

**Hydrothermal vent fluid perturbations related to seismic activity at Axial Seamount,**

**Juan de Fuca Ridge**

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## **Abstract**

Mid-ocean ridges are dynamic environments that transfer the largest amount of heat and chemicals from the Earth's lithosphere to the hydrosphere. Continuous observations of the changes in mid-ocean ridge environments over long time scales are difficult. Axial Seamount is located on the southern part of the Juan de Fuca Ridge and experiences frequent volcanism and seismicity with past eruptions occurring in 1998, 2011, and 2015. To better understand mid-ocean ridge processes, a wide assortment of instruments are deployed across the Axial Seamount caldera as part of the Ocean Observatories Initiative. These instruments continuously measure seismic and hydrothermal vent field activity including: (1) the hypocenter and moment magnitude of each seismic event (2) hydrothermal vent fluid temperature and chloride concentration from a chimney located in the southern part of the caldera. This study explores the correlation between seismic events and temporal changes in temperature and chloride concentration of hydrothermal vent fluid. Results suggest that there is a long-term correlation between an increase in frequency of seismic events and an increase in hydrothermal vent fluid temperature at this location. This may be signaling more contact between circulating hydrothermal fluids and magma. Increased magma supply and increasing seismicity may indicate that the next eruption of Axial Seamount will experience lava flows in the southern part of the caldera, similar to 1998 and 2011. Further monitoring of the hydrothermal vent fluids before, during, and after the next eruption could provide more insight into the link between hydrothermal vent field activity, earthquakes, and volcanism.

## **Plain Language Summary**

Mid-ocean ridges are seafloor environments of constant activity where the Earth's tectonic plates are being pulled apart which allows magma to rise to the surface of the seafloor. These regions are characterized by frequent volcanic eruptions and earthquakes. Cracks in the crust from earthquakes allow seawater to flow through the crust where it can come into contact with magma. This heats the seawater and turns it into a high temperature fluid that rises to the surface where it discharges into the ocean. This process, known as hydrothermal circulation, plays a role in controlling the ocean's concentration of many elements that are involved in supporting life. Axial Seamount is an underwater volcano located on the southern part of the Juan de Fuca (mid-ocean) Ridge. Scientific instruments measure earthquakes and the fluid being discharged from hydrothermal circulation at this location. This study investigates whether earthquakes cause changes to hydrothermal fluid. The results suggest that there is a correlation between the frequency of earthquakes and an increase in temperature of hydrothermal fluid at this location. These results are unique in that the increase in temperature occurs over a period of multiple years during which earthquake frequency is increasing. This may suggest that hydrothermal circulation is strongly related to earthquakes and volcanism at this location. Future monitoring of these hydrothermal vent fluids before, during, and after the next volcanic eruption could provide even more insight into this link.

## Introduction

The lithosphere at mid-ocean ridges is in constant extension which creates sea floor spreading centers. About 75% of the magmatism on Earth occurs at these spreading centers (Crisp 1984), which are actively producing new oceanic crust. These regions experience volcanism and seismicity as magma rises due to decompression melting at the divergent boundary. Mid-ocean ridge processes operate on geologic time scales but can be characterized by frequent short-term volcanic and tectonic events (Kelley et al. 2014). However, continuous observations of the changes in mid-ocean ridge environments over long time scales are rare due to the fact that these locations are difficult and expensive to access. Therefore, knowledge of the linkage between mid-ocean ridge volcanic and seismic processes and hydrothermal vents is limited.

The tectonic and volcanic processes that occur at mid-ocean ridges create fissures allowing seawater to flow down through the lithosphere. When this water comes in contact with magma, it is heated and circulated back to the seafloor where it discharges from vent structures. The process, known as hydrothermal circulation, accounts for 34% of the global heat flux from the lithosphere to the hydrosphere (Stein and Stein 1994). The amount of heat flux,  $H$ , during hydrothermal circulation can be calculated by using the equation  $H=QT$ , where  $T$  is the difference in temperature between seawater and hydrothermal fluid and  $Q$  is the volume flux (Johnson et al. 2000). If the volume flux and temperature of seawater is assumed to be constant, changes in hydrothermal fluid temperature can be used as a proxy for heat flux.

Hydrothermal fluid circulating within the lithosphere can be heated above the boiling point, causing phase separation. This process results in one phase that is dense and enriched in chloride and one phase that is less dense and enriched in dissolved gases. Concentrations of

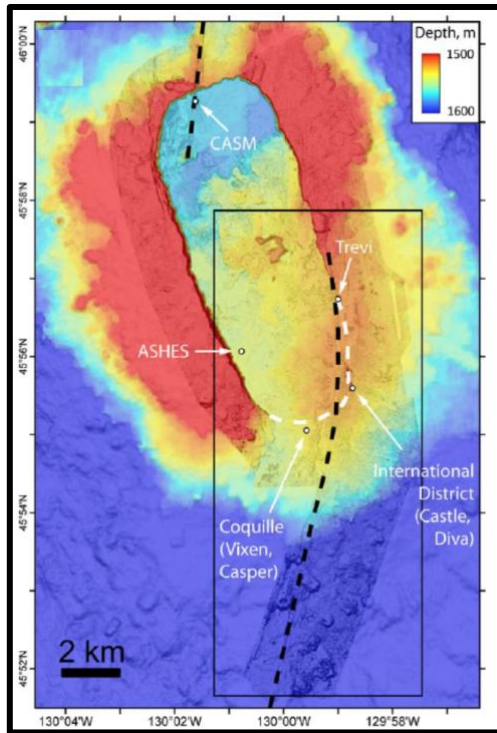
major elements are well correlated with chlorinity, and dissolved gas concentrations in the lowest chlorinity fluids are approximately twice as high as in the highest chlorinity fluids (Butterfield et al. 1994). Hydrothermal vent fluids contain concentrations of dissolved gases such as CO<sub>2</sub> that are most often an order of magnitude greater than seawater (German and Von Damm 2004). Perturbations to the discharge of hydrothermal fluids can be monitored by recording the temperature and chloride concentration over time. Changes in chloride concentrations can indicate varying levels of phase separation which can be related to changes in temperature. Therefore, hydrothermal vent fluid temperature changes have been observed to be coupled with changes in chloride concentration (Larson et al. 2007).

Previous studies have associated earthquake sequences with changes in vent fluid temperature of high temperature hydrothermal systems (Sohn et al. 1998; Dziak et al. 2003) and low temperature hydrothermal systems (Johnson et al. 2001). Connections between seismicity and hydrothermal vent systems have also been made through observations of variations in vent flow rate that correspond to earthquake swarms (Crone et al. 2010). From June 1 to June 7, 2000, 170 earthquakes were recorded on the Blanco Transform fault adjacent to the southernmost portion of the Juan de Fuca Ridge. Two temperature probes were deployed in chimneys at the Vent1 and Plume hydrothermal fields along the southern portion of Juan de Fuca Ridge. The probe at Vent1 recorded a temperature decrease of 3.1°C about 17 days before the swarm started, a decrease of 3°C during the swarm, and an 18°C decrease 10 days after the swarm before leveling off (Dziak et al. 2003). The probe at Plume recorded a decrease of 4.9°C following the mainshock, an increase of 2.9°C for 3 days and then a decrease of 2.8°C during the next 18 days. The Plume record also showed rapid decreases in temperature ranging two hours to 13 days following small seismic events outside the time frame of the earthquake swarm. The authors

proposed that a regional stress reduction caused by the mainshock of  $M_w$  6.2 led to an increased permeability of the crust which increased the mass flow rate of the hydrothermal system. They suggested that if no new heat sources were added, the flux rate should increase as a result of the permeability increase which decreases fluid temperature based on Germanovich et al. (2001). A mechanism proposed for the coseismic decrease in temperature observed at Plume was the removal of solid precipitate blocking the fluid-flow pathways of the hydrothermal system which would rapidly change the flow rate causing a sudden decrease in temperature.

Within a 3-hour period on March 22, 1995, a swarm of 162 earthquakes were recorded on the East Pacific Rise crest. The fluid temperatures of Bio9 vent were stable at about  $365^\circ\text{C}$  for about a year before the event (Sohn et al. 1998). Four days after the swarm, vent fluid temperatures increased by  $1^\circ\text{C}$  for the next 7 days and peaked at  $373^\circ\text{C}$ . After this period, the fluid temperatures gradually decreased to pre-swarm levels over the next 70 days. Following the leveling off of this decrease, the Bio9 vent fluids began a period of steady increase reaching  $373^\circ\text{C}$  by the end of 1997. The authors suggested that the vent fluid temperature anomalies observed after the swarm indicated that new fractures in the crust allowed circulating fluids to penetrate fresh rock and possibly reach fluids that had been previously isolated. The study demonstrated that this hydrothermal vent system is a dynamic convection system that responds quickly to seismic perturbations.

Axial Seamount is located on the southern part of the Juan de Fuca Ridge off the coast of Oregon. Axial Seamount has frequent volcanism with past eruptions occurring in 1998, 2011, and 2015. Lavas from the 1998 eruption were observed to have erupted over approximately 9 km of the upper portion of the south rift zone (Figure 1).



**Figure 1.** Axial Seamount Caldera. The black dotted line in the bottom and middle portion of the figure is the south rift zone. The black dotted line in the top portion of the figure is the north rift zone. The white dotted line is the caldera fault. Taken from Chadwick et al. 2013.

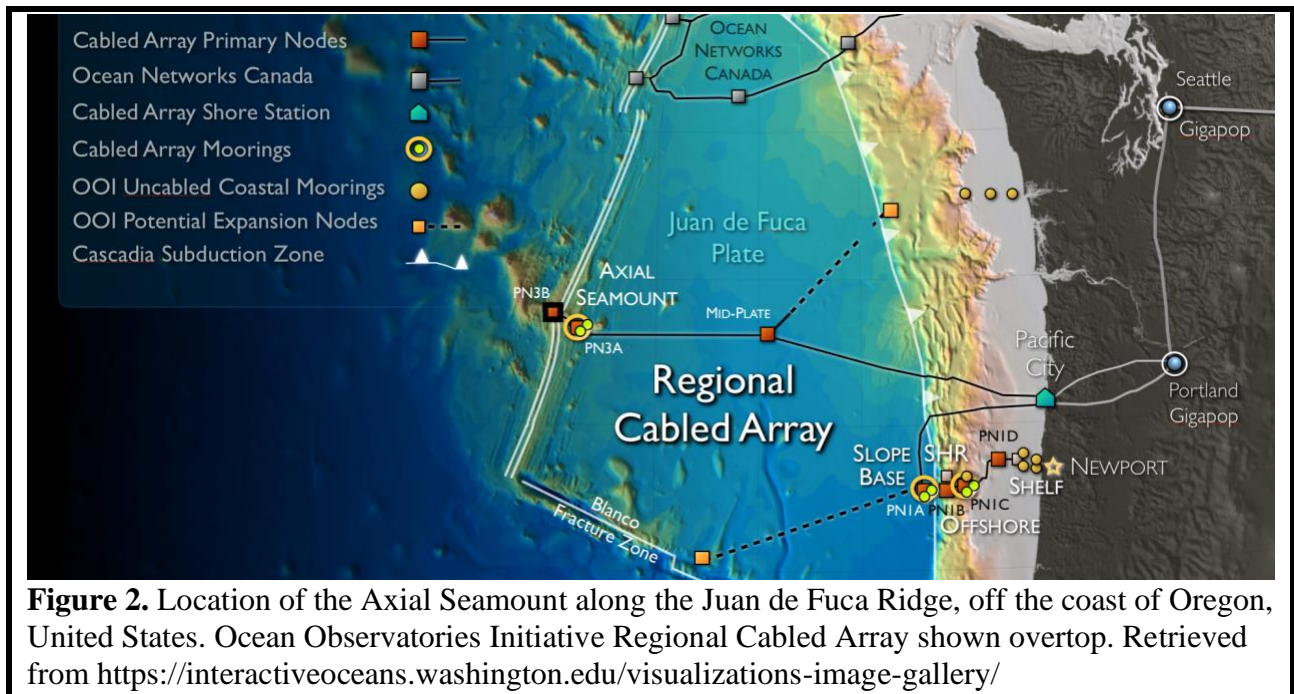
In 2011, the second recorded eruption occurred in a similar location as in 1998, using many of the same eruptive fissures (Chadwick et al. 2013). About 58% of the area of the 1998 lava flows is now covered with lava from the 2011 eruption. The 2015 eruption was mapped to have erupted from 13 fissures, over a distance of 19 km. All the 2015 lava flows occurred north of the 1998

and 2011 flows and progressed northwards along the eastern caldera wall eventually reaching the north rift zone (Figure 1). Extensive seismic activity and inflation of the seamount were recorded by in situ scientific instruments (Wilcock et al. 2016). However, the 2015 eruption lava flows and seismic activity were north of the hydrothermal vent fields that had instruments installed in them.

I hypothesize that a correlation exists between seismic events at Axial Seamount and temporal changes in temperature and chloride concentration of the hydrothermal vent fluid that is discharged at this location. The data used were collected from January 2015 through June 2020 at the International District Hydrothermal Vent Field located in the southeastern part of the Axial Seamount Caldera. The goal of this study is to improve the understanding of possible mechanisms that can change the exchange of heat and chemicals between the lithosphere and the hydrosphere during hydrothermal vent field activity.

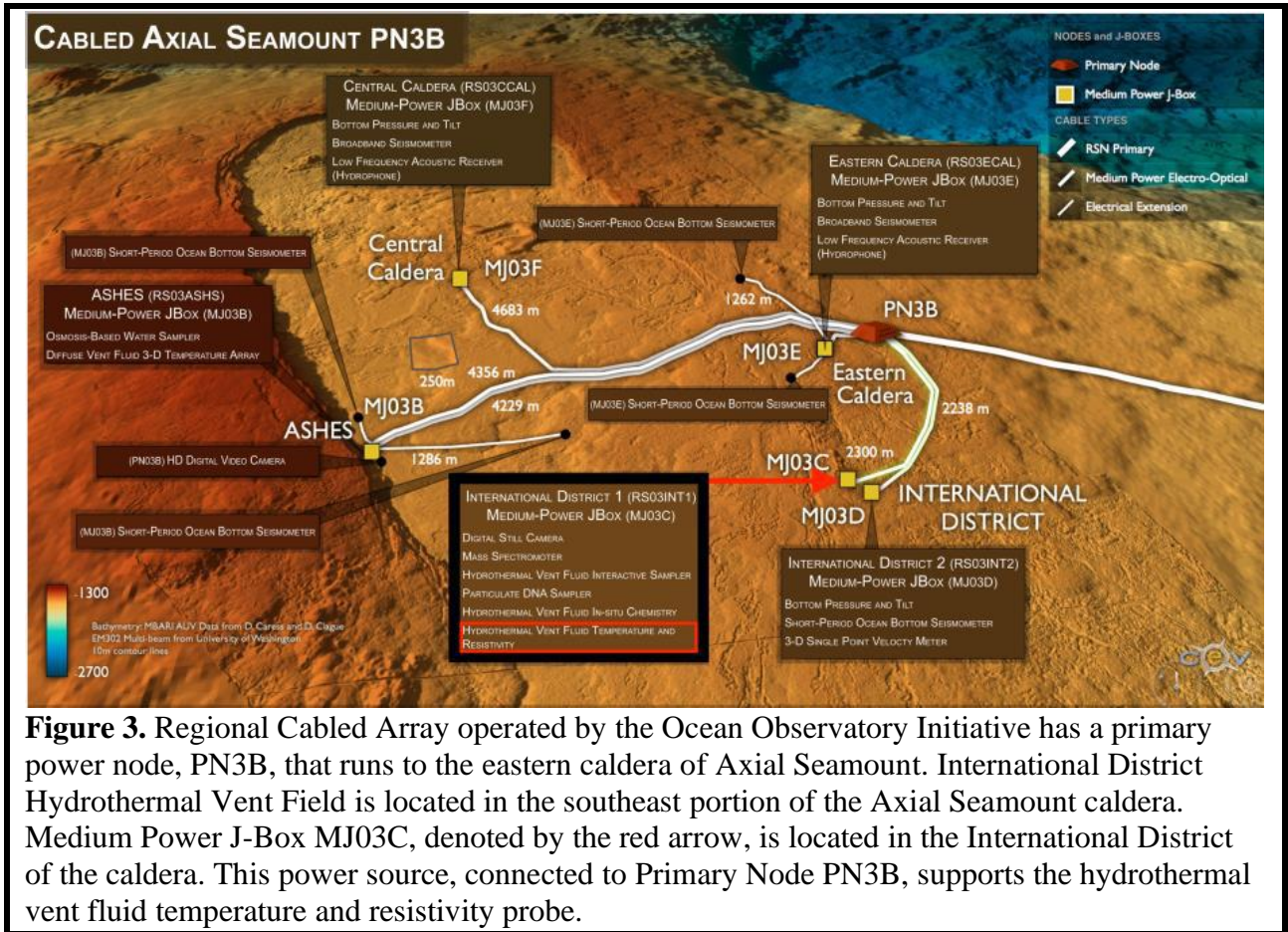
## Methods

The data were collected by the Ocean Observatories Initiative Regional Cabled Array which provides power for scientific instruments along the Cascadia Subduction Zone and the Juan de Fuca Ridge. Cables extending across the Juan de Fuca Plate connect to two primary power nodes at the eastern base of Axial Seamount and in the caldera of Axial Seamount (Figure 2).



The seismic data were collected by seismometers that make up a seismic network in the Axial Seamount caldera (Figure 3). The temperature and resistivity data were collected by a probe instrument installed on the Escargot sulfide chimney structure in the International District Hydrothermal Vent Field (Figure 4). The temperature and resistivity probe was designed for a study at the Main Endeavour Field on the northern portion Juan de Fuca Ridge by Larson et al. (2007). The probe design was further developed to be included as a permanent instrument of the Regional Cabled Array. Before deployment, the probe is calibrated under simulated

hydrothermal conditions of up to 380°C temperature and 300 bar pressure. With the exception of 2018, the instrument has been serviced and then redeployed each summer since its original installation in September 2014. This annual maintenance of the probe instrument causes gaps in the data that are about a day long in 2015 and 2016, about a week long in 2017, and approximately two months long in 2019.



**Figure 3.** Regional Cabled Array operated by the Ocean Observatory Initiative has a primary power node, PN3B, that runs to the eastern caldera of Axial Seamount. International District Hydrothermal Vent Field is located in the southeast portion of the Axial Seamount caldera. Medium Power J-Box MJ03C, denoted by the red arrow, is located in the International District of the caldera. This power source, connected to Primary Node PN3B, supports the hydrothermal vent fluid temperature and resistivity probe.

Seismic data were obtained from the Axial Seamount Earthquake Catalog (<http://axial.ocean.washington.edu>, Wilcock et al. 2016, 2017). The catalog provides real time earthquake detections, locations, and moment magnitudes. Earthquake events occurring within 1 km of the International District Hydrothermal Field were selected for the analysis. Vent fluid

temperature and chloride concentration (from resistivity) data were obtained from the OOI Data Explorer (<https://dataexplorer.oceanobservatories.org/#metadata/104335/station/2004/sensor/data>, <https://dataexplorer.oceanobservatories.org/#metadata/104335/station/2005/sensor/data>). The chloride concentration data were downloaded as a weekly mean to eliminate outliers due to instrumentation malfunctions.



**Figure 4.** The temperature and resistivity probe embedded in the Escargot hydrothermal chimney (in the International District Hydrothermal Vent Field) at a depth of 1520 m. The probe was developed for the Regional Cabled Array by Dr. Marv Lilley of the University of Washington. It was installed in September 2014. Image retrieved from: <https://interactiveoceans.washington.edu/instruments/resistivity-temperature-probe/>

All data were analyzed using Python software. X-Y plots were made of the cumulative moment sum of earthquakes over time, temperature over time, and chloride concentration over time. Histograms were made of the number of earthquakes per day. The earthquake catalog data were loaded into python in csv file type while the temperature and chloride concentration data were loaded into python in netCDF format. The data were manipulated using the numpy, pandas,

datetime, and netCDF4 packages. The matplotlib.pyplot and matplotlib.dates packages were used to create the X-Y plots and histogram plots. Cumulative seismic moment, vent fluid temperature, and vent fluid chloride concentration were made as X-Y plots over time. Histogram plots were created to display earthquake counts per day. First, plots were made for each of the four variables over the entire time series from January 2015 through June 2020. Long-term correlations, detected from the overall time series plots, were analyzed with plots in intervals of multiple years. To detect short-term correlations, plots of each variable were made every three months with a one month overlap for the entire time series.

## **Results**

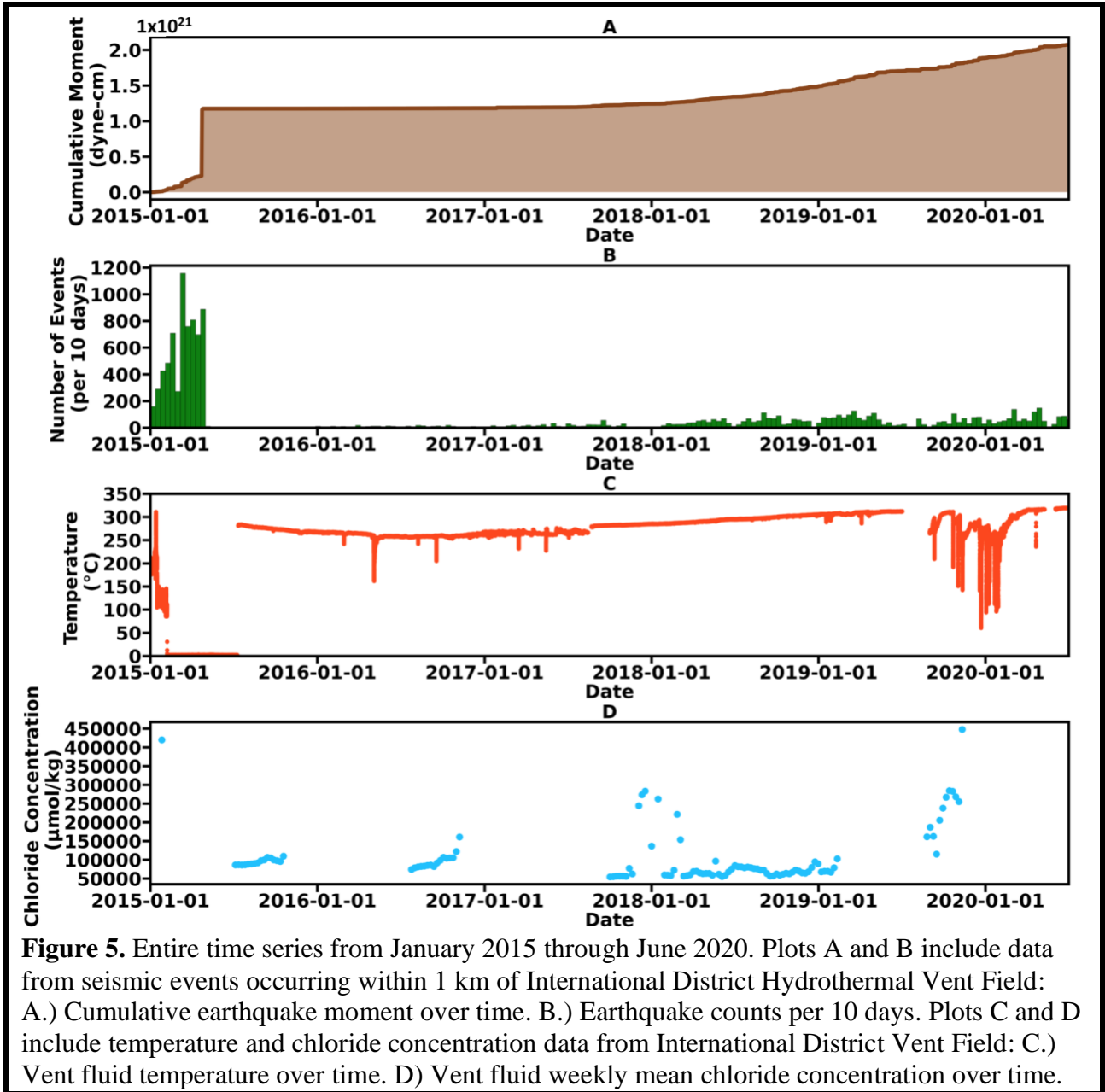
From January 2015 through June 2020 there is a large amount of variability in vent fluid temperature and chloride concentration over time (Figure 5). There is also variability in the earthquake cumulative moment and counts. The cumulative moment spikes by almost  $1.0 \times 10^{21}$  dyne-cm during the first half of 2015 (Figure 5A). This corresponds to the thousands of earthquakes that occurred immediately preceding and during the Axial Seamount eruption in April 2015 (Figure 5B). Unfortunately, the temperature probe was not properly collecting data during the time of the eruption as shown by the zero values from February 2015 to July 2015 (Figure 5C).

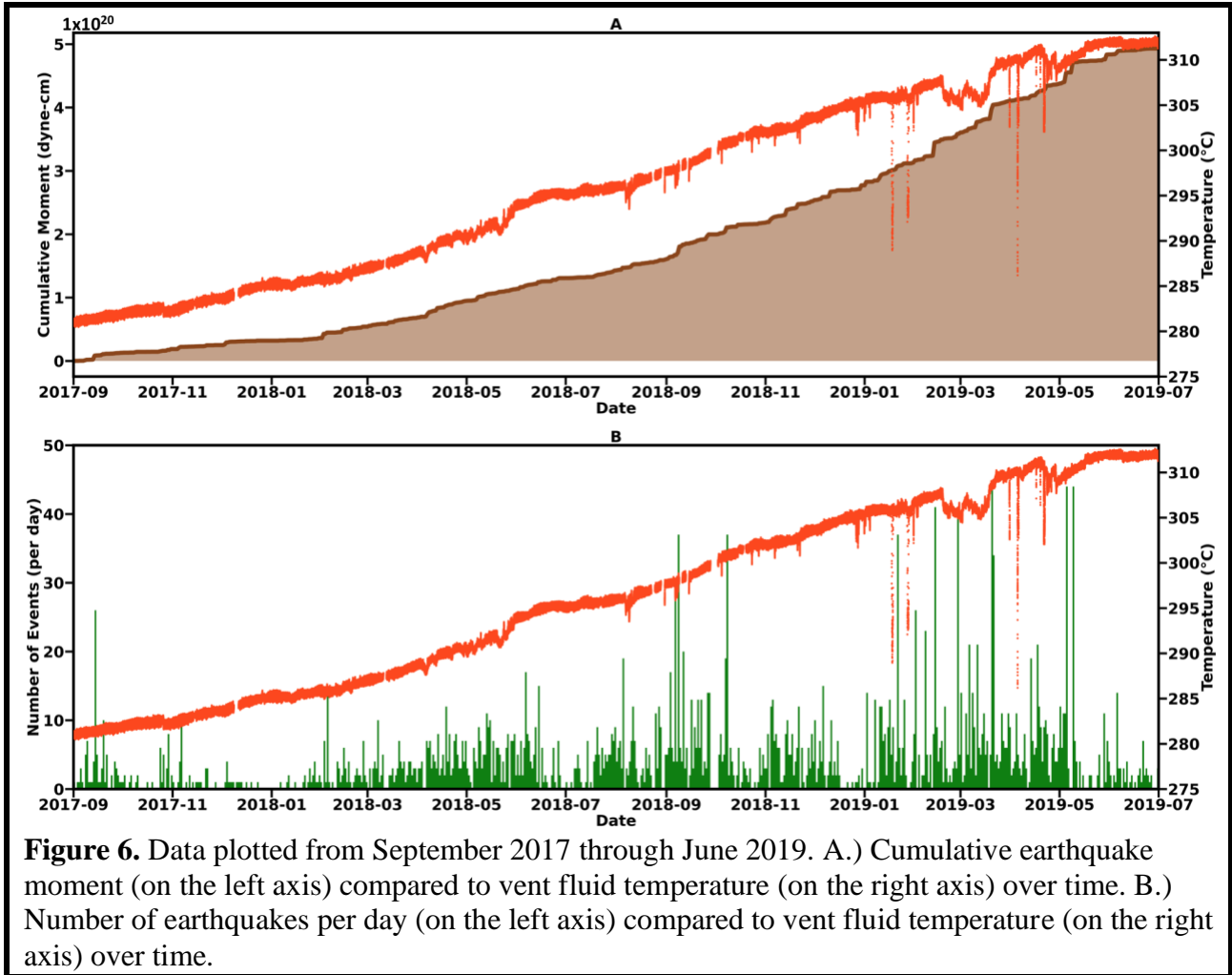
When the temperature probe resumed collecting measurements during the second half of 2015, it recorded a vent fluid temperature decrease of about  $20^{\circ}\text{C}$  between July 2015 and July 2016 (Figure 5C). This temperature decrease occurs during a period of low seismic activity (Figure 5 A, B). From July 2016 to August 2017 there is a gradual increase in vent temperature of about  $10^{\circ}\text{C}$  (Figure 5C). There is a week gap in temperature data collection in August 2017.

When the temperature probe resumes taking measurements in late August 2017, the vent fluid temperature is 280°C. This begins a continuous long-term increase in vent fluid temperature from late August 2017 through June 2019 (Figure 5C). The temperature data is again interrupted by maintenance in summer 2019. When the probe resumes collecting data, there is a large variability in vent temperature with large decreasing spikes of over 100°C (Figure 5C). Towards the end of the data range in early 2020, vent fluid temperature levels off at about 310°C, similar to the temperature in July 2019.

Throughout the time series, the vent fluid chloride concentration data has large gaps and is not continuous due to instrument malfunction. All chloride concentration values are below 540500  $\mu\text{mol/kg}$  which is the approximate chloride concentration of seawater. Two outlier points suggest the chloride concentration of vent fluid in this system can reach 450000  $\mu\text{mol/kg}$  (Figure 5D). Most of the data measurements that are collected range from 50000  $\mu\text{mol/kg}$  to 150000  $\mu\text{mol/kg}$  (Figure 5D). This is well above the chloride concentration of freshwater which has a maximum of about 5000  $\mu\text{mol/kg}$ . There is also a collection of data points in 2019 that suggest a gradual increase in chloride concentration to at least 250000  $\mu\text{mol/kg}$  (Figure 5D).

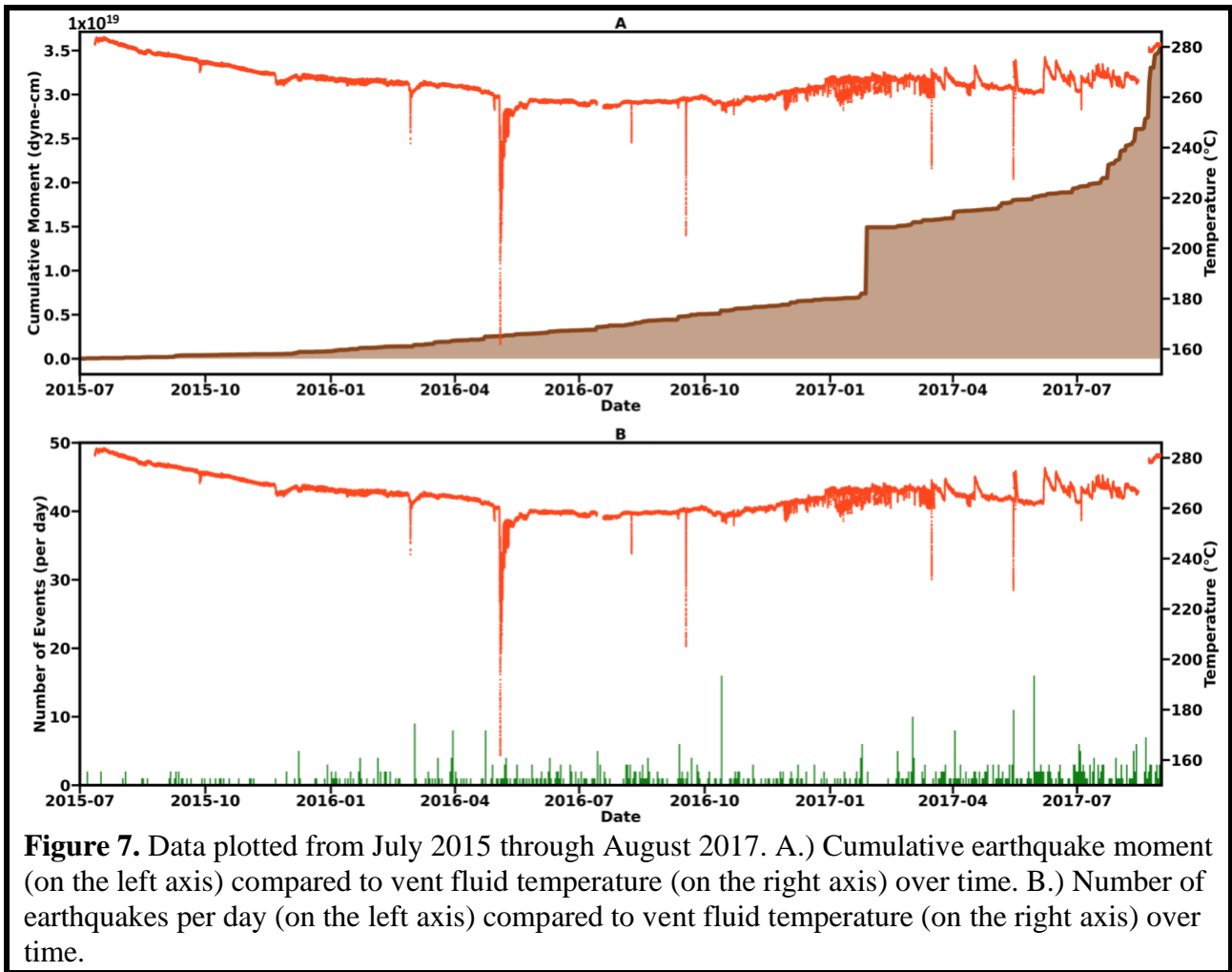
The continuous long-term increase in vent fluid temperature shown in Figure 5 starts around September 2017 at about 282°C and ends at the end of June 2019 at about 312°C. This long-term increase of approximately 30°C occurs over a period of 22 months (Figure 6). This steady increase in vent fluid temperature is concurrent with an uptick in seismic activity. From September 2017 through June 2019, there is a cumulative moment that reaches close to  $5 \times 10^{20}$  dyne-cm (Figure 6A). This steady increase in cumulative moment is caused by a rise in the number of seismic events per day which was frequently ten or more during 2019 (Figure 6B). The total number of seismic events during this 668-day period was 2758.



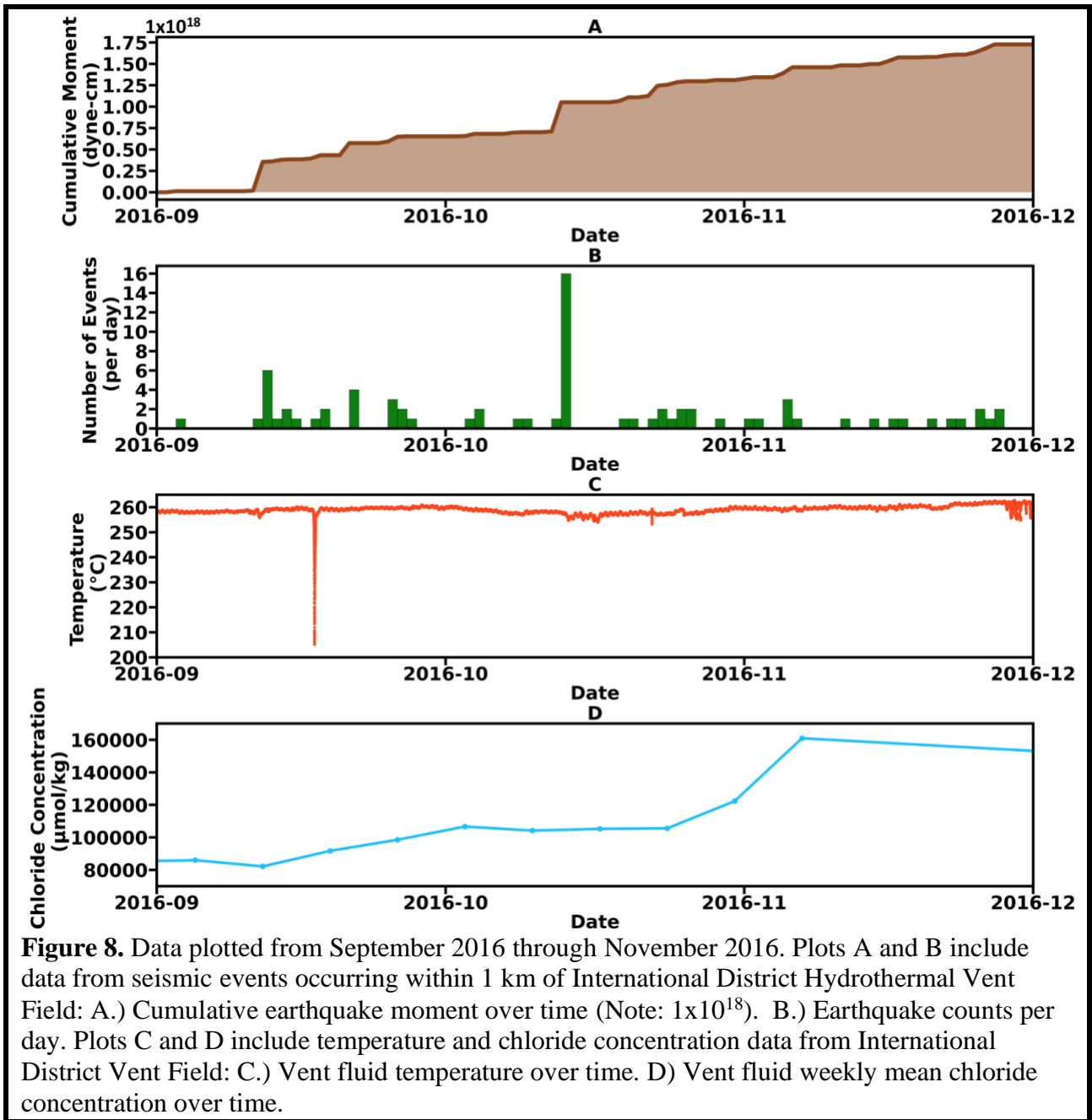


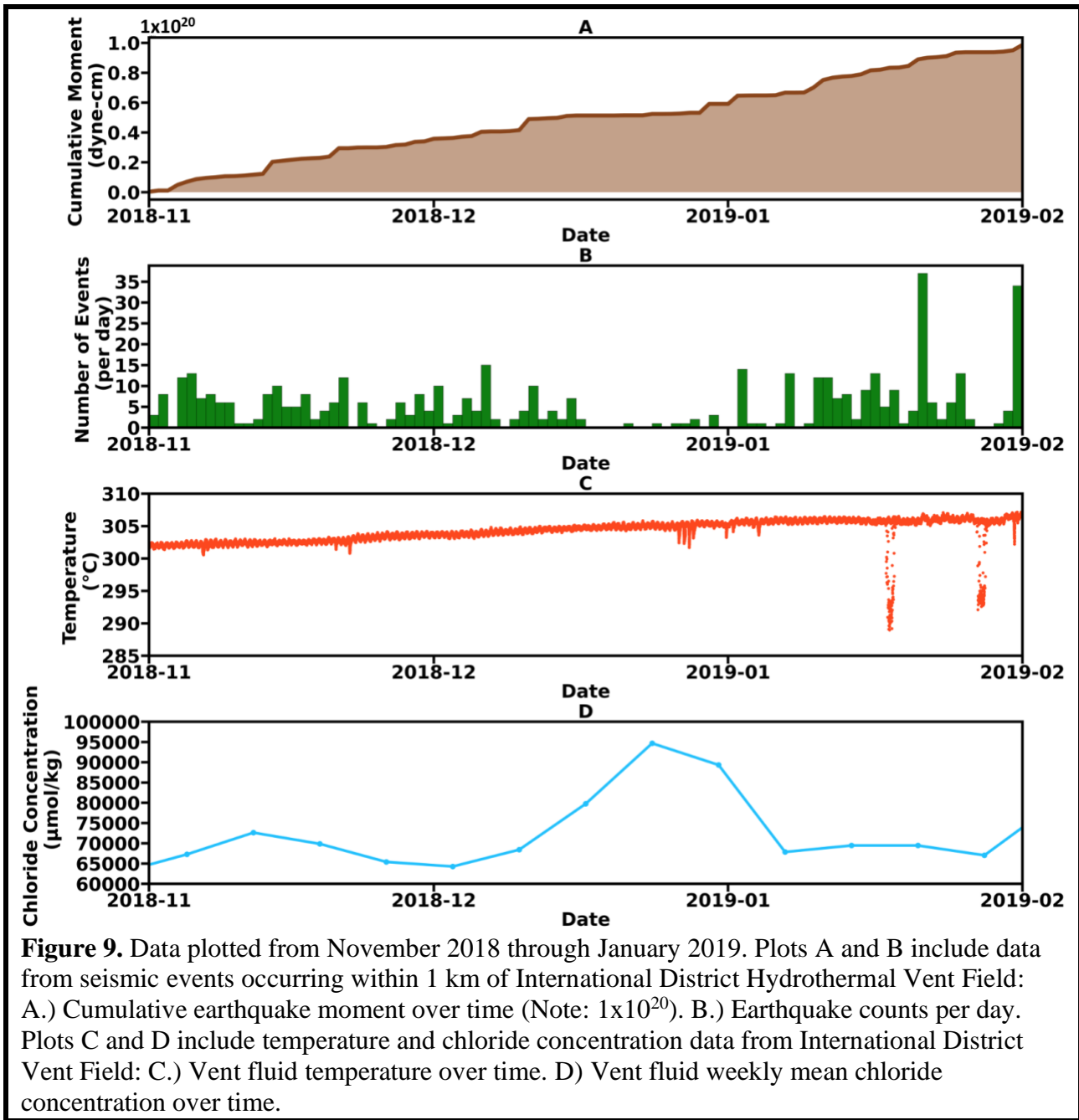
**Figure 6.** Data plotted from September 2017 through June 2019. A.) Cumulative earthquake moment (on the left axis) compared to vent fluid temperature (on the right axis) over time. B.) Number of earthquakes per day (on the left axis) compared to vent fluid temperature (on the right axis) over time.

The characteristics of the 22-month period from September 2017 through June 2019 contrasts with the preceding 26-month period. From July 2015 through July 2016 there was a gradual decrease of vent fluid temperature followed by a gradual temperature increase from July 2015 through August 2017. These fluctuations combined for a net decrease of 10°C. This period is also marked by low seismic activity. From July 2015 through August 2017 there was a cumulative moment of about  $3.5 \times 10^{19}$  dyne-cm. The total number of seismic events during this 793-day period was 676.



On short time scales there are many occurrences of sudden drops in vent fluid temperature. These spikes of decreasing vent fluid temperature range from a couple degrees to over 50°C such as in September 2016 (Figure 8C). Some of these sudden decreases in vent fluid temperature are concurrent with seismic activity and fluctuations appear to be occurring during the same time period as seismic events. An example of vent fluid temperature fluctuations after a spike in seismic events is shown in October 2016 (Figure 8C). However, most variations and drops in temperature occur independent of seismic activity (Figure 9C). Short-term vent fluid chloride concentration changes occur independent of seismic activity and vent fluid temperature changes (Figure 8,9).





## Discussion

The observed long-term changes in vent fluid temperature are gradual over periods of a year or more. The long-term vent fluid temperature increase is correlated to an increase in seismic activity. The observed short-term perturbations of vent fluid temperatures are most often sudden

decreases in temperature. These decreases can be included in short-term variability where temperature fluctuates both down and up. A small number of these time periods of variability can follow an uptick in seismicity. After the period of thousands of earthquakes during the 2015 eruption, there is a period of about two years low seismicity. This period has seismic event counts frequently below five per day and not exceeding 20 per day. There is then a gradual increase in the number of earthquakes for the remaining three years of the study's time frame. By 2019, ten seismic events per day is frequent and there are multiple occurrences of more than 30 seismic events per day. Throughout this increase in seismic activity, there are no dramatic spikes or decreases on short time scales. This differs from past literature (Sohn et al. 1998; Dziak et al. 2003, Johnson et al. 2001, Crone et al. 2010) which all correlated vent fluid perturbations to clearly distinguishable earthquake swarm sequences. The ongoing occurrence of earthquakes with no swarm sequences that clearly stand out from the background seismicity creates less certainty in the detection of correlations in this study.

The observed long term gradual increase in vent fluid temperature starts in September 2017 and continues through June 2019. During this time period, the temperature increase of 30°C is an approximately 16°C increase per year. This trend is similar in length to the long-term increase seen in the Sohn et al. (1998) study from late 1995 through 1997. While similar in the duration of increase, the rate of increase of approximately 16°C per year at the International District Vent Field was about five times more than the rate of increase of approximately 3°C per year observed in Sohn et al. (1998). The seismic data collected by Sohn et al. (1998) recorded the main swarm of 162 events that was correlated to the 7°C increase in vent fluid temperature that occurred in the 11 days after the swarm. A secondary swarm of 25 events that occurred 22 days later during the 70-day period of 7°C decrease was also recorded. However, seismic data was not

recorded during the 7°C vent fluid increase from late 1995 through 1997 (Sohn et al. 1999). In this study, seismic activity was increasing during the 22 months that the increase in vent fluid temperature took place. The cumulative moment during the period of increase was an order of magnitude greater than the cumulative moment of the 26 months prior. This was due to a large difference in earthquake counts. There were 2,082 more seismic events recorded during the time period of September 2017 through June 2019 compared to July 2015 through August 2017. The contrast in seismicity between these periods combined with the 10°C decrease in vent fluid temperature from July 2015 through August 2017 compared to the increase of 30°C from September 2017 through June 2019, support the hypothesis that there is a correlation between seismic activity and vent fluid temperature.

The results suggest that the circulating hydrothermal vent fluid in this system is penetrating into new heat sources within the crust. This increase in heat flux may be due to an increase in local magma supply below the International District Vent Field. As explained by Arnoux et al. (2017), a recent recharge of magma can cause seismogenic cracking that results in earthquakes. This increases the permeability of the crust and allows increased contact between magma and vent fluid. Currently, the Axial Seamount is inflating, and the next eruption is predicted to occur between 2022 and 2025 ([https://www.pmel.noaa.gov/eoi/axial\\_blog.html](https://www.pmel.noaa.gov/eoi/axial_blog.html)). The increase in magma could be related to the inflation of the seamount as the next eruption approaches. The gradual heating of the International District Vent Field as magma builds up and reaches further up towards the surface of the crust may be linked to the next eruption of Axial Seamount. Following the 2015 eruption, the rate of inflation of Axial Seamount was relatively high. However, the observed gradual decrease of vent fluid temperature from July 2015 to July 2016 suggests a lack of magma recharge in the region beneath the International District Vent

Field immediately after the 2015 eruption. The decrease in vent fluid temperature and low seismicity during this period is again consistent with Arnoux et al. (2017). The reduced presence of local magma reduces cracking of the crust which results in decreased permeability and even clogging of the hydrothermal system. Reducing the pathways for circulation of hydrothermal fluid causes the system to be less efficient. Less hydrothermal fluid can penetrate deep enough into the crust to reach the layer where conduction of heat can occur between magma and the hydrothermal fluid.

The observed sudden decreases in vent fluid temperature occur on short time scales on the order of days. There are noticeable occurrences where a temperature perturbation appears to be influenced by seismicity. This may be a result of new cracks allowing seawater or previously isolated fluids to enter the hydrothermal system. However, most frequently, these short-term perturbations do not appear correlated to seismicity. These vent fluid temperature decreases that are not connected to seismicity are similar to the vent fluid temperature decrease that occurred before the earthquake sequence as observed by Dziak et al. (2003), which the authors acknowledged may have been caused by local, non-seismic mechanisms. Given that most of the sudden decreases in vent fluid temperature are not related to seismicity in this study, there is a reasonable possibility that the occurrences where sudden decreases appear to be related to seismicity may be due to chance. Therefore, these correlations cannot be confirmed by the data in this study.

The frequent, large decreasing spikes in vent fluid temperature of over 100°C during the time period from September 2019 through June 2020 could be inaccurate data measurements caused by instrument malfunction. These large variations in vent fluid temperature could also be real data measurements influenced by disturbances to the structure of the hydrothermal chimney

where the temperature and resistivity probe is located. The hydrothermal chimney may have experienced a breach in its structure, allowing seawater to enter the chimney and mix with the vent fluid before it is recorded by the temperature and resistivity probe. Gaps or cracks in the hydrothermal chimney could be filled by precipitating minerals which would reduce the volume of seawater entering the chimney and cause the temperature to rebound. Openings may reform before the chimney is permanently sealed off to seawater, allowing the volume of seawater entering the chimney to again increase and lead to a decrease in vent fluid temperature. This repeated process could occur on short times scales which would be consistent with the period of extreme variability in vent fluid temperature from September 2019 through June 2020. Although there does appear to be an increase in chloride concentration during this time period, there is not enough continuous chloride concentration data to confirm that seawater is entering the vent fluid. September 2019 through June 2020 is not strongly considered in this study due to the lack of knowledge about the accuracy of the vent fluid temperature data during this time period.

During the entire time series, the vent fluid chloride concentration stays below the level of seawater which is about 540500  $\mu\text{mol/kg}$ . This is consistent with the fact that International District Vent Field is a high temperature hydrothermal vent system that discharges fluids that have undergone phase separation within the lithosphere. While the vent fluid chloride concentration stays consistently low, it appears that it is slightly lower during periods of increases in temperature. From July 2015 through August 2017, the chloride concentration ranged on average from about 80000  $\mu\text{mol/kg}$  to about 120000  $\mu\text{mol/kg}$  which was concurrent with the net vent fluid temperature decrease of 10°C. From September 2017 through June 2019, the chloride concentration on average ranged from about 50000  $\mu\text{mol/kg}$  to about 90000  $\mu\text{mol/kg}$  which was concurrent with the vent fluid temperature increase of 30°C. While this is

not a strong signal, it suggests that more of the vent fluid is undergoing phase separation when there is an increase in vent fluid temperature. The observed increase in chloride concentration in 2019 could be a result of seawater entering the system or the introduction of brine into the system during circulation within the crust.

This study is unique in that the OOI Regional Cabled Array provides continuous data for greater than 5 years which exceeds previous studies on this topic. The OOI Regional Cabled Array is a key asset that can continue to be used to improve the knowledge of processes occurring at the Axial Seamount. During the time period of data being used in this study, earthquake data is continuous while temperature data is mostly continuous. Chloride concentration data from resistivity has numerous gaps due to instrument error and redeployments. Unfortunately, this makes detecting clear signals in the data difficult. Improvements in data collection and further continuous time series data will allow future studies to expand on this study.

## **Conclusion**

Observations from this study suggest that there is a long-term correlation between earthquake activity and the temperature of vent fluids at International District Hydrothermal Vent Field. As the rate of seismicity increases, the vent fluid becomes warmer. This may be signaling more contact between circulating hydrothermal fluid and magma at this location. Increased volumes of magma could potentially be reaching further up through the crust towards the surface, increasing the heat source for the circulating fluid. Increased magma supply and steady seismicity that is increasing, may foreshadow the next eruption of Axial Seamount and may suggest there will be lava flows in the southern part of the caldera, similar to 1998 and

2011. Further monitoring of the International District Vent Field before, during, and after the next eruption should provide more insight into the link between hydrothermal vent field activity, earthquakes, and volcanism.

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