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Seismicity Patterns Due to Magma Intrusions Underneath Geothermal Power Plants

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ABSTRACT

The Reykjanes Peninsula, Iceland, could soon see a once-in-a-millennium eruption, based on its current unrest and its historical record. This period of volcano-tectonic events threatens nearby airfields, geothermal power plants, and the capital, Reykjavik, where two thirds of Iceland's population reside. The main sources of risk are lava, volcanic ash, and M > 6 earthquakes on large strike-slip faults. Six such known faults lie between 15-35 km from the capital. Here, we investigate whether such large earthquakes and/or an eruption are likely, based on the seismicity seen so far. To do so, we look for specific seismicity patterns indicative of magmatically-induced deformation, and compare seismicity overviews of the current unrest, previous decades, and swarm activity in the 1970s. We identify several cascades of boundary movements in both the current unrest and the 1970s activity, that have neighboring segments activate from east to west along the peninsula. This direction is reversed during the current unrest in a slower cascade, which ended with a ~50 km long boundary segment moving. Based on this and other observations, we suggest that magma intrusion has accelerated boundary deformation significantly. We identify another pattern, where seismicity and surface deformation in Svartsengi, the most seismically active region during this period, is greatly reduced when this activity swaps to the neighboring Reykjanes system. We suggest magma intrusion is halted in one volcanic system, in favor of intrusion in another, and describe several possible mechanisms. We further describe possible scenarios, and their likelihood, for the evolution of the current unrest, which range from a rapid return to quiescence, to full-scale eruption. Whichever scenario occurs, M > 6 earthquakes on known faults near Reykjavik are likely.

1. INTRODUCTION

Besides providing an abundant supply of geothermal energy, the Reykjanes Peninsula (RP) in SW Iceland is also a volcanic area with extensive eruptive periods estimated to occur every 800 to 1000 years that last for 200-300 years (e.g. Sæmundsson, 2020). These eruptive periods (historically termed "fires") are characterized by fissure eruptions, interspersed with decades of quiescence. Since late 2019, a period of volcano-tectonic events is ongoing on the RP, without eruption so far. This period is characterized by episodes of uplift and subsidence, combined with tens-of-thousands of detected earthquakes in several volcanic systems on the RP. If these events signal the beginning of a new eruptive episode, then nearby towns and airports would be at great risk, as would the local geothermal power plants. Considerable risk exists even if there is no eruption, as the seismic release could activate large faults in the area (Einarsson et al., 2020), that may produce events M > 6. One large event (M 5.6) already occurred in October 2020. Simultaneous events pose the biggest risk to the capital, which hosts two thirds of Iceland's population (Einarsson et al., 2020).

A trans-tensional plate boundary cuts through the RP, between the Eurasian and North American plates. The total spreading rate is ~1.8 cm/yr (e.g. Einarsson, 2008). The strain release at the locked part of the plate boundary has been proposed to occur in either a seismic ("dry") or a magmatic ("wet") mode (Einarsson, 2008). The seismic mode occurs every ~30 years, with episodes in 1900, 1929-1935, 1971-1976, and 2000-2004. This mode mostly consists of earthquake swarms and large NS-strike-slip earthquakes (Einarsson, 2008; Björnsson et al., 2020). As crustal deformation is concentrated on these faults during these periods, this model has a missing extensional component of the required crustal deformation. This is the case between 1993-1998 (Hreinsdóttir et al., 2001), whereas some extension occurred between 1997-2006 (Keiding et al., 2009). The accumulated extensional component is expected to be released during the magmatic mode (e.g. Hreinsdóttir et al., 2001). During this mode dykes intrude on both sides of the plate boundary, which may subsequently activate the fissure swarms (Einarsson 2008). Evidence for such magmatic activity would be prolonged surface inflation, volcanic tremors, and/or earthquake swarms propagating along the fissure swarms.

As this model predicts seismicity differences between modes, we compare the seismicity of the current unrest to that in the preceding decades (1991-2019), and a period of dry-mode movements in the 1970s (Klein et al., 1977; Björnsson et al., 2020). Additionally, we visualize the seismicity in 3D to identify patterns uncommon in dry-mode and expected in magmatic-mode deformation.

The questions we address are: 1) Is the present unrest magma driven? 2) What might we be able to predict about its future evolution? 3) What new insights can we gain about dry and magmatic mode boundary movements from the seismicity of the current unrest? 4) What impact would this have on the local power plants and the development of new fields/plants? 5) What might power projects in other areas take away from what we learn from this period of unrest?

1.1 The Reykjanes Peninsula

The RP is an active oblique rift between the Eurasian and North-American plates. It hosts several volcanic systems; from west to east: Reykjanes, Svartsengi, Fagradalsfjall, Krýsuvík, Brennisteinsfjöll, and Hengill (Sæmundsson, 2020). Of these, both Svartsengi and Hengill have a greater tectonic significance. Three distinct plate boundaries meet at the Hengill triple junction, whereas the plate-boundary strike and, therefore, its obliquity to the spreading direction change in Svartsengi. The boundary strike is ~79° to the east of Svartsengi and 60° to its west, such that the obliquity changes from 30° in the east of Svartsengi to 0° on the Reykjanes Ridge (Hreinsdóttir et al., 2001; Clifton and Kattenhorn, 2006). This change in obliquity was investigated using analogue modeling (Clifton et al., 2000), and is used to explain the larger fault density in the west. Such faults have been thoroughly mapped at the surface (e.g. Clifton and Kattenhorn, 2006; Einarsson et al., 2020) and were delineated at depth using seismicity (e.g. Clifton and Kattenhorn, 2006). The center of the peninsula has a lower fault density and is dominated by NS strike-slip faults, which tend to increase in length towards the east, which is also the direction of increasing crustal thickness (Weir et al. 2001).

The largest faults lie in the Brennisteinsfjöll area and pose considerable risk to Reykjavik (Einarsson et al., 2020), with M 6-6.3 earthquakes occurring in 1968 and 1929. However, micro-seismicity has in general been low in the Brennisteinsfjöll area during the past three decades. Geothermal power plants currently operate in the Reykjanes, Svartsengi, and Hengill areas. Another power plant is considered in the Krýsuvík area, in conjunction with the IceLink project (Sasaki and Nakayama, 2016a,b), a ~1 GW electricity connector, which would run below the sea between Iceland and the UK. The seismicity in the Krýsuvík and Fagradalsfjall area is tectonically driven, with Krýsuvík having hydrothermal activity as a secondary seismicity driver (Keiding et al., 2009). Krýsuvík has also been investigated due to uplift and subsidence episodes between 2009 and 2018 (Gudjonsdottir et al., 2018; Hobé et al., 2021).

Multiple eruptive periods have occurred in the RP's volcanic systems over the past 4000 years (Sæmundsson et al., 2020). Their periodicity is on the order of 800-1000 years. These effusive eruptions occurred on elongated volcanic features, called fissure swarms, which lie in an en-echolon arrangement every ~5 km. Only one volcanic system tends to erupt at a time, and this activity tends to jump systems from east to west with 100-200-year intermissions. Some of the fissure swarms reach into the capital area, as do some lava flows (Einarsson, 2019a,b; Sigurgeirsson and Einarsson, 2019). Effusive lava flows and fault displacements thus pose risk to both the capital and the geothermal power plants, which have been built on top of such lavas.

1.2 What are we looking for?

Several authors have predicted seismic phenomena, that are likely to occur during a period of magmatic-mode deformation, based on mapped faults and numerical modeling (e.g. Hreinsdóttir, 2001; Clifton and Kattenhorn, 2006). Chief among these are extensional features, e.g., normal faults, eruptive fissures, and features aligned with the eruptive fissures (Klein et al., 1973). Such features can form above and alongside upwardly propagating dykes, which perturb the prevailing stress-field. The normal faults can have a different surface expression, compared to their orientation at depth (Grant and Kattenhorn, 2004; Einarsson et al., 2020).

During magmatic-mode deformation, all mapped orientations are expected to be activated (not just the fissure-parallel extensional features, e.g., Clifton and Kattenhorn, 2006). This includes the NS strike-slip faults, which are the preferred mode of deformation of the dry mode. Such faults were successively activated in the year 2000, when three M ≥ 5 earthquakes followed seconds after a M 6.6 event over 80 km to the east (Árnadóttir et al., 2004; Clifton and Kattenhorn, 2006). Based on these arguments, observations indicating dry-mode deformation would be seismicity confined mainly on NS strike-slip faults, whereas ample seismic activity on all fault orientations, including features striking parallel to the fissures, would indicate magmatic-mode deformation.

2. DATA AND METHODS

The dataset is comprised of event locations and origin times from the SIL-catalog (1992-2020), obtained using the South Icelandic Lowlands (SIL) network and some stations from the Reykjanet network (Horálek, 2013; Doubravová, 2020). This earthquake catalog is produced at the Icelandic Meteorological Office using automated event detection, followed by manual determination of arrival times of p and s waves, referred to as "picks" by analysts. These picks are used to produce the earthquake locations and origin times using iterative methods described by Böðvarsson et al., (1999). Inherent to earthquake location, is that the accuracy of the horizontal coordinates is better within the network, compared to that of the depth coordinate. However, an accurate depth for the seismicity is of little importance to find features parallel to the fissures. Only off-shore events lay outside of the network, which is why we will not use them when describing fissure parallel features.

We visualize the SIL-catalog events using VisIt (Childs et al., 2012), an open-source visualization platform for which we have produced a custom made work flow. VisIt allows users to query data subsets from a variety of sources, constrained by any of the available values, which simplifies our seismicity analysis. As seismicity is a 4D phenomenon (three spatial dimensions and time), we investigated it as such (Ross et al., 2020), though the presented results are 2D images of 3D views.

3. RESULTS

We first present overviews of the 1970s dry-mode events, the current unrest, and the general seismicity between 1990-2019 exemplified by two active years. Next, we present specific seismicity periods in 3D.

3.1 Seismicity Overviews

Figs. 1-4 show seismicity overviews of the three periods to illuminate the inter-swarm sequences. The sequence in the 1970s (Fig. 1) lasted 4 years and 2 months and had ~50 km of the plate boundary illuminated by 8 swarms (Björnsson et al., 2020). These swarms were intense and short lived (maximum duration ~14 days), with long periods of quiescence in between (~4-10 months), though several swarms were closer in time (~2-15 days in between). The first three swarms occurred in rapid succession and were situated quite far from each other. A large distance also separated the last two swarms. Four consecutive swarms overlapped in their locations between December 1971 and July 1974, which included the swarm affecting the longest plate-boundary segment. This swarm, which occurred in 1973, also included the largest events of the 1970s sequences (M ≥ 5). The last three swarms occurred within the next two years, before the start of a decades-long period of quiescence.

The swarm sequence of the current unrest (Fig. 2) is more rapid, compared to the 1970s swarms, with 12 swarms occurring within 11 months, compared to 8 in 5 years during the 1970s sequence. The recent swarms also last much longer, e.g. near Svartsengi lasting up to ~ 2 months, and switching between regions more often.

Except for the swarm at Krýsuvík starting on March 1st 2020, the activity switched to an adjacent region. Such jumps further aligned into cascades (gray arrows in Fig. 2), in which region activation occurred in succession from east to west, or west to east along the peninsula. At least three such swarm cascades occurred. The initial cascade jumped from Fagradalsfjall (15.Dec.2019), past Svartsengi (22.Jan.2020), to Reykjanes (16.Feb.2020), and had a two-week respite between the first and second swarms. A second, more rapid cascade started in Krýsuvík (01.Mar.2020), skipped most of Fagradalsfjall, and individually activated all other regions up to Eldey (28.Mar.2020). The third cascade started in Reykjanes (06.May.2020), and slowly moved east, ending in Krýsuvík (August 2020). This last cascade included larger segments compared to the first two cascades. The investigated period ends shortly after a M 5.6 event on October 20th in Krýsuvík, the aftershocks of which illuminated a ~50 km long boundary segment, similar to the 1973 swarm in Fig. 1.

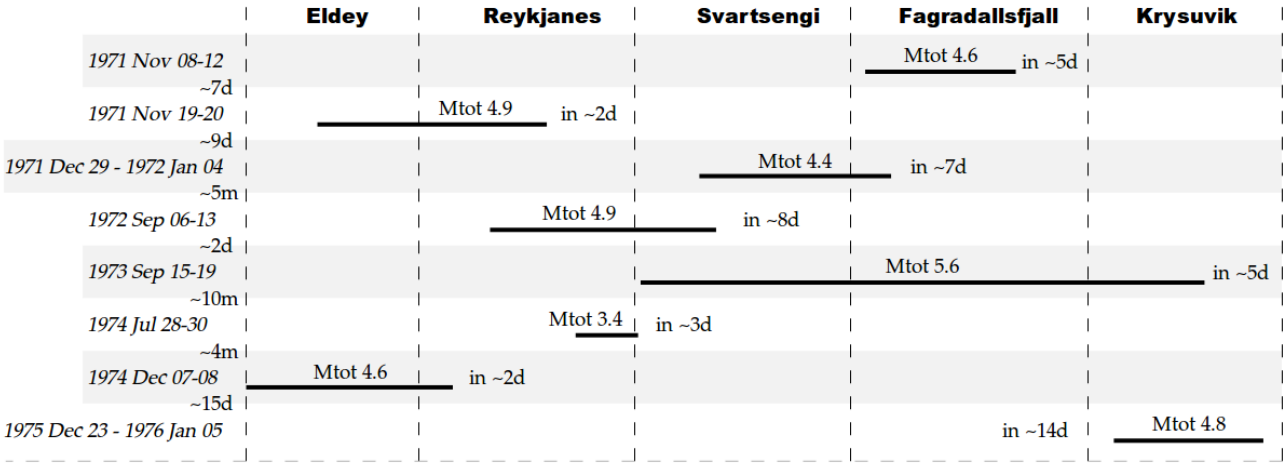

Figure 1: Overview of the 1970s swarms (based on Björnsson et al., 2020). Indicated are: regions at the top, dates and intermission length on the left, and each swarm's east-west width (line), cumulative magnitude (Mtot) and duration.

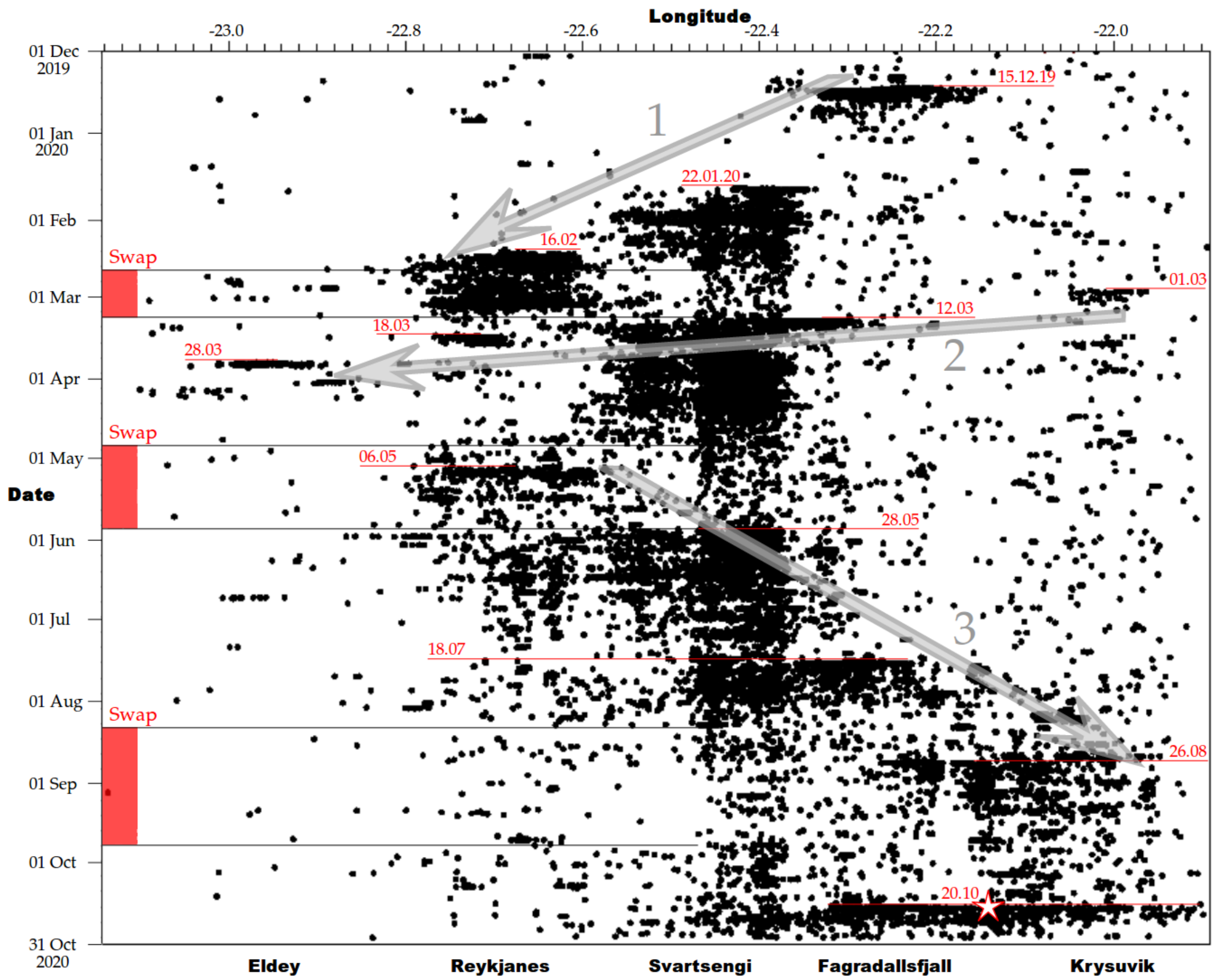

Figure 2: Seismicity distribution for the period of 01.Dec.2019 - 31.Oct.2020 as a function of longitude and time. Indicated are: each swarm's starting date, three inferred swarm cascades (gray arrows), periods where the seismicity "swaps" between Svartsengi and another region (see text for explanation), and the M 5.6 event on 20.Oct.2020 (star).

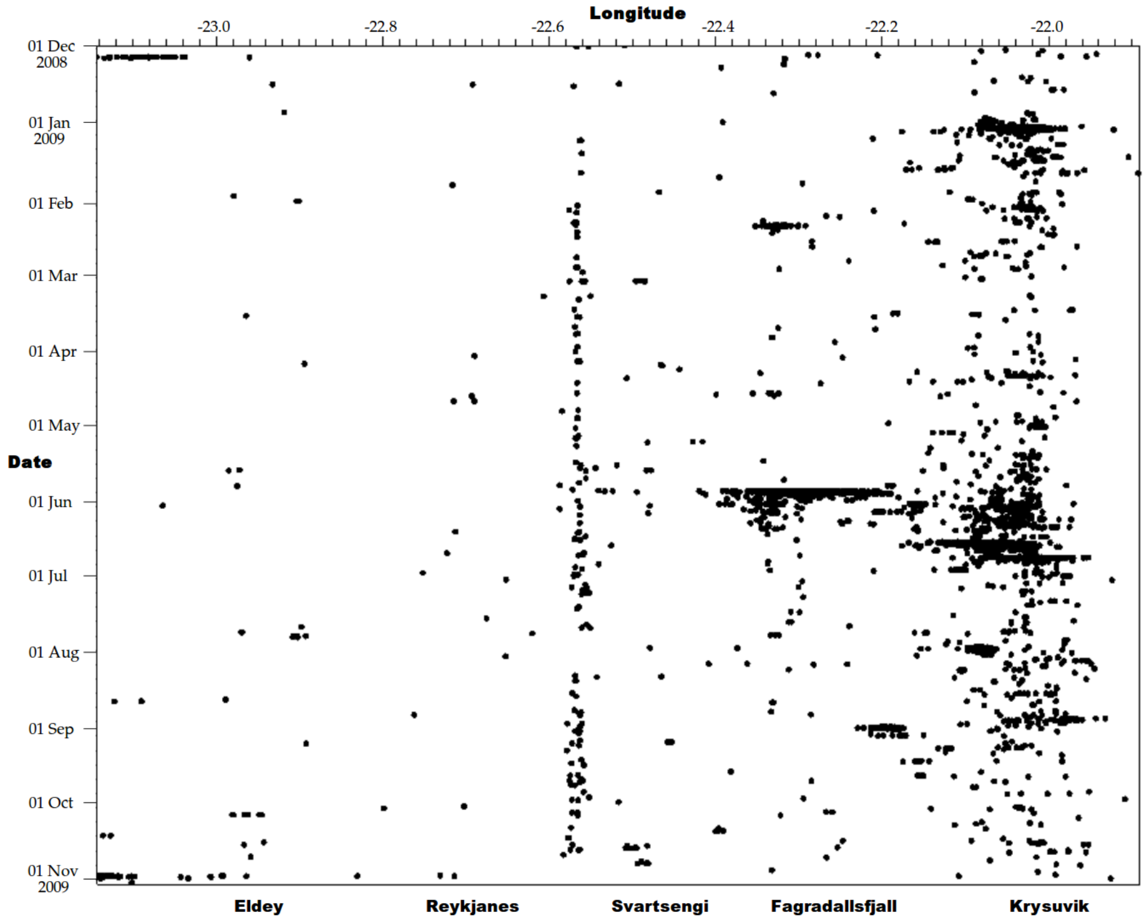

Figure 3: Seismicity distribution as a function of longitude and time between 01.Dec.2008 and 04.Sep.2009.

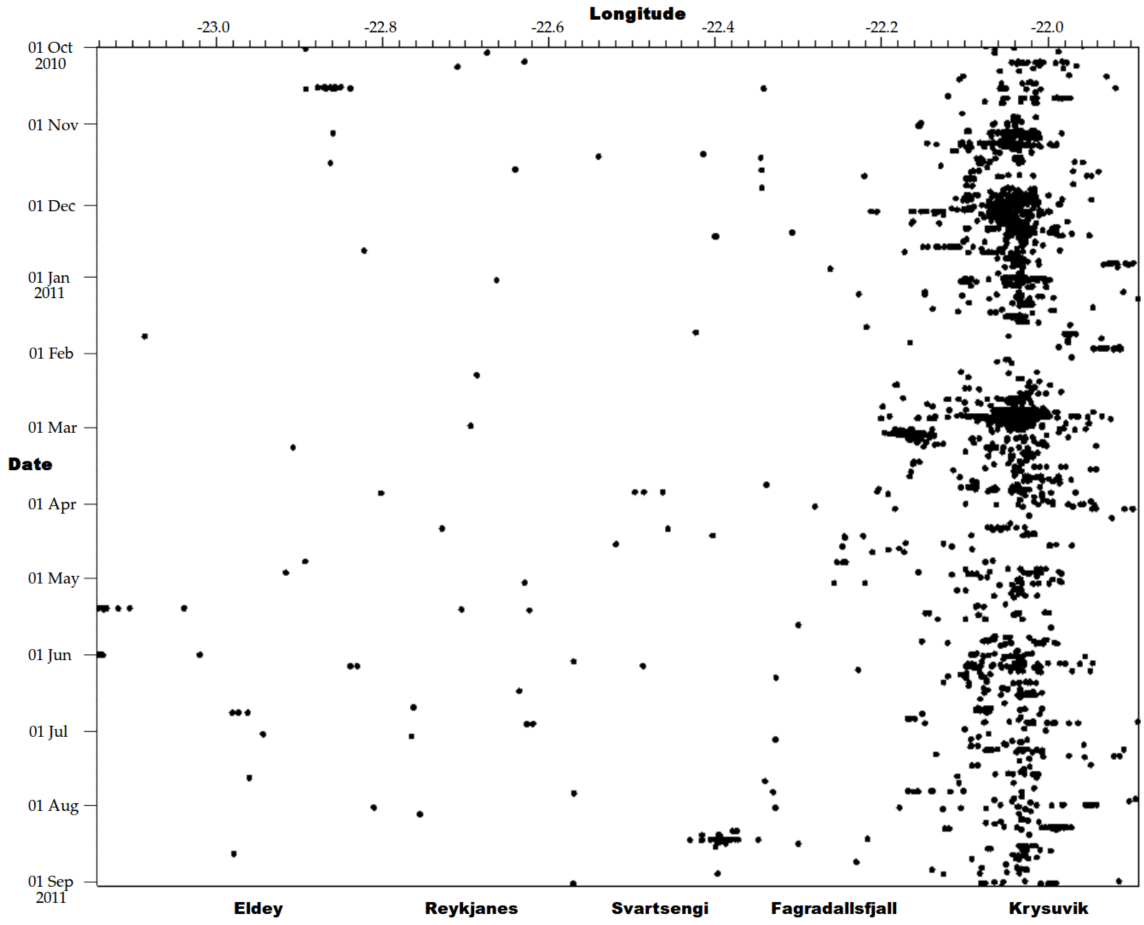

Figure 4: Seismicity distribution as a function of longitude and time between 01.Oct.2010 and 04.Sep.2011.

Next to these cascades, another phenomenon is apparent in Fig. 2 (indicated as “Swap”). Though the Svartsengi region is the most active throughout, its seismicity is often greatly reduced while another area shows more seismicity. The most prominent cases are when: 1) The Reykjanes swarm starts on February 16th 2020. The seismicity returns to Svartsengi on March 12th 2020, along with the largest event (M 4.9) in the region. 2) A Reykjanes swarm starts on May 6th 2020. The seismicity returns to Svartsengi on May 28th 2020, and 3) The Krýsuvík area starts showing more seismicity around August 6th 2020.

Compared to the current unrest, the described cascades are absent during the preceding decades (Figs. 3 and 4 show two representative years), during which seismicity at Svartsengi was low, and Krýsuvík was the most active region. Fewer events occurred in Krýsuvík during the current unrest until August 2020 (Fig. 2). Figs. 3 and 4 further show low seismicity in all other regions, except for periods with swarm activity. The seismicity at -22.57° longitude (Fig. 3) is interpreted as induced due to injection into the Svartsengi geothermal field (Flóvenz et al., 2015).

3.2 Seismicity in 3D

Here we focus on specific seismicity visualization in 3D. We present: an overview of events M > 4 in the last 30 years (Fig. 5), a general overview of the current unrest (Fig. 6), its initial 4 swarms (Fig. 7), and a M 4.9 event on March 12th 2020 (Fig. 8).

In the decades preceding the current unrest, there were 28 events M > 4 occurring in ten periods (blue events in Fig. 5). In contrast, there have so far been seven periods with 11 events M > 4 in the initial 9 months of the current unrest. It is thus not uncommon to have multiple large events on a single day (11 M > 4 in June 2000; Árnadóttir et al., 2004). Interestingly, all large events during the current unrest lie within the boundary-deformation zone, whereas most large events during prior decades (1992-2019) were outside of this zone. Finally, Fig. 5 demonstrates Krýsuvík’s potential for large earthquakes, which the current unrest could still activate.

The seismicity overview of the current unrest (Fig. 6) is similar to that of the 1970s swarms (Fig. 12 in Björnsson et al., 2020). The seismicity is mainly located along the plate boundary and extends from Eldey to Krýsuvík. Two parallel swaths of seismicity occur in Fagradalsfjall with a WSW to ENE strike (bottom left image in Fig. 6). The northern swath connects to the seismicity in the west and ends just before Krýsuvík in the east. The southern swath (discussed in detail below) connects to the seismicity in Krýsuvík through the location of the M 5.6 event on October 20th 2020 (event Q in Fig. 5), and has a seismicity void to the west. Several such voids occur and with large events near their western borders. The majority of the events in the Svartsengi region have low magnitudes, whereas Fagradalsfjall and Krýsuvík generally have larger magnitude events, in comparison.

The initial four swarms of the current unrest (Fig. 7) were clearly spatially separated. The first swarm (Dec. 2019 in Fagradalsfjall) was aligned with the plate boundary, yet lay further south to its assumed center and of the swarms in the prior decades. Those swarms were located within the northern swath in Fig. 6, whereas this first swarm comprises most of that Figure’s southern swath. If swarms in the previous decades identify the plate boundary, then this swarm clearly lies outside of the usual deformation zone. The second swarm (in Svartsengi) was less uniform. It was composed of a distribution of small events, and several structures, aligned either NS or with a strike of ~50°. The third swarm (in Reykjanes) also illuminated an aligned subsurface structure (strike ~45°). This latter alignment is parallel to the fissure swarm in the Reykjanes geothermal field (Fig. 10 of Sæmundsson et al., 2020).

After a short period of quiescence from 8-12 March 2020, a M 4.9 event occurred in Svartsengi (Fig. 8). A few foreshocks occurred near the location of this event, and it was followed by hundreds of smaller events. These events together illuminated a set of conjugate faults, one NS and another ENE, with additional smaller NS faults near the surface. Before this M 4.9 event (L in Fig. 5), the seismicity in Svartsengi had a void on both its east and west flanks. Both flanks were first activated after this M 4.9 event. All seismicity in the Svartsengi region (mostly small magnitudes) seems bounded by the NS structure illuminated here (Fig. 6).

4. DISCUSSION

We have compared the overall seismicity of the current unrest on the Reykjanes Peninsula (RP) with that of the prior decades, and with an overview of a period of dry-mode boundary movements in the 1970s. Additionally, we found specific patterns in the seismicity using 3D visualization. Although this investigation only scratches the surface of what can still be done with this dataset, the results suffice for our questions. They are each discussed in their own sub-Section below.

4.1 Is the Current Unrest Magma Driven?

Evidence for such magmatic activity would be: prolonged surface inflation, volcanic tremors, and/or earthquake swarms propagating along fissure swarms (Einarsson, 2008). Prolonged surface deformation stemming from localized inflationary bodies has been observed above multiple volcanic systems (Svartsengi, Reykjanes, and Krýsuvík) in 2020 (Geirsson et al., 2020), whereas volcanic tremors have not been observed so far (Jónsdóttir, personal communication). Although the Krýsuvík area had swarms distributed over parts of its fissure swarm, none propagated along it.

Additional indications for magmatic-mode deformation would come from extensional structures being activated (Hreinsdóttir et al., 2001; Clifton and Kattenhorn, 2006). As seen in Fig. 7, this is clearly the case, as the seismicity aligns with the extensional fissure swarm in the Reykjanes geothermal field, and because “Pure shear [on the RP] will only occur on faults exactly parallel to the rift axis. Faults striking east or ENE must have some component of extension” (Klein et al., 1973). Seismicity patterns aligned with the fissure swarms would thus additionally indicate activation of extensional structures. Such patterns are also visible in Figs. 6 and 8.

A comparison between Figs. 1-4 shows that the current unrest is different from a period of dry-mode deformation. The prolonged activity in the Reykjanes and Svartsengi systems is unlike the activity seen in Figs. 3 and 4. Magmatic activity would explain this increased and prolonged activity as follows: Magma causes earthquakes directly during intrusion, and indirectly through dry-rock stress-transfer and through existing and/or exsolved fluids destabilizing faults and fractures. Additionally, swarm cascades occurred twice from east to west, followed by a slower cascade from west to east. The second cascade had a rapid succession of swarms, without a reduction in seismicity in Svartsengi. Therefore, we suggest that the great number of swarms in such a short length of time, compared to the 1970s swarms, must be due to magma intrusion that accelerates the boundary deformation.

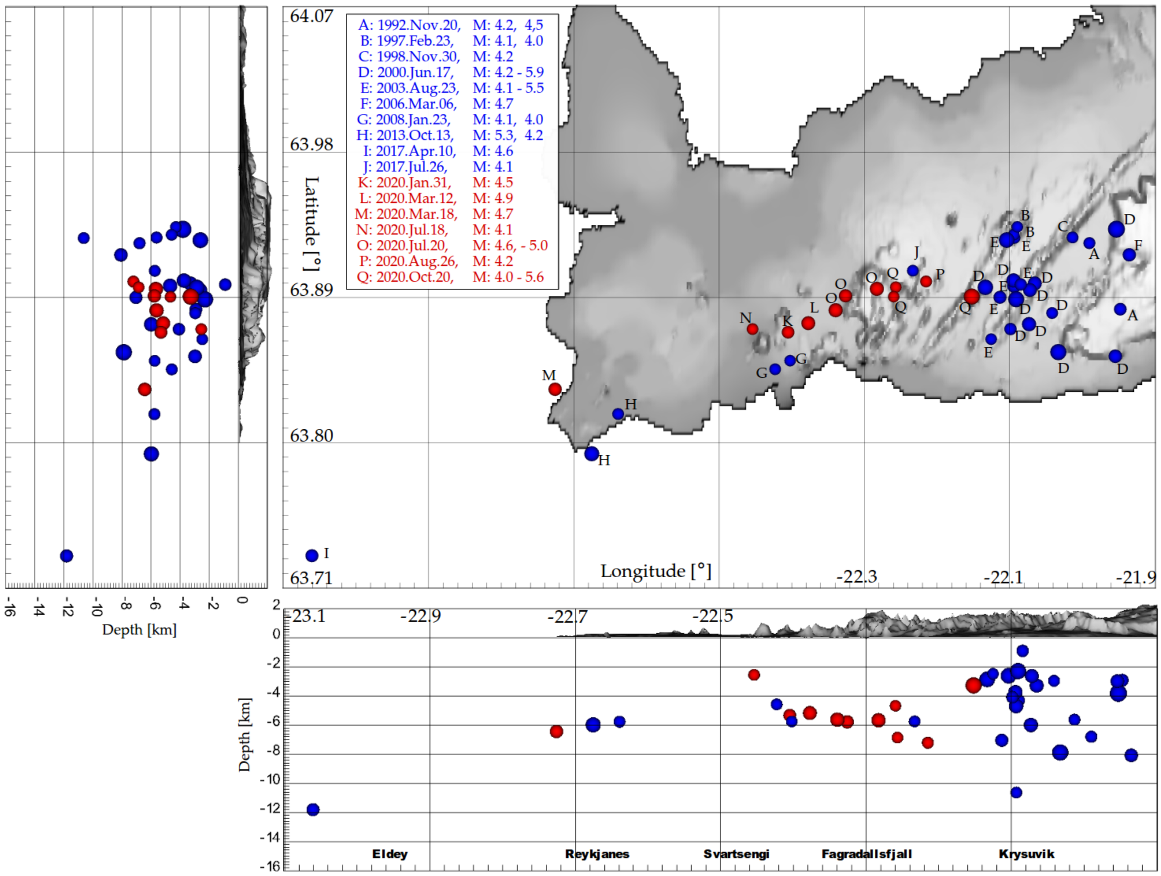

Figure 5: M > 4 events between 1991 and 2020. Blue and red balls show events from before and during the current unrest, respectively. Occurrence dates and magnitudes are shown in the inlay, with magnitude ranges for dates with more than 2 events M > 4. Of these, D had 11, E: 6, O: 3, and Q: 3 events. Topography is exaggerated by a factor of 5.

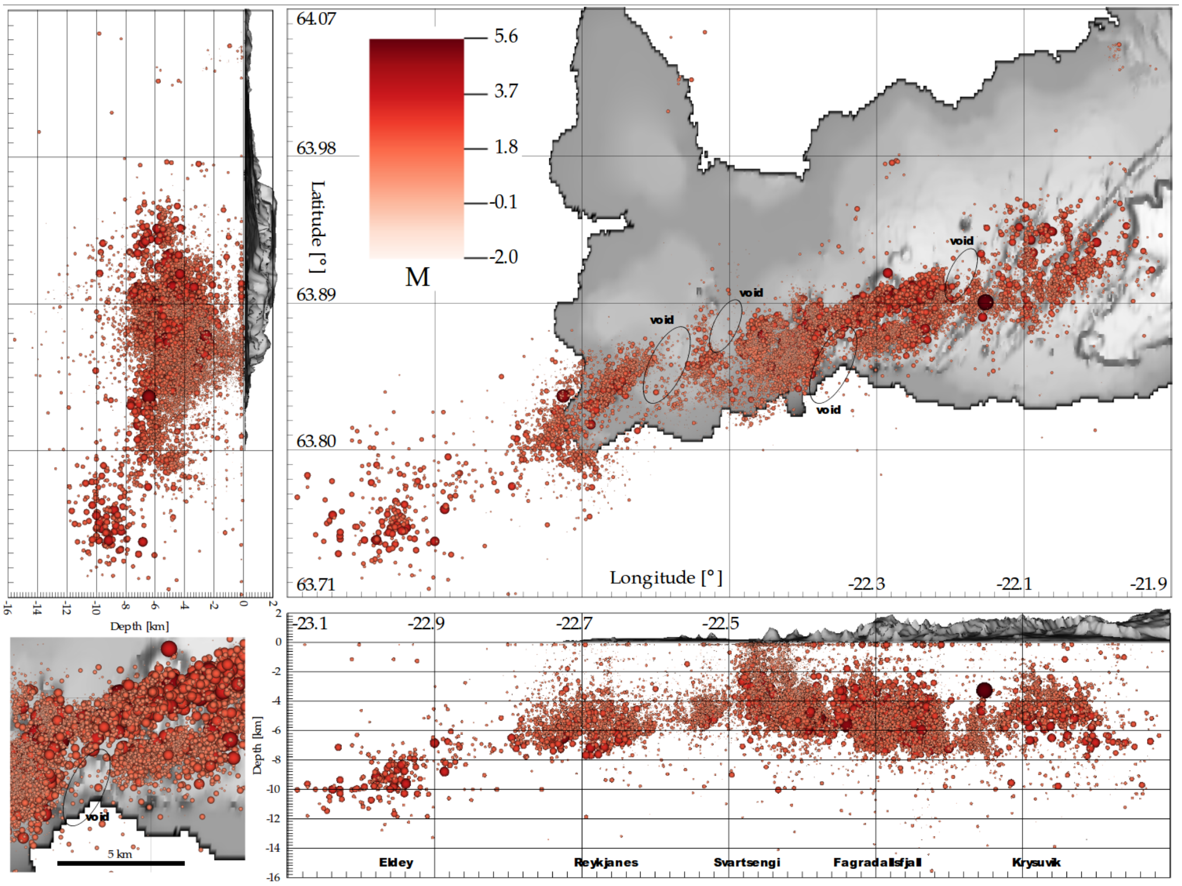

Figure 6: Seismicity overview for the current unrest (01.Dec.2019-31.Oct.20), with seismic voids indicated. Sizes and colors show event magnitudes. The bottom-left image shows a close-up of Fagradalsfjall and Svartsengi.

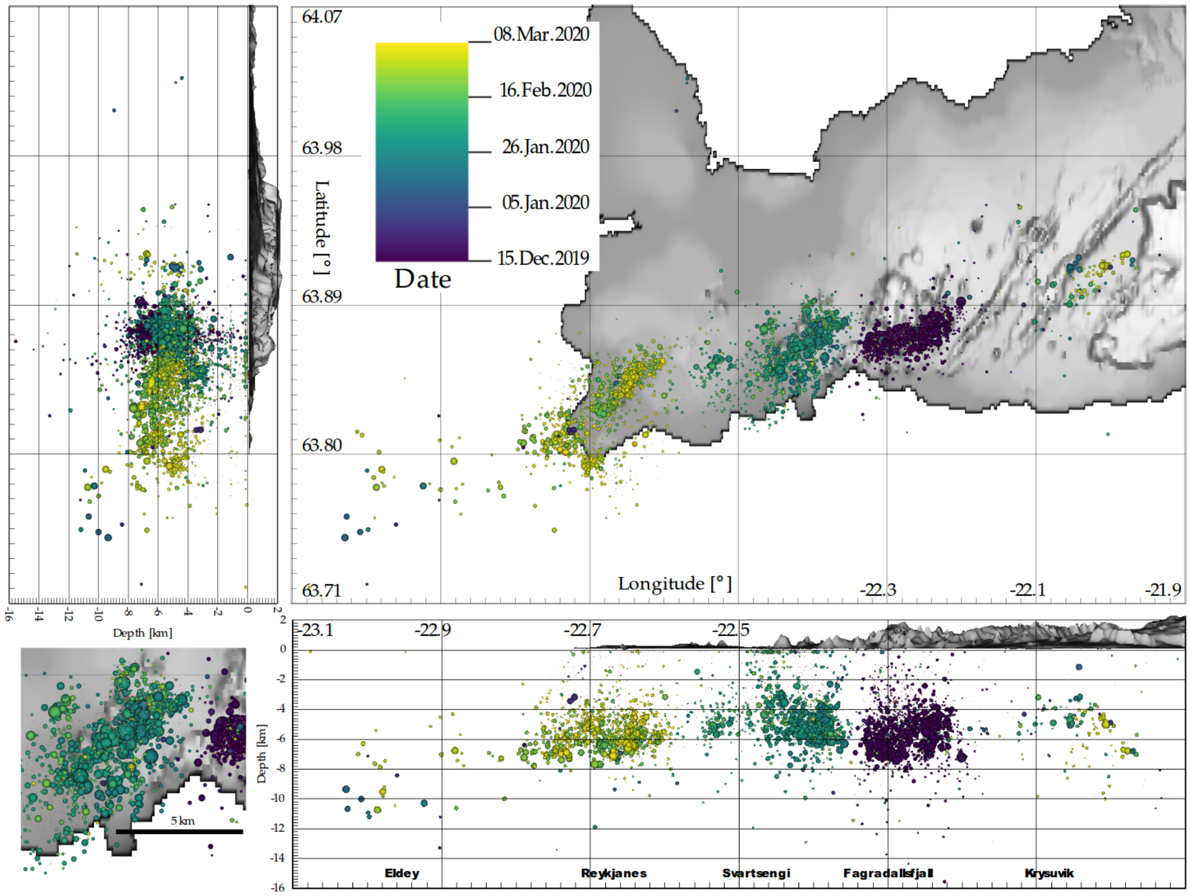

Figure 7: The initial four swarms of the current unrest. Sizes show event magnitude and color shows the occurrence date.

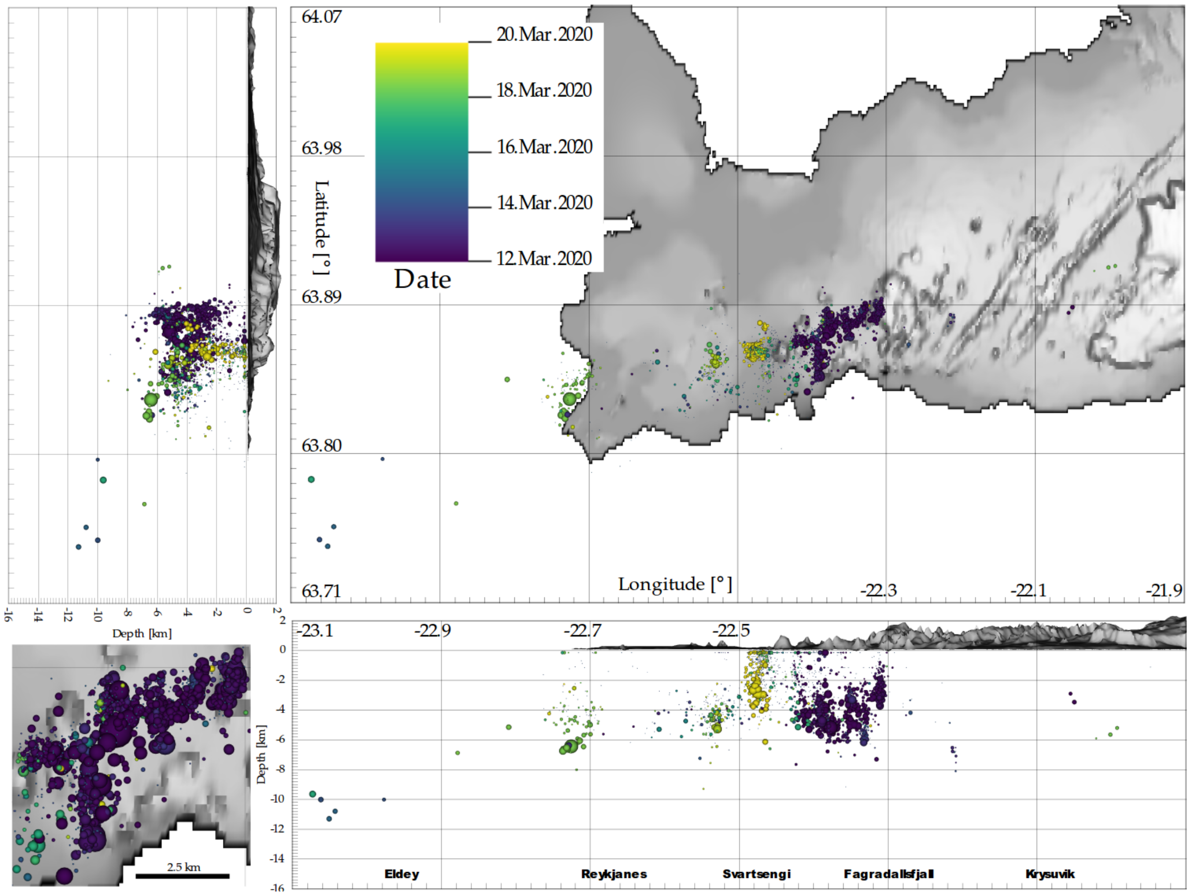

Figure 8: Seismicity from 12-20.Mar.2020. The bottom left image shows a close-up of the events on 12.Mar.2020.

4.2 What can be predicted about its coming evolution?

Though the current unrest involves much more seismicity (Figs 1-4), compared to the 1970s swarms, it could follow a similar pattern. The 1970s swarms exemplify a period of dry-mode movements. These movements were accompanied by seismic swarms on multiple segments, with a ~50 km segment moving at once during a single swarm in 1973. We suggest that similar movements on multiple segments occurred at least three times during the current unrest: 1) Three steps occurred between December 2019 and February 2020. 2) A cascade of four boundary movements took place in quick succession in March 2020 from east to west (Krýsuvík to Eldey). 3) A slower progression of movements jumped from west to east between May and September of 2020. This last cascade had seismic activity on broader segments compared to the first two cascades and ended in the activation of a long segment between Krýsuvík and Svartsengi following the M 5.6 earthquake near Krýsuvík, similar to the 1970s swarms. In that period, the activation of the largest segment marked the beginning of the unrest's end, which occurred after a few more, smaller swarms. The RP was seismically quiescent for the next few decades (Björnsson et al., 2020). This could be how the current unrest ends. In which case, large events on known faults in and just east of Krýsuvík will likely still occur. (Fig. 5; Fig. 7 in Clifton and Kattenhorn, 2006; Einarsson et al., 2020). If this is the case, lesser activity with a few swarms could continue for another 2 years before the unrest ends.

The magmatic nature of the current unrest could alter this future progression significantly. The following are three scenarios of one possible continuum. The order moves from a benign end member through an intermediate case to the other extreme: Scenario A) It has been suggested that deformation and seismicity associated with magma movements damages and weakens the host rock (Carrier et al., 2015). Here we speculate that crustal weakening due to the magmatically "induced" seismicity has accelerated the time line of boundary movements compared to the 1970s example. This crustal weakening may additionally have allowed a more rapid dissipation of 1) stresses, 2) secondary effects (e.g. redistribution of crustal fluids, fracture healing, and changes to fluid reservoir properties), and 3) higher-order effects (e.g. dissolution and precipitation of minerals as [changed] fluids [re-]equilibrate with their [changed] surroundings). In this scenario, the dissipation of seismic activity could be much more rapid and the RP could see a longer period of quiescence rather soon, because the stresses would need to build up again to reach levels required for large events.

Scenario B) Magma continues to intrude underneath the RP in a similar manner to what has occurred so far. This scenario has magma intrude slowly enough for the system to accommodate such intrusions without leading to an eruption. This could, e.g., be accommodated by the following mechanism: The difference in strength between the host rock and intrusions of the RP makes it more likely that new intrusions are emplaced below older ones (Gudmundsson, 2011; Barnett and Gudmundsson, 2014). This scenario thus requires that magma intrusion does not occur in the same place, or in sufficient amounts in the same place as not to overcome the failure criterion of the host rock (Sigmundsson et al., 2020).

Scenario C) Rapid and continuous influx of magma could use the overall crustal weakening to make a path towards the surface, or produce one by overcoming the failure criterion of the host rock (Sigmundsson et al., 2020). Though it is unclear at this time if an eruption is underway, the three signals described above (inflation, volcanic tremor, and propagating swarms) would provide some advance notice (minutes to weeks), if the current unrest evolves into a large-scale eruption (Einarsson, 2018).

4.3 New insights into dry and magmatic mode boundary movements

The first period of surface deformation occurred where two boundary segments with different obliquity meet (e.g. Hreinsdóttir et al., 2001). We suggest that this juncture (in Svartsengi) represents a path of least resistance for magma to intrude. This is probably connected to the observation that the seismicity in Svartsengi lowers when another region is active (Fig. 2). We suggest that there must be one or more mechanisms that stopped magma intruding in the shallow crust in Svartsengi, whilst magma intruded in Reykjanes. The following are preliminary hypotheses: 1) The source region's over-pressure found a path towards Reykjanes, thus removing the pressure feeding the intrusion in Svartsengi. 2) As the intrusion in Svartsengi grew, the pressure along its feeder increased, which pushed open a path to another region. 3) Stress transfer along the plate boundary created an unfavorable stress regime in Svartsengi which halted intrusion. 4) An over pressure in hypothesis 3 could lead to the cases in hypotheses 1 or 2. Hypothesis 2 is unlikely, as this scenario would have been accompanied with seismicity moving from Svartsengi to Reykjanes, which is absent from Figs. 6-8. Hypotheses 1, 3, and 4 require further investigation beyond the scope of this work.

The current unrest has seen magma intrusions changing the stress regime, which led to increased seismicity. This increase was concentrated in pockets, adjacent to seismicity voids . Both provide insight into existing and newly formed subsurface structures and prevailing stress distributions before and during the current unrest. Fig. 8 shows the example of a NS fault structure which seems to contain the southern seismicity in the Svartsengi region. The adjacent seismicity void is clearly visible in Fig. 6.

Certain seismically quiescent areas (Figs. 6-8) seem to require a big event to move (the east of Svartsengi on March 12th 2020, Fagradalsfjall on July 19th 2020, and especially the west of Krýsuvík on October 20th 2020). This could indicate these segments of the boundary are locked, i.e., requiring catastrophic failure to move, without the possibility of releasing stress in smaller magnitude seismicity. Brennisteinsfjöll (just east of Krýsuvík) is the next obvious candidate for an area which may require catastrophic failure. This area has not had significant activity for decades and has historically housed the largest events on the RP. Brennisteinsfjöll is also the most likely area to be the first to erupt, based on the previous three eruptive cycles (Fig. 3 in Sæmundsson et al., 2020).

Both dry and wet modes seem to prefer boundary movements to occur on smaller segments from east to west (Figs. 1 and 2). Movement on a larger segment seems to be preceded in both modes by a crustal weakening on smaller segments. This weakening occurred in a slower cascade in the opposite direction, during the current unrest, which we suggest prepared the boundary in front of the stuck region in Krýsuvík. The activation of this region released enough energy to then activate a ~50 km boundary segment.

Further investigations into these described mechanisms, and the current unrest in general, using, e.g., focal mechanisms (e.g. Keiding et al., 2009), analogue models (e.g. Whitjack and Jamison 1986; Clifton and Schlische 2003), and numerical modelling (e.g. Barnett and Gudmundsson, 2014; Duclaux et al., 2020), should further enhance our understanding of boundary deformation on the RP.

4.4 Impacts on existing and upcoming fields and power plants

The local power plants have been built with the area's activity in mind. Therefore, a M 6 event would be an inconvenience and not necessarily the end of production. The largest risk of such large events would be to the distribution to the customers and to the costumers themselves. These risks would then feed back to the power plant. Effusive eruptions would pose larger problems, as the Svartsengi and Reykjanes power plants are built on lavas, as are parts of Reykjavik (Einarsson, 2019a,b; Sigurgeirsson and Einarsson, 2019). The most expensive and vulnerable infrastructure would be: 1) The wells, 2) the pipes leading to the power plant, 3) the turbines in the power plant , and 4) buildings and roads. These could also all be dissected by surface faulting associated with dyke propagation.

New magma could heat up existing reservoirs directly, or become a new target for exploration. The weakening of the crust and redistribution of fluids could have, and may still 1) bring hot material and increased pressures to existing reservoirs, 2) remove hot material and reduce pressure in existing reservoirs, and/or 3) swap fluids between reservoirs at different depths (Geoffroy and Dorbath, 2008). This last scenario could have a similar effect to the first, though the overall systemic effects could differ greatly between the scenarios. The development of new fields may, therefore, suffer from needing to re-explore, because of this possible redistribution of fluids, and because of new opportunities in the form of shallow intrusions.

The seismicity indicates that a large fracture network (e.g. Hobé et al., 2018) has been created, with or without existing fluids, in this high-enthalpy region. This would also be a prime target for a possible Enhanced Geothermal System. The temporal availability of this network could however be limited due to fracture healing (Hobé et al., 2021).

4.5 Takeaways for power projects in other areas

The RP is not the only oblique rift with geothermal power plants. The East-African Rift System (EARS) is another example, which we will use to demonstrate how these analyses could translate to oblique rifts in general. The volcano-tectonic processes described here could translate directly to the EARS, even though the crustal structure is different (Agostini, et al., 2011; Sani et al., 2019). Like on the RP, intrusion of magma into the EARS would fundamentally alter the stress regime. This in turn would activate and/or create structures in a different way compared to dry-mode movements, again, leading to seismicity concentrations and voids based on the prevailing stresses and subsurface structures. Because the geometry of EARS is complex with adjacent segments with different obliquity, these areas could be a path of least resistance where magmatic-mode processes could commence. The placement of a power plant could thus become an optimization problem between where seismicity tends to concentrate and where there tends to be a seismicity void. On the RP, the latter is between bigger faults with the potential for large earthquakes.

Any processes that produce a large number of earthquakes could prove both beneficial and detrimental for power plants in general. The creation of a fracture network could both drain an existing reservoir and become a new potential reservoir. The risk and opportunities of such positive and negative "black swan" events, i.e., events with low probability and high impact (Taleb, 2007; Knoblauch et al., 2018), would require careful study. Without such study it would be unclear if a "reservoir-draining" event should be part of a power plant's risk assessment and strategy. Such study would especially be required to prepare for an unexpected reservoir creation, because fracture healing could limit the time window in which its exploitation would have to start.

5. CONCLUSIONS

We investigated the seismicity of the current unrest on the Reykjanes Peninsula (RP), using 3D visualization and by comparing seismicity overviews of the current unrest, with that in preceding decades, and with a period of dry-mode deformation in the 1970s. Based on the argumentations above we conclude that:

- The seismicity patterns of extensional features (parallel to a fissure), when added to existing observations, identify the current unrest on the RP as a period of magmatic-mode deformation.
- The pattern of seismic activity diminishing in one field while increasing in another, we suggest is indicative of magma intrusion halting in the former system while starting in the latter.
- The plate boundary seems to prefer moving in cascades from east to west, and crustal weakening, which occurred in a slower cascade from west to east during the current unrest, seems to prepare for a ~50 km boundary segment to move.
- There are at least four possible scenarios for the upcoming evolution of this unrest. They range from a rapid return to quiescence due to the wide-spread weakening of the crust, to the eruption of one or more fissure swarms. Which one will occur is unclear at this time, though it is more likely that the unrest will continue for a considerable length of time.
- Whichever scenario occurs, M 6 earthquakes on large faults near Reykjavik are likely.
- We suggest that the analyses of this period can be transferred to the East-African Rift System and oblique rifts in general. In summary: we suggest a path of least resistance for the commencement of magma intrusion where two levels of obliquity meet, that seismicity concentrations and voids would behave in a similar way, and that these will prove to be powerful indications of prevailing stress regimes and subsurface structures.
- These seismicity concentrations and voids pose several risks and opportunities for geothermal power plants, namely, draining of existing reservoirs and creation of new potential reservoirs, as well as placement criteria for new power plants.

The current unrest on the RP has provided, and will continue to provide us with massive datasets, of which seismicity is only one. The insights above are only a glimpse into what we might learn from this period.

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