal ($\geq$15) number of stations within a range of 500 km. Finally, for m_R 4.0 (Figure 7.2c), a good coverage is shown for most of the country, with an excellent coverage for the central-south, southeast, northeast and some of the northern areas of the country.

Another way to quantify RSBR coverage is by evaluating the maximum azimuthal gap, as shown in Figure 7.3 where magnitudes and distances previously adopted are again used. Whereas Figure 7.2 relates to the RSBR capacity for detecting and locating an earthquake, Figure 7.3 relates to the RSBR capacity for resolving focal mechanism solutions (and also to the robustness of the location solutions). Earthquakes with magnitude $m_R < 2.5$ (Figure 7.3a) show little or no capacity for resolution of focal mechanism. For earthquakes with magnitudes close to m_R 3.5, some areas near the coast and in southeast and northeast Brazil give maximum azimuthal gaps less than 90°, which may be sufficient to resolve focal mechanisms. For larger earthquakes, of m_R 4.0 or more, a good azimuthal coverage is expected for most of the country, except near the borders: stations outside the RSBR network were not considered in these calculations.

Obviously these analyses should not be considered to represent the actual RSBR resolution but merely a first approximation of the current coverages. Here, stations operated by other networks were not included as RSBR has no control over data latency or influence over neighboring network configuration to optimize any joint operation. When other stations are included, such as in some of the Andean countries, RSBR capacity is greatly improved, resulting in earthquakes with m_R 3.0 being well located automatically along the margins bordering northeast Argentina, Chile and Bolivia.

Station Deployment Quality

As RSBR was a distributed network created by combining sub-networks from different institutions (Table 7.1) an effort was made from the beginning of the project to have some uniformity in the site installations. A major decision was to install stations on surface bedrock (there was no budget allowance for borehole installation) and cover the sensors with sand or soil to guarantee the needed temperature stability and wind protection and to avoid any tilt-induced noise. Another consideration was to bury cables in pipes and install data-loggers inside small masonry constructions to achieve a long-lasting installation. Finally, the stations were mostly sited on private property and normally surrounded by fences for general protection.

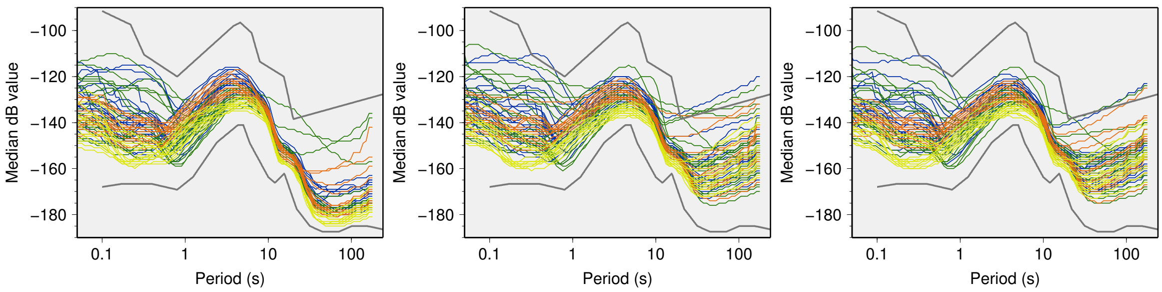
Two typical station installations are shown in Figure 7.4, with a tall structure housing the data-loggers, transmission and power equipment next to another over the sensor pit filled with sand or soil for insulation. At some stations the box around the sensor is now being covered by a soil dome that should result in lower noise levels by reducing heat-induced ground tilt.

A power density function (PDF) comparison of site noise for each station (Figure 7.5a-c) and by sub-network medians (Figure 7.5d-f) reveals some interesting aspects for RSBR stations.

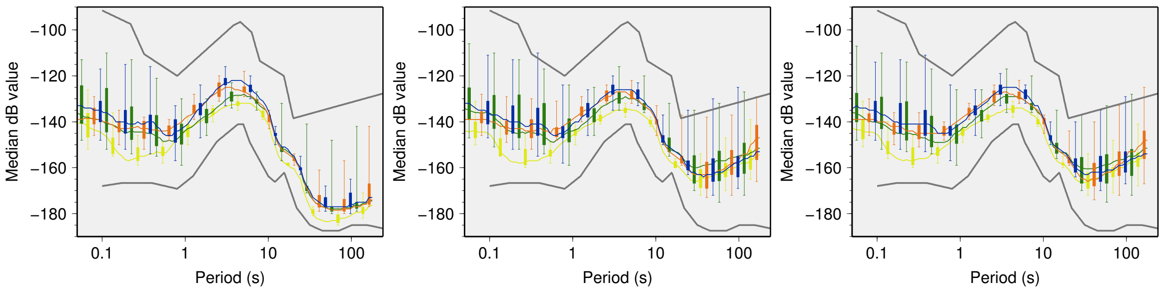
At first glance, stations from the NB network (yellow traces on Figure 7.5a-c) show the lowest noise levels,

(a) Station BL/PLTB, South Brazil (b) Station ON/CAM01, Southeast Brazil

Figure 7.4: *Example station sites from the BL and ON networks. Solar panels, batteries, data-loggers, transmission equipment are hosted by the tall masonry constructions separate from lower constructions hosting the sensors and filled with soil/sand materials. Cables ducts are protected by masonry to avoid undesired vibration.*



(a) Individual Station, HHZ (b) Individual Station, HHN (c) Individual Station, HHE



(d) Network Average, HHZ (e) Network Average, HHN (f) Network Average, HHE

Figure 7.5: *PDF plots for RSBR stations, where (a), (b) and (c) are compilations of individual station PDF curves colored according to network code, and (d), (e) and (f) are network-median PDF curves (using 0%, 25%, 75% and 100% percentile box-and-whisker-plots). Green is for the BR (UnB) sub-network, orange for ON (ON), yellow for NB (UFRN) and blue for BL (USP). Stations with problems in metadata or components were manually removed from the comparison.*

especially for the vertical component. On the horizontal components the noise levels are still relatively low at the lower periods but are less so for the higher periods. BL stations (blue traces on Figure 7.5a-c) generally have the highest PDF values on all channels, predominantly at the lower to intermediate periods as they are sited in areas of the country with greater population and industrialization levels, but more average behavior for the longer periods. The other two networks, ON (orange) and BR (green), show intermediate values but with a larger scatter of noise levels for the BR network.

From the comparison of the network-median plots (Figure 7.5d-f) it can be seen that the BL and BR networks show larger boxes for the 25% and 75% quartiles and also larger whiskers. One explanation for this is that the BL and BR networks are the more widespread across the continent, covering the interior, and are thus not similar to the ON and NB networks that cover smaller and more uniform regions. Finally, it is important to observe that RSBR sub-network median PDFs are generally below that for the standard high-noise model, though there is still room for improvement, especially at shorter periods, as the best site was not always chosen because of connectivity constraints.

Data Distribution and Processing

Ground-motion data collected at the stations are transmitted in real-time to their sub-network data-center for processing and re-distribution. Table 7.2 and Figure 7.1 indicate which stations transmit data in real-time and what transmission technology is currently employed. The final link availability is technology dependent.

During the first weeks of March 2015 an average availability of 99.97±0.07% was observed for the satellite stations (BL and BR networks). BL stations had 96±5% for 2G/3G links and 98.6±1.0% for stations connected through local wireless providers. While satellite is the most uniform link with lowest standard deviation, and local wireless provides good link availability with a small standard deviation, mobile 2G/3G links with a standard deviation of 5% are considered to be an acceptable non-uniform technology across the whole country. Final link availability will later be reflected in near real-time data archives as on-site collection is still happening for now after six months on average. Collected field data will continue to be used to fill gaps in local archives, which are finally synchronized using the rsync tool (see http://rsync.samba.org/) at the ON data-center for final archiving and distribution.

Even before the final archiving occurs, data are distributed using SeisComP3 systems installed at each institution. SeisComP3 was the chosen platform for data exchange and earthquake location adopted by RSBR from the beginning. SeedLink and ArcLink servers implemented in the SeisComP3 system are extensively used at RSBR and, for compatibility, all data stored by RSBR are organized into SDS file-structure archives. Using SeisComP3 standard tools, real-time data are shared using the SeedLink protocol, and archived data can be obtained from each institution, using the ArcLink protocol, or from the master ON ArcLink server. SeedLink and ArcLink server addresses for the RSBR sub-networks are shown in Table 7.3 and access is openly available for anyone. The ground-motion data policy for RSBR stations is that **data are open and freely distributed to anyone**.

So far, most of the RSBR effort has been directed to deploying the stations, recording and archiving the ground-motion data. Less time has been devoted to compiling an earthquake bulletin and catalogue. In time, RSBR will produce a composite Bulletin merging all earthquake origins from each node. Each

Table 7.3: *ArcLink (near-realtime, archive data) and SeedLink (realtime) internet server addresses used for network data distribution.*

Node	Network(s)	SeedLink (address:port)	ArcLink (address:port)
ON	ALL	**rsis1.on.br:18000**	**rsis1.on.br:18001**
UFRN	NB	sislink.geofisica.ufrn.br:18000	
USP	BL/BR	seisrequest.iag.usp.br:18000	seisrequest.iag.usp.br:18001
UnB	BR	datasis.unb.br:18000	datasis.unb.br:18001

All servers are open to anyone.

institution should be authoritative for its area while RSBR should be authoritative for Brazil. So far (December, 2015), parametric data (time and amplitude picks, and origins and magnitudes) are exchanged between USP and ON using the scimex tool, which relays the SeisComP3 parametric data messages from one node to another. These messages feed a master SeisComP3 system that drives the main RSBR web-page and an alert service when appropriate.

Earthquake Solutions

At present ON and USP contribute to the RSBR earthquake solutions. USP is responsible for most of the location revision, having allocated two analysts (who were historically responsible for reviewing the BSB) working full-time during weekdays a) to review the automatic solutions coming from the standard SeisComP3 process, and b) to visually inspect day-plots, searching for and locating Brazilian earthquakes with magnitudes close to m_R 3.0 that are for now not processed by the automatic system.

USP and ON seismologists collaborate to improve the automatic system by attempting to tune the RSBR SeisComP3 system working on two fronts: (1) by developing and testing a SeisComP3 plugin for computing the Brazilian regional magnitude (m_R) historically used in Brazil for the BSB, and (2) by tuning trigger and location parameters for the RSBR configuration to minimize false locations normally associated with PKP phases recorded at RSBR stations.

This work forms the first RSBR efforts to maintain a national service of near real-time earthquake locations and alerts in Brazil. Although individual institutions may be currently involved with the location processing, most of the reviewing process is done at USP and injected into the RSBR server located at the ON observatory, where each origin should conform to one RSBR event. Further cooperation between the institutions to improve earthquake locations will depend not only on new technological tools and workflows still to be developed but also on regular training for analysts working on local events at each institution.

RSBR and the Pisagua, Chile 2014, Earthquake Sequence

One way to evaluate RSBR capabilities is to examine results for an earthquake sequence, such as the one that occurred during March/April 2014 near the coast of northern Chile. The Pisagua sequence started on March 16th and culminated with a major Mw 8.1 event on April 1st, followed by the Mw 7.6 event on April 2nd. The sequence was recorded by many RSBR stations (in networks BL and BR

- others networks had transmission problems at the time) together with other South American stations in the G, GT and IU networks. A total of 265 events were automatically located and manually revised by USP seismologists. The results are discussed here.

Figure 7.6 shows all the event locations determined with RSBR stations after phases had been repicked. Hypocenter depths are indicated in the associated profile in Figure 7.6. Depths here were set fixed (to an average value of 40 km) only when the location algorithm did not converge with a reasonable depth (usually from 0 to 100 km).

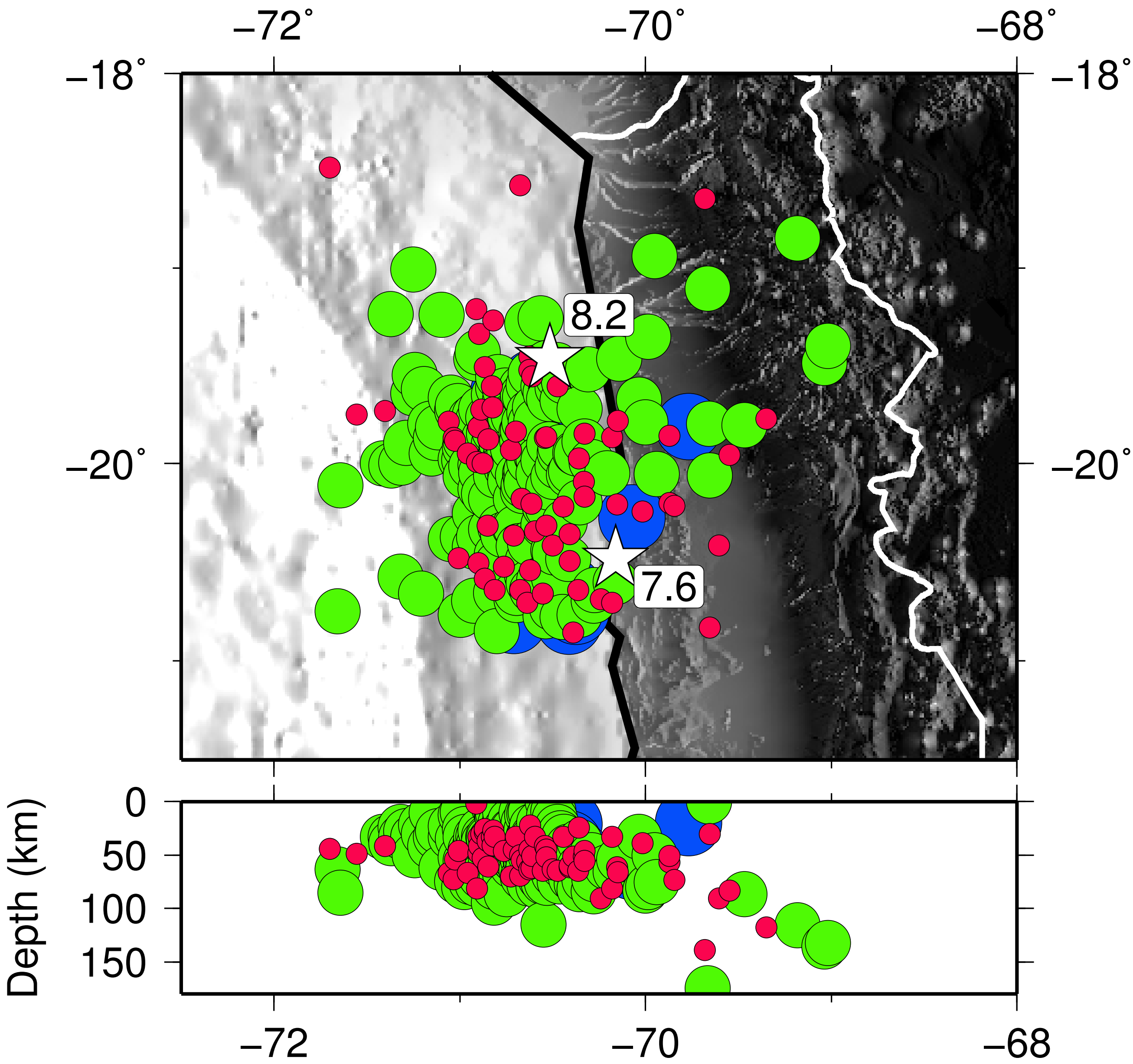


Figure 7.6: *Pisagua earthquake sequence map and depth profile determined using RSBR stations and other South American stations in the global G, GT and IU networks. Events with M < 4.0 are shown green, between M 4.0 and M 5.5 are red and M > 5.5 are blue.*

A first attempt to characterize the RSBR network capability examines the elapsed times taken to automatically locate each earthquake origin in the repeated processing sequence and the observed deviations. Figure 7.7 shows the median delay for the determinations of event origins for events in the sequence. The delay times were calculated using

$$\delta s = O_s - P^t \tag{7.3}$$

where δs is the delay time for the sth solution, s being the solution sequence number starting at 0 for the first solution for an event, 1 for the second and so on. O_s is the origin creation-time for solution s and P^t is the preferred origin-time for the event, simply here the determined origin-time for the event.

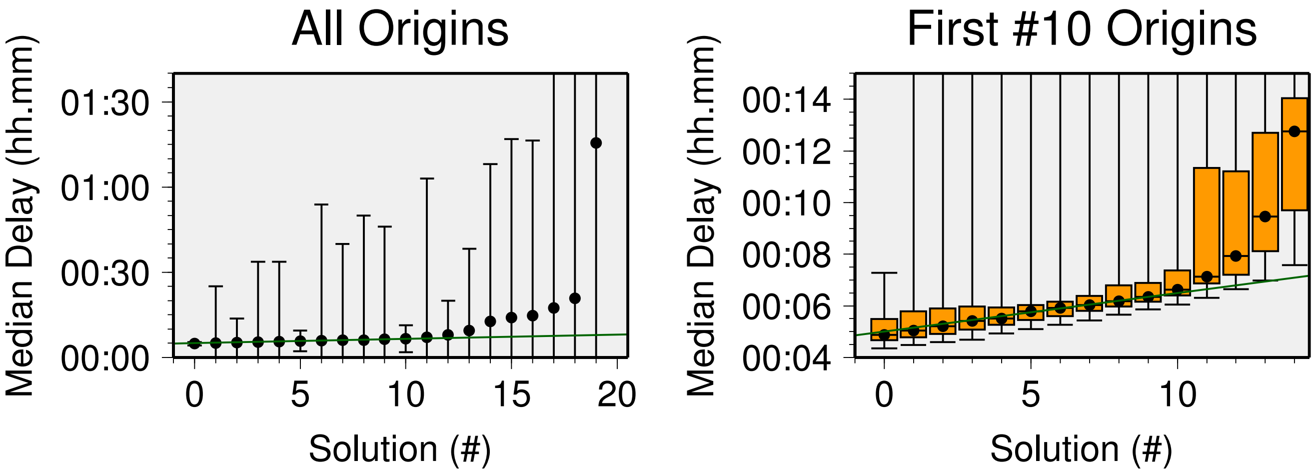


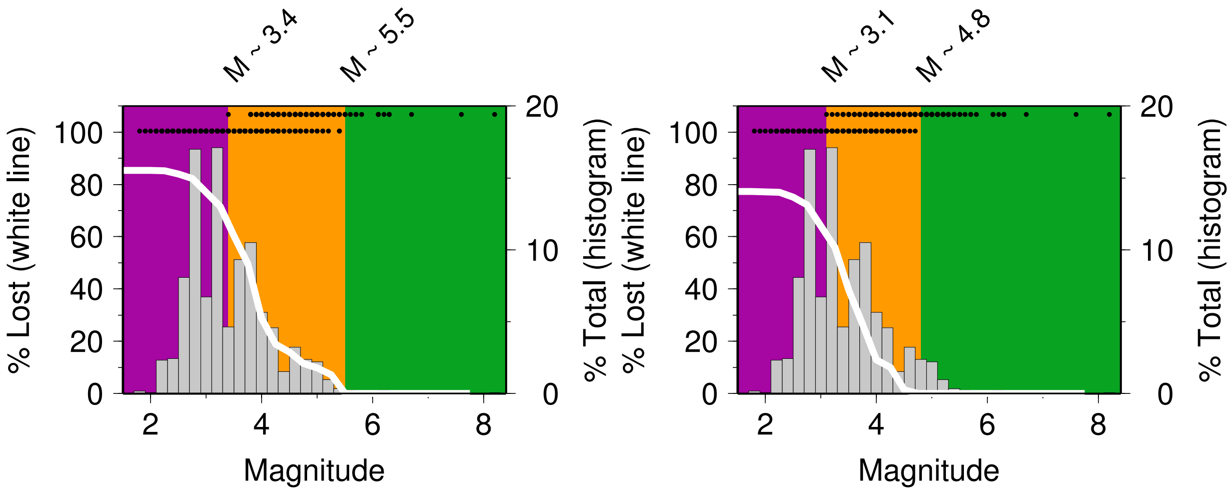
Figure 7.7: *Median delays for automatic origin determinations of RSBR events. A first origin solution was usually determined after about 5±1 minutes. Solution #10 was usually determined after about 6.5±1 minutes. Orange boxes represent 25% and 75% limits for the delay in determining origin-times and the whiskers represent the 0% and 100% limits. The green line represents a linear model where subsequent origin determinations for an event are each delayed an extra nine seconds. Some later origins are still being determined after a delay of more than one hour.*

Figure 7.7 shows that the first solutions were determined within about the first 5±1 minutes after the occurrence time of an event, and subsequent solutions were each delayed by about an extra nine seconds until the tenth solution for an event. The range between 25 and 75 percentiles for the delay times shows some uniformity until the tenth solution, after which this range changes abruptly from ±1 minute to ±4 minutes. The determination of the tenth solution for an event was generated within about 6.5±1 minutes, which corresponds to a travel-time distance of about 32° for the P arrival and marks the approximate limit in range of the RSBR network for the Pisagua sequence. Later solutions for events usually incorporated data from additional stations of the global network sited in other continents, giving a delay greater than the earlier extra nine seconds per solution because of the longer transmission times over the internet in addition to the greater seismic travel-times. Furthermore, the larger whiskers in Figure 7.7 may be due to other link delays that could have affected some events, causing the system to take longer to resolve and generate solutions for the later events.

Next we compared the catalogue of RSBR events with the catalogue of the University of Chile (UCL), which has a total of 1804 events. A similar comparison was made with the 474 events located by the United States Geological Survey (USGS/NEIC/PDE) for the same region (latitude from 21°S to 18°S and longitude from 72°W to 69°W) and period (from 2014-03-16 00:00:00 UTC to 2014-05-02 00:00:00 UTC). We assumed that the UCL catalogue is the most complete and most accurate as it used observations from many local stations near the epicentral region.

The event association process was carried out in two stages. First the source catalogue was self-associated by grouping close individual origins into single events to minimize the effect of the chosen comparison parameters (mainly the distance and time differences) on the association process. In the second stage a cross-association process was done between the auto-associated source catalogue and the target catalogue. Association was based on a maximum epicenter separation of 120 km, maximum origin-time difference of 60 s and a magnitude difference of two that allowed a one-to-one association and minimized the number of orphan events (events in target catalogue that didn't match any event in the source catalogue). Finally, once the origins were associated we estimated the completeness of the RSBR and NEIC catalogues in relation to the UCL catalogue. Using the parameters indicated in the above resulted in 31 origins being isolated in the UCL catalogue auto-association and the final cross-associations resulted in 7 RSBR orphan origins and 66 NEIC orphan origins (i.e., events located by RSBR or NEIC but not included in the UCL catalogue).

The completeness of the RSBR and NEIC catalogues is compared to the UCL catalogue in Figure 7.8. With the auto-association carried out for RSBR and NEIC catalogues the performance for RSBR is slightly poorer than that for NEIC. The RSBR magnitude threshold is M 3.4 *vs* M 3.1 (NEIC), with a minimum complete magnitude of M 5.5 *vs* M 4.8 (NEIC) and an event-loss percentage of 85% *vs* 77% (NEIC). However, it is important to note that NEIC receives a direct contribution of arrival picks and parameter data from UCL stations and other partners in South America not yet used in RSBR operations. When this taken into account, the minimum detected event size for RSBR (M 3.4) is more similar to that for NEIC (M 3.1). Nevertheless, the RSBR completeness magnitude (M 5.5) is much higher than that for NEIC (M 4.8), which indicates a need to improve the SeisComP3 detection parameters presently being used in the absence of manual scans for near-threshold events as done currently by the analysts searching for missed Brazilian regional events.

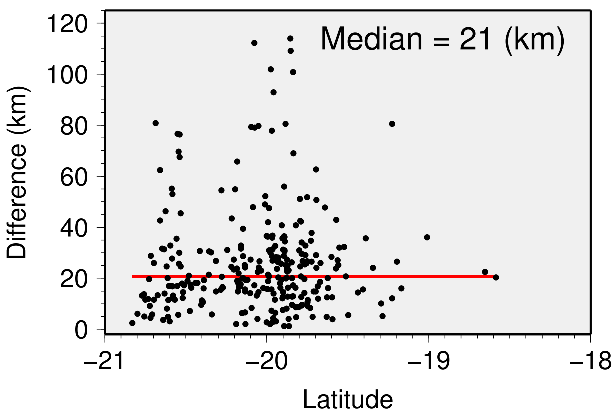


(a) RSBR vs UCL

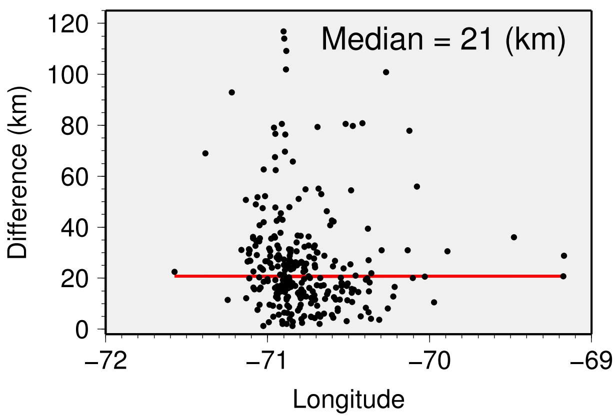
(b) NEIC vs UCL

Figure 7.8: *Comparison histograms for catalogue completeness. The purple, orange and green zones indicate magnitudes ranges where the target catalogue has no events, is partly complete or complete, respectively, according to the UCL reference catalogue. A white line indicates the accumulated-loss percentage, grey bars show the UCL catalogue magnitude histogram, and the black dots indicate the magnitudes of individual events that are only in the UCL catalogue (lower dots) or are also in the target catalogue (upper dots).*

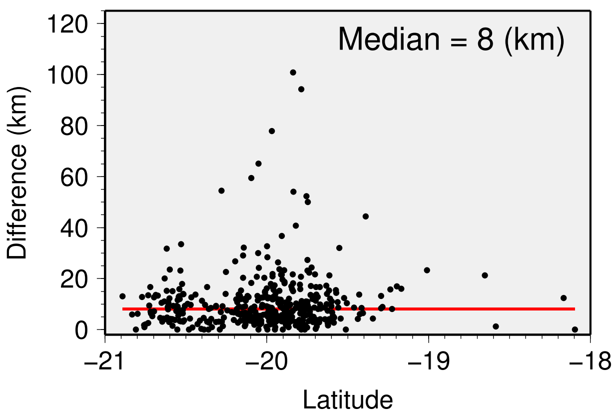
Further, the differences in location (Figure 7.9), depth (Figure 7.10) and magnitude (Figure 7.11) can be compared for the associated events. Figure 7.9 shows the differences in latitude and longitude of the target catalogue origin (RSBR or NEIC) from the reference catalogue (UCL) origin against the latitude or longitude for the UCL origin. RSBR has median differences in location of 21 km whereas NEIC has median differences of only 8 km. The NEIC origins are therefore closer to the corresponding UCL locations. Figure 7.9b suggests a trend of larger differences to the west (towards the trench, see Figure 7.6), which may be related to RSBR solutions not having fixed depths and a trade-off of depth against longitude when most of the stations are sited to the east. The NEIC origins do not show this behavior but, as indicated in Figure 7.10, the NEIC focal depths are usually under-estimated relative to the UCL depths.



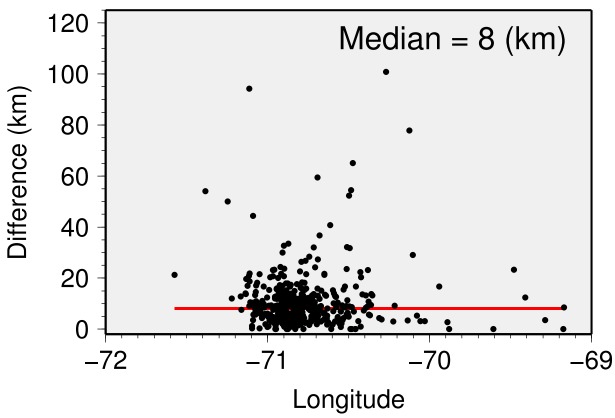
(a) RSBR vs UCL



(b) RSBR vs UCL



(c) NEIC vs UCL



(d) NEIC vs UCL

Figure 7.9: *Location offsets for associated events, showing the differences in latitude and longitude between the target and reference catalogue (UCL) epicenters. The red lines indicate the medians of differences from the UCL latitude or longitude.*

Figure 7.10a compares the depth distribution from the RSBR and NEIC catalogues with that of UCL. Whereas Figure 7.10b shows that the UCL catalogue has depths concentrated at ∼40 km, RSBR does not show any dominant depth range, with values scattered from 0 to 90 km. Deep events (probably not associated with the sequence) are well correlated, however, showing a slightly deeper trend for RSBR that is possibly reflected also in the earthquake location. On the other hand, NEIC solutions are mostly shallower than corresponding UCL solutions, although the deep events are almost perfectly correlated. NEIC depths cloud around 15 km while UCL depths concentrate around 40 km.

Finally, the magnitude comparisons in Figure 7.11 show more uniform characteristics. First, RSBR and

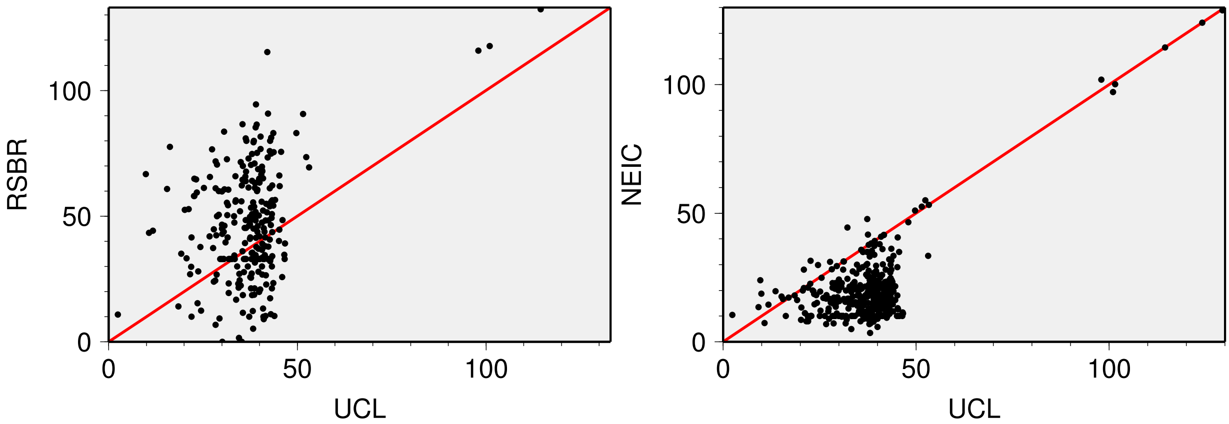


Figure 7.10: *Depth comparison plots. Each dot represents an event in the target catalogue, either RSBR or NEIC, associated with an event in the reference UCL catalogue. The red line represents the line of perfect correlation.*

NEIC magnitudes are more closely matched to the UCL value for magnitudes larger than M 5.5. For smaller events, the RSBR magnitudes tend to be lower while NEIC magnitudes tend to be higher than the UCL estimates. These features should be investigated further, but ultimately with consideration of the different magnitude scales used.

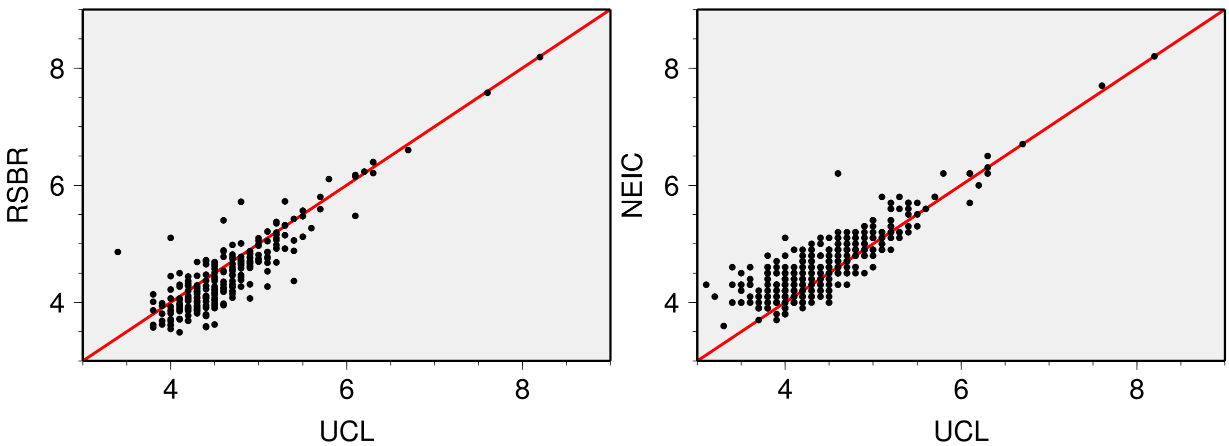


Figure 7.11: *Magnitude comparison plots. Each dot represents an event in the target catalogue, either RSBR or NEIC, associated with an event in the reference UCL catalogue. The red line represents the line of perfect correlation.*

7.1.4 Future

Given the vast size of Brazil and its low seismicity, the development of a national network was always going to be a challenge. With Petrobras support and joint efforts from four research institutions, the RSBR network has grown in the last few years and has become a reality. The initial installation plan is now almost complete: there are still two more stations planned for the Amazon region. The next challenge facing each of the four institutions is the sustainability of their sub-network, including maintenance costs as well as minimum personnel for field work and routine analyses.

The network design fulfils its initial goals. For example, one of the major products of RSBR today is the improvement of the Brazilian Seismic Bulletin with on-line information. However, further work is still necessary to tune the detection parameters, review workflows and improve inter-institution data exchange for routine analysis, as demonstrated by the results for the Pisagua sequence earthquakes. Some important points that need to be considered are: how to increase the detectability of the network to match NEIC levels in South America; and how to estimate earthquake depths more reliably in the Andean region without origin-depth trade-offs given that we have larger errors for our earthquake locations there. Also, a velocity model more representative of the Brazilian lithosphere should be implemented to improve earthquake locations in Brazil generally.

The choice of SeisComP3 software for the operation of the whole RSBR network has proved to be quite a useful coordinating platform. The implementation of robust protocols and the large user community allows the development of additional specific tools for the network operation and control, such as the implementation of the Brazilian regional magnitude m_R. As all the four nodes use the same tools and similar workflows, solutions and manpower for common problems can be easily shared.

7.1.5 Acknowledgments

Although RSBR resulted from the joint efforts of four institutions (National Observatory, ON, Rio Grande Federal University, UFRN, University of Brasília, UnB and University of São Paulo, USP), directly supported by Petrobras, many other groups also contributed significantly in the installation of several stations. We thank colleagues from IPT (Institute of Technological Research, São Paulo), UFMS (Federal University of Mato Grosso do Sul, Campo Grande and Aquidauana), UNESP (State University of São Paulo, Rio Claro), Unipampa (Univ. dos Pampas, Caçapava do Sul), UFRR (Federal Univ. of Rondonia, Boa Vista) as well as all government organizations and farm owners for allowing installation of seismic stations on their lands.

7.1.6 References

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