Volcanologists and Remote Sensing:

Prediction and Mitigation of Volcanic Eruptions

By

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March 1, 2022

ABSTRACT

Nearly all of the world's nearly 1,500 active volcanoes are located in remote, rugged terrain. However, each represent the potential for massive destruction and loss of human life. The study and monitoring of volcanoes in third world countries continues to be challenging. In fact, in situ monitoring of many volcano locations in the United States, Japan, and Europe often prove to be challenging and nearly impossible. Therefore, volcanologists today depend on the technology of remote sensing. Obtaining spatial resolution data from multiple disciplines of remote sensing, allows for accurate mapping of volcanoes, forecasting of potential eruption sites, and collection of post eruption data drastically aids emergency response personnel help save lives of those affected by the energy released from volcanic activity. The following paper discusses the differences of remote sensing technologies used by volcanologists, and emergency response personnel.

Introduction

Killing over 300 people and dislocating over 230,000 more, the 2010 eruption of Mount Merapi in Indonesia is one of the deadliest in modern history(Staff, 2018). Furthermore, major eruptions in Peru (1999), the Democratic Republic of Congo (2002), Japan (2014), Guatemala (2018), and Hawaii (Kilauea, continuous from 1983-2018) added to the number of deaths and homeless people around the globe (Staff, 2018). Over 1,500 of the world's volcanoes are active today, many of which lie within the remote and rugged terrain of third world countries (Galle, et al., 2003). Even in the United States, Japan, and Europe, their remoteness often renders in situ data collection nearly impossible. However, volcanologists and emergency response personnel successfully utilize data collection via remote sensing technology to predict potential eruptions, and respond accordingly to the devasting aftermath of an eruption.

Throughout history, many cultures related volcanic eruptions to angry gods. In fact, even today, many native Hawaiians refer to Madame Pele (the Goddess of Fire) when discussing the volcanic activities of Mauna Loa or Kilauea located on the island of Hawaii (Nimmo, 1986). While no human sacrifices are made to Madame Pele, many look upon this mythological goddess as the creator of the longest volcanic eruption of the twentieth century. However, today's volcanologists rely more heavily on scientific data collected via remote sensing than on ancient myth.

Thomas A. Jaggar began his in-depth study of volcanoes in 1909, and in 1911 he joined forces with volcanologist Frank Perret to open the Hawaii Volcano Observatory (Anchieta , 2009). Working with the most modern of seismometers at the time, the two volcanologists placed seismic sensors around the caldera of the active volcano Kilauea, as well as her sister Mauna Loa in hopes of recording seismic activity of a volcano pre and post eruption (Anchieta , 2009). Their volcano observatory (now named the Jaggar Observatory, located in Volcanoes National Park, Hawaii) and seismic data collection system brought the science of volcanology into the twentieth century. Recording and analyzing the first reliable in situ volcanic data, Jaggar and Perret became known as the fathers of volcanology (Anchieta , 2009).

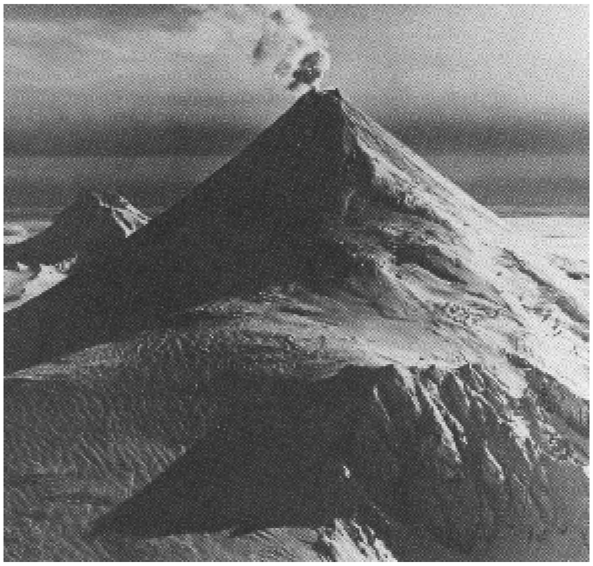
Jaggar and Perret opted for the volcanoes on Hawaii island due to their ease of access. However, during World War II technology evolved at a rapid pace. Working with the United States military, the Kodak Eastman Corporation engineered new film technologies to allow for aerial photography of enemy troop deployments, gun batteries and potential bombing targets (Jensen, 2004). Continued improvements of film technology and the advent of the transistor by William Shockley in 1948 catapulted the science of remote sensing into the late twentieth century (Watkins, 2019).

During the last fifty years, remote sensing data collection quickly became the tool of choice for data collection among volcanologists. No longer are remote, desolate locations a hinderance for data collection. Balloons, helicopters, airplanes, and satellites equipped with Synthetic Aperture Radar (SAR), Light Detection and Ranging (LIDAR) instruments, infrared sensors, spectrographic instrumentation, and high-resolution digital cameras allow for the safe collection of data for real time analysis of volcanic activity.

Part 1: 3-Dimensional Mapping of Volcanic Terrain

Most volcanoes fall into two basic classifications (sub classifications do exist, however for the general purposes of this paper, they will not be discussed) (Watson J. , 2011). The cinder cone volcano is the most widely recognized classification, as its appearance of an upside-down funnel is often depicted in Hollywood movies and elementary school science books. Cinder cone volcanoes usually have steep sides, that may tower to great heights, and at the summit of the slopes lies a large crater from which lava and other debris are expelled during an eruption (See Photograph 1).

Photograph 1:

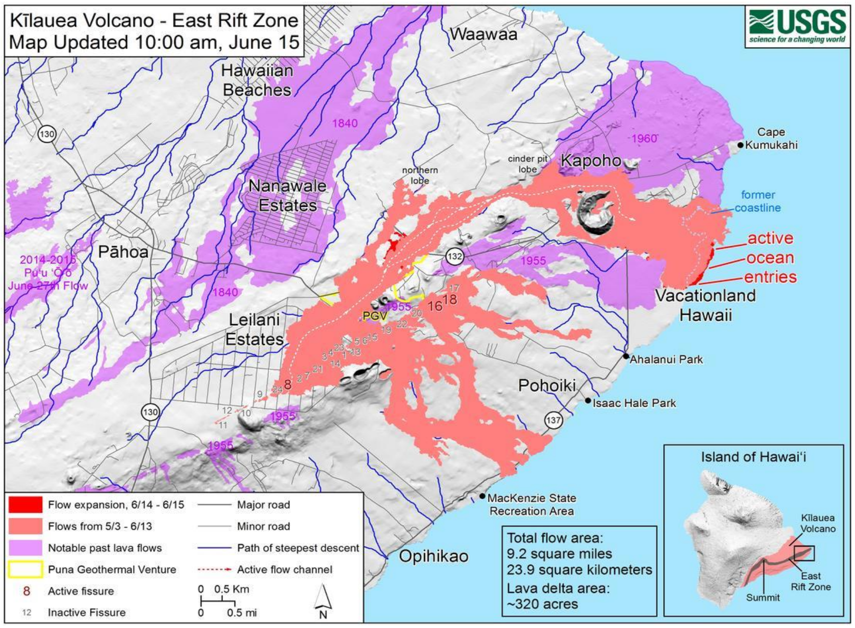

(Watson J. , 2011)

The shield volcano, the more dangerous of the two, has long sloping sides which tower to heights of over 5,000 meters in elevation, and often will cover hundreds of square kilometers of land. Eruptions produced by shield volcanoes may not always exit from the caldera proper (from the crater atop the volcano). In fact, most eruptions from shield volcanoes will occur several kilometers from the caldera (Watson J. , 2011). Volcanologists term these distant eruption sites as volcanic rift zones (See image 1). Because of the shield volcano's ability to erupt anywhere within its geological footprint, volcanologists must accurately map the entirety of the volcano.

Low to medium resolution images of 30-meter pixels, collected via satellite imagery, may allow for some excellent studies of a volcano's size, and are relatively inexpensive to obtain. However, volcanologists believe that more detail is needed for accurate 3D mapping of volcanoes. Therefore, researchers are now investigating moderate to high resolution imaging

(10m-100m pixel) obtained from satellite and aircraft instrumentation (Kervin, Kervin, Goossens, Rowland, & Ernts, 2007).

Image 1:



(Watson J. , 2011)

Three-dimensional mapping relies heavily on obtaining accurate elevation data, and processing the data with Digital Elevation Models (DEM). Accurate data collection is often performed in remote areas via stereoscopic instrumentation mounted on an aircraft or satellite and digital photogrammetry (Kervin, Kervin, Goossens, Rowland, & Ernts, 2007). However, with recent advancements in technology, radar interferometry and laser scanning of an area via satellite may offer a less costly means of data collection (Kervin, Kervin, Goossens, Rowland, & Ernts, 2007). These techniques of data acquisition are preferable to the early methods of in situ field surveys, and offer nearly continuous real time data collection.

In 1989, researchers took advantage of the fine resolution provided by Landsat 5's Thematic Mapper (TM) and successfully mapped the spatial evolution of to identify active volcanoes in the Andes Mountain range in South America (Kervin, Kervin, Goossens, Rowland,

& Ernts, 2007). With the resolution provided by TM, volcanologists determined that several volcanoes within this region exhibited a great deal of crater morphology and post glacial activity. After these discoveries, which were the first volcanic data sets provided by Landsat 5, volcanologists have relied heavily on continued use of Landsat's TM ability to provide data post eruption activity due to the data recording over multiple wavelengths. Furthermore, data collected by Landsat is offered at no cost to the researcher, but data acquisition may take upwards of 14 days following a pass over of a given region (Kervin, Kervin, Goossens, Rowland, & Ernts, 2007).

Therefore, researchers do not solely rely upon one particular satellite to obtain data. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) launched on December 18, 1999 and is housed in the TERRA satellite (Kervin, Kervin, Goossens, Rowland, & Ernts, 2007). The ASTER instrumentation suite includes sensors for the visible and near infrared wavelengths (15m pixel resolution), as well as short wave (30m pixel resolution) and thermal infrared (90m pixel resolution) wavelengths. With a total of 14 spectral bands covering an image scene of 61.5m x 63m, ASTER is the instrument of choice when mapping the world's volcanoes (Kervin, Kervin, Goossens, Rowland, & Ernts, 2007).

ASTER's ability to produce stereoscopic imaging through three telescopes (one looking forward of nadir, one at nadir, and one looking backwards along its track) allows researchers to obtain 15m resolution stereoscopic images of a given volcano, which is nearly perfect data for the DEM to produce amazing quality 3D maps of a volcano's terrain (Kervin, Kervin, Goossens, Rowland, & Ernts, 2007). While the self-contained stereoscopic ability of ASTER is advantageous, ASTER's data collection ability is often hindered by cloud cover. Therefore, volcanoes lying in tropical climates often require several passes before reliable data is obtained.

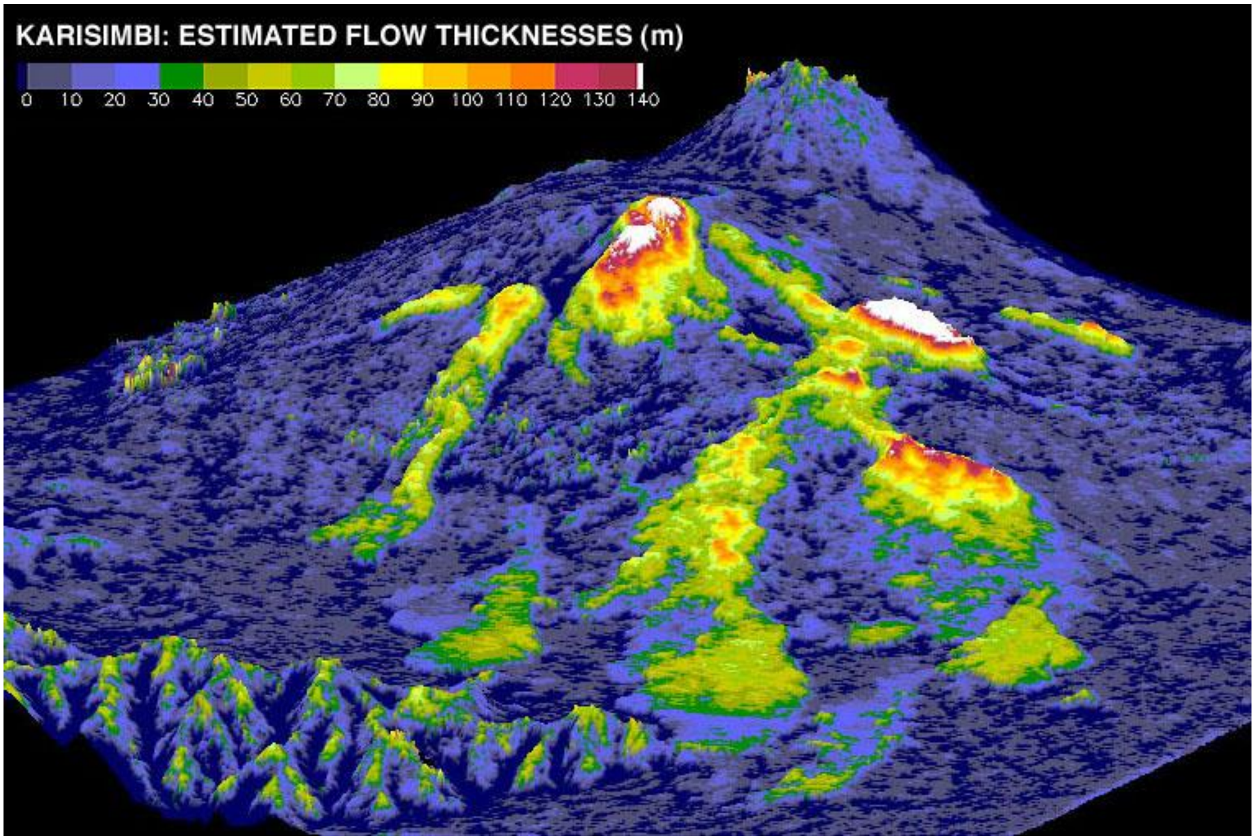
The SPOT satellites offer yet another excellent opportunity for data collection. While they are limited in spectral bands as compared to LANDSAT 5 or ASTER, SPOT satellites offer higher resolution (ranging from 2.5m pixel to 20m pixel depending on the satellite). Furthermore, with three SPOT satellites in operation, nearly the entire surface of the Earth can be covered in twenty-four hours (Kervin, Kervin, Goossens, Rowland, & Ernts, 2007).

With the help of early SPOT imagery, researchers successfully mapped lava flows, steam vents and structure evolution of volcanoes located in the Galapagos region. The panchromatic imagery data provided by the SPOT satellites allowed for accurate mapping of lava flow boundaries, as well as proper age identification of past lava flows (Kervin, Kervin, Goossens, Rowland, & Ernts, 2007). Continuing study of the high-resolution imagery also allowed for the identification of several small cinder deposits measuring only a few meters in height (Kervin, Kervin, Goossens, Rowland, & Ernts, 2007).

The SPOT satellites produce amazing images and provide a wealth of data concerning the world's volcanoes. However, similar to the afore mentioned satellites and instruments, these satellites are limited in their abilities. Cloud cover will hamper infrared sensor abilities, and as mentioned above, the spectral band coverage is much lower. Finally, the cost per image scene exceeds 100 euros for non-European researchers or citizens (Kervin, Kervin, Goossens, Rowland, & Ernts, 2007).

After collection of data from one or more of the methods detailed above, researchers must assimilate the data for accurate mapping. This work is performed by the DEM software, which is capable of producing 3D topographical mapping with a scale of 1:100,000. Below is a culmination of data collection. The digitized, 3D image is that of the island of Hawaii, and was produced using data combined from LANDSAT, ASTER and SPOT instruments (Staff, EarthView–Kilauea, Mauna Loa Volcanoes Shape the Face of Hawaii, 2019). This image accurately depicts how volcanologists and geologists accurately map volcanoes within a given region, and utilize the imaging data to estimate lava flow thickness.

Image 2:



(Staff, EarthView–Kilauea, Mauna Loa Volcanoes Shape the Face of Hawaii, 2019)

Accurate mapping allows volcanologists to gain a better understanding of the sheer size of the world's volcanoes. Furthermore, the study of prior lava flows using 3D maps may aid in the prediction of where future lava flows may run; therefore, giving emergency response personnel some insight into planning evacuations for future eruptions. However, mapping alone does not help with the prediction of when an eruption is likely to occur.

Part 2: Volcano Deformation

Seismic activity and land deformation at volcanic sites are often clues as to when a volcano may erupt. Pressure from a rising lava source creates ground swells, creating minor earthquakes (usually less than 3.0 magnitudes) near the potential site of an eruption (Reath, et al., 2018). Measuring seismic activity is most often performed by in situ seismic sensors, however in remote regions of Latin America, ground swell and deformation measurements are made possible with the use of remote sensing technology.

A team of researchers led by Dr. Reath of Cornell University studied 47 of Latin America's most active and remote volcanoes over a period of 17 years. The goals of their study included data acquisition of land deformation (swelling or deflation of land formations) of the volcanoes in question, in an attempt to better understand the correlation between land deformation and eruption. Therefore, allowing for more accurate eruption predictions in the future (Reath, et al., 2018).

The team worked with the Canadian Space Agency (CSA), the Japanese Space Agency (JAXA), and the European Space Agency (ESA) to obtain radar altimeter, radar ranging, and panchromatic stereo mapping data to continually and accurately monitor ground elevation levels (Reath, et al., 2018).

CSA provided access to their RADARSAT data. Beginning with RADARSAT-1, launched in November of 1995, Dr. Reath's team collected radar data producing resolutions ranging from low to high (100m-5m). In 2007, the team then relied upon new data provided by RADARSAT-2, capable of a very high spatial resolution of 3m (Reath, et al., 2018).

The high and very high resolution rates did limit the swath paths of both satellites to 20 kilometers, however larger swath path coverages of 50-500 kilometers allowed for low to moderate resolution rates (between 16m-100m) (Reath, et al., 2018). For the purposes of the study, the lower resolution rates were undesirable; therefore, data collection for the moderate and higher resolutions took more times, as more return visits were needed to accurately measure deformations near a the target sites (Reath, et al., 2018).

ESA provided data from two satellites, the Sentinel-1 and Envisat. Both satellites are equipped with synthetic aperture radar (SAR). Ground Range Detection (GRD) data was provided by Sentinel-1 and allowed for multiple looks of the target, and slant range coordinates, giving researchers an approximate square spatial resolution image, and produced less speckling of the image (Reath, et al., 2018).

Envisat, launched in 2002, is the largest Earth observation civilian satellite and is equipped with ten different instruments. The most informative instrument for measuring land deformation is by far the Radar Altimeter-2 (RA2). RA2 is capable of extreme accuracy, measuring the time delay of reflected radar waves to within a nanosecond! Furthermore, the instrument is capable of determine the shape of reflected pulses, allowing for greater detail of the target image (Reath, et al., 2018).

JAXA’s Advanced Land Observing Satellite (ALOS), provided panchromatic imaging of the 47 target volcanoes. Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) gave the researchers digital elevation data, with resolutions of 2.5m (Reath, et al., 2018). PRISM’s widest field of view is 70 kilometers at nadir, with that being cut in half during triplet stereo imaging mode (three stereoscopic images, produced without mechanical yaw changes to the satellite) (Reath, et al., 2018).

Combining data obtained from multiple satellites and sources (radar and panchromatic), proved somewhat difficult. Spatial resolution differences, instrument thresholds, and time data was coordinated by software specifically designed for the research team. During their study and collection of data, an alarming trend was noticed with the deformation of land near the Copahue volcano in Chile. In one year (2011), the team's data showed ground swell between 12-15 centimeters in 2011, leading them to forecast an imminent eruption. Over the next year, data continued to show deformation at the rate of 2cm per month! The volcano erupted on May 27, 2013. No loss of human life occurred, but emergency personnel evacuated over 2,000 people (Reath, et al., 2018).

While volcanologists can not yet predict the exact day, month, or year when a volcano may erupt, using the incident mentioned above strongly suggests that remote sensing of volcanoes to measure their continuous deformation properties, allows for advanced warning of future eruptions.

Part 3: Thermal Detection

Thermal emissions produced by active volcanoes give volcanologists another clue toward the prediction of future eruptions. Many active volcanoes continuously release thermal energy via steam vents, or into nearby ponds or lakes, or through the surface release of volcanic gasses (Pyle, Mather, & Biggs, 2013). The concept of using infrared (IR) sensing to detect thermal increases of volcanic regions quite possible began soon after infrared sensors began to be manufactured. However, in more recent years, IR data is not only used in models to predict eruptions, but it is also utilized by emergency response agencies to track hot gaseous clouds and ash plumes (Pyle, Mather, & Biggs, 2013).

ASTER and shortwave infrared (SWIR) provided researchers with detailed thermal imaging of the Lascar Volcano in Chile, during the year of 2010. The data obtained suggested an increase in thermal activity of the volcano, however in situ readings disagreed with space-based data (Pyle, Mather, & Biggs, 2013). This anomaly is believed to have been caused by atmospheric temporal noise, and led researchers of the Lascar Volcano to begin using the Kalman filter (a filter which dampens any atmospheric temporal noise) (Pyle, Mather, & Biggs, 2013).

The Kalman filter had been used successfully during the eruptions of Mount Etna in 2002 and Mount Nyamulagira in 2010, and has proven to be a successful addition to aid in the SWIR detection of thermal activity near volcanoes. Therefore, volcanologists now employ the Kalman filter methodology for all remote IR sensing of volcanoes (Pyle, Mather, & Biggs, 2013).

Using remote sensing thermal detection from ASTER and SWIR, researchers delved into the Andes Mountain Range, examining over 150 volcanoes between the years 2000-2010. The results astonished many volcanologists, as several low-amplitude hot volcanic hotspots were detected from space, near or at volcanoes that showed little to no surface thermal activity when compared to in situ data (Pyle, Mather, & Biggs, 2013).

Researchers today believe these volcanic hotspots are more common than originally thought, and with continued monitoring from space-based remote IR sensing platforms, they suggest these hotspots will lead to a greater understanding of the internal size of a given volcano (Pyle, Mather, & Biggs, 2013). Combining IR imaging within the 3D mapping systems detailed above, researchers are able to pinpoint hotspots and believe they will be able to predict exact locations of future eruptions for shield classified volcanoes (Pyle, Mather, & Biggs, 2013).

When a volcano erupts, the emit massive amounts of volcanic ash and dangerous sulfuric gas. In fact, if the volcano’s molten lava enters a water source, even more deadly gases can be formed (Pyle, Mather, & Biggs, 2013). To help prevent these dangerous post eruption emissions from harming human life, emergency personnel also utilize IR data obtained from remote sensing technology.

Tracking of ash clouds may be accomplished via the visible spectrum wavelengths with a digital camera. However, nighttime tracking is made extremely difficult in the visible wavelengths. Therefore, emergency response agencies rely on IR tracking of ash clouds (Pyle, Mather, & Biggs, 2013). Ash cloud fall out can be harmful to the human respiratory system and in some cases cause death, but with proper tracking of an ash cloud, emergency personnel can evacuate those living within the predicted path of fall out (Pyle, Mather, & Biggs, 2013).

More deadly than ash fall out, is the presence of sulfuric gases emitted by a volcano. In fact, some volcanoes emit sulfuric gases non-stop (prior to eruption, during eruption and post eruption). The gases emitted can be detected remotely, using IR sensors. The danger of volcanic gases lies within their invisibility to the human eye. However, satellite IR imaging in combination with spectrographic data can locate and determine the path of dangerous gas clouds (Pyle, Mather, & Biggs, 2013).

Remote sensing data collection in the IR wavelengths continues to be a valuable tool to researchers with the goal of predicting volcanic activity. Furthermore, IR imaging gives emergency personnel a valuable tool to help save lives. When combined with spectrographic data, IR imaging also allows researchers to determine if air quality near a volcano is within safe limits, thereby allowing for any in situ measurements necessary.

Part 4: Spectrometer and Dangerous Gases

Sulfuric gas is one of the deadly gases emitted by a volcano, and not necessarily only during eruption. With the aid of a correlation spectrograph (COSPEC), volcanologists monitor all forms of gases expelled by volcanoes. COSPEC instrumentation may be used either in situ or located kilometers from the source. In fact, helicopters are often the preferred method of collecting data with COSPEC instrumentation (Watson, et al., 2004).

Spectrograph data acquired via remote sensing can be verified with in situ instrumentation, if the terrain and air quality permit such in situ monitoring. However, remote spectrometry data collection is preferred due to safety concerns (Burton, Oppenheimer, Horrocks, & Francis, 2000). Spectrographic data collected from several volcanoes around the world, show a presence of sulfuric gas, hydrochloric gas, carbon monoxide, carbon dioxide and fluoride gases (Burton, Oppenheimer, Horrocks, & Francis, 2000).

This combination of emitted gases is deadly. While this data offers volcanologists and geologists insight into the internal makeup of a volcano and its associated lava pools, the data itself does not contain predictive information for an eruption. However, for those living near volcanoes, this data is of extreme importance.

In Volcanoes National Park (located on the Island of Hawaii), one instrument suite monitoring the Kilauea caldera is equipped with a COSPEC instrument. Furthermore, the U.S. Geological Survey routinely monitors the surrounding area with a helicopter equipped with IR sensors and a COSPEC instrument (Watson, et al., 2004). The data is monitored and analyzed daily, and is used to close the park (or areas thereof), when dangerous gas levels are exceeded.

During an eruption, lava flows may come into contact with large water sources, such as ponds, lakes or oceans. In the photograph below (Photograph 2, shown in the visible wavelength spectrum), one can see the cloud of steam created when a flow enters into the ocean. While the steam cloud appears relatively harmless, this cloud contains hydrochloric acid, sulfur dioxide, sulfuric acid, and microscope particles of metal (released from basaltic lava during the rapid cooling process). Prior to spectrometry and analysis of spectrographic data, sampling such a cloud was impossible.

The image below contains a wealth of information for volcanologists and the emergency agencies on the island of Hawaii. Data collected by a helicopter equipped with a COSPEC instrument showed the steam cloud to contain sulfuric gases and acid, along with lethal amounts of fluoride gas (Watson, et al., 2004)

(Staff, EarthView–Kilauea, Mauna Loa Volcanoes Shape the Face of Hawaii, 2019)

Not all gaseous emissions from volcanoes are immediately deadly. For example, recent studies using spectrometer analysis of air columns near active volcanoes, shows a much higher concentration of carbon gases (CO and CO2) (Burton, Oppenheimer, Horrocks, & Francis, 2000). While the effects of greenhouse gases had not been fully modeled at the time of Dr. Burtons, publication of “Remote sensing of CO2 and H2O emission rates from Masaya volcano, Nicaragua”, carbon gases were known to add to the greenhouse effect.

In 2009, JAXA launched GOSAT, which is the first satellite solely dedicated to the monitoring of Earth's atmospheric greenhouse gas (Pyle, Mather, & Biggs, 2013). GOSAT's ability to detect CO2 and Methane (CH4) relies on spectrometer technology in combination with IR sensors which measure emitted and reflected IR light waves. Processing the IR light collected through the Fourier Transform Spectrometer (FTS) and the Cloud and Aerosol Imager (CAI) allows researchers to determine the total amount of CO2 and CH4 in a given column of air (Pyle, Mather, & Biggs, 2013).

GOSAT's mission is to determine high sources of CO2 and CH4 emissions using its IR technology, coupled with FTS and CAI. However, volcanologists are concerned about gas emissions from volcanoes, so they collect data obtained from GOSAT when the satellite flies over or nearly over volcanic regions (Pyle, Mather, & Biggs, 2013). Again, this data may not lead to the prediction of volcanic eruptions, but it does tend to suggest when a volcano's thermal indices are increasing (Burton, Oppenheimer, Horrocks, & Francis, 2000).

Part 5: Conclusion

The advent of remote sensing technology forever changed life for humans on Earth. Remote sensing imaging and data collection may be employed by several scientific disciplines. Volcanologists and emergency response agencies use remote sensing data of various types to prepare and react to volcanic eruptions.

Today's visible wavelength photography performed via aircraft or satellites offer volcanologist amazing overhead images of a volcano and its surround area. However, delving deeper into the mechanisms of a volcano and its eruption process, requires more than just visible wavelength photographs. Therefore, researchers look toward other remote sensing technologies to unravel the mysteries of volcanic activity.

Synthetic aperture radar is a valuable tool for the accurate mapping of the entirety of a volcano. Radar images and ranging also allow volcanologists to determine the deformation process pre and post eruption of a volcano. When combined with thermal imaging from IR sensing and panchromatic imaging, volcanologists successfully predicted an eruption. This prediction allowed emergency personnel to plan for the eruption (in fact, they had nearly two years to plan for the example given in the body of this paper), and develop safe evacuation routes for those living in the affected area.

IR remote sensing adds another layer of information to the DEM system, giving volcanologists valuable thermal data which aids in the prediction of eruptions. Also, emergency agencies can successfully track hot ash and gas clouds, giving them time to evacuate regions where the clouds will travel, thus saving lives in the process.

Spectrometry and spectrographic data collected in situ or via remote sensing techniques allows for the continued study of volcanic gaseous emissions. Emergency agencies and governmental agencies use spectrometer data to determine air quality near volcanoes, pre and post eruption. Often this data may correlate into the closure of parks, or areas near volcanic activity. Furthermore, spectrometry may be used to determine the total carbon and greenhouse gas emissions from volcanoes.

The science of volcanology continues to evolve, even today improved remote sensing techniques and instruments continue to be developed. No longer must volcanologists rely solely upon in situ seismic reading, as did Jagger and Perret in 1911. With continued monitoring and use of remote sensing technologies, volcanologists will continue to successfully predict eruptions (possibly even be able to give more accurate eruption dates/times), and give emergency agencies time to prepare for those eruptions.

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