Scientific Report for Loan 1153

Mechanics of dyke intrusion in oblique-slip tectonic settings: Unravelling the causes of the March 2022 rare seismic swarm in São Jorge Island, Azores

PI Ana Ferreira (UCL), Co-I Ricardo Ramalho (Univ. Cardiff), Co-I Neil Mitchell (Univ. Manchester)

Report written by Maria Tsekhmistrenko (UCL).
Instrument deployment and recovery by João Fontiela (Universidade de Évora), Augustin Marignier (ANU), William Sturgeon (UCL) & Maria Tsekhmistrenko (UCL).
With support from CIVISA (Rita Silva, Arturo Garcia, Rui Marques, Adriano Pimentel), IPMA (Sandra Sequeira, Fernando Carrilho, Miguel Miranda), OKEANOS (Octavio Melo, Filipe Porteiro), Terceira municipality (Miguel Mendonça) & IDL (Graca Silveira, Nuno Dias).

Abstract

A passive seismology data collection experiment was conducted over 4.5 months in the central Azores, Portugal, in 2022. Starting on the 19th March 2022 on São Jorge Island, the region's seismicity levels rose extraordinarily from only 5 events recorded during 01/01-18/03, to >29,000 M=2-3.3 events recorded until beginning of April. The objective of the loan of 10 SEIS-UK seismic stations equipped with Pegasus data loggers and Trillium Compact sensors was to monitor the ongoing seismicity on São Jorge Island. The deployment and data collection after 4.5 months (June – November 2022) were successful and all instruments yielded high quality data. A preliminary analysis of the seismicity shows >9000 tightly-clustered local seismic events beneath São Jorge Island.

Background

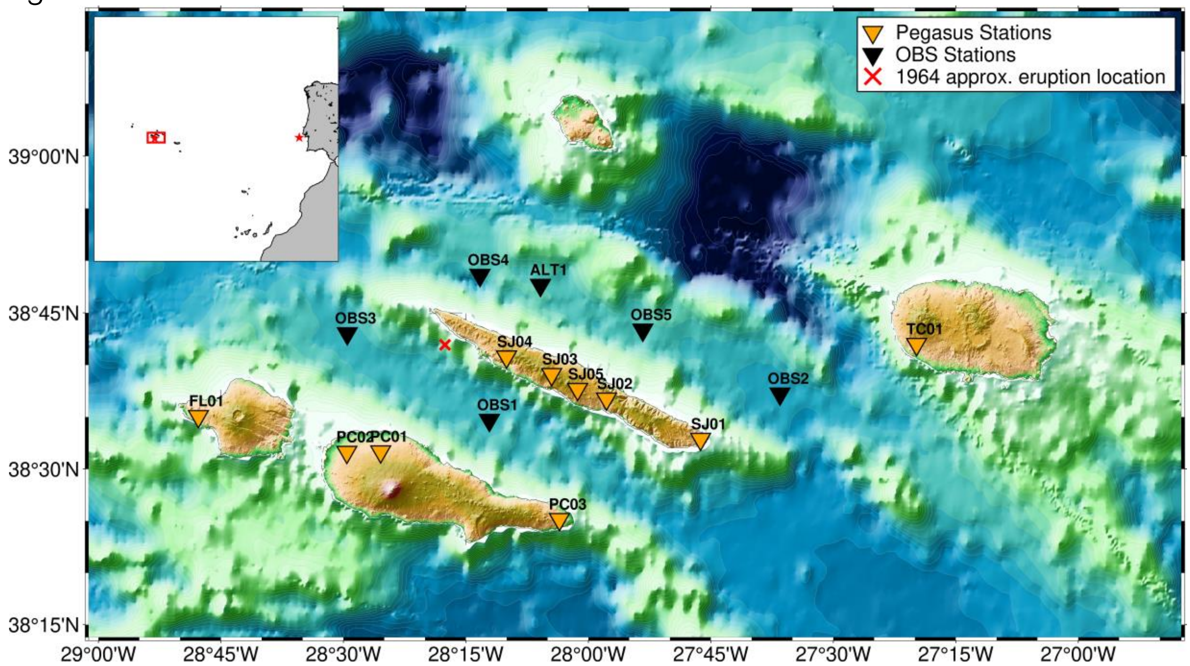


Figure 1: Overview map showing locations where instruments were deployed between June and November 20222. Orange triangles show deployment sites on four islands (Terceira, São Jorge, Pico and Faial) of 10 SEIS-UK instruments (Ferreira at al., 2026a). Red cross shows the approximate location of a 1964 submarine eruption. Black triangles show deployment sites of six OBS stations provided by OBIC (Ferreira et al., 2026b).

From March 19th, 2022, São Jorge Island experienced a dramatic increase in seismicity levels from only five events recorded between 01/01/2022 and 18/03/2022 to >29,000 M=2-3.3 events recorded until the beginning of April. Based on preliminary event locations by Portuguese agencies and deformation captured by InSAR, a dyke intrusion beneath the island's main volcanic fissure zone, which has hosted three eruptions over the last 450 years, was inferred. Current earthquake locations are subjected to substantial uncertain orthogonal to the uniquely elongated island because of the geometric limitations of the existing onshore networks. Moreover, low-magnitude events are poorly recorded (or not at all) on adjacent islands, preventing us from locating events relative to known faults and volcanic centres (this is being overcome using data from ocean bottom seismometers). The limited data coverage and quality of existing networks (mostly composed of aged short-period seismometers) have hindered the construction of detailed 3-D seismic tomography images of the region, with only 1-D velocity models being available for the São Jorge area based on land data.

A previous seismic crisis on São Jorge in 1964 lasted for nearly a year and was followed by a possible deep submarine eruption (Fig. 1 red "x"), but there was no seismic network established then. São Jorge lies within a trans-tensional diffuse plate boundary, which extends over 150 km southwest of the Terceira Rift. Crucially, it contains narrow volcanic fissure systems coinciding with oblique-slip movement, as demonstrated by the presence of laterally-sheared volcanic cones. It is unclear if dyke intrusion in such environments, in general, should be guided by tectonic fracturing or if other mechanisms such as gravitational stresses are involved, as most dyke intrusion research has been carried out on simple orthogonal active rifts such as those in Iceland and East Africa. Further, it is unclear how the balance of these stresses controls the ascent path of magma to the surface to produce an eruption. Thus, the high-resolution seismological data obtained from São Jorge should be important for advancing our understanding of the governing magmatic and tectonic processes in volcanic rifts, and their possible interplay.

Moreover, the data from the array will uniquely allow the construction of the first 3-D tomography images of the volcanic system, thus bringing key insights into the structure and plumbing network of tall and narrow fissure-fed volcanic systems such as São Jorge. It will also bring new constraints on the mechanics of dyke intrusions and their kinematic evolution in general.

Survey procedure

This experiment was the first use of SEIS-UK's recently acquired instruments exclusively dedicated for urgency grants. All stations comprised the new recorder type Pegasus and Trillium Compact seismometers. We chose locations that were within ~200 meters of quieter, secondary roads so that they could be reached by car.

The stations were chosen to minimise environmental and anthropogenic noise and to ensure that they were secure. In one case, the instrument was sheltered in a vault (FL01) next to an already existing short-period seismometer by CIVISA. Five stations (PC01, SJ01, SJ02, SJ05, TC01) were installed in fields where animals (mostly cows) are free to roam. The remaining four stations were installed close to man-made infrastructures (e.g. public parks or ranger stations). In all cases, local authorities (e.g. civil protection officers, park guards, etc.) were alerted and involved in the deployment and recovery activities. They helped us raise awareness about the instruments' safety with local communities.

To ensure the safety of the sites, most stations were surrounded by a fence, fashioned out of wooden poles and chicken wire. In the case of SJ05, the protection was unfortunately not enough. A cow broke through the fence and trampled on the box containing the recorder, regulator and battery, prematurely interrupting the recording. However, only the regulator and plastic box suffered slight damage.

The setup and installation of the 10 Seis-UK stations took place between 2022-06-22 and 2022-07-06 (see Table 1) and were distributed across four islands (Fig. 1). The sampling rate on all stations was set to 200 sps for high-fidelity recording of microseismicity.

Each box with recorder, regulator, and battery was usually buried less than a meter deep. The sensor depth varied depending on soil property. The sensors were installed some distance (1-2 meters) from the solar panel and other instruments (Pegasus recorder and battery) to reduce noise (Fig. 2). On São Jorge Island, an employee of the municipal office provided an auger to dig cylindrical holes so that the sensor could be deposited very easily, reducing the time and effort of digging the second hole. On Terceira Island, a small digger was used to excavate a deep hole for the seismometer, installing it at 1.5 m depth.

The sensor would be usually placed inside the hole with foil loosely wrapped around it (for protection against temperature variations, dirt and moisture), on top of some sand, and then levelled and aligned.

Note the foil would have some small holes at the bottom to prevent water from accumulating in the foil and drowning the Trillium Compact. After levelling and adjusting orientation, the foil would be taped up around the cable which connects the sensor to the regulator. The levelling would then be once more checked on the Pegasus mobile application and further adjustments by moving the seismometer on the sand were made. The resulting alignment had an error margin of around ±5 degrees. We plan to re-orient the horizontal components using the recorded data. Finally, the hole was back-filled and the area was covered with a tarp and fixed with rocks (Fig. 2).

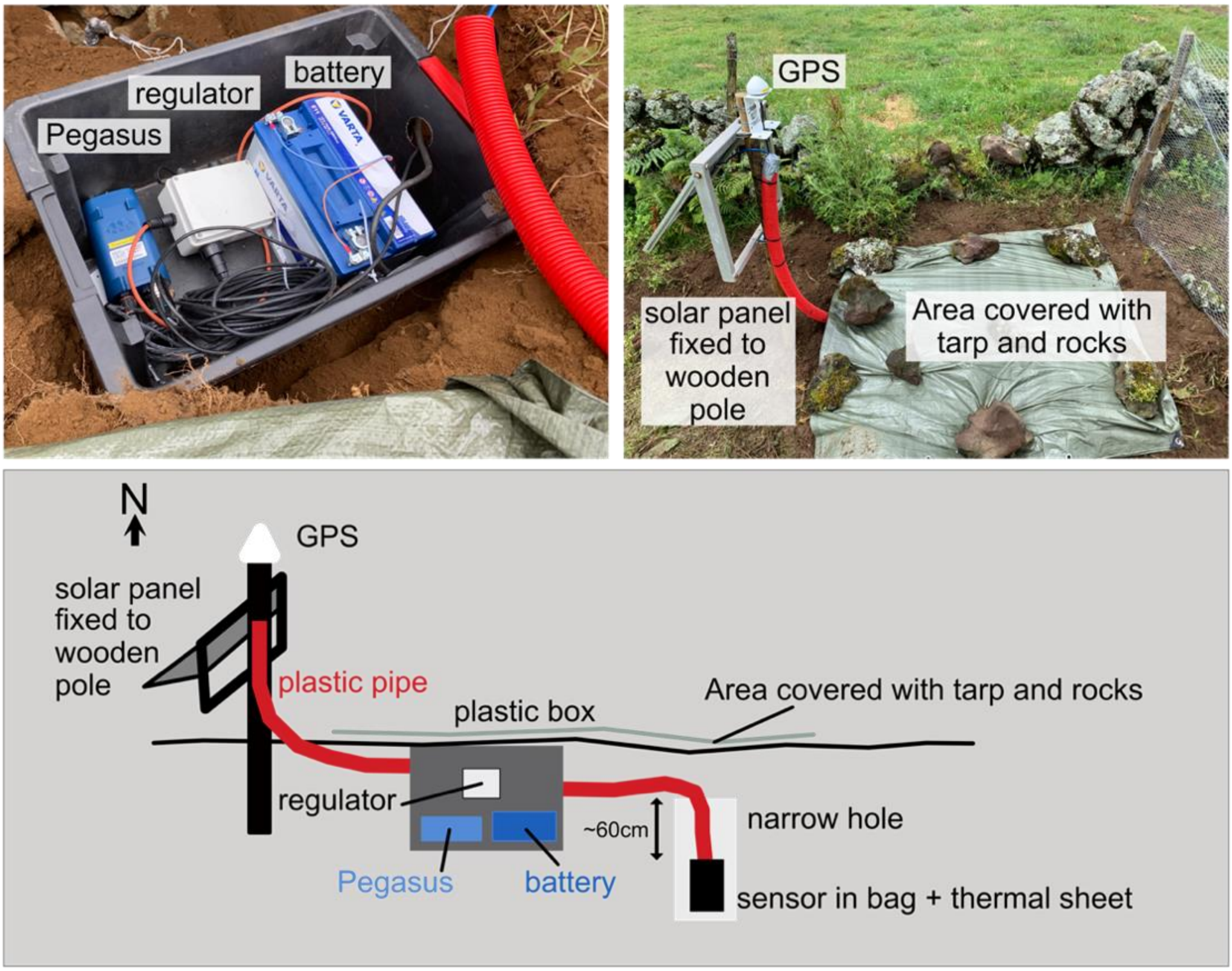


Figure 2: Typical deployment setup of seismic stations on the Azores. Upper left panel: plastic box containing a Pegasus unit, regulator and battery, all parts are connected via cables to each other. The plastic box is connected via cables to the Trillium Compact seismometer, GPS and solar panel. Upper right panel: view of deployment side. Lower panel: schematic of deployment.

The installation of the stations was straightforward, though the biggest concern was to find, buy and/or borrow equipment for the installation. The Azores Islands, though remote, have hardware stores for buying all the additional equipment needed for the installation (e.g. car batteries, plastic boxes, plastic pipe, wooden stakes, chicken wire, etc.). We purchased car batteries locally with higher specs than strictly needed (12V; 74Ah) so that they could power the system independently of the solar panel. This is because the sun exposure in the Azores can be limited, particularly in the winter due to cloud cover. In similar locations like Iceland, higher specs car batteries (yet still affordable) have provided power for whole deployments.

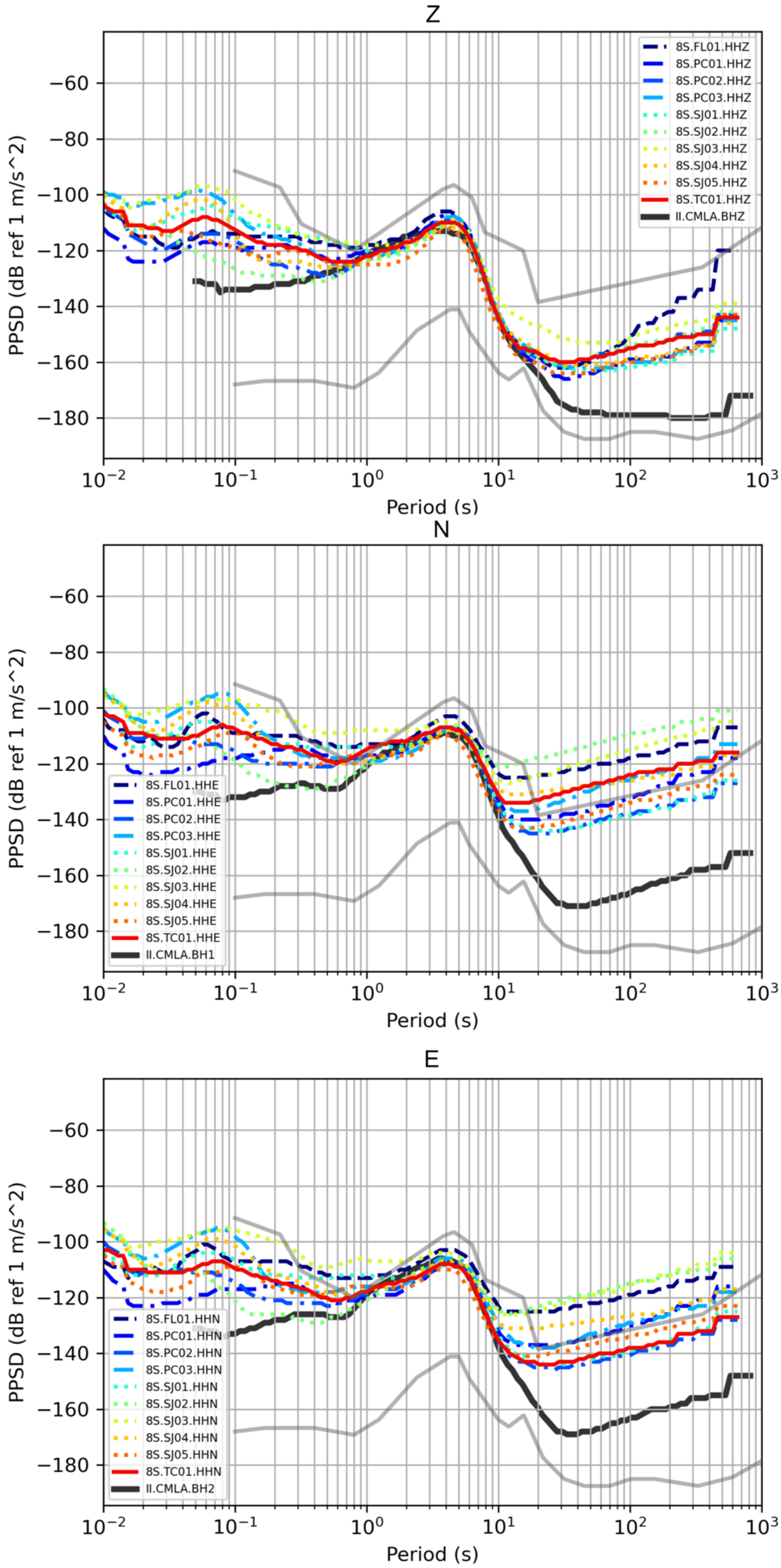


Figure 3 Median PPSD for all stations and channels. the vertical components are for most stations in periods 10 – 100 seconds between the upper and lower noise level (Peterson, 1993). Between 1 – 10 seconds the noise increases and for periods < 1s the noise level stays high but does not surpass the upper noise level. The horizontal components (N and E channels) are nosier than land stations and the PPSD is more like an OBS than land station. This is to be expected due to the exposure to waves and wind on the islands.

Shovels, pikes and hammers were borrowed from various institutes or municipal offices. The key to the successful deployment was to have a native speaker who knows the area and scientific community. Through that person, we were able to find secure locations for the stations and get all the logistical provisions for the deployment.

Though unavoidable, a lot of plastic waste was generated during each installation. Also, not all auxiliary gear could be handed down to the local institutes (e.g. wooden stakes and chicken wire). Most tarps, plastic boxes and tubes were unusable after dissembling the station. The foil wrapping, one-use cable ties and the duct tape holding were all disposed of as local refuse. In our opinion, future researchers should consider what to do with the supplementary equipment and waste after the project is finished. A future improvement might be the use of more sustainable (e.g., recycled or compostable material) for short deployments.

Data quality

All stations performed very well with data recovery rates of ~99% (Tab. 1) and high-quality recordings, with the exception of SJ05, due to the cow incident mentioned above. The individual probabilistic power spectral density (PPSD) figures (Fig. A5-8) give insight into the overall noise levels of the stations. Some stations have short gaps in their recordings (see Field Deployment Data or PPSDs). SJ03 was installed on top of a tourist footpath (leading towards Pico da Esperança summit) and therefore shows higher noise levels throughout all periods and channels. It is also possible that the stations located closest to the seismic swarm (SJ03, SJ04), may have slightly elevated noise levels at 2-20 Hz due to the high rate of seismicity.

As evidenced by Fig. 3, we observe that the median of the vertical components in the period range 10 – 100 seconds falls within the boundaries of the New High Noise Model (NHNM) and New Low Noise Model (NLNM) (Peterson, 1993). Between 1 – 10 seconds the noise increases and for periods < 1s the noise level stays high but does not surpass the NHNM line. Generally, the PPSDs are more similar to those of OBS stations than typical land stations. Figure 3 compares the temporary stations to CMLA (a CIVISA permanent island station; black solid line). CMLA shows considerably lower noise levels than the temporary installment on the horizontal components. This is to be expected due to the island's exposure to waves and wind.

Another way to examine the quality of the stations is by looking at a box-whisker plot (Fig. A4), which shows the data station and period-disaggregated. For instance, PC01 seems to be one of the quietest stations.

Processing

During the period of the deployment, 33 teleseismic events (identified from the GCMT catalogue) occurred with a magnitude larger than M6. Fig. 4 shows an example recording of an event which occurred in Michoacan, Mexico (2022-09-22T06:16:09) with M=6.8. The onset of the first arrival is clearly visible on the broad-band filtered seismograms. Additionally, numerous low-magnitude events occurred during the deployment which are still being analysed. An example of such an event occurred on 2022-10-04T20:41:26 in São Jorge with M=2.1 and was localized by CIVISA. This event was clearly recorded on seven out of nine stations (Fig. A3).

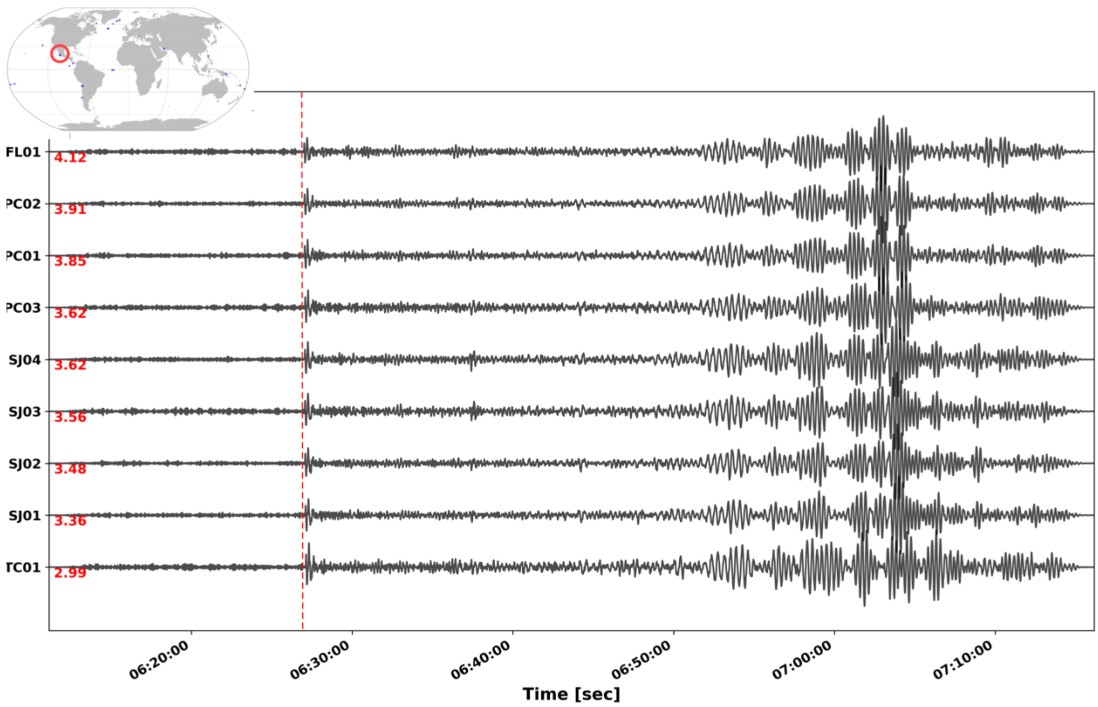


Figure 4 Example of a teleseismic event (2022-09-22T06:16:09 M=6.8) recorded on the stations (vertical component). The seismograms are broadband filtered and show a clear onset of the first arrival (red dashed line). The stations are sorted by epicentral distance. The overview globe marks the location of the event in central America. The other blue scatters show locations of all teleseismic events with M > 6 during the time of deployment on the Azores island. SJ05 did not record this event due to an early stop of recording.

Preliminary Interpretation

Fig. 5 shows daytime plots throughout the deployment, extracted from the PPSD for station TC01 (vertical component; see Figures A5-8 in the appendix for all other stations). TC01 shows increased noise from 9 a.m. to 6 p.m. on the vertical component, which was the only station installed 1.5 meters deep. The station was also located around 100 meters from a busy road, which might explain the increased noise on the vertical component during the daytime period. On almost all stations an increase in (anthropogenic?) noise during the daytime comes up either on the vertical and/or the horizontal components. Noteworthy is the increase in noise towards the winter months. Usually from the end of September, the noise increases on all the stations and channels.

The desired signals are observable despite the various noise types present in the recording. Teleseismic events and local events are abundant in the records. The daytime plots show events as grey streaks and almost all of them correspond to the 33 teleseismic events known from the GCMT catalogue. On the other hand, the other grey streaks correlate to local events, e.g. the local M2.4 event previously described.

Analysis of local seismicity is ongoing. Arrival times have been determined using the EQTransformer attenative deep-learning model (Mousavi et al., 2020), which were then associated into events using a Bayesian Gaussian mixture model (GaMMA software; Zhu et al., 2022). Preliminary findings show roughly 9000 well-localised events. Fig. 6 shows an overview of the preliminary located local earthquakes. The cross sections A-A' and B-B' show a near-simultaneous deepening and shallowing time-progression of seismicity, with two particularly clear dipping bands of between 5 and 10 km depth. In map view, many of these earthquakes line up with the Pico de Carvão Fault Zone mapped at the surface (Madeira and Brum da Silveira, 2003).

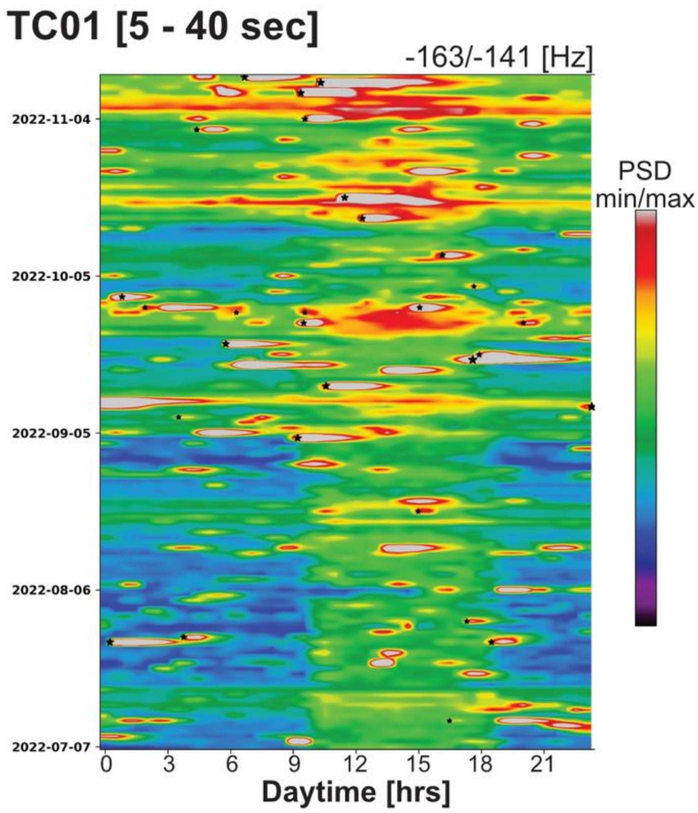


Figure 5 Daytime plot throughout the installation period for station TC01 for the vertical component. The background image comprises a stack of day-long acceleration spectrograms. These stacks were extracted from the previously generated PPSD for periods between 5 and 40 seconds. The x-axis is in hours of an Earth day. The y-axis extends from the deployment time of TC01 until its recovery. The upper right corner of each panel shows the minimum and maximum value for the colour bar. The black stars (★) represent global earthquakes with a minimum magnitude 6. Many of the black stars correspond, especially in the vertical component (Z), with higher amplitudes (grey streaks). Many of these small grey streaks don't correspond to global earthquakes and might be an indication of local events.

Conclusions and recommendations

Between deployment in May 2022 and recovery in November 2022, the 10 seismic stations from the emergency pool of SEIS-UK produced high quality data with noise levels largely falling within existing noise level models (NHNM and NLNM). The quality of the data is high, with most noise levels within existing noise level models (NHNM and NLNM). Many teleseismic and local earthquakes were recorded. Preliminary findings from local seismicity show a temporal progression of events beneath the island. Relative relocation of clustering seismicity is ongoing, and local earthquakes will form the basis for a new tomographic model beneath the Azores Islands, while teleseismic events will help to constrain the large-scale crustal structure of the region.

SEIS-UK provided exceptional support throughout the whole process. This ranged from the training day for the new Pegasus stations to being continually available to answer questions during the deployment and recovery period.

Our recommendations for future deployments and installations in the Azores and other similar remote island settings are:

- Avoid unnecessary plastic waste by using reusable or compostable materials throughout the deployments.
- Fencing all the stations is essential but, as in our experience, not always sufficient. Digging deeper holes for the instruments or using sturdier boxes should be considered.
- Involving local authorities for support (borrowed equipment; resell or donate auxiliary equipment after experiment) and communication with the communities (e.g. scientific outreach) is crucial.
- Using more powerful batteries in areas with intermittent and significant cloud cover is helpful to ensure the power supply remains sufficient.
    - These batteries can then be resold or donated to the local institutes.
- For this emergency grant it took significant time to install the instruments arising from:
    - Customs difficulties because of Brexit
    - Delayed schedule

From this experience, we suggest that an expedited process of shipping scientific equipment ought ideally be developed/agreed on with the UK government and NERC.

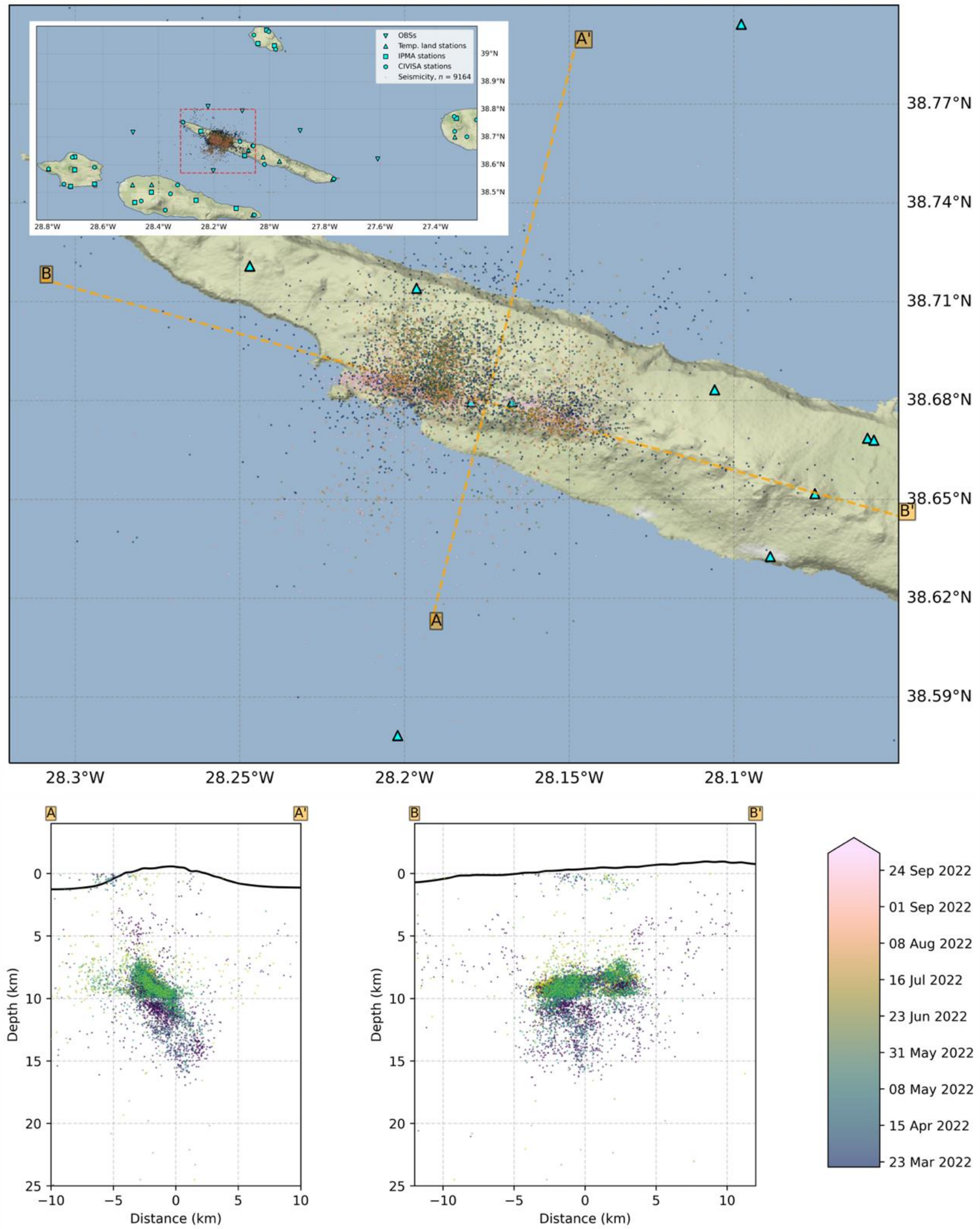
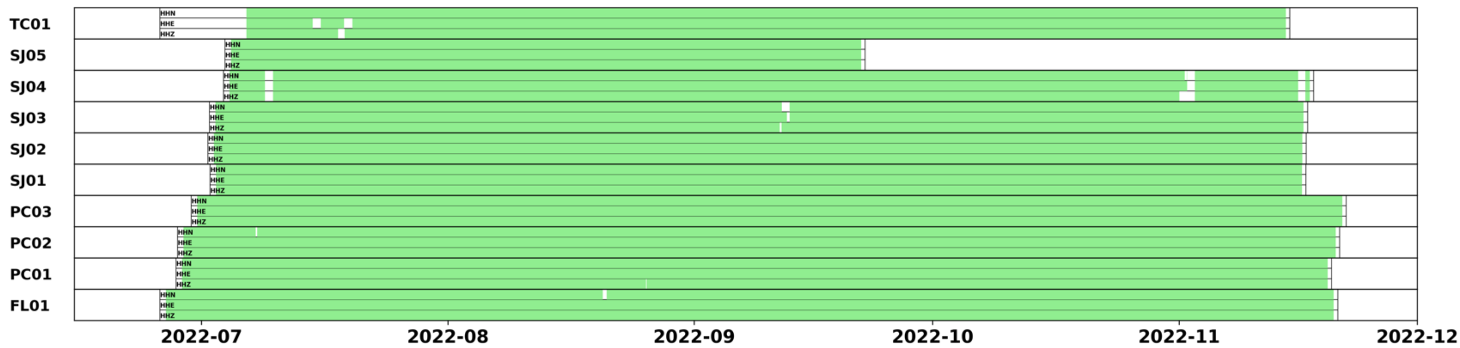


Figure 6 Overview of seismicity localisation using NonLinLoc. The upper panel shows a map view of Northern São Jorge with the location of cross-sections A-A' and B-B'. The localised earthquakes are projected towards the surface. The lower panels show cross sections. A-A' crosses NNE-SSW through the island. We observe a time progression of the seismicity from 15km to almost 5km over the duration of 6 months. For the early months of March until June local stations from IPMA were used for the seismicity analysis. The shape of the earthquake distribution is sloped and indicates a correlation to a fault. B-B' crosses WWN-EES and shows a similar picture as the previous cross-section, whereas the earthquakes are slopping less.

A table of instrument deployment details including locations

Field Deployment Data

Station	Latitude	Longitude	Elevation [m]	Deployment	Recovery	Comments
FL01 (AZ01)	38.584	-28.796	242	2022-06-22	2022-11-20	Installed in vault next to existing seismometer
PC01 (AZ02)	38.527	-28.424	322.4	2022-06-28	2022-11-19	Field
PC02 (AZ03)	38.527	-28.493	151.6	2022-06-28	2022-11-20	Installed in a public garden; closed during night
PC03 (AZ04)	38.419	-28.059	166.1	2022-06-30	2022-11-21	Installed in closed of area in Azores agriculture centre
SJ01 (AZ05)	38.547	-27.771	206	2022-07-01	2022-11-16	Field
SJ02 (AZ06)	38.612	-27.963	499.1	2022-07-02	2022-11-16	Field
SJ03 (AZ07)	38.651	-28.075	1023.5	2022-07-02	2022-11-16	Installed on Pico da Esperança e Planalto Central
SJ04 (AZ08)	38.679	-28.167	475.4	2022-07-03	2022-11-23	In a grove close to a street
SJ05 (AZ09)	38.627	-28.022	643.5	2022-07-04	2022-11-16	Field; early stop due to animal stomping
TC01 (AZ10)	38.699	-27.330	263.9	2022-07-06	2022-11-14	Field; very deep installation



Location of the archived data

IRIS: https://ds.iris.edu/mda/8S_2022/
Estimated Release Date of the Data: 2026-01-01
Network Code: 8S
Network Name: Azores Network
Network Dates: 2022-01-01 - 2022-12-31

IRIS: https://ds.iris.edu/mda/4U_2022/
Estimated Release Date of the Data: 2026-01-01
Network Code: 4U
Network Name: Azores Network
Network Dates: 2022-01-01 - 2023-12-31

Publications (including conference presentations)

S. Hicks et. al. Growing an ocean island: high-precision seismicity evolution during the 2022 São Jorge, Azores seismic crisis. AGU abstract. https://agu.confex.com/agu/fm23/prelim.cgi/Paper/1359943

References

Ferreira, A. M. G., Ramalho, R. D. S. & Mitchell, N. Azores Network. 81000 MB International Federation of Digital Seismograph Networks https://doi.org/10.7914/FGP0-C809 (2026a).

Ferreira, A. M. G., Mitchell, N., Ramalho, R. D. S., Hicks, S. & Tsekhmistrenko, M. São Jorge OBS Network. 115000 MB International Federation of Digital Seismograph Networks https://doi.org/10.7914/D5W4-V395 (2026b).

Madeira, J., and Brum da Silveira, A. Active tectonics and first paleoseismological results in Faial, Picoand S. Jorge islands (Azores, Portugal). *Annals of geophysics* (2003).

Mousavi, S.M., Ellsworth, W.L., Zhu, W. *et al.* Earthquake transformer—an attentive deep-learning model for simultaneous earthquake detection and phase picking. *Nat Commun* **11**, 3952 (2020). https://doi.org/10.1038/s41467-020-17591-w

Peterson, J. Observation and modeling of seismic background noise. *Seismological Research Letters* vol. 79 (1993).

Zhu, W., McBrearty, I. W., Mousavi, S. M., Ellsworth, W. L., & Beroza, G. C. (2022). Earthquake phase association using a Bayesian Gaussian Mixture Model. *Journal of Geophysical Research: Solid Earth*, 127, e2021JB023249. https://doi.org/10.1029/2021JB023249

Appendix

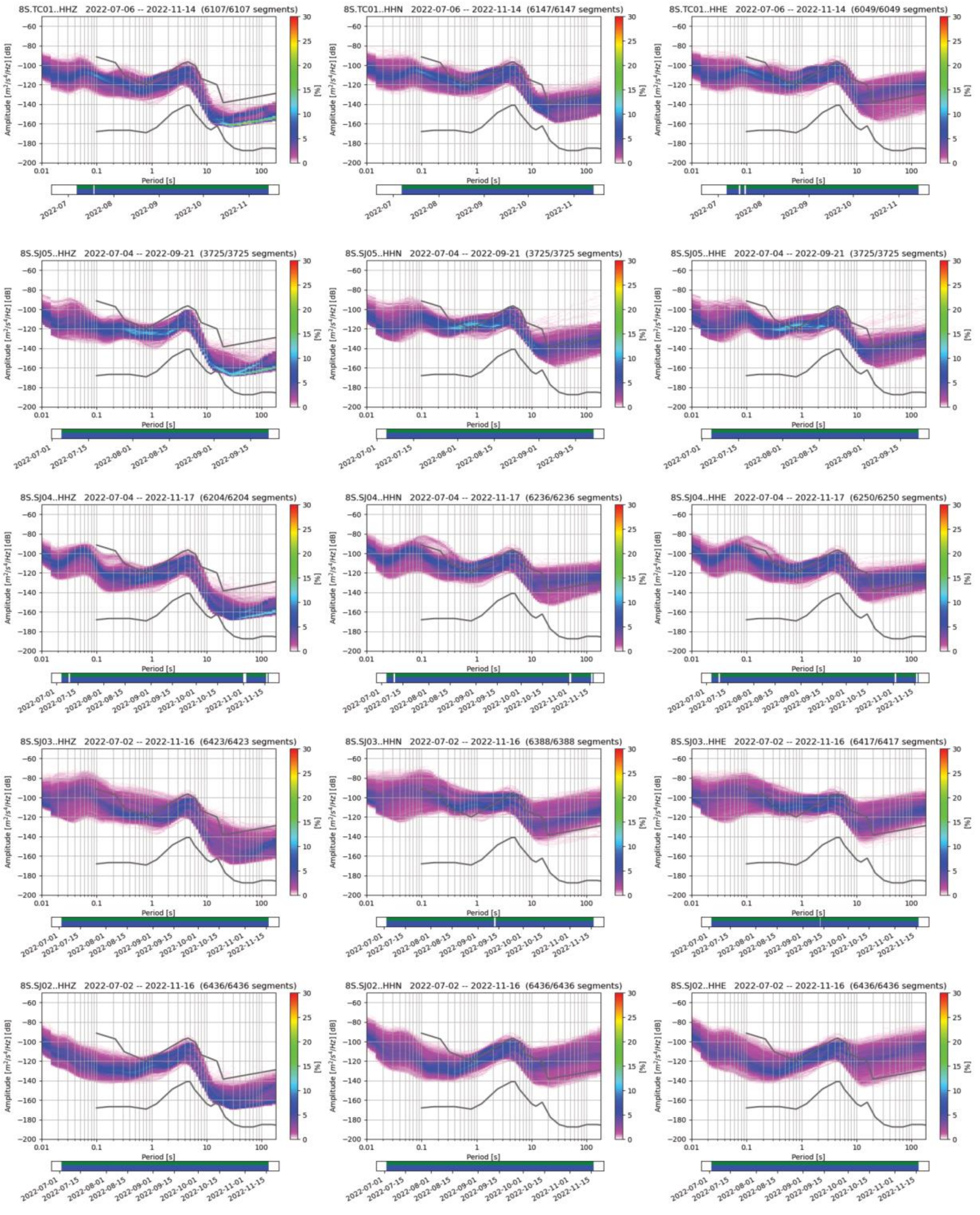


Figure A1 Collection of PPSD for stations TC01, SJ05, SJ04, SJ03 and SJ02. Each row contains three channels (vertical and two horizontal).

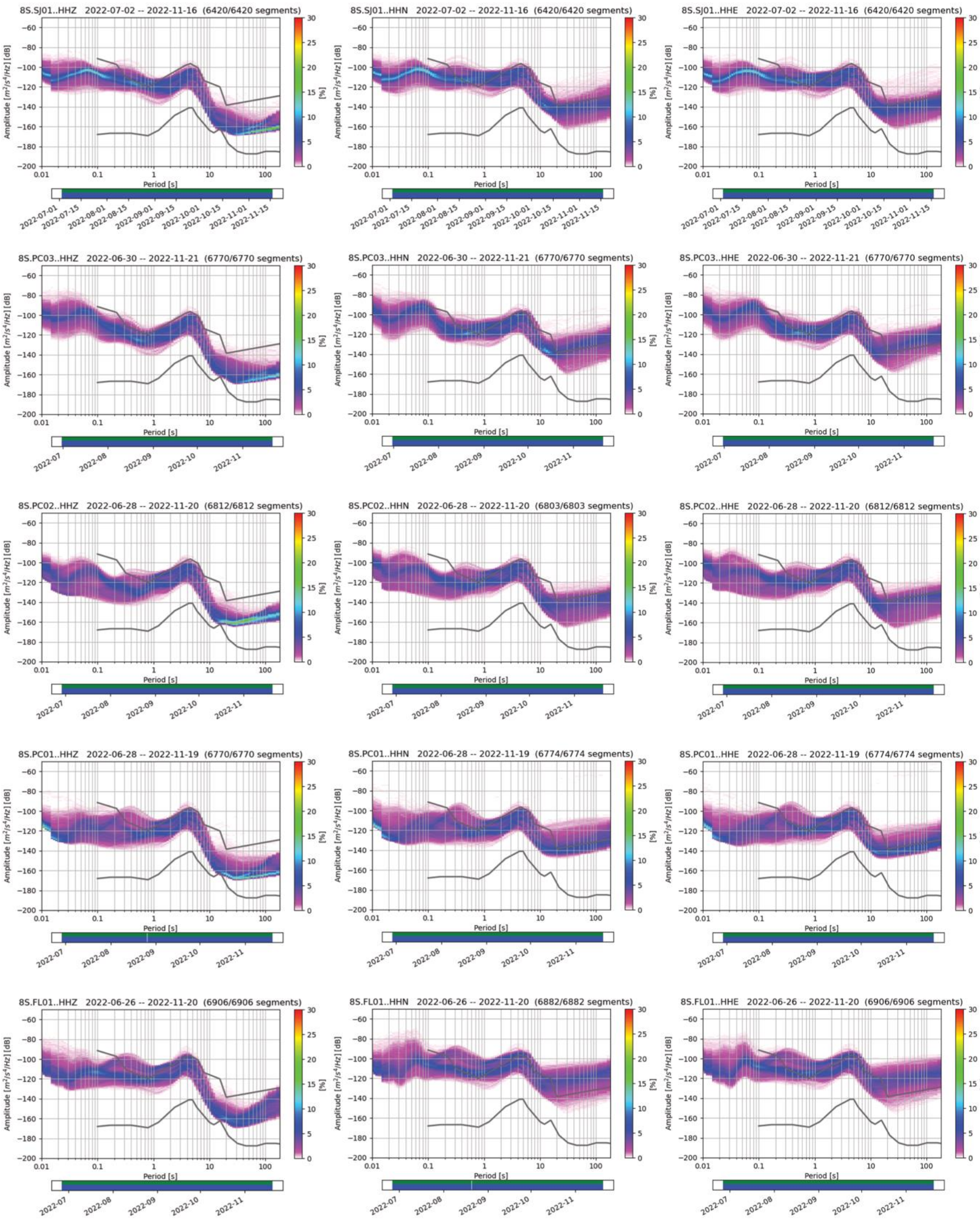


Figure A2 Continuation of Fig. A1 for stations SJ01, PC03, PC02, PC01 and FL01.

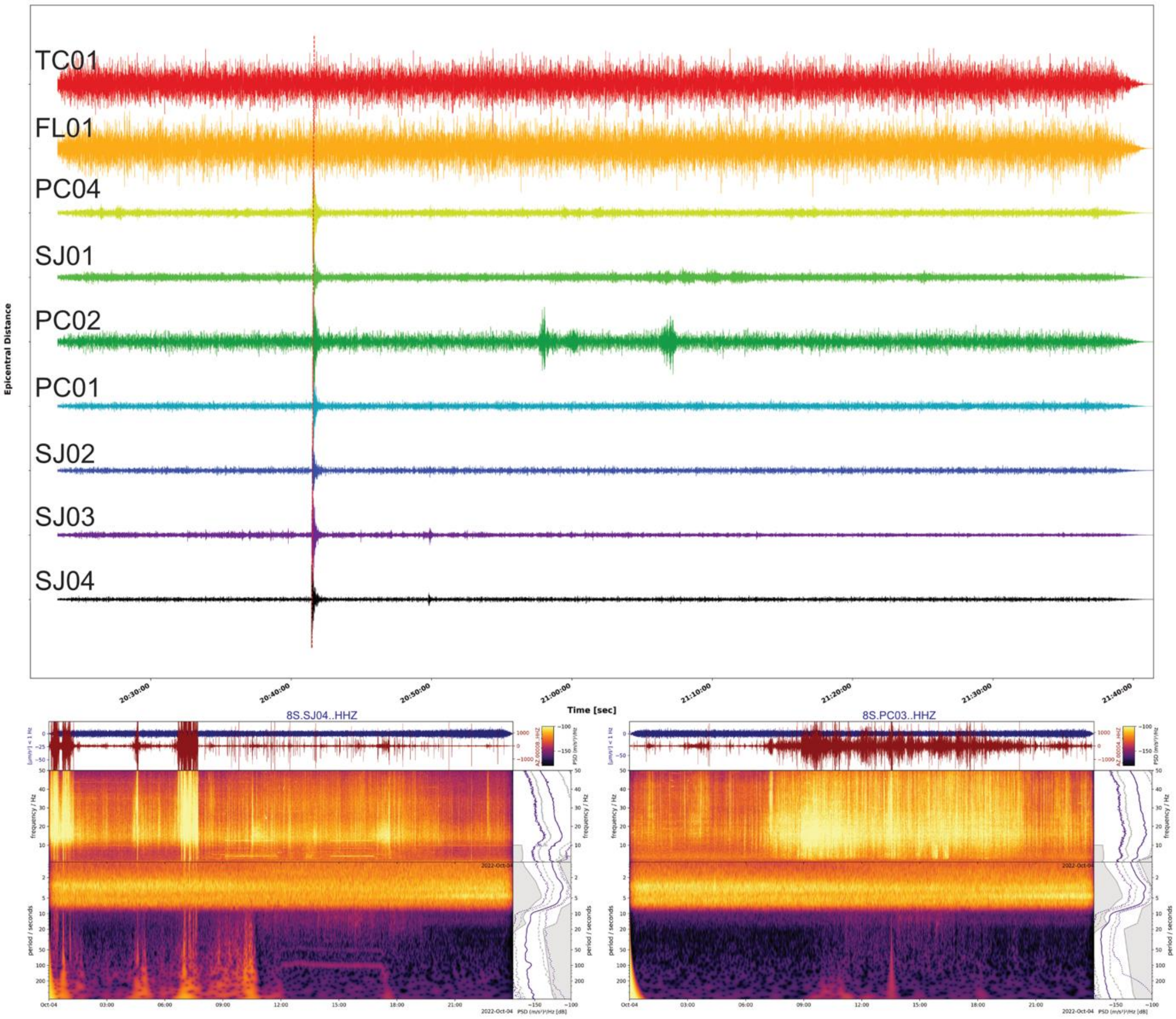


Figure A3 Example of local event (2022-10-04T20:41:26) close to São Jorge, M2.1.

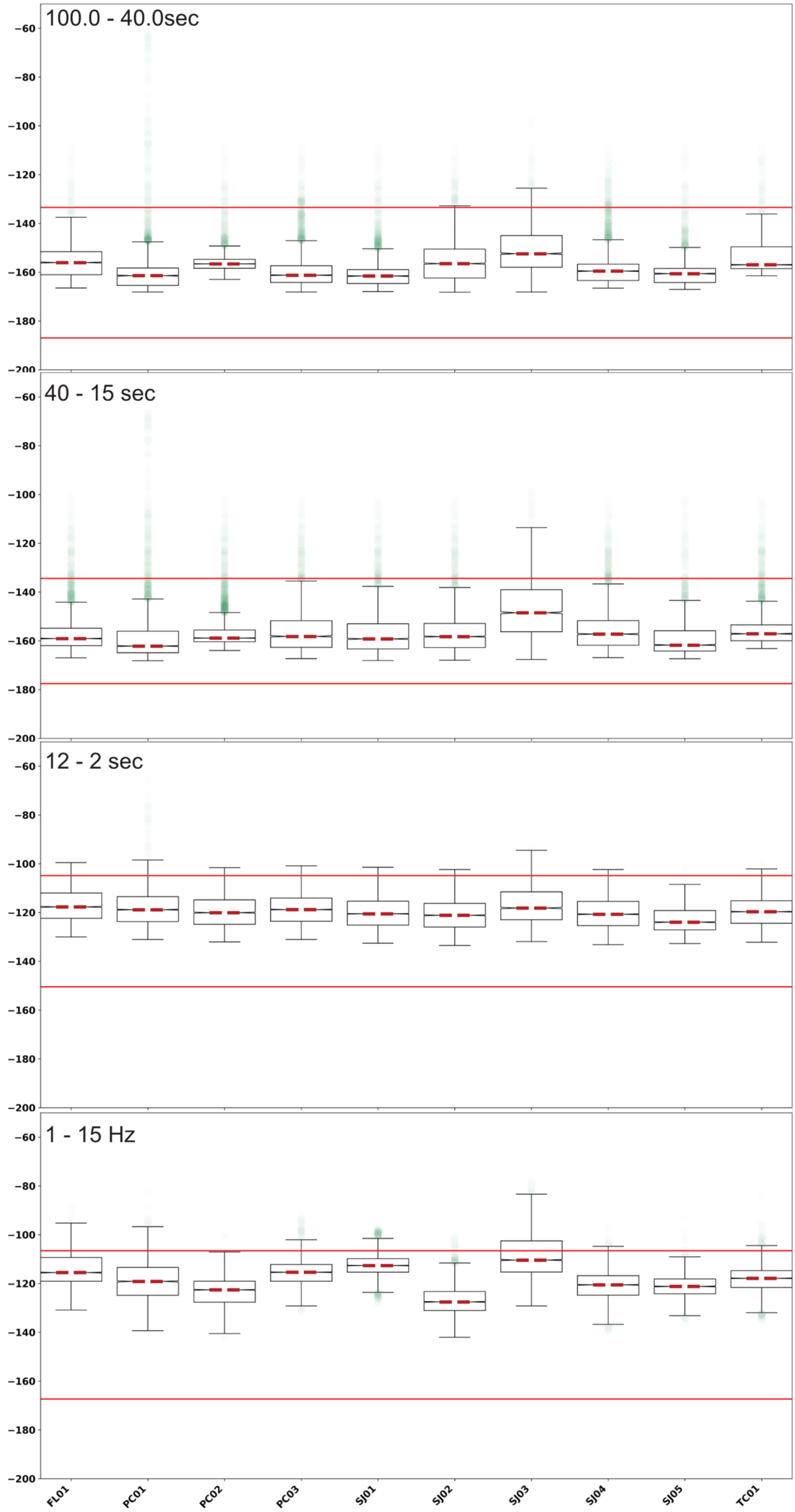


Figure A4 Boxplot figures for all stations. A boxplot, or box-and-whisker plot, provides a summary of the dataset by displaying the minimum, first quartile (Q1), median (Q2 or second quartile), third quartile (Q3), and maximum values. This visualization method offers information about the central tendency, spread, and skewness of the dat.

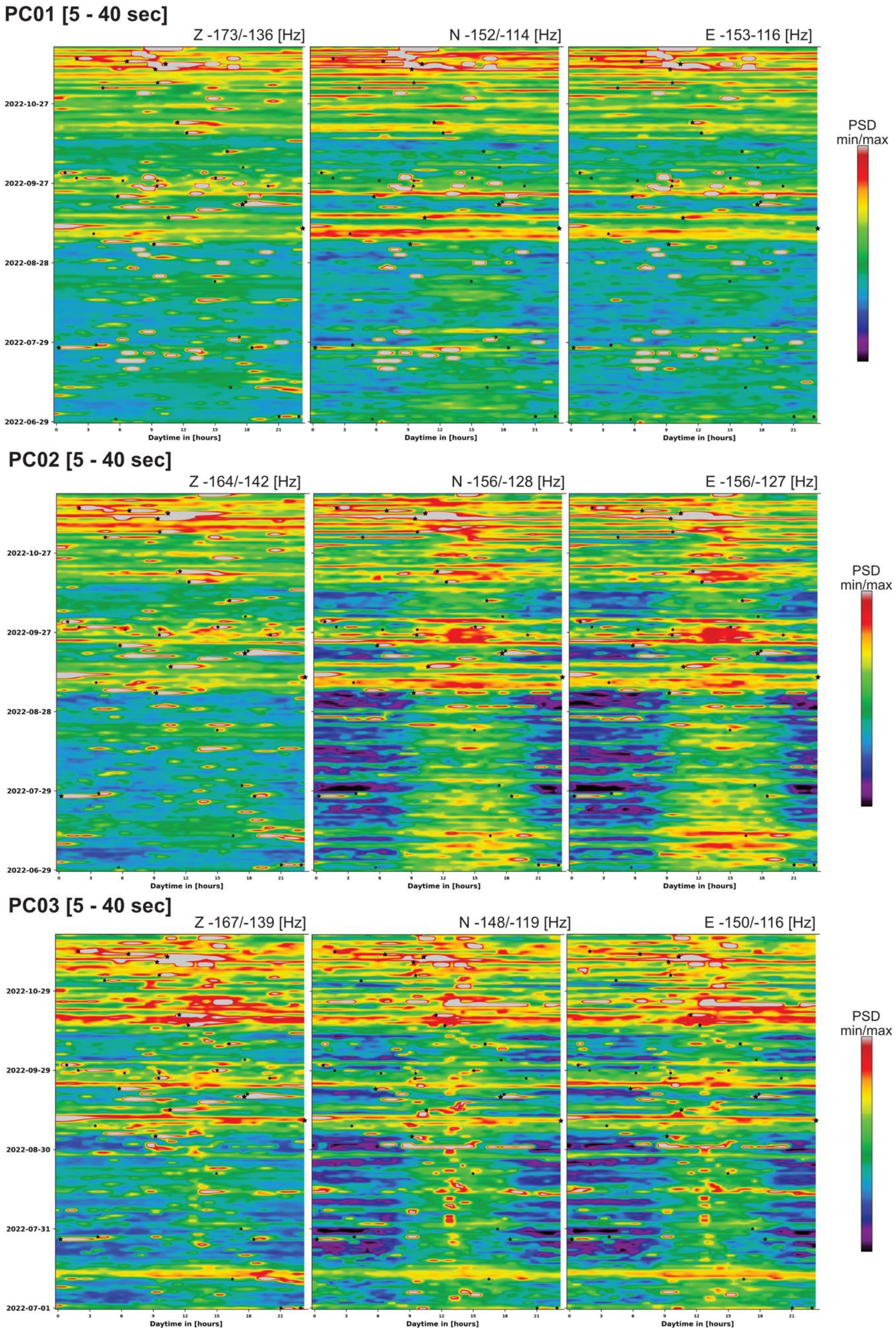


Figure A5 Dayplots for all stations for frequency ranges 5-40 sec. Same figure setting as in Figure 5.

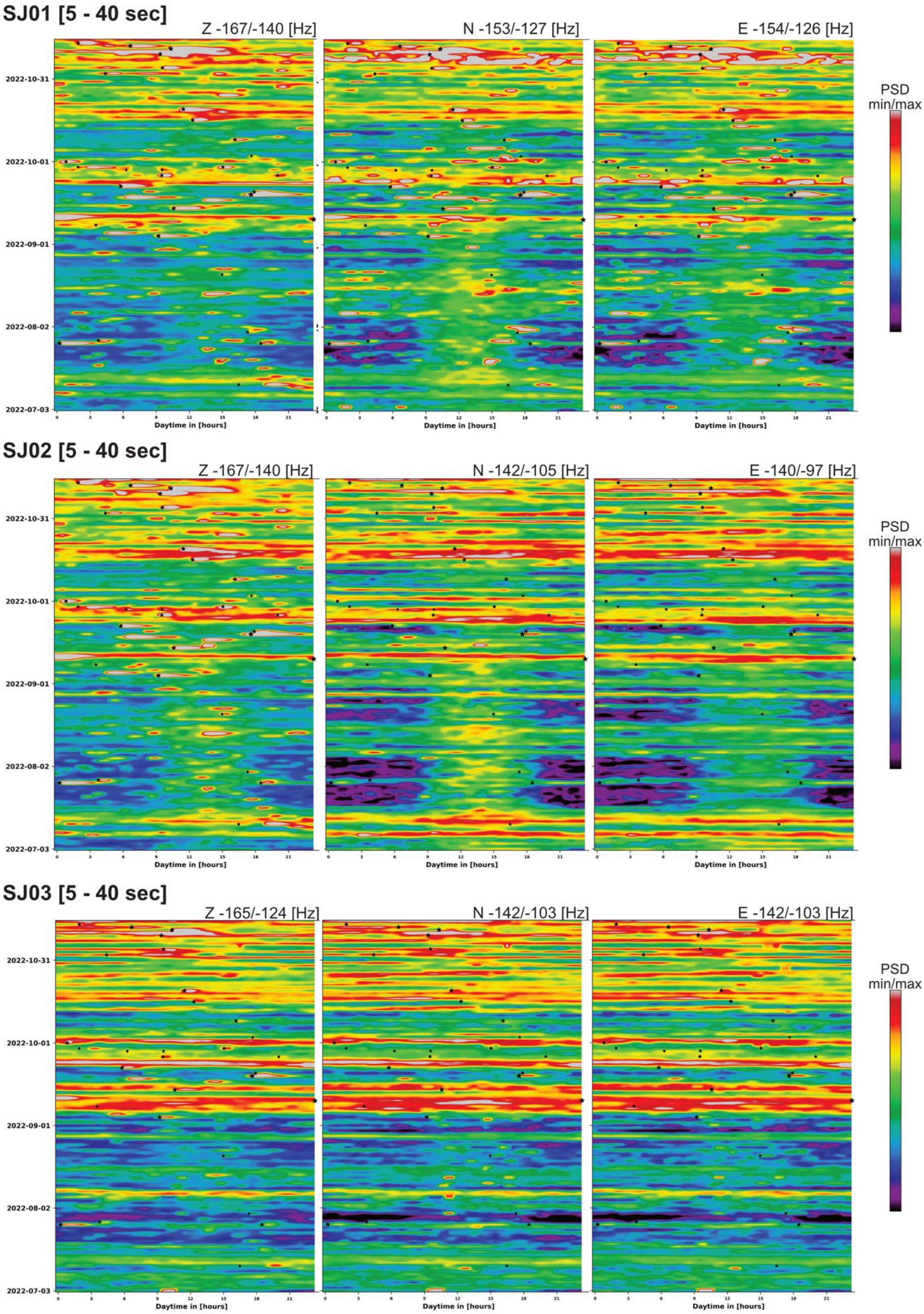


Figure A6 Continuation of Figure A5.

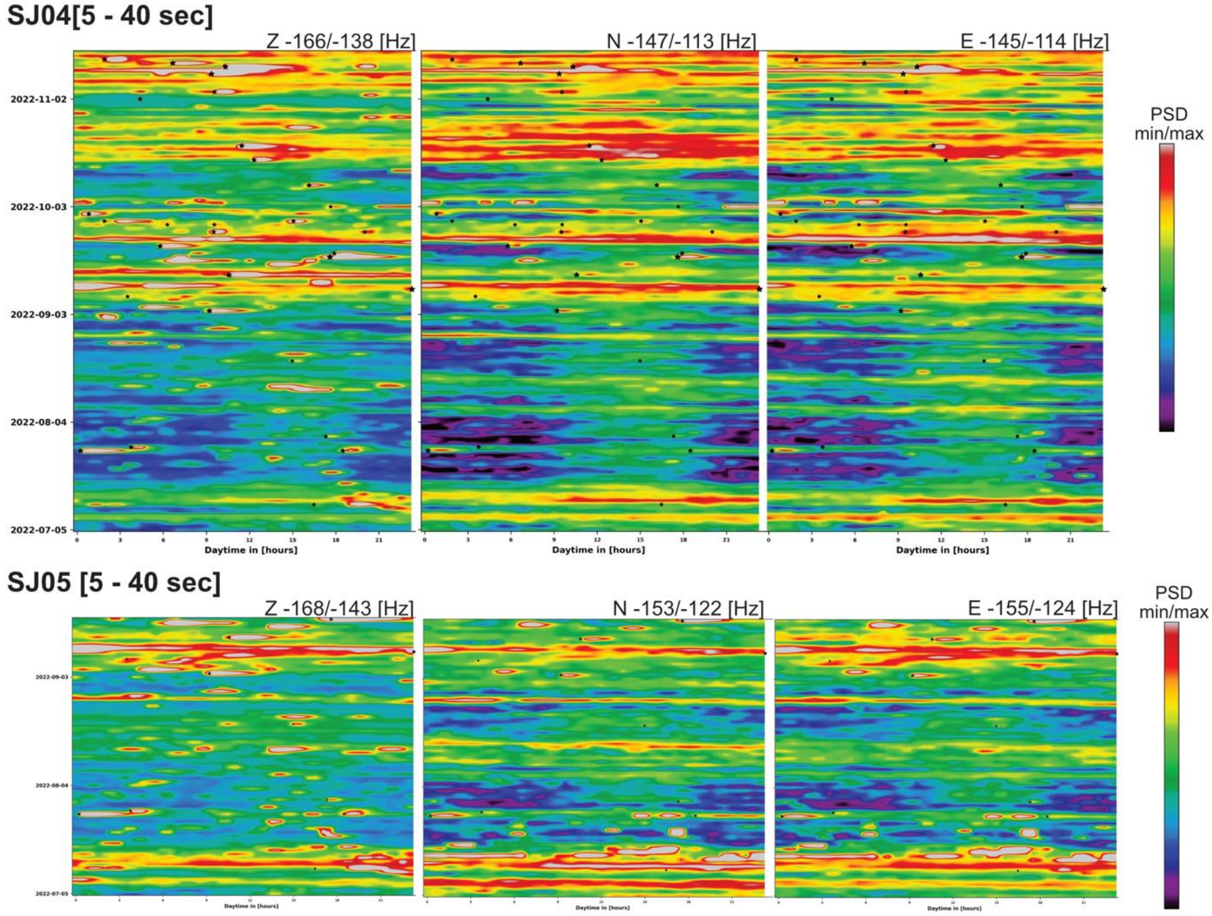


Figure A7 Continuation of Figure A6.

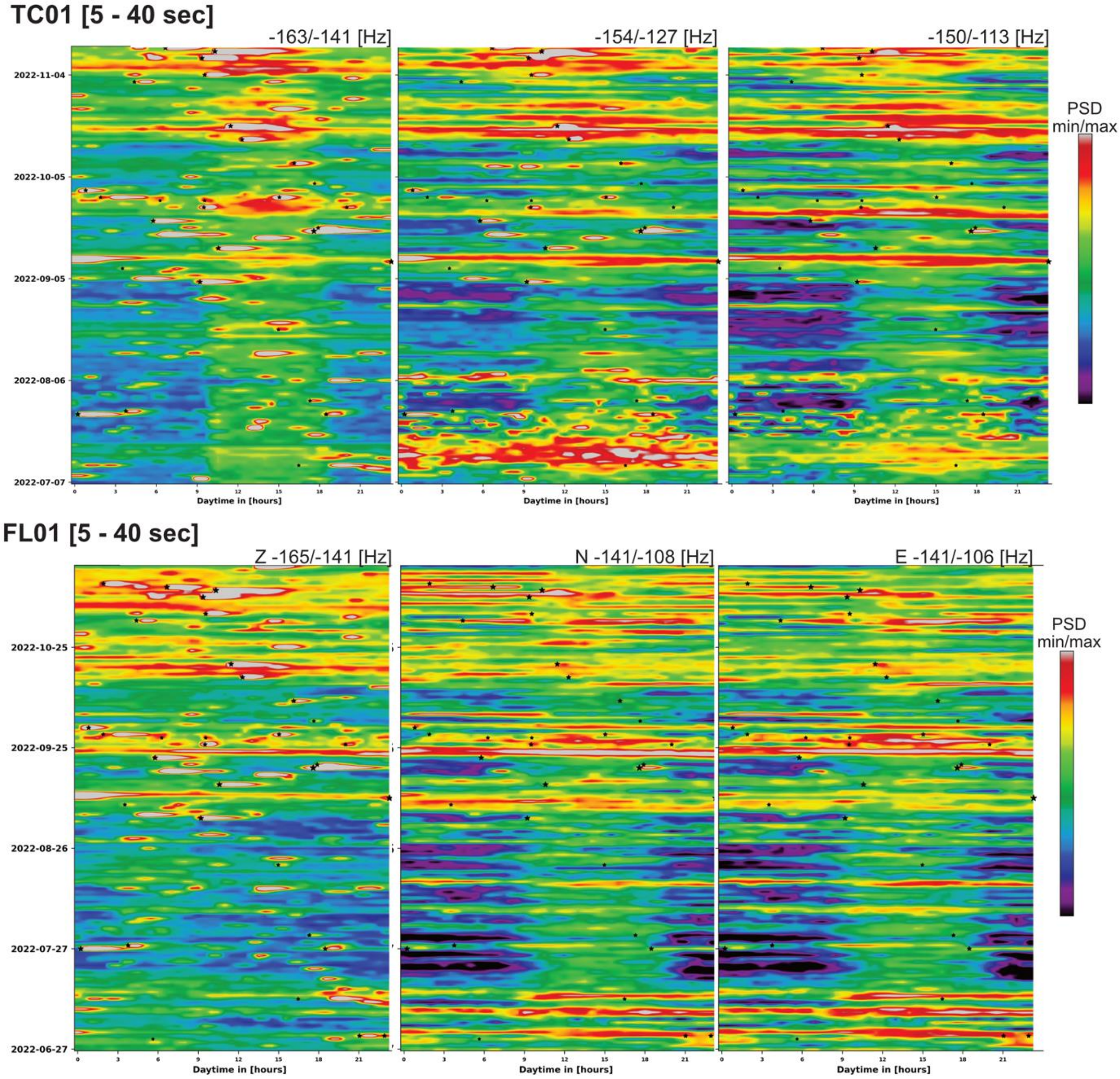


Figure A8 Continuation of Figure A7.