Brazilian Journal of Geophysics (2021) 39(4): 629-644
© 2021 Brazilian Geophysical Society
ISSN 0102-261X
DOI: 10.22564/rbgf.v39i4.2129

SEISMO-ACOUSTIC SIGNAL ANALYSIS AND YIELD ESTIMATE OF THE BEIRUT, LEBANON, ACCIDENTAL EXPLOSION ON AUGUST 4, 2020

Lucas Vieira Barros [1], Brandow Lee Neri [2], Darlan Portela Fontenele [2],
Diogo Farrapo Albuquerque [1], Ronnie Quintero Quintero [3], Juraci Mario Carvalho [1]

ABSTRACT. The Beirut, Lebanon, explosion on August 4, 2020, one of the largest non-nuclear explosion in world history, was detected by infrasound and seismic stations of the International Monitoring System (IMS), a network designed to detect and locate nuclear explosions in violation to the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The explosion was registered by five infrasound and three seismic stations, located up to 6,000 km and 2,400 km distant, respectively. These IMS data, complemented by data from seven ocean bottom stations, were used to estimate epicenter, magnitudes (mb = 3.6 and Mw = 3.3) and explosive yield. The explosion location was determined by infrasound (33,864ºN and 34,311ºE) and seismic (33,859ºN and 35,567ºE) technologies. The yield was calculated using two approaches: the seismic P-wave magnitude and the maximum amplitude of the infrasonic signal, resulting in 0.40 kt and 1.48 kt of trinitrotoluene (TNT) equivalent, respectively. The aim of this work is testing the performance of the IMS network in detection, location and characterizing of an explosion, developing skills and capacity of researchers to accurately locate events of interest to the CTBT. Additionally, we intend to highlight the importance of CTBT and arouse interest in the use of IMS data.

Keywords: Beirut explosion; seismic event detection; infrasound event detection; CTBTO; nuclear explosion.

RESUMO. A explosão de Beirute, Líbano, em 4 de agosto de 2020, uma das maiores explosões não nucleares da história mundial, foi detectada por estações de infrassom e sísmica do Sistema de Monitoramento Internacional (IMS), uma rede designada para detectar e localizar explosões nucleares em violação ao Tratado de Proibição Total de Testes Nucleares (CTBT). A explosão foi registrada por cinco estações de infrassom e três estações sísmicas, localizadas a até 6.000 km e 2.400 km de distância, respectivamente. Esses dados IMS, complementados por dados de sete estações de fundo oceânico, foram usados para estimar o epicentro, magnitudes (mb = 3,6 e Mw = 3,3) e rendimento explosivo. O local da explosão foi determinado pelas tecnologias infrassônica (33.864ºN e 34.311ºE) e sísmica (33.859ºN e 35.567ºE). O rendimento foi calculado usando duas abordagens: a magnitude da onda P e a amplitude máxima do sinal infrassônico, resultando em 0,40 kt e 1,48 kt equivalente de trinitrotolueno (TNT), respectivamente. O objetivo deste trabalho é testar o desempenho da rede IMS na detecção, localização e caracterização de uma explosão, desenvolver habilidades e capacidade dos pesquisadores para localizar com precisão eventos de interesse do CTBT. Adicionalmente, pretendemos divulgar a importância do CTBT e despertar o interesse na utilização dos dados do IMS.

Palavras-chave: Explosão em Beirute; detecção de evento sísmico; detecção de evento infrassônico; CTBTO, explosão nuclear.

*Corresponding author: Brandow Lee Neri

[11]Universidade de Brasília - UnB, Observatório Sismológico, Prédio SG -13 - Campus Universitário Darcy Ribeiro - Asa Norte, SGAN 70910 900 Brasília, DF, Brazil – E-mails: lucas.v.barros@gmail.com, diogofarrapo@gmail.com, juraci@unb.br
[2]Universidade de Brasília - UnB, Instituto de Geociências, 70910-900 Brasília, DF, Brazil – E-mails: brandowlee@outlook.com, dpfontenele@gmail.com
[3] Universidad Nacional de Costa Rica, Observatorio Vulcanológico y Sismológico de Costa Rica - Ovisicori, Heredia, Costa Rica – E-mail: rquinter@una.cr

INTRODUCTION

The devastating chemical explosion occurred at the Beirut harbor on August 4, 2020, at 18:08 (local time) or 15:08 (UTC), killing 207 people, leaving approximately 7,500 injured, 300,000 homeless and causing 15-billion-dollar loss (Reuters, 2020). Within a radius of 400 meters from the source, almost everything was knocked down: ships anchored at the port were sunk, buildings and houses collapsed, and cars were destroyed (Fig. 1). The shock waves were felt in Turkey, Syria, Palestine and were heard in Nicosia, Cyprus, more than 240 km away from the source. Soon after the explosion, a large cloud of black smoke washed over the port area.

The explosion was caused by the detonation of 2,750 tons of ammonium nitrate that had been stored in a warehouse at the port since 2013. Ammonium nitrate is a fertilizer used in agriculture, but it can burn up when subjected to temperatures of about 300 degrees Celsius (Pubchem, 2021). A fire in a neighboring warehouse triggered the first small detonation, which triggered the second big explosion of ammonium nitrate. Had it been a subsurface explosion, and considering an approximate efficiency of 50%, it would have a yield equivalent to a nuclear explosion with more than 1 kt of Trinitrotoluene (TNT), enough to generate seismic waves with energy equivalent to a four-magnitude earthquake. Nevertheless, the USGS estimated a magnitude of 3.3 mb. In this work, we estimated magnitudes equal to 3.3 Mw and 3.6 mb.

A big underground nuclear test, of about hundreds of kilotons, can generate energy capable of spreading throughout the planet in the form of disturbances detectable by a certain type of geophysical sensors. In this context, the International Monitoring System (IMS) was designed for detection and location of clandestine nuclear tests. Composed by sensors of four technologies, the IMS can monitor nuclear explosions in any of three possible environments: atmosphere, underground and underwater masses.

The Seismological Observatory of the University of Brasilia (SIS-UnB), DF, Brazil, collaborates with the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), a United Nations (UN) organization based in Vienna, Austria, which aims to verify the compliance with the CTBT. Brazil contributes to this organization with data from the Brazilian IMS stations as well as data analysis and interpretation obtained by analysts and experts. Any nuclear explosion, whether it is underground, underwater or in the atmosphere, with a power of at least 1 kt of TNT can be detected by the IMS network at any time and place.

In this work, we present the Beirut chemical explosion source parameters (epicentral location, magnitudes, and yield) determined using infrasound and seismic data. First, we briefly introduce the CTBT multilateral treaty, its verification regime and the seismic and infrasound technologies employed here. We also aim to arouse interest of Latin American researchers in the use of IMS technologies. However, under a confidentiality clause, the IMS data can only be used by States Parties.

A BRIEF REVIEW OF THE CTBT TREATY AND ITS VERIFICATION REGIME

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) prohibits nuclear explosions on a global scale. The CTBT, although not yet in force, has a mature International Monitoring System (IMS) based on geophysical sensors, capable of globally detect any nuclear test with a power equal to or greater than 1 kt of TNT. Data from the IMS network are transmitted to the International Data Centre (IDC), located at the United Nations in Vienna, Austria, where they are processed, analyzed and interpreted to identify possible signals related to clandestine nuclear explosions as well as for issuing bulletins and reports on any events of interest in compliance with the Treaty.

The IMS Network is a global nuclear test surveillance system composed of 337 installations with four technologies distributed to guarantee a global surveillance against nuclear tests. More than 90% of the IMS Network is already in operation. Since we used data only from seismic and infrasound technologies, we only present the global distribution of these stations (Fig. 2).

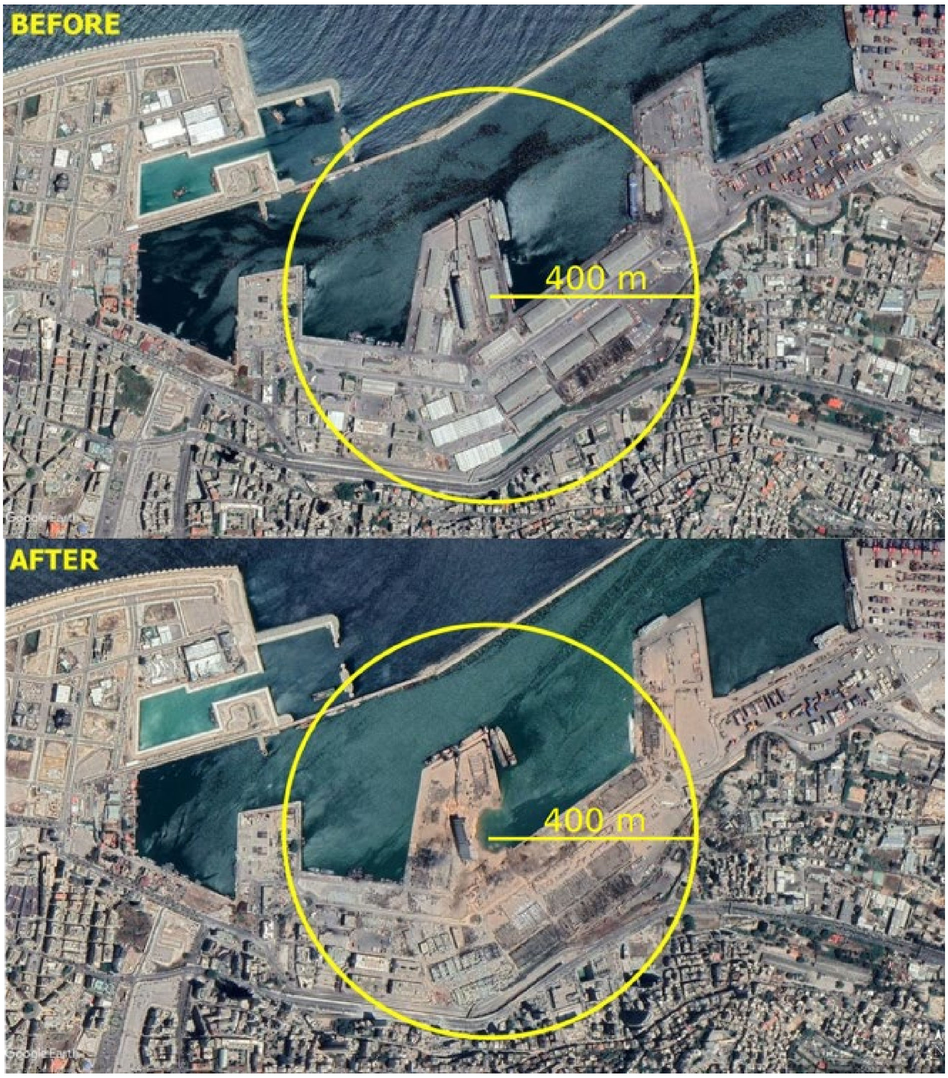

Figure 1 - Images before and after the explosion at the Beirut port. The destruction reached a radius of 400 meters from the explosion location.

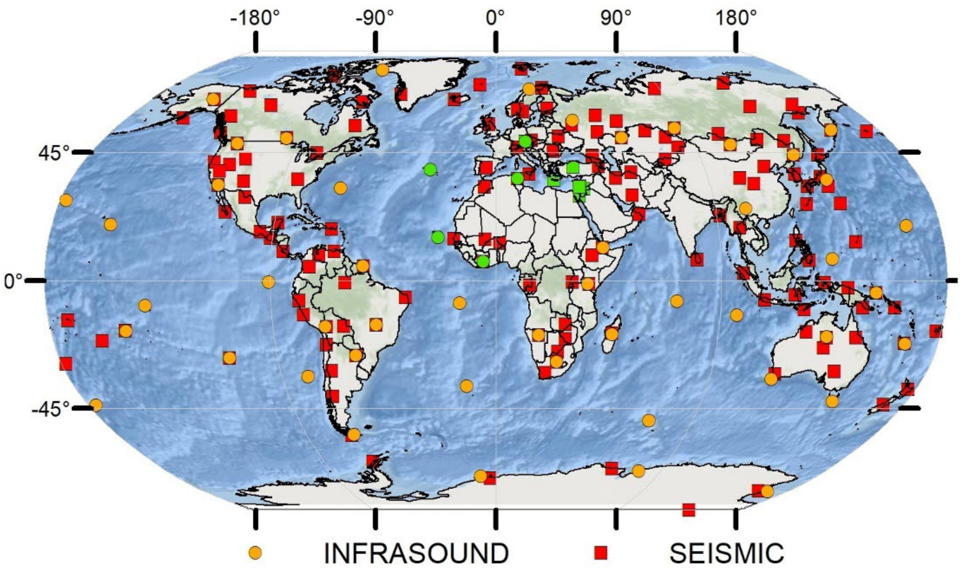

Figure 2 - IMS seismic and infrasound networks: 50 primary stations; 120 auxiliary stations (square); and 60 infrasound stations (circle). The green symbols denote stations that detected the Beirut accidental explosion.

Seismic technology

Similarly to an earthquake, a subsurface explosion generates seismic waves that can be detected by seismographic stations over long distance. The IMS seismographic network was designed to detect mainly subsurface nuclear explosions. It consists of 170 seismic stations: 50 primary and 120 auxiliary stations (Fig. 2). There are two types of seismic stations: array stations, a set of seismic sensors spatially distributed with a given geometry, usually in the form of concentric rings; and three-component stations (3C), which detect ground motion caused by the passage of seismic waves in three tri-orthogonal directions (one vertical and two horizontals). The sensors at these stations are usually installed in deep wells, 100 meters or more in depth. The seismographic arrays have the advantage of enhancing the signal-to-noise ratio (SNR) by data signal processing like beamforming technique; hence, they can detect small signals (Bormann et al., 2013; Tormod & Frode, 2013, Gibbons, 2014; Díaz, 2016).

Infrasound technology

Sound waves are variations in air pressure or acoustic disturbances that can be detected by microbarometers. Nuclear explosions in the atmosphere generate variations in air pressure (infrasound) that travel long distances according to the temperature and wind speed. The infrasound stations can detect very low frequency, non-audible sound waves in the range of 0.001 Hz to 16 Hz, emitted by natural or artificial sources, such as volcanic eruptions, storms, nuclear explosions, supersonic airplanes, among others. Due to their low frequency, infrasonic waves propagate through the atmosphere over long distances suffering low attenuation, making infrasound technology suitable for detecting nuclear tests in the atmosphere (Le Pichon et al., 2010).

An infrasound station is an array of microbarometer usually installed at the vertices of an equilateral triangle with a central sensor. This is the minimum configuration, but there are other possible configurations, according to the number and the spatial arrangement of the elements (Cansi & Le Pichon, 2009; Christie and Campus, 2010). The determination of the azimuth (direction of the wavefront that arrives to the stations) is based on the difference of the arrival times of infrasound waves in each element of the array (Brachet et al., 2010; Le Pichon et al., 2010). The IMS infrasound network is composed by 60 stations (Fig. 2).

Hydroacoustic and radionuclide technologies

Although these technologies do not rely on sensors for detecting explosions neither in the atmosphere nor in the underground, we will briefly describe them for a comprehensive vision of the CTBT verification regime. Beirut chemical explosion was not detected by the IMS hydroacoustic stations nor by the radionuclide ones. The hydroacoustic technology was developed to detect signals resulting from changes in water pressure, generated by sound waves in the seas or oceans. These waves can be caused by a variety of natural sources (e.g., noise caused by icebergs, whales and earthquakes) or man-made sources, such as marine seismic survey explosions, gust fishing and nuclear explosions (Hildebrand, 2009; Dahlman et al., 2011).

This monitoring technology is used to detect underwater nuclear explosions or nuclear explosions close to the surface or on the coast, which was the case of the Beirut harbor explosion. Given its high effectiveness, 11 stations are already sufficient to monitor the conduction of a clandestine nuclear explosion in aquatic environments across the planet (CTBTO, 2015).

The radionuclide monitoring is carried out by a network of 80 stations globally distributed, which allows a continuous worldwide observation of aerosol samples of radionuclides or radionuclide particles. To increase the efficiency of radionuclide monitoring, half of these stations are equipped with technology for monitoring noble gases generated by nuclear explosions (CTBTO, 2015).

Each CTBT verification technology is suitable for detecting nuclear explosions in one of the three possible environments: atmosphere, underground and underwater. The radionuclide technology is used to confirm if a suspect event has a radioactive origin source. However, it is also possible to have synergy between the four technologies, that is, more than one technology can contribute to the validation of a nuclear test. For example, underground nuclear tests can be detected by seismic, infrasonic and radionuclide technologies, with seismic being the main technology. Atmospheric nuclear tests can also be detected by infrasonic, seismic and radionuclide technologies, with infrasound being the most appropriate technology. The synergy occurs because the same event can be detected by different technologies and, thus, the analysis becomes complementary (Gaebler et al., 2019, Barros et al., 2020). The explosion in Beirut was detected by two technologies: seismic and infrasound.

Brazilian stations belonging to the IMS network

Brazil has signed (on September 26, 1996) and ratified (on July 24, 1998) the CTBT and contributes with data from three technologies: seismic, infrasound and radionuclides. The SIS-UnB contributes with data from two stations, one primary 3C seismic station (PS07) and one infrasound array (IS09), both installed inside the Brasilia National Park (PNB). The data from these stations are transmitted to the SIS-UnB, where they are recorded, analyzed and retransmitted to the IDC in Vienna. The other IMS stations in Brazil are two auxiliary seismic stations, located in the states of Rio Grande do Norte and Amazonas; two radionuclide stations, located in Rio de Janeiro and Recife (the latter not yet deployed), and a radionuclide laboratory, located at the Institute of Radioprotection and Dosimetry (IRD), also in the city of Rio de Janeiro (Fig. 3).

METHOD AND ANALYSIS

We analyzed infrasound and seismic data using software tools developed by Provisional Technical Secretariat of the Comprehensive Nuclear-Test-Ban Treaty Organization (PTS-CTBTO) and released as a package in a virtual machine named NDC-in-a-Box: Geotool for seismic data analysis; and DTK-GPMCC for infrasound data analysis (CEA/DASE, 2016). Due to the long distance (~10,000 km) and energy dissipation, the Beirut explosion was not recorded by any IMS infrasound station located in South America. Here, for the source parameter estimation, we used five IMS infrasound stations (Fig. 4), three IMS seismic stations (one seismic array and two 3-component stations), seven open data seismic stations and one IRIS (Incorporated Research Institutions for Seismology) station.

The Progressive Multi-Channel Correlation (PMCC) technique, used for infrasound analysis, was originally developed for the application in seismic data, but it was adapted for detecting low amplitude infrasound signals contaminated by different forms of noise. This method proved to be efficient for the routine identification of coherent low amplitude signals contaminated by incoherent noise (Mialle et al., 2019). This technique is done by combining consecutively the array elements 3 to 3, typically in eleven frequency bands between 0.07 and 4.0 Hz (IDC configuration), and in adjacent time windows covering the entire analysis period (Fig. 5). The duration of the processing window inversely depends on the frequency band. This ranges from 60 seconds for the lowest frequency to 30 seconds for the highest frequency. Neighboring pixel groups make up a PMCC family (Cansi,1995; Cansi and Klinger, 1997; Cansi and Le Pichon, 2009).

The first stage of processing produces elementary detections that are called PMCC pixel, which satisfies the criteria of correlation and consistency. After this, individual pixels with similar signal attributes in time, frequency, backazimuth, and horizontal velocity are grouped to form PMCC families. An elementary family is composed by at least seven pixels, with the maximum of 2000 pixels.

Waveform analysis and results

The event was located using infrasound and seismic data requested by SIS-UnB to the IDC – CTBTO (IMS data) and Incorporated Research Institutions for Seismology (IRIS) Website (open access data). The IRIS is a consortium of over 100 US universities dedicated to the operation of science facilities for the acquisition, management,

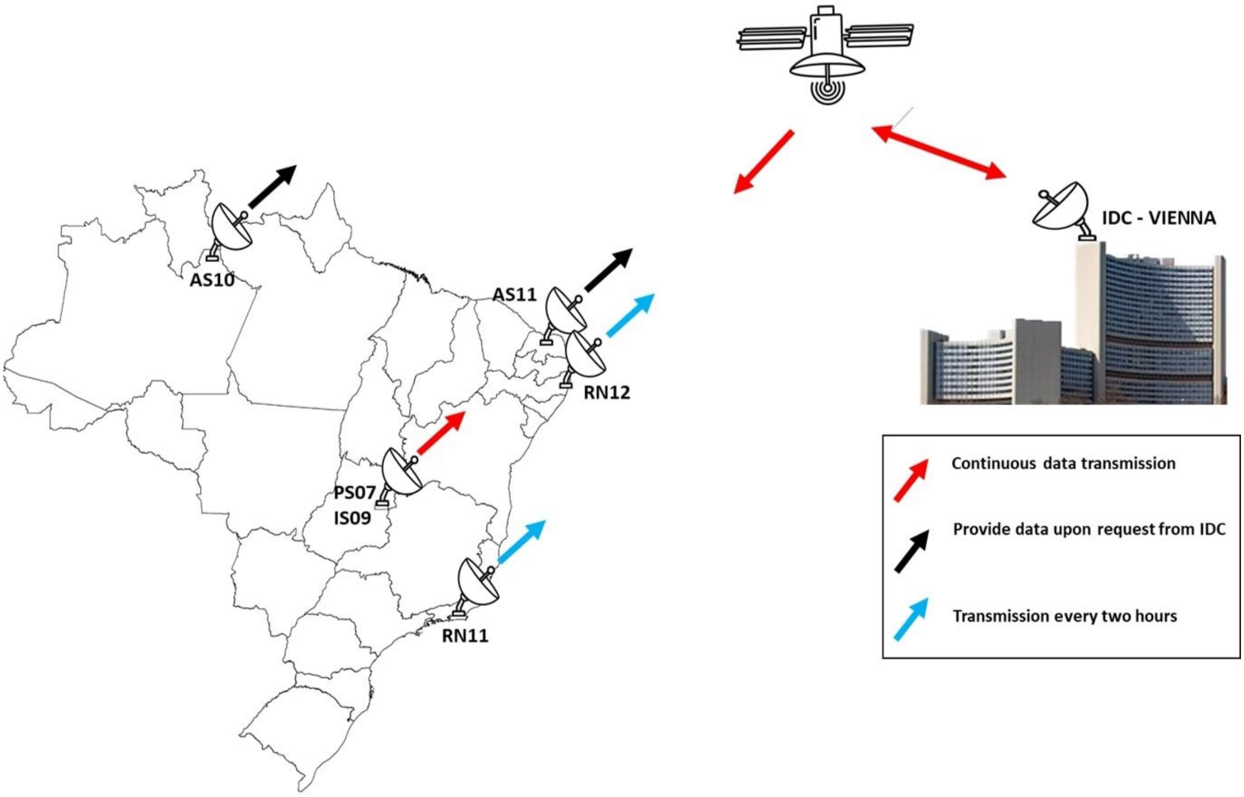

Figure 3 - Locations of Brazilian IMS stations and how they transmit data to the IDC in Vienna, Austria. AS10 and AS11 are auxiliary seismic stations, RN11 and RN12 are radionuclide stations, PS07 and IS09 are primary seismic and infrasound stations.

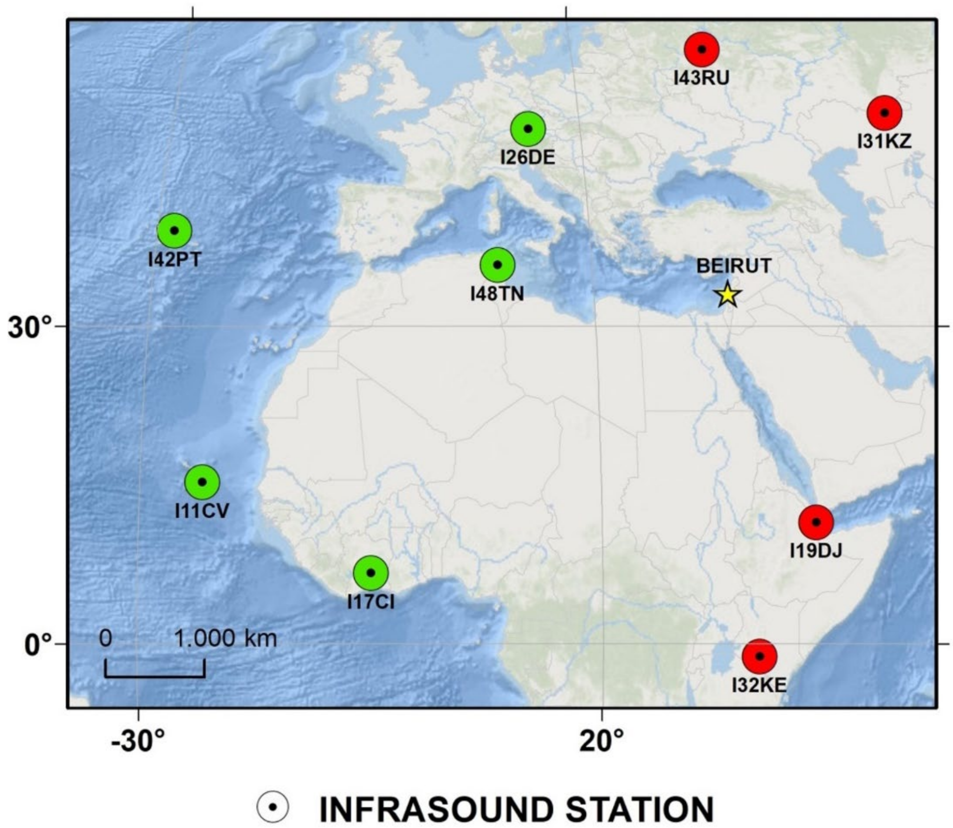

Figure 4 - IMS infrasound stations that detected the event (green circles) and those that did not (red circles). The yellow star indicates the explosion location.

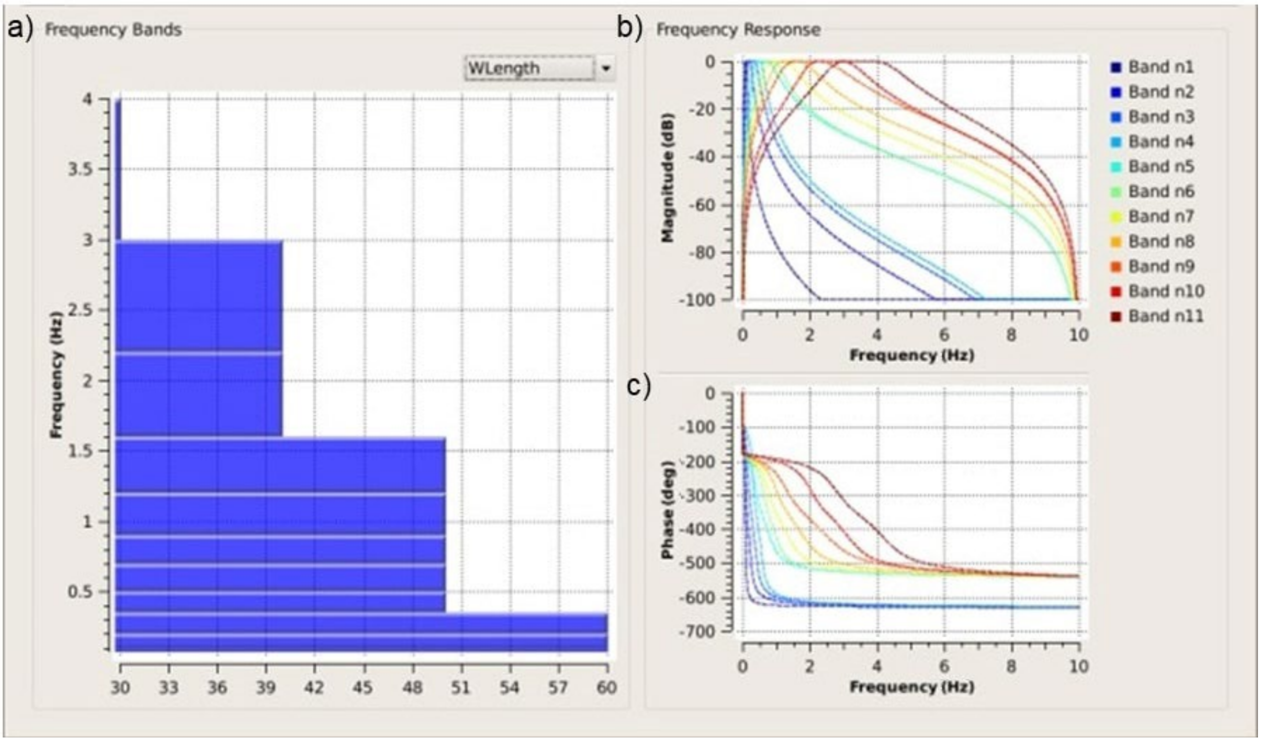

Figure 5 - Frequency bands used in the data processing. (a) Bands duration (seconds) of the eleven bands used. Note that the duration of the windows (x-axis) is variable. (b) Frequency response of the used bands; and (c) Phase response of the used bands.

and distribution of seismological data. IRIS programs contribute to scholarly research, education, earthquake hazard mitigation, and verification of the Comprehensive Nuclear-Test-Ban Treaty (www.iris.edu).

Infrasound waveforms

To locate the explosion occurred in Beirut, we initially used data from the five IMS infrasound stations indicated by the green circles in Figure 5. The stations in Tunisia (I48TN, 2,400 km), Germany (I26DE, 2,500 km), Côte d'Ivoire (I17CI, 5,000 km), Azores, Portugal (I42PT, 5,600 km) and Cape Verde (I11CV, 6,136 km) recorded clear infrasound families, with low variation in the event backazimuth. Azimuthal rays of each station point to the source of infrasound waves. The analysis using PMCC technique generates PMCC families' outputs with information of wavefront backazimuth, frequency band of infrasound signals, average infrasound speed, arrival time, and correlation between element traces.

The results of the PMCC analysis of the Beirut explosion in five IMS infrasound stations are shown in Figures 6 to 10 in the following order: register in stations I48TN (Tunisia), I26DE (Germany), I17CI (Côte d'Ivoire), I42PT (Azores - Portugal) and I11CV (Cape Verde). In all figures, the upper and middle graphs correspond to the average azimuth and speed of the infrasound wavefronts arriving at each station, respectively. At the bottom it is shown the array beamforming of waveform signals registered by each station and on the right, the polar plot indicates the average azimuth and speed of the wavefront arriving at the station. The event was located based on the station azimuth.

We were able to find pressure disturbance at infrasound stations located to the west of the source. Table 1 shows the stable azimuth and wavefront speed for the five stations, corresponding to 88.6 degrees and 348 m/s in Tunisia (I48TN); 125 degrees and 346 m/s in Germany (I26DE); 47.2 degrees and 348 m/s in Côte d'Ivoire (I17CI); 80.1 degrees and 341 m/s in Portugal (I42PT) and 60.6 degrees and 349 m/s in Cape Verde (I11CV). The location is acquired by tracing the rays from the stations to the source, using the correspondent azimuth. The epicenter is the point to where the rays intersect (see Fig. 11).

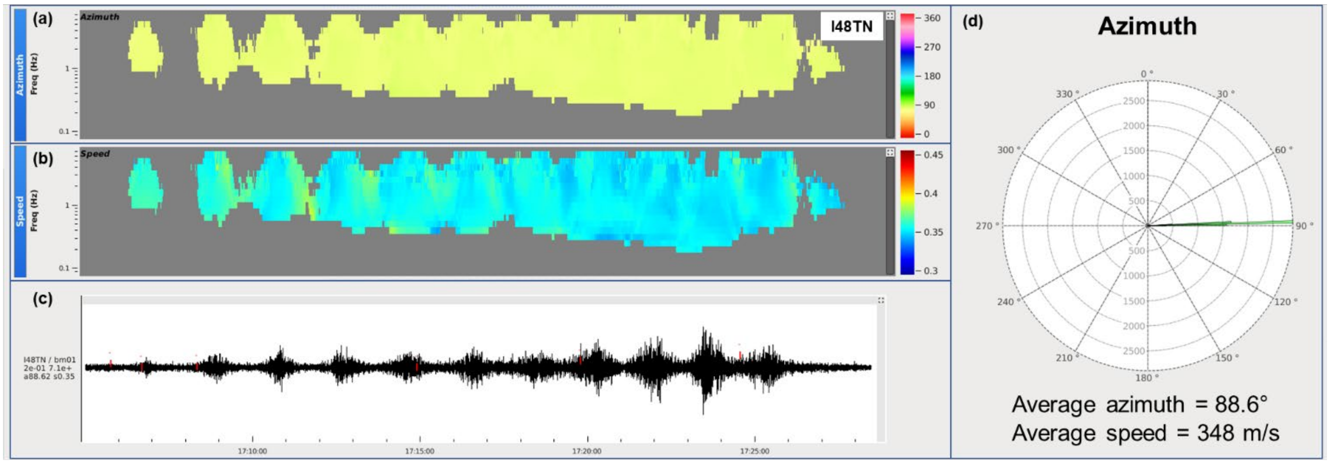

Figure 6 - Information on the detection of the Beirut explosion recorded by the infrasound station located in Tunisia (I48TN). PMCC-families indicating: (a) average azimuth, (b) speed, and (c) beamforming of the seven element stations. In (d), polar plot showing the average azimuth.

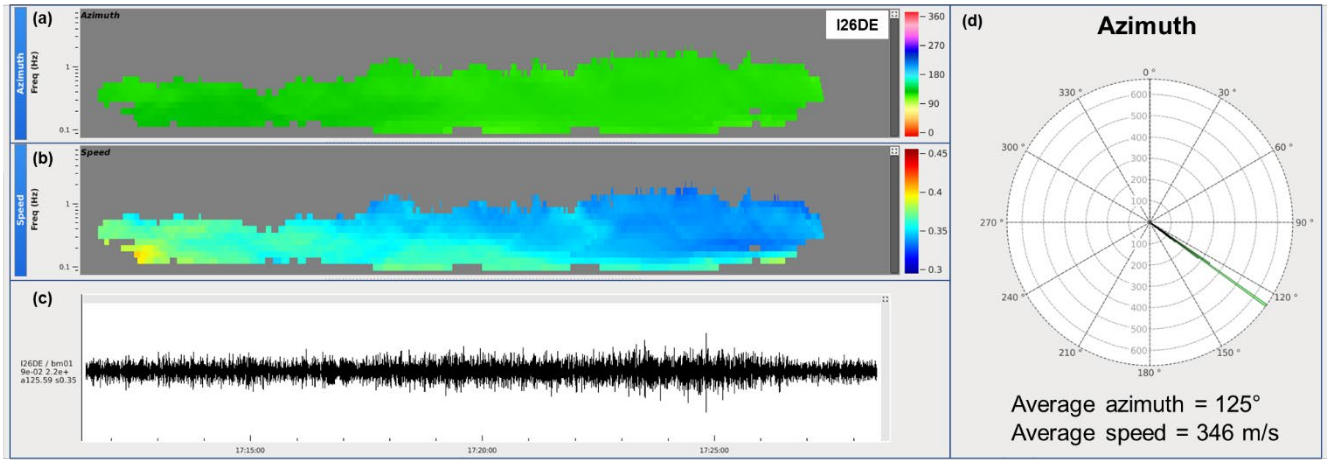

Figure 7 - Information on the detection of the Beirut explosion recorded by the infrasound station located in Germany (I26DE). PMCC-families indicating: (a) average azimuth, (b) speed, and (c) beamforming of the eight element stations. In (d), polar plot showing the average azimuth.

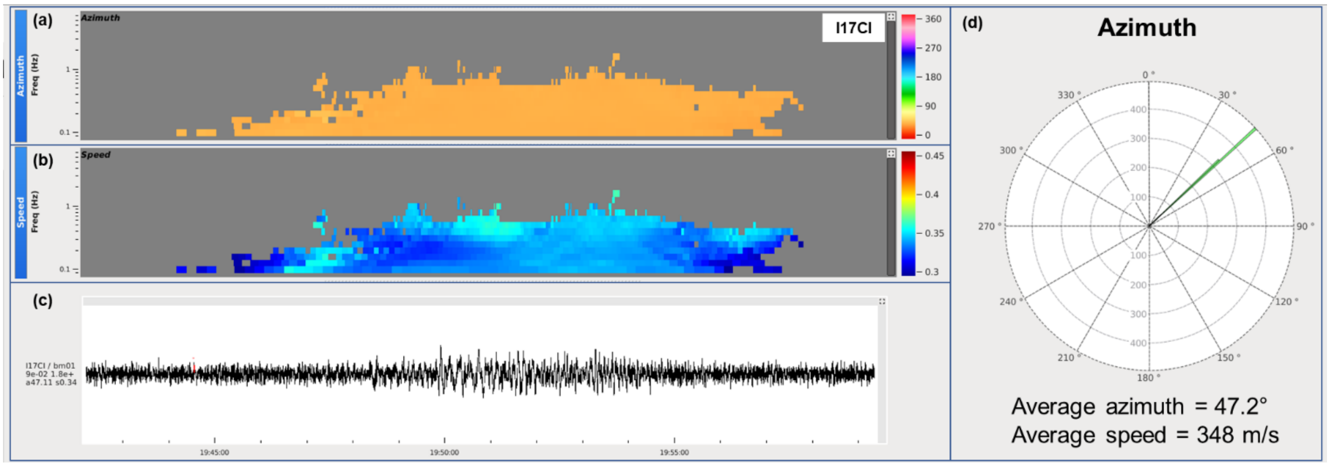

Figure 8 - Information on the detection of the Beirut explosion recorded by the infrasound station located in Côte d'Ivoire (I17CI). PMCC-families indicating: (a) average azimuth, (b) speed, and (c) beamforming of the four element stations. In (d), polar plot showing the average azimuth.

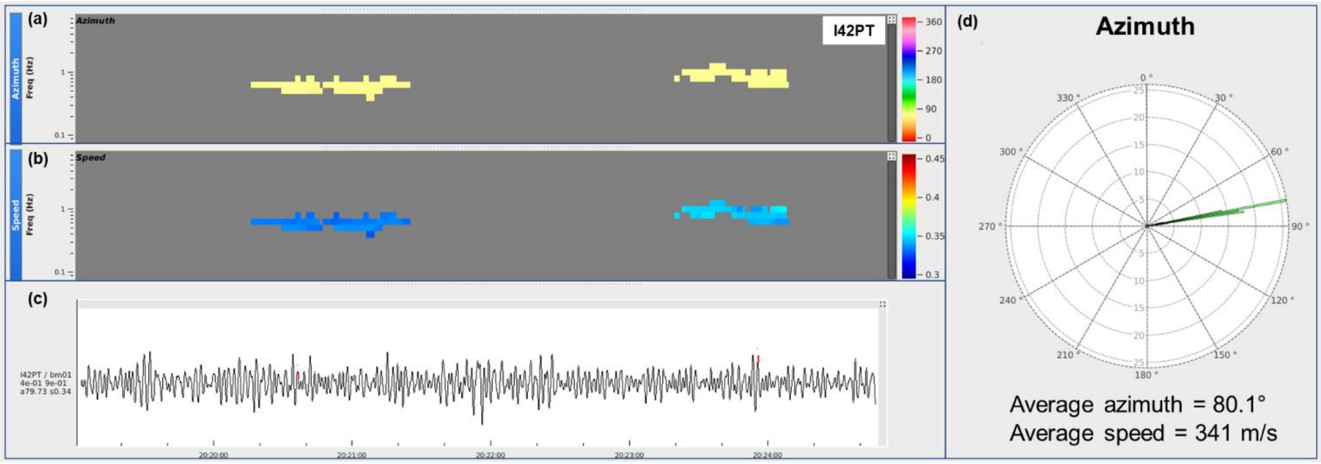

Figure 9 - Information on the detection of the Beirut explosion recorded by the infrasound station located in Portugal (I42PT). PMCC-families indicating: (a) average azimuth, (b) speed, and (c) beamforming of the eight element stations. In (d), polar plot showing the average azimuth.

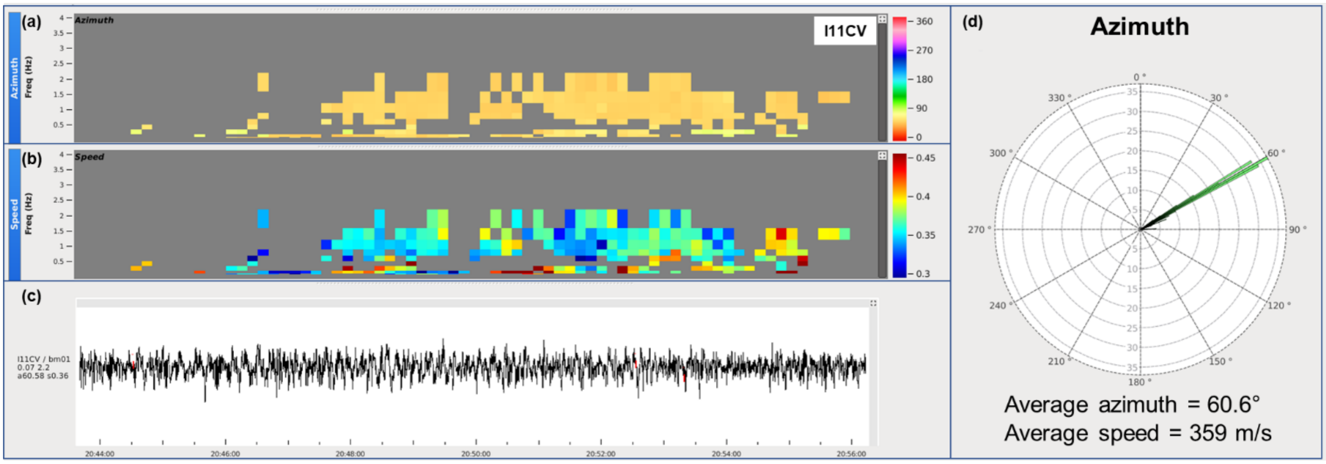

Figure 10 - Information on the detection of the Beirut explosion recorded by the infrasound station located in Cape Verde (I11CV). PMCC-families indicating: (a) average azimuth, (b) speed, and (c) beamforming of the eight element stations. In (d), polar plot showing the average azimuth.

Table 1 - Output parameters determined for the infrasound signals detected by the five stations.

Station	Distance (km)	Time HH:MM:SS	Azimuth (º) real	Azimuth (º) cal.	Speed (km/s)	Duration (s)	Frequency (Hz)	Corr. avg	Max. Amp. (Pa)	Fam. Size
I11CV	6,206	20:44:31	59.09	60.58(±6.33)	0.359(±0.047)	680.0	0.815(± 0.554)	0.4712	0.2915	218
I17CI	5,128	19:44:32	48.21	47.11(±0.89)	0.342(±0.011)	808.4	0.375(±0.234)	0.6188	0.1324	949
I26DE	2,450	17:12:21	124.68	125.60(±2.09)	0.346(±0.011)	926.9	0.548(±0.341)	0.6471	0.1329	1,929
I42PT	5,625	20:20:37	74.92	79.73(±1.51)	0.338(±0.006)	69.0	0.623(±0.401)	0.3286	0.0259	42
I42PT	5,625	20:23:56	74.92	80.17(±1.51)	0.349(±0.006)	50.6	0.909(±0.401)	0.2676	0.0184	44
I48TN	2,400	17:06:41	87.40	87.17(±1.08)	0.364(±0.006)	63.3	2.448(±1.694)	0.3250	0.0272	241
I48TN	2,400	17:08:20	87.40	88.67(±1.08)	0.359(±0.006)	395.6	2.541(±1.694)	0.3935	0.1026	2,000
I48TN	2,400	17:14:54	87.40	88.32(±1.08)	0.357(±0.006)	318.6	2.551(±1.694)	0.4290	0.1873	2,000
I48TN	2,400	17:19:47	87.40	88.62(±1.08)	0.354(±0.006)	278.3	2.563(±1.694)	0.5136	0.4817	2,000
I48TN	2,400	17:24:33	87.40	89.35(±1.08)	0.353(±0.006)	203.6	2.532(±1.694)	0.3984	0.1147	958

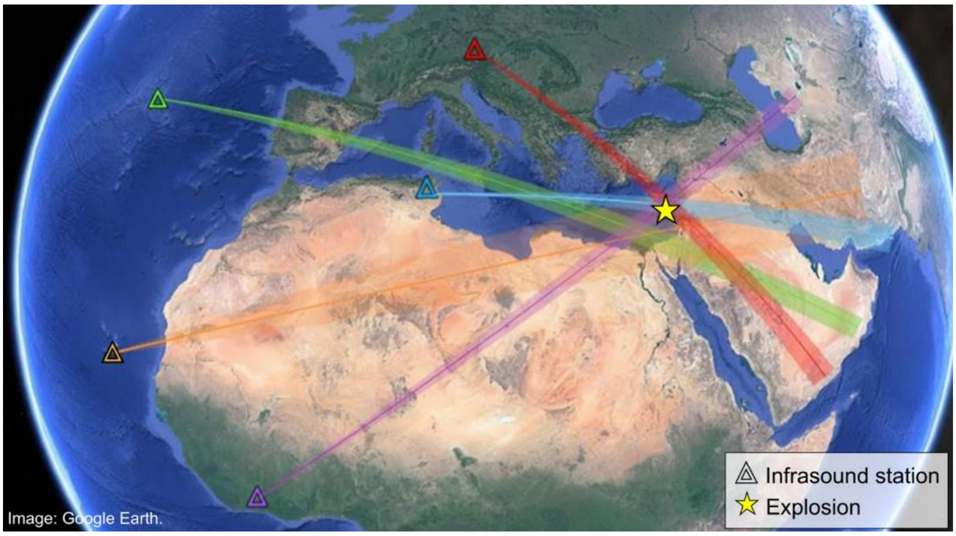

Figure 11 - Location of the explosion (yellow star). The triangles indicate the infrasound stations used in this study. Colored rays from stations I26DE (Germany), I48TN (Tunisia), I17CI (Côte d'Ivoire), I42PT (Azores, Portugal) and I11CV (Cape Verde) point in the direction of the source (Beirut).

Despite the long distances from the stations, the orientation calculated by the PMCC algorithm is satisfactory, based on the known explosion site, we found with an error of about 100 km. This analysis, performed with only five infrasound stations, will be improved using data from seismic stations. Table 1 shows the output parameters computed by GPMCC for the infrasound signals detected by each station: speed (km/s) is how fast each infrasound wavefront travelled; duration (s) is the duration in pixels of each infrasound family; frequency is the average frequency of each PMCC family; correlation is the waveform correlation (indices) between the array elements; max. amp (Pa) is the maximum amplitude of the infrasound signal in each PMCC family; family size represents the number of pixels in each PMCC family; and NE is the element number for each array.

The coordinates of the explosion location determined by infrasound technology are 33.864ºN, 34.311ºE, and the origin time is 15:03:32.351 (UTC). The depth was fixed on the surface (Fig. 11). As it will be described later, the obtained location from the infrasound data is not as accurate as the location from the seismic data. However, this kind of event is generally jointly studied by both technologies. The dispersion around the azimuth radius represents the deviation from the estimated average azimuth value, i.e., the greater the distance, the greater can be the error in the location.

Although with low magnitude (3.3 Ml, according to USGS and 3.6 mb in this work), this explosion was recorded by infrasound stations considerably far. In fact, infrasound waves with low frequency and long wavelengths have low attenuation and propagate long distances (Gossard and Hooke, 1975; Marty, 2019). Also, the wind propagation direction helped its propagation to the west. Stations located on the east side, although closer to those on the west, did not register the event, suggesting that the wind direction propagation was from east to west (Fig. 5).

The energy released by the explosion was greater than the energy that would have been released by a 3.3 magnitude earthquake. Because earthquakes occur underground, most part of their energy is converted into seismic waves. This is not the case for explosions on the surface, where part of the energy is converted into sound and shock waves.

Seismic waveforms

We analyzed data from 11 seismic stations: 3 belonging to IMS, 7 belonging to Cyprus, International Miscellaneous (IM) network, and 1 from Incorporated Research Institutions for Seismology (IRIS) (Fig. 12). The open access data were downloaded from the IRIS website.

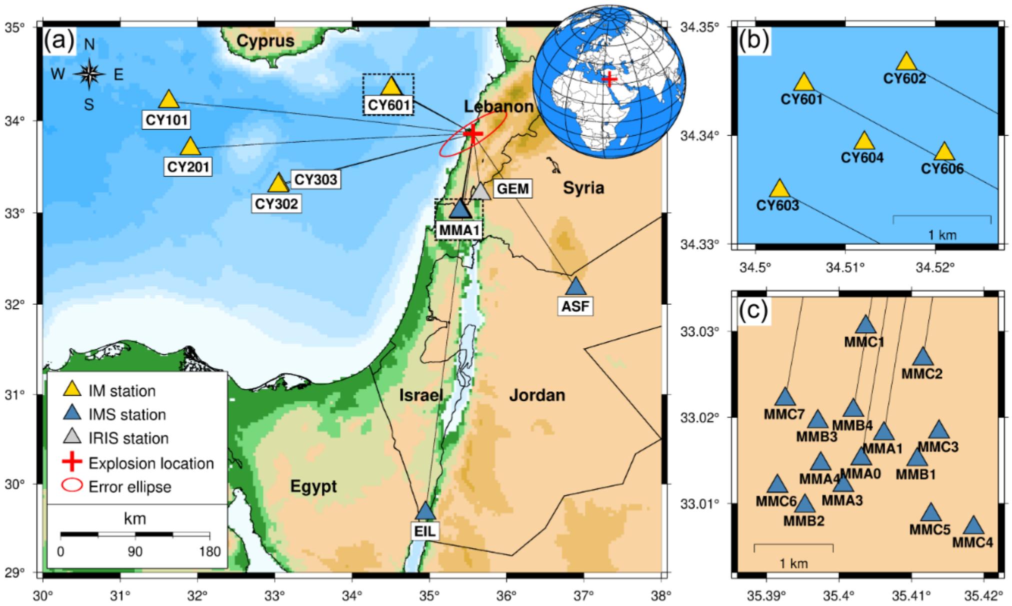

Figure 12 - Seismic stations used for hypocentral location. The blue triangles are IMS stations, the yellow ones are ocean bottom stations, and the green triangle is the IRIS station. The zoomed figure on the right shows the array elements.

The location estimated using Geotool with seismic data is 33.859ºN and 35.567º E, fixed depth in the surface (0 km), origin time 15:08:18.3 (UTC), and magnitude equal to 3.6 mb and 3.3 Mw. The azimuthal gap is equal to 206º, the minimum station distance is 73 km, and the maximum is 467 km. Figure 13 shows the seismic waveforms, vertical components, and Figure 14 shows the locations using infrasound data (yellow star), seismic data (green star), IDC location (red star) and true location (black star).

Yield estimation

Rapid and accurate assessment of the yield of a major urban explosion is important for implementing emergency response plans, estimating areas of major and minor risk, as well as providing policy makers and the general public with more information about the event (Rigby et al., 2020).

The yield of an explosion gives information mainly on its potential for damage. Thus, nuclear test explosions are done to know its destructive power. Different methods have been developed for the yield estimation. For example, Gitterman and Hofstetter (2012), in a GT0 calibration experiment, utilized high-pressure gauges to record air-blast in order to evaluate the efficiency of the charge design and energy generation to provide a reliable estimation of the actual explosion yield. Kim et al. (2009) used the ratio of the Pn and Pg displacement amplitude spectra between nearly co-located two North Korea Underground Nuclear Explosions (UNEs) recorded at the same seismic stations by eliminating the path effect. Goldstein (2020) used the crater dimensions to estimate the yield of Beirut 2020, August 4th, explosion and found to be equivalent to approximately 1.4 kt of TNT with a lower bound of about 0.7 kt. The crater-size based yield determination is estimated on crater radius measurements from satellite imagery, empirical curves and data for scaled crater radius from past chemical and nuclear explosions. Lu (2020) used a similar methodology to estimate the energy of the Beirut explosion. Based on the fireball radius, air density and time, the author estimated the power released by the explosion and found 0.6624 kt of TNT equivalent, corresponding to 2,070 ton of ammonium nitrate. Stevens et al. (2002), measuring digitized records of atmospheric nuclear explosions taken by the USSR between 1957 and 1961, developed a formula to calculate the yield from measurements of the records of infrasound signals:

$$log(P) = 3.37 + 0.68\, log\, log\, W \; - 1.36\, log\, log\, R\,, \qquad (1)$$

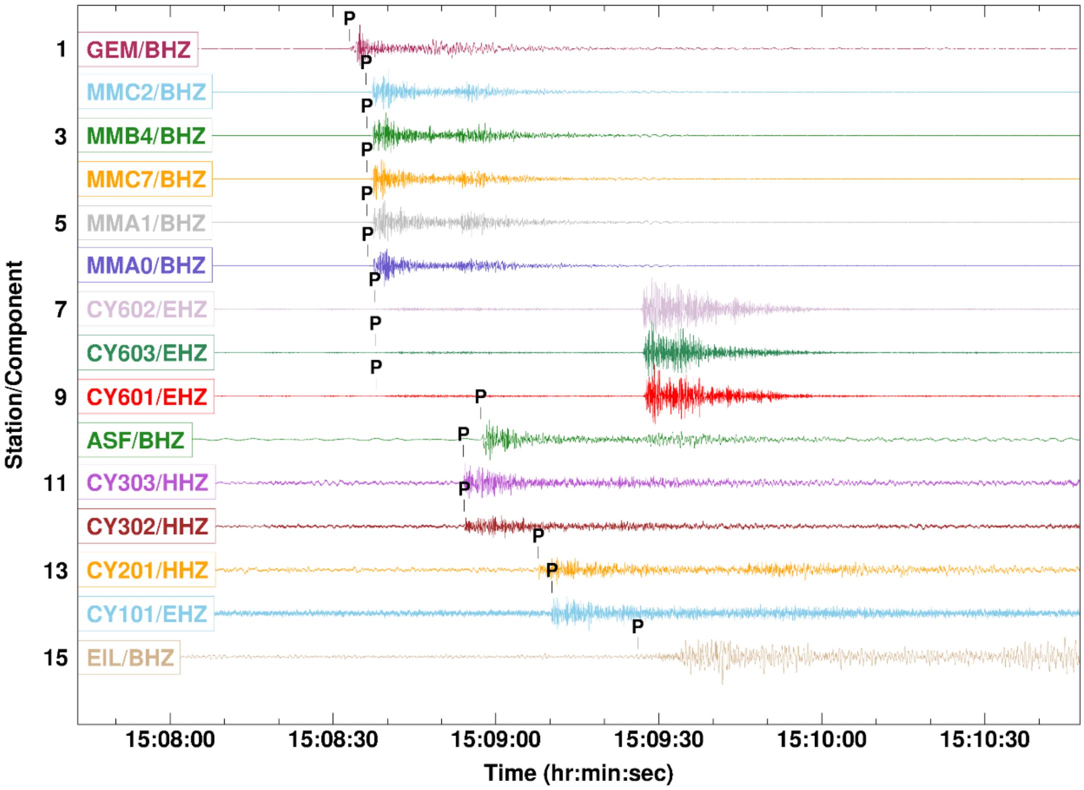

Figure 13 - Beirut explosion seismic waveforms, vertical components. The event was located by 3 IMS stations, 7 IM stations and 1 IRIS station. Stations 2 to 6 belong to the same array.

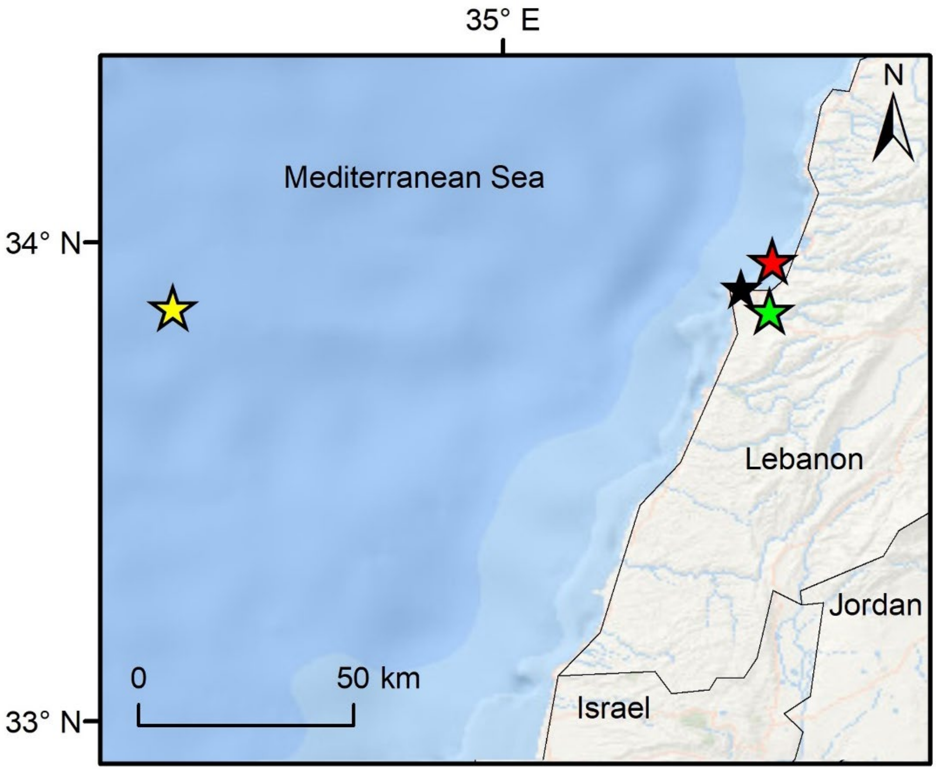

Figure 14 - Beirut explosion locations: true location (black star); IDC location (red star); SIS-UnB location (seismic data - green star, and infrasound data - yellow star).

where P is zero to peak pressure amplitude in Pascals, W is the yield in kilotons, and R is the distance from source to receiver in kilometers. Using this approach, we computed the average yield from five stations, and we found 2.21 kt TNT. However, if we eliminate the most distant station (I11CV) the yield becomes 1.48 kt TNT. Therefore, we decided to use the data from 4 stations with better SNR. This is a reasonable value if we consider a 50% (1.38 kt TNT) efficiency in 2.75 kt TNT ammonium nitrate.

An UNE, when well-conditioned, is expected to have a high isotropic component, i.e., low percentage of Double Couple (DC%). Gaebler et al. (2019) showed that the waveform inversion for the seismic moment tensor of the September 3, 2017, the North Korean nuclear explosion has presented a dominant isotropic component, showing the explosive character of the event. However, an analysis of the source mechanism of a tremor that occurred about 8 minutes after the test in the vicinity of the test site suggested that it was a collapse of the cavity. Indeed, the seismic source parameters reflect information on the event nature.

In this work, the waveform inversion for the moment tensor using Zahradnik and Sokos' approach (2018), applied to IMS seismic data only, did not produce a satisfactory result in terms of correlation between synthetics and observed data. However, using additional data, from ocean bottom seismic stations located in the Mediterranean Sea, we estimated a magnitude of 3.3 Mw and a small isotropic component of 8%. These values should have been affected by the superficial nature of the explosion, which causes almost all energy to be emitted to space and converted in shock waves that propagate up to 240 km away, consequently being heard in Nicosia, Cyprus's capital.

The most used parameter to estimate an explosion yield is based on the seismic body wave magnitude (mb). Widely used for underground nuclear test monitoring, it can also be used to provide a lower limit of a surface explosive source (Pilger et al., 2021). In this case, different empirical relationships must be developed for different areas. These empirical formulas are of the type *mb = a + b log (Y),* where Y is the explosion equivalent yield in kt of TNT. The constants *a* and *b* are dependent of the test location. Murphy (1981) determined the constant values for Nevada Test, as follows:

$$mb = 3.92 + 0.81\, log\, log\, (Y) \qquad (2)$$

For the magnitude mb = 3.6, determined in this work from magnitude average for 15 array elements of MMA1 seismic array, the yield is Y = 0.4027 kt TNT equivalent. This value represents a lower bound estimate of the Beirut explosion yield, as the equation was originally formulated for underground explosions.

DISCUSSION AND CONCLUSIONS

One of the objectives of this work was to test the performance of the IMS Network in the detection, location, and characterization of an event like a clandestine nuclear explosion of power equivalent to 1 kt of TNT, as well as to develop the skills and improve the capability of the State Parties researchers in accurately locating the events of interest to CTBT. It was not possible to lead to an accurate study of the event using only the data from the IMS Network. However, by adding data from additional stations, the results were improved, and the explosion was located with a precision of about 6 km. The improved location precision from the additional seismic stations showed the importance of the IDC counting on additional data from the States Parties. It is important to highlight that the Beirut explosion is a GT0 (Ground Truth) event for the seismic and infrasound technologies since its location and origin time are well known.

In this work we approached fundamental requirements for understanding the CTBT and its verification regime, as a way of disseminating the Treaty and showing the scope of the verification technologies and also attracting the interest of researchers for the importance of the infrasound data application in the scientific and social areas. As can be seen in Figure 14, the SIS – UnB explosion location, using seismic data, is similar to the IDC location.

A well-conditioned underground nuclear explosion, with a power equivalent to 1 kt of TNT (15 times smaller than the atomic bomb detonated over Hiroshima), releases energy like a 4.0 magnitude earthquake (Bormann, et al., 2013).

However, the Beirut explosion released only 0.40 kiloton of TNT determined using body wave magnitude (Eq. 2). Other seismological institutions encountered different magnitude values. For example, the Jordan Seismological Observatory estimated a magnitude of 4.5, considerably higher than the result of USGS that found a magnitude of 3.3. The value of 0.4 kt TNT seems to be underestimated; in fact this is true because part of the explosive energy was converted into shock waves that propagated over long distances, reaching Nicosia, Cyprus' capital (Reuters, 2020), 240 km away. The GFZ (Geo-research Centre), Germany, estimated a magnitude of 3.5, while the SIS-UnB, using the averaged magnitudes from the IMS stations and the seismic stations from the bottom of the Mediterranean Sea, estimated a magnitude equal to 3.6 mb. This value, 0.4 kt TNT, represents only a lower bound.

Using equation (2), the yield encountered was 1.48 kt TNT, that represents an upper bound of the yield explosion. Comparing our results with others gotten by different authors using different methodologies, we verified that our results are reasonable (Table 2).

The Beirut explosion was useful for the Preparatory Commission of the Comprehensive Nuclear Test Ban Treaty Organization, due to its charge and similarity to a nuclear test, as it served to calibrate the nuclear explosion International Monitoring Network (IMS). Its power and detonation characteristics generated enough infrasonic waves to reach infrasound stations located more than 6,000 km away. Therefore, this work was useful for the following reasons:

1. To disseminate the CTBT Treaty and its verification technologies to attract the interest of researchers in their use of data from the IMS network in the scientific and social areas, as well as to develop group skills in the study of clandestine nuclear explosions.
2. To test the performance of the IMS network in the detection, location and discrimination of events of interest to the Treaty, considering the great similarity of this chemical explosion with a nuclear test for which the network was designed to detect, with a yield on the order of magnitude of 1 kt.
3. To check if Brazil is able to fulfill its role in verifying the CTBT, in terms of ability to analyze and interpret infrasonic signals as a way to identify signs of events of interest to the Treaty.

Table 2 – Yield summary gotten with different methodologies.

Reference	Yield lower bound kt TNT	Yield upper bound kt TNT	Methodology
Rigby et al., 2020	0.5	1.12	Social media video footage
Goldstein, 2020	0.7	1.4	Seismic body wave and crater size
Pilger et al., 2021	0.13 - 0.34	0.8 - 1.1	Seismic body wave and InSAR
Barros et al., 2021 (this work)	0.41	1.48	Seismic body wave and infrasonic signal

ACKNOWLEDGEMENTS

The authors thank very much the PTS-CTBTO for the data and opportunity in training; The Seismological Observatory of the University of Brasilia for the support in a scholarship for the second author; Mrs. Vesna R. Barros for the judicious text reading, suggestion, and English corrections. We thank the two anonymous reviewers.

REFERENCES

BARROS, L., NERI, B., CARVALHO, J., FONTENELE, D. 2020. A Participação brasileira no sistema de verificação do tratado de proibição total de testes nucleares, – Tubarão, Brazil: Copiart, 2020.152 pp.

BORMANN, P., WENDT, S., DIGIACOMO, D. 2013. Seismic Sources and Source Parameters. In: Bormann, P. (Ed.). New Manual of Seismological Observatory Practice 2 (NMSOP2), Potsdam: Deutsches GeoForschungsZentrum GFZ, 1-259. DOI: 10.2312/GFZ.NMSOP-2_ch3

BRACHET N., BROWN D., LE BRAS R., CANSI Y., MIALLE P., COYNE J. 2009. Monitoring the Earth's Atmosphere with the Global IMS Infrasound Network. In: Le Pichon A., Blanc E., Hauchecorne A. Infrasound Monitoring for Atmospheric Studies. Part I - History, Instrumentation, Network. Springer, Dordrecht. p. 77-118. DOI: 10.1007/978-1-4020-9508-5_3

CANSI, Y. 1995. An automatic seismic event processing for detection and location: The P.M.C.C. Method. Geophysical Research Letters, 22(9), 1021–1024. DOI: 10.1029/95GL00468

CANSI, Y, & KLINGER, Y. 1997. An automated data processing method for mini-arrays. CSEM/EMSC European-Mediterranean Seismological Centre. News Lett 11:1021–1024

CANSI, Y, & LE PICHON, A. 2009. Infrasound Event Detection Using the Progressive Multi-Channel Correlation Algorithm. In Handbook of Signal Processing in Acoustics, (pp. 1425–1435). DOI: 10.1007/978-0-387-30441-0_77

CEA/DASE. 2016. GPMCC User Operation and Technical Manual. Version 5.5. 103 p.

CHRISTIE, D.R., CAMPUS, P. 2010. The IMS Infrasound Network: Design and Establishment of Infrasound Stations. In: Le Pichon, A., Blanc, E., Hauchecorne, A. Infrasound Monitoring for Atmospheric Studies. Springer, Dordrecht. DOI: 10.1007/978-1-4020-9508-5_2

CTBTO, 2015. Disaster warning and promoting human welfare – the civil and scientific uses of CTBTO data. Preparatory Commission for the Comprehensive Nuclear Test-Ban Treaty Organization. Vienna, Austria. 6 pp. Available online: https://www.ctbto.org/fileadmin/user_upload/public_information/2015/CSA_final_2015_web.pdf (accessed on 17 September 2020).

DAHLMAN O., MACKBY J., MYKKELTVEIT S., HAAK H. 2011. Verifying the CTBT—A State Perspective. In: Detect and Deter: Can Countries Verify the Nuclear Test Ban?. Springer, Dordrecht. chapter 7, p 181–213. DOI: 10.1007/978-94-007-1676-6_7

DÍAZ J. 2016. On the origin of the signals observed across the seismic spectrum, Earth-Science Reviews 161: 224-232., Pages 224-232, ISSN0012-8252, DOI: 10.1016/j.earscirev.2016.07 .006

GAEBLER, P., CERANNA, L., NOOSHIRI, N., BARTH, A., CESCA, S., FREI, M., GRÜNBERG, I., HARTMANN, G., KOCH, K., PILGER, C., ROSS, J. O., DAHM, T. 2019. A multi-technology analysis of the 2017 North Korean nuclear test, Solid Earth, 10, 59–78. DOI: 10.5194/se-10-59-2019

GOLDSTEIN, P. 2020. Beirut Explosion Yield and Mushroom Cloud Height – Effects of the Near Source Environment, Lawrence Livermore National Laboratory - LLNL-TR-815803.

GOSSARD E., HOOKE W. 1975. Waves in the atmosphere: atmospheric infrasound and gravity waves-their generation and propagation. In Amsterdam by Elsevier scientific. 46 p.

GIBBONS, S. 2014. The Applicability of Incoherent Array Processing to IMS Seismic Arrays. Pure Appl. Geophys. 171, 377–394. DOI: 10.1007/s00024-012-0613-2

GITTERMAN, Y., HOFSTETTER, R. 2012. GT0 Explosion Sources for IMS Infrasound Calibration: Charge Design and Yield Estimation from Near-source Observations. Pure Appl. Geophys. 171, 599–619. DOI: 10.1007/s00024-012-0575-4

HILDEBRAND J. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar Ecol

Prog Ser 395:5-20. DOI: 10.3354/meps08353

IRIS - Incorporated Research Institutions for Seismology (www.iris.edu).

KIM, T., I.-B. KANG, G.-Y. KIM. 2009. Yield ratio estimates using regional Pn and Pg from North Korea's underground nuclear explosions, Geophys. Res. Lett., 36, L22302, DOI: 10.1029/2009GL040495

LE PICHON, A., MATOZA, R., BRACHET, N., & CANSI, Y. 2010 Recent enhancements of the PMCC infrasound signal detector. Inframatics, 26: p. 5-8.

LU L. 2020. Estimation of the Energy Released in the Beirut Explosion. DOI: 10.13140/RG.2.2.21310.31041

MARTY J. 2019. The IMS Infrasound Network: Current Status and Technological Developments. In: Le Pichon A., Blanc E., Hauchecorne A. Infrasound Monitoring for Atmospheric studies. Part I - Instrumentation, Network and Processing: Instrumentation. 2nd ed., Springer, Cham. p. 3-62. DOI: 10.1007/978-3-319-75140-5_1

MIALLE P., BROWN D., ARORA N., COLLEAGUES FROM IDC. 2019. Advances in operational processing at the International Data Centre. In: Le Pichon A, Blanc E, Hauchecorne A Infrasound monitoring for atmospheric studies, studies. Part II - Instrumentation, Network and Processing: Processing. Springer, Cham, p 209–248.

MURPHY, J. 1981. Identification of Seismic Sources — Earthquake or Underground Explosion, chap. P Wave Coupling of Underground Explosions in Various Geologic Media, In: Husebye, E.S., Mykkeltveit, S. (Eds.). Identification of Seismic Sources — Earthquake or Underground Explosion. NATO Advanced Study Institutes Series, vol 74. Springer, Dordrecht. p. 201–205. (Springer Netherlands, Dordrecht, 1981).

PILGER, C., GAEBLER, P., HUPE, P., KALIA, A., SCHNEIDER, F., STEINBERG, A., SUDHAUS, H., CERANNA, L. 2021. Yield estimation of the 2020 Beirut explosion using open-access waveform and remote sensing data. Sci Rep 11, 14144. DOI: 10.1038/s41598-021-93690-y

PUBCHEM. 2021. Ammonium nitrate. National Center for Biotechnology Information. PubChem Compound Summary for CID 22985. Available online: https://pubchem.ncbi.nlm.nih.gov/compound/Ammonium-nitrate (accessed on 19 April 2021).

Reuters. 2020. Beirut port blast death toll rises to 190. Emerging Markets. Available online: https://www.reuters.com/article/us-lebanon-crisis-blast-casualties-idUSKBN25Q08H (accessed on 30 August 2020).

RIGBY, S., LODGE, T., ALOTAIBI, S., BARR, A., CLARKE, S., LANGDON, G., TYAS, A. 2020. Preliminary yield estimation of the 2020 Beirut explosion using video footage from social media. ShockWaves (2020) 30:671–675 DOI: 10.1007/s00193-020-00970-z

STEVENS J., DIVNOV I., ADAMS, J., MURPHY, BOURCHIK V. 2002. Constraints on Infrasound Scaling and Attenuation Relations from Soviet Explosion Data. Pure Appl. Geophys. 159, 1045–1062 (2002). DOI: 10.1007/s00024-002-8672-4

TORMOD K., FRODE R. 2013. Detection Capability of the Seismic Network of the International Monitoring System for the Comprehensive Nuclear-Test-Ban Treaty. Bulletin of the Seismological Society of America; 103 (2A): 759–772. DOI: 10.1785/0120120248

ZAHRADNIK J., SOKOS E. 2018. ISOLA Code for Multiple-Point Source Modeling—Review. In: D'AMICO S (Ed.). Moment Tensor Solutions: A Useful Tool for Seismotectonics. Springer Natural Hazards. Springer, Cham. Chapter. 1 p. 1–28. DOI: 10.1007/978-3-319-77359-9_1

L.V.B.: responsible for writing the article and general coordination; **B.L.N.:** contributed to the processing of infrasonic and seismic data and helped in the writing of the paper; **D.P.F.:** contributed significantly to the writing of the paper and the processing of seismic data; **D.F.A.:** contributed to the seismic processing and the writing of the paper; **R.Q.Q.:** assisted in the discussions of the data analysis results; **J.M.C.:** helped in the discussions of the data analysis results.

Received on December 4, 2021 / Accepted on May 6, 2022