PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2025
SGP-TR-229

An Early Warning System for Volcanic Eruptions

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Keywords: Svartsengi, volcanic eruption, forecasting, reservoir pressure

ABSTRACT

A period of geological unrest started in the Svartsengi volcanic system with a swarm of earthquakes on October 25th, 2023, followed by a dike propagation event on November 10th, and seven subsequent volcanic eruptions to date. The energy utility HS Orka operates a geothermal power plant approximately 1.6 km away from the closest point of the dike intrusion. The utility has been operating a downhole pressure and temperature logger in well SV-12 since 2018 to monitor how the reservoir responds to production and injection. During the event on November 10th, 2023, the logger picked up a pressure signal which had not been observed before in the history of the monitoring system. It was characterized by a rapid pressure increase, most likely due to magma movement associated with the dike propagation. This signal was again observed 35 minutes before the volcanic eruption on December 18th, which prompted the department of resource management at HS Orka to design an early warning system for volcanic eruptions. The resulting system continuously monitors the speed of measured pressure changes and sends a warning to the Icelandic Meteorological Office (IMO) if they pass a certain threshold. The system was deployed on January 11th and sent a warning about an impending eruption to the IMO more than four hours before the eruption on January 14th. Since then, it has been able to predict the subsequent eruptions at least 25 minutes in advance. During those events, the warnings strengthened the confidence of the relevant authorities that a volcanic eruption was imminent and better enabled them to take appropriate measures to ensure public safety.

1. INTRODUCTION

The Svartsengi volcanic system on the Reykjanes Peninsula entered a period of unrest on October 25th, 2023, marked by an intense earthquake swarm. Sixteen days later, on November 10th, the first dike intrusion along the Sundhnúkur crater row took place. This was by all measures a significant geophysical event, where it has been estimated that up to 7400 m^3/s of magma flowed into a 15 km long dike, which propagated under the town of Grindavík (Sigmundsson et al., 2024).

The first fissure eruption occurred on December 18th, 2023 (IMO, 2024a). Since then, six subsequent eruptions have occurred along the Sundhnúkur crater row, with the most recent one taking place on November 20th, 2024 (IMO, 2024b). During these eruptions, lava flows have threatened critical infrastructure, including Svartsengi power plant, the town of Grindavík, and the Blue Lagoon — a popular tourist destination. Due to the proximity of these eruptions to populated areas and vital facilities, it is crucial for Civil Protection Services to receive adequate advance notice of impending eruptions to ensure public safety through measures such as evacuation notices and to make precautions to minimize material damage.

After the November dike intrusion, the government of Iceland began constructing embankments to protect critical infrastructure, particularly the Svartsengi power plant — the sole provider of hot water for district heating throughout most of the Reykjanes peninsula. These embankments have proven their value by successfully diverting lava flows from the power plant, Grindavík, and the Blue Lagoon.

1.1 Forecasting Volcanic Eruptions

Volcanic eruptions can pose substantial risks to population centers and critical infrastructure near eruption sites. Forecasting these events remains a challenging problem but is crucial to ensure public safety and to minimize material damage. The main precursors that have historically been used for this purpose have been seismic activity, ground deformation, gas emissions, and thermal anomalies.

Seismic activity is one of the most reliable precursors of volcanic eruptions because magma movement generates earthquakes, particularly swarms (McNutt, 2005). As magma ascends through the Earth's crust, it exerts pressure on surrounding rocks, generating seismic waves. The intensity and frequency of these earthquakes increase as magma comes closer to the surface, forming swarms of small to moderate tremors. In addition, fluid motion caused by magma movement can also produce harmonic tremors. Monitoring these seismic patterns is critical for detecting early warning signs of potential volcanic activity (Buurman et al., 2010).

Ground deformation is also a key precursor as magma intrusion or withdrawal typically cause an uplift or subsidence of the ground (Hazarika et al., 2024). GNSS (Global Navigation Satellite System) and InSAR (Interferometric Synthetic Aperture Radar) measurements are geospatial techniques used to monitor ground deformation. GNSS measures precise positional changes and InSAR maps surface displacements over wide areas. As magma, gas, or hydrothermal fluids intrude into the crust, an uplift or a shift may be detected. Patterns of inflations in volcanically active areas often indicate magma accumulation while deflation post-eruption may signal magma withdrawal.

Both seismic and GNSS sensors can be affected by intense winds generating noise and vibrations, thereby reducing their ability to detect an imminent eruption in harsh weather conditions (Dybing et al., 2019). However, these eruption indicators may also reflect changes in subsurface conditions within nearby geothermal systems, which could potentially be identified through reservoir monitoring. Geothermal systems are often located near volcanically active regions as they harness heat from magmatic sources. In addition to seismic events and ground deformation, increase in thermal activity and in gas emissions have been detected in geothermal systems prior to volcanic eruptions (Dietrich et al., 2018).

In Japan, increased gas emission in a geothermal reservoir near Mount Aso's caldera and increased thermal activity have been linked to magmatic intrusions (Matsushima et al., 2003). In Puna, Hawaii, increased seismic activity and ground deformation were observed prior to an eruption in 2018 (Neal et al., 2019). These signs prompted precautionary measures, including removal of flammable pentane from the site prior to lava reaching the geothermal site. In Iceland, eruptions occurred near the Krafla geothermal field between 1975 and 1984 during the Krafla Fires (Björnsson et al., 1986). Significant seismicity and ground deformation were observed prior to the eruptions. The same goes for the volcanic activity near the Svartsengi geothermal system at the Reykjanes Peninsula.

1.2 Volcanic Eruptions and Hydrological Pressure Changes

Water level and pressure changes in groundwater during the onset of magmatic activity have frequently been recorded throughout history. Changes in pore pressure have been related to heating or compaction of the aquifer. The time scale of these mechanisms differs, whereas while pressure changes due to mechanical compression occur rapidly, the pressure changes due to heating in a volcano-sized aquifer happen over months or years (Newhall et al., 2001). Different physical processes can be the cause for those changes, where deep magma intrusions can both dilate and compress aquifers, affecting water levels and pore pressure. These changes can propagate either slowly (months to years) through heating and convection, or quickly (minutes to days) through mechanical compression (Newhall et al., 2001).

An example of changes in groundwater level can be found prior to the 2000 eruption of the Usu Volcano in Japan, where systematic water level changes in two wells within 1 km of the eventual vent were observed months before the eruption. One well showed a steadily increasing rate of water level decline from October 1999, while a second well displayed brief uplift followed by gradual decline, then a sudden 5 m drop several days before the eruption. Three days after the eruption, the water level in the well increased again and it began flowing like a fountain. These changes were interpreted as responses to magma intrusion widening fractures and compressing the surrounding crust (Shibata and Akita, 2001). A similar mechanism is also believed to have been at play, during a magma intrusion event on May 21st, 2001, in the Kīlauea Volcano, Hawaii, where an abrupt water level drop was observed during a magma intrusion.

Another example of changes in groundwater level due to magma intrusion comes from the Izu Peninsula, Japan. The waterlevel in the Omuroyama-kita well was correlated with volumetric strain changes measured at the nearby Higashi-Izu station during four earthquake swarms between 1995-1998. Three pre-seismic groundwater level changes were detected and were attributed to crustal deformation caused by magma intrusions prior to the swarm activity (Koizumi et. al, 1999).

In the Krafla Fires in Iceland, abrupt water level changes were observed in well KG-5 prior to, and during, the eruption that took place on April 27th, 1977. On April 26th, the water level was measured at 90 m depth, but during the eruption it rose to approximately 5 m depth. In the following weeks, it gradually declined and was roughly down to its original level on May 25th (Steingrímsson, 1977a,b).

2. MEASUREMENTS IN WELL SV-12

2.1 Well History and Logging Technologies

Well SV-12 is a 1488 m deep well which was drilled in the Svartsengi Geothermal field in March 1982. The sequence of the well shows a typical Icelandic volcanic stratigraphy with alternating hyaloclastite and crystalline basalt formations, with various degrees of alteration. The well shows increasing hydrothermal alteration with depth, where the formation temperature below 600 meters has been estimated in the range of 230 to 240 °C. The well is cased down to 607 meters and has multiple feed zones, with the three largest ones located at 1008 m, 1109 m and 1195 m.

Well SV-12 was used as an injection well from 1984 to 1988, when it was turned around to supply the Svartsengi powerplant with steam. It was used as a producer until 1998 and was turned into a monitoring well in October 1999 and has served that purpose since that time.

In March 2018, a GEOKON Model 4500HT Series vibrating wire high temperature piezometer, with a standard range of 7.5 MPa, was installed at a depth of 850 meters in well SV-12. The high-temperature piezometer (Model 4500HT Series) offers a measurement accuracy of ±0.1% full scale and a resolution of 0.025% full scale, with its signal processed at the wellhead using a Campbell AVW200 two-channel vibrating wire analyzer module. The measurements are then read into a database operated by COWI, where it is stored along with data from multiple other loggers which COWI operates for HS Orka. For well SV-12, these measurements are written to a datalake every minute, where they are continuously analyzed by HS Orka.

The logger is situated in the open hole, below the water table and was originally intended to continuously monitor reservoir response to injection and production for the Svartsengi geothermal power plant. This had previously only been done with downhole measurements at regular intervals, usually three times per year. After giving pressure and temperature readouts for almost five years, the first

GEOKON logger failed in January 2023, but was replaced in June the same year and has been logging the pressure and temperature in the well since then.

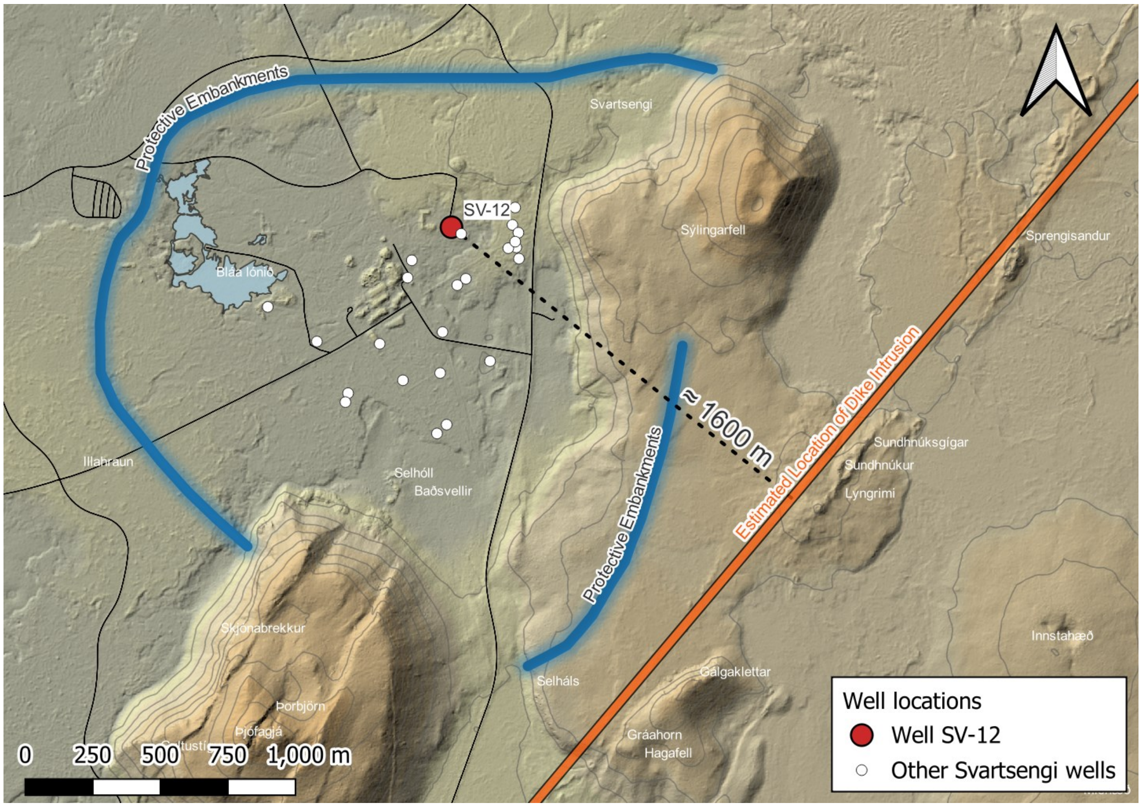

Figure 1: Location of well SV-12 relative to the Sundhnúkur crater row dike intrusion.

2.2. Response of the Pressure Signal During Earthquakes

Before the current volcanic episode at the Sundhnúkur crater row, large earthquakes would often show up in the monitoring data, either as a fast increase in pressure or decrease. However, the pressure would also reach its former equilibrium relatively soon. Figure 2 shows how the pressure at 850 m depth responded to an earthquake swarm close to the Svartsengi geothermal field. In this event the pressure quickly rose by approximately 29 kPa, decreased again by approximately 10 kPa in 30 minutes, and then gradually reached the former pressure trend in around 20 days.

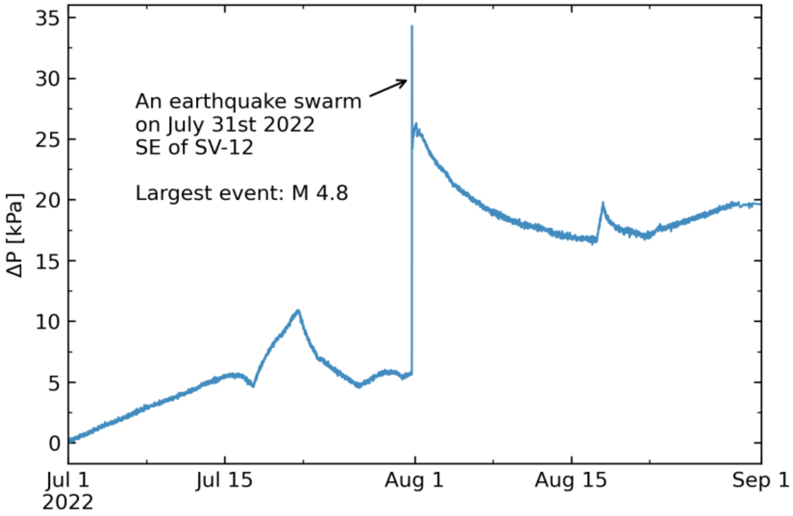

Figure 2: Pressure changes at 850 m depth in well SV-12 during the earthquake swarm of July 31st, 2022. The largest event was approximately 3.4 km to the SE from well SV-12, with a magnitude of 4.8.

2.3 The Dike Intrusion on November 10th, 2023

The pressure at 850 m depth in well SV-12 during the first five hours of this event is shown in Figure 3. It is characterized by very rapid changes in pressure, often coinciding with large earthquakes. It is also interesting to note that this pressure response did not seem to converge to the former equilibrium at a similar timescale as the earthquake signal. The reason for this could be due to a longer lasting compression of the aquifer during the dyke intrusion.

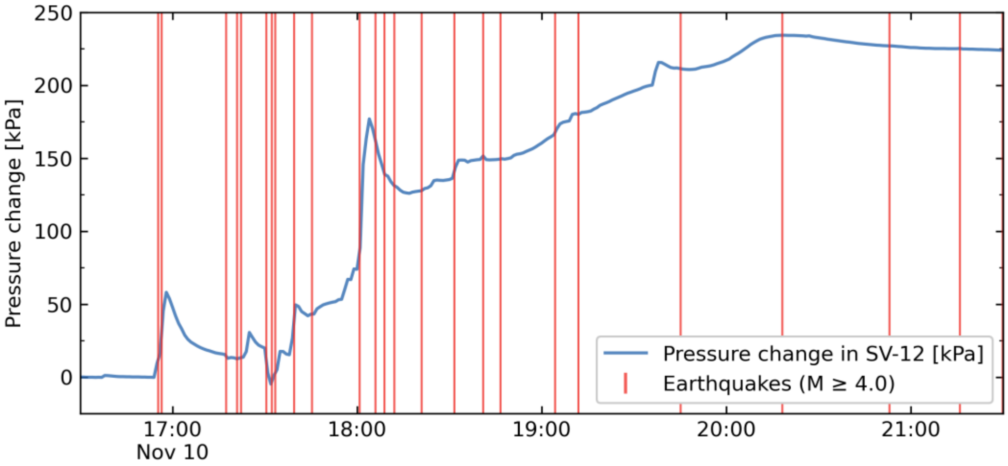

Figure 3: Pressure changes at 850 m depth in well SV-12 during the November 10th dike intrusion in 2023. The timing of earthquakes with a magnitude above 4, is shown as red lines. (Earthquake data retrieved from the Icelandic Meteorological Office).

2.4 Pressure Signals in Well SV-12 Prior to Volcanic Eruptions

The first volcanic eruption of the ongoing volcanic episode on the Sundhnúkur crater row started at 22:17 on December 18th, 2023. The pressure response, along with its time derivative, can be seen in Figure 4. During this event the pressure at 850 m depth in well SV-12 rose by approximately 80 kPa in one hour. Since such a fast pressure increase had also been seen on November 10th, it was concluded that this kind of signal indicated an ongoing dike intrusion and could therefore be used to give a warning about an impending volcanic eruption.

Since it was mostly the rate of pressure change that indicated if a dike intrusion was taking place, the time derivative of the pressure was determined to be a suitable criterion to send a warning about an impending eruption. Since these pressure changes are at the limit of the resolution of the pressure logger, there tended to be some noise in the signal. This problem was at first mitigated by taking the five-minute running average of the time derivative of the pressure. However, after the logger had triggered several false warnings using that criterion, it was later changed so that three consecutive values of the time derivative would have to be above 0.2 kPa/min to send a warning.

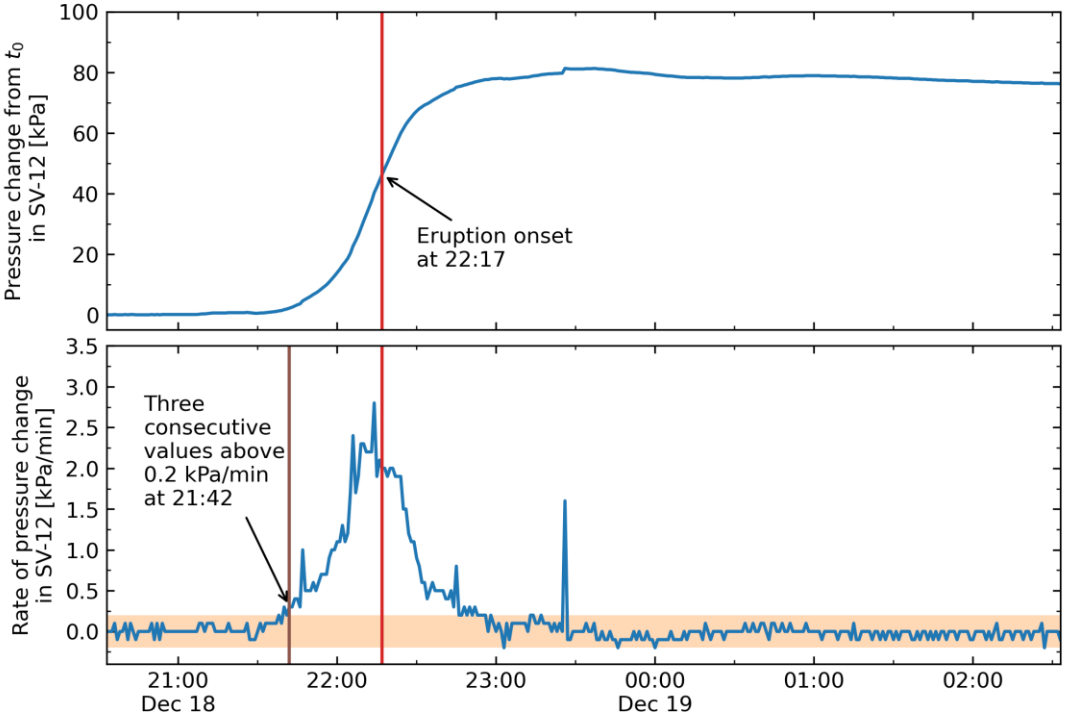

Figure 4: Pressure changes at a depth of 850 m in well SV-12, as well as its time derivative, prior to the December 18th eruption in 2023.

The first version of the early warning system was deployed on January 11th, 2024, where the system retrieved a pressure measurement from the logger every minute, to see if its time derivative would pass the threshold. Three days later, on January 14th, the system sent a warning to the Icelandic Meteorological Office (IMO) about an impending eruption four hours and twenty minutes before it began. The signal triggering the warning can be seen in Figure 5.

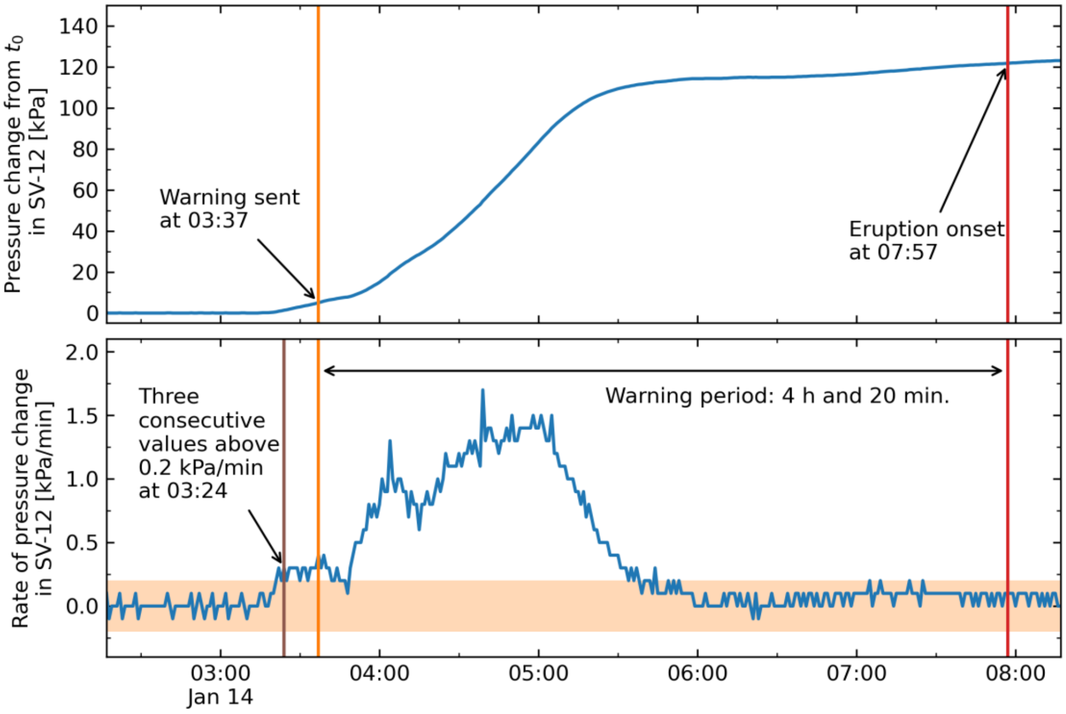

Figure 5: Pressure changes at 850 m depth in well SV-12 prior to the January 14th, 2024 eruption. The brown line indicates when the rate of change first exceeded the threshold of 0.2 kPa/min for three consecutive measurements. The orange line marks when the warning was sent to the Icelandic Meteorological Office, and the red line denotes the eruption onset.

On February 8th, 2024, another eruption was successfully predicted, with a warning sent to the IMO 25 minutes before the onset. Due to the relatively short warning time in this eruption, the data processing was subsequently improved to minimize the delay from when the threshold is passed, until a warning is sent to the IMO.

Another eruption took place on March 16th, 2024. However, due to a server outage at the consultant which runs and maintains the pressure logger, a warning was not sent prior to the eruption. Consequently, the IMO and Civil Defense were not able to warn the public about the impending eruption. After this, the warning system was improved so that it sends a warning if new data has not been retrieved for 15 minutes.

The warning system has since then successfully predicted every eruption. Those eruptions took place on May 29th, August 22nd and November 21st, 2024. In Table 1, the time when the threshold was passed, the time when a warning was sent to the IMO, and the time of the onset of the eruption can be seen.

Table 1: The table shows the time when the threshold to send out a warning is first passed, when a warning is sent to the IMO, when the eruption begins and the resulting length of the warning period.

Date of eruption	**Threshold passed**	**Warning sent**	**Eruption onset**	**Warning period**
Dec 18, 2023	21:42	N/A	22:17	N/A
Jan 14, 2024	03:24	03:37	07:57	4 h and 20 min
Feb 8, 2024	05:29	05:37	06:02	25 min
Mar 16, 2024	19:46	N/A	20:23	N/A
May 29, 2024	11:48	11:51	12:46	55 min
Aug 22, 2024	20:51	20:53	21:26	33 min
Nov 20, 2024	22:35	22:37	23:14	37 min

Figure 6 shows a comparison of the pressure signal in all dike intrusions and volcanic eruptions since December 18th, 2023. The November 10th dike intrusion is not shown on this graph, since the rate of pressure changed measured in that event would dwarf all the other events. During the January event, the pressure increased more slowly than in other events and exhibited the longest interval between threshold being passed until the eruption onset. This longer duration may be attributed to its southernmost location, requiring magma to travel a greater distance to reach the surface.

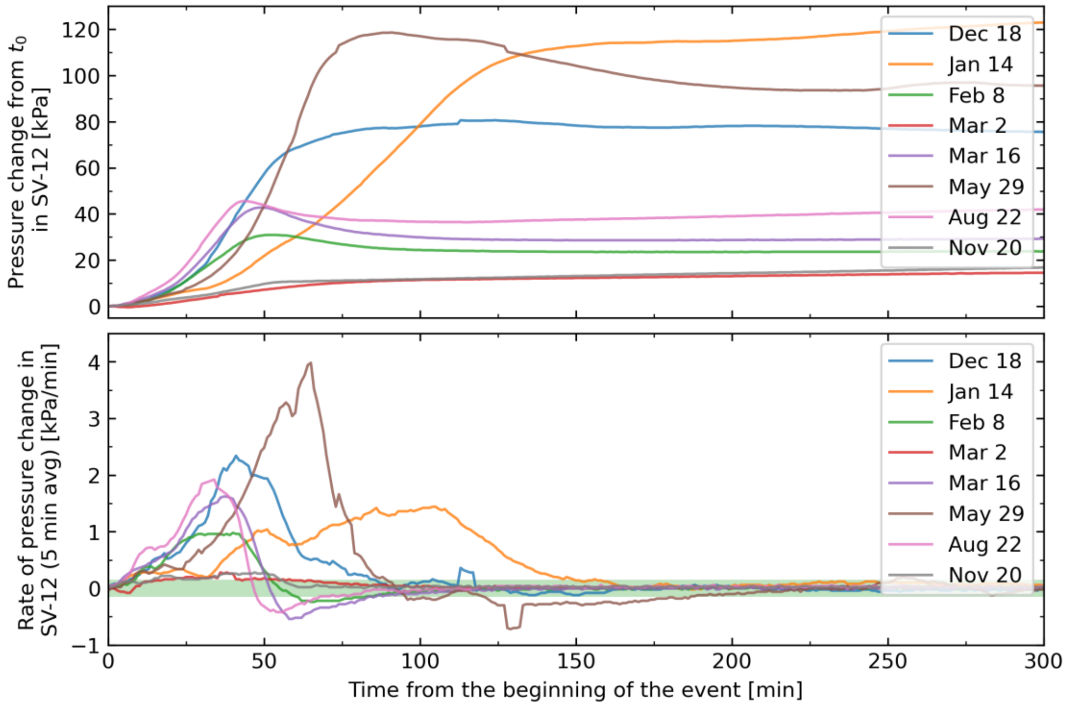

Figure 6: A comparison of the pressure changes and their rates during all eruptions in the Sundhnúkur crater row and the March 2nd dike intrusion. All the signals exhibit similar patterns.

2.5 False Positives About Impending Eruptions

2.5.1 A Minor Dike Intrusion on March 2nd, 2024

On March the 2nd, 2024, a minor dike intrusion occurred along the Sundhnúkur crater row. This dike intrusion, however, remained confined in the subsurface dike system without progressing to an effusive phase. At this time the early warning system was still using the five-minute running average as a criterion, which passed the 0.2 kPa/min threshold at 16:25. Three minutes later, at 16:28, it sent a warning to the IMO about an impending eruption.

The warning system is based on the rate of pressure changes. Therefore, it cannot distinguish between a dike intrusion that enters an effusive phase, and a dike intrusion that remains subterranean.

2.5.2 Pressure Fluctuations on May 21st to May 25th, 2024

During the period from May 21st to May 25th, 2024, the pressure sensor picked up rapid pressure changes in the system which are shown in Figure 7. At this time the warning criterion was still defined by when the five-minute running average passed 0.2 kPa/min. Several of those changes passed this threshold and sent a warning to the IMO. However, as no seismic activity was detected, it was clear that an eruption was unlikely. When those pressure changes were later analyzed, it was seen that those pressure changes were significantly smaller, and less persistent, than those during dike intrusions.

One possible reason for those pressure fluctuations could be gas travelling through the geothermal system after magma degassing. This event would not have triggered a warning message, after the criterion was changed so that it required three consecutive values of the rate of pressure change to be above 0.2 kPa/min, instead of using the five-minute running average.

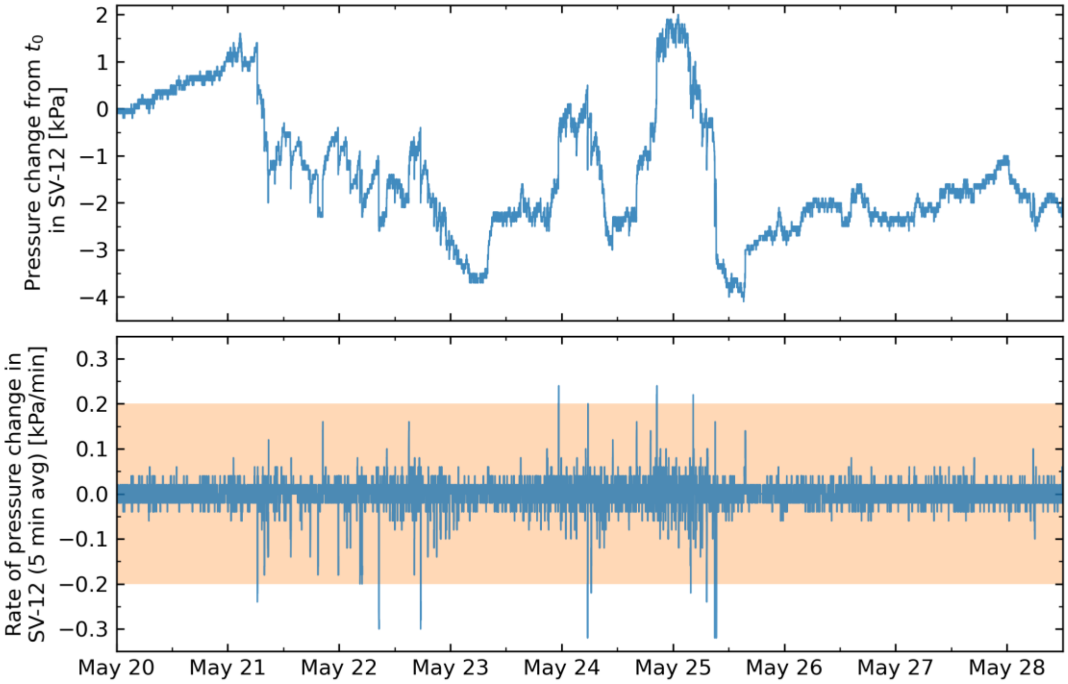

Figure 7: Pressure fluctuations during a possible magma degassing event in late May 2024. The upper figure shows the pressure changes [kPa] from midnight on May 20th. The lower figure shows the five-minute running average of the rate of pressure changes [kPa/min] along with the threshold that was defined for sending a warning to the IMO, which was defined at 0.2 kPa/min.

2.5.3 Jumps in Pressure, Possibly Due to Mechanical Issues in the Logger

Since the monitoring system was put online in January 2024, there have been several instances of jumps in pressure, two of which have resulted in a false alarm. Those occurred on the 8th of June and on the 4th of July 2024. The latter event can be seen in Figure 8. This did however not result in the IMO warning about an impending eruption, since there was both a lack of seismic activity at the time and it was clear that the shape of this signal was very different from the ones that had previously been observed during ongoing dike intrusions.

It is not known what causes these pressure jumps. However, the monitoring system is working at the limit of both the resolution and the accuracy of the GEOKON logger, so the pressure jumps could be caused by some mechanical or electrical issues.

The false alarm on July 4th, prompted the department of resource management to explore if a more robust criterion could be established to say if a volcanic eruption was imminent. After backtesting several criteria on historical data, it was decided to send a warning to the IMO if the rate of pressure change was above 0.2 kPa/min three minutes in a row. This criterion would replace the five-minute running average that was used before. This criterion would never have sent a false alarm, except for in the dike intrusions which did not reach the effusive phase. There has also not been a false alarm after the new criterion was established.

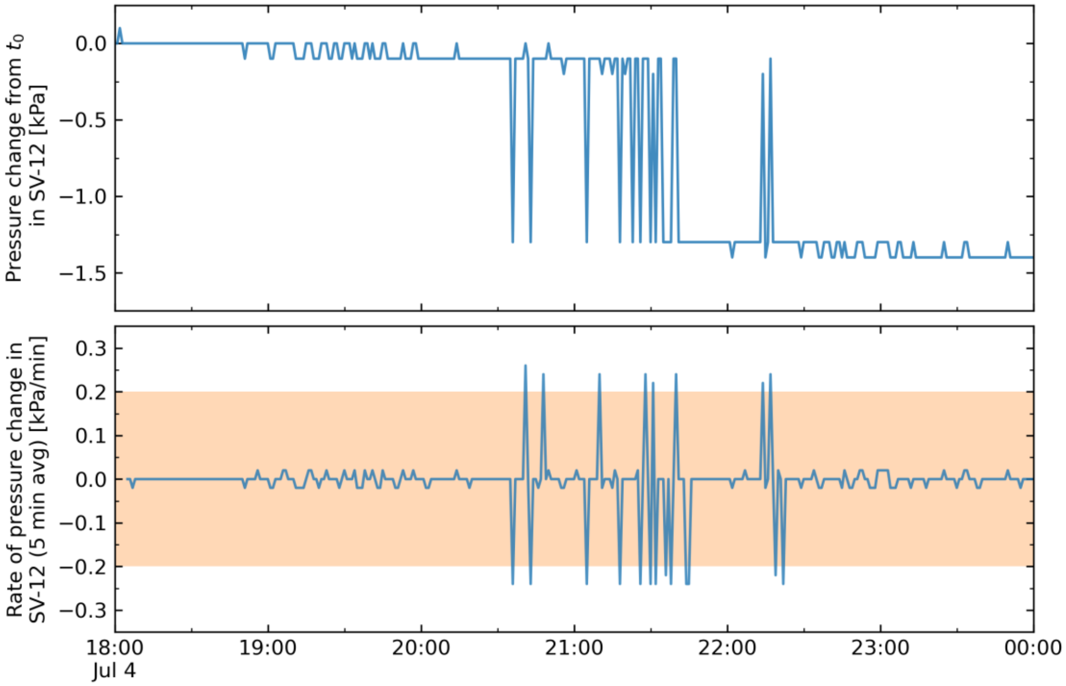

Figure 8: This figure shows jumps in pressure readouts from the logger on July 4, 2024. The logger shows approximately 1.5 kPa jumps in pressure, until it seems to reach a new, and slightly lower pressure equilibrium. The orange band shows the threshold to send a warning to the IMO.

3. DISCUSSION

The pressure response in well SV-12 during dike intrusions exhibits a notably consistent pattern. This consistency likely results from the dike intrusion elastically deforming the surrounding rock, increasing its volumetric strain. This deformation decreases the pore space volume and raises the water level in the geothermal system, thereby increasing the hydrostatic pressure recorded by the logger beneath the water table. The consistency of this signal may be attributed to the reservoir's high porosity and permeability, where fluid pressure changes accommodate a larger proportion of the stress. The most comparable examples of pressure changes during volcanic eruptions are found in the Krafla events of 1977 (Steingrímsson, 1977a,b).

The pressure data from well SV-12 during dike intrusions offers significant opportunities for further analysis, particularly regarding how the spatial and temporal characteristics of the dike intrusions influence the magnitude and rate of pressure response. For instance, during the southernmost eruption on January 14th, 2024, the pressure response exhibited a slower growth rate and longer duration compared to other eruptions. Further analysis of the pressure signals and dike intrusion characteristics could also provide insights into reservoir properties, such as porosity and permeability.

The pressure sensor in well SV-12 has proven effective as an early warning system for volcanic eruptions, successfully predicting five eruptions with warning periods ranging from 25 minutes to 4 hours and 20 minutes. To the authors' knowledge, this is the first system of its kind worldwide. The system offers advantages over traditional volcanic eruption prediction methods, such as GNSS-based deformation analysis, which can be affected by weather conditions. Since seismic data alone is often insufficient to determine the imminence of a volcanic eruption, this monitoring system has become crucial in IMO's assessment of impending volcanic activity.

4. CONCLUSIONS

Having near real-time measurements of pressure and temperature just 1.5 km away from a rift where a volcanic episode is currently actively occurring presents a unique opportunity to examine the interplay between magma intrusions and hydrological pressure changes. The resource management team at HS Orka has leveraged this setup to develop an early warning system for volcanic eruptions. To date, the system has successfully predicted five imminent eruptions, with warning times ranging from 25 minutes to 4 hours and 20 minutes. This system has become a crucial tool for the Icelandic Meteorological Office in determining imminent volcanic eruptions along the Sundhnúkur crater row, providing civil protection services with additional time to implement appropriate safety measures.

REFERENCES

Björnsson, A., et al.: The Krafla geothermal field, Iceland, Bulletin of Volcanology, 48(1), (1986), 15-22.

Buurman, H., and West, M.: Seismic Precursors to Volcanic Explosions During the 2006 Eruption of Augustine Volcano, The 2006 Eruption of Augustine Volcano, Alaska, (2010), 1769.

Dietrich, V.J., Chiodini, G., and Schwandner, F.M.: The Hydrothermal System and Geothermal Activity, In: Nisyros Volcano, Active Volcanoes of the World, Springer, Cham, (2018).

Dybing, S.N., Ringler, A.T., Wilson, D.C., and Anthony, R.E.: Characteristics and spatial variability of wind noise on near-surface broadband seismometers, Bulletin of the Seismological Society of America, 109(3), (2019), 1082-1098.

Hazarika, P.J., Dasgupta, R., Baruah, A., et al.: Ground surface displacements and stress localization driven by dual magma chamber dynamics: analytical and numerical model estimates, International Journal of Earth Sciences, 113, (2024), 1475-1494.

IMO: Volcanic unrest Grindavík - older updates, Icelandic Meteorological Office, accessed 30 January 2024, https://en.vedur.is/about-imo/news/volcanic-unrest-grindavik-older-updates, (2024a).

IMO: Eruption begins on the Sundhnúkur fissure swarm, Icelandic Meteorological Office News, accessed 30 January 2024, https://en.vedur.is/about-imo/news/eruption-begins-on-the-sundhnukur-fissure-swarm, (2024b).

Koizumi, N., Tsukuda, E., Kamigaichi, O., Matsumoto, N., Takahashi, M., and Sato, T.: Preseismic changes in groundwater level and volumetric strain associated with earthquake swarms off the east coast of the Izu Peninsula, Japan, Geophysical Research Letters, 26(23), (1999), 3509-3512.

Matsushima, N., et al.: Gas emissions and volcanic activity at Mount Aso, Earth and Planetary Science Letters, 211(1-2), (2003), 111-123.

McNutt, S.R.: Volcanic Seismology, Annual Review of Earth and Planetary Sciences, 33, (2005), 461-491.

Neal, C.A., Brantley, S.R., Antolik, L., Babb, J.L., Burgess, M., Calles, K., Cappos, M., et al.: The 2018 rift eruption and summit collapse of Kīlauea Volcano, Science, 363(6425), (2019), 367-374.

Newhall, C.G., Albano, S.E., Matsumoto, N., and Sandoval, T.: Roles of groundwater in volcanic unrest, Journal of the Geological Society of the Philippines, 56, (2001), 69-84.

Shibata, T., and Akita, F.: Precursory changes in well water level prior to the March, 2000 eruption of Usu volcano, Japan, Geophysical Research Letters, 28(9), (2001), 1799-1802.

Sigmundsson, F., Parks, M., Geirsson, H., Hooper, A., Drouin, V., Vogfjörd, K.S., Ófeigsson, B.G., Greiner, S.H.M., Yang, Y., et al.: Fracturing and tectonic stress drive ultrarapid magma flow into dikes, Science, 383(6688), (2024), 1228-1235.

Steingrímsson, B., and Gíslason, G.: Holubréf nr. 5, Report No. 77-06-02, Orkustofnun, Reykjavík, (1977a).

Steingrímsson, B., Gíslason, G., and Hauksson, T.: Holubréf nr. 6, Report No. 77-09-29, Orkustofnun, Reykjavík, (1977b).