Capturing, Preserving, and Digitizing Legacy Seismic Data from the Montserrat Volcano Observatory Analog Seismic Network, July 1995–December 2004

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Abstract

An eruption of the Soufrière Hills Volcano (SHV) on the eastern Caribbean island of Montserrat began on 18 July 1995 and continued until February 2010. Within nine days of the eruption onset, an existing four-station analog seismic network (ASN) was expanded to 10 sites. Telemetered data from this network were recorded, processed, and archived locally using a system developed by scientists from the U.S. Geological Survey (USGS) Volcano Disaster Assistance Program (VDAP). In October 1996, a digital seismic network (DSN) was deployed with the ability to capture larger amplitude signals across a broader frequency range. These two networks operated in parallel until December 2004, with separate telemetry and acquisition systems (analysis systems were merged in March 2001). Although the DSN provided better quality data for research, the ASN featured superior real-time monitoring tools and captured valuable data including the only seismic data from the first 15 months of the eruption. These successes of the ASN have been rather overlooked. This article documents the evolution of the ASN, the VDAP system, the original data captured, and the recovery and conversion of more than 230,000 seismic events from legacy SUDS, Hypo71, and Seislog formats into Seisan database with waveform data in miniSEED format. No digital catalog existed for these events, but students at the University of South Florida have classified two-thirds of the 40,000 events that were captured between July 1995 and October 1996. Locations and magnitudes were recovered for ~10,000 of these events. Real-time seismic amplitude measurement, seismic spectral amplitude measurement, and tiltmeter data were also captured. The result is that the ASN seismic dataset is now more discoverable, accessible, and reusable, in accordance with FAIR data principles. These efforts could catalyze new research on the 1995–2010 SHV eruption. Furthermore, many observatories have data in these same legacy data formats and might benefit from procedures and codes documented here.

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Supplemental Material

Introduction

On 18 July 1995, a phreatic explosion of the Soufrière Hills Volcano (SHV) heralded the beginning of more than 14.5 yr of volcanic activity that dramatically changed life on Montserrat, a small (~100 km^2) island in the eastern Caribbean. This was an exceptionally well-observed and well-monitored volcanic eruption that featured Vulcanian and sub-Plinian explosive eruptions, five phases of dome extrusion, pyroclastic density currents and lahars that reached the coast, major dome collapses (up to ~210 million m^3) and a sector collapse, and lateral blast (Wadge *et al.*, 2014). All of these processes generated distinct signals that were recorded on two seismic networks operated by the Montserrat Volcano Observatory (MVO): one analog, one digital. A 10-station analog seismic network (ASN), installed by the Seismic Research Center (SRC) and the U.S. Geological Survey (USGS) Volcano Disaster Assistance

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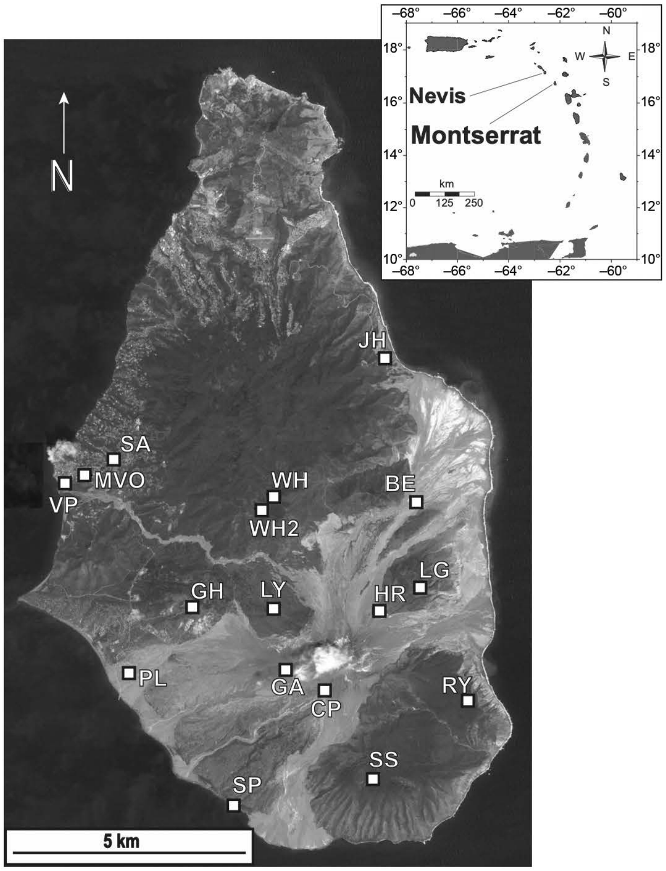

Figure 1. Sites of the Montserrat Volcano Observatory (MVO) analog seismic stations between 27 July 1995 and 16 December 2004. Created with Google Earth, Landsat/Copernicus imagery date 11 April 2014 (2019 CNES/Airbus). The crater of the Soufrière Hills Volcano is in the region between sites GA, CP, HR, and LY. Areas most severely impacted by pyroclastic and lahar deposits of the 1995–2010 eruption are clearly visible in light gray. We plot sites rather than stations because some sites hosted multiple stations. (Inset) Locations of the islands of Montserrat and Nevis within the eastern Caribbean. Puerto Rico is to the upper left; Trinidad is toward the lower right. The station MNEV located on Nevis is part of the regional seismic network of the Seismic Research Center (SRC). Locations of the tiltmeter stations are not shown as records of location coordinates are not available.

Program (VDAP), became operational on 27 July 1995 (Fig. 1), just nine days after the initial explosion. Three biaxial tiltmeters were installed in the following week. An eight-station digital seismic network (DSN), installed by the British Geological Survey (BGS), became operational on 19 October 1996 (Neuberg *et al.*, 1998).

The DSN dataset is of higher quality than the ASN dataset because it featured 24-bit telemetry compared with the 12-bit analog-to-digital converter (ADC) cards used for the ASN, allowing much larger signals to be recorded on-scale. Moreover, continuous waveform data were captured from the DSN, whereas the ASN only captured triggered waveform data. Finally, the DSN dataset is stored in Seisan format (Havskov and Ottemöller, 1999), which is still widely used today; whereas the ASN dataset was recorded in PC-SUDS format (Banfill, 1999), which fell out of favor around year 2000. The ASN dataset ended on 16 December 2004 as all analog telemetry was phased out as part of an upgrade to the DSN. Only site JH was lost as the DSN expanded from 8 to 13 stations (Luckett *et al.*, 2007). The DSN continues to operate in January 2020 using the equipment funded in 2003 and installed in 2005, showing remarkable data continuity. Consequently, most research on SHV seismicity has used the DSN dataset.

We believe the ASN dataset is still of significant value to the research community, particularly as it includes the only seismic data from the first 15 months of the eruption. Moreover, given that the DSN featured no more than eight operational stations between 1996 and 2004, and as few as one in 1997, much could be learned by combining data from both networks to improve event detection, classification, and location. But there are many barriers to using the ASN dataset. First, data discovery: most volcano-seismologists do not even know this dataset exists. Second, data accessibility: the data were recorded in legacy data formats on recording media that are hard to read today and make it challenging to work with. Third, metadata describing station locations, on–off dates, and calibrations are sparse. Finally, the systems that generated these data are not well documented. Consequently, the ASN dataset has been underutilized in the past 15 yr.

This article has multiple goals. It documents efforts undertaken to recover, assemble, organize, digitize, and convert a valuable legacy dataset into modern seismic formats. It documents the VDAP system used to generate this legacy dataset. Throughout the 1990s, VDAP installed similar systems throughout the world as part of their mission to support foreign governments responding to volcanic crises, so documenting the VDAP system employed at MVO is likely to have a widespread impact, as other volcano observatories likely have data in the same legacy formats. By documenting the steps we have taken to convert the MVO ASN dataset to modern formats, and by providing the software we used, we hope this will aid the conversion of other legacy seismic datasets and catalyze new research on these datasets, using modern analysis techniques.

The dates of many volcanic and seismic events and changes to the seismic monitoring networks are mentioned in this article. To help guide the reader, a timeline is given in Figure 2. Many abbreviations and technical terms are used in this article, and these are listed in Table S1 (available in the supplemental material to this article).

The ASN on Montserrat

There had been at least one analog short-period seismic station on Montserrat since March 1966, operated by the SRC based at

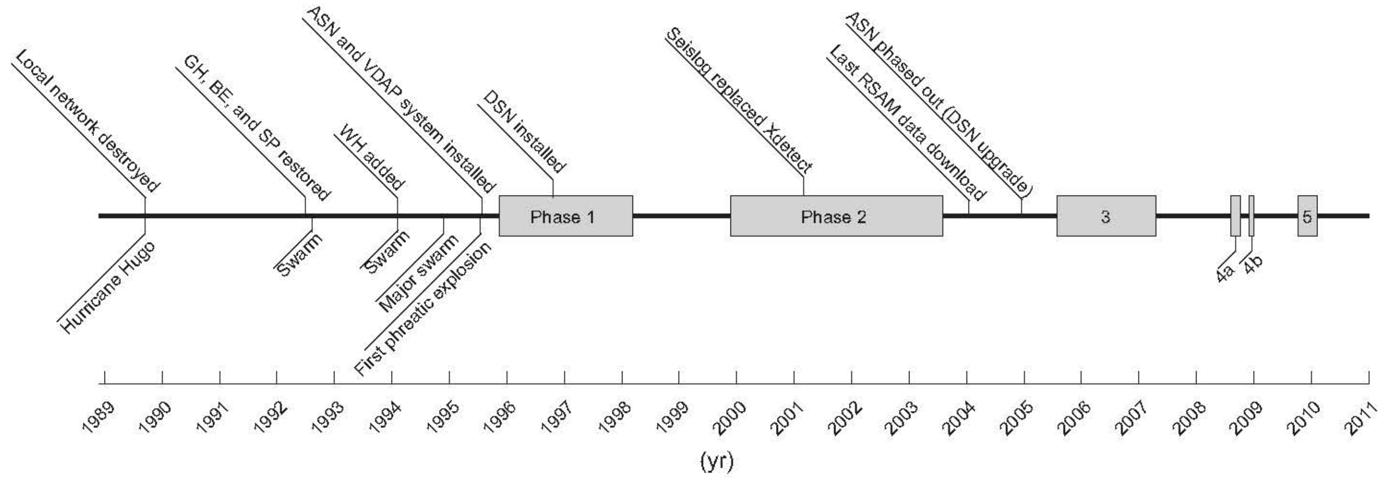

Figure 2. Timeline of events discussed in this article including major developments in Montserrat seismic networks (above solid line) and natural events (below line). Gray rectangles show periods of lava dome extrusion (MVO recognizes five main phases from 1995 to 2010). ASN, analog seismic network; DSN, digital seismic network; RSAM, real-time seismic amplitude measurement; VDAP, Volcano Disaster Assistance Program.

the University of the West Indies in Trinidad. Regional earthquake and volcano monitoring of the Leeward Islands before the Internet was primarily facilitated via a leased telephone circuit accessible via Boggy Peak, Antigua. This circuit allowed the SRC to operate eight analog FM telemetered stations, including St. George's Hill (site GH in Fig. 1) on Montserrat (Table 1). In response to volcanic unrest on Montserrat in late 1988–1989, two new stations at Bethel (BE) and St. Patrick's (SP) were established and telemetered at the expense of stations on Barbuda and Dominica. For a review of SRC seismic monitoring of the eastern Caribbean since 1953, see Dondin *et al.* (2019).

On 17 September 1989, hurricane Hugo devastated stations on Montserrat (Fig. 2). The infrastructure at GH, BE, and SP was restored in mid-1992. Seismic activity was similar in character as that observed pre-Hugo consisting of episodic bursts of local, shallow events with a few reaching up to duration magnitude 3.5, as illustrated by 174 local tectonic earthquakes recorded between 9 August and 24 September 1992 (Figs. 2 and 3). Following a swarm of 59 earthquakes on 2–3 June 1994, SRC added a fourth station at Windy Hill (WH) and deployed a data acquisition and processing system locally (Dondin *et al.*, 2019). Montserrat high school students were trained in operating the system, preprocessing the data, and reading *P*-phase arrivals, which they faxed to the SRC for further processing.

Seismicity escalated between 27 November and 7 December 1994 with 522 earthquakes recorded on Montserrat (Figs. 2 and 3). Even so, this could not be taken as irrefutable evidence of an impending eruption, because there had been similar seismic crises on Montserrat in the 1890s, 1930s, and 1960s that had not led to an eruption (Shepherd *et al.*, 2002). Between October 1933 and July 1936, for example, hundreds of felt earthquakes were noted (far more than in the 1990s). SRC staff visited Montserrat and wanted to expand the network to at least eight stations but lacked funding support to do so (Shepherd *et al.*, 2002). Lynch, the SRC's lead field engineer, requested help from VDAP, a team of USGS scientists who began supporting foreign volcano observatories in the 1980s (Lowenstern and Ramsey, 2017).

The VDAP team provided additional equipment and manpower and by 27 July 1995, nine days after the first explosion, VDAP and SRC scientists had added seismic stations at Gage's Mountain (GA), Roach's Yard (RY), Long Ground (LG), Plymouth (PL), Salem (SA), and the Vue Pointe hotel (VP), expanding the network to 10 sites (Fig. 1). VDAP upgraded some sensors from geophones to Mark Products L-4 and L-22 short-period seismometers and added Applied Geomechanics 701-1 biaxial tiltmeters at Long Ground (next to the seismic station) and at Spring Estate and Amersham (two new sites). VDAP also added their data acquisition and analysis system, hereafter referred to as "the VDAP system", and described later. We refer to this short-period network as "the ASN," because it used analog UHF FM radio telemetry. The seismic instrumentation and telemetry equipment are similar to those used by VDAP during the 1991 Pinatubo crisis, described by Lockhart *et al.* (1996).

The VDAP System, July 1995–March 2001

The VDAP system installed on Montserrat became operational on 27 July 1995 (Fig. 2). It evolved from an IBM-compatible personal computer (PC)-based seismic acquisition and earthquake detection system that had originally been developed in California (Lee *et al.*, 1988) and had been installed at the Alaska Volcano Observatory in Fairbanks prior to the 1989–1990 eruption of Redoubt volcano (March and Power, 1990). Further development was spurred by the 1991 eruption of Mount Pinatubo in the Philippines, which validated the

TABLE 1
Sites Occupied by Stations of the Montserrat Volcano Observatory (MVO) Analog Seismic Network

Site Code	Name	Latitude (°)	Longitude (°)	Elevation (m)	Station Codes at This Site	First On Date (yyyy/mm/dd)	Last Off Date (yyyy/mm/dd)
BE	Bethel	16.7410	−62.1627	99	MBET	1995/07/27	1997/08/22
CP	Chances Peak	16.7068	−62.1812	759	MCPZ, MCPN, MCPE, MCPT	1996/02/09	1997/10/08
GA	Gage's Mountain	16.7102	−62.1887	479	MGAT, MGT2	1995/07/27	1997/07/30
GH	St. George's Hill	16.7217	−62.2068	351	MGHZ	1995/07/27	2004/12/16
HR	Hermitage	16.7208	−62.1705	382	MHRE, MHRN, MHRV	1996/01/29	1996/09/26
JH	Jack Boy Hill	16.7672	−62.1698	149	MJHL, MJHT	1997/08/22	2004/12/16
LG	Long Ground	16.7250	−62.1623	287	MLGL, MLGT	1995/07/27	2004/12/16
LY	Lee's Yard	16.7213	−62.1910	355	MLYT	1997/07/30	2004/12/16
MVO	MVO Old Towne	16.7465	−62.2283	80	MVOE, MVON, MVOV	1997/01/14	1997/10/08
NEV	Nevis	17.1357	−62.5694	226	MNEV	2001/10/31	2002/01/01
PL	Plymouth	16.7088	−62.2198	20	MPEW, MPNS, MPVE	1995/07/27	1995/08/22
RY	Roach's Yard	16.7038	−62.1532	355	MRYT	1995/07/27	2004/12/16
SA	Salem	16.7480	−62.2210	195	MSAT	1995/07/27	1995/10/23
SP	St Patrick's	16.6835	−62.1992	127	MSPT	1995/07/27	1998/01/19
SS	South Soufrière Hills	16.6900	−62.1720	665	MSSE, MSSN, MSSZ	1995/12/09	1996/12/14
VP	Vue Pointe Hotel	16.7435	−62.2357	23	MVPE, MVPN, MVPV, MVPZ	1996/08/26	1996/12/14
WH	Windy Hill	16.7422	−62.1908	407	MWEH, MWEL, MWHE, MWHN, MWHZ, MWNH, MWNL, MWZH, MWZL	1996/09/12	2004/12/16
WH2	Windy Hill 2	16.7398	−62.1932	411	MWH2	1996/01/27	1996/12/24

Site code column is used to identify site location in Figure 1. Each site may have been occupied by multiple stations. Station codes come from headers in waveform files that exist in the master dataset. Site NEV was a station on Nevis, an island northwest of Montserrat, used to help discriminate between local and regional seismic events.

concept of a mobile volcano-seismic monitoring system that could be deployed rapidly (Murray, Ewert, *et al.*, 1996; Murray, Power, *et al.*, 1996). This system consisted of four PCs (named PC-SEIS, RSAM PC, TILT, and BRAINS) that performed specific seismic acquisition and analysis functions and were connected using LANtastic—a commercially available peer-to-peer local area network. A flowchart of the system installed at MVO is given in Figure 4 and described later.

An amplified seismic signal (a voltage) from each short-period seismic station was transmitted over analog seismic telemetry (e.g., Lee and Stewart, 1981). At MVO, these were fed into the discriminator rack, which demodulated the signals from each station and restored the amplified seismic signals. Four demodulated signals were recorded on helical drum recorders (helicorders; Fig. S1). Up to 16 channels were acquired on the PC-SEIS PC and up to eight were recorded on the RSAM PC (Fig. 4). The modulated seismic signal from Gages (site GA), received on a radio scanner, was broadcast over a speaker within the MVO operations room. Seismicity due to large events audibly modulated the tone alerting MVO staff to the possibility of pyroclastic density currents. The MVO staff could then notify people in the exclusion zone via two-way citizens band radio. This system remained in use at MVO for many years.

PC-SEIS was a PC running MS-DOS. Channels were sampled using a 12-bit ADC (maximum amplitude 2047 counts) at 100 Hz and continuously displayed by Xdetect (Tottingham and Lee, 1989; Rogers, 1993) providing a real-time data quality check. Xdetect's primary function was to detect seismic events using an amplitude-based, short-term average to long-term average (STA/LTA) algorithm. For each detected seismic event, a waveform file containing all stations was recorded in multiplexed SUDS format (Banfill, 1999). Time signals from a Global Positioning System clock were added as an IRIG-E (Range Commanders Council, 2004) channel to each SUDS file.

Several times a day, MVO seismic analysts ran the program Transfer.bas (Murray, 1994) on the BRAINS PC (an i386 PC, running Windows 3.11) (Fig. 4). This moved multiplexed SUDS files from the PC-SEIS PC, and time corrected and

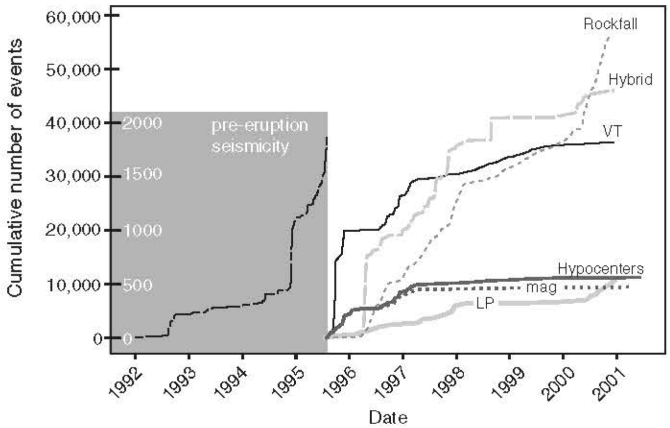

Figure 3. Cumulative number of seismic events recorded in Montserrat between 1 January 1992 and 13 December 2000. A total of 1766 events were recorded by the SRC between 1 January 1992 and 27 July 1995, before installation of the VDAP system. These are scaled by a factor of 20 so that pre-eruption escalations in seismicity are clear. We have no waveform, classification, location, or magnitude data for these events. From 27 July 1995, ASN event counts were manually compiled from helicorder plots and event logbooks. The main event classifications are 36,379 volcano-tectonic (VT) earthquakes, 45,990 hybrid earthquakes, 10,499 long-period (LP) earthquakes, and 58,828 rockfall signals. Cumulative number of hypocenters (11,189) and magnitudes (9,235) computed with Hypo71 are also shown.

demultiplexed SUDS files using programs named Irig and Demux. Each demultiplexed SUDS file was then processed using Budspick (a modified version of Sudspick), which enabled analysts to pick phase arrivals, locate earthquakes, and estimate magnitudes using Hypo71 (Lee and Valdes, 1985). Volquake (Hoblitt *et al.*, 1996) allowed MVO staff to visualize hypocenters in near-real time.

During the early stages of the Montserrat eruption, most detected seismic events were volcano-tectonic or hybrid earthquakes (Miller *et al.*, 1998; Rowe *et al.*, 2004; Roman *et al.*, 2008), many of which could be located with Hypo71. Once the dome began growing in November 1995, there were also many hybrid earthquakes and rockfall signals (Fig. 3). These events rarely exhibit P or S phases and therefore could not be located. A separate method was needed to record event times and classifications. These were noted in handwritten “seismic event logbooks” (Fig. S3), which was the most complete catalog of the ASN events (ASNEs). The event rate was sometimes so high that notetaking could not keep up.

The tools mentioned so far were designed to transient seismic events. For volcano-seismic monitoring, however, analysis of continuous data is vital as earthquake swarms and tremor are the main precursors to explosive volcanism (e.g., McNutt, 1996; McNutt and Roman, 2015; White and McCausland, 2019). STA/LTA detection algorithms such as Xdetect break down when events begin to coalesce and volcanic tremor is present, which is when it is most important to monitor volcanic seismicity. Although Xdetect was capable of recording continuous waveform data files, this would amount to ~10 MB/hr when only 40 MB of hard drive storage was available. To prevent data loss, files would have to be moved to backup media several times per day, which was impractical and prohibitively expensive (hard drive storage cost about $500 U.S. per GB in 1995). A different approach was needed.

This problem was solved by the RSAM system (Murray and Endo, 1989; Endo and Murray, 1991), which at MVO ran on an PC running Windows 3.11 and a 12-bit ADC (Fig. 4). RSAM development began in 1985 during the 1980–1986 eruption of Mount St. Helens. The RSAM system featured real-time bar graphs of average seismic amplitude at sampling intervals of 2.56 s, 1 min, and 10 min (Fig. S2), which made it easy to quantify changing seismic amplitudes during vigorous seismic swarms and periods of volcanic tremor. To a trained observer, they also indicated where seismicity was occurring. The 1 min RSAM data were saved to binary files requiring only 2 MB per channel per year, making it possible to store continuous data without difficulty even in the 1990s. Tiltmeter x-axis and y-axis data were acquired every 10 min on the TILT PC (Fig. 4) and recorded in the same binary file format. The RSAM system also featured a simple event detection system and an alarm system (which MVO began to use in 1999) designed to alert scientists to high-amplitude events and long duration tremor signals.

During the 1989–1990 Redoubt eruption, the seismic spectral amplitude measurement (SSAM) system (Stephens *et al.*, 1994) had been developed to monitor seismic amplitude in different frequency bands, which could better identify escalations in volcanic tremor and changes in dominant frequency content of ongoing seismicity. Fast Fourier transforms (FFTs) were computed on the PC-SEIS PC and transferred to the BRAINS PC. These data could be visualized as low-resolution spectrograms (Power *et al.*, 1996).

For monitoring the volcanic crisis, it was helpful to see all MVO time-series data within the same application and on the same time axis. The software package Bob was developed for this purpose (Murray, 1990a,b). It featured a simple macro language that could be used to plot trends in event counts alongside data from RSAM, SSAM, tiltmeters, surveying, and monitoring of SO_2 emission rate, and dome growth rate. This was a very useful tool in the midst of a crisis, such as a major dome collapse. This analysis software coupled with the small data volume also meant that long time series of RSAM data, for example, in excess of a year, could be quickly plotted. This was revolutionary for examining long-term trends in continuous seismic data.

Event waveform data files, recorded in SUDS format, were archived primarily to Iomega Zip disks, using a parallel port Iomega Zip drive. Each disk cost about $16 U.S., and, had a capacity of 100 MB, typically storing about a week of event files. Some data were archived to compact discs (CDs), others

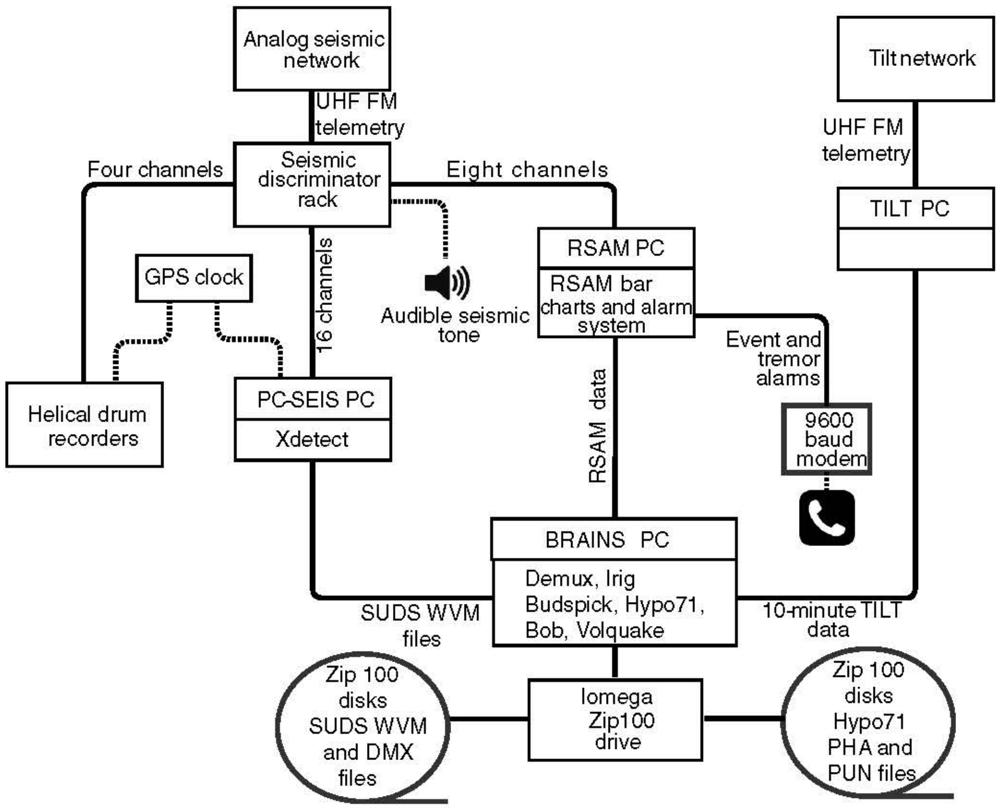

Figure 4. Diagram of the VDAP system in use at the MVO from July 1995 to March 2001. The modular system was based around four personal computers (PCs) called "PC-SEIS," "RSAM," "TILT," and "BRAINS" running MS-DOS or MS-Windows, which made it easy to support. GPS, Global Positioning System.

to tracker tapes. All media were subsequently stored in a fireproof safe at the MVO.

Data Recovery from Original Archive Media

There were three motivations for the data recovery efforts that began in 2001. First, following a 20-month pause in the eruption, dome growth had resumed in November 1999, and it became important to compare seismicity between phases 1 and 2. This required measuring the amplitude, energy, and duration of waveform data stored on archive media. Second, data archive media used in phase 1 of the eruption were reaching the end of their expected 5 yr lifespans. Third, there was a danger of archive media becoming unreadable as storage technology changed. Thompson led these efforts as MVO seismic network manager. Hard drive capacity was expanded from 4 to ~300 GB. Data were recovered from ~300 Iomega Zip100 disks (~30 GB) and 10 CDs. No device was ever found for reading tracker tapes. Unfortunately, many Zip100 disks were unreadable, and others were missing (exact records were not kept).

Event waveform data files from the ASN were recovered in multiplexed (WVM file extension) and demultiplexed (DMX file extension) SUDS formats (Table 2). All files were reorganized into yr/month directories, demultiplexed (with Demux) and time corrected (with Irig). SUDS DMX to Seisan format conversion was accomplished using Sudsei, which is part of the Windows version of the Seisan software package (Havskov and Ottemöller, 1999). The Linux and MacOS versions of Seisan do not include this functionality. A Seisan database named IRIG was built from all the available ASN waveform data files once converted to Seisan format. This made it far easier to analyze ASN data alongside DSN data, because both were now in Seisan databases.

The Seislog–Seisan Data Acquisition and Analysis System, March 2001–December 2004

The VDAP system ran until 1 March 2001 (Fig. 2). Sometime before January 2000, the LANtastic computer network between the PCs of the VDAP system stopped working. Data had to be transferred manually using an Iomega Zip100 drive, and this led to loss of ASNE waveform files on the PC-SEIS PC. On 2 March 2001, the BGS Seismology group replaced the PC-SEIS PC (which ran Xdetect) with a more powerful PC running the QNX operating system and the Seislog event detection system (Utheim *et al.*, 2001). BRAINS/Budspick (Fig. 4) and the seismic event logbooks (Fig. S3) became obsolete. ASNE waveform data files were converted to Seisan format, merged with event waveform files from the DSN and processed using the Seisan software package, producing a Seisan database named MVOE (for MVO events). The database was archived to DDS-3 DAT tapes. These had a capacity of 24 GB and yet were similar in price to the Iomega Zip disks that stored only 100 MB. A diagram of this modified ASN acquisition, analysis, and archival system is given in Figure S4. Merging event waveform files from the ASN and DSN into the same data processing and archival workflows was significant for two reasons: first, it improved the quality of event classifications and locations because more waveforms were available for each event; second, it streamlined MVO seismic monitoring operations because events only needed to be processed and archived on one

TABLE 2
Data Types and Filename Formats in the Analog Seismic Network Archive at MVO

Program	Filename Format*	Description of Data Type	Total Number in USF Archive
Xdetect output	YYYYMMDDNN.WVM	Multiplexed SUDS event waveform files	175,892
Demux output	YYYYMMDDNN.DMX	Demultiplexed SUDS event waveform files	183,187†
Budspick output, Hypo71 input	YYYYMMDDNN.PHA	Phase readings for each event picked	11,278
Hypo71 output	YYYYMMDDNN.PUN	One-line hypocenter summary for each event	4,999
Hypo71 output	SummaryAll.dat	PUN files were often appended to this file and then deleted	One file but it contains hypocenter data for $>10,000$ events
(Various conversion programs)	YYYYMMDDNN.mseed	Event waveform data in miniSEED format	182,764‡
RSAM	WIN_RSAM_/RSAM_1/STATYYYY.DAT	1 min RSAM data	131
	WIN_RSAM_/RSAM_10/STATYYYY.DAT	10 min RSAM data	60
	WIN_RSAM_/TRIG/STATYYYY.TRG	Text files of single-channel triggers (detections)	72
	WIN_RSAM_/EVNT_10/STATYYYY.DAT	10 min RSAM event counts (from triggers)	102
	WIN_RSAM_/ALARM.LOG	Text file logging event and tremor alarms sent	
TILT	TILT/STAT/XAXSYYYY.DAT; TILT/STAT/YAXSYYYY.DAT	*X*-axis and *Y*-axis tiltmeter data, averaged every 10 min	50
Xdetect	SSAM/ASCII/STAT/DDMMMYY.DAT	Daily files of 1 min averaged SSAM data for each station of percent of signal in 17 frequency bands	3,864
Xdetect	SSAM/binary/FFT/YYYY/YYMMDDHH.FFT	Hourly files of SSAM data	29,834
(Hand-edited)	Counts.dat	Daily count of volcano-tectonic, hybrid, long-period, and rockfall seismic events	1

These were produced by the Volcano Disaster Assistance Program (VDAP) system except for miniSEED files and Counts.dat. RSAM, real-time seismic amplitude measurement; SSAM, seismic spectral amplitude measurement; USF, University of South Florida.

*For filename format, the following abbreviations are used: STAT is a four-letter station code, YYYY is a four-digit year, MM is a two-digit month, DD is a two-digit day, and NN is a two-digit base-36 (0–9, A–Z) event counter capable of tracking up to 1296 events per day.

†About 58 DMX files have a size of 0 byte. About 77 DMX files could not be converted to miniSEED. These 135 DMX files are not counted.

‡About 324 miniSEED files with incorrect time are not counted (they claim to be recorded on 1 January 1970).

system, and the amount of computer hardware and software systems to maintain was reduced.

Continuous and event waveform data files from the DSN were also recovered from ~200 DDS-1 DAT tapes. The event waveform data files had been recorded in Seisan format and were merged into the MVOE database. The continuous waveform data files were converted from Seislog to Seisan format, and a third Seisan database named DSNC (for DSN continuous) was built. In June 2003, when Thompson left MVO, the IRIG, MVOE, and DSNC databases were on hard drive and DDS-3 DAT tapes at MVO. Copies were also delivered to the BGS on DDS-3 tapes.

The ASN Data Archive at University of South Florida

The data recovery and conversion work at MVO from 2001 to 2003 targeted only the event waveform data files. Recently, we have tried to master all datasets deriving from the ASN, including event catalog metadata such as event classifications, phase picks, hypocenters, and magnitudes, along with datasets from the RSAM and TILT PCs.

Event waveform, phase arrival, hypocenter, and magnitude data

The VDAP system generated up to four file types per event: (1) multiplexed SUDS files with extension WVM; (2) demultiplexed SUDS files with extension DMX; (3) phase pick files with extension PHA; and (4) Hypo71 summary files with extension PUN. For example, the 10th event detected by Xdetect on 31 July 1995 was stored as file 95073109.WVM. It was demultiplexed (producing 95073109.DMX), phases were manually picked (producing 95073109.PHA), and the event was located with Hypo71 (producing 95073109.PUN). This set of four files represents a single event. The Sudsei program we had used in 2001 failed to work in our 2019 trials. Multiple conversion workflows we tried are detailed in the supplemental material to provide additional information for other observatories wishing to convert SUDS files. The underlying cause of these difficulties is that data were recorded using software developed in the 1980s to run on 16-bit PCs. Our best solution is encapsulated in a Python3 Jupyter notebook, Vdap2seisanDB.ipynb (see Data and Resources). The notebook is an interactive tutorial on how to convert one event from SUDS/Hypo71 to a Seisan database. It performs the following actions:

1. SUDS file is demultiplexed, time corrected, and converted to Seismic Analysis Code (SAC) format using the programs Irig, Demux, and Sud2sac in Win-SUDS Utilities (Banfill, 2003).
2. SAC files are converted to miniSEED files using ObsPy (Krischer *et al.*, 2015). Direct conversion from SUDS to miniSEED format using Sud2msed in Win-SUDS did not work.
3. The event is registered into the Seisan database using Autoreg from the Seisan package (Havskov and Ottemöller, 1999). This step creates a Seisan S-file in Nordic format.
4. The PHA file is converted to Nordic format using Hypnor from the Seisan package and inserted into the S-file.
5. The PUN file is converted to Nordic format and inserted into the S-file.

We have recovered additional data not available at MVO in 2003. VDAP scientists who were involved in the crisis from 1995 to 1997 (including Power, Lockhart, and White) copied some MVO seismic and tiltmeter data to CDs during their visits. By 2001, many Iomega Zip100 disks were unreadable, but the CD backups were readable in 2019. Willy Aspinall also shared PHA and PUN files from repicking and relocating events for Aspinall *et al.* (1998). We recovered a total of

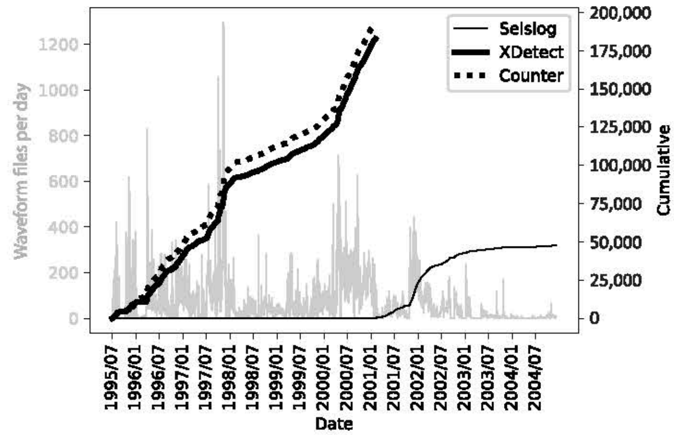

Figure 5. Bars show daily number of event waveform files recovered from the ASN data archive. The thick solid line shows the cumulative number of event waveform files detected by Xdetect (27 July 1995–1 March 2001). The thinner line shows those detected by Seislog (2 March 2001–16 December 2004). The QNX appears to have been configured to be less sensitive as volcanic activity continued to escalate from 2000 to 2003. Total number of event waveform files is 230,314. Dotted line shows the cumulative number of events triggered by Xdetect, based on the highest two-digit base-36 counter. At least 11,140 event waveform files that were triggered are missing. There are also many events recorded in the handwritten seismic event logbooks, or visible in helicorder plots, for which event waveform files were not recoverable.

175,892 WVM files, 183,187 DMX files, 11,278 PHA files, and 4,999 PUN files (Table 2). We organized these into yr/month directories, and batch converted the entire collection of events using Vdap2seisanDB.py, a Python3 program based heavily on the notebook. The result is a Seisan database we named ASNE. ASNE contains 182,590 events recorded between 27 July 1995 and 1 March 2001, when the VDAP system was phased out. We added 47,724 events recorded by the QNX/Seislog system between 2 March 2001 and 16 December 2004 to ASNE for a total of 230,314 events (Fig. 5). ASNE also contains 11,189 hypocenters; these were located with Hypo71 (Fig. 3) and represent only about 6% of the events recorded up to 1 March 2001. Few events were located after February 1997 as the volcano-tectonic earthquake rate (Fig. 3) declined sharply. Located events are shown in Figures S5 and S6. Magnitudes are available for 9325 of these events. The magnitude of completeness appears to be around 1.1, and the largest magnitude is 2.3 (Fig. S7) probably due to signals being clipped.

We think the ASNE database contains all extant digital waveform data, phase picks, hypocenters, and magnitudes available from the ASN. There are 61 network-station-location-channel ids and 39 unique stations at 17 sites in this dataset. Many different sensors were used at the same site at different times or even at the same time. The ability to detect and locate earthquakes depends on the number of independent

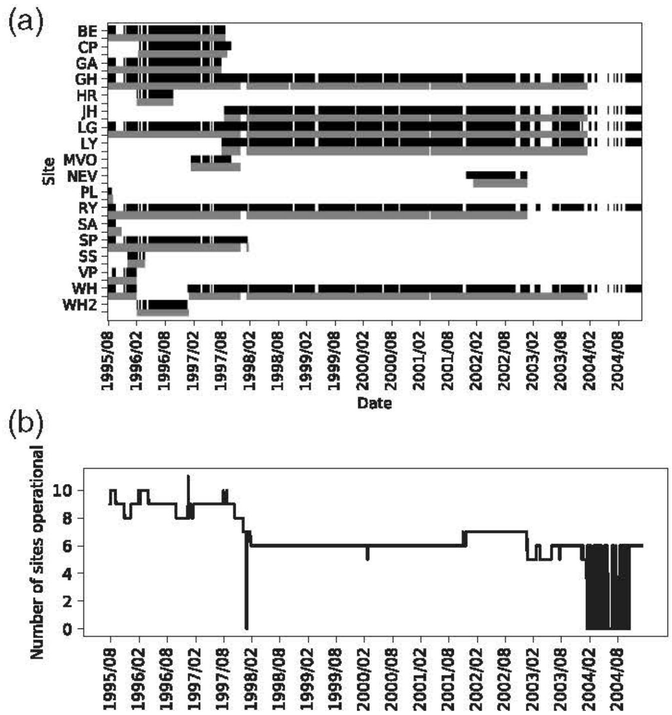

Figure 6. Data completeness for all ASN sites. The network operated from 27 July 1995 through 16 December 2004. (a) For each site, there are two rows. Black denotes event waveform files exist from that site on that day. Gray denotes 1 min RSAM data exist from that site on that day. White denotes no data for that site for that day. Data quality is not indicated, only that data were recorded. Sites GH, LG, and RY operated throughout. WH, JH, and LY for more than 6 yr. However, the event waveform file archive has numerous gaps seen as vertical white stripes. These are caused by missing or unreadable backup media, or by outages of the data acquisition system. The 1 min RSAM data are remarkably complete through the last download on 10 January 2004. (b) Total number of ASN sites operational each day, based on the existence of either event waveform files or 1 min RSAM data. Through the first 15 months of the eruption (before the DSN was installed), the ASN had 8 to 10 operational sites. Following the escalation of volcanic activity throughout 1997, there were typically five to seven sites. The only significant outages are seen after 10 January 2004, a period for which we have no 1 min RSAM data.

operational sites, and Figure 6a aggregates recovered event waveform and 1 min RSAM data according to the station-site mapping shown in Table 1. The most common number of sites was six (50%) and the maximum was 11 (Fig. 6b). Sites GH, LG, RY, and WH had sensors throughout most of the operational period of the ASN. However, significant data gaps exist, reflecting the complex history of capturing, recovering, and converting the data from legacy formats. The biggest gap in recovered waveform data during the period when the VDAP system was in operation is 19 days from 22 September to 11 October 1995 (Table 3), but RSAM data do exist for this period (Fig. 6a).

Event classifications

Many types of seismic events have been recognized in the ASN dataset. The most common types are volcano-tectonic, hybrid, and long-period earthquakes and rockfall signals (e.g., Miller *et al.*, 1998; Thompson, 2015). MVO analysts routinely classified almost all events. Classifications were not recorded digitally and exist only in handwritten event logbooks (Fig. S3). In March 2019, MVO shared scans of the logbooks. We tried several optical character recognition software packages to digitize the classification data, without success.

Reclassifying ~230, 000 events manually would take a long time. An experienced analyst might process 500 events per day, so this effort would take around 2 yr. The most critical time period is July 1995–October 1996, since in late October 1996 the DSN was installed, and events detected on that network already exist in the MVOE Seisan database. In September 2019, a Python program was written to allow students at the University of South Florida (USF) to check out days of unprocessed waveform files and classify them using information from the logbooks. Once a day is fully processed, an extra check is performed to ensure all events in the logbook have been recorded in the database (some have missing waveform files). Sometimes waveform files exist, but there is no corresponding event in the logbooks, in which case the student has to use their own judgment. Each student kept a list of events that they found difficult to classify, and these were reviewed by GT. As of February 2020, eight USF students have transcribed the original classifications of 26,878 events into the ASNE Seisan database for the period of January to October 1996. Of these, 24,279 have existing waveform files. Only 876 waveform files remain to be processed for this 10-month time period.

The period from 27 July to 31 December 1995 will require a different approach because logbooks do not exist (and perhaps never existed). Each student has processed at least 1000 events from 1996 and could probably classify events from 1995 with reasonable accuracy. A different approach would be to develop an automated supervised classifier now that we have 24,279 events with labels. The difficulty here is the quality of the ASN data. Because of the 12-bit analog telemetry, many signals were clipped or plagued by interference, dropouts, and spikes. But even if only 60%–70% of events can be confidently classified automatically, this would greatly reduce the workload for human analysts.

Daily event counts

Although ~200, 000 events in the ASNE database lack classification information, a daily count of volcano-tectonic, hybrid, long-period, and rockfall seismic events was made during the first 2 yr of the eruption and recorded in a text file named Counts.dat. We updated the file by compiling daily event counts from the event logbooks (Fig. S3) from 1997 through 13 December 2000 when the records end. The data are shown

TABLE 3
Data Gaps of at Least 10 Days in the Existing Event Waveform File Archive

Start Date (yyyy/mm/dd)	End Date (yyyy/mm/dd)	Gap Size (Days)
1995/09/22	1995/10/11	19
1995/10/23	1995/11/07	15
1995/11/15	1995/12/01	16
1997/03/20	1997/04/01	12
1997/06/01	1997/06/18	17
1999/03/24	1999/04/10	17
2001/10/31	2001/11/15	15
2002/09/30	2002/11/01	32
2003/01/02	2003/02/01	30
2003/03/12	2003/05/28	77
2003/12/16	2004/01/13	28
2004/02/07	2004/02/24	17
2004/04/15	2004/05/03	18
2004/05/25	2004/06/25	31
2004/07/05	2004/07/20	15
2004/07/20	2004/08/12	23

In addition, there were 56 gaps of between two and nine days. Single-day gaps are ignored. There were an equal number of gaps before and after the upgrade in March 2001, suggesting the VDAP system and QNX were equally reliable. VDAP, Volcano Disaster Assistance Program.

in Figure 3. In 1995, most seismic events detected were volcano-tectonic earthquakes. From February 1996 to February 2000, seismicity was dominated by similar rates of hybrid earthquakes and rockfall events. Thereafter, rockfall activity began to dominate, as a series of large domes were built. Long-period earthquakes also became more abundant. Because both rockfall signals and long-period earthquakes lack discernable *P* and *S* phases, this explains why fewer and fewer events were located as the eruption progressed. Amplitude-based source location methods were developed at MVO in 2000 to locate more of these events (Jolly *et al.*, 2002).

RSAM data

The only continuous digital data are the 1 and 10 min RSAM data (the number of minutes is the sampling interval) and SSAM data. The binary file format used for RSAM (and tilt) data consists of a 4-byte floating-point number for every sample. The data are preceded by a header (equivalent in size to an extra day of data), which includes metadata such as sampling interval (1 or 10 min). The GISMO toolbox (Thompson and Reyes, 2019) enables these DAT files to be read and analyzed (Thompson, 2015).

Figure 6a shows the availability of 1 min RSAM continuous data (indicated by gray shading) for each seismic site. Figure S9 shows a more detailed breakdown by station. There are 17 sites and 39 stations in the ASN dataset. The only significant gap in RSAM data occurs from 3 December 1997 to 2 January 1998. See Table S2 for the exact start and end dates of the 1 min RSAM data. There are one hundred and thirty-one 1 min RSAM files and sixty 10 min RSAM files in the archive (Table 2).

The RSAM system also recorded three other types of data: (1) RSAM triggers, (2) RSAM events, and (3) RSAM event and tremor alarms. RSAM triggers are detections for each channel, recorded in text files. RSAM events are the number of RSAM triggers in nonoverlapping 10 min time windows. These were the only measure of event rate available in real time and were often plotted alongside 1 min RSAM data using the Bob software. The last download of these data was on 10 January 2001 (Fig. 2). There are 72 RSAM trigger files and 102 RSAM event files in the archive (Table 2). The RSAM alarm system played a central role in monitoring the eruption, and so we describe this next.

Throughout phase 1 of the eruption (July 1995–March 1998; Fig. 2), the Operations Room was staffed 24 hr a day. This was no longer sustainable by February 1999, so MVO began using the RSAM alarm system. For an alarm to be declared, a preset amplitude and duration threshold had to be exceeded for multiple channels. RSAM event alarms were designed to catch high-amplitude, short-duration events of up to 2 min, such as a pyroclastic flow signal. RSAM tremor alarms were designed to capture moderate amplitude signals lasting up to tens of minutes such as tremor, swarms, lahars, and dome collapses. Between February 1999 and March 2003, more than 3100 event alarms and 900 tremor alarms were issued (Fig. S10). These are extracted from the RSAM log file, which gives a detailed history of what thresholds were set for each channel for each alarm and records the signal level. The high alarm rate was deemed necessary by successive MVO directors, because even a small pyroclastic flow could generate an ash cloud that could pose a threat to regional aviation. The alarm thresholds for each station were increased several times through 1999 and 2000, as volcano-seismicity escalated.

SSAM data

SSAM data were derived from FFTs of 1 min time windows of seismic data and were computed by Xdetect on the PC-SEIS PC. The FFTs were saved into binary files with an FFT extension. The archive has 29,834 FFT files recorded between 20 March 1996 and 31 August 2000 (Table 2), but we do not currently have a program to read these potentially valuable data. The percentage of the signal in 17 frequency bins was recorded in ASCII files with a DAT extension. The archive has 3864 of these files between 1 August 1995 and 27 October 1997. These data are easier to work with and could be used to make low-resolution spectrograms or spectral ratio plots.

Tiltmeter data

Tilt data were also acquired via the VDAP system. Because tilt monitoring was the next most important real-time monitoring technique, we have archived these data also. Data from three tiltmeters (Fig. S11) were recorded between July 1995 and October 2000 in 10 min DAT files. Tilt data were recorded in the same format as 10 min RSAM data and can be read with the same GISMO tool. There are 50 tilt data files in the archive (Table 2), two per station per year. Table S3 gives the exact start and end dates of the 10 min TILT data. These are discussed in more detail in the supplemental material.

Discussion

The VDAP system was well designed for volcano-seismic monitoring and played a key role in public safety on Montserrat from July 1995 to December 2004. It featured real-time monitoring tools (audio tone, helicorders, RSAM bar graphs, and alarm system), captured continuous seismicity (RSAM and SSAM), and included a full seismic event detection, classification, and location system (Xdetect, Budspick, Hypo71). By utilizing inexpensive widely available PC technology and common operating systems, the VDAP system could be rapidly deployed and easily supported in most countries. The idea of free, community-shared seismic monitoring software was a powerful concept in pooling the limited development resources at many volcano observatories that would otherwise have had to develop their own systems and might have struggled to respond effectively to volcanic unrest.

Of all components of the VDAP system, the robustness of the RSAM system is remarkable. Our archive indicates there were only 34 days of data loss during 102 months of continuous operation. The gap from 3 to 31 December 1997 is likely due to the data (stored in year files) being downloaded 28 days before the end of the year, so the actual downtime of the RSAM system may have been as little as six days. The RSAM real-time bar graphs and RSAM alarm system were two other critical components of the system. These useful aspects of the RSAM system have since been absorbed into later generations of USGS software based on Earthworm (1995). Helicorders have largely been phased out now due to the emergence of SWARM (2005). SSAM was replaced by web-based multistation spectrogram browsers such as IceWeb (1998) and Pensive (2015). See Thompson (2015) for a review of volcano-seismic monitoring software.

The main weaknesses of the VDAP system were the lack of continuous waveform data archiving and the handwritten event catalog. The former was hard to achieve affordably with early 1990s technology and was compensated for to some extent by the RSAM, SSAM, and helicorder systems. The latter could have been overcome using a program to log seismic event classifications with the corresponding event file names, times, and analyst initials as the USF students are now doing. But overall, the VDAP system was robust and easy to learn because it relied on technology already in operation at USGS volcano observatories.

Most of the data discussed here would likely have been lost, except for efforts that began in 2001 to recover them from old media. Many scientific papers have benefitted from that previously undocumented work. Of particular value is the ASNE database from July 1995 to October 1996—a period before the DSN was in operation. The recovered continuous 1 min RSAM and SSAM data add another dimension. Event waveforms only capture transient events less than 2 min in duration, and the detection algorithms do not record the most interesting and hazardous events recorded seismically such as swarms (once events overlap), tremor, dome collapse, or lahar signals. RSAM data are, therefore, complementary to the ASNE database. SSAM data further illuminate the RSAM data by revealing the changing frequency content of the continuous data. Nobody has yet examined, for example, whether changes in tremor frequency preceded the five eruptive episodes at SHV.

Conversion of SUDS data has been the most time-consuming part of this study. As documented in the supplemental material, several different conversion tools needed to be used at different times, and these sometimes involved running old versions of MS-Windows or MS-DOS or emulators so that old conversion codes written when SUDS format was popular could be used. We hope the codes and procedures documented here will help others. Ultimately, a cross-platform code to convert SUDS format directly to miniSEED would be ideal. A SUDS reader for ObsPy is probably the most useful way to achieve this, because ObsPy already writes to miniSEED and other formats.

Volcano-seismic event classification is challenging and subjective (Thompson, 2015). Many different people classified seismic events at MVO between 1995 and 2004, with levels of expertise ranging from volunteers to VDAP volcano-seismologists. Reanalysis by Rowe *et al.* (2004) suggests that most volcano-tectonic earthquakes from September 1995 throughout February 1996 should be reclassified as hybrid earthquakes and that examination of helicorder plots showed that these hybrid earthquakes occurred in swarms of several thousand events. STA/LTA detection algorithms such as Xdetect and Seislog were incapable of detecting these, once event codas began to overlap with the onset of new events. There is also open debate in the volcano-seismology community regarding a possible continuum between long-period and hybrid events, or between hybrid and volcano-tectonic events. The classified event counts shown in Figure 3 should, therefore, be viewed with skepticism.

The ASN data are the only seismic data from the first 15 months of the eruption, and they complement data from the DSN thereafter. Classifications have been added for 26,878 of the 40,000 events recorded during this time period so far. We plan to continue building the ASN dataset by adding improved phase picks and hypocenters relocated by Rowe *et al.* (2004)

and Roman *et al.* (2008). Once completed, we aim to merge the ASNE database with DSN data, resulting in a complete digital catalog for the eruption. If other scientists have ASN data and are willing to collaborate on building this archive, the date ranges to focus on are those given in Table 3. Gaps in 1995 are especially important to fill, as this was before the DSN operation.

FAIR data principles (Wilkinson *et al.*, 2016) provide guidance for scientific data management and stewardship. The work described in this article makes the ASN seismic dataset more discoverable, accessible, and reusable, in accordance with these principles.

Conclusions

The MVO ASN ran from July 1995 through December 2004, and data were acquired using a system developed by VDAP. The original data archive consisted of more than 230,000 STA/LTA-triggered event waveform files; continuous RSAM, SSAM, and tiltmeter data; RSAM triggers and event counts; RSAM event and tremor alarms; and Hypo71 phase arrival, hypocenter, and magnitude information for $\sim 10,000$ events. Without the efforts to recover data in 2001, before aging media deteriorated, it is possible that little of this dataset would remain today.

The dataset has been converted to modern seismic data formats to exploit it using contemporary analysis software. Waveform data have been converted to miniSEED format, and these have been organized and registered into a Seisan database—a common approach in the volcano observatory community. Phase arrival, hypocenter, and magnitude data have been incorporated into the same Seisan database and augmented by refined phase picks and hypocenters from published studies. USF students have classified 26,878 of the 40,000 events that occurred between July 1995 and October 1996, using handwritten event logbooks for guidance, closing in on the goal of a unified catalog for the whole eruption. RSAM, SSAM, and tiltmeter data have not been converted, but GISMO provides read functions for each of these formats. We envisage that these efforts will catalyze further research on the 1995–2010 eruption of the SHV.

Our data conversion codes are available in GitHub. We hope they will help other observatories with large archives in legacy SUDS, and Hypo71 formats convert their data and lead to new insights on seismicity at many volcanoes.

Data and Resources

The data discussed in this article were collected by the Montserrat Volcano Observatory (MVO) between July 1995 and December 2004. Archives of the SUDS event waveform files and Hypo71 files were compiled by G. T. in 2001 and are held at MVO and at the British Geological Survey (BGS). These legacy data are joint copyright of MVO and BGS and available from either agency on request. The value-added dataset described in this article is stored at the University of South Florida (USF) and is available on request with permission from the MVO director. This is likely to be on a case-by-case basis in accordance with the MVO data license policy. Most components of the seismic data acquisition and processing system used to generate the data were developed by the U.S. Geological Survey scientists. Codes used in this study are referenced and include PC-SUDS Utilities, Win-SUDS Utilities, CONVSEIS, Seisan, ObsPy, and GISMO. Codes developed for this study are shared at http://github.com/gthompson/AnalogSeismicNetworkPaper (last accessed March 2020). This includes Python3 notebooks and the data required to generate many of the figures in this article and in the supplemental material to this article. The supplemental material includes additional figures and tables that expand on the dataset discussed in this article and provides more details of the workflows and software packages we attempted to use to convert SUDS data.

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