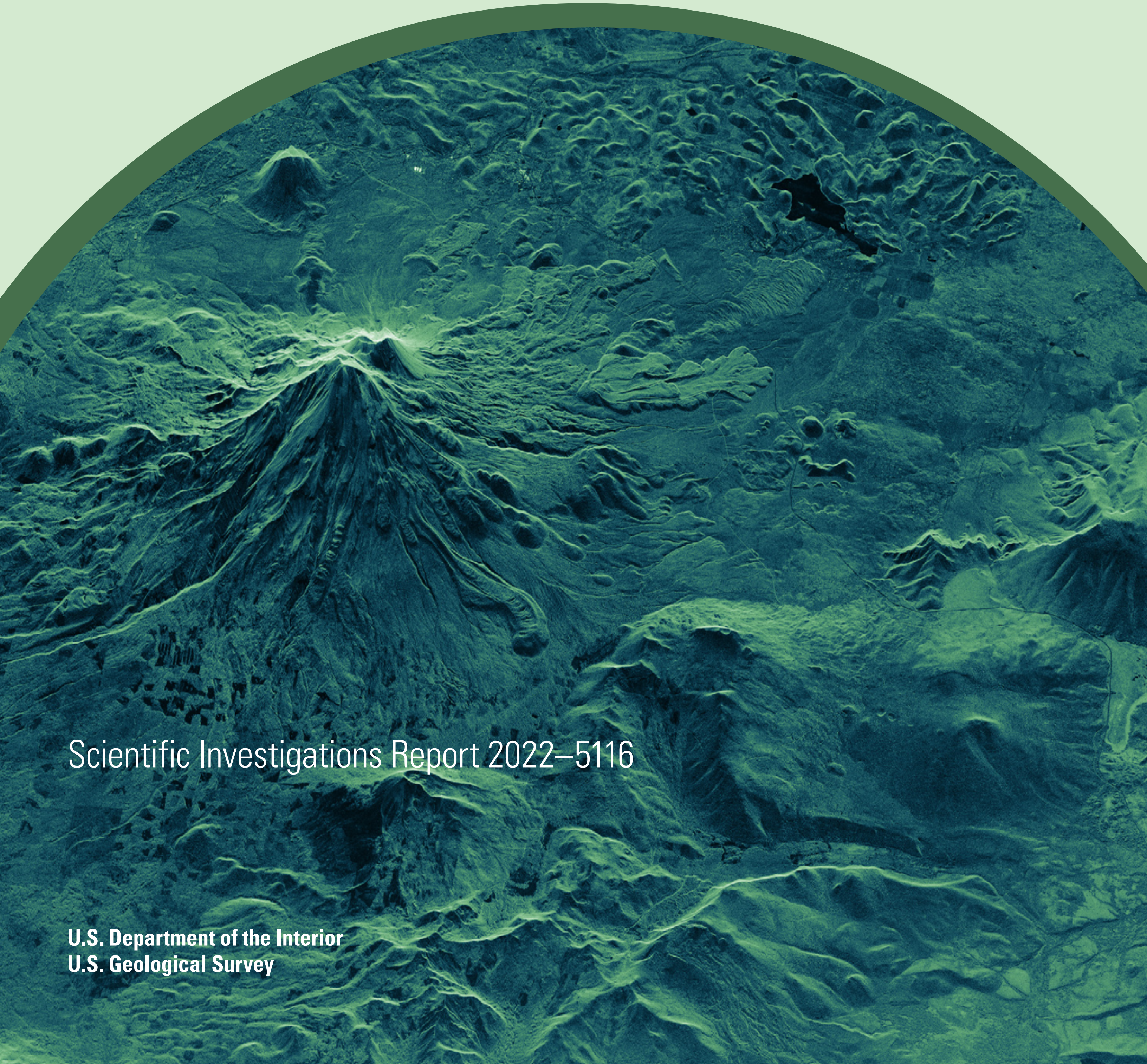
Optimizing Satellite Resources for the Global Assessment and Mitigation of Volcanic Hazards—Suggestions from the USGS Powell Center Volcano Remote Sensing Working Group



Scientific Investigations Report 2022–5116

U.S. Department of the Interior
U.S. Geological Survey

Cover: Synthetic aperture radar (SAR) image of Mount Shasta, California, acquired with the ICEYE SAR satellite constellation on February 23, 2021, at 22:57 UTC. North is to the right and illumination is from the west. Used with permission.

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M.E. Pritchard, M. Poland, K. Reath, B. Andrews, M. Bagnardi, J. Biggs, S. Carn, D. Coppola, S.K. Ebmeier, M.A. Furtney, T. Girona, J. Griswold, T. Lopez, P. Lundgren, S. Ogburn, M. Pavolonis, E. Rumpf, G. Vaughan, C. Wauthier, R. Wessels, R. Wright, K.R. Anderson, M.G. Bato, and A. Roman

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Abbreviations and Instrument Names

ABI	Advanced Baseline Imager
ACE	Atmospheric Chemistry Experiment
AHI	Advanced Himawari Imager
AIRS	Atmospheric Infrared Sounder
ALI	Advanced Land Imager
ALOS	Advanced Land Observation Satellite
ARIA	Advanced Rapid Imaging and Analysis
ASF	Alaska Satellite Facility
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVA	ASTER Volcano Archive
AVHRR	Advanced Very High Resolution Radiometer
AVO	Alaska Volcano Observatory
CEOS	Committee on Earth Observation Satellites
CGMS	Coordination Group for Meteorological Satellites
COMET	Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics
COSMO	COnstellation of small Satellites for the Mediterranean basin Observation
CSK	COSMO-SkyMed
CrIS	Cross-track Infrared Sounder
DEM	digital elevation model
DRM	Disaster Risk Management
DSCOVR	Deep Space Climate Observatory
EDM	Electronic Distance Measurement
Envisat	Environmental Satellite
EO	Earth observation
EO-1	Earth Observing-1
EP TOMS	Earth Probe TOMS
EPIC	Earth Polychromatic Imaging Camera
ERS	European Remote-Sensing Satellite
ESA	European Space Agency
GCOM-SGLI	Global Change Observation Mission-Second generation GLobal Imager
GCW	Global Cryosphere Watch
GEDI	Global Ecosystem Dynamics Investigation
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GEMS	Geostationary Environment Monitoring Spectrometer
GEP	Geohazards Exploitation Platform
GLISTIN-A	Glacier and Ice Surface Topography Interferometer–Airborne
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GOME	Global Ozone Monitoring Experiment
GOSAT	Greenhouse Gases Observing Satellite
GPS	Global Positioning System
GSNL	Geohazard Supersites and Natural Laboratories
GVM	Global Volcano Model
GVP	Global Volcanism Program
HDDS	Hazards Data Distribution System (USGS)
HIRS	High-resolution Infrared Radiation Sounder
HRWS	High Resolution Wide Swath

IASI	Infrared Atmospheric Sounding Interferometer
IAVCEI	International Association of Volcanology and Chemistry of the Earth's Interior
IAVW	International Airways Volcano Watch
ICAO	International Civil Aviation Organization
ICESAT	Ice, Cloud and Land Elevation Satellite
IR	infrared
InSAR	interferometric synthetic aperture radar
IPY	International Polar Year
JPL	Jet Propulsion Laboratory
KOMPSAT	Korean Multi-Purpose Satellite
LiCSAR	Looking into Continents from Space with Synthetic Aperture Radar
lidar	light detection and ranging
MetOp	Meteorological Operational satellite
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MIR	middle infrared
MIROVA	Middle InfraRed Observation of Volcanic Activity
MLS	Microwave Limb Sounder
MODIS	Moderate Resolution Imaging Spectroradiometer
MODVOLC	MODIS Volcano algorithm
MOPITT	Measurements of Pollution in the Troposphere
MOUNTS	Monitoring Unrest from Space
MSG	Meteosat Second Generation
N7 TOMS	Nimbus-7 TOMS
NASA	National Aeronautics and Space Administration
NERC	National Environmental Research Council (UK)
NIR	near infrared
NISAR	NASA–Indian Space Research Organization Synthetic Aperture Radar
NOAA	National Oceanic and Atmospheric Administration
OCO	Orbiting Carbon Observatory
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping and Profiler Suite
PEI	Population Exposure Index
PowellVolc	USGS Powell Center Volcano Remote Sensing Working Group
PPV	positive predictive value
PSTG	Polar Space Task Group
RSAT	RADARSAT
SAOCOM	Satélite Argentino de Observación COn Microondas [Argentine Microwaves Observation Satellite]

SAR	synthetic aperture radar
SARVIEWS	SAR Volcano Integrated Early Warning System (ASF SAR processor)
SBUV	Solar Backscatter Ultraviolet Instrument
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SNPP	Suomi National Polar-orbiting Partnership
SPOT	Satellite Pour l'Observation de la Terre [Satellite for Observation of Earth]
STAR	ASTER Science Team Acquisition Request
STREVA	Strengthening Resilience in Volcanic Areas
SWIR	shortwave infrared
TanDEM-X	TerraSAR-X add-on for Digital Elevation Measurement
TES	Tropospheric Emission Spectrometer
TIR	thermal infrared
TIROS	Television and InfraRed Operational Satellite
TOMS	Total Ozone Mapping Spectrometer
TOVS	TIROS Operational Vertical Sounder
TROPOMI	Tropospheric Monitoring Instrument
UAS	unoccupied aerial system
UAV	unoccupied aerial vehicle
UAVSAR	Uninhabited Aerial Vehicle Synthetic Aperture Radar
U.N.	United Nations
URP	ASTER Urgent Request Protocol
USGS	U.S. Geological Survey
UV	ultraviolet
VAA	Volcanic Ash Advisory
VAAC	Volcano Ash Advisory Center
VAL	Volcano Alert Level
VDAP	Volcano Disaster Assistance Program
VEI	Volcanic Explosivity Index
VIIRS	Visible Infrared Imaging Radiometer Suite
Vis.	visible wavelength
VOTW	Volcanoes of the World (Smithsonian Institution Global Volcanism Program database)
VSTG	Volcano Space Task Group
WMO	World Meteorological Organization
WOVO	World Organization of Volcano Observatories
WOVOdat	World Organization of Volcano Observatories database

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Executive Summary

A significant number of the world's active subaerial volcanoes are unmonitored by ground-based sensors yet constitute a potential hazard to nearby residents and infrastructure, as well as air travel and global commerce. Less than 35 percent of the approximately 600 volcanoes known to have erupted since 1500 C.E. have continuous ground monitoring. Data from an international constellation of more than 60 current satellite instruments provide a cost-effective means of tracking activity and potentially forecasting hazards at volcanoes around the world. These data span the electromagnetic spectrum—ultraviolet, optical, infrared, and microwave (synthetic aperture radar [SAR]). They can measure volcanic thermal and gas emissions, ground displacement, and surface and topographic change. Satellites offer the unique potential to globally monitor all approximately 1,400 subaerial volcanoes with Holocene eruptions using a common set of sensors to address one of the grand challenges in volcanology—to overcome our incomplete understanding of the relation between volcanic unrest and eruption, which is currently based on only a few well-studied volcanoes. Remote observations by satellite or aircraft will never replace ground-based volcano monitoring for timely assessments of volcanic activity, but both are needed to achieve the necessary spatial and temporal sampling on the scale of all the world's potentially active volcanoes.

Although the potential of volcano remote sensing has been recognized for decades, there are also well-known hurdles to clear before remote sensing data can be used fully by all volcano observatories. These include: (1) the limited temporal and spatial coverage of active volcanoes by satellites and the delayed distribution of those data; (2) the lack of background data acquired at all volcanoes; and (3) limited access to, and utilization of, remote sensing data in some areas due to a lack of expertise, licensing, user-friendly formats, data access portals, or computational infrastructure.

Recognizing these hurdles, an ad hoc working group of 25 scientists called PowellVolc was funded by the U.S. Geological Survey (USGS) Powell Center for Analysis and Synthesis to optimize satellite resources acquired from volcano remote sensing. PowellVolc has four aims:

- Coordinate and improve existing efforts to develop and link databases of satellite observations of volcanic thermal activity, outgassing, and ground deformation.
- Use these databases to answer a series of fundamental scientific questions about the value of multiparameter global volcano remote sensing and the relation between volcanic unrest and eruption.
- Make suggestions to space agencies about the best strategy for establishing a global volcano observatory that spans disciplinary and agency boundaries and can exploit the complete international constellation of Earth-observing satellites.

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[13]Pennsylvania State University.

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- Facilitate the use and interpretation of satellite data by local volcano observatories and other governmental agencies that are responsible for volcano monitoring and public outreach/civil protection worldwide.

We summarize three important lessons learned from the PowellVolc series of workshops and multidisciplinary publications:

- **There is value in combining multiple types of remote sensing.** Over 411 volcanoes (more than 66 in the United States) have produced signals of volcanic unrest (thermal anomalies, outgassing, and (or) deformation) that have been remotely detected by satellite from 1978 to 2021. Many more volcanoes have had no detectable signals despite high-quality measurements, although these null results need to be better documented. Satellite data have greatly increased the number of volcanoes with known unrest—for example, the number of volcanoes known to be deforming increased five-fold between 1997 and 2017. There is value in using multiparameter satellite data as each contributes unique but complementary information. In combination, these multiparameter observations can be used to classify volcanoes based on how eruptions are related to patterns of outgassing and deformation, which is important for understanding the relation between unrest and eruption. Satellite observations can help determine if a volcano is open (outgassing without deformation), closed (deformation without outgassing), or is in a different category. Our analysis of global remote sensing data confirms previous work that shows that volcano deformation can precede eruptions by several years but that currently available remotely sensed thermal emission and outgassing data are too coarse to consistently resolve precursory signals.

- **Remote sensing data complement ground monitoring (even at volcanoes with lots of sensors) but won't replace it.** Remote sensing data are being used by volcano observatories around the world operationally and synergistically with ground sensors to fill gaps in ground networks, evaluate noise in the ground observations, and decide alert levels. There are systematic differences between the types of signals and volcanic processes that are detected using satellite and ground-based data due to differences in spatial and temporal characteristics, measurement sensitivity, and differences in noise sources. Satellites may miss volcanic activity detected on the ground using sensors with higher spatio-temporal resolution and lower detection thresholds. Ground networks may miss signals detected in satellites that have superior synoptic coverage and (or) because existing ground networks lack certain types of sensors.

- **Remote sensing data are not yet fully exploited.** Satellites are not always collecting the optimal types of data at the relevant volcanoes with sufficiently high temporal sampling to facilitate eruption forecasting. A coordinated international observation strategy for volcanoes, similar to one used by the cryosphere community, along with a volcano space task group to maximize the utility of satellite data for volcano monitoring would be highly beneficial. We have developed a list of suggested observation frequencies for SAR and thermal sensors based on activity and SAR data quality for each of the approximately 1,400 potentially active subaerial volcanoes that can be used in developing such a strategy, but this list only addresses part of the problem. Other challenges are that the data collected are not always openly available, data processing may not be timely, and data products may be provided in a format that is neither user-friendly nor useful for forecasting. Error analysis on satellite data products that are quickly available during a crisis are sometimes cursory or interpretations from multiple external analysts are in conflict, which complicates exploitation by volcano observatories. To overcome these problems, we propose regular workshops linking volcano observatories around the world with remote sensing experts as well as a closed-forum communication tool to strengthen networks of expertise. Efforts to make data products more rapidly and readily available, for example, from interferometric SAR, should be encouraged.

We conclude with a vision for how the volcano remote sensing community could develop by 2030 to include (1) global coordination of satellite observations (as done for polar regions) for background monitoring and eruption response, (2) open data that can be rapidly distributed during crises, (3) communication tools and forums for discussion of satellite data, (4) integrated ground and satellite databases of unrest, and (5) global capacity building.

Key Points for Volcano Observatories

[Further information is provided in the sections noted in brackets.]

- Remote observations complement, but will never replace, ground-based volcano monitoring—both are needed to achieve the spatial and temporal sampling on the scale of all the world's volcanoes that is required for early warning, optimal situational awareness, and accurate hazard assessment. Only ground-based sensors can measure seismic waves. [Section 2.2.]

- Satellite data are being used routinely to detect eruptions and track changes in eruptive activity, but they can also be valuable for assessing levels of activity in the longer term and, in some cases, can contribute to datasets used for shorter-term forecasting. [Sections 2.2.2, 3.2.]

- There are several freely available sources of satellite data, as well as databases of satellite detections that can be used to guide future exploitation. However, these collections are often incomplete, are missing volcanoes without detections, and are neither user friendly nor well-linked to ground observations, thus limiting their use in forecasting. [Sections 3.1, 3.6.]
- Some volcano observatories (for example, in the United States and Iceland) routinely use satellite data to assess the current state of a volcano and to inform forecasts, but in many observatories around the world satellite data are not available in near-real-time, and the capacity to download and interpret information is limited. [Section 4.2.]
- The capabilities of the international satellite constellation to measure volcanic thermal output, outgassing, and deformation, are increasing, as are data volumes—automatic detection schemes are needed to track all these datasets in near real time. [Section 4.2.2.]
- Regular workshops linking volcano observatories with remote sensing experts, as well as a closed-forum communication tool, can strengthen networks of expertise, particularly during crises. Additionally, social media provides opportunities for partnerships between remote sensing experts, groups of hobbyists, tourists, and the volcano observatories. [Section 4.3.]

Key Points for Space Agencies

[Further information is provided in the sections noted in brackets.]

- An international effort to optimize volcano observation strategies from the international satellite constellation, following the model of the cryosphere community, would be beneficial. [Section 5.1.]
- There is a need to collect the right types of data (wavelength, repeat interval, spatial resolution) at the right volcanoes. A draft observation plan for the approximately 1,400 cataloged subaerial volcanoes, based primarily on levels of past activity, can provide a basis for prioritizing satellite data acquisitions. [Section 4.1.5, appendix 1.]
- Volcanic activity is most often observed by satellites in the thermal infrared. Yet the capability to make global high-spatial-resolution (<100 meters per pixel) satellite observations in the thermal infrared is being lost this decade and no immediate replacement is planned. [Section 4.1.1.]
- Background observations outside periods of unrest are critical for producing long time series and global coverage that can be used to assess potential unrest and forecast future behavior, but not all satellites acquire data at all volcanoes of interest, nor are all these data available to the communities that need them. [Sections 4.1, 5.1.]
- Free access to sustained, systematically acquired, global datasets is enhancing the work of volcano observatories and contributing to decisions regarding alert levels. Advances in processing and analysis strategies, including automation, will increase uptake of the data. [Section 4.2.2.]
- Restricted datasets that provide a diversity of wavelengths and higher resolutions have been critical to saving lives during some eruptions by supplying otherwise missing information that is critical to emergency response officials and volcanologists. Making these data more widely and easily available would greatly improve hazard response. [Section 4.2.1.]
- During volcanic crises, it is important that the acquisition plans are sufficiently flexible to accommodate additional tasking, and the data are provided at low latency. [Section 4.2.2]
- Increases in the availability and quality of satellite imagery are leading to important advances in the understanding of volcanic and magmatic processes and are directly contributing to the forecasting of volcanic hazards. [Sections 3.1, 3.4, 3.5.]

Key Points for Volcanologists

[Further information is provided in the sections noted in the brackets.]

- Global remote sensing of volcanoes addresses the current biased understanding of volcanic processes based on only a few well-studied volcanoes by increasing the number of observed volcanic systems by orders of magnitude. [Sections 3.1,3.4, 3.5.]
- Remote observations complement, but will never replace, ground-based volcano monitoring—both are needed to achieve the spatial and temporal sampling on the scale of all of the world's potentially active volcanoes to support early warning. [Section 2.2.]
- As with ground-based data, using multiparameter satellite data (for example, thermal emissions, outgassing, and deformation) improves the chances of detecting anomalies and understanding underlying volcanic processes. Each contributes unique insights, but all are fundamentally interconnected. [Section 3.1.]

- Multiparameter time series can be used to constrain statistical, conceptual, and physical models of magmatic plumbing systems, which are key for future improvement in understanding and forecasting the evolution of unrest and eruptions. [Section 3.4.]

- The abundance of satellite data facilitates the identification of common processes at unique volcanoes. For example, volcanic systems have been classified as open, closed, or other (Reath and others, 2019b) based on the relationship between outgassing, deformation, and eruption, and this information can be used to identify other volcanoes with similar patterns of behavior. [Section 3.4.]

- Thermal emissions, outgassing, and deformation satellite detections can precede eruptions, in some cases by months to years, but currently available global datasets are too coarse both spatially and temporally to systematically and reliably resolve precursory signals from background activity. [Section 3.3.]

- Future developments in understanding and forecasting volcanic behavior will come from the synthesis of satellite and ground-based data with conceptual and quantitative models that address the spectrum of global magmatic systems. [Section 5.4.]

1. Introduction

In recent years, there has been a dramatic increase in the number and capabilities of satellites to monitor the world's volcanoes. Nonetheless, most of these satellites are not yet optimized or coordinated for global application to volcano hazards. Here, we outline the current state of the art and limitations for volcano remote sensing and outline steps to improve the utilization of satellite data for volcano science and hazard mitigation.

1.1. Motivation for the Study

Volcanic eruptions pose a clear danger to society, with hazards including lava flows, debris avalanches, lateral blasts, pyroclastic density currents, tsunamis, lava dome growth and collapse, mudflows, and ash and gas clouds that can cause disruptions at both local (populations close to the volcano) and global (air traffic and climate disruptions) scales (Loughlin and others, 2015; National Academies of Sciences, Engineering, and Medicine, 2017). Despite the potential impacts of eruptions, relatively few of the world's approximately 1,400 potentially active[15] subaerial volcanoes

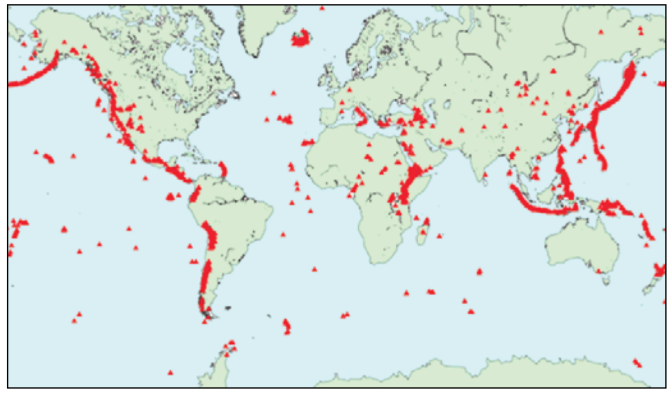


Figure 1. Global map of volcanoes known to have erupted within the Holocene (red triangles). Modified from Global Volcanism Program (2013).

(fig. 1) are monitored by ground-based systems due to the expense associated with the installation and maintenance of monitoring infrastructure, as well as the remote locations of many volcanoes. In fact, only about half of the potentially active volcanoes on Earth have any ground-based monitoring, and less than 35 percent of the volcanoes known to have erupted since 1500 C.E. are continuously monitored using ground sensors (Brown, Loughlin, and others, 2015; Brown, Sparks, and others, 2015; Loughlin and others, 2015).

A growing number of volcano monitoring parameters are now measurable from space. The blending of complementary satellite and ground-based datasets of volcano parameters will lead to greater recognition and quantification of thermal, ash, and gas emissions, surface change, and deformation (for example, figs. 2, 3; Francis and others, 1996; Francis and Rothery, 2000; Mouginis-Mark and others, 2000; Hooper and others, 2012; Dean and Dehn, 2015; Poland and others, 2020). Satellite observations are not meant to replace ground-based volcano monitoring as both are needed to collect the necessary spatial and temporal information on a worldwide scale to detect changes in volcanic activity (see section 2.2). Satellite data are collected by an ever-increasing number of instruments in the international satellite constellation (called a virtual constellation by some; for example, Wulder and others, 2015) spanning the electromagnetic spectrum (table 1; fig. 4): ultraviolet (UV), optical, infrared (IR, subdivided into shortwave [SWIR], middle [MIR], and thermal [TIR]), and microwave (synthetic aperture radar [SAR]). During the past ~40 years (1978–2021), these remote sensing observations have proven their worth both in volcano monitoring by detecting and tracking unrest[16] and eruptions as well as for eruption forecasting and understanding the fundamental processes occurring at volcanoes (for example, Dean, Osiensky, and others, 2015; National Academies of Sciences, Engineering, and Medicine, 2017; Pritchard and others, 2018; Garthwaite and others, 2019; Poland and Anderson, 2020).

[15] What is a potentially active volcano? Some lists include only volcanoes (fig. 1) that have erupted in the Holocene (the last 12,000 years), but as we discuss in section 2.2.1., older volcanoes also have activity (for example, seismicity, deformation, thermal features) and should be included. Table 3 and appendix 1 include different classifications of activity for approximately 1,400 subaerial volcanoes, depending on detected activity and eruptions.

[16] Unrest is defined as: "the deviation from the background or baseline behavior of a volcano towards a behavior which is a cause for concern in the short-term because it might prelude an eruption" (Phillipson and others, 2013).

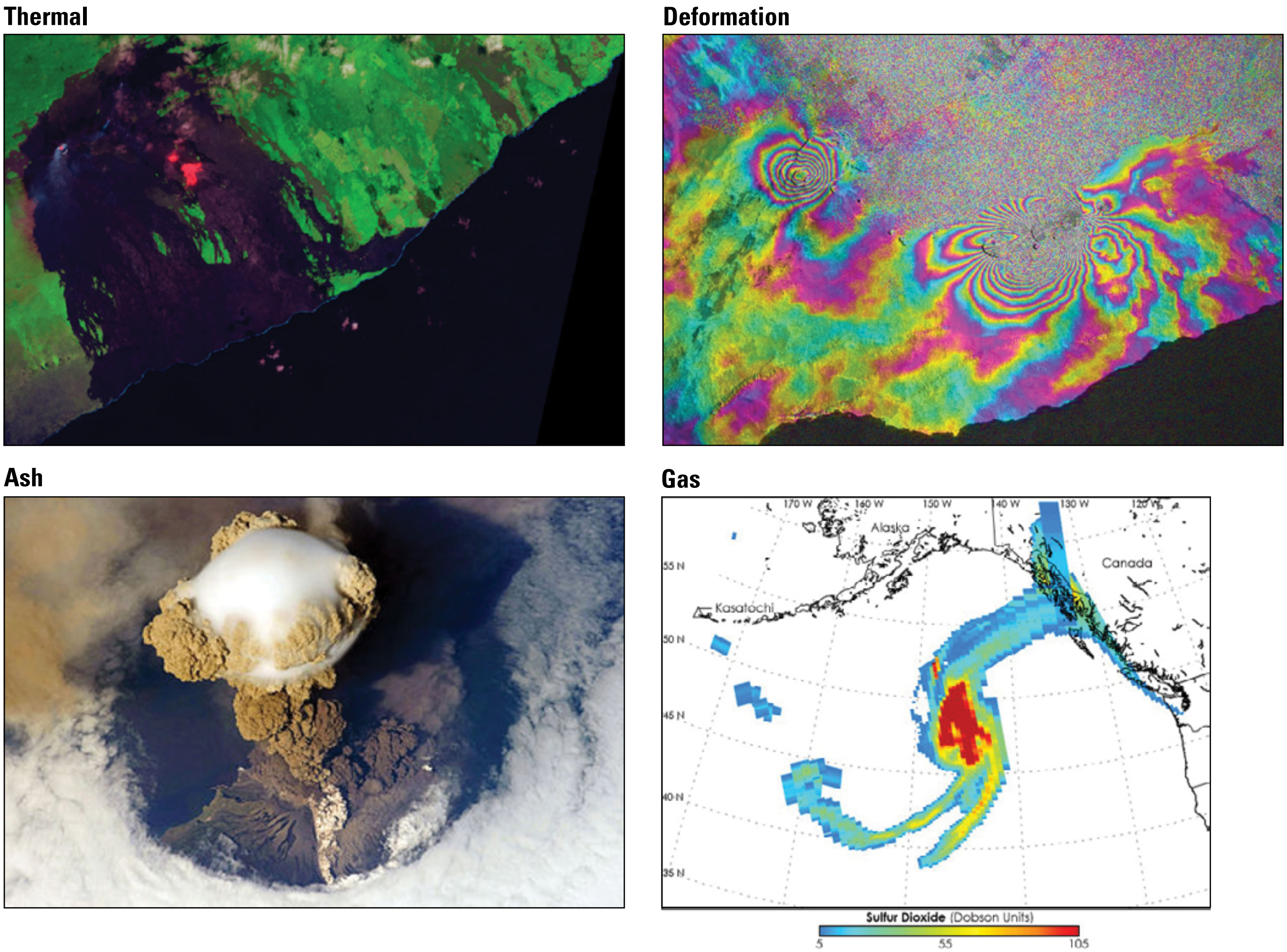
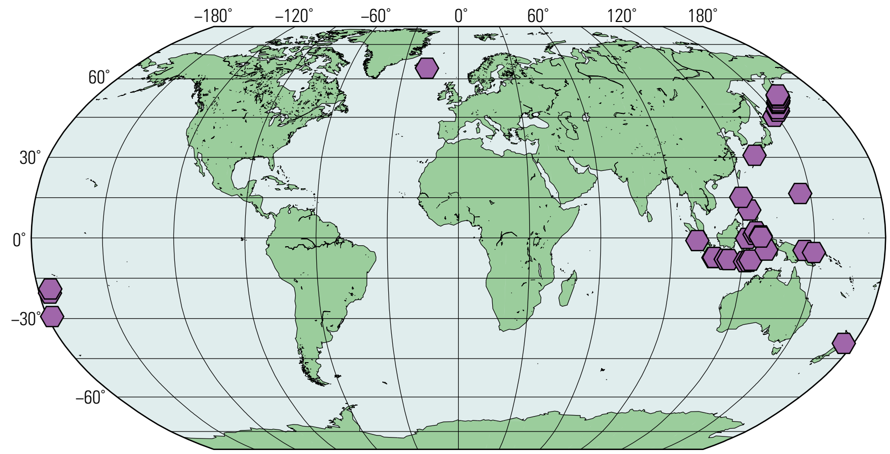


Figure 2. Images showing examples of satellite volcano-monitoring products illustrating the detection of thermal emissions (Kīlauea from the Advanced Land Imager [ALI] on NASA's Earth Observing-1 [EO-1] satellite, January 16, 2010; courtesy of the USGS Hawaiian Volcano Observatory); ash emissions (Sarychev Peak, Kuril Islands, eruption from the International Space Station, July 12, 2009; courtesy of NASA, Astronaut photo ISS020-E-9048); deformation of Earth's surface (Kīlauea East Rift Zone intrusion/eruption interferogram from COSMO-SkyMed data, collected between February 11, 2011, and March 7, 2011); and gas (SO_2) emissions (Kasatochi, Alaska, eruption in 2008 from Ozone Monitoring Instrument [OMI], August 10, 2008; Krotkov and others, 2010).

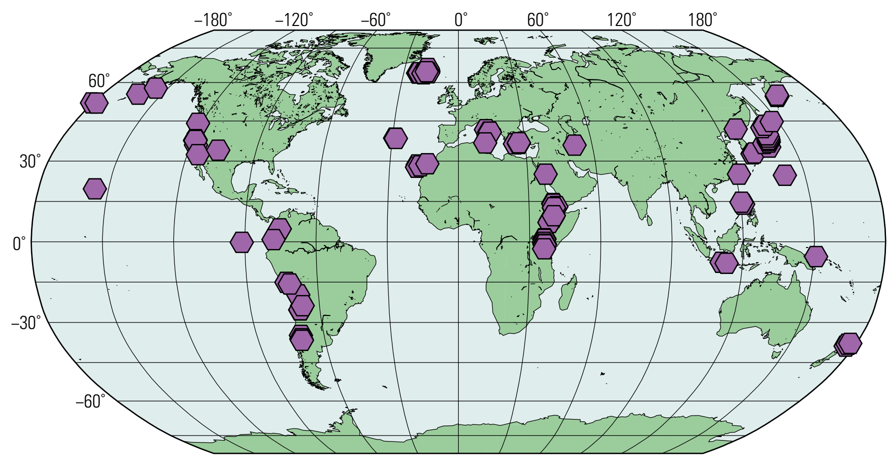
For example, Volcanic Ash Advisory Centers (VAACs) operationally use satellite data in combination with other data and models to issue Volcanic Ash Advisories (VAAs) for aircraft safety, a service mandated by the United Nations (U.N.) International Civil Aviation Organization (ICAO) International Airways Volcano Watch (IAVW) (for example, Prata and Tupper, 2009; Lechner and others, 2018; ICAO, 2019; Pallister, Papale, and others, 2019). IAVW has noted the need for improved information on preeruptive activity (World Meteorological Organization [WMO], 2019).

Satellites offer the unique potential to globally monitor all subaerial (and some submarine) volcanoes with a common set of instruments that can address one of the grand challenges in volcanology—to overcome biases in our current understanding of the relation between volcanic unrest and eruption, which is currently based on only a few well-studied volcanoes (for example, Cashman and Biggs, 2014; National Academies of Sciences, Engineering, and Medicine, 2017). The ultimate goal for most volcanologists is to improve forecasts of volcanic hazards in order to save lives and property. Incorporating

***A*. Volcanoes with anomalies only detected by UV satellites**



***B*. Volcanoes with anomalies only detected by SAR satellites**



***C*. Volcanoes with anomalies only detected by TIR satellites**

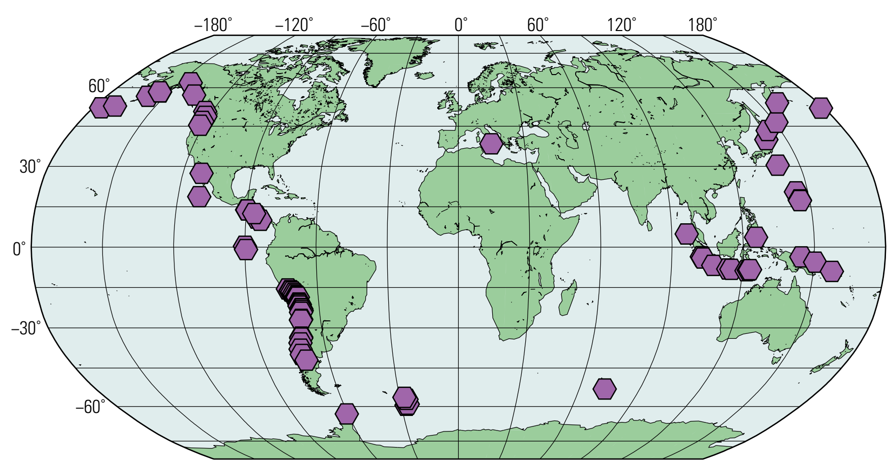


Figure 3. Global maps showing locations of satellite detections of volcanic unrest between 1978 and 2020 compiled from available databases (appendix 1), modified from Furtney and others (2018). Volcanoes that are detected by only one satellite technique are shown—volcanoes detected by multiple techniques are not included. UV, ultraviolet; SAR, synthetic aperture radar; TIR; thermal infrared.

Table 1. Civilian satellite instruments frequently used for volcano remote sensing as of 2021.

[Some older satellites are included if they are multigenerational satellites with similar capabilities. See definition of wavelength bands in the electromagnetic spectrum in figure 4. Information taken from National Aeronautics and Space Administration (NASA) (2018); Pritchard and Yun (2018); and Hormann (2021). Satellites with restricted data policies are at the bottom of the table. See "Abbreviations and Instrument Names" list for definitions of instrument names. For some synthetic aperture radar (SAR) sensors, a range of spatial resolution is given where there are different observation modes (spotlight, stripmap, scansar, and so on) with different spatial resolutions. For gas emissions, we list whether the sensor only detects large-magnitude signals (E, large eruptions only) or both eruptions and passive detections (B). Another key attribute not described is the observation strategy that some satellites collect only targeted, not global, data or only during the day. m, meters; UV, ultraviolet; Vis., visible wavelength; NIR, near infrared; SWIR, shortwave infrared; MIR, mid infrared; TIR, thermal infrared; high res., high resolution; DEM, digital elevation model]

Data source	Lifespan	Sampling rate (days)	Data focus	UV	Vis.	NIR	SWIR	MIR	TIR	Radar
				(m/pixel)*						
Open data policy										
Sentinel-2	2015–	5	Optical and thermal		10	10	20			
Sentinel-3	2017–; 2018–	2–3	Thermal		~300	~300	~500	~500	~500	
Himawari-8/ ABI	2015–	<1	Thermal		500	1,000	1,000	2,000	2,000	
GCOM-SGLI	2012–	2–3	Optical and thermal		250	250	250	250	250	
AVHRR	1978–1980; 1979–1986; 1981–1986; 1983–1985; 1984–1994; 1986–1991; 1988–1994; 1991–1994; 1994–2007; 1998–; 2000–2014; 2002–2013; 2005–; 2006–; 2009–; 2012–	<1	Thermal		1,500	1,500	1,500	1,500	1,500	
Landsat-5	1984–2013	16	Optical and thermal		30	30	30		120	
Landsat-7	1999–	16	Optical and thermal		15	30	30		60	
Landsat-8	2013–	16	Optical and thermal		15	30	30		100	
Landsat-9	2021–	16	Optical and thermal		15	30	30		100	
GOES-16/17	2016–	<1	Thermal and outgassing (E)	2,000	500	1,000	2,000	2,000	2,000	
ASTER	1999–	16	Thermal and outgassing (B)		15	15	30 (died in 2008)		90[a]	
MODIS	1999–; 2002–	<1	Thermal and outgassing (E)		250	250	250	~1,000	~1,000[b]	

Table 1. Civilian satellite instruments frequently used for volcano remote sensing as of 2021.—Continued

Data source	Lifespan	Sampling rate (days)	Data focus	UV	Vis.	NIR	SWIR	MIR	TIR	Radar
				(m/pixel)*						
SNPP/VIIRS	2011–	<1	Thermal and Outgassing (E)		375	375	375	375	375	
TOMS	1978–1993; 1991–1994; 1996–2005	1	Outgassing (E)	4,700[c]						
Aura/OMI	2004–	1	Outgassing (E)	13,000[c]						
SNPP/OMPS	2011–	1	Outgassing (B)	50,000						
NOAA-20/OMPS	2017–	1	Outgassing (B)	50,000						
MetOp/IASI	2006–; 2012–	<1	Outgassing (E)	12,000						
S5P/TRO-POMI	2017–	1	Outgassing (B)	3,500						
Aqua/AIRS	2002–	<1	Outgassing (E)	13,500						
DSCOVR/EPIC	2015–	<1	Outgassing (E)	10,000						
MetOp/GOME-2	2006–; 2012–	1	Outgassing (B)	40,000						
Sentinel-1a,1b	2014–; 2016–2021	12, 6	Deformation							5–40
Restricted data policy										
TerraSAR-X; TanDEM-X; Paz	6/2007–; 6/2010–; 2/2018–	4, 7, 11	Deformation, high-res. SAR imagery and radar DEMs							1–16
RADAR-SAT-2	12/2007–	24	Deformation							3–100
COSMO-SkyMed	6/2007–; 12/2007–; 10/2008–; 11/2010–	1, 3, 4, 8	Deformation and high-res. SAR imagery							1–100
ALOS-2	2014–	14	Deformation							1–100
ICEYE	7+ satellites 2018–	1–22	High-res. SAR imagery							0.25–15
Capella Space	7+ satelltes 2020–	1+	High-res. SAR imagery							0.5–12
MSG/SEVIRI	2004–	<1	Outgassing (E)	3,000				5,000	5,000	
Pleiades 1A, 1B	2011–; 2012–	~7	Optical DEMs and imagery		<1	<1				

Table 1. Civilian satellite instruments frequently used for volcano remote sensing as of 2021.—Continued

Data source	Lifespan	Sampling rate (days)	Data focus	UV	Vis.	NIR	SWIR	MIR	TIR	Radar
							(m/pixel)*			
SPOT 6, 7	2012–; 2014–	~7	Optical DEMs and imagery		1–6	1–6				
Planet	100+ Cubesats 2013–	<1	Optical imagery		<1–5	<1–5				
WorldView	2007–; 2009–; 2014–	~7	Optical DEMs and imagery; thermal		<1	<1	3.7 (WV 3)			

*Approximate spatial resolution specified at nadir (except for SAR sensors), with the wavelength of the band given where resolution changes with wavelength band.

[a]Data used by Furtney and others (2018) for global compilation of thermal activity at volcanoes for selected regions

[b]Data used by Furtney and others (2018) for global compilation of thermal activity at volcanoes.

[c]Data used by Furtney and others (2018) for global compilation of degassing activity at volcanoes

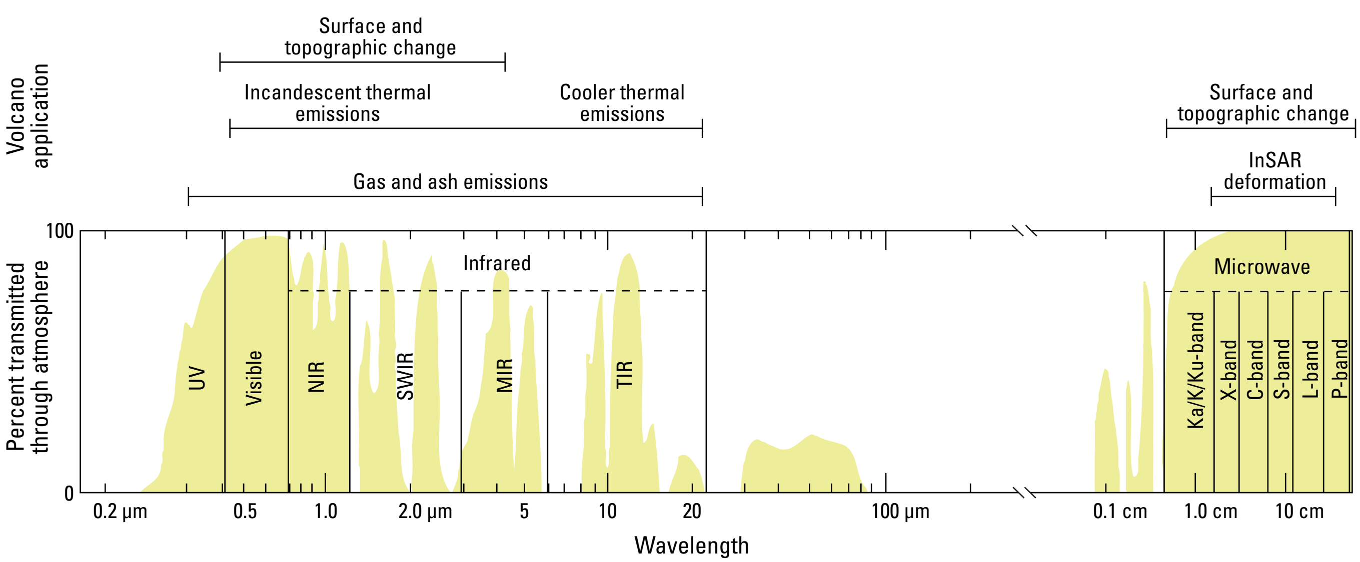


Figure 4. Plot of transmission of electromagnetic radiation through the atmosphere as a function of wavelength, with the various wavelength regions and bands labeled along with volcanological applications. There is a break in scale between the infrared and microwave regions and different wavelength scales in each region. The microwave region is subdivided into radar bands, corresponding to defined frequencies and wavelengths (Bruder, 2013). Modified from NASA (https://earthobservatory.nasa.gov/features/RemoteSensing/remote_04.php). UV, ultraviolet; NIR, near infrared; SWIR, shortwave infrared; MIR, mid infrared; TIR, thermal infrared; InSAR, interferometric synthetic aperture radar; µm, micrometer; cm, centimeter.

satellite and ground-based observations into global databases of volcanic unrest (for example, Newhall and others, 2017; Costa and others, 2019) will enable the field of "comparative volcanology" (or "global volcanology") to further develop. One testable hypothesis centers on the idea that practically no volcano is totally unique in all aspects, so similar patterns of behavior and thus common processes and features among disparate systems (sometimes called analogues or peer groups [Cashman and Biggs, 2014]) may be identifiable. Given the limits of ground-based monitoring already mentioned, satellite observations are needed to achieve a more representative global sampling. For example, satellites enable routine monitoring of volcanoes that are not currently active but might become active, because volcanoes without previously recorded activity may not have ground-based baseline data. Satellites can also monitor volcanoes that are away from population centers and (or) air travel corridors and thus have not been prioritized for ground-based monitoring. A major advantage of satellite observations is that they can be made in locations that are inaccessible or too dangerous for ground-based sensors. It is critical that a volcano database include unrest (detected on the ground and by satellites) that leads to eruption as well as unrest that stalls without eruption. Such a database should encompass a spectrum of volcano types and tectonic settings. A comprehensive approach to both satellite- and ground-based data are needed to avoid losing information about unrest that doesn't lead to eruption (so called "failed eruptions"), because information on failed eruptions is not commonly published in the literature (for example, Moran and others, 2011).

Exploitation of satellite data for the global assessment and mitigation of volcanic hazards has not yet achieved its full potential, even at the VAACs (Zehner, 2010), for several reasons (for example, Ernst and others, 2008; Bally, 2012; Garthwaite and others, 2019). No satellite dedicated to volcano monitoring has been launched, and so neither the instruments nor observation strategies of existing satellites are optimized for volcanoes (for example, Francis and others, 1996; Wadge, 2002; Harris, 2013). Furthermore, there are challenges to using the satellite data acquired in operational and scientific studies by the more than 100 volcano observatories (Loughlin and others, 2015) that are governmentally responsible for volcano monitoring (called State Volcano Observatories by ICAO, most of which are listed on the World Organization of Volcano Observatories [WOVO] website,[17] https://wovo.iavceivolcano.org/observatories). Obstacles to broader use of remote sensing data by volcano observatories include the following: some satellite data are prohibitively expensive, especially for volcano-monitoring agencies in developing countries where some of the most severe volcanic risk exists; images are not always acquired over active volcanoes and, when they are, the distribution of those data is not always timely; international space agencies receive conflicting requests, leading to inconsistent acquisitions over active volcanoes; and access and utilization of remote sensing data are limited in some areas owing to a lack of expertise, licensing, user-friendly data formats or access portals, or computational infrastructure (for example, Ernst and others, 2008; Bally, 2012; Sparks, Biggs, and Neuberg, 2012; Sparks, Loughlin, and others, 2012; Garthwaite and others, 2019). More broadly, Bally (2012) noted that challenges for using remote sensing data across all disciplines include constantly changing satellite datasets and lack of knowledge about what remotely sensed data are available, how they have been successfully applied, and how they could benefit the end user.

The problems identified above have been recognized by the international volcano remote sensing community for years (for example, National Research Council, 1995; Francis and Rothery, 2000; Wadge, 2002; Stevens and Wadge, 2004; Lechner and others, 2009), and there has been some progress to date on addressing key issues. Although there are no

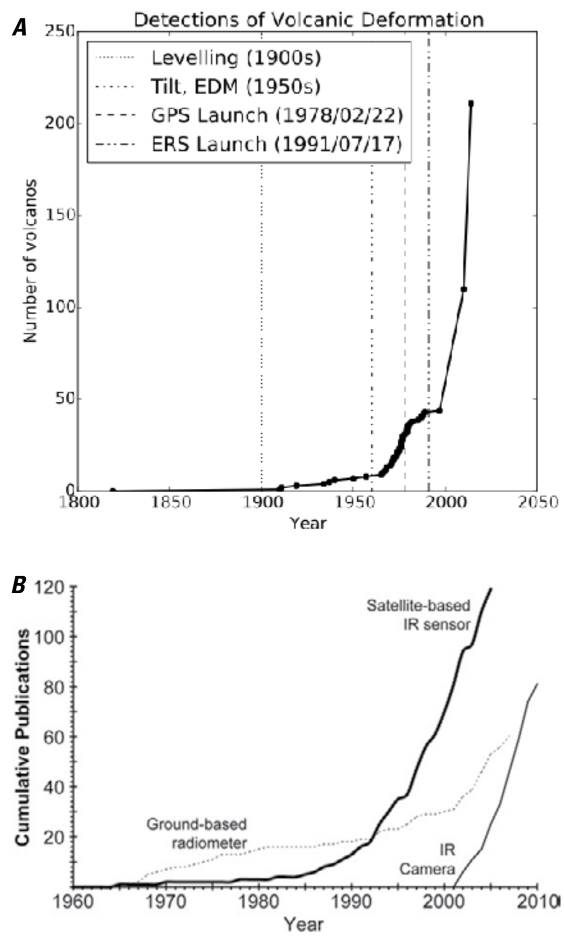


Figure 5. Plots showing growth in the number of volcanoes with ground deformation detected mostly using satellites (top) (from Henderson, 2015) and the number of publications using thermal sensor data to study volcanoes (bottom) (from Ramsey and Harris, 2013). EDM, electronic distance measurement; GPS, Global Positioning System; ERS, European Remote-Sensing Satellite; IR, infrared.

[17]See also list of volcano observatories in Brown, Sparks, and others (2015) and International Civil Aviation Organization (2019).

satellites devoted to volcano monitoring, there are significant resources already in orbit (table 1), and acquisitions by those sensors are increasingly being coordinated and made more widely and rapidly available. As a result, the number of volcanoes known to be hosting thermal emissions, outgassing, and (or) deforming has been increasing (fig. 5). One important achievement in understanding what is possible from space in terms of volcano remote sensing was the development of global compilations of volcanoes with satellite-detected thermal emissions (Wright, 2015), gas emissions (Carn and others, 2017), and deformation (Biggs and others, 2014; Biggs and Pritchard, 2017; Ebmeier and others, 2018), which can span multiple decades (see section 3). While each compilation is incomplete, for the first time it is possible to make a global assessment of the value of satellite remote sensing from multiple datasets in varied environments and at volcanoes with different characteristics—a necessary step in developing an appropriate global volcano observation strategy. With respect to such a strategy, a major milestone was the 2012 European Space Agency (ESA) "Santorini report" that envisioned an integrated global remote sensing geohazard monitoring effort for disaster risk management spanning 5 to 10 years (Bally, 2012). Several efforts since then have advanced the goals of the Santorini report, including the volcano pilot and demonstrator projects of the Committee on Earth Observation Satellites (CEOS) (Pritchard and others, 2018; Delgado and others, 2019), and the Geohazard Supersites and Natural Laboratories (GSNL) initiative of the Group on Earth Observations (GEO) (Salvi, 2016).

1.2. Goals and Scope of the Powell Center Volcano Remote Sensing Working Group

To capitalize on developments since the Santorini report (Bally, 2012), we brought together representatives of several volcano remote sensing initiatives, as well as other scientists from the volcano remote sensing community. With support from a 3-year grant (2016–2019) from the U.S. Geological Survey (USGS) Powell Center for Analysis and Synthesis, this team became the Powell Center Volcano Remote Sensing Working Group (abbreviated as PowellVolc). The USGS Powell Center funded three week-long workshops for a working group of about 25 people and partially funded a postdoctoral fellow for 2 years (see appendix 2 for list of participants in each year). Although workshop participation was limited to this small group, we sought input from a larger community during conference presentations, workshops, and other venues, especially during a 2-day workshop of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) in 2017 (Reath and others, 2017, 2018) and an online 4-day workshop in 2021 (Pritchard, 2021).

The goals of the working group were to

1. Coordinate and improve existing efforts to develop and link databases of satellite observations of volcanic activity.
2. Use these databases to understand relations among quiescence, unrest, eruption, and remote sensing data by addressing the following scientific questions:
   - What remote sensing datasets are most critical for detecting changes in eruptive activity given varied styles of volcanism and diverse environmental settings?
   - Are there conditions in which certain types of satellite-detected unrest are more useful than others?
   - If we detect unrest at a volcano from satellites, when does it indicate an impending eruption and when does it not?
   - When a volcano erupts without satellite detected unrest, is the lack of detection due to limited spatial, temporal, or spectral resolution, or is it a true reflection of a magmatic system that doesn't provide reliable precursors?
3. Make suggestions to space agencies regarding a strategy for a global volcano observatory that spans disciplinary and agency boundaries and exploits the complete international constellation of more than 60 relevant satellites.
4. Facilitate the use and interpretation of satellite data by volcano observatories and other agencies that are responsible for volcano monitoring, public outreach, and civil protection.

These four goals will be addressed in different parts of this report: goals 1 and 2 are addressed in section 3, and goals 3 and 4 are addressed in section 4. These goals all focused on satellites because of their global monitoring capabilities. We also discuss ground-based and airborne observations, especially with regard to the increasing importance of unoccupied aerial vehicles (UAVs, also known as drones or unoccupied aerial systems [UAS]), which are critical complements to satellite observations.

This document is the final report of PowellVolc and specifies the progress toward the four goals outlined above, as well as some of the remaining work to be done. We expect the team to informally continue working toward the overall goals outlined above, taking advantage of the relationships and knowledge gained during the formal years of the project. In the following sections, we

1. provide a brief overview of the wide array of types of volcano remote sensing and how they are used by volcano observatories (section 2);
2. describe lessons learned from compiling global observations of volcanic activity from satellites (section 3) and expose barriers to the wider use of remote sensing data to study volcanoes (section 4);
3. suggest possible pathways to overcome these barriers (section 4); and
4. present a vision for improving global volcano remote sensing and eruption forecasting (section 5).

2. Background on Satellite Volcano Remote Sensing

Since 1978, more than 60 satellites have been used in a wide variety of volcanological studies (table 1). As we illustrate in section 3, the advantage of having so many remote sensing tools is that using them simultaneously can provide abundant information on magmatic source processes and can overcome the limitations of each technique. However, it is rarely practical to be an expert in all remote sensing techniques, so interdisciplinary collaboration among remote sensing experts is required. This challenge is not unique to satellite data, and interdisciplinary collaboration is a requirement of volcano science.

To increase awareness of the multitude of tools available, we provide a brief survey of the different types of volcano remote sensing and their capabilities in section 2.1. There is no modern review paper or book that covers all of volcano remote sensing—the best available are Mouginis-Mark and others (2000); Joyce and others (2009); Hooper and others (2012); Dean and Dehn (2015); and Poland and others (2020), but all have gaps in important areas. In the sections that follow, we refer to technique-specific review papers and textbooks for more indepth information. We focus on methods that monitor changes in volcanic activity, in particular techniques that can be used to anticipate eruptions (for example, Papale, 2017). We do not discuss the rich literature that investigates volcanoes during time periods when they aren't changing—to determine the relative age or composition of a volcano or lava flow based on morphological features (for example, de Silva and Francis, 1991), multi- or hyperspectral data (for example, Kahle and others, 1988; Bonneville and others, 1989), topography (for example, Wright and others, 2006; Huggel and others, 2008), or radar characteristics (for example, Farr, 1992; Rowland and others, 1994) on Earth or other planets (for example, Head, 1976; Head and others, 1992; Hamilton and others, 2001; Davies, 2008).

Not all techniques used to monitor volcanoes are at the same level of maturity or used widely at all of Earth's potentially active volcanoes. To give a sense of these different maturity levels, we describe when each method was first used for volcano monitoring, and when the first global compilations of volcanic activity using that technique were attempted (if they exist).

In section 2.2.1, we document why the synoptic view of satellite remote sensing is useful for monitoring Pleistocene or even Pliocene volcanoes (within the last 5.3 million years)—as well as Holocene (within the last 11,600 years) or historically active volcanoes (within the last few thousand years, depending on the location). Finally, in section 2.2.2, we document how satellite observations are being used today at volcano observatories in multisensor volcano monitoring.

2.1. Types of Volcano Remote Sensing

2.1.1. Thermal Emissions

Volcanic thermal features associated with, for example, lava flows, lava lakes, hot ash clouds, hot springs, warm crater lakes, and hot vents or fumaroles can be detected using TIR, SWIR, or MIR satellite sensors (table 1; fig. 4). Three distinct categories of sensors exist (table 1): (1) low-spatial-resolution but high-temporal-resolution geostationary weather satellites, such as Himawari and Geostationary Operational Environmental Satellite (GOES), which have a spatial resolution of more than 1 kilometer per pixel (km/pixel) and images every few minutes (MIR, TIR); (2) moderate spatial and temporal resolution polar-orbiting sensors such as Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS), which provide several images per day at pixel spacing greater than or equal to 0.375 km/pixel; and (3) high-spatial-resolution but low-temporal-resolution SWIR and TIR systems such, as Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Landsat-8 and -9, and Sentinel-2, which provide images at resolutions of less than or equal to 100 meters per pixel (m/pixel) but have revisit intervals of days to weeks or longer. There are several review articles on thermal remote sensing of volcanoes (Harris and others, 2000; Flynn and others, 2000; Ramsey and Harris, 2013; Ramsey and others, 2015, 2022; Carn, 2015a; Dehn and Harris, 2015) as well as a textbook (Harris, 2013).

Temperature increases associated with eruptions were historically among the first detections of volcanic eruptions from space, dating back to the early weather satellites in the 1960s (for example, Gawarecki and others, 1965; Williams and Friedman, 1970), although thermal data weren't used quantitatively until the 1980s (Harris, 2013). Now, an important application of these data is inferring the effusion rates of lava flows (Harris and others, 2007). Compilations of global thermal activity were made using moderate spatial resolution MIR/TIR sensors by Wright (2015), but no global compilation of low-spatial-resolution MIR/TIR or high-spatial-resolution TIR (<100 m/pixel) spanning multiple decades has been completed. Regional surveys indicate 3 to 4 times more volcanoes show thermal detections in high-resolution TIR imagery, which can reveal low-temperature thermal emissions like fumaroles, compared to lower resolution MIR and TIR imagery that only detect high-temperature lava near the surface (for example, Jay and others, 2013; Reath and others, 2019a). Moderate-resolution MIR and TIR and high-resolution TIR measurements are complementary—whereas the former measures the thermal flux during an ongoing eruption, without saturation, the latter allows detection of thermal emissions at lower temperatures.

2.1.2. Gas Emissions

Satellite measurements of volcanic outgassing focus almost exclusively on sulfur dioxide (SO_2) emissions even though SO_2 emissions represent less than 5 percent of the total volcanic gas flux (Carn and others, 2016). These emissions are easily detectable by UV and MIR or TIR instruments designed to measure other atmospheric constituents, such as ozone, water vapor, and clouds. Consequently, measurements of volcanic SO_2 have been available since 1978 (Carn and others, 2016), whereas satellite detection of other volcanic gas species (fig. 6) such as H_2S, HCl, BrO, and CO_2 (for example, Theys and others, 2009; Clarisse and others, 2011; Schwandner and others, 2017) have been made only occasionally and only for more recent eruptions (from about 2006 to present). Gas and ash emitted from volcanoes are sometimes grouped together under the categories of “volcanic emissions” or “volcanic clouds” (for example, Krueger and others, 2000), and the contributions of each can be difficult to separate in fresh (few-hours-old) eruption clouds. Therefore, simultaneous study of both is needed (Prata, Dean, and Watson, 2015). We have separated outgassing and ash emissions for the purpose of this discussion because gas emissions can occur without eruption (called passive outgassing) . Although global compilations of SO_2 emissions spanning multiple decades have been assembled, no such database exists for ash (see section 2.1.5). Several review papers describe methods to detect and quantify volcanic gases (for example, Krueger and others, 2000; Realmuto, 2000; Brenot and others, 2014; Carn, 2015a; Prata, Bluth, and others, 2015; Carn and others, 2016; Prata, 2016). The first satellite observations of volcanic outgassing were the unexpected detection of SO_2 from the El Chichón, Mexico, eruption in 1982 by the Total Ozone Mapping Spectrometer (TOMS) ozone sensor (Krueger, 1983). Inventories of global satellite SO_2 outgassing during eruptions are available from 1978 to present (Carn, 2015b) and during noneruptive periods from 2005 to present (Carn and others, 2017).

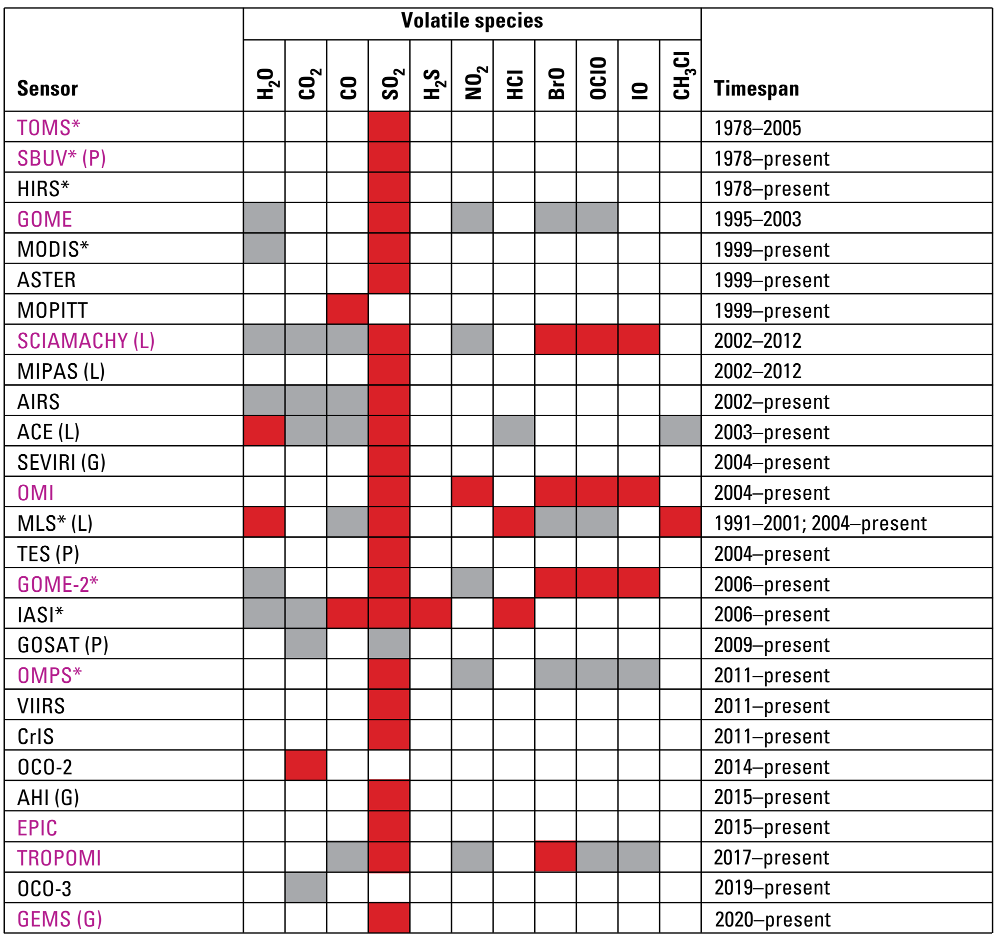


Figure 6. Chart showing past and current satellite sensors capable of detecting volcanic gases. Sensor names in magenta text are ultraviolet sensors. *, sensors flown on multiple satellites. P, nadir profiling and (or) pointable instrument (limited mapping capability); L, limb instrument (vertical profiling). Red boxes indicate confirmed detection in a volcanic plume; gray boxes indicate potential sensitivity but no confirmed detection in a volcanic plume to date. The only two datasets used in the global compilation of outgassing volcanoes by Furtney and others (2018) are from OMI and TOMS. See figure 23 to compare the pixel sizes of these different instruments and figure 4 and table 1 for the electromagnetic wavelengths used and whether the data are open access or restricted. Modified from Carn and others (2016). See “Abbreviations and Instrument Names” list for definitions of instrument names.

2.1.3. Surface and Topographic Change[18]

Satellite imagery from optical and SAR satellites, particularly at spatial resolutions of a few meters per pixel or better (see table 1), are extremely useful during volcanic crises for tracking surface changes related to extrusions and explosions. In fact, SAR imagery was the primary satellite data that contributed to warnings credited with saving thousands of lives during the 2010 eruption at Merapi, Indonesia (Pallister and others, 2013), because of its ability to detect surface changes through most clouds and collect useful data during the day or night. Surface changes detectable from space by high-spatial-resolution SAR and optical imagery can be caused by a variety of processes, including explosions, lava flows (for example, Wadge and others, 2012), dome growth (for example, Pallister and others, 2013; Chaussard, 2017; Pallister, Wessels, and others, 2019), ashfall (Arnold and others, 2018), and pyroclastic flows or lahars (for example, Pallister, Wessels, and others, 2019). Images collected at different times can be compared manually by an analyst or through automatic change detection algorithms. For SAR imagery, surface change can be detected in several ways (for example, Pritchard and Yun, 2018): backscatter[19] (Yun and others, 2007); coherence (for example, Zebker and others, 1996; Dietterich and others, 2012); and phase (section 2.1.4). While there is not a review article yet on surface change detection at volcanoes from optical and SAR imagery, there are reviews of the use of ASTER data (Duda and others, 2009), the use of SAR data in Alaska (Lu and Dzurisin, 2014) and all of the United States (Dzurisin and others, 2019), and general reviews on the techniques applied to a variety of Earth processes (for example, Ajadi and others, 2016; Pritchard and Yun, 2018). Surface changes were first observed in the 1980s in satellite optical images of a volcano when images with spatial resolution of 10 m/pixel or better became available (for example, Chorowicz and others, 1992). The first surface changes detected using SAR were noted in the 1990s (for example, Patrick and others, 2003).

Airborne assets are also available to assess surface change, and this capability is especially relevant during volcanic eruptions. Examples of airborne systems include the National Aeronautics and Space Administration (NASA) Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) program, which included a repeat pass L-band interferometric synthetic aperture radar (InSAR) system (see fig. 4 for band definition) for surface deformation (for example, Lundgren and others, 2013), and the Glacier and Ice Surface Topography Interferometer–Airborne (GLISTIN–A) single-pass Ka-band InSAR system for topographic change (Lundgren and others, 2019). Both the UAVSAR and GLISTIN-A instruments are carried on a NASA Gulfstream III jet that, with its global reach, makes it a viable observational tool for high-temporal-resolution sampling during prolonged eruptions, like the 2018 lower East Rift Zone eruption of Kīlauea, Hawai‘i. Similarly, UAVs are gaining in prominence as reflected in the wealth of important and unique data collected during the 2018 Kīlauea eruption (for example, Diefenbach and others, 2018; Dietterich and others, 2018). While these airborne assets are beyond the scope of this report, their importance is clear and they have strong overlap with, and complement, satellite observing systems.

Both satellite optical and SAR data can be used to make high-spatial-resolution (<5 m/pixel) measurements of topography and topographic change. These measurements are used for such applications as estimating effusion rates (for example, Poland, 2014; Arnold and others, 2016, 2017; Bagnardi and others, 2016), lava lake height (Moore and others, 2019), and updating hazards maps (for example, Richter and others, 2016). There are several methods to measure topography either as two-dimensional digital elevation models (DEMs) or one-dimensional profiles: using stereo or tri-stereo images (through photogrammetry or structure-from-motion techniques), SAR shadow and interferometric methods, and space-based light detection and ranging (lidar) like the Ice, Cloud and Land Elevation Satellites (ICESAT-1 and -2) and the Global Ecosystem Dynamics Investigation (GEDI)[20]. Lidar observations can also be used to make DEMs, but to date these have only been done on airborne systems and not from space. There is not yet a review article on all types of topographic change detection at volcanoes from space but there is one that describes the use of data from one mission (TanDEM-X SAR data) (Kubanek and others, 2021), and reviews on techniques applied to a variety of Earth processes exist (for example, Fonstad and others, 2013; Di Traglia and others, 2018). Sansosti and others (1999) and Lu and others (2003) quantified the first topographic changes at volcanoes using satellite data; Lu and others (2003) utilized airborne data. In a regional study of topographic change in Latin America, Pritchard and others (2018) noted measurable topographic change at about 35 percent of the most active volcanoes in the region (15 of the 42 that were studied), suggesting high-spatial-resolution DEMs over volcanoes need to be more frequently acquired.

2.1.4. Deformation[18]

Space-based measurements of ground displacements in volcanic areas are made by the Global Navigation Satellite System (GNSS) (which includes the Global Positioning System [GPS]) and repeat-pass InSAR. Both techniques can measure subcentimeter ground displacements—at individual locations with GNSS or with imaging radar spanning

[18]Topographic change and surface deformation (section 2.1.4) are usually related but they have been separated here as in the NASA Decadal Survey (National Academies of Science, Engineering, and Medicine, 2018) because the magnitude of change detectable and the techniques involved are different. Compare sections 2.1.4 and 2.1.3.

[19]Transmitted microwave energy returned to the satellite, also called SAR amplitude or intensity imagery.

[20]ICESAT-1/2 and GEDI have not yet been used at volcanoes, to our knowledge.

areas as large as hundreds of kilometers wide. In volcanic areas, ground displacements provide information regarding movement of magma, faults, or fluids[21] in the subsurface, and on landslides or cooling deposits (lava or pyroclastic flows) at the surface. Several review papers (Massonnet and Sigmundsson, 2000; Zebker and others, 2000; Hooper and others, 2012; Pinel and others, 2014; Fernández and others, 2017) and textbooks (Dzurisin, 2006; Lu and Dzurisin, 2014) have been written about how InSAR works, its limitations, and various methods used to combine data into a time series of observations. Civilian satellite InSAR data began to be widely used for volcanoes after 1993 and was first applied to a volcano by Massonnet and others (1995). The first global compilations of InSAR observations of volcanoes from multiple satellites were developed 15 years later (Fournier and others, 2010; Biggs and others, 2014; Chaussard and Amelung, 2014; Biggs and Pritchard, 2017; Ebmeier and others, 2018); however, these compilations are incomplete because observations at some volcanoes are lacking during certain time periods or are of poor quality.

2.1.5. Ash

Volcanic ash clouds are of particular concern for aviation (for example, Miller and Casadevall, 1999; Prata and Tupper, 2009; Prata and Rose, 2015) and are routinely tracked using meteorological satellites, especially geostationary ones because of their high-temporal resolution (for example, Prata, 2009). There are several review articles on the use of satellite data to detect ash clouds (Sawada, 1996; Prata, 2009; Zehner, 2010), as well as chapters in two monographs (Dean and Dehn, 2015; Mackie and others, 2016). In the late 1960s, cosmonauts made the first observations of ash clouds from space (Carn and Krotkov, 2016), and in 1973, Skylab astronauts observed ash from the 1973 eruption of Fernandina in the Galápagos, ash that was also detected by weather satellites (Dean, Rothery, and Eichelberger, 2015). Sawada (1987) made the first systematic study of ash clouds by weather satellites. There are not yet any global databases of satellite ash detections spanning multiple decades, but there are several IAVCEI catalogs—one developed by the IAVCEI Remote Sensing Commission spanning 2008–2014 (https://web.archive.org/web/20210423124119/https://sites.google.com/site/iavceirscweb/Home) and another from the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) instrument onboard the Environmental Satellite (Envisat) from 2006–2011 (Griessbach and others, 2012).

[21]We define fluids (in the broad sense) to include brines, gas, supercritical fluids, or a combination. They can include volatiles derived from stagnant cooling/crystallizing magma batches ("magmatic fluids" in Dzurisin and others, 2012) or result from mixing of meteoric water and groundwater water within the hydrothermal system ("hydrothermal fluids" in Dzurisin and others, 2012).

2.2. Current Use of Satellite Data in Volcano Observatories

Satellite data are widely used by the scientific community for retrospective analysis of volcanic and magmatic processes. In this section, we focus on the ways in which satellite data are currently used in volcano observatories, especially during periods of evolving volcanic unrest, and on the value added by remote sensing data.

2.2.1. Review of Current Remote Sensing Data Use by Volcano Observatories

Remote sensing data are effective at providing information on several different stages of the eruption cycle (for example, Pyle and others, 2013; fig. 7). Zehner (2010) noted that the data are useful for three different applications:

> "Identification of phenomena: Locating and identifying potentially hazardous or important features such as fumaroles, lava domes, lava flows and crater lakes, and establishing 'background' levels of activity.
>
> Monitoring of expansion/development of phenomena: Collection of a time series of data that chronicles changing levels of activity from background to hazardous levels. Time frames for such monitoring vary widely from days to years. Such data can help in modeling possible impacts of future hazardous events.
>
> Generation of hazard [maps]: Identifying where hazards are being generated and areas impacted or likely to be impacted can help with search and rescue or damage assessment. Impacts and extents are essential to understanding major events—often close access is impossible during or shortly after major volcanic events. Data can be used to improve future models of hazards and their impacts."

Remote sensing data are being used in all three of these different stages by volcano observatories, but the capabilities of volcano observatories to use remote sensing data vary greatly.

There is no well-documented global review that provides an understanding of how satellite data are used operationally. Garthwaite and others (2019) compiled survey results (see their supplemental material) for the current use of InSAR for volcano monitoring in five countries (France, Iceland, New Zealand, Japan, and the United States), where the use varied from routine near-real-time analysis to on-demand analysis only. Since its founding in 1988, the Alaska Volcano Observatory (AVO) has used remote sensing data because of the large number of remote volcanoes in Alaska and their hazard to northern Pacific air traffic (for example, Schneider and others, 2000; Schneider and Pavolonis, 2017). AVO is one of the few volcano observatories globally that regularly uses most of the techniques described in section 2.1, employing

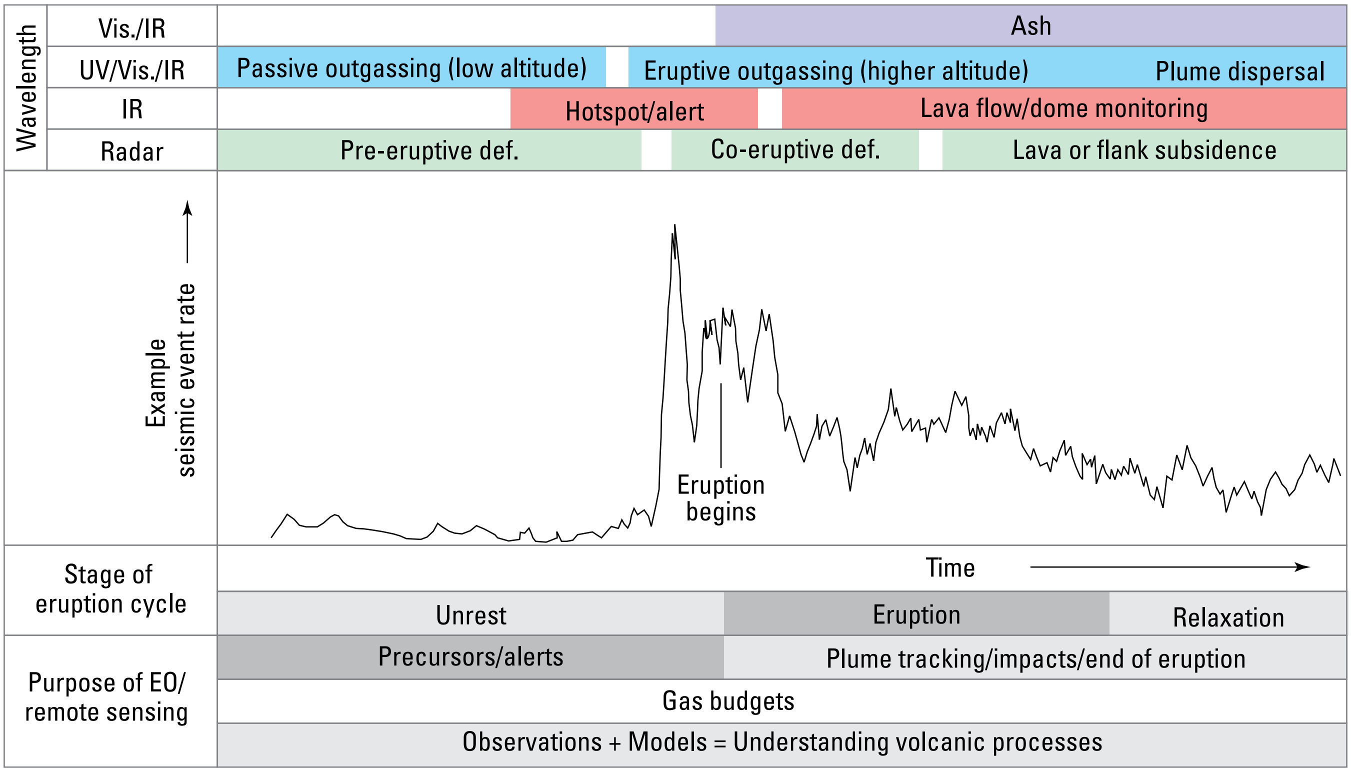


Figure 7. Chart showing some applications of remote sensing techniques to a volcano during a hypothetical eruption cycle. The example seismic event rate is intended to be schematic and is based on the number of seismic events per hour with magnitudes greater than 3.2, from March 20 to May 28, 1980, at Mount St. Helens. Vis., visible; IR, infrared; UV, ultraviolet; def., deformation; EO, Earth observation. From Pyle and others (2013).

satellite data both to track eruptions already underway as well as during daily monitoring for signs of unrest or new eruptive activity (Cameron and others, 2018). In addition to remote sensing tools used by specific volcano observatories, there are also online resources that provide global operational-level access to specific data types. For example, to monitor thermal emissions, the Middle InfraRed Observation of Volcanic Activity (MIROVA) system is used operationally by 15 volcano observatories (Coppola and others, 2020) and MODIS Volcano (MODVOLC) is also widely used (Wright, 2015).

To expand the view of how other volcano observatories are using remote sensing data, we received completed questionnaires from 8 volcano observatories in seven Latin American countries that were previously published (Pritchard and others, 2018) and 10 newer questionnaire responses from 7 volcano observatories across Africa (Democratic Republic of Congo and two in Ethiopia), Southeast Asia (Indonesia), Latin America (two from Costa Rica, two from Guatemala), and the Caribbean (Trinidad and Tobago, Montserrat). At some observatories, staff routinely exploit remote sensing either through their own analysis or by using data processed by others and made available on the web (for example, NASA SO_2 data from https://so2.gsfc.nasa.gov/; MODVOLC and MIROVA thermal alerts). At other observatories, remote sensing data are used infrequently because of a lack of staff time and (or) training to acquire the satellite data in a timely manner. Interestingly, even where more than one response was gathered from the same institution, answers sometimes differed in the understanding of what was currently used and even the number of volcanoes where remote sensing data were being analyzed. In summary, even well-equipped observatories like AVO do not yet fully exploit remote sensing data. This is even more true at other volcano observatories, especially in developing nations.

2.2.2. Value of Volcano Remote Sensing Data for Volcano Observatories

Remote sensing data are not being fully exploited by volcano observatories. Therefore, it is worth asking—do these data add value to ground observations, and if so, how? Based on our questionnaires, we learned that remote sensing data have impacted decision-making at volcano observatories (Pritchard and others, 2018). Some examples include (1) installing instruments in areas that were discovered to be active based on satellite data, and thus supporting situational awareness during volcanic crises (for example, decisions to maintain or change Volcano Alert Levels (VALs); Surono and others, 2012); (2) contributing to the interpretation that a large eruption was not imminent (thus allowing an observatory to lower an alert level or keep it low); (3) showing that a signal from a ground sensor was spurious; and (4) modeling of ground deformation to compensate for ground-based data having gaps or lacking synoptic coverage (Pritchard and others, 2018). Below we describe in more detail four different ways that satellite data were shown to be useful based on the surveys of volcano observatories.

1. **Satellite data provide the only observations at volcanoes with no ground monitoring.** Satellite data have revealed the first signs of activity at many volcanoes without ground sensors (for example, Patrick and others, 2005; Pritchard and others, 2018; Dzurisin and others, 2019). The number of volcanoes without ground sensors varies among countries, and efforts are ongoing to document these variations through the Global Volcano Monitoring Infrastructure Database (https://wovodat.org/gvmid/home.php; Pritchard and others, 2022). Based on Brown, Sparks, and others (2015), most volcanoes do not have temporally continuous ground monitoring. In Latin America, more than 60 percent of the 319 Holocene volcanoes have no ground-based monitoring, and an even larger percentage do not have continuous monitoring (Brown, Loughlin, and others, 2015). In Japan, 55 percent of the 111 active volcanoes do not have continuous ground monitoring (Garthwaite and others, 2019, supplemental material). In Alaska, ground-based monitoring has increased with time: more than 75 percent of the 52 historically active Alaska volcanoes did not have seismic monitoring in 2000 (Schneider and others, 2000), but in 2017, only 40 percent did not have ground monitoring (Schneider and Pavolonis, 2017). However, considering that there are more than 100 potentially active volcanoes in Alaska, the majority are only being monitored by remote sensing even today.

2. **Satellite data fill spatial gaps in ground coverage.** Spatial gaps in ground coverage can be filled in several ways. Satellite data can provide information for areas between ground-based stations (fig. 8). Remote sensing data provide a synoptic view of a signal that is larger than the small footprint of sensors on the ground (fig. 8). Sensors on the ground may detect a signal but have insufficient spatial coverage to determine the cause of the signal without complementary satellite observations. Finally, a single sensor on the ground may detect a signal, but there will be uncertainty about whether the signal is real or an instrumental artifact; satellite data can help evaluate whether the sensor is malfunctioning.

3. **Satellite data provide a capability not available in the existing ground network.** In some cases, a ground network does not include a full range of sensor types—satellites can augment the ground network with other data types. Frequently, a period of unrest is detected with one type of sensor (for example, a seismometer), but the exact cause of the unrest is unknown. Satellite data can address this lack of information, for example, by providing evidence that there isn't a large quantity of magma moving near the surface—such absence of significant magma accumulation was important during the 2013–2014 seismic crisis at Chiles–Cerro Negro on the Ecuador–Colombia border (Ebmeier and others, 2016). Multiparameter data are useful for determining whether unrest is caused by magmatic or nonmagmatic processes, and some data types may only be available from satellites (Pritchard and others, 2019). Even with ground and satellite observations, the source of unrest is often ambiguous (Pritchard and others, 2019, and references therein).

4. **Satellite data provide perspectives not available from the ground.** The synoptic view from above provided by satellites, for example, inside craters, is difficult or impossible to achieve on the ground, especially at an erupting volcano where instruments are destroyed. In particular, very high spatial-resolution (<2 m/pixel) satellite radar imagery allows a view through the clouds, and such imagery has been used in combination with other data during several volcanic crises (for example, Pallister and others, 2013; Pallister, Wessels, and others, 2019). Airborne sensors (including from instruments mounted on drones) can potentially provide similar perspectives but are not yet used routinely. To be most useful for an evolving crisis, radar imagery needs to be available from multiple satellites (providing images every few days; fig. 9) with low latency. During phases of unrest, thermal data are also important for the timely detection of the arrival of magma at the surface, especially at high-altitude volcanoes with deep summit craters where continuous aerial or ground surveys are dangerous and expensive. When ground-based sensors are unable to see directly into a crater and aerial observations are infrequent, satellite observations are a principal resource for assessing changes caused by unrest or eruptions (for example, Poland and others, 2020).

These examples illustrate that satellite and ground-based data are synergistic in providing sufficient spatial and temporal coverage and sensitivity for all global volcanoes of interest. Ground-based sensors provide continuous and real-time measurements (for example, Honda and Nagai, 2002; Casagli and others, 2010; Sparks, Biggs, and Neuberg, 2012) that are impossible to acquire by all but low-spatial-resolution geostationary satellites (Rodon and others, 2013; Pavolonis and others, 2018). This dense temporal sampling by ground sensors can reveal processes that occur between satellite overflights, like tilt cycles immediately preceding moderate volcanic explosions (fig. 10*B*; Arnold, 2018, and references therein). However, ground sensors may be unable to resolve the extent of surface deformation needed to constrain physical

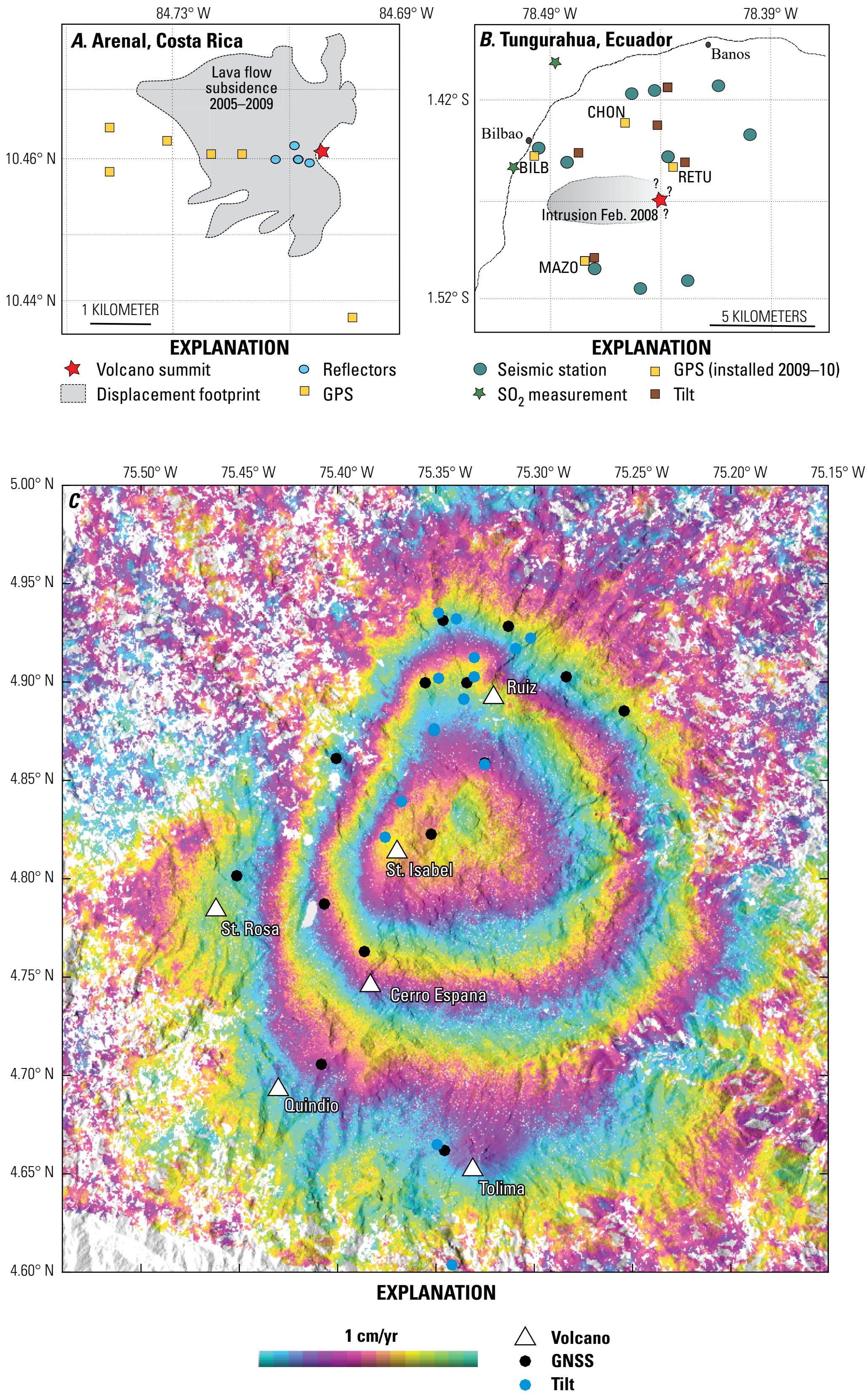


Figure 8. Maps showing three examples of remote sensing data filling gaps in ground networks. *A*, *B*, Examples of localized displacement signals detected by satellite interferometric synthetic aperture radar (InSAR) (footprint area of displacement indicated by gray polygons) compared to the locations of the stations that make up ground-based monitoring networks at Arenal, Costa Rica (landsliding and gravity-driven slip) (*A*), and Tungurahua, Ecuador (co-eruptive endogenous growth) (*B*). Modified from Ebmeier and others (2018). *C*, Ground deformation near Nevado del Ruiz, Colombia, and other volcanoes (triangles) detected by InSAR between 2012 and 2015, which is larger than the footprint of the ground-based tilt and Global Navigation Satellite Systems (GNSS) stations (John Londoño, Servicio Geológico Colombiano, written commun., 2019). Modified from Lundgren and others (2015). GPS, Global Positioning System; cm/yr, centimeters per year.

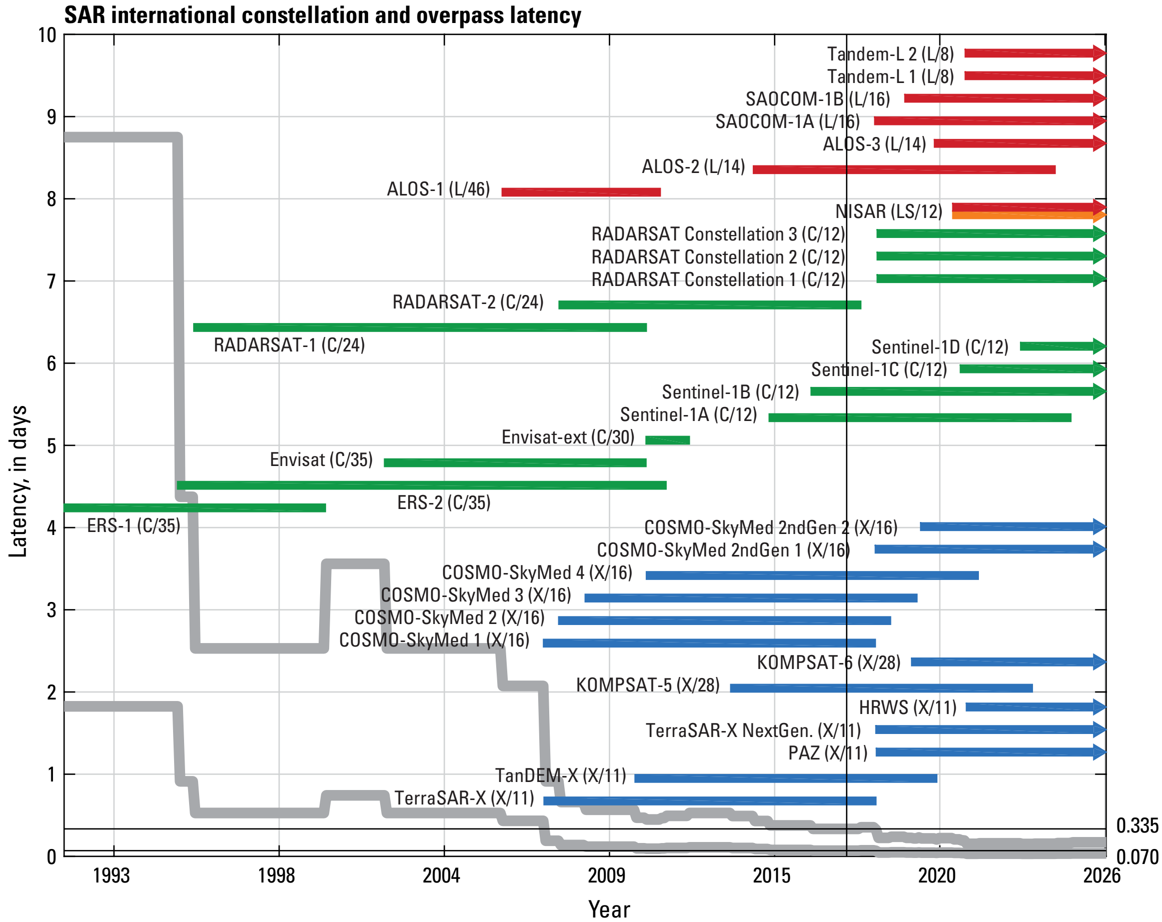


Figure 9. Plot of potential latency (time between overflights) between synthetic aperture radar (SAR) data acquisitions as a function of time for the international civilian constellation of satellites (red, orange, green and blue lines) over volcanoes assuming that all satellites are always acquiring data. The bottom gray line corresponds to volcanoes at about lat 78° N. or S. and the top gray line is for volcanoes near the equator. Blue lines show X-band radar missions (~3-centimeter [cm] wavelength), green lines show C-band radar missions (~6 cm), orange line shows S-band radar mission (~12 cm), and red lines show L-band radar missions (~24 cm); see figure 4 for all SAR bands. The number inside the parenthesis refers to the repeat time in days of each individual satellite. The vertical line shows the date the plot was created in June 2017, and we assume that planned satellite launches occur as scheduled from 2017 until 2026. Used with permission from Sang-Ho Yun, Jet Propulsion Laboratory, written commun., 2017. See "Abbreviations and Instrument Names" list for definitions of instrument names.

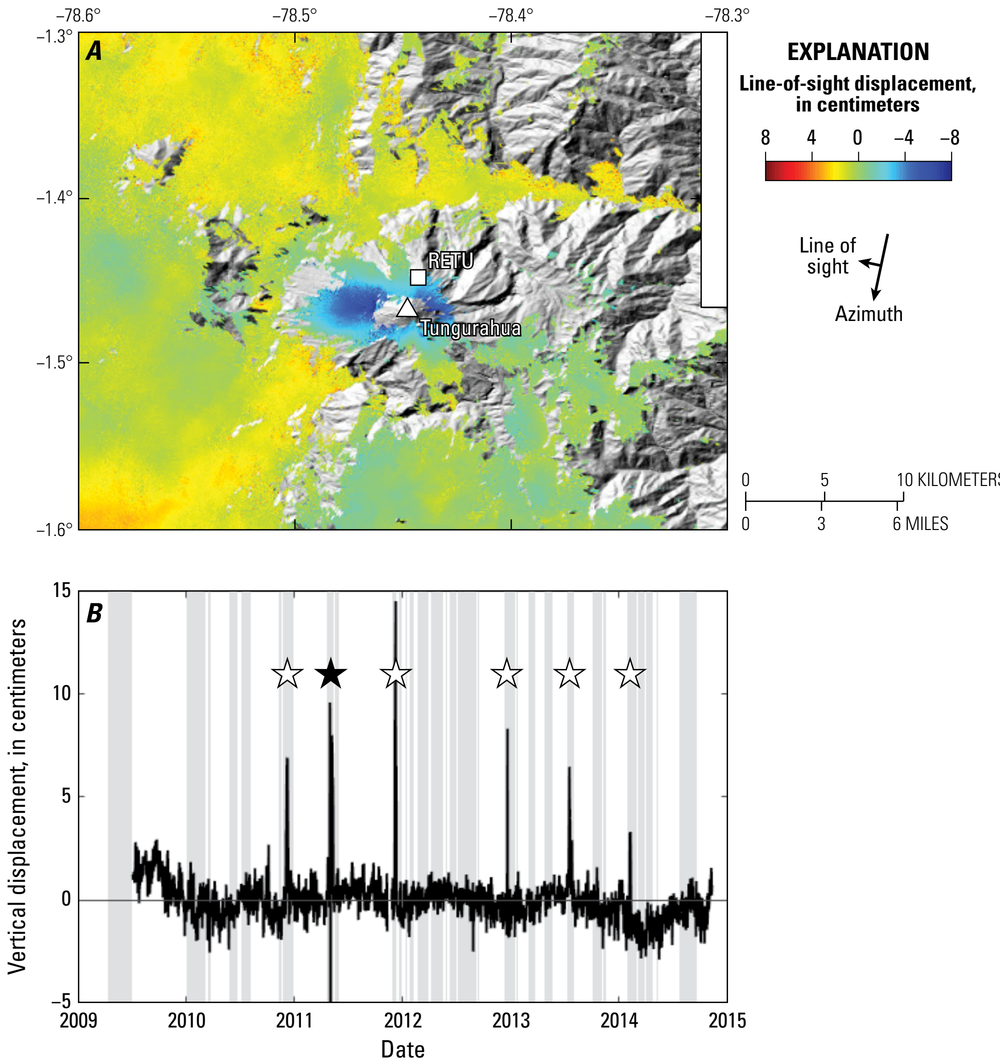


Figure 10. *A*, Map showing a transient deformation episode at Tungurahua, Ecuador, that occurred between April 15 and May 9, 2011, as recorded in a RADARSAT-2 interferogram, plotted over hillshaded topography. The deformation has the opposite sign in the next interferogram. The interpretation is that the deformation signal is completely reversible. This type of reversible deformation lasting only a few days requires daily observations not routinely available from satellites, and so it is detected here fortuitously. The maximum observed deformation was 6 centimeters (cm) toward the satellite on the west flank and 4 cm on the east flank. White triangle is the location of the summit vent; white square labelled RETU is the location of the most proximal Global Positioning System (GPS) station (data shown in *B*; see figure 8*B* for the location of other ground sensors at Tungurahua). *B*, Plot of average daily vertical displacement measured by the RETU GPS station. Gray bars are periods of eruptive activity. Black star is transient deformation event observed in *A*; white stars are transient deformation events that occurred between satellite acquisition dates (lasting 3 to 12 days) and were therefore not imaged by interferometric synthetic aperture radar (InSAR). GPS data provided by Instituto Geofísico, Escuela Politécnica Nacional of Ecuador; and the RADARSAT-2 InSAR data are provided by the Committee on Earth Observation Satellites Latin America Pilot Project; the Canadian Space Agency; MacDonald, Dettwiler and Associates Ltd.; and the Science and Operational Applications Research program. From Arnold (2018).

models; opportunistically timed satellite observations could augment ground observations and provide data to constrain models (fig. 10). Ground-based sensors provide sensitivity to unrest unattainable by satellite sensors (see section 3.6) and they can provide new insights into physical processes that may be occurring. For example, de Moor and others (2016a, b) were able to make more complex and revealing interpretations relating to preeruptive processes at Poás and Turrialba in Costa Rica using ground-based gas monitoring than was possible from the available satellite imagery (for example, Reath and others, 2019a). However, ground sensors can be damaged during an eruption, and replacement or maintenance of the monitoring network on the ground can be very difficult and dangerous. This vulnerability of ground sensors can temporarily blind an observatory during a potentially critical time. The ongoing observations provided from space could allow essential information on activity in progress and permit an evaluation of evolving hazards in order to plan a safe restoration of the ground-based monitoring network.

Considering that remote sensing data have shown value to volcano observatories, there must be other explanations for why they are not more fully utilized. We explore these barriers and ways to overcome them in section 4. But first, in section 3, we describe what can be learned on a global basis from volcano remote sensing.

3. State-of-the-Art Global Volcano Remote Sensing Databases

It has long been recognized that volcanic unrest and its relationship to eruption is of vital importance for hazard assessment (Newhall and Dzurisin, 1988, and references therein). In the early 1980s, motivated largely by a seismic crisis at Long Valley Caldera, California, Chris Newhall and Dan Dzurisin (USGS) tried to quickly compile information about previous episodes of volcano unrest and their relation to eruption. The project produced a more than 1,100-page bulletin that documented nearly 1,300 unrest episodes at 138 volcanoes (Newhall and Dzurisin, 1988). While we currently cannot quickly reproduce the work of Newhall and Dzurisin (1988), modern tools are in development to allow users to compile information on volcanic unrest and eruptions at the Global Volcanism Program's (GVP) Volcanoes of the World (VOTW) database (GVP, 2013) at the Smithsonian Institution and the WOVO database (WOVOdat) hosted at the Earth Observatory of Singapore (Newhall and others, 2017; Costa and others, 2019). It is currently not possible to access global databases for satellite observations of volcanic thermal emissions, outgassing, and deformation (described in section 2) and to compare the different parameters and relate them to the eruption chronology.

The choice of what information should be recorded in a database of satellite detections is nontrivial and requires an understanding of both the uncertainties of different measurement techniques and an understanding of the connections between observable signals and the physical processes behind any unrest. For example, with ground deformation, there are many different parameters that could be recorded—maximum horizontal or vertical displacement and its sign, size of the deformation field, and so on. Using InSAR or electronic distance measurement (EDM) deformation data adds ambiguities as the measurements from one satellite overpass or EDM line are one dimensional (in the line of sight), so direct comparison to horizontal and vertical displacement requires additional measurements or models. For thermal observations of volcanoes, there are also several different quantities that could be recorded: spectral radiance, radiant power, maximum temperature, area of a thermally perturbed region, and so on. Before expending significant effort to create a database of global satellite detections of volcanic activity through WOVOdat or GVP, it is worth asking some basic questions about the utility of the records of remote observations using the available databases. Are all types of satellite data (thermal emissions, outgassing, and deformation) useful, or are they, to some extent, redundant? Given the generally noncontinuous nature of satellite measurements and their low spatial resolution, what volcanic activity do satellites detect, and what do they miss? Are there conditions (for example, volcano composition or tectonic setting) when one type of satellite detection is more useful? Could satellite observations be used in eruption forecasting? In the wake of the 2010 Eyjafjallajökull, Iceland, eruption, which produced an ash cloud that shut down European airspace for many days at a cost of more than $3 billion in lost revenue, there was significant interest in improving satellite studies of ash clouds and precursors (for example, Zehner, 2010). At an ESA-sponsored workshop (Zehner, 2010), a list of satellite observational objectives specifically targeting thermal emission and outgassing precursors to eruptions was generated (table 2), and, to our knowledge, most of these objectives have still not been met.

We answer the questions posed above and others in the remainder of section 3, building off the work by PowellVolc and recent contributions by other researchers and groups. In particular, we use databases of global thermal emissions, outgassing, and deformation data obtained from satellites and spanning the period from 1978–2016, compiled by Furtney and others (2018) and updated by PowellVolc (for example, Reath and others, 2021; Way and others, 2022), and which are listed in tables 3–5. Despite using the best-available global compilations, these databases do not fully reflect the capabilities of satellites to detect volcanic activity in several respects. The limitations of current databases are discussed more fully in section 3.6.

Table 2. Suggested satellite observation objectives and measurements from a European Space Agency report following the 2010 eruption of Eyjafjallajökull volcano, Iceland.

[These objectives are focused on volcanic eruption precursors. To date, they are as yet unfulfilled. From Zehner (2010)]

Objective	Related quantitative measures
Correlation between thermal precursors and eruptive activity	-Percentage of thermal anomalies that precede eruptions as a function of anomaly area and intensity, for a given volcano -Rate of increase/decrease of anomaly intensity/flux as a function of eruption duration/volume/flux
Correlation between gas emissions from permanent outgassing plumes (summit craters and fumarole fields) and volcanic eruptive activity	Rate of increase/decrease of SO_2, CO_2, H_2O (primary) concentration/flux in preeruptive periods and during eruptive activity
Correlation between volcanic aerosols from permanent outgassing plumes (summit craters and fumarole fields) and volcanic ash plumes emitted during the eruptive activity	Changes in the aerosol concentrations in preeruptive periods, aerosol optical thickness variation as a function of time
Temporal, spatial, energetic, and instrumental limits on remote thermal anomaly detection	Required sampling frequency for >90 percent detection certainty as a function of anomaly intensity, instrumental resolution and scene noise
Sensitivity of detection thresholds to intrinsic and extrinsic variables	Scene noise relative to the anomaly as a function of scene roughness, topography, temperature, emissivity, atmospheric water vapor, cloud cover, volcanogenic emissions, seasonal variables
Global Thermal Anomaly Catalogue	Geographic information system locations of anomalous pixels as a function of time referenced by radiant intensity and (or) time at the surface (atmospherically corrected /temperature-emissivity-separated) or at the instrument
Systematic surveys of all eruptions	Time-series distribution of radiant intensity/flux of thermal anomalies as a function of time/distance from the eruption apex and (or) vent

Table 3. Activity classification of global Holocene and restless Pleistocene volcanoes that might usefully be targeted by currently available satellites.

[Population Exposure Index (PEI) from the United Nations Global Assessment of Risk (Brown, Loughlin, and others, 2015), which is based on populations within 10, 30, and 100 kilometers (km) of a volcano. Index scores range from 1 to 7 (with 1 being the lowest); a PEI ≥2 has a weighted population of >3,000. Submarine volcanoes classified by the Global Volcanism Program (GVP) are not given an activity classification, although at least three have gas emissions detected from space, and pumice rafts produced by submarine eruptions have been tracked by satellites (Jutzeler and others, 2014). No., number; SAR, synthetic aperture radar; TIR; thermal infrared; res. resolution; InSAR, interferometric synthetic aperture radar]

Class	No. of volcanoes	Definition	Suggested timescale of observation (SAR)	Suggested timescale of observation (high-spatial-res. TIR)
A1 “Active”	178	Eruptions since 1990 in populated regions with PEI ≥2 (Loughlin and others, 2015) or eruptions anywhere from 2014 to 2019	Weekly	Night observation every 16 days
A2 “Active”	54	Eruption between 1990 and 2013 with a PEI of 1–2	Monthly to weekly to maintain coherence	≥4 cloud-free night observations per year
B1 “Quiescent”	181	Satellite detected unrest since 1990 without eruption (Furtney and others, 2018; Reath and others, 2019a, 2021; Way and others, 2022)	Monthly to weekly to maintain InSAR coherence	≥4 cloud-free night observations per year
B2 “Quiescent” (ground-based)	107	Ground or GVP (2013) report of unrest since 1990 without eruption; seismic swarm database from Phillipson and others (2013); White and McCausland (2016).	Monthly to weekly to maintain InSAR coherence as needed	≥4 cloud-free night observations per year
C “Inactive”	839	No satellite unrest detections or eruptions since 1990	Quarterly or more frequent to maintain InSAR coherence	≥2 cloud-free night observations per year

Table 4. Satellite detections of volcanic activity by country and type of monitoring data, 1978–2021.

[Counts of volcanoes with different types of activity are synthesized from the data in appendix 1. Note that an individual volcano may be counted multiple times. In the Volcanoes of the World database, some volcanoes that are on a border are listed in a combined country category, for example, Chile–Argentina. For this table, we have counted those volcanoes separately under both Chile and Argentina. Also, this table (following Furtney and others, 2018) counts multiple volcanoes in the footprint of what could be a single deformation source—for example, Mammoth Mountain, Mono–Inyo craters, and Long Valley Caldera are counted as separate deformations when it is possible that observed deformation from 1980–2021 is related to only unrest in Long Valley Caldera. Def, deformation; G, gas; T, thermal; no., number]

Countries	Type of detection							Volcanoes without detections	Total no. of volcanoes	Total detections	Percentage with detections	Total Def	Total G	Total T
	Def	Def, G	Def, G, T	Def, T	G	G, T	T							
Indonesia			7	3	1	24	36	61	132	71	54	10	32	70
United States	14	2	14	20	1	5	10	106	172	66	38	50	22	49
Chile	7		10	4		2	17	63	103	40	39	21	12	33
Japan	13	4	3		1	3	3	84	111	27	24	20	11	9
Russia	3		5		8	6	2	119	143	24	17	8	19	13
Iceland	10	1	4		1			21	37	16	43	15	6	4
Ecuador	2		8	2		1	2	21	36	15	42	12	9	13
Ethiopia	11		3	1				40	55	15	27	15	3	4
Argentina	4		2	2			6	25	39	14	36	8	2	10
Peru	2		1	1		1	6	7	18	11	61	4	2	9
Papua New Guinea	1		1		2	4	2	40	50	10	20	2	7	7
Bolivia	1			1			6	6	14	8	57	2	0	7
New Zealand	4	1			2	1		22	30	8	27	5	4	1
Nicaragua			1			5	2	10	18	8	44	1	6	8
Italy	4		1			1	1	8	15	7	47	5	2	3
Mexico	1		1	1		2	2	34	41	7	17	3	3	6
United Kingdom			1			2	4	6	13	7	54	1	3	7
Kenya	6							16	22	6	27	6	0	0
Philippines	2	1	1		2			42	48	6	13	4	4	1
Colombia	2		2			1		10	15	5	33	4	3	3
Costa Rica				1		2	2	5	10	5	50	1	2	5
Vanuatu			1			4		9	14	5	36	1	5	5
El Salvador			1			1	2	16	20	4	20	1	2	4
Spain	3		1					4	8	4	50	4	1	1
Greece	3							3	6	3	50	3	0	0
Guatemala			2			1		21	24	3	13	2	3	3
Tonga					2	1		17	20	3	15	0	3	1

Table 4. Satellite detections of volcanic activity by country and type of monitoring data, 1978–2021.—Continued

Countries	Type of detection							Volcanoes without detections	Total no. of volcanoes	Total detections	Percentage with detections	Total Def	Total G	Total T
	Def	Def, G	Def, G, T	Def, T	G	G, T	T							
Antarctica						1	1	19	21	2	10	0	1	2
Australia						1	1	1	3	2	67	0	1	2
Democratic Republic of the Congo			2					2	4	2	50	2	2	2
France	1		1					19	21	2	10	2	1	1
Japan—administered by Russia	1				1			13	15	2	13	1	1	0
Portugal	2							11	13	2	15	2	0	0
Solomon Islands						1	1	7	9	2	22	0	1	2
Tanzania	1			1				6	8	2	25	2	0	1
Yemen		1	1					9	11	2	18	2	2	1
Cameroon						1		2	3	1	33	0	1	1
Canada							1	23	24	1	4	0	0	1
Cape Verde			1					1	2	1	50	1	1	1
China	1							9	10	1	10	1	0	0
Comoros			1					1	2	1	50	1	1	1
Eritrea			1					7	8	1	13	1	1	1
India						1		1	2	1	50	0	1	1
Iran	1							5	6	1	17	1	0	0
North Korea	1							1	2	1	50	1	0	0
Saint Vincent and the Grenadines			1						1	1	100	1	1	1
Saudi Arabia	1							7	8	1	13	1	0	0
Taiwan	1							1	2	1	50	1	0	0
Turkey				1				9	10	1	10	1	0	1
Total												**229**	**181**	**295**

Table 5. Satellite detections of volcanic activity by region and type of monitoring data, 1978–2021.

[Counts of volcanoes with different types of activity are synthesized from the data in appendix 1. Note that an individual volcano may be counted multiple times. In the Volcanoes of the World database, some volcanoes that are on a border are listed in a combined country category, for example, Chile–Argentina. For this table, we have counted those volcanoes separately under both Chile and Argentina. Also, this table (following Furtney and others, 2018) counts multiple volcanoes in the footprint of what could be a single deformation source—for example, Mammoth Mountain, Mono–Inyo craters, and Long Valley Caldera are counted as separate deformations when it is possible that observed deformation from 1980–2021 is related to only unrest in Long Valley Caldera. Def, deformation; G, gas; T, thermal; no., number; SE, Southeast]

GVP Regions	Type of detection							Volcanoes without detections	Total no. of volcanoes	Total Def	Total G	Total T	Percentage with detections	Total detections
	Def	Def, G	Def, G, T	Def, T	G	G, T	T							
1. Mediterranean and Western Asia	7		1	1		1	1	32	43	9	2	4	26	11
2. Africa and Red Sea	18	1	7	2		1		95	124	28	9	10	23	29
3. Middle East and Indian Ocean	3		2			1	1	35	42	5	3	4	17	7
4. New Zealand to Fiji	4	1			4	2		50	61	5	7	2	18	11
5. Melanesia and Australia	1		2		2	9	3	60	77	3	13	14	22	17
6. Indonesia			7	3	1	25	36	62	134	10	33	71	54	72
7. Philippines and SE Asia	2	1	1		2			51	57	4	4	1	11	6
8. Japan, Taiwan, Marianas	14	4	4		2	4	5	105	138	22	14	13	24	33
9. Kuril Islands	1				5	3	1	35	45	1	8	4	22	10
10. Kamchatka and Mainland Asia	4		5		4	3	1	109	126	9	12	9	13	17
11. Alaska	5	2	10	17		4	5	45	88	34	16	36	49	43
12. Canada and Western United States	8		1	3			4	54	70	12	1	8	23	16
13. Hawai‘i and Pacific Ocean	1		2					30	33	3	2	2	9	3
14. México and Central America	1		5	2		11	8	89	116	8	16	26	23	27
15. South America	13		21	10		5	27	119	195	44	26	63	39	76
16. West Indies			2					15	17	2	2	2	12	2
17. Iceland and Arctic Ocean	10	1	4		1			23	39	15	6	4	41	16
18. Atlantic Ocean	5		2					21	28	7	2	2	25	7
19. Antarctica						3	5	22	30	0	3	8	27	8
Total global values	**97**	**10**	**76**	**38**	**21**	**72**	**97**	**1,052**	**1,463**	**221**	**179**	**283**	**28**	**411**

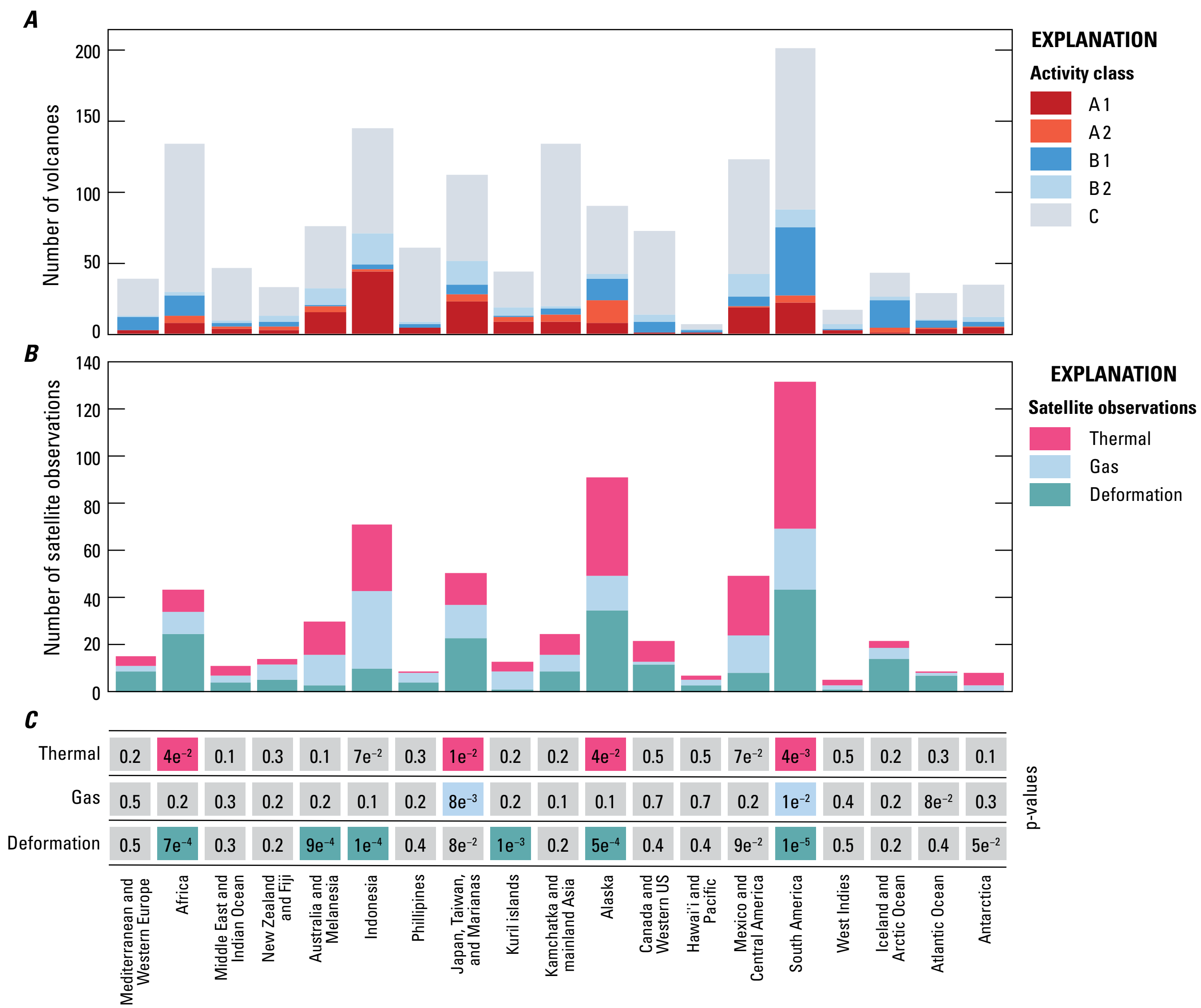
3.1. Number of Volcanoes with Activity That Can Be Monitored from Space

We have identified 411 volcanoes that have had thermal emissions, outgassing, or deformation detected from space between 1978 and 2021 (appendix 1; tables 4–5) in 47 different countries and Antarctica. This number is updated from the 306 volcanoes identified in Furtney and others (2018) and it includes any type of activity on a volcano detected from space (for example, emplacement of volcanic deposits, deformation, and surface change due to earthquakes and landslides). For reference, 251 different volcanoes erupted during this time globally, with 1,323 different eruption episodes recorded in the VOTW database. Each activity type (thermal emissions, outgassing, or deformation) has, respectively, 283, 179, and 221 volcanoes with satellite-detected activity (table 5), so each technique makes a unique and distinct contribution. Although there are hundreds of volcanoes that have good quality data without a satellite detection, these non-detections have not yet been globally compiled. Volcanoes with quality data but no satellite detections have been recorded on a regional level for deformation (for example, Biggs and others, 2009, 2011; Ebmeier and others, 2013; Lu and Dzurisin, 2014) and the best available global dataset is in the Biggs and others (2014) supplemental tables.

The geographical distribution of satellite observations of volcanic activity is not uniform. Tables 4 and 5, respectively, break down detections of volcanic activity by country and by the regional groupings used by the VOTW database (GVP, 2013). Globally, about 27 percent of potentially active volcanoes have satellite detections of activity, but in some regions the percentage is as great as 39–54 percent (for example, Indonesia, Iceland, South America, Alaska), whereas elsewhere only 10–15 percent of volcanoes have detections of activity (West Indies, Kamchatka and mainland Asia, and the Philippines and Southeast Asia). Thus, the percentage of volcanoes with detectable activity varies by more than a factor of three (table 4), but whether these different percentages are an observational bias or a real difference in the nature of volcanic activity among regions remains an open question.

We test the apparent completeness of our satellite record of volcanic thermal emissions, outgassing, and deformation using volcanic regions defined by the GVP. We limit our analysis to recently active volcanoes, based on the classifications described in table 3 (described in section 4.1.5), which use eruptions since 1990 and the Population Exposure Index (PEI) from the U.N. Global Assessment of Risk (Brown, Loughlin, and others, 2015) to identify volcanoes for which satellite observations need to be made weekly or monthly to detect changes in activity (Classes A1 and A2; fig. 11*A*; table 3). Globally, thermal signals have been detected at 76 percent of Class A volcanoes, outgassing at 71 percent, and deformation at 45 percent. We test the null hypothesis that each type of satellite-detected unrest (fig. 11*B*) is equally likely to occur at any A1 or A2 volcano, no matter where it is in the world. We use a Fisher's exact test of independence to calculate probabilities that the number of satellite observations for thermal emissions, outgassing, or deformation is part of the global distribution (in a similar manner to Ebmeier and others, 2013). Significant values (at 95 percent level, $p<0.05$) are shown in color in figure 11*C* and indicate either higher numbers (for example, thermal emissions, outgassing, and deformation for South America) or lower numbers (for example, deformation in Kuril Islands and Melanesia) of observations than expected from the global dataset (fig. 11*D*). Regions where observations are less consistent with the global dataset (lowest p-values) include deformation in Indonesia (p=1 E−4, 20 percent of all Class A volcanoes) and deformation in Africa (p=8 E−4, 92 percent of Class A volcanoes). In Indonesia (and to a lesser extent Australia/Melanesia), the relative lack of deformation observations from InSAR is consistent with the obstacles to measurement presented by dense tropical vegetation and highly variable tropospheric water vapor. That deformation has been measured at such a high proportion of Class A volcanoes in Africa may be due to a combination of the high rates of deformation associated with dike intrusions and fissure eruptions, excellent coherence (in northern Ethiopia and the Red Sea region), and the recent occurrence of several long-lived eruptions (for example, at Ol Doinyo Lengai, Nyamuragira, Nyiragongo). The global distributions of thermal and gas measurements at Class A volcanoes are more uniform than for deformation, with the most significant deviations being a lower than expected number of reported gas detections (p=5 E−3, 48 percent of Class A volcanoes) and thermal detections (p=2 E−5, 41 percent of Class A volcanoes) in Japan and higher than expected numbers of satellite detections in South America. Thermal detections have also now been made at 95 percent of the Class A volcanoes in Indonesia (p=1 E−4). Deviation from our null hypothesis of evenly spread satellite detections may also be due to regional differences in measurement uncertainties (for example, depending on volcano elevation, type of vegetation, ice cover, and so on), volcanic processes (for example, gas fluxes, proportion of effusive eruptions, shallow intrusions), and differences in the level of focus of the remote sensing community on different regions (for example, both the CEOS Volcano Pilot and an early PowellVolc time series analysis focused on South America; Pritchard and others, 2018; Reath and others, 2019b).

How have satellites expanded the ground-based detections of thermal emissions, outgassing, deformation, and volcanic unrest? We are not aware of any recent global compilation for this type of thermal data and outgassing, but the growth of the number of volcanoes with deformation detections can be seen in figure 5. Ground-based studies found deformation at 44 volcanoes in 1997 (Dvorak and Dzurisin, 1997), whereas Biggs and Pritchard (2017) documented more



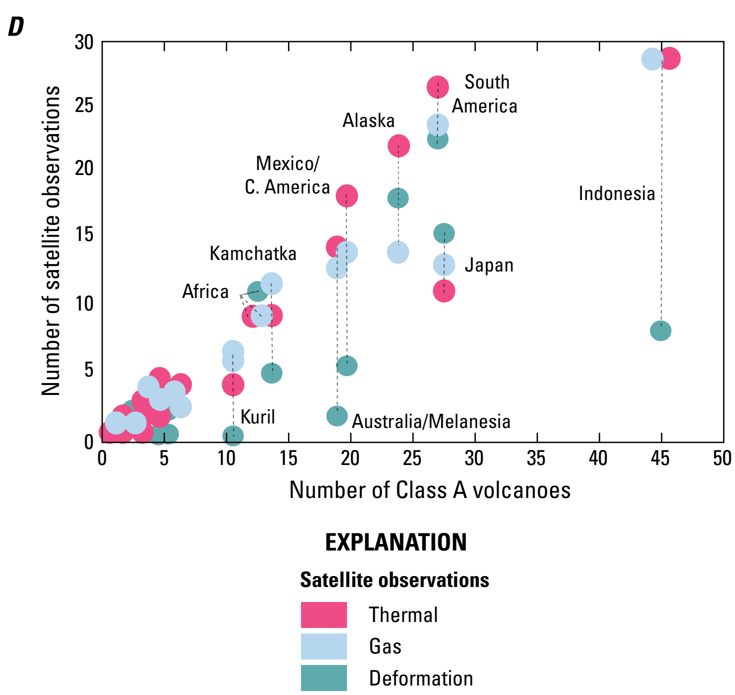


Figure 11. Plots comparing regional distribution of volcano activity and satellite observations. *A*, Distribution of volcano classifications (defined in table 3), divided by volcanic region as determined by the Smithsonian Institution's Volcanoes of the World database. *B*, Number of satellite observations of thermal emissions, outgassing, and deformation, divided by volcanic region. *C*, p-values from Fisher's exact test of independence for the null hypothesis that satellite detections of thermal emissions, outgassing, and deformation are equally probable for all Class A volcanoes. Significant values (at 95 percent level, $p<0.05$) are shown in color and indicate regions for which numbers of observations deviate strongly from the global rates. *D*, Illustration of the relationship between number of Class A volcanoes and number of satellite observations of thermal emissions, outgassing, and deformation parsed according to volcanic region.

than 220 volcanoes, as shown in table 5 [22]—an increase by a factor of five in two decades. There are systematic differences in the characteristics of historical deformation signals measured using satellite and ground-based instruments, with ground-based networks much more focused on magmatic activity at frequently erupting volcanoes (Ebmeier and others, 2018). The number of volcanoes with detected SO_2 emissions (Furtney and others, 2018) at least doubled between the early 1970s and mid-1990s (Andres and Kasgnoc, 1998). The use of satellite data is greatly expanding the number of volcanoes that can be monitored and those that have detected activity.

The United States has the second-most satellite detections of active volcanoes of any country behind Indonesia (table 4), which is a result of the United States having the most potentially active volcanoes in the VOTW database (172) and a relatively high proportion (38 percent) of volcanoes with detectable activity. Within the United States, table 4 shows that there are at least 66 out of 172 potentially active volcanoes that have had satellite detections of volcanic activity (eruptive or noneruptive) from 1978–2021. Of these, 49 detections are from thermal observations, 22 are of SO_2 outgassing, and 50 are from InSAR detecting surface/topographic change[23] (table 4). There are more than 350 different episodes of activity at the 66 U.S. volcanoes where activity has been remotely sensed, not counting the thousands of MODVOLC detections of thermal alerts, mostly from Kīlauea volcano (Furtney and others, 2018, supplemental material). The numbers of episodes and volcanoes compiled are a minimum because of the limits to the available databases (see section 3.6).

To put the number of satellite detections of U.S. volcanic activity in context, we note that the best compilation of U.S. eruptive and noneruptive volcanic activity is by Diefenbach and others (2009) and updated by Ewert and others (2018). They summarized volcanic eruptions and unrest at Holocene volcanoes in the United States from 1980 to 2017: 44 volcanoes produced 120 eruptions and 45 episodes of unrest. Diefenbach and others (2009) defined “unrest episodes” based on the “criterion that a volcano observatory responded in some way to each episode.” Using this criterion, much of the satellite-detected volcanic activity documented in the previous paragraph would be considered background activity and not unrest. We suspect that many more than 45 episodes of unrest would be documented if all available satellite data were included in an accounting of volcanic unrest in the United States, but further work is needed to assess this supposition.

Compiling remote sensing data globally and in the United States is important because the capabilities of satellites are not widely known. For example, Bally (2012) noted in the Santorini report: “In the end, the largest barrier towards progress in the uptake of EO [Earth observation]-based solutions remains lack of awareness of what is available, what has been accomplished and how this contributes to the benefits expected by the user.” Other challenges to the broader use of remote sensing data and how to overcome them are discussed in section 4.

3.2. Frequency of Eruption Following Satellite Detection of Volcanic Unrest

Although we cannot yet quantitatively relate any given satellite-detected unrest event to an eruption, satellite data are being used to issue alerts (see examples in Schneider and others, 2000; Pallister and others, 2013; Pritchard and others, 2018). Fundamentally, our understanding of volcanic processes is almost always inadequate to quantitatively relate observations of unrest with what comes next (eruption or no eruption, the style of the possible eruption, and so on). Only by observing both unrest and eruptions can we start to understand the physical processes that are occurring, and satellites allow us to observe many more of both. Satellite data can help inform a holistic understanding of the physical causes of unrest, whether it is magmatic or not (Pritchard and others, 2019), and if it is magmatic, whether such unrest will stall or lead to eruption or intrusion (Moran and others, 2011). Progress in quantitative forecasting of the likelihood of different outcomes is advancing through the development of such tools as Bayesian Event Trees, which account for the uncertainty in the physical causes of unrest (Newhall and Hoblitt, 2002; Pritchard and others, 2019). Today, many forecasts are based on expert opinion derived in large part from monitoring data (Papale, 2017). If we detect unrest, one of the best ways to quantify the likelihoods of future outcomes is to refer to global statistics (Newhall and Pallister, 2015). Remote sensing can add a larger sample size over a greater

[22]The “more than 220” number in Biggs and Pritchard (2017) includes both ground and satellite detections of magmatic as well as nonmagmatic deformation, so it is larger than the number of satellite-only magmatic detections in Furtney and others (2018), which excludes deformation of flow deposits. Table 5 shows 221 satellite detections of deformation that include deformation by landslides, volcanic earthquakes, and deposit subsidence.

[23]This number (50) is higher than the 37 listed in the supplemental material of Furtney and others (2018) because they did not include Kiska Volcano, Alaska, or Socorro magma body, New Mexico (the former is just hydrothermal and not thought to be an eruption precursor, and the latter is not a Holocene volcano). Nor did they include deposit subsidence at Hualālai, Hawai‘i, or Mount Cleveland, Mount Gareloi, Redoubt Volcano, Mount Cerberus, Yunaska volcano, or Novarupta, Alaska. Furtney and others (2018) did not include flow deposits because they could not be used as a precursor to eruption, but we include them to give a more accurate reflection of the background activity that can be detected from space at U.S. volcanoes. This list of deforming volcanoes detected by satellite (see appendix 1) also includes some volcanoes not included in the list from Dzurisin and others (2019) such as Coso Peak, California; Hualālai; and Socorro magma body (Biggs and Pritchard, 2017); and Bogoslof volcano, Alaska (http://www.avo.alaska.edu/images/image.php?id=109311). There are also at least three U.S. volcanoes with deformation that has only been detected on the ground (Mount Baker, Washington; Redoubt Volcano; and Anatahan volcano, Northern Mariana Islands) that are not included on these lists.

geographic area compared to ground-based studies alone, so there is an important synergy in combining satellite and ground-based methods in statistical forecasting.

Several studies have shown that the relation between unrest and eruption depends on the nature of unrest and the type of volcano. Pesicek and others (2018) synthesized several studies that used a variety of different proxies for unrest (seismic-only, satellite detections, and so on) and found that unrest was associated with eruption in 30–67 percent of cases depending on the methods used to detect unrest (for example, Klein, 1982, 1984; Newhall and Dzurisin, 1988; Gudmundsson, 2006; Phillipson and others, 2013; Biggs and others, 2014, Winson and others, 2014). Furtney and others (2018) compared the timing of satellite detections and eruption and found that most thermal emission and outgassing detections are co-eruptive (~80 percent for thermal emissions and ~95 percent for outgassing), while about 50 percent of satellite deformation detections preceded eruption. The large percentage of co-eruptive thermal emission and outgassing satellite observations is likely related to low-spatial and low-temporal resolution of the global satellite datasets used (see section 3.6). Analysis of ground-based data indicates that all three data types presage eruptions. Phillipson and others (2013) showed that from 2000 to 2010, deformation was detected a mean of 1,001 days before an eruption, thermal features were detected a mean of 36 days before an eruption, and outgassing was detected a mean of 341 days before an eruption. Similarly, Furtney and others (2018) determined that detected unrest preceded eruptions by 274, 51, and 797 days for satellite-detected thermal emissions, SO_2 outgassing, and deformation, respectively. A consistent result from Phillipson and others (2013), Biggs and others (2014), and Furtney and others (2018) is that deformation is associated with eruption in roughly half of all cases (although the spread is much wider when the dataset is divided according to deformation and volcano characteristics). On average, deformation begins years before eruption. In section 3.4, we discuss the evidence that unrest without eruption and eruption without unrest are related to volcano characteristics (composition, repose interval, open versus closed behavior, and so on).

Previous studies have focused on binary detection (for example, deformation or no deformation) of volcanic unrest, but it is likely that the characteristics of the signal are also related to the probability that unrest will lead to eruption. For example, Medicine Lake volcano, California, has been subsiding at a constant rate of about 1 centimeter (cm) per year for at least 60 years without eruption (Parker and others, 2014), whereas Sierra Negra volcano in the Galápagos experienced accelerating uplift of more than 2 meters (m) during the 2.5 years before an eruption in 2005 (Chadwick and others, 2006). Here we use the deformation catalogue of Biggs and Pritchard (2017) to investigate the relationship between the rate and duration of deformation and eruption.[24] We divide the 485 distinct deformation events (Biggs and Pritchard, 2017, supplemental information) into bins based on rate and duration, and we calculate the proportion of deformation events that were associated with eruption in each bin (fig. 12). Statistically this is known as a positive predictive value (PPV). Deformation rates calculated using aliased observations[25] are unreliable; thus, we plot two sets of calculations including and excluding those data points. Figure 12*A* shows that the PPV decreases with increasing duration over a threshold of about 1 week. Conversely, the PPV increases with increasing deformation rate and, as expected, the relationship is clearer once the aliased[25] rate measurements are removed (fig. 12*B*). For deformation rates in excess of 1 meter per year (m/yr) the PPV is 1, meaning that all deformation episodes at this rate have led to or correspond to an eruption. For deformation episodes that are very slow (<1 millimeter per year) or very long (>1 year), the PPV drops below 0.4, meaning that the probability of eruption is lower but is still statistically significant.

Considering time series of satellite data as opposed to binary detection or non-detection is also important for identifying unrest in the first place (activity above background; see definition in footnote 16), especially for persistently active volcanoes showing almost continuous thermal emissions and outgassing. In these cases, a sign of unrest is more likely to be identified by a particular trend or pattern in the long-term or short-term emission history (in other words, increasing heat flux or outgassing before eruption). An indepth analysis of the ability to forecast eruptions using satellite data should also include the recognition of unrest from trend analysis and changes to the spatial pattern, not just the presence or absence of thermal emissions, outgassing, or deformation. The trend could be an increase or decrease in thermal emissions, outgassing, or deformation preceding eruptions (for example, fig. 12; Matthews and others, 1997; Pieri and Abrams 2005; Carn and others, 2016) or an increase in variability of the observed parameter (for example, Reath and others, 2016, 2019b). Of particular interest is an ability to search for precursors that precede potentially deadly phreatic eruptions that appear to provide little apparent warning using conventional monitoring techniques (for example, Girona and others, 2021).

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[24]We have not considered the sign of the deformation, but it is important—uplift is more likely before eruption than subsidence.

[25]Volcanoes with aliased observations are specified in the appendix of Biggs and Pritchard (2017) and defined by Fournier and others (2010) as any deformation that does not show a change with time.

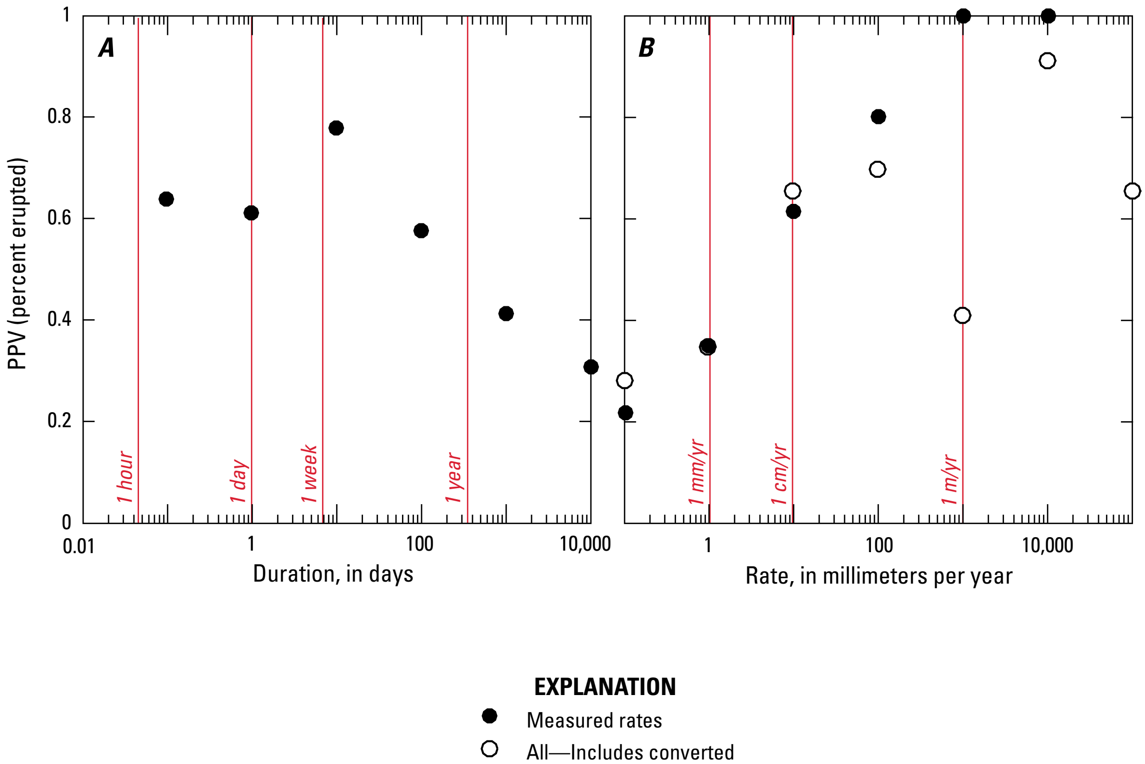

Figure 12. Plots showing statistical link between deformation and eruption considering duration (*A*) and rate (*B*) of deformation. Data are from a compilation of 485 distinct deformation episodes. From Biggs and Pritchard (2017), supplemental material. The positive predictive value (PPV) is the proportion of deformation episodes associated with an eruption for each bin. The PPV increases with increasing deformation rate and decreases with duration. Solid circles include only measurements not considered to be aliased (Biggs and Pritchard, 2017, supplemental material, column P). Empty circles include all data points from Biggs and Pritchard (2017), including those that have been converted to a rate using the maximum total displacement divided by the duration (columns N and K in Biggs and Pritchard, 2017). mm/yr, millimeter per year; cm/yr, centimeter per year; m/yr, meter per year.

3.3. Satellite Detection Capability Before, During, or After Eruption

Most volcanic activity that culminates in an eruption provides signals that can be detected before, during, or after the eruption, but detectability depends on the eruption size. In the compilation by Furtney and others (2018), there were 54 volcanoes (22 percent) that erupted without satellite detection; thus, 78 percent of volcanoes that erupted had activity detected by at least one satellite-based method. The 22 percent of erupting volcanoes with activity not detected by satellite fall into three key categories: (1) the eruptions were small—93 percent previously had eruptions with a Volcanic Explosivity Index (VEI) (Newhall and Self, 1982) less than 4. Detectability depends on eruption size; for example, SO_2 was detected by satellite in only 4 to 13 percent of frequent VEI 1–2 eruptions (fig. 13; Carn and others, 2016); (2) the eruptions occurred when there was little satellite data available—for example, 71 percent of those eruptions were before the year 2000, which predates the thermal detection capability provided by the ASTER and MODIS instruments; and (3) the eruptions occurred after the year 2000 but were previously studied with only low-spatial-resolution thermal data. Using higher spatial resolution thermal data, Furtney and others (2018) found satellite-detectable activity at 14 volcanoes, which reduces the number of volcanoes without satellite detections to 40. Thus, more than 83 percent of eruptions studied by Furtney and others (2018) were detected

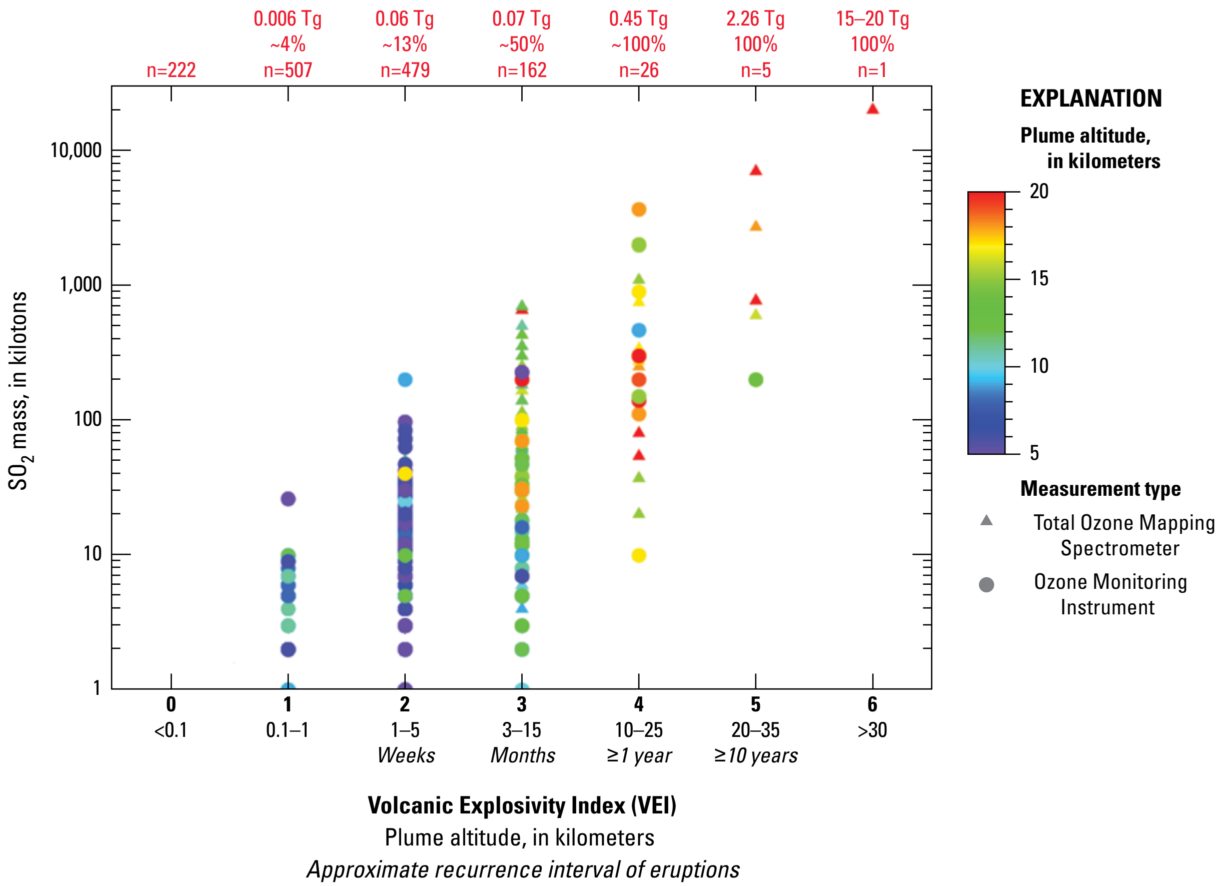

Figure 13. Plot of satellite measurements of SO_2 from the Ozone Monitoring Instrument (OMI) and Total Ozone Mapping Spectrometer (TOMS) sensors between 1978 and 2014 showing the mass of SO_2 and the height of the eruption plume (colors and second row of *x*-axis) as a function of Volcanic Explosivity Index (VEI). The approximate recurrence intervals of eruptions in each VEI category are listed in the third row of the *x*-axis. The numbers in red in each VEI category indicate the total number of eruptions (n) during the time period in that category, the percentage of those eruptions that had satellite detected SO_2, and the total mass of SO_2, in teragrams (Tg). Data from Carn and others (2016).

by satellite. Further work is needed to determine how this percentage depends on eruption size by updating figure 13 using all available modern satellite datasets.

Although tables 4–5 and appendix 1 do not list whether satellite detections are associated with eruptions, Furtney and others (2018) found that when volcanic activity is detected with more than one technique, the chances increase that the activity is associated with an erupting volcano. Of the volcanoes with one type of satellite-detected activity (deformation, outgassing, or thermal emissions), 44 percent had erupted (Furtney and others, 2018). But if the volcano had two types of detected activity, 96 percent had erupted, and if all three types of activity were detected, 98 percent erupted. Only one volcano with all 3 types of activity didn’t erupt: Lastarria, on the Chile–Argentina border. An active area of research addresses the question: when a volcano erupts without satellite-detected unrest, is the lack of detection owing to limited spatial or temporal resolution or does it reflect a magmatic system that doesn’t present reliable precursors detectable from space? For example, some volcanoes generate only earthquakes or deformation, and (or) outgassing and thermal emissions that are rapidly changing or too small to be observed from space. There are several examples of well-monitored volcanoes (based on ground sensors) that erupted without detectable unrest. These eruptions are discussed in section 3.4.

3.4. Most Critical Remote Sensing Datasets for Different Volcanoes and Styles of Volcanism

Several ground-based studies provide clues to the types of data that are most useful at different types of volcanoes. Winson and others (2014) used ground-based data from 194 eruptions at 60 volcanoes to determine the conditions under which volcano alerts were effective at providing a warning of impending eruption. We highlight two key results of this study, illustrated in figure 14. First, Winson and others (2014) found that the percentage of effective alerts increased with the number of instruments in the monitoring network—in essence, more data improved warning. Although they did not include remote sensing data, on the basis of their results we hypothesize that adding satellite data would also help improve warnings. Second, Winson and others (2014) found that even at well-monitored volcanoes, the alert level is raised in a timely or almost timely manner in only 50 percent of eruptions. They suggest that this disconnect between data collection and issuance of timely alerts at several volcanoes is due in part to the fact that small eruptions and eruptions at open-vent volcanoes[26] are more difficult to forecast than large eruptions and eruptions at closed-vent volcanoes. Two recent studies using data from Alaskan volcanoes confirm the conclusions of Winson and others (2014). Those studies show that eruptions at volcanoes with long repose times (>15 years) and high-silica-content magmas (andesites) are more likely to be forecast than those with short repose times (<15 years) and largely mafic compositions like basalt and basaltic-andesite (Cameron and others, 2018; Pesicek and others, 2018). Tectonic setting and volcano type (stratovolcano or caldera) are also important in relating the frequency of unrest and eruption. The strongest relationship between eruption and deformation occurs in basaltic systems, whereas there have been many false positives (deformation without eruption) at calderas and many false negatives (eruption without deformation) at stratovolcanoes (Biggs and others, 2014). Although characteristics such as repose time, composition, and tectonic setting can be used to varying degrees to forecast eruptions, the size of an eruption cannot be forecast in all situations (for example, Papale and Marzocchi, 2019). However, eruption characteristics such as duration, direction of pyroclastic flows, and whether the eruption is effusive or explosive are being forecast in some cases (for example, Swanson and others, 1983; Ogburn and others, 2015; Cassidy and others, 2018; Wolpert and others, 2018).

To our knowledge, there is no global database of open and closed volcanoes, and indeed the definition itself is widely variable.[26] PowellVolc compiled 17 years of thermal emission, outgassing, and deformation data at the 47 most active volcanoes in Latin America and found that while there are clearly some volcanoes that fall into the end-member classifications of open or closed, 28 percent fit into neither classification, and several changed classifications over the observation period (figs. 15, 16; Reath and others, 2019b, 2020). There are intriguing regional differences in open and closed systems that are not yet understood (fig. 17)—for instance, open systems are common in Central America and Peru, whereas closed systems dominate in the central Andes. Can these regional patterns change with time? Work is ongoing to see if there are temporal clusters/patterns of activity among volcanoes, testing the idea of “common processes at unique volcanoes” from Cashman and Biggs (2014). Of the 47 volcanoes studied in Latin America by Reath and others (2019b), 44 had robust enough satellite data to classify into 4 groups and 10 subgroups with common behavioral characteristics (Reath and others, 2020) in terms of the volcanic system (open, closed, and eruptive) and unrest mechanisms (intrusion, evolution, and withdrawal).

In summary, there is evidence from ground-based monitoring that the likelihood of volcanic unrest culminating in an eruption depends partly on whether a volcano is an open or closed system. Thus, it is necessary to create a global database of open, closed, and “other” volcanic systems, and to discern whether these systems evolve through time. Multiparameter remote sensing can help generate such a database globally, as well as help determine whether volcanoes change classifications with time. Furthermore,

[26]Several definitions exist in literature for open-vent (open) and closed-vent (closed) volcanic systems or partly overlapping terms like “quiescently active” (Stix, 2007). The classification of Newhall (2007) focuses primarily on gas emissions—open volcanic systems passively outgas volatiles due to a permeable conduit, while in a closed system, these exsolved gases cannot separate from their host magma due to a high magma viscosity or impermeable conduit. Chaussard and others (2013) defined open and closed systems based on characteristics of surface deformation—in an open system, when gases or pressure from an influx of magma enters the system, pressure is relieved in a short time span through the open conduit without significant observable surficial deformation. The opposite is true of closed systems, where detectable deformation is common. Both studies rely on measuring different types of unrest but are related. Passive outgassing commonly pairs with a lack of deformation within open systems and the opposite may hold true for closed systems.

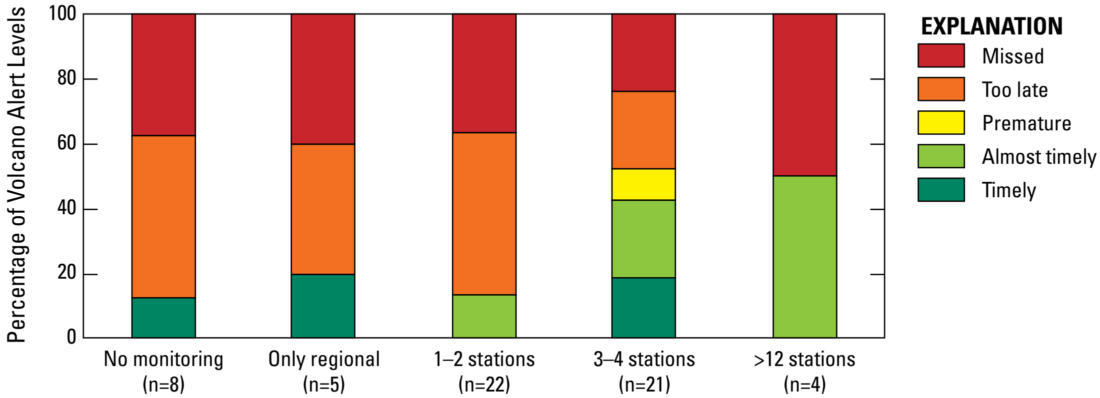

Figure 14. Chart showing the effect of monitoring level (number of monitoring stations, increasing along *x*-axis) on the quality of Volcano Alert Levels (VALs) for forecasting eruptions. The *y*-axis shows the percentage of VALs within that monitoring group that were before eruption (timely or almost timely—see definition in Winson and others [2014]), premature, too late, or missed (not issued). The sample size for each group (n, number of volcanoes) is shown along the *x*-axis. Modified from Winson and others (2014).

multiparameter remote sensing provides additional constraints on the physical processes occurring within the volcano—for example, satellite detection of outgassing and deformation have been used together to determine the compressibility of magma (Kilbride and others, 2016) and all three datasets were used to develop conceptual models for dozens of volcanoes (Reath and others, 2020). Various combinations of remotely sensed thermal emissions, outgassing, topographic change (erupted volume), and deformation have been used to compute and compare magmatic fluxes from volcanoes (Anderson and Poland, 2016; Coppola and others, 2019). Thus, multiparameter satellite data (as in fig. 15) are useful for illuminating volcanic processes.

Finally, in order to detect volcanic unrest globally and to determine how it is related to eruptions, different styles of volcanism and diverse environmental settings of volcanoes must be considered. For example, some volcanoes need observations made at high spatial resolution, whereas others can be monitored at lower resolution over a larger spatial area. Some vegetated volcanoes need a combination of long radar wavelengths (L-band, about 24 cm), specific polarizations, frequent revisits, and high spatial resolution to accurately measure ground deformation (for example, Pritchard and others, 2018). Owing to common cloud cover, volcanoes in the tropics need frequent (weekly or daily, depending on the volcano) observations using optical, UV, and IR methods to achieve a minimum set of useful annual observations (for example, Reath and others, 2019a). In section 4, we discuss how the international constellation of satellites is not always collecting the right data over the right volcanoes, and we offer an observation strategy that needs to be regularly updated to improve the current situation of satellite data acquisition.

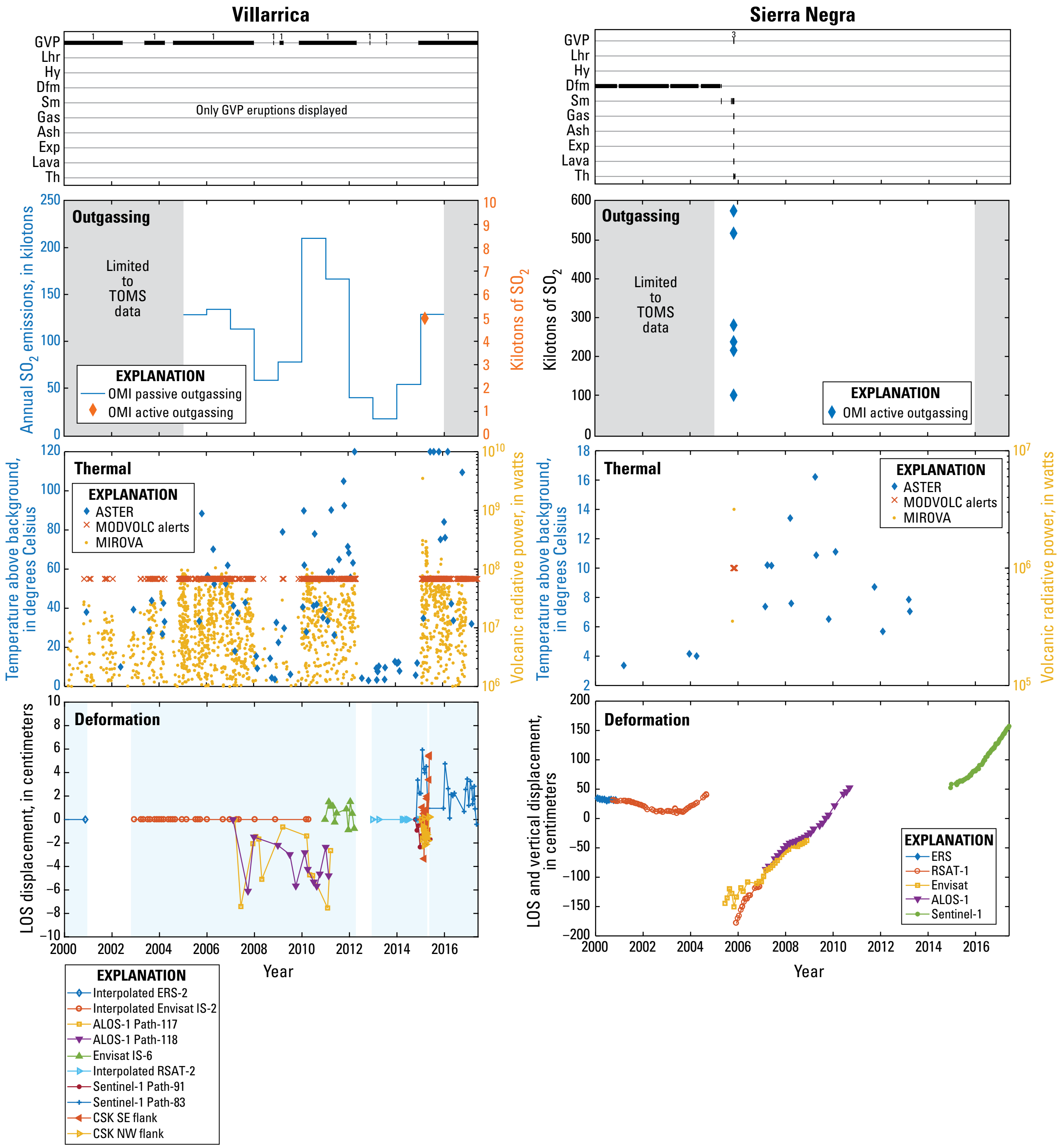
Villarrica
Sierra Negra
GVP
Lhr
Hy
Dfm
Sm
Gas
Ash
Exp
Lava
Th
Only GVP eruptions displayed
Outgassing
Limited to TOMS data
EXPLANATION
OMI passive outgassing
OMI active outgassing
Annual SO_2 emissions, in kilotons
Kilotons of SO_2
Thermal
EXPLANATION
ASTER
MODVOLC alerts
MIROVA
Temperature above background, in degrees Celsius
Volcanic radiative power, in watts
Deformation
LOS displacement, in centimeters
LOS and vertical displacement, in centimeters
Year
EXPLANATION
Interpolated ERS-2
Interpolated Envisat IS-2
ALOS-1 Path-117
ALOS-1 Path-118
Envisat IS-6
Interpolated RSAT-2
Sentinel-1 Path-91
Sentinel-1 Path-83
CSK SE flank
CSK NW flank
EXPLANATION
ERS
RSAT-1
Envisat
ALOS-1
Sentinel-1

Figure 15 (page 34). Comparisons of remote sensing time series over 17 years at an open-vent (left: Villarrica, Chile) and closed-vent (right: Sierra Negra, Ecuador) volcano. The open system shows significant outgassing and thermal emissions variation with limited deformation (variations are mostly within the noise level), whereas the closed system shows deformation, but outgassing occurs only during eruptions and thermal anomalies are minor. Modified from Reath and others (2019b), figures 2 (explanation), S39 (right), and S40 (left). Top row, Ground-based monitoring derived from Bulletin of the Global Volcanism Network. Black bars indicate times where activity types have been noted. GVP, eruption timing as indicated by Global Volcanism Program—numbers correspond to Volcanic Explosivity Index (VEI); Lhr, lahars; Hy, hydrothermal event; Dfm, deformation; Sm, seismicity; Gas, gas emission; Ash, ash emission; Exp, explosive eruption; Lava, effusive eruption; Th, thermal anomaly. Second row, Satellite-based SO_2 emission masses from the OMI sensor. Gray-shaded areas designate times when data are limited; no data were analyzed for 2017. Passive outgassing is represented as a bar averaged over a year, whereas active outgassing from discrete measurements is represented by single points (typically associated with explosive eruptions). Third row, Satellite-based thermal data. ASTER temperature above background data plotted on left axis, MIROVA volcanic radiative power data plotted on right axis, and MODVOLC data showing timing of thermal alerts (when a band ratio exceeds a threshold) plotted in the center of the *y*-axis. Bottom row, Satellite-based deformation data. Datasets with open points are interpolated from the general displacement trend of the data and do not represent the measured displacements values of the data points. LOS, line of sight; RSAT, RADARSAT. Bottom left, Light blue area marks the period over which the rate of any magmatic deformation is thought to be below the measurement threshold; any apparent variability is believed to be the result of atmospheric interference (atmospheric error ~7 centimeters). CSK data analyzed on the southeast (SE) flank of the volcano captured an inflation signal occurring from April to May 2015; however, on the northwest (NW) flank no deformation was reliably detected. Bottom right, ERS, RSAT-1, Envisat, and ALOS-1 ascending-descending deformation data are used to invert for the vertical deformation component. See "Abbreviations and Instrument Names" list for definitions of instrument names.

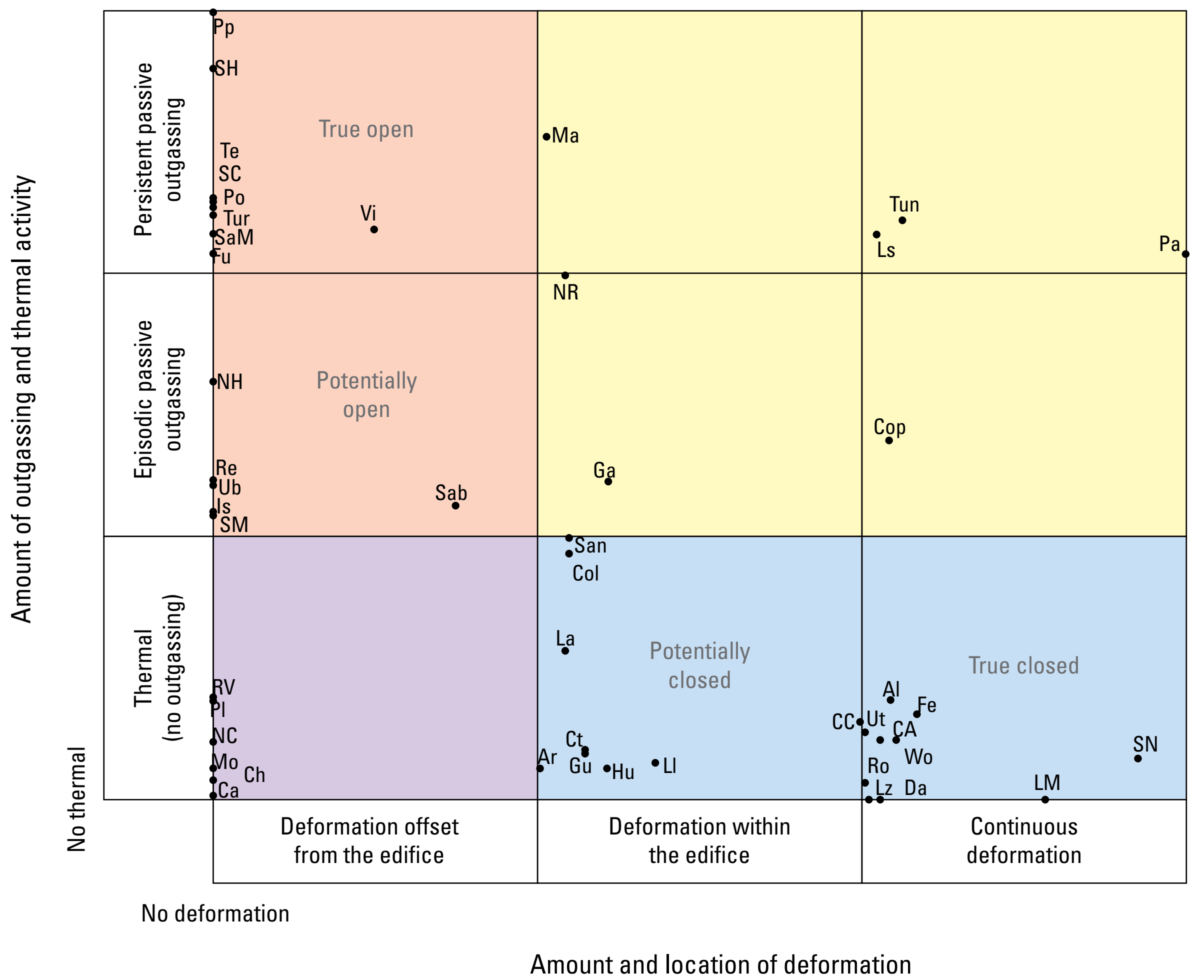

Figure 16. Chart showing classification of the 47 study volcanoes in Latin America based on the amount of outgassing and thermal output produced compared to the amount of deformation detected. Volcano and volcano region names are abbreviated: Al, Alcedo; Ar, Arenal; Ca, Calbuco; CA, Cerro Azul; Ch, Chaitén; Col, Colima; Cop, Copahue; CC, Cordón Caulle; Ct, Cotopaxi; Da, Darwin; Fe, Fernandina; Fu, Fuego; Ga, Galeras; Gu, Guagua Pichincha; Hu, Hudson; Is, Isluga; La, Láscar; Ls, Lastarria; Lz, Lazufre; Ll, Llaima; Ma, Masaya; LM, Laguna del Maule; Mo, Momotombo; Pa, Pacaya; Pl, Planchón-Peteroa; Po, Poás; Pp, Popocatépetl; Re, Reventador; RV, Rincón de la Vieja; Ro, Robledo; NC, Nevados de Chillán; NH, Nevado del Huila; NR, Nevado del Ruiz; Sab, Sabancaya; SC, San Cristóbal; SM, San Miguel; San, Sangay; SaM, Santa María; SN, Sierra Negra; SH, Soufrière Hills; Te, Telica; Tun, Tungurahua; Tur, Turrialba; Ub, Ubinas; Ut, Uturuncu; Vi, Villarrica; Wo, Wolf. Modified from Reath and others (2019b).

Figure 17. Map showing regional classification of 47 active volcanoes in Latin America as open or closed systems as defined using satellite observations and Global Volcanism Program data (see fig. 16). From Reath and others (2019b).

3.5. Lessons from Global Compilations of Volcanic Activity from Remote Sensing Data

Global compilations of remote sensing observations of volcanoes have revealed several features of global volcanism that aren't illuminated in studies of single or small numbers of volcanoes. This is expected because remote sensing increases the sample size of volcanoes under observation and there is a bias created by studying only a small number of volcanic systems (for example, Cashman and Biggs, 2014). Ebmeier and others (2018) found several differences between volcano deformation observed by InSAR and ground-based-only studies (fig. 18). For example, a higher proportion of InSAR studies report noneruptive and nonmagmatic deformation, and they detect more volcanoes deforming in underdeveloped countries, than do studies that rely solely on ground-based

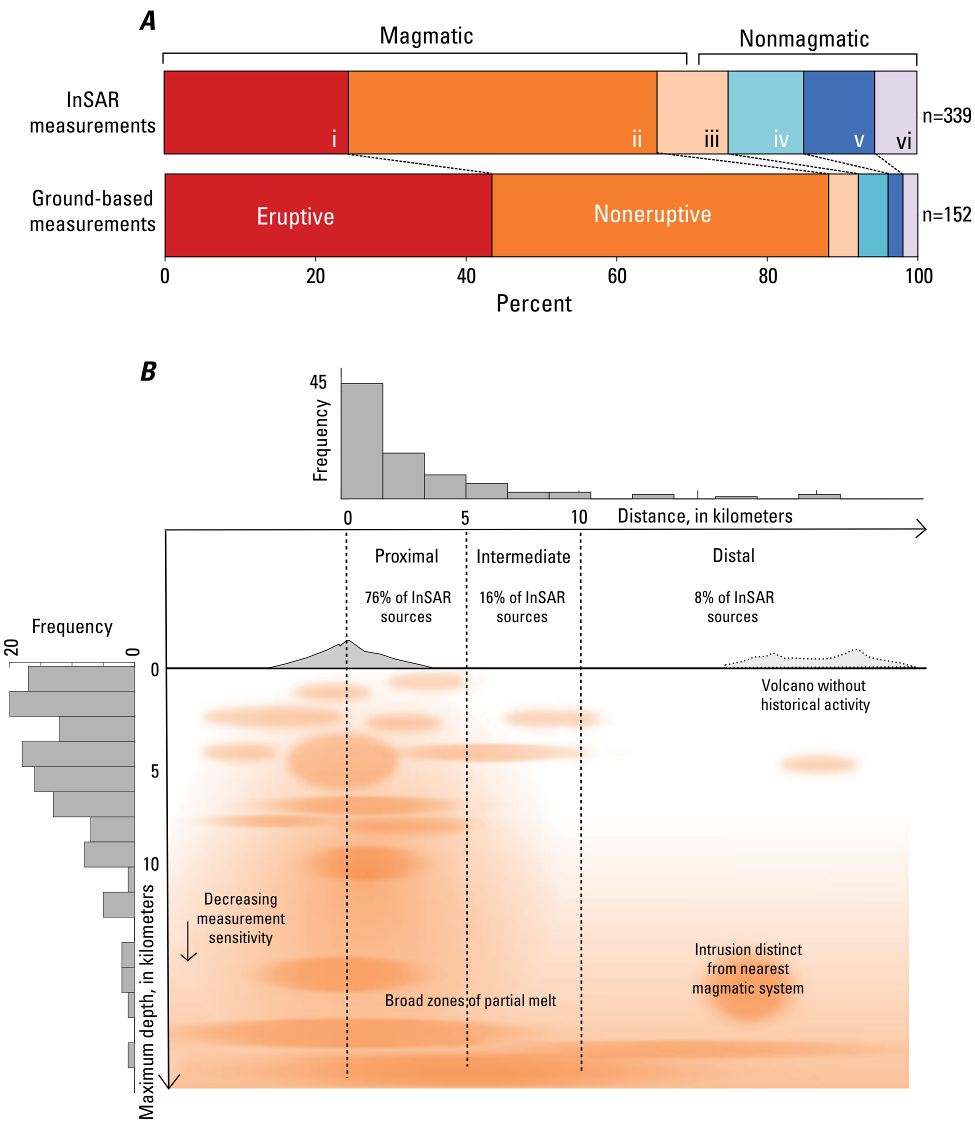

Figure 18. Diagram showing synthesis of volcano deformation characteristics as measured by satellite interferometric synthetic aperture radar (InSAR) between 1992 and 2016. From Ebmeier and others (2018). *A*, Comparison of InSAR and ground-based measurements of ground deformation in terms of inferred origins: i, attributed to magmatic processes during period of eruption; ii, attributed to magmatic processes not associated with eruption; iii, either magmatic or hydrothermal or both in combination, not associated with eruption; iv, attributed to hydrothermal system; v, settling of recent flow deposits; and vi, displacements associated with faulting or gravity-driven collapse on any scale. InSAR captures almost three times as many noneruptive deformation episodes as ground-based detections and also recognizes more nonmagmatic processes. *B*, Distances between the center of volcano deformation attributed to selected magmatic reservoirs observed by InSAR and the nearest volcanic edifice catalogued in the Global Volcanism Program's Volcanoes of the World database with respect to inferred source depth. Distances and depths have been binned and displayed as histograms on the *x*- and *y*-axes. Percentages of deformation at given distances from the edifice are listed. Examples are limited to those sources interpreted to be associated with persistent magma storage (in other words, not short-lived intrusions), normally modeled as a sill, point source, or ellipsoid. No vertical exaggeration. %, percent.

instrument networks. About 24 percent of all volcanoes with deformation from magmatic sources detected by InSAR have the deformation centered more than 5 km away from the nearest active volcanic vent (fig. 18; Ebmeier and others, 2018). However, deformation events spanning both short time intervals and multiple decades are, to date, better recorded by ground networks, given their greater temporal resolution and longer period of use on volcanoes (Ebmeier and others, 2018). Satellite measurements have constrained the global flux and trends of volcanic SO_2, from both passive and active outgassing during eruptions, and by inference emissions of other volcanic gases and toxic trace metals (Carn and others, 2016, 2017). Similarly, global volcano thermal output and its variations have been measured (Wright, 2015). Satellites have also detected variations in deformation[27] and thermal emissions and outgassing at volcanoes following large earthquakes (Delle Donne and others, 2010; Pritchard and others, 2013; Takada and Fukushima, 2013; Avouris and others, 2017).

[27]While a global study of post-earthquake ground deformation has not yet been completed, there are hints of a volcano response on a regional level: 12 volcanoes deformed in response to the 2011 moment magnitude (M_w) 9 Tohoku, Japan, earthquake (Takada and Fukushima, 2013) and the 2010 M_w 8.8 Maule, Chile, earthquake (Pritchard and others, 2013, with two additional volcanoes found by Delgado, 2018, and Reath and others, 2019b).

3.6. Limitations of Current Databases

We know that the global satellite databases of volcanic activity (tables 4–5, appendix 1) are limited but could be improved with available and future datasets. One basic limitation to comparing the datasets available from satellites is that thermal emission, outgassing, and deformation data are available over different timescales in Furtney and others (2018)—thermal emissions from 1960s to 2016 (but quantitative global coverage from 2000 to 2016 in that paper); outgassing from 1978 to 2016; and deformation from 1992 to 2016—and data quality is not uniform over time (figs. 19, 20). Another key limitation is that not all satellite datasets have been included in databases. For thermal emissions, only the MODIS data are globally available, supplemented by some regional ASTER data (table 1); for outgassing, data are primarily from the Ozone Monitoring Instrument (OMI) and TOMS sensors, with some from Infrared Atmospheric Sounding Interferometer (IASI) and Atmospheric Infrared Sounder (AIRS) (fig. 6); and for deformation, not all volcanoes have useful data collected during the entire time interval over which measurements have been possible. For example, in the compilation of Furtney and others (2018), the number of instances of satellite-detected unrest is low for SO_2 because of the limited spatial and temporal resolution of satellite outgassing data. In terms of

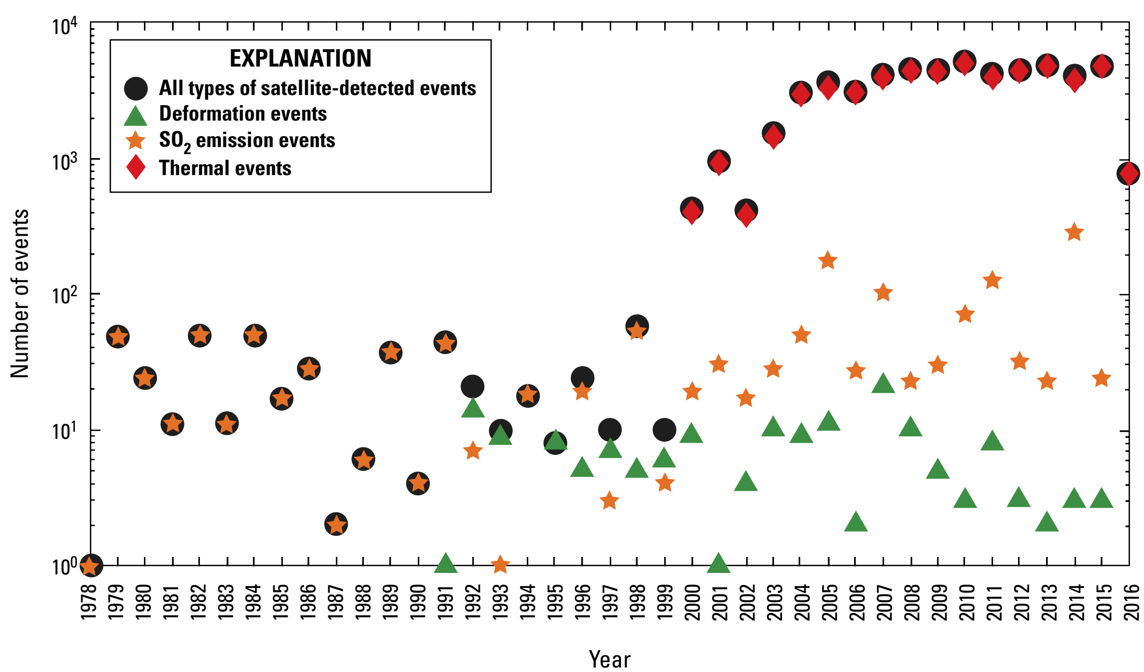

Figure 19. Plot showing the number of volcanoes with activity detected by at least one satellite sensor per year between 1978 and 2016. See Furtney and others (2018) for satellites used and how detections of activity were classified. Note that some symbols plot on top of each other—before 1992, all satellite detections were from SO_2 emission, and since 2000, most detections are thermal. Volcanic activity is binned into yearly data according to the start of the satellite-detected activity. We suspect the decrease in the number of satellite detections in 2016 is related to data processing and publication lags (we include only published reports of deformation; the latest deformation data are available online at https://comet.nerc.ac.uk/volcanoes/). From Furtney and others (2018).

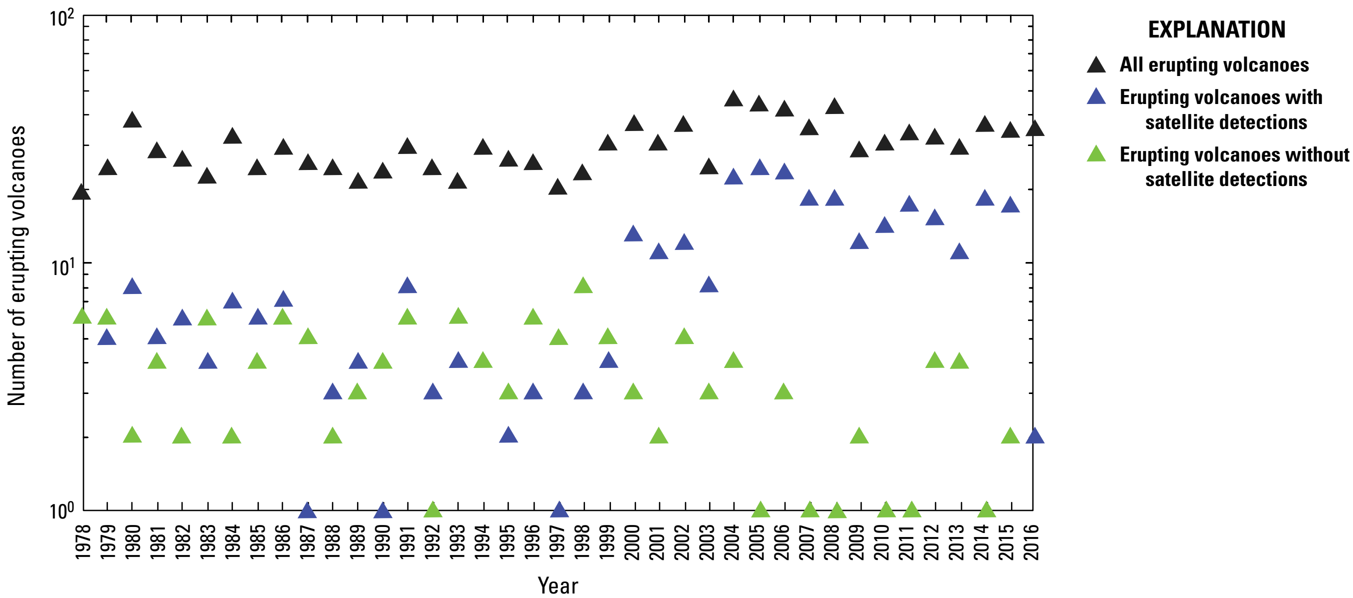

Figure 20. Plot showing the number of volcanoes with activity detected by at least one satellite sensor per year between 1978 and 2016. See Furtney and others (2018) for satellites used and how detections of activity were classified. Note that some symbols plot on top of each other—before 1992, all satellite detections were from SO_2 emission, and since 2000, most detections are thermal. Volcanic activity is binned into yearly data according to the start of the satellite-detected activity. We suspect the decrease in the number of satellite detections in 2016 is related to data processing and publication lags (we include only published reports of deformation; the latest deformation data are available online at https://comet.nerc.ac.uk/volcanoes/). From Furtney and others (2018).

thermal anomalies, Furtney and others (2018) mostly used co-eruptive data from MODVOLC. As one way of assessing the completeness of the thermal database, we suggest that every episode of volcanic outgassing should also have a thermal signature. In Latin America, where Reath and others (2019b) undertook a thorough survey of high-resolution satellite thermal data, a thermal anomaly is associated with every outgassing volcano, although the two detections are not necessarily coincident in time (fig. 21; table 5). We hypothesize that a global survey using higher-resolution satellite thermal data (<100 m/pixel) would reduce the gas-only ("G") category in table 5 by moving more volcanoes to the thermal-and-gas detections category. Therefore, to better understand the questions posed in sections 3.1–3.5, we need higher spatial resolution global databases than we currently have openly available (see section 6).

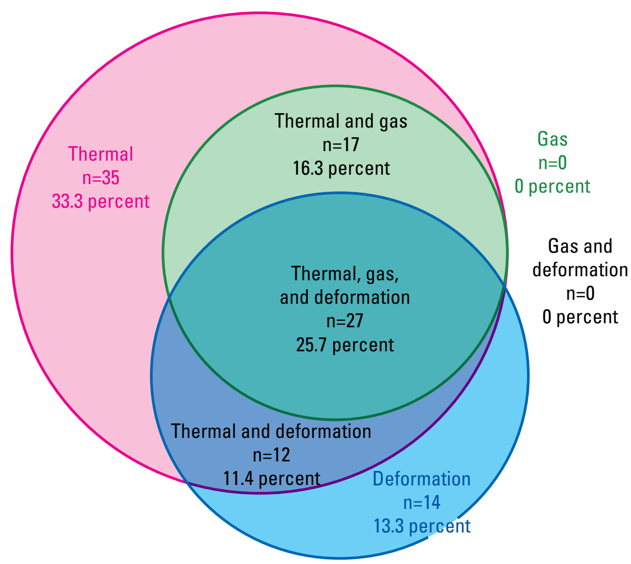

Figure 21. Venn diagram of satellite detections of volcanic activity in Latin America. Of the 330 Holocene volcanoes, satellites detected activity at 105, which are divided by category of detection—thermal emissions, outgassing, deformation, or any combination of the three methods. Data modified from Furtney and others (2018); Reath and others (2019a). See table 5.

4. Overcoming Barriers to an End-to-End System for Global Satellite Volcano Monitoring

An end-to-end system for global volcano monitoring includes data acquisition, analysis, and use to mitigate volcanic hazards. The development of such a capability will require the global volcanology community to work with space agencies and local volcano observatories. Toward achieving this end, PowellVolc organized two workshops with the goals of discussing current capabilities of satellites for volcanology, training users in some online tools, and starting a dialogue about limitations to current volcano monitoring with satellites: (1) a two-day workshop at the 2017 IAVCEI Scientific Assembly in Portland, Oregon, entitled “Promoting the use of satellite observations at volcano observatories,” attended by 45 people from 17 countries and 12 volcano observatories, and (2) a four-day online “Workshop on volcano monitoring infrastructure on the ground and in space” held February 2021 that had more than 200 participants including at least 20 volcano observatories (Pritchard, 2021; Pritchard and others 2022). Recordings of presentations from 2021 are available at https://wovodat.org/about/cov_timeline.php.

Based on the outcome of these workshops and subsequent discussions, we identified five barriers to greater use of satellite observations for forecasting volcanic activity on a global basis: (1) satellites are not always collecting the most useful types of data at the most important volcanoes; (2) data that are collected are not always openly available; (3) data processing is neither timely nor systematic, nor are data products provided in a format that is user-friendly; (4) error analysis is cursory or interpretations from multiple external analysts are in conflict; and (5) communication between end users and remote sensing experts, which is critical for capacity building, is limited. In the following sections, we discuss each of these barriers and provide suggestions to overcome them.

4.1. Data Acquisition

One approach to volcano monitoring is to collect data from all relevant satellites in the global constellation over all of the world’s volcanoes on every pass. Given limits on satellite resources and user capability, however, this is neither a realistic nor efficient strategy. As a pragmatic solution, the 2012 Santorini report suggested an integrated, international, global effort that focused satellite observations at volcanoes depending on their level of activity: global background observations at all Holocene volcanoes (but with observation frequency unspecified); weekly observations at restless volcanoes; and daily observations at erupting volcanoes (Bally, 2012). While we concur with the suggestions of the Santorini report for monitoring volcanoes, we note that they are not yet achievable without further international coordination. For example, the global background monitoring effort is incomplete, restless volcanoes are not observed on a weekly basis nor are erupting volcanoes observed daily by all types of satellites. At the present time, the suggested observation strategy also does not include the level of risk (number of people around volcano, air traffic, and so on) in the prioritization.

4.1.1. Thermal Emissions

Volcano thermal emissions measured from space could best be recorded by the international constellation in different resolution categories (see section 2.1.1). Observations at low (>1 km/pixel) and moderate (>0.375 km/pixel) spatial resolution are made at least several times per day, and every few minutes by some low-resolution sensors (table 1). These sensors can detect the signature and evolution of large eruptions in near-real-time (for example, Wright and others, 2004; Brenot and others, 2014; Dehn and Harris, 2015; Pavolonis and others, 2016). At the Alaska Volcano Observatory, nearly all eruptions are detected in the frequent thermal imagery (more than one acquisition per day) that is available at high latitudes, where polar satellite orbits provide overlapping coverage (Dehn and Harris, 2015). For effusive eruptions, thermal data with low to moderate spatial resolution are currently the only satellite tools capable of monitoring effusion rates daily. Those data are used to guide real-time modeling of lava flow propagation for quick evaluation of associated hazard (Ganci and others, 2012; Harris and others, 2017). However, subtle thermal changes, like those that may precede some eruptions (for example, Dehn and others, 2002; Pieri and Abrams, 2005; Reath and others, 2016; Schneider and Pavolonis, 2017), can only be detected at higher spatial resolution (<100 m/pixel). Furthermore, when high-spatial-resolution thermal data are acquired at night, they have a high signal-to-noise ratio (owing to a lack of solar heating), providing a more effective dataset for measuring subtle thermal features (Pieri and Abrams, 2004).

Although several satellites have high-spatial-resolution thermal infrared imaging capabilities, such as Landsat-8 and -9 and ASTER, they are not providing sufficient nighttime data at potentially active volcanoes (Ramsey, 2016). In 1999, an ASTER Science Team Acquisition Request (STAR) for volcanoes was developed to use the ASTER instrument to make routine observations of the world’s volcanoes broken into Classes A, B, and C based on levels of known activity. The Volcano STAR plan was updated over the years by adding and removing volcanoes and changing the frequency of observation at each volcano as needed (Urai and others, 1999; Urai and Pieri, 2010). In the plan, Class A volcanoes receive about 19 acquisitions per year, 11 of which are acquired at night, whereas Class B and C volcanoes receive 4 and 2 acquisitions per year, respectively, regardless of time of day. However, with about 20 more years of data, we now have a better understanding of the total number and distribution of active volcanoes (for example, Ebmeier and others, 2018; Furtney and others, 2018; Pritchard and others, 2018; Reath and others, 2019a). Thus, the frequency of observations in each category needs to be updated to reflect this additional understanding.

Exploitation of thermal satellite data over volcanoes is challenged by variations in the quality of high-spatial-resolution data. For example, unlike ASTER, Landsat-8 thermal data cannot be used for quantitative analysis because the data are resampled from 100 to 30 m/pixel, introducing an unknown amount of error (Reath and others, 2019a). Increasing the frequency of nighttime observations for all high-spatial-resolution (<100 m/pixel) TIR sensors would be an improvement over current operations, because many volcanoes are receiving fewer than two cloud free images per year (for example, Reath and others, 2019a). The available high-spatial-resolution TIR sensors (for example, ASTER) are nearing the ends of their missions, and a gap in those data in the future is a near certainty. However, lower-spatial-resolution, but high-temporal-resolution data collected in the MIR, SWIR, and TIR bands will continue (Zehner, 2010; Dehn and Harris, 2015; National Academies of Sciences, Engineering, and Medicine, 2018).

4.1.2. Gas Emissions

An international constellation of at least 15 satellites (both polar orbiting and geostationary), carrying more than 20 sensors operating in the UV, IR, and microwave bands, routinely measures volcanic emissions of SO_2 gas into the atmosphere, albeit with different spatial resolutions (~3.5–50 km), altitude sensitivities, and detection thresholds (table 1; figs. 22, 23; Brenot and others, 2014; Carn, 2015a; Carn and others, 2016). These sensors can potentially provide as many as about 36 daily overpasses of a volcano (more at high latitudes; fig. 22) for detection of significant eruptions, but only eight of these overpasses are by sensors that have sufficiently high spatial resolution (for example, OMI, see fig. 23) to detect passive (noneruptive) volcanic SO_2 outgassing at low altitudes (<10 km). Most of the sensors that can detect passive outgassing utilize daytime-only UV measurements (by OMI, Ozone Mapping and Profiler Suite [OMPS], Global Ozone Monitoring Experiment [GOME]-2, and Tropospheric Monitoring Instrument [TROPOMI]). Only a single operating IR sensor (ASTER) is capable of routinely detecting passive or preeruptive SO_2 emissions at night (Urai, 2004; Henney and others, 2012); thus, nighttime observations of passive volcanic outgassing are currently limited.

Figure 22. Diagram showing relative timing of volcanic gas measurements during the day and night for satellites measuring gas emissions (see figs. 6, 13; table 1). Modified from Brenot and others (2014). See "Abbreviations and Instrument Names" list for definitions of instrument names.

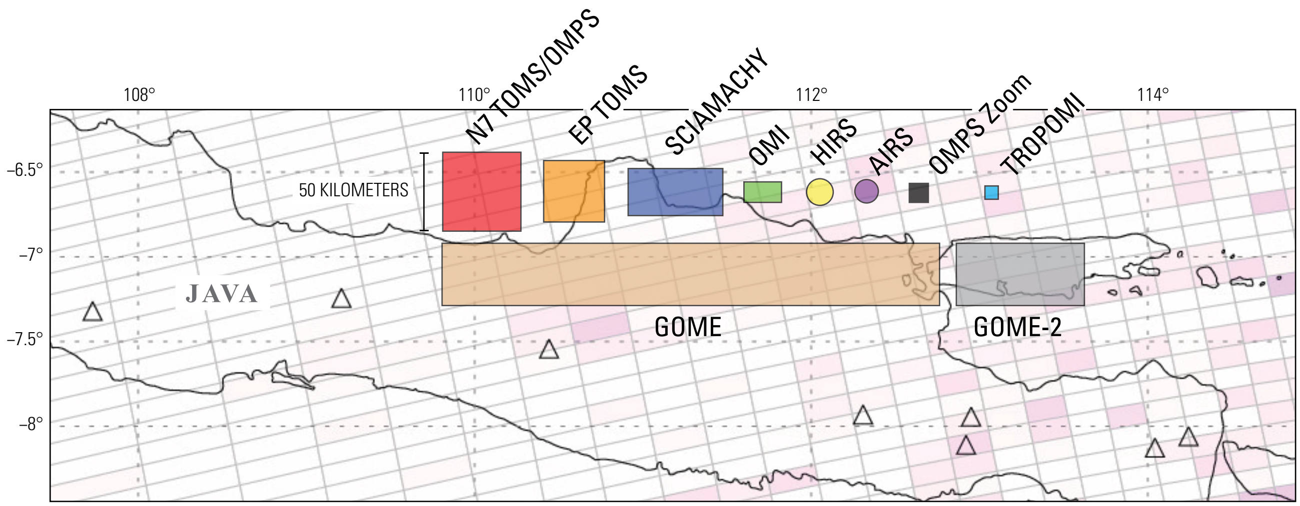

Figure 23. Diagram of pixel sizes of some ultraviolet and infrared instruments used to detect volcanic gases (see fig. 6) superimposed on a map of Java, Indonesia, with volcanoes shown as triangles. Background colors correspond to an OMI image. See "Abbreviations and Instrument Names" list for definitions of instrument names.

Detection of volcanic CO_2 emissions is possible from space (for example, with Orbiting Carbon Observatory [OCO]-2; Schwandner and others, 2017) but remains challenging and is not yet sufficient to be an effective volcano monitoring tool.

4.1.3. Surface and Topographic Change from SAR, Optical Images, and Lidar

To date, no high-spatial-resolution optical or SAR imagery (<5 m/pixel) that can be used for surface or topographic change detection is openly available for scientific use without restriction (table 1), although limited datasets can be utilized with special agreements. Furthermore, many satellites with a high-spatial-resolution mode do not have a routinely updated global volcano background observation plan, although there are useful data acquired for selectively targeted volcanoes (for example, Pallister and others, 2013), and data are occasionally acquired before, during, and (or) after eruption (for example, Castro and others, 2016). As was noted in section 2.1.3, detection from space of topographic change at volcanoes using high-spatial-resolution imagery or lidar is poorly documented, and the number of volcanoes worldwide having such change detected is uncertain. Thus, there is a need for a coordinated global volcano observation strategy and increased data access among the extensive constellation of high-spatial-resolution satellites to better define how many volcanoes need to be targeted with these observations, and how frequently.

4.1.4. Surface Deformation

Satellite InSAR has revealed a variety of surface and subsurface processes causing surface deformation at volcanoes (for example, Pinel and others, 2014; Biggs and Pritchard, 2017; Ebmeier and others, 2018). However, except for Sentinel-1A/1B, most past and current SAR satellites do not sample all the world's volcanoes up to the limit of their repeat interval due to limited onboard data storage, duty cycle, and down-link capacities. In cases where there is a robust background observation plan, such as the Sentinel-1A/1B constellation, data processing and analysis by end users are challenging (see section 4.2.2). To overcome the limitations of any given SAR system, scientists often combine observations from all available satellites to inform analysis and hazard response. No SAR satellite or constellation of satellites is making routine daily observations yet, but if the entire international constellation of more than 20 SAR satellites (table 1) targeted a given volcano during every overflight, daily or subdaily observations would be possible (depending on latitude, see fig. 9)—an especially useful capability during a crisis. The disadvantage of this approach is that the data from the different satellites are not directly comparable (for example, they have different spatial resolution and viewing geometry, and interferograms cannot be made from different types of satellites), which complicates interpretation. As an example of the international coordination that would be needed, a recent study found that the international constellation of SAR satellites was not routinely acquiring data that are useful for ground deformation studies at all high-priority volcanoes in Latin America because observations were too infrequent, in the wrong location, or with an observation mode that could not resolve deformation (Pritchard and others, 2018). Over the next three years it is expected that the launch of new InSAR satellites, such as the NASA–Indian Space Research Organization Synthetic Aperture Radar (NISAR) mission, will observe all global volcanoes at repeat intervals (12 days or less) that are increasingly relevant toward volcano science and response. The growing amount of InSAR data will increase the need for robust methods of rapid signal detection within vast data volumes (section 4.2.2). But even with the expansion of openly available datasets, access to restricted datasets is still needed in order to improve temporal resolution.

4.1.5. Global Volcano Observation Strategy

Determining which volcanoes to prioritize with specific satellite remote sensing techniques remains a challenge. Ideally, we would target all volcanoes all the time; although some sensors essentially achieve this goal, they are limited (table 1; Valade and others, 2019, and references therein). Satellites with large fields of view and low-to-moderate spatial resolution (for example, geostationary sensors, MODIS, VIIRS) routinely cover all available land areas. Although they already observe all subaerial volcanoes, they miss volcanic signals because of clouds and low spatial resolution. Similarly, global SO_2 gas measurements are made daily by several UV and IR sensors, but they are not optimized for volcanic signals. For other sensors (especially SAR), there are usually limits on the volume of data that can be downloaded or collected, so acquisition plans do not allow targeting of all volcanoes. For this reason, prioritized lists of volcanoes have been determined in several ways. Some sensors focus on the most active volcanoes or those located closest to population centers, whereas others focus on all volcanoes with historical or Holocene eruptions. We suggest the remote sensing community consider a wider view of volcanic monitoring: one that includes all restless volcanoes, even those without historical or Holocene eruptions. Every few years, an eruption occurs at a volcano with no known historical activity (for example, Chaitén, Chile; Soufrière Hills, Montserrat; Sinabung, Indonesia), and, though rare, there have even been eruptions from volcanoes that were not previously recognized as volcanoes (for example, Mt. Lamington, Papua New Guinea; GVP, 2001).

To facilitate international satellite observations of volcanoes, we have developed a list (table 3 and appendix 1) of volcanoes with eruptions in the Holocene (GVP, 2013), as well as those having unrest detected by ground-based instruments or by satellites using information from GVP (2013), Furtney (2016), White and McCausland (2016), and Biggs and Pritchard (2017). Our list includes volcanoes that have not erupted in the Holocene but have shown some seismicity, deformation, or thermal activity—about 50 of these Pleistocene volcanoes are from GVP's VOTW database plus about 10 volcanoes that aren't in the GVP database but have activity described in published papers (for example, Sillajhuay, Chile: Pritchard and others, 2014; Bay of Plenty, New Zealand: Hamling and others, 2016).

To develop a prioritized list of "target" volcanoes, instead of using common terms like "active," "restless," and "dormant," we have classified volcanoes based on whether they have erupted since 1990, their PEI from the U.N. Global Assessment of Risk (Brown, Loughlin, and others, 2015), and whether they have had ground- or satellite-detected activity (seismicity, thermal emissions, outgassing, or deformation; see table 3 headnote for details). The prioritization is thus based on a combination of recent activity and population exposure, rather than on various indicators of threat potential as calculated by USGS to support a National Volcano Early Warning System (Ewert and others, 2018). We offer suggestions for a repeat interval of satellite SAR and thermal observations based on the level of volcanic activity (table 3) but make no suggestions for outgassing observation strategies since these data are already globally available. For SAR, we suggest focusing dense temporal observations at about 500 of the approximately 1,400 potentially active volcanoes (defined as those having had at least one eruption in the Holocene or those with satellite detected unrest but no Holocene record of eruptions). This suggested number of target volcanoes is much greater than the 100 volcanoes considered restless or erupting annually according to the Santorini report (Bally, 2012).

Although there have been many efforts to monitor global volcanoes using SAR, none have had a truly global background observation plan focused on all approximately 1,400 potentially active subaerial volcanoes until the Sentinel-1 mission launched in 2014 (Hooper and others, 2018).[28] Using Sentinel-1, at least 900 volcanoes are being monitored and data are processed by the Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET) Looking into Continents from Space with Synthetic Aperture Radar (LiCSAR) system (Anantrasirichai and others, 2018), but not yet in real time. Based on preliminary data, we provide a note in appendix 1 detailing whether the routine SAR observations being made by the Sentinel-1A/1B satellites are of sufficient quality to monitor a volcano for ground deformation, or if additional satellite observations are needed because of too much vegetation or the need for high spatial resolution data (section 4.2.1). Further

[28]For example, there were 16 "decade volcanoes" that were a focus of study in the 1990s; 56 volcanoes were part of the 2010 ESA GlobVolcano Initiative; and 805 volcanoes were being imaged in background mode by the RADARSAT-2 satellite as of 2012 (Mahmood, 2014). Only a few percent of the data collected by RADARSAT-2 have been analyzed, however, because the data are not freely available (Pritchard and others, 2018).

work is needed to assess whether our preliminary assessments of Sentinel-1A/1B quality need to be updated.

Appendix 1 and table 3 suggest a scheme to help prioritize high-spatial-resolution MIR and TIR satellite measurements at target volcanoes. This scheme specifically expands upon volcanoes included in the Volcano STAR plan. The plan currently requires that top-priority volcanoes, or volcanoes we have classified as A1 “Active” in table 3, receive about 11 nighttime observations per year (every 32 days), which equates to acquiring every other possible night observation for volcanoes at the equator. Ramsey (2016) reported that these volcanoes were only receiving 85 percent of the observations in the Volcano STAR plan, and even those that met this number were not adequate to provide rapid assessments to discriminate short-term anomalous thermal activity. The ASTER Urgent Request Protocol (URP) was developed to improve detection of transient thermal anomalies at as many as 25 of the most active volcanoes worldwide (for example, Ramsey and Flynn, 2004; Duda and others, 2009; Ramsey, 2016). To move beyond these 25 volcanoes, we suggest increasing the number of night observations to about 23 per year (every 16 days), or every available acquisition at the equator for all top-priority volcanoes. Additionally, we suggest both mid-level- (Classes A2, B1, B2) and low-level-priority (Class C) volcanoes have at least four and two nighttime, cloud-free, acquisitions per year, respectively. This is the same number suggested by the Volcano STAR plan, but the cloud-free consideration maximizes the likelihood that these data will provide useful information for establishing baseline behavior and for identifying new activity. Regional cloud percentages calculated by Reath and others (2019a) provide a guideline to determine the number of acquisitions needed in different regions to achieve the desired number of cloud-free images. Given a lack of planned, new high-spatial-resolution TIR instruments, new satellites with this capability are needed (National Academies of Sciences, Engineering and Medicine, 2018). We encourage maintaining the low- to moderate-spatial-resolution, but high-temporal-resolution MIR, TIR, and SWIR systems (such as VIIRS, MODIS, and so on; table 1), as well as expanding capability for high-spatial-resolution sensors, like Sentinel-2, to record in TIR and at night.

Some types of satellite data are more useful at certain volcanoes than others. Specifically, high-spatial-resolution data are needed to track certain types of low-temperature thermal activity (≤90 m/pixel; Jay and others, 2013), outgassing (plume areas larger than the image pixel area; Lopez and others, 2013), and deformation near the summit crater (on the order of 1 m/pixel; Salzer and others, 2014) at some volcanoes, where critical signals take place over tens to hundreds of meters. However, these parameters will not be useful in all situations. Small-spatial-footprint, high-resolution sensing modes are inadequate to track changes at volcanoes with deformation sources that are deep or offset from the volcano’s summit (for example, those in Lu and Dzurisin, 2014; Delgado and others, 2017; and Ebmeier and others, 2018). In addition, background outgassing or low rates of deformation at many volcanoes will go undetected unless spatial and temporal averaging of multiple satellite images is conducted (Carn and others, 2017). Much smaller pixel areas than those sensed by OMI (13 km ×24 km) are needed to detect small plumes (<10 km in cross section) associated with background outgassing. TROPOMI has improved spatial resolution relative to OMI and shows significant promise for enabling passive outgassing to be routinely detected from space (Theys and others, 2019). Similarly, the forthcoming IASI-Next Generation will have improved spatial and spectral resolution compared to IASI. Our list of suggested satellite-observation rates at each volcano (appendix 1) includes notes that some volcanoes require high spatial resolution or broad, synoptic views. As activity waxes and wanes at individual volcanoes and new priority volcanoes are identified, appendix 1 can periodically be revised. To achieve the goal of consensus targeting of volcanoes at specific frequencies, the global volcanological community and relevant space agencies need to coordinate and collaborate.

4.1.6. Coordination

There is currently no globally coordinated effort to ensure that volcanoes are imaged by the most appropriate sensors. As a model for what the volcanology community may use to address this need, we consider the international coordination of satellite and ground-based observations of the cryosphere through the Global Cryosphere Watch (GCW). This program was founded as a legacy of the International Polar Year (IPY; 2007–2009) by the WMO (Key and others, 2015). During the IPY, a Space Task Group was formed to coordinate international satellite “snapshots” of the polar regions (Drinkwater and others, 2008; Jezek and Drinkwater, 2010). Following the IPY, cooperation among space agencies continued through the Polar Space Task Group (PSTG), a group composed of the GCW, the WMO (Key and others, 2015), and a global network of volunteers. The volcanology community could follow this model as a means of ensuring that appropriate data are being collected at all the world’s volcanoes and of avoiding conflicting requests to space agencies and satellite companies—in other words, tasking the satellite with compatible modes that do not interrupt time series acquisitions. A common point of contact for this work would reduce the potential for conflicts in satellite tasking. The appropriate organization(s) to host global coordination of satellite volcano observations is an open question, but existing international coordination groups, such as CEOS, GEO, and Coordination Group for Meteorological Satellites (CGMS), could be leveraged, with additional linkages to WOVO and IAVCEI also being key. Partnership with the Volcano Observatories Best Practice workshops would also be advantageous (Pallister, Papale, and others, 2019).

4.2. Data Access

4.2.1. Open Data Policies

Many satellites have open data policies (table 1), but a few important satellites for thermal emissions, outgassing, and optical observations do not (for example, Satellite Pour l'Observation de la Terre [SPOT], Pleiades, Planet, Worldview 1–3, IASI). For SAR, most satellites have restricted data policies, yet some of these provide high-spatial-resolution data that have proven critical in observing volcano surface changes. An important exception is the Sentinel-1 mission, which has an open data policy and represents a major step forward in terms of volcano observation owing to its frequent repeat times and global acquisition strategy (globally every 12 to 24 days, or more frequently during a crisis). This is significant progress, but there are still gaps in Sentinel-1 coverage; for example, low interferometric coherence due to vegetation or persistent snow/ice, and where volcanic processes are occurring at timescales shorter than 12 or 24 days (for example, Nobile and others, 2017; Pritchard and others, 2018; Garthwaite and others, 2019). Therefore, more frequent observations and use of other satellites are needed. Some volcanic processes (related to dome growth or eruptive vent evolution; for example, Richter and others, 2013; Salzer and others, 2014) happen at small spatial scales that cannot be resolved by Sentinel-1 but can be imaged by other restricted satellites (table 1).

Most of the satellites with restricted data policies (table 1) have special programs that provide quotas of data at reduced or no cost for volcano research. Additional means of securing large volumes of SAR data for volcano monitoring and research include the GEO GSNL volcano initiative, which targets about 20 volcanoes worldwide (Salvi, 2016); the CEOS Disaster Risk Management (DRM) Latin America volcano pilot project (Pritchard and others, 2018), which focused study on all Holocene volcanoes in Latin America (319) for a limited time (2014–2017); and the CEOS Volcano Demonstrator project (2019–2024), which includes volcanoes in Latin America, Southeast Asia, and Africa. The International Charter Space and Major Disasters (http://www.disasterscharter.org) is an effective mechanism for providing data after a major event but cannot be used for background observations or in anticipation of an eruption, and its SAR data are usually restricted to amplitude data. Only a few volcanic crises per year have data available through the Charter; it has been activated 35 times for volcanoes between 2000–2019 despite more than 700 eruptions having occurred in that time. The USGS Hazards Data Distribution System (HDDS) (Lamb and Jones, 2012; https://hddsexplorer.usgs.gov/) also makes available both open and restricted satellite data (optical and SAR) to approved users for all types of natural hazards. From 2004–2019, about 6 percent of the data distributed via the HDDS supported 25 volcanic crises worldwide. Considering that there are approximately 1,400 volcanoes of interest and more than 100 episodes of volcanic unrest per year (Bally, 2012), these projects need to be greatly expanded globally and data availability greatly increased.

4.2.2. Timely Processed Data in Formats the User Needs

Several types of satellite data are routinely processed automatically in near-real time (Valade and others, 2019, and references therein). Examples of such systems operating globally include MODVOLC and MIROVA for thermal detections by the MODIS instruments (Wright and others, 2004; Coppola and others, 2016) and OMI/OMPS SO_2 mass calculations for subregions that may include multiple volcanoes (Carn and others, 2016). Global detections of activity above background at volcanoes from weather satellites (usually limited to eruption detections), including thermal and ash detections (Pavolonis and others, 2016; Pavolonis and others, 2018) and SO_2 (Brenot and others, 2014), are available through notification systems that send an email to subscribed users under pre-defined circumstances. For a selected number of volcanoes (currently about 20), the Monitoring Unrest from Space (MOUNTS) project (Valade and others, 2019) provides IR, UV, and SAR data in near-real time from the Sentinel satellites. A variety of other algorithms and approaches for rapid global to regional detections are available, each with their own strengths and limitations (Steffke and Harris, 2011). These automated algorithms are essential for global volcano monitoring given the large volumes of available data—weather satellites alone acquire over 1 trillion Earth observations per day, resulting in tens of thousands of images relevant to volcano monitoring, and petabytes of data are projected to be collected annually from Sentinel and NISAR alone. There are too many data for individuals to examine a whole region, or even a single country, in a timely manner. Available automated routines are limited to large-magnitude signals and, given the available spatial resolution, they may be of insufficient resolution to identify all volcanic signals. In most cases, the automated detections are more useful for identifying, rather than forecasting, eruptions (see section 2), but these automated routines remain useful for tracking volcanic hazards, like ash clouds and lava flows (Dehn and Harris, 2015).

A large amount of satellite data (especially SAR, either as amplitude images or interferograms) are not currently available to the global community in a timely manner in either a raw or processed form. There are a variety of efforts underway to improve this situation (for example, Advanced Rapid Imaging and Analysis [ARIA], Hua and others, 2013; COMET-LiCSAR, Spaans and others, 2017; SAR Volcano Integrated Early Warning System [SARVIEWS], Meyer and others, 2015; simplified processing chain of Garthwaite and others, 2019; MOUNTS project, Valade and others, 2019). Much of the SAR data do not require downloading from the satellite and processing in near real time, as the data are not time sensitive, but developing capabilities to expedite selected data that are needed during a crisis would be valuable. Tools to search for signals within the vast and growing data volumes, such as artificial intelligence and machine learning, are needed to take advantage of those data that are delivered to volcanologists (for example, Anantrasirichai and others, 2018; Gaddes and others, 2018; Valade and others, 2019).

Further work is needed to determine the data products of most value to end users. For volcano monitoring, volcano observatories are the end users—they are typically mandated by governments to provide situational awareness and information about the possible hazards from the volcanoes within their jurisdictions. For some volcanoes, there is no official volcano observatory, but there are scientific organizations (like a geological survey or university) who are the end users. There are opportunities for outside scientists to work with volcano observatories, and best practices have been established for these interactions (Newhall and others, 1999; Lowenstern and Ewert, 2020). For example, it is best if space agencies and external scientists communicate directly with volcano observatories, because communicating instead with governments or local communities themselves would be confusing and undermine the work of the observatories (Newhall and others, 1999). Further, it is best if outside scientists establish multiyear relationships with volcano observatories (Lowenstern and Ewert, 2020). Each volcano observatory is unique in the number of staff and amount of resources available; thus, while some observatories have staff that take an active role in processing raw satellite data, other observatories do not have the necessary resources and instead rely on external partners to process data and provide interpretations. Capabilities of volcano observatories are not static and can grow or shrink as levels of volcanic activity change, depending on budget conditions. All volcano observatories struggle with analyzing and storing vast quantities of remote sensing data ("big data"). The creators of data products should consider that some observatories have limited downlink capability, storage capacity, and ability to pay for annual software licenses.

4.2.3 Uncertainty Quantification and Dealing with Conflicting Interpretations

A key goal of volcano remote sensing is to provide enough information for useful data interpretation and error analysis. As mentioned in section 4.2.2, each volcano observatory is unique in whether they want to receive raw, processed, or interpreted data. When data are sent with an interpretation, observatories request that uncertainties be included in any notifications or products they receive—specifically whether a given signal is likely to be volcanic in origin or some other type of nonvolcanic artifact (for example, Pritchard and others, 2018). Even data received without interpretation need a discussion of potential sources of error. As with other communications during volcanic crises, the remote sensing community needs a set of "best practices" to follow when communicating with a volcano observatory directly or posting results on social media (for example, Williams and Krippner, 2018; Bartel and others, 2019). First, external experts analyzing remotely sensed data need to coordinate to provide a range of scientifically plausible interpretations (avoiding groupthink), while also considering ethical and legal implications (for example, Aspinall, 2011; Bretton and others, 2015; Papale, 2017). Communications with end users who need data for hazard assessments and disaster response need to be clear and consistent (not contradictory). Second, those providing satellite data to observatories can help to build capacity at the observatory (see section 4.3) to process the data or at least to interpret the satellite products.

To achieve these goals, it is essential to develop working relationships between volcano observatories and remote sensing experts before a volcanic crisis develops (Lowenstern and Ewert, 2020). These relationships can be fostered through capacity building activities and the use of tools that facilitate electronic communication. An example of a mechanism to improve communication is an email listserv like the Volcanic Clouds Groups.io email group (https://groups.io/g/volcanicclouds) that has 98 members who discuss ash and SO_2 cloud observations and impacts, including those from satellite remote sensing. The group started in 2001 as a Yahoo! Group and had over 300 members until Yahoo! stopped the service in December 2020. Such an email list would be most useful by providing context for new satellite measurements as they are shared with the volcano community. For example, how does a measurement of SO_2 emissions compare to measurements over recent days or weeks? Moderators or designated individuals on the list could provide summaries or context of the various opinions and datasets that are shared so that all users understand the big picture on a fluid timeline as needed.

4.3. Building Capacity and Collaboration Networks

Although useful and easy-to-interpret data products with error analysis will be of most use to end users, increased capacity at volcano observatories to use remote sensing observations will ultimately contribute to risk mitigation. The goal is for volcano observatory staff to become familiar with remote sensing data, to know what data are available and where, and to determine what level of products best meet their needs (for example, raw data, pre-interpreted products, and so on). It is critical that such familiarity become established before a volcanic crisis starts. It is also critical that observatories and external experts (such as remote sensing experts at other volcano observatories, universities, or other agencies) establish collaborative relationships so that external experts can aid in data interpretation as needed (Lowenstern and Ewert, 2020). Several different types of capacity building currently exist, including short courses, visits by remote sensing experts to observatories or visits by observatory staff to satellite data processing centers, and student exchanges and training (for example, Pritchard and others, 2018). Sentinel Asia (Kaku and Held, 2013) provides another example of how capacity building can be fostered. Volcano observatories in Southeast Asia send requests for data to Sentinel Asia, and multiple partner agencies process the data and provide interpretations. Such efforts could be expanded globally but with the recognition that there is no one-size-fits-all solution, as illustrated by feedback from eight volcano observatories that participated in the CEOS Latin America pilot project (Pritchard and others, 2018). For example, this feedback revealed that although short courses serve an important role to spread awareness of remote sensing among a large group and facilitate networking between observatories and remote sensing experts, they are too limited to train observatory personnel to do their own processing. On the other hand, indepth training of students or staff, either within their country or externally and lasting months or years, has a much greater impact and more effectively spreads the capability (if not the resources). As this training relies on a single or small number of individuals (trainers and trainees), however, it is not robust.

Social media provides an opportunity to share information about volcanic activity widely, but with the challenge that both accurate and inaccurate information can be widely disseminated. Social media users span a wide range of levels of expertise from volcanology experts to hobbyists and tourists, and they all get an equal platform on social media. Even if best practices are established for experts to share volcanological information on social media, it is nearly impossible for all groups to follow these guidelines. Yet, social media provides an opportunity to improve the analysis and dispersal of accurate information. Some hobbyists closely follow their favorite volcanoes and routinely post satellite data, helping create event timelines. Given the large volume of data, citizen scientists could assist in data analysis. There is a role for partnerships among remote sensing experts, groups of hobbyists who work with the volcano observatories, and the volcano observatories where each clearly knows what the others need.

5. Vision for a Global Volcano Remote Sensing Observatory

Here, we outline a vision to improve the state-of-the-art in global volcano monitoring by 2030. We have outlined the problems with current volcano remote sensing in sections 3 and 4. Like many challenges facing society, volcanism poses global challenges that require international solutions among an array of stakeholders: space agencies, volcano observatories, research institutions and universities, governments, civil protection organizations, emergency managers, the aviation industry, business leaders, and others. Identifying the problems and finding solutions among many stakeholders across many disciplines and nations is complicated, but we think there is value in outlining a common vision. Our intention is that this vision will inspire others to pick up the mantle and help to carry this project forward, toward implementation within the next decade.

5.1. Global Coordination of Background Satellite Observations and Eruption Response

Our vision is that by 2030, an international committee will meet at least annually to assess the state of global volcano remote sensing and determine if the right background data from optical, UV, IR, and SAR satellites of interest are being collected at all potentially active volcanoes. The default background observation plan could use an updated version of appendix 1 as a starting point and suggest revisions to satellite observation plans. The state of ground-monitoring at volcanoes would be assessed by the Global Volcano Monitoring Infrastructure Database (https://wovodat.org/gvmid/home.php; Pritchard and others, 2022), and volcanoes without sufficient ground-monitoring would be targeted. The committee would discuss gaps in the capabilities of available satellites and emerging technologies, which could motivate proposals to develop new instruments and launch new satellites. Although the committee would not write mission proposals to space agencies, their analyses could be used to develop proposals. A subgroup could be called on short notice (by the full committee, space agencies, or volcano observatories) to coordinate observations of a volcanic eruption and to ensure that there are no conflicts among end users of the data. This subcommittee would be independent of The International Charter Space and Major Disasters (http://www.disasterscharter.org) but would work closely with the charter when it was invoked. It would also work with volcano observatories and other national agencies to coordinate remote sensing data distribution (for example, HDDS in the United States, Lamb and Jones, 2012). For large eruptions, especially those having a potential effect on climate, an international effort to collect space, airborne, and ground data would be undertaken (for example, NASA, 2018). By 2030, modest funding for the committee's work would be secured through a combination of international agencies and volunteer efforts to write proposals. We propose that the committee be called the Volcano Space Task Group (VSTG) by analogy with the cryosphere PSTG (see section 4.1.6). Like the PSTG, the VSTG would be composed of about 20 people from the space agencies and an additional 20 to 30 other stakeholders: volcano observatories, VAACs and ICAO, international groups like CEOS, CGMS, GEO, Global Earth Observation System of Systems (GEOSS), WOVO, and IAVCEI, and remote sensing experts. In particular, the VSTG would closely communicate with pertinent ICAO and WMO working groups (for example, WMO, 2019) as well as IAVCEI and WOVO regarding volcano observatory best practices (Pallister, Papale, and others, 2019).

5.2. Rapid Distribution of Open Data

By 2030, our vision is that the international virtual constellation of satellites observing volcanic activity will include more than 30 space vehicles (plus hundreds of miniaturized cube-shaped satellites called CubeSats) launched by governments and companies, and nearly all space agencies and companies will have agreed to make their data over volcanoes openly available. During volcanic crises where data are not already available through the International Charter Space and Major Disasters or other programs, the VSTG would suggest where low-latency data would be useful and help to avoid conflicts in tasking requests. Volcano observatories could use satellite data to detect significant preeruptive signals and alert aircraft through appropriate operational channels (Lechner and others, 2018). The instrument suite required to optimally respond to a crisis spans a range of wavelengths (UV, visible, IR, microwave), spatial resolutions (submeter to several km per pixel), and revisit times (minutes for geostationary satellites, hours for CubeSats, and days to weeks for polar orbiting single satellites). The VSTG would regularly review data acquisition plans of these satellites to make sure they are optimized for volcanic activity and make suggestions to space agencies regarding tasking.

5.3. Communication Tools for Discussion of Satellite Volcano Data

In our vision, volcano observatory staff and remote sensing experts would communicate with each other using a series of closed online discussion groups hosted by WOVO, IAVCEI, and other agencies. There, processed satellite data could be shared and interpretations discussed. The discussion groups would collaborate to evaluate specific satellite detections to determine which reflect real volcanic activity and which do not. For real activity, the implications of the activity, as well as uncertainties in the interpretation, would be discussed. One of the groups would be focused on ash detection and would be a continuation of the Volcanic Clouds Groups.io email group (https://groups.io/g/volcanicclouds). Decisions about who would join the group, what types of detections merit discussion, and other pertinent issues would be decided by the community and platform moderators in an open process, as done in the Volcanic Clouds Groups.io discussion board.

By the year 2030, closed forums would continue to allow for discussions among many experts, but public statements would still be made by the governmental agencies in charge of hazard assessments (Newhall and others, 1999). When data are presented on social media, guidelines recommended by the Communications Working Group of IAVCEI (Bartel and others, 2019) will be followed to minimize the impacts of well-intentioned but misinformed messages and messengers, to coordinate messaging among agencies charged with public safety, and to find individuals who can disseminate and support official messaging by speaking with the media and sharing preliminary results.

5.4. Data-Model Fusion for Understanding and Forecasting Volcanic Behavior

Satellite data are useful not only for detecting and monitoring volcanic unrest, but also for constraining models. Data-model fusion techniques can be used to estimate the properties of volcanic systems and, in some cases, forecast future behavior. Such techniques have been demonstrated (for example, Anderson and Segall, 2013; Segall, 2013; Zhan and others, 2017; Bato and others, 2018) but are not widely applied, in part owing to a lack of datasets adequate for developing and constraining relatively complex models. Our vision is that by 2030, diverse, low-latency satellite data, coupled with data from ground-based networks when available, would provide observatories and partners with the observations they need to develop mathematical models that more accurately characterize volcanic systems and how those systems change over time. These models would be based on fundamental magma physics and relate interdisciplinary observations, such as thermal emissions and outgassing, eruption rates, and ground deformation rates, to one another in a quantitative framework. The parameters of the models could be constrained (estimated) using probabilistic data-model fusion (inverse) techniques, utilizing prior information derived from global remote sensing studies. Estimated parameters could yield insight into properties of volcanic systems, such as locations of magma storage, magma flow rates, and volatile concentrations. Models could also be used to infer how a volcano evolves between observations. With low-latency data, it would be possible in some cases to utilize data assimilation algorithms, such as the Ensemble Kalman filter (for example, Gregg and Pettijohn, 2016; Bato and others, 2017), to enable near-real-time estimates of changing conditions in a volcano. These estimates of changing conditions, in combination with deterministic volcano models, would facilitate forecasting of the state of the system. Model-based forecasts must always be interpreted with caution owing to fundamental limitations in our ability to understand and model volcanic processes. Rather than standing alone, model forecasts could serve as inputs into broader forecasting frameworks (for example, Bayesian Event Trees; Newhall and Hoblitt, 2002) that utilize eruption statistics (both global and local), along with expert opinion and other relevant sources of information (Poland and Anderson, 2020).

5.5. Databases

By the year 2030, our vision is that processed volcano remote sensing data would be openly accessed through a series of linked databases, and raw data would be available from space agencies and private companies. Near-real-time processed data could be made available through web portals funded by various groups in different countries, as is the practice today (for example, Global Sulfur Dioxide Monitoring Homepage, http://so2.gsfc.nasa.gov/; MODVOLC thermal monitoring of hotspots, http://modis.higp.hawaii.edu/cgi-bin/modisnew.cgi; ASTER Volcano Archive, https://ava.jpl.nasa.gov/; Middle Infrared Observations of Volcanic Activity, http://www.mirovaweb.it/; COMET volcano deformation and InSAR catalog, https://comet.nerc.ac.uk/volcanoes/; Volcano Monitoring System powered by Sentinel satellites, http://www.mounts-project.com). Given large and ever-growing data volumes, automatic detection algorithms are critical to ensure that all data are examined shortly after acquisition. For example, near-real-time ash concentrations would be provided in a publicly available ash database to help mitigate hazards. In our vision, past satellite observations of volcanic activity would be routinely made available in two international databases containing numeric data values and information on detections (timing, magnitude, spatial characteristics, and so on). In the first database, archived time series of volcanic activity (including thermal emissions, outgassing, deformation, and surface and topographic change[18] from multiple satellites would be available along with ground-based observations (including all of the previously mentioned observations plus seismic activity) in WOVOdat (Newhall and others, 2017; Costa and others, 2019). Second, the GVP (2013) would include records of satellite and ground-based observations of deformation, outgassing, and thermal emissions, along with their long record of volcanic eruptions and weekly and monthly bulletins of volcanic activity. Both databases would be quickly searchable so that a new episode of unrest at one volcano could be compared with other unrest phases of similar character that have occurred in the past at the same and other volcanoes. This would be a new capability—the GVP currently provides narrative reports but does not consistently report background levels of activity. Currently, reports are produced only when something out of the ordinary happens, so low-level signals might not be reported and thus might not be added to the database. Capturing all unrest events is critical in future databases. The fraction of times that unrest leads to eruption can then be input into a Bayesian Event Tree (for example, Newhall and Hoblitt, 2002) or similar technique, and the probable outcomes of the unrest can be computed.

5.6. Building Capacity

By 2030, international workshops would be held regularly to discuss the latest developments in volcano remote sensing and to provide training targeted primarily at volcano observatory staff and volcanology students, such as the 2017 and 2021 IAVCEI workshops (https://wovodat.org/about/cov_timeline.php). These workshops would be held in conjunction with major international volcanological meetings (IAVCEI, Cities on Volcanoes), as well as with regional geologic congresses. International networks of collaborators would be maintained between meetings using the communication tools outlined in section 5.3. As funds are available, exchanges among students and staff from volcano observatories, international governments, and academic institutions would be encouraged. The VSTG would promote capacity building by keeping a record of workshop planning and maintaining a suite of materials covering a continuously updated curriculum to be used in the workshops (with example datasets, websites, lecture materials, and exercises). There are opportunities to leverage the growing remote training capacity, including massive open online courses.

5.7. Leveraging Existing Efforts

Multiple international efforts will always be aimed at using remote sensing data to reduce volcanic risk. In 2022 these efforts include (but are not limited to) the CEOS volcano demonstrator; the IAVCEI remote sensing and volcano geodesy commissions; the Global Volcano Model (GVM) (Sparks, Loughlin, and others, 2012); GSNL (Salvi, 2016); efforts that routinely process data from a single type of satellite sensor globally or from multiple satellites over a given region (for example, MODVOLC/MIROVA, Wright and others, 2004, and Coppola and others, 2016; COMET-LiCSAR, Spaans and others, 2017; MOUNTS, Valade and others, 2019; NASA–Jet Propulsion Laboratory [JPL]/ARIA, Hua and others, 2013; Alaska Satellite Facility [ASF]/SARVIEWS, Meyer and others, 2015; ASTER Volcano Archive [AVA, https://ava.jpl.nasa.gov/]; the International Charter Space and Major Disasters [http://www.disasterscharter.org]; the Geohazards Exploitation Platform [GEP; https://geohazards-tep.eu/]; the HDDS, Lamb and Jones, 2012; the GVP [http://volcano.si.edu]; and WOVOdat, Newhall and others, 2017). PowellVolc brought many of these groups together and demonstrated that improved communication among groups can advance both basic and applied volcano science. Formation of a VSTG would improve coordination for satellite observations and capacity building and will make it possible to leverage efforts of a diverse collection of international groups. By 2030, financial support for these projects would come from space agencies, observatories, and individual national funding agencies, but, like other international monitoring efforts (for example, for weather or cryosphere monitoring), international support is required at each stage of the processing chain, from data acquisition to interpretation and dissemination. Cloud computing makes it likely that research groups would be able to develop machine learning algorithms and satellite data analysis systems by 2030. Leveraging these efforts to work synergistically would be one of the VSTG objectives.

Satellite observations have been used to study volcanoes for more than 40 years (1978–2022) and as satellite sensors improve with time, we expect that data collected over the next 40 years will be superior to the legacy data. But it is not a forgone conclusion that data will continue to be of optimal use for volcano science and forecasting hazards or that the legacy data will be preserved. For outgassing and deformation, there are already sensors in orbit with improved spatial and temporal resolution and global coverage compared to the first generations of sensors (for example, TROPOMI in fig. 23, and various new SAR satellites), but the continued operation of these satellites into the next generation must be justified. Furthermore, the capability for high-spatial-resolution

TIR detections will be lost in the next decade owing to the retirement of existing sensors; this concern was raised in the NASA Decadal Survey (National Academies of Sciences, Engineering, and Medicine, 2018). The vision outlined above would increase the chances that by 2030 proper and useful data are acquired at the world's volcanoes of greatest concern and that those data will be useful in forecasting volcanic hazards and providing fodder for research that advances understanding of hazards and forecasting capabilities.

6. Summary and Conclusions

Our summary and conclusions are divided into two sections focused on using remote sensing for applied volcano science and fundamental volcano research.

6.1. Applied Volcano Science

Remote sensing data are used by volcano observatories around the world and are valuable in all stages of the eruption cycle, including identification of unrest, detecting eruptions, monitoring changes in activity, and forecasting hazards. However, more work, including improvements in data processing, visualization, and interpretation, is needed before satellite data are routinely used in eruption forecasting. Satellites have detected volcano unrest and motivated volcano observatories to install ground-based instruments, revealed failures in ground sensors, filled gaps in ground-based monitoring, and provided synoptic coverage to work synergistically with ground-based sensors to achieve higher levels of knowledge. Finally, satellite observations have supported situational awareness during volcanic crises. That awareness had direct impacts on VALs set by volcano observatories and notices of hazard issued by other agencies (for example, VAACs issuing VAAs). In the future, improved volcano monitoring and eruption forecasts facilitated by remote sensing data could help volcano observatories provide advance notifications of potential eruptions to the aviation community.

Satellites have detected thermal emissions, outgassing, and deformation activity at over 411 volcanoes worldwide during the past 40 years; significantly more volcanoes have no detections, although documentation could be improved (see section 3.1). Satellite data have greatly increased the number of volcanoes with known activity—for example, the number of volcanoes known to be deforming increased five-fold between 1997 and 2017. Multiparameter satellite data are valuable (for example, thermal emissions, outgassing, and deformation) as each parameter contributes unique information. Remote sensing data will never replace terrestrial monitoring; rather, they provide a critical complement to ground monitoring, even at volcanoes with comprehensive ground-based networks. The resources available for volcano remote sensing are increasing, owing to the availability of newer and more capable satellites that allow measurements that were not previously possible, such as deformation time series at all the world's volcanoes, volcanic CO_2 emissions from volcanoes, and observations of volcanic clouds every few minutes from CubeSats and geostationary satellites. Further developments in artificial intelligence and machine learning will enable rapid exploitation of these vast datasets. Despite these many successes and future potential, barriers to full exploitation of satellite data remain and were identified by PowellVolc. We suggest the following actions to overcome these challenges:

- Coordination of international satellite assets can ensure that optimal data are collected for volcano monitoring and eruption-forecasting capabilities. There are significant satellite resources in orbit, and a coordinated international observation strategy for volcanoes is needed. We suggest an effort be established and named the Volcano Space Task Group, following the strategy for the cryosphere (Polar Space Task Group, Key and others, 2015) and involving international organizations like the Committee on Earth Observation Satellites, Coordination Group for Meteorological Satellites, Group on Earth Observations, World Organization of Volcano Observatories, and the International Association of Volcanology and Chemistry of the Earth's Interior. As a first step, we developed a background observation strategy for each of the approximately 1,400 subaerial volcanoes having either Holocene eruptions or instrumentally recorded activity and the needed repeat time to obtain useful synthetic aperture radar data (appendix 1). The list of these volcanoes can be updated as activity waxes and wanes at individual volcanoes and as additional volcanoes become active. The observation strategy can be flexible enough to increase data acquisitions and reduce latency during a crisis.

- Efforts to make volcano remote sensing data publicly available for hazards assessment and mitigation, like Geohazard Supersites and Natural Laboratories, need to be continued and expanded.

- Data processing needs to be timely enough to respond to crises, and data products must be provided in formats that are user-friendly and useful for forecasting. Several efforts are underway to make data products more rapidly and readily available. Further work is needed to determine the data products of most value to end users. This effort must consider that some observatories have limited downlink capability, storage capacity, and software licensing.

- Uncertainty analysis on satellite data products is often cursory, and interpretations from multiple external analysts are sometimes in conflict, which complicates exploitation by volcano observatories. It is imperative that uncertainties be included in any notifications or products sent to observatories. In particular, information that identifies sources of uncertainty and whether a given signal is likely to be of volcanic origin or some other type of nonvolcanic artifact is needed. When multiple groups are interpreting satellite observations and communicating with a volcano observatory that does not have remote sensing expertise, best practice protocols need to be established and followed. Such protocols will allow coordination among external groups and observatories to provide one consensus interpretation or a range of scientifically reasonable interpretations. Best-practice protocols are needed owing to (1) the growing availability of open-access satellite data; (2) the explosion of use of social media platforms that allow anyone the ability to offer interpretation of unrest—opinions that could undermine the responsibility and credibility of volcano observatories; and (3) the need to minimize miscommunications among non-observatory remote sensing experts and observatories that may lack a resident remote sensing expert. Observatories can consider formalizing relationships with trusted non-experts who may be able to assist in "watching" a volcano using the ever-growing amount of satellite data.

- Before a volcanic crisis occurs, end users should establish connections with remote sensing experts and be trained to use remote sensing data. Ongoing capacity-building efforts should continue, including short courses, visits by remote sensing experts to observatories or visits by observatory staff to satellite data processing centers, and student exchanges and training. For many volcano observatories, indepth, long-lasting (months to years) training of students or staff, either within their country or externally, has the most impact. In addition, the remote sensing and observatory communities can consider communicating through closed groups, modeled by the Volcanic Clouds group, to share remote sensing data, context, and uncertainties.

6.2. Fundamental Volcano Research

Global remote sensing of volcanoes allows us to overcome our current biased understanding of volcanic processes based on only a few well-studied volcanoes, although we must be aware of satellite biases as well. For example, a global census of volcano deformation reveals differences between what is seen by satellite versus ground-based monitoring in terms of the type of deformation, duration of events, and location of deformation source(s).

By combining thermal emission, outgassing, and deformation observations, we can better evaluate ideas for how volcanoes behave, including the concept of open and closed volcanoes, which relates volcanic emissions and deformation to eruption. In Latin America, 28 percent of all volcanoes do not fit either classification while several volcanoes show evidence for both types of behaviors, changing over time. There are intriguing regional differences in open and closed volcanic systems as well. Open systems are common in Central America and Peru, whereas closed systems dominate in the central Andes, and the patterns for each system are still to be understood. A global assessment of open and closed systems has yet to be done but is important given that ground-based studies show that the chance that unrest will lead to eruption depends in part on whether the volcano is open or closed.

Our global remote sensing analysis confirms previous work that ground deformation events can precede eruption by several years, but that currently available global datasets of thermal emission and outgassing data are too coarse to unambiguously resolve precursory activity. Several individual case studies using combined satellite and ground-based data, however, reveal thermal and gas eruption precursors, suggesting that greater spatio-temporal resolution in satellite thermal emission and outgassing data may enhance space-based eruption forecasting.

We have identified several questions about how future work with satellite data could improve scientific understanding of volcanoes:

- Do thermal anomalies precede eruptions globally and, if so, under what conditions? What are the physical processes causing the eruption thermal precursors—for example, increased flux of hot fluids through the conduit or magma near the surface? There are several case studies where thermal precursors are observed before eruptions, but we need a better understanding of which types of volcanoes produce thermal precursors, and the manifestations of those precursors (table 2). Currently available global databases are not sufficient to answer these questions (Furtney and others, 2018); thus, a global high-spatial-resolution (<100 m/pixel) thermal database is needed. High spatial resolution can be coupled with increased temporal resolution. Eruptions can be preceded by the appearance of thermal anomalies only weeks, days, or hours before eruption. It is critical that new satellite missions include thermal sensors (middle infrared and thermal infrared) with revisit times of 3–5 days at high spatial resolution (<100 m/pixel) such as the Sentinel-2 mission (but with expanded spectral capabilities and including nighttime measurements). Also, future missions that extend the Moderate Resolution Imaging Spectroradiometer (MODIS) capability are fundamental for continuing a decades-long time-series of heat flux and for detecting long-term precursors at persistently active volcanoes. The Visible Infrared Imaging Radiometer Suite (VIIRS) sensor is proving adept at measuring volcano thermal anomalies (for example, Cao and others, 2013; Blackett, 2015) but automatic algorithms to detect these in near real time would be beneficial (for example, Trifonov and others, 2017).

- Do changes in outgassing precede eruptions globally and, if so, how and under what conditions? What are the physical processes causing changes in outgassing before eruption? Again, there are several examples of changes in outgassing before eruption, but a global database with high spatial and temporal resolution is needed to have a representative sample size. Changes in CO_2 are more likely to be detected prior to an eruption but are harder to measure from space with current technology.

- How often can surface and topographic change be detected from space given the limits on satellite resolution and the frequency of volcanic events of sufficient magnitude? What are the physical processes causing surface and topographic change—lava flows, landslides, explosions, subsurface intrusions, melting snow or ice, or something else? With improved spatial and temporal resolution of sensors over time there is a growing list of examples where these surface and topographic changes have been observed, but no global compilation of these observations has been attempted. Thus, we do not know how often these data need to be acquired, and at which volcanoes, to maximize their utility. Repeat topography measurements might be the most critical of these measurements, given their importance in hazards assessment and the need to quickly georectify radar images (for example, from the National Aeronautics and Space Administration–Indian Space Research Organization Synthetic Aperture Radar [NISAR]; Zebker, 2017). Furthermore, topographic data are critical for measuring erupted volumes, which are used to constrain eruption models (for example, Anderson and Poland, 2016; Delgado and others, 2019).

- How many and which volcanoes have no detectable unrest prior to eruption? We need to develop a robust catalogue of volcanoes with no detections for all satellite methods. Further, we need to document the conditions where satellite measurements could not be made because of clouds, vegetation, snow/ice, and so on, in order to understand how to improve background observations. For example, do the differences in the numbers of volcanoes with satellite thermal emissions, outgassing, and deformation detections in different regions relative to the global mean (fig. 11) reflect different manifestations of volcanic activity? Or are those differences indicative of the ability to detect activity by satellite?

- Increasing the number of ground-based stations has been shown to increase the chances that an eruption can be successfully forecast (Winson and others, 2014), but to what extent can wider use of remote sensing data improve the percentage of eruptions that are forecasted? Including remote sensing data in eruption forecasts will require decreased latency between data acquisition and delivery, as well as improved data quality and data-model fusion. Are there certain characteristics of unrest that are robustly connected to a greater likelihood of eruption (for example, the duration or rate of deformation; fig. 12)? An open question is whether satellite data (or any monitoring data) can reliably be used to forecast eruption size.

- Globally, does the likelihood that volcanic unrest leads to eruption depend on volcano characteristics, such as eruption repose times, silica composition, eruption size, tectonic setting, and volcano type? These parameters have been shown to be important influences on eruptions of volcanoes on a regional basis, but more satellite observations could help assess if there are regional variations. To undertake this study, both positive and null results of relations between unrest and eruption are required.

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Appendixes 1 and 2

Appendix 1. Supplemental Table of Global Volcano Observation Strategy

Table of global observation strategy for Holocene volcanoes and older volcanoes that have shown some background activity. This appendix table is available online only as a static Excel (.xlsx) file at https://doi.org/10.3133/sir20225116 and at the Open Science Framework where it will be periodically updated (https://doi.org/10.17605/OSF.IO/E4TXG).

Columns A–C and J–S.—Volcano information from the Global Volcanism Program (GVP) (2013) where available. Where volcanoes have been removed from the GVP we include the old information and an "X" before the number in column A. Areas of detected activity (usually Pleistocene or Pliocene volcanoes) that are not in the GVP catalog of Holocene volcanoes do not have numbers, but a reference is given in column K as well as an approximate location in columns M, O, and P. Submarine volcanoes classified by the Global Volcanism Program (GVP) are not given an activity classification, although at least three have gas emissions detected from space, and pumice rafts produced by submarine eruptions have been tracked by satellites (Jutzeler and others, 2014).

Columns D and E.—Activity classification (see table 3).

Column F.—Whether the routine synthetic aperture radar observations being made by the Sentinel-1A/1B satellites are of sufficient quality to monitor a volcano for ground deformation (based on preliminary data), or if additional satellite observations are needed because of too much vegetation or the need for high spatial resolution data (section 4.2.1). Further work is needed to assess whether our preliminary assessments of Sentinel-1A/1B quality need to be updated.

Column G.—Whether the volcano has had thermal emissions (T), outgassing (G), or deformation (Def) detected from space between 1978 and 2021 based on results published in the scientific literature (Biggs and Pritchard, 2017; Furtney and others 2018; Reath and others 2019a, b, 2021; Way and others, 2022). This number is updated from the 306 volcanoes identified in Furtney and others (2018) and it includes any type of activity on a volcano detected from space (for example, emplacement of volcanic deposits, deformation, and surface change due to earthquakes and landslides).

Column H.—Type of activity detected for selected volcanoes. Satellite thermal emissions are from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) or the Moderate Resolution Imaging Spectroradiometer (MODIS). Ground-based seismic swarms come from the databases of Phillipson and others (2013) and White and McCausland (2016).

Column I.—Population Exposure Index (PEI) from the United Nations Global Assessment of Risk (Brown, Loughlin, and others, 2015), which is based on populations within 10, 30, and 100 kilometers of a volcano. Index scores range from 1 to 7 (with 1 being the lowest); a PEI ≥ 2 has a weighted population >3,000.

Appendix 2. PowellVolc Workshop Participants

[USGS, U.S. Geological Survey; NASA, National Aeronautics and Space Administration; JPL, Jet Propulsion Laboratory; NOAA, National Oceanic and Atmospheric Administration; R, remote participation]

Name	Institution	2017	2018	2019
Kyle Anderson	USGS			X
Ben Andrews	Smithsonian Institution	X	X	
Grace Bato	NASA JPL			X
Marco Bagnardi	NASA JPL and Goddard		X	
Juliet Biggs	University of Bristol	X	X	X
Simon Carn	Michigan Technological University	X	X	X
Diego Coppola	University of Turin, Italy		R	
Susanna Ebmeier	University of Leeds		X	X
Társilo Girona	NASA JPL		X	X
Julie Griswold	USGS	X	X	
Brenda Jones	USGS	R		
Ryan Longhenry	USGS		R	
Taryn Lopez	University of Alaska Fairbanks	X	X	
Sue Loughlin	British Geological Survey	R	R	
Paul Lundgren	NASA JPL	X	X	X
Sarah Ogburn	USGS	X	X	
Mike Pavolonis	NOAA National Environmental Satellite, Data, and Information Service	R	R	X
Mike Poland	USGS	X	X	X
Matt Pritchard	Cornell University	X	X	X
Kevin Reath	Cornell University	X	X	X
Alberto Roman	NASA JPL			X
Elise Rumpf	USGS	X	X	X
Christelle Wauthier	Pennsylvania State University	X	R	
Peter Webley	University of Alaska Fairbanks	X		
Rick Wessels	USGS	X	X	
Rob Wright	University of Hawaiʻi at Mānoa	X	X	
Simon Young	Willis Tower Watson		R	

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