The volcano-tectonic unrest in the Reykjanes Peninsula in Iceland in 2021 and the new seismic and strong-motion arrays in Southwest Iceland

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Abstract: An intense period of volcano-tectonic unrest in the Reykjanes Peninsula Oblique Rift (RPOR) zone in Southwest Iceland commenced on 24/02/2021 with a M_w5.64 earthquake in the central part of the Peninsula, followed by a drastic increase in seismic activity over the western-central RPOR and clear deformation signals associated with a dike intrusion. The sequence that saw six NS-striking earthquakes of M_w5 and larger along the ~10 km long NE-SW striking dike intrusion culminated on 19/3/2021 in an eruption in Mt. Fagradalsfjall near the centre of the dike. Thereafter, magnitudes and intensity decreased along with generally ceasing seismicity. The movement of the magma front repeatedly caused remarkable accelerations of seismicity with increases in the frequency of phase detections, known to reduce the sensitivity and reliability of real-time hypocenter location estimates of regional networks. This potentially had practical implications due to the proximity of the unrest to the capital region of Reykjavik (15-25 km NE) and the town of Grindavik (6 km SW). Therefore, both the improved seismic monitoring of the advancing magma front was essential to cope with the high seismicity as well as mapping the spatial differences in ground motion amplitudes inside the closest town of Grindavik, 6 km SW of the volcanic eruption. We therefore set up a new seismic and strong-motion array consisting of 6 stations in Grindavik (on 12 March 2021) that streamed data in real-time to a local SeisComP server. Calibration of the array processing involved tuning Gempa's interactive and automatic LAMBDA and AUTOLAMBDA modules applying the Progressive Multi Channel Correlation and FK-analysis methods. We calculated back-azimuth and slowness values for known earthquakes and compared them with official permanent network locations. For most events, the back-azimuths deviate by less than 10° and on average, the distribution of residuals is Gaussian. The ground motions in Grindavik itself show resonance at 3 Hz, typical of lava-layers in the region. In addition, a new seismic array was deployed on 23 March 202 in the mountains about 6 km E of the dike intrusion, improving hypocentral locations of small events and tracking the magma migration in the sub-surface.

Keywords: SeisComP, TURNkey, RISE, dike, detection, backazimuth

1 Introduction

Iceland is the most seismically active region in northern Europe. It is situated in the North Atlantic Ocean where the Icelandic Hotspot, a broad, localized upwelling of magma from deep within the mantle, elevates the seafloor so that it is partly exposed and forms land (see Figure 1). The Icelandic Hotspot drives the volcanism and seismicity of Iceland along with the Mid-Atlantic Ridge, a plate margin of active tectonic horizontal extension that runs along the entire length of the Atlantic Ocean between the Arctics and approaches Iceland from the southwest and central north. The presence of the Icelandic Hotspot, the centre of which is located approximately under the northwest part of the largest glacier in Iceland, causes an eastward ridge-jump on land in Iceland. As a result, two fracture zones characterized by transform motion have formed in the South and North of Iceland, respectively. These zones are the South Iceland Seismic Zone (SISZ) and Reykjanes Peninsula Oblique Rift in Southwest Iceland (RPOR), and the Tjörnes Fracture Zone (TFZ) in Northern Iceland (Fig. 1). The potential for large destructive earthquakes is largest in these zones as confirmed by historical annals spanning 1000 years (Einarsson 1991, 2008, 2014).

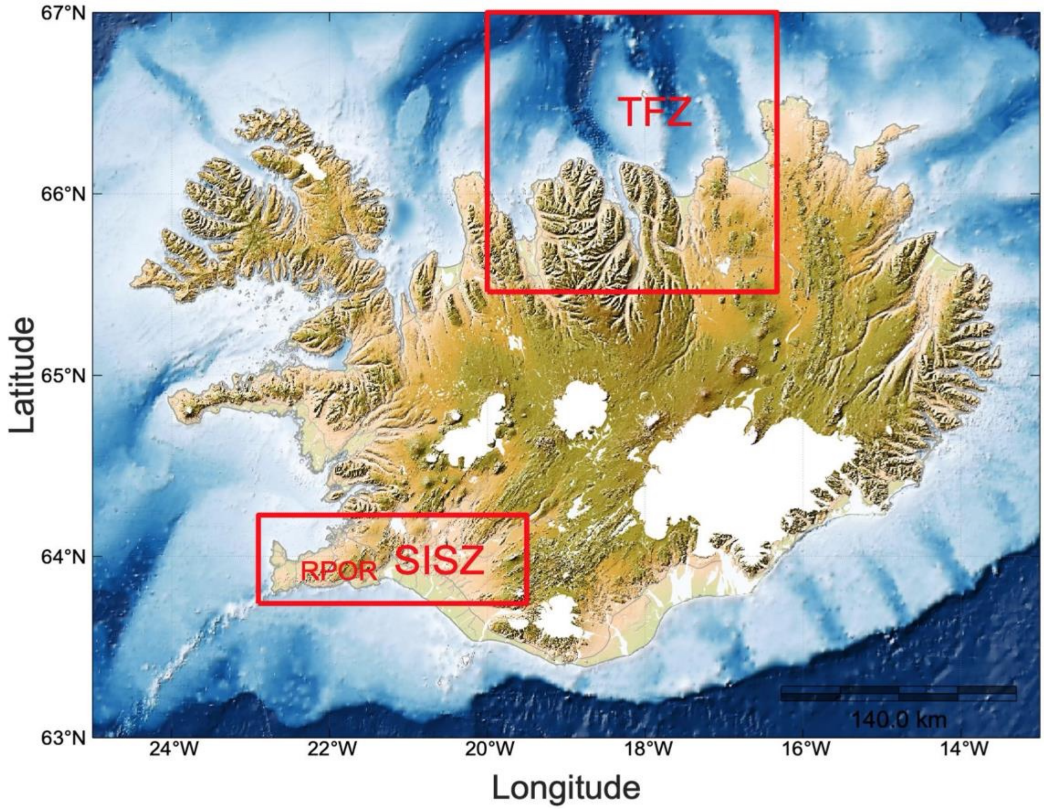

Fig. 1 - Map of Iceland's topography and bathymetry, outlining the transform fault systems of Iceland, the SISZ+RPOR in the South, and the TFZ in the North.

The SISZ and RPOR take up the transform motion of the eastward jump of the Mid-Atlantic Ridge in southwest Iceland. Instead of a sinistral transform fault system in the SISZ, parallel to the direction of the zone, a „bookshelf" faulting system of near vertical dextral strike-slip faults takes up the transform motion (Einarsson 1991, 2008, 2014; Steigerwald et al. 2020) (Fig. 1).

The volcano-tectonic earthquakes in the three volcanic systems of the RPOR are assumed to have a minimum contributing role to the seismic risk in the region. Moreover, volcanic seismicity has been shown to occur episodically and to be associated with active tectonic extensions along the SW-NE oriented fissure swarms of the volcanic systems. The time period between such episodes is believed to be about 600 to 800 years, with each of the four volcanic systems being activated one by one, with the period between volcanic episodes of each single system being about 900-1100 years. The active periods can last many decades with intervals of quiescence in-between (Sæmundsson et al. 2020).

Thus, in between such volcanic episodes the release of tectonic deformation is taken up by transform motion on the bookshelf system. Recently, the bookshelf system long known to be the origin of strong earthquakes in the SISZ has been shown to be continuous across the Hengill Triple Junction and along the RPOR (Steigerwald et al. 2020, and references therein). The system is characterized by an array of parallel north-south near vertical dextral strike-slip faults. The distance between the faults is assumed to be of the order of ~1-5 km. There is however evidence that the distances between faults decrease towards the west of the RPOR, even down to a few hundred meters (Einarsson 2014; Einarsson et al. 2020).

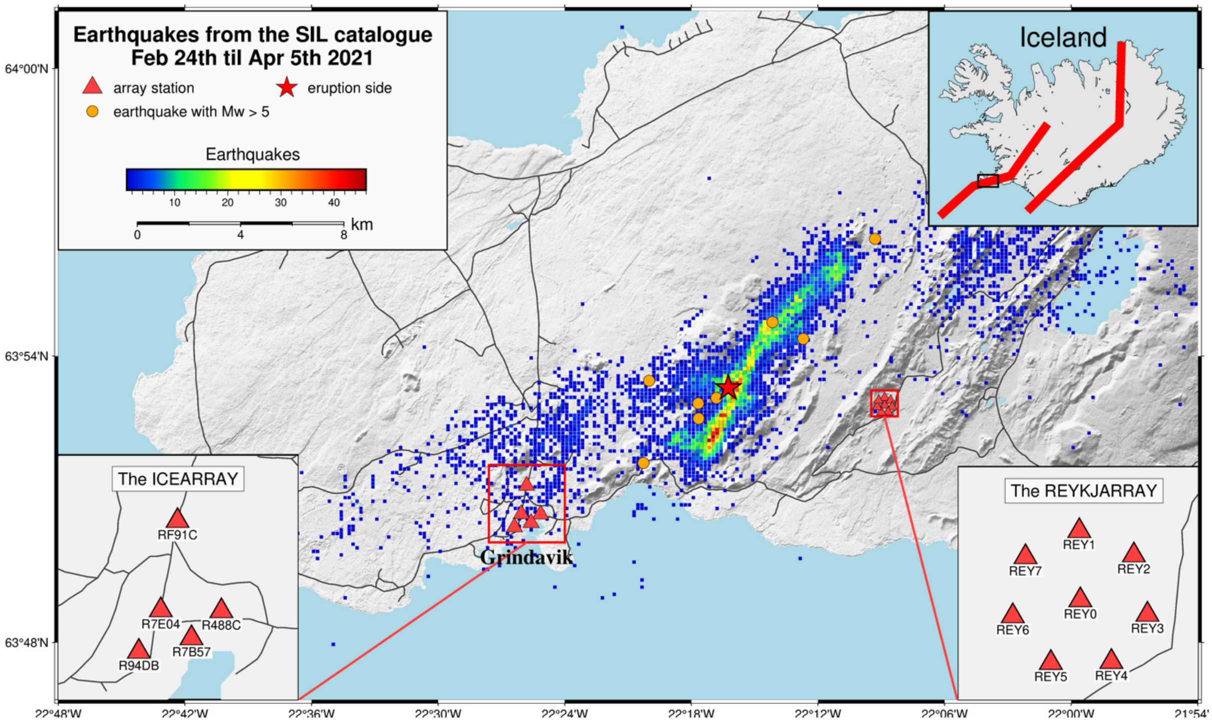

Fig. 2 - The seismicity in the RPOR during 24/2-05/4/2021 (blue dots) with epicentral locations of M_w5 and larger earthquakes as orange circles. The colour scheme shows the spatial clustering and the Fagradalsfjall eruption site is shown with a star. The small, inserted maps indicate the locations of the ICEARRAY3 (left), the strong-motion and seismic array in the town of Grindavik, and the seismic REYKJARRAY at Núpshlídarháls, east of the dike intrusion.

2 The 2021 volcano-tectonic unrest on Reykjanes Peninsula

A series of unusual volcano-tectonic events took place in the Reykjanes Peninsula almost continuously from December 2019, culminating in a volcanic eruption in Fagradalsfjall on 19 March 2021 that lasted for 6 months. Over 5000 earthquakes of M2 or larger were detected by the National seismic network (SIL) of the Icelandic Meteorological Office, six of which were moderate i.e., M_w5-5.64. They took place on the bookshelf fault system on near-vertical S-N striking fault planes. The earthquake sequence commenced with the largest of these earthquakes, the M_w5.64 earthquake that took place in Fagradalsfjall on 24/02/2021 and was immediately followed by a drastic increase in seismic activity in the western-central RPOR as shown in Fig. 2. The seismicity was primarily concentrated on an approximately 10 km long SW-NE lineament in between the Reykjanes-Svartsengi and Krýsuvík volcanic systems. More notably, the moderate size earthquakes were all, apart from two, located at or near the dike lineament. The last moderate event recorded during the sequence was the M_w5.33 earthquake that occurred on 14 March 2021, 2,5 km off the SW end of the lineament.

Since the onset of the seismic sequence a clear deformation signal had been recorded by the GNSS instruments in the region. The signal was characterized by horizontal motions towards the SE East of the lineament and towards the NW West of the lineament, clearly indicating a vertical dike intrusion along a NE-SW extensional fissure illuminated by the seismicity. The seismicity, followed by the deformation signature, started near the central part of the lineament, and from there propagated towards NE for a few days and then migrated from the centre towards the SW. The sequence then culminated in a volcanic eruption on 19/2/2021 at Fagradalsfjall, an extremely rare extensional event as the last eruption in this location was 6000 years ago. The commencement of the eruption had a drastic effect on the seismicity, as it effectively marked the cessation of the occurrence of earthquakes larger than M3 over the next few months along with the intensity of the sequence, as only roughly 200 earthquakes of M2 or larger were recorded in the region during the six months that the eruption lasted.

3 The seismic REYKJARRAY in Reykjanes Peninsula

The seismic REYKJARRAY was deployed on 23 March, 2021 in the Núpshlídarháls hyaloclastite mountain ridge, centred approximately 6 km E of the centre of the dike, and as Fig. 2 shows, approximately at right-angles to the seismicity. The array consists of one central and seven peripheral stations in a classic circular design with an aperture of 600 m and smallest inter-station distance of 260 m. Each station consists of a three-component Lennartz LE-3D/5s seismometer (5 s eigen period) and a REFTEK 130-01 recorder, collecting data at a rate of 100 Hz with high gain. The circular design of the array ensures equal hypocentral location capability in all directions and the aperture and interstation distance is optimized to resolve the range of phase velocities and frequencies expected in the P and S body waves radiating from crustal microearthquakes at small distances. The configuration is expected to enable high precision tracking of magma migration in the crust and to provide greater insight into the spatio-temporal behaviour of dike propagation during magmatic intrusions.

The instruments were obtained from the Icelandic seismic instrument bank LOKI at the Icelandic Meteorological Office and deployed as part of the H2020 EUROVOLC and RISE projects. The stations were powered by solar panels with battery backup and recorded data in-situ, so the data were not available for real-time monitoring of seismicity. When the data were downloaded three months later, it was found that some of the recorders had not been able to operate in the cold Icelandic conditions (≤ 9°C). After replacing the faulty recorders, the array was operational and is still operating. The data processing and analyses are currently ongoing.

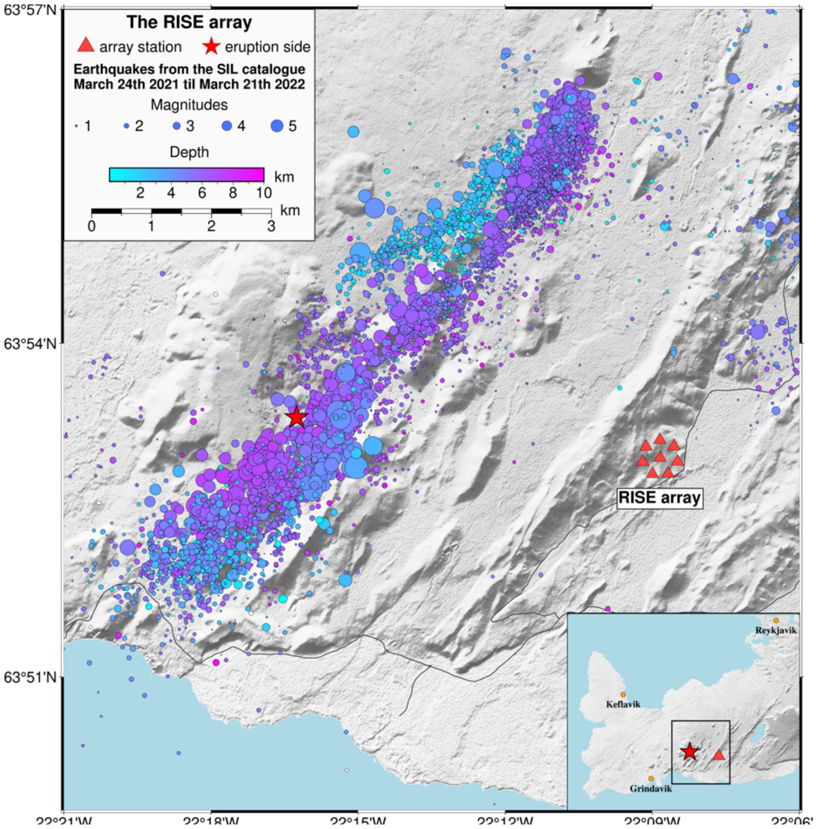

Fig. 2 – The epicentral locations of the seismic sequence from 24/2-21/3/2021 in Reykjanes, along with the station locations of the REYKJARRAY seismic array (red triangles). The eruption site is designated by a star.

4 The ICEARRAY3 strong-motion array in Grindavik, Southwest Iceland

In addition to the regional SIL seismic network, the intense seismic sequence was well recorded by a new regional strong-motion network deployed as a part of the TURNkey H2020 project (Meslem et al. 2021). In the vicinity of the sequence the new network consists of 9 Raspberry Shake 4D three-component accelerographs with a range of 2g along with a single-component vertical 4.5 Hz geophone, along with the digitizers, the hyper dampers, and the computer into a single box. The RS4D has been shown to be an excellent all-in-one solution improving ground motion monitoring complementary to an existing sensor network. With the geophone it is optimized for earthquake early warning applications (Anthony et al. 2019). In Iceland, we take advantage of the continuous real-time streaming capabilities that the extensive coverage of the 4G mobile network allows. Moreover, in the TURNkey project the implementation of the new Common Acquisition Protocol Server (CAPS) module has reduced the required bandwidth by a factor of 5. In addition, a new TURNkey GNSS instrument has been developed by YetItMoves! in collaboration with Gempa. The development has seen the RS4D being upgraded to the „TURNkey multisensor unit“ where other monitoring sensors for any geophysical markers (in this case, GNSS) can be connected to the RS4D with the new CAPS server marrying the datastreams into a consistent format and using the communication protocol of the RS4D for the collocated data streams. The data is streamed to a local SeisComP system and forwarded to a centralized cloud-based system for the development of the TURNkey platform.

During 11-12 March 2021 an additional six-station urban array, referred to as ICEARRAY3, was deployed in the town of Grindavik, approximately 10 km away from the eventual eruption site, for the purpose of using correlation analysis on seismic signals to provide additional information on the real-time location of the front of the dike intrusion as it advanced to the SW, edging closer to the town that is located 6 km WSW of the southern end of the intrusion. Namely, as the lateral movement of the magma front repeatedly caused a marked increase in the frequency of phase detections that were shown to affect the reliability of real-time hypocenter location estimates. The array has an aperture of 1970 m and minimum interstation distance of 430 m. Another purpose of the array deployment was to map the character and level of differences in seismic ground motions across the town. Fig. 3 shows the array configuration and its relative geometry and backazimuth to the seismicity.

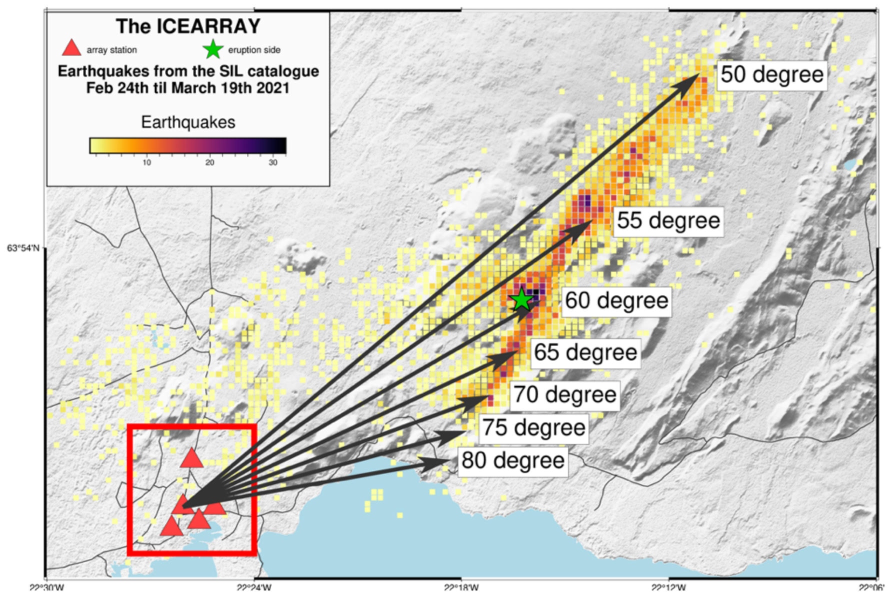

Fig. 3 – The seismicity from 24/2-19/3/2021 along with the backazimuthal range of the central station of the ICEARRAY3, with the eruption site indicated by the star. One array station is not shown as it was not used in the array processing due to a persistent phase delay due to localized site conditions.

Only one week passed from the deployment of the ICEARRAY3 until the eruption started, and even shortly before that the level of seismicity decreased considerably, as shown in Fig. 3. Nevertheless, the data recorded on the array during this time period sufficed for the calibration of the array.

4.1 Methods

For the processing of the ICEARRAY3 data, we used the LAMBDA and AUTOLAMBDA modules by Gempa for the SeisComP software package. While the LAMBDA module has a GUI for interactive data processing, the AUTOLAMBDA module runs as a daemon module in the background or is executed on the command line for processing both real-time and archived data. We used the LAMBDA GUI to select various parameters that can be adjusted according to the characteristics of the data. The seismometers and recording devices of all five stations in the ICEARRAY3 are identical making correction of the instrument response redundant. Both modules offer four different array processing algorithms of which we used the FK (frequency wavenumber) and the PMCC (Progressive Multichannel Correlation) method.

The FK method is a grid search over a pre-defined range of back azimuths and slownesses in the frequency domain. For each grid point, the wavelets are stacked to form a beam and the beam with the highest energy is selected. Potential shortcomings of this method are aliasing which occurs when the phase wavelet is short compared to the analysed window length as well as wrongful detections caused by correlating noise.

The PMCC method (Cansi 1995) uses inter-station correlation functions to estimate the back azimuth and slowness of the incoming wavefield. Like the FK method, it is performed in the frequency domain, but several distinct frequency bands are used rather than one range of frequencies. A sub-array consisting of only three stations is used to make a first estimate of back azimuth and slowness and then the other stations are successively added but only value pairs close to the initial estimate are accepted. This approach reduces the risk of correlating noise or other local maxima and does not require a strong correlation of the wavelets across the entire array, allowing for the detection of incoming signals with wavelengths shorter than the array aperture.

Both Gempa modules require several parameters to be adjusted according to the properties of the data. We used the LAMBDA module to test the default parameters using a short (2-hour) dataset and compared the detections to the catalogue of the regional seismic network to assess performance. We then looked at the earthquakes in the catalogue at lower magnitudes that were not detected by the array and made appropriate changes to the parameters. This process was repeated until the detection rate could not be significantly improved further. We ignored wrongful detections, rather focusing on missing as few real events as possible and instead later cleaned the detections by eliminating those with a back azimuth smaller than 30° and greater than 90° as well as slownesses smaller than 5 s/deg and greater than 25 s/deg. We then used the AUTOLAMBDA module to apply the parameters that were identified to the complete data set.

The event determination during 11-20 March is shown in Fig. 4. The smallest detected event was a magnitude ~0.6 but from comparison with the SIL detections, the magnitude of completeness of the array is about 2. On average, the array processing results show an insignificant bias in the array backazimuthal and slowness detections, compared to those calculated from the reported hypocentral locations by the SIL network. The back azimuths are on average 2°-4° degrees smaller and the slownesses are 0.015 s/km higher when compared with the hypocentral locations reported by the regional network. This discrepancy, albeit statistically insignificant on average, is most likely caused by the local geology underneath the array which is highly fractured with prominent NS and SW-NE strike directions, respectively.

The accuracy is however more than sufficient to shed light on the real-time spatial progression of intense sequences.

As Fig. 4 shows, indicated by the shaded region, the entire dike is shown to be within the 50°-80° azimuthal range from the ICEARRAY3. Admittedly, this is a narrow view window which may limit the accuracy of our estimates and the ability to discriminate event locations. However, the seismic REYKJARRAY located at more or less along the normal from the center of the dike is free from such limitations. Joint array analysis of data from both arrays is expected to provide much greater location accuracies. This will be examined for some common time windows. Figure 4 also shows that the PMCC results provide much less uncertainty in the backazimuthal estimates than the FK analysis results, and the PMCC results also show that the activity starts to concentrate under the eruption site 2-3 days before the eruption onset in the evening of March 19th. We observe that the array detects many more events in near-real time than the SIL network reports during times of rapid onsets of P phases from small earthquakes, as shown in Fig. 5. Such situations generally cause difficulties of relatively sparse networks where wrong phase associations can go undetected and cause great inaccuracies in the hypocentral location estimates.

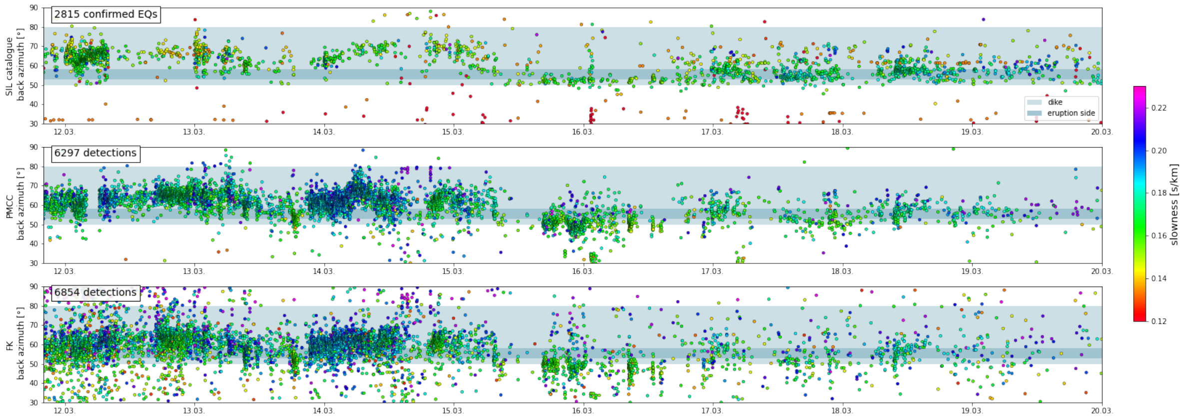

Fig. 4 - Back azimuths and slownesses calculated from SIL catalogue locations (top), PMCC algorithm results (middle) and FK algorithm results (bottom) from the array installation date to the onset of the eruption.

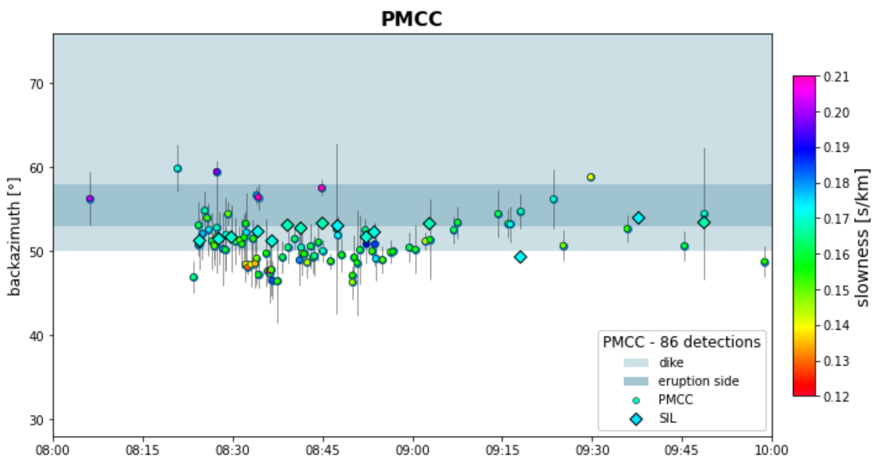

Fig. 5 - Comparison of national network and array detections for a 2-hour-window with quick succession of small earthquakes. The national network detected 15 earthquakes, the array with the PMCC method could identify 86 individual phase arrivals.

4.2 Ground motion levels in Grindavík

The ICEARRAY3 has recorded a large variability of ground motion intensities across the town of Grindavík. Fig. 6 shows the distribution of the recorded peak ground accelerations and peak pseudo-acceleration spectral response across the town of Grindavík. For comparison, a suite of five newly established Bayesian empirical hybrid ground motion models (Kowsari et al. 2020) and their mean values are shown. The model predictions conform well to the observed recordings, except at the structural period of 0.3 s (3.33 Hz) where the models are shown to underestimate the observations, a common feature of other lava-rock locations in Southwest Iceland (Rahpeyma et al. 2016, 2019, 2021). Finally, the recorded peak acceleration values in Grindavík are comparable to the amplitudes for aseismic design of structures according to the current building standard (Eurocode 8). However, the vast majority of the structures in the region were constructed with lower design values. Nevertheless, insignificant damage was observed in the town.

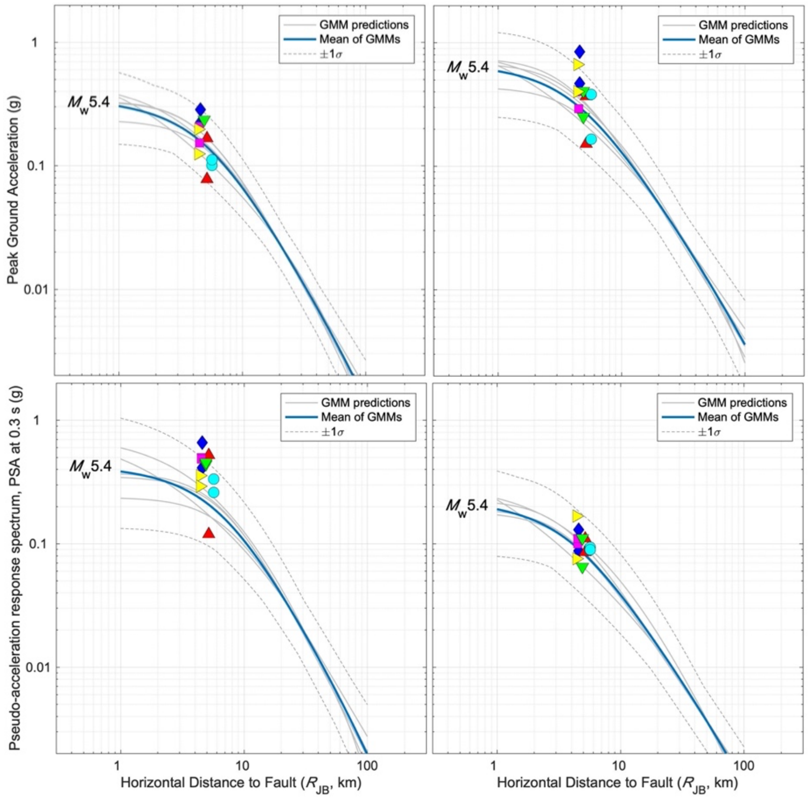

Fig. 6 – Recorded peak ground acceleration (top left) values at the ICEARRAY3 recording sites in Grindavík, along with the pseudo-acceleration spectral response values at three different oscillator periods (0.2 s top right, 0.3 s bottom left, and 1.0 s bottom right). For comparison, new ground motion model predictions are plotted.

5 Conclusions

Dike intrusions are often accompanied by numerous small earthquakes that sometimes occur in quick succession or swarms over short intervals. While regional seismic networks perform reliably when detecting individual earthquakes, detection may become incomplete in such cases when the inter-event time is greatly reduced. One approach to enhance the network performance is its densification but this is expensive and time intensive in inaccessible areas such as rural Iceland. A cost-effective addition to regional networks are small-aperture arrays which can be quickly deployed at practically feasible locations, and that way monitor seismic activity while being unaffected by many other limitations.

When the most recent seismic sequence started in the Reykjanes Peninsula Oblique Rift zone in February 2021, efforts immediately commenced to prepare and install an urban seismic and strong-motion array in cost- and time-efficient manner. The result was a new array in the nearby town of Grindavik, which was deployed on 11 and 12 March. The array consists of six RS4D instruments (5 of which are used in the array processing) that each contains three accelerometric sensors and one vertical geophone. The units became part of the TURNkey network that recently has been deployed in Iceland. Later, the REYKJARRAY seismic array was deployed in a more optimal location with respect to the seismicity and the dike alignment.

The ICEARRAY3 immediately started to monitor the seismic sequence that was caused by a dike intrusion that eventually culminated in a volcanic fissure eruption eight days after the array installation. Since the deployment, array data processing methods have been applied continuously on the real-time seismic data using SeisComP together with LAMBDA and AUTOLAMBDA by Gempa. LAMBDA and AUTOLAMBDA were applied to measure back azimuth and slowness pairs of incoming waves. In addition, extensive sensitivity analyses have been carried out to investigate the reliability of the results of the analyses. Comparing the array detections to the earthquake catalogue from the regional network shows that the magnitude of completeness of the array is about 2 but in favourable conditions, earthquakes of magnitudes as small as 0.6 are detected reliably. On average, the ICEARRAY3 array processing results show a slight but insignificant bias in the array backazimuthal and slowness detections, compared to those calculated from the reported hypocentral locations by the SIL network, most likely caused by the local geology underneath the array which is highly fractured with prominent NS and SW-NE strike directions, respectively. Nevertheless, the relative changes in backazimuth and slowness are shown to provide considerable detailed view of the volcano-tectonic seismicity that greatly exceeds the resolution of the regional network earthquake locations. Thus, with the considerable advantages such as low-cost and fast deployment in urban areas, small aperture arrays appear to be a robust and valuable addition to local and regional networks for the monitoring of imminent seismic and volcanic events, and in particular the rapid microearthquake occurrence, possibly associated with magma movements.

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