



INSTITUTO NACIONAL DE SISMOLOGÍA, VULCANOLOGÍA,
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GUATEMALAN VOLCANOES RELATIVE THREAT RANKING RESULTS

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UNIDAD DE VULCANOLOGÍA

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Guatemalan Volcanoes Relative Threat Ranking Results

Mérida Boogher, Edgar Roberto¹; More, Thibault²; Chun Quinillo, Carla María Fernanda¹; González Domínguez, Dulce María Esther¹; Roca Palma, Amilcar Elías¹; Juárez Cacao, Francisco Javier¹; Chigna Marroquín, Gustavo Adolfo¹; Simmons, Isla³.

1. Departamento de Investigación y Servicios Geofísicos, Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología, INSIVUMEH, Guatemala.
2. École Nationale Supérieure de Géologie, Université de Lorraine, France.
3. School of Geosciences, University of Edinburgh, Scotland.

Executive Summary

INSIVUMEH is looking forward to improve and extend the volcanic monitoring and hazard assessment capabilities of its Volcanology section, in order to ensure that Guatemalan volcanoes can be properly monitored in advance of any eruption that could threaten both people and infrastructure.

Since the beginning of the Volcanology group labors, monitoring has been limited to the three most active volcanoes in recent times, Santiaguito, Pacaya and Fuego, and relying heavily on the cooperation of foreign agencies and universities who provide training, instrumentation and knowledge. Unfortunately, improvements have been made in a responsive act to high impact eruptions like those at Pacaya in 2010, Santiaguito in 2014 and Fuego in 2018, the latter with a tragic outcome.

The relative threat ranking of Guatemalan volcanoes was devised as a tool to recognize the volcanoes to be treated as priority targets and effectively direct the cooperation efforts towards the identified needs on them, both instrumentation and research. Volcanic threat is the combination of both the hazards, phenomena happening at the volcano, and the exposure, represented by the people and infrastructure that could be affected by the volcanic activity.

Based on their threat, 25 active and potentially active volcanoes were grouped in five categories: from very high to very low threat. These categories were used to determine the disciplines and instruments needed to perform the appropriate monitoring and identify the existing gaps in relation to the current state. A knowledge gap was also quantified by the review and classification of the relevant data available for each volcano.

As a result of the ranking analysis, the highest priority targets for monitoring improvements are the three volcanoes in the very high threat group and currently erupting: Santiaguito, Fuego and Pacaya, as well as the six volcanoes in the high threat group: Atitlán, Cerro Quemado, Tacaná, Acatenango-Yepocapa, Tolimán and Agua, with special attention to the first two, given their higher hazard and relatively easier access to have instruments installed around them.

The 19 volcanoes in the medium, low and very low threat groups can be addressed with the development of a much more dense regional seismic network, that can be improved to their specific monitoring requirements in a mid to long time term.

High priority research and hazard assessment targets should address not only the very high and very high threat volcanoes, but also poorly understood volcanoes of credible or suspected explosive nature, such as Agua, Tajumulco and Ixtepeque.

This improvements represent an increase in the investment needed not only to acquire the instruments and incorporate more qualified personnel, but also in the recurrent expenses for operation and maintenance. It is necessary to formulate the implementation framework with the participation of technical staff and authorities of both INSIVUMEH as well as its cooperation partners.

By doing all of this, INSIVUMEH can be prepared to properly monitor the onset of unrest that could lead to a volcanic crisis and provide useful data before, during and after the event to the risk and emergency management agencies. This agencies, as well as the government planners and decision makers at local, regional and national level, will benefit from the data presented in the hazard assessments of the volcanoes that INSIVUMEH should produce as result of the improvement of its capabilities.

Introduction

This report presents an assessment of the monitoring and research needs for the 25 active and potentially active volcanoes in Guatemala. Based on the threats posed by each of them, the volcanoes were ranked from the most to the least dangerous and were grouped in five categories. These categories are linked to specific requirements in order to perform a proper monitoring of the unrest ahead from an eruption. By comparing these requirements to the current state of the monitoring capabilities by INSIVUMEH, the monitoring needs were identified. In the same way, a review of the current state of knowledge of the volcanoes resulted in the identification of extensive gaps on what we know about them.

INSIVUMEH's Volcanology section has been working since 1987 on the monitoring and hazard assessments of Guatemalan volcanoes, with the aid of cooperation programs such as USGS-VDAP and CEPREDENAC, as well with universities such as Michigan Tech, Liverpool, Bristol and many more. Several disciplines have been worked since, not all of them continuously and most of them at a very basic level, doing deformation, seismology and geology in the first years, occasional gas measurements, and currently working on seismology, infrasound and satellite images.

Currently, three volcanoes are being monitored: Santiaguito-Santa María, Fuego and Pacaya. Their eruptions in historical times have caused thousands of fatalities and disrupted infrastructure, economic activities and terrestrial as well as air transportation. From 1987 to present, Santiaguito's explosive activity has produced pyroclastic flows that nearly destroyed its observatory on May 2014, Pacaya's eruptions disrupted air traffic with tephra fall over the international airport in Guatemala City on May 1998 and 2010, and more recently, Fuego's eruption on June 3rd 2018 resulted in a tragedy that led INSIVUMEH to seek the ways to improve the monitoring and assessment capabilities, in order to prevent such an event happening again.

Other volcanoes with recorded activity in the recent past may have not caused a big impact before, but given the growth of the population and the development of urban and rural settlements, hundreds of thousands to millions of people are living now in zones exposed to volcanic hazards.

Overview of Guatemalan volcanoes

Guatemalan volcanoes are located in the northern-most segment of the Central American Volcanic Arc or CAVA. The CAVA can be subdivided into the volcanic front and the behind the volcanic front areas. The volcanic front (VF) stretches continuously for about 1100 km from the Guatemala/Mexico border to central Costa Rica as a direct manifestation of the subduction of the Cocos plate beneath the Caribbean plate, while the behind the volcanic front volcanism (BVF) is related to the segmentation of both the subducting and the overriding plates and it occurs in discontinuous and scattered fields associated with grabens bounded by N-S normal faults (Walker et al. 1995).

The volcanic front in Guatemala is divided into the Western, Central and Eastern segments as proposed by Stoiber and Carr (1973). Most of the volcanic centers in this front are made up of one or more large composite cones and stratovolcanoes whose lavas are calc-alkaline basalts, andesites and dacites (Carr et al. 1979), forming a chain from Tacaná to Moyuta volcanoes.

To the north of the volcanic front, is a much more widely spaced chain of volcano-tectonic depressions and calderas which have produced voluminous silicic ash flows and Plinian airfall deposits (Carr et al. 1979), such as Xela, Atitlán and Amatitlán.

The greatest concentration of behind the volcanic front volcanism (BVF) in Central America is in southeastern Guatemala (Walker et al. 1995), where most of the cinder cones can be grouped in two major cone fields: the Ipala Graben and the Cuilapa-Barberena fields (Walker, 1981). Relatively small calderas, composite cones and shield volcanoes also exist behind the front in southeastern Guatemala (Walker et al. 1995), for example, Ayarza and Retana calderas, Ixtepeque, Jumay, Chingo and Ipala volcanoes (Carr et al. 1979; Walker, 1981).

Different attempts have been made in order to list and classify the Guatemalan volcanoes, being the works by Bohnenberger (1964) and Gall (1976) the most relevant to date. The first produced a list of 324 Quaternary volcanic vents in the country, based on the previous research by Sapper (1925), Meyer-Abich (1956), Williams (1960) and Williams, McBirney and Dengo (1964) as well as with the aid of topographic maps and aerial photographs.

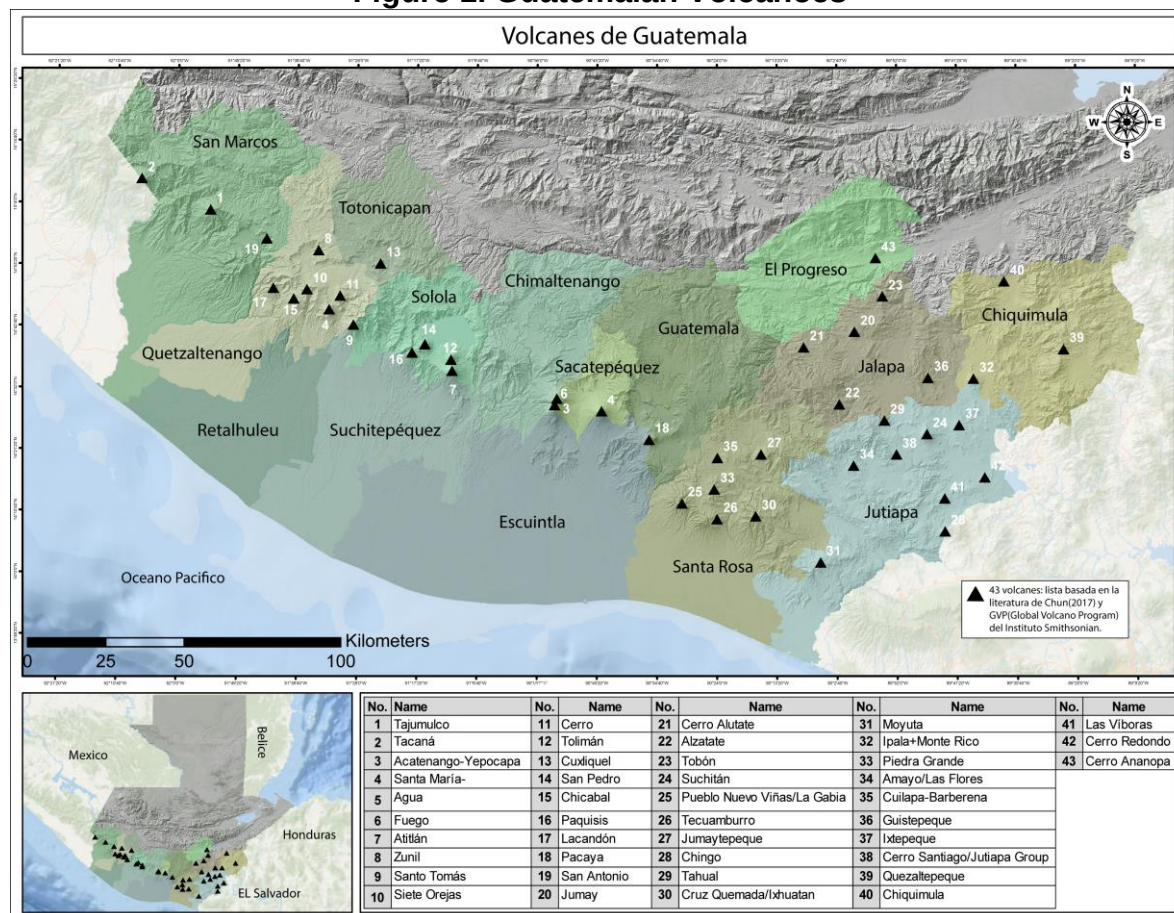
Gall compiled a Geographic Dictionary (Diccionario Geográfico de Guatemala, by the Instituto Geográfico Nacional). This dictionary included the main geographic accidents recognized as volcanoes at the time, and is the basis for the official list of volcanoes in the country. Chun (2017) compiled a list of the 39 structures recognized as volcanoes in the Diccionario Geográfico Nacional.

The Smithsonian Institute GVP lists a total of 36 entries for Guatemalan volcanoes, and after comparing this and the 39 volcanoes list compiled by Chun (2017), some differences were noted. The main difference resides in the approach that every author and/or institution take on what a volcano is.

The Diccionario Geográfico Nacional, for example, lists the volcanoes as singular geographic accidents, while the work of Bohnenberger (1964) and the Global Volcanism Program of the Smithsonian Institute (GVP) for example, have a true geological/volcanological background and categorizes them both in singular structures such as cinder and parasite cones as well as composite stratovolcanoes, dome complexes and volcanic fields. There are some volcanic structures, such as stratovolcanoes, volcanic fields and calderas (the last not considered for this assessment) listed by the GVP, that may be listed under other names or features in the Diccionario Geográfico Nacional, or well, not listed at all.

A comprehensive review of the lists from Chun (2017) and the GVP allows to produce a more accurate and representative list of the Guatemalan volcanoes, rearranged in a total of 43 structures, with their names and location displayed in the following figure.

Figure 1. Guatemalan Volcanoes



Most of them are towering stratovolcanoes with intermediate to acidic lavas and moderate to highly explosive eruptions. Just seven volcanoes (Tacaná, Santa María, Santiaguito, Cerro Quemado, Atitlán, Fuego and Pacaya) have historical recorded activity, including fumaroles, phreatic explosions, lahars, lava flows, tephra emission, pyroclastic flows, dome/sector collapse and lateral blasts. Despite the occurrence of this variety of volcanic phenomena, a large number of human settlements have been established around the volcanoes since colonial times, especially due to the fertile soils and strategic reasons. To date, more than the half of the country's population is estimated to be living in major cities and rural towns around a volcano.

The latitude and longitude of the 43 volcanoes, their summit elevation in meters above sea level, the department of Guatemala where they are located and the type of volcano are listed on the following table.

Table 1. List of Guatemalan volcanoes

Number	Name	Latitude N	Longitude W	Summit elevation	Department	Type
1	Tajumulco	15.043	-91.904	4220	San Marcos	Stratovolcano
2	Tacaná	15.131	-92.100	4092	San Marcos	Stratovolcano
3	Acatenango-Yepocapa	14.500	-90.870	3976	Chimaltenango, Sacatepéquez	Stratovolcano
4	Santa María-Santiaguito	14.756	-91.550	3772	Quetzaltenango	Stratovolcano
5	Agua	14.465	-90.743	3766	Escuintla, Sacatepéquez	Stratovolcano
6	Fuego	14.475	-90.880	3763	Chimaltenango, Escuintla, Sacatepéquez	Stratovolcano
7	Atitlán	14.584	-91.186	3597	Sololá, Suchitepéquez	Stratovolcano
8	Zunil	14.740	-91.450	3542	Quetzaltenango, Sololá	Stratovolcano
9	Santo Tomás	14.712	-91.479	3530	Quetzaltenango, Sololá, Suchitepéquez	Stratovolcano
10	Siete Orejas	14.815	-91.618	3370	Quetzaltenango	Stratovolcano
11	Cerro Quemado	14.797	-91.519	3197	Quetzaltenango	Stratovolcano
12	Tolimán	14.613	-91.189	3150	Sololá	Stratovolcano
13	Cuxliquel	14.889	-91.399	3031	Totonicapán	Lava dome
14	San Pedro	14.657	-91.267	3020	Sololá	Stratovolcano
15	Chicabal	14.79	-91.652	2900	Quetzaltenango	Stratovolcano

16	Paquisis	14.633	-91.304	2846	Sololá, Suchitepéquez	Stratovolcano
17	Lacandón	14.817	-91.717	2759	Quetzaltenango	Stratovolcano
18	Pacaya	14.380	-90.600	2552	Escuintla, Guatemala	Complex
19	San Antonio	14.959	-91.737	2517	San Marcos	Lava dome.
20	Jumay	14.694	-89.993	2182	Jalapa	Stratovolcano
21	Cerro Alutate	14.648	-90.144	2115	Jalapa	Stratovolcano
22	Alzatate	14.484	-90.039	2062	Jalapa	Stratovolcano
23	Tobón	14.795	-89.910	2060	Jalapa	Lava Dome
24	Suchitán	14.399	-89.779	2042	Jutiapa	Stratovolcano
25	Pueblo Nuevo Viñas/ La Gabia	14.199	-90.505	1961	Santa Rosa	Stratovolcano
26	Tecumburro	14.156	-90.407	1840	Santa Rosa	Stratovolcano
27	Jumaytepeque	14.340	-90.270	1815	Santa Rosa	Stratovolcano
28	Chingo	14.118	-89.727	1775	Jutiapa	Stratovolcano
29	Tahual	14.437	-89.905	1716	Jutiapa	Stratovolcano
30	Cruz Quemada/ Ixhuatan	14.161	-90.286	1694	Santa Rosa	Complex
31	Moyuta	14.030	-90.095	1662	Jutiapa	Stratovolcano
32	Ipala+Monte Rico	14.556	-89.640	1650	Chiquimula, Jutiapa	Stratovolcano
33	Piedra Grande	14.239	-90.409	1649	Santa Rosa	Stratovolcano
34	Amayo/Las Flores	14.307	-89.996	1600	Jutiapa	Stratovolcano
35	Cuilapa-Barberena	14.330	-90.400	1458	Guatemala, Santa Rosa	Volcanic field
36	Guistepeque	14.561	-89.775	1351	Jalapa	Volcanic field
37	Ixtepeque	14.424	-89.684	1292	Jutiapa	Lava dome(s)
38	Cerro Santiago/ Jutiapa Group	14.339	-89.870	1260	Jutiapa	Volcanic field
39	Quezaltepeque	14.641	-89.373	1200	Chiquimula	Volcanic field
40	Chiquimula	14.837	-89.549	1192	Chiquimula	Volcanic field
41	Las Víboras	14.212	-89.727	1108	Jutiapa	Shield
42	Cerro Redondo	14.272	-89.608	775	Jutiapa	Shield
43	Cerro Ananopa	14.900	-89.931	383	El Progreso	Volcanic field

Methods of threat assessment and gap analysis

For the purposes of the threat assessment ranking of the Guatemalan volcanoes by the Volcanology section of INSIVUMEH, the process was divided in a series of steps, involving several actors and procedures in order to come up with the preliminary results presented in this report.

First at all, the 43 volcanoes were subject to an extensive bibliographical review by the personnel at INSIVUMEH's Volcanology section, the aim was to find as much information as possible about the geology, eruptive history, hazards and geophysical records about them. The different publications and records in a digital format were uploaded to a cloud server.

After the bibliographical review and a comparative analysis of the sources found and others such as the Global Volcanism Program of the Smithsonian Institute, the list of volcanoes subject to the ranking was finally reduced to 25, as explained in the results section.

In order to apply the gathered data to a quantitative classification of the volcanoes, the INSIVUMEH's Volcanology section participated in a Volcano Threat Assessment Workshop with geologists from the USGS-VDAP program. A volcano threat assessment is critical to prioritize the monitoring and research efforts on a group of volcanoes in concordance with the measure of their hazards.

The proposed methodology follows the one proposed by Ewert (2007), a system based on the concept of *threat* as the qualitative risk posed by a volcano to people and property as independent of the mitigation efforts. In natural hazard studies, risk is usually expressed as a function of three elements: the probability of the hazard occurrence, the exposure of people and infrastructure to the hazard and the vulnerability of these to the hazard (Aspinall & Blong, 2015). In the case of the assessment system by Ewert (2007), the vulnerability as a factor is not taken in consideration.

The "System for Ranking Relative Threats of U.S. Volcanoes", Ewert (2007), gives a score using hazard factors (inherent to the volcano geology, eruptive style and eruptive history), historical unrest factors (volcanic unrest since last eruption) and exposure factors (population, infrastructure and aviation exposures). These factors are adapted to the specific needs of the workgroup and are incorporated into two categories (hazards and exposure) with a score for each of them, and these two scores are multiplied to obtain a final *threat* score for each volcano.

The different factors considered are shown in the next table, modified after the one in Ewert (2007), following the advice of the VDAP-USGS and OVDAS-SERNAGEOMIN geologists about the scores adjustments required to meet the workgroup perception of the hazards and exposures for the Guatemalan volcanoes; each factor shows in brackets the score rank.

Table 2. Hazard, unrest and exposure factors

Hazard factors	Historical unrest factors	Exposure factors
<ul style="list-style-type: none"> • Volcano type (0-1) • Maximum VEI (0-3) • Explosive activity (0-1) • Major explosive activity (0-1) • Eruption recurrence (0-4) • Holocene pyroclastic flows (0-2) • Holocene lahars (0-2) • Holocene lava flows (0-2) • Hydrothermal explosion potential (0-1) • Sector collapse potential (0-1) 	<ul style="list-style-type: none"> • Observed seismic unrest (0-1) • Observed ground deformation (0-1) • Observed fumarolic or magmatic degassing (0-1) 	<ul style="list-style-type: none"> • Distal and proximal volcano population index (log10) • Historical fatalities (0-1) • Historical evacuations (0-1) • Local aviation exposure (0-2) • Regional aviation exposure (log10) • Power infrastructure (0-1) • Transportation infrastructure (0-1) • Important development or sensitive areas (0-1)

The volcano type is based on what the GVP-Smithsonian indicates for each volcano in the list, as well for the VEI's. The explosive activity and its recurrence is calculated from the data on the GVP-Smithsonian and/or other publications of each volcano. The score regarding the pyroclastic, lava and laharic flows during the Holocene considers not only their mere occurrence during this period of time, but also if they reached a then or now populated area in Guatemalan territory. The score for other phenomena such as sector collapse or hydrothermal explosion potential depends just in the occurrence or not of these.

The human population related scores were calculated using the results of the 2018 Population and Housing Census, conducted by the Guatemalan Statistics Institute (INE) and the United Nations Fund for Population Activities (UNFPA). The results come down to the municipal unit level but still not to a geographical distribution of lower level units such as towns and villages in relation to the volcano. The radius used for the calculus of the distal populations was set at 20 km for all the volcanoes, while the proximal radius (between 5 and 15 km) was calculated depending on the volcano relative height, using the intervals shown in the following table.

Table 3. Volcano relative height and proximal radius determination

Relative height	Radius
>2000 m	15 km
1000-2000 m	10 km
<1000 m	5 km
Extremely irregular edifice	5 km

The score for the historical death or evacuations considers just the occurrence of these but not the figures of affected people in each case. In the other hand, the impact on the aviation (local and regional) is measured with the numbers of daily passengers moving through the Guatemalan and nearby countries airports. By multiplying the sums of the hazard and historical unrest plus the exposure factors, a threat score is obtained. The resulting scores were used to group the volcanoes in five different threat levels: very high, high, moderate, low and very low.

Besides the measurement of the *threat* level that every volcano in the list poses, it is critical to have measurements of the current monitoring and knowledge levels to evaluate how well monitored and well known the Guatemalan volcanoes are, in concordance with the *threat* scores obtained. The identification of the gaps in monitoring and knowledge levels will set the path to better prioritize the efforts on setting up instrumentation networks and research development.

Based on the threat scores obtained for each volcano, it is necessary to relate this results to a monitoring improvement strategy, defining levels with particular instrumentation requirements for each group of volcanoes according to their threat level. Comparing the ideal versus the current levels allows to identify the existing gaps on the monitoring labor.

Following the advice of the USGS-VDAP geologists, the Volcanology section personnel used the monitoring levels, monitoring gap analysis and the instrumentation recommendations proposed by Ewert et. al. 2005 and Moran et. al. 2008.

The monitoring gap considers the main methods applied to volcanoes: seismic, deformation, gas, hydrologic and remote-sensing and each one is ranked between 0 and 4, following the levels of monitoring.

Instead of a sum of all the scores for the different methods mentioned above, it is just the seismic score the value that determines the monitoring gap, between the required level (related to the threat level) and the current seismic score. Table 4 shows the monitoring levels, capabilities and associated volcano threat levels from the two previously mentioned publications. The instrumentation requirements for each level were adapted to the specific needs and capabilities of the Volcanology section and are shown in the results discussion as well as in the appendices.

Table 3. Monitoring levels and capabilities

LEVELS OF MONITORING	LEVEL 0 (NO GROUND BASED MONITORING)	LEVEL 1 (MINIMAL MONITORING)	LEVEL 2 (LIMITED MONITORING FOR CHANGE DETECTION)	LEVEL 3 (BASIC REAL TIME MONITORING)	LEVEL 4 (WELL MONITORED IN REAL TIME)
VOLCANO THREAT LEVEL		VERY LOW THREAT	LOW THREAT	MODERATE THREAT	HIGH AND VERY HIGH THREAT
CAPABILITIES	No real-time data from ground-based sensors are available. Eruption confirmation is provided only by remote-sensing data or from people observing the event.	Detection of eruption occurring or gross changes are occurring/have occurred near a volcano, data is not collected systematically or at very long intervals (more than 5 years).	Detection and tracking of activity frequently enough in near-real time to recognize that something anomalous is occurring.	Detection and tracking of pre-eruptive and eruptive changes in real-time, with a basic understanding of what is occurring.	Tracking detailed changes in real-time and developing, testing and applying models of ongoing and expected activity.

To identify the current level of knowledge on the Guatemalan volcanoes and measure the gaps to fill onto an ideal scenario, a quantitative system to assign scores was developed by the personnel of the Volcanology section in collaboration with the geologists from the USGS-VDAP program.

A total of 14 factors considered of high importance to build the desired knowledge of a volcano were determined, comprising the geology, geochemistry, geophysical records, maps, remote sensing, GIS, communication and crisis management for each of the volcanoes. A score rank was assigned to every factor, as shown in the following table.

Table 4. Knowledge gap analysis factors and their scores

<ul style="list-style-type: none"> • Geological map (0-3) • Hazards map (0-3) • GIS (0-2) • Eruptive history (0-2) • Tephra stratigraphy (0-2) • Petrology (0-2) • Geochemistry (0-2) 	<ul style="list-style-type: none"> • Seismology (0-4) • Geodesy (0-3) • Remote sensing (0-3) • Conceptual model (0-2) • Events tree (0-2) • Public outreach (0-3) • Emergency protocols (0-1)
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After calculating the scores and threat levels, as well as the knowledge and monitoring gaps, this results were compared against each other in order to identify the target volcanoes for the short, mid and long term monitoring improvements by the Volcanology section of INSIVUMEH.

Threat ranking results and discussion

The Guatemalan volcanoes included in the relative threat ranking are those considered to be active or potentially active, with confirmed, credible or suspected activity during the Holocene. The Smithsonian GVP have 23 entries for Guatemala in the Holocene Volcano List. Considered less likely to become active again, the Guatemalan volcanoes in the Smithsonian GVP Pleistocene Volcano List were left out, except for two: Zunil and Siete Orejas. This two volcanoes have large and currently active hydrothermal systems that could potentially trigger phreatic explosions. In total, 25 volcanoes are subject to this ranking.

The threat scores are shown in the following table, along with the threat group and the last year of recorded/known activity for each volcano. A complete breakdown of the hazard, exposure and threat scores can be found in the appendices. The threat scores were divided into five classes using the natural breaks classification on ArcGIS, obtaining the next categories: very high, high, moderate, low and very low. Depending on the scores for the hazard, exposure and the current state of the volcano, some adjustments were made to include some volcanoes in a higher threat group than that dictated by the natural breaks alone. For example, Pacaya into the very high threat group because of it continuous activity or Agua into the high threat group because of it high exposure score (the highest of all volcanoes in the list) and the great impact expected if it starts an eruption.

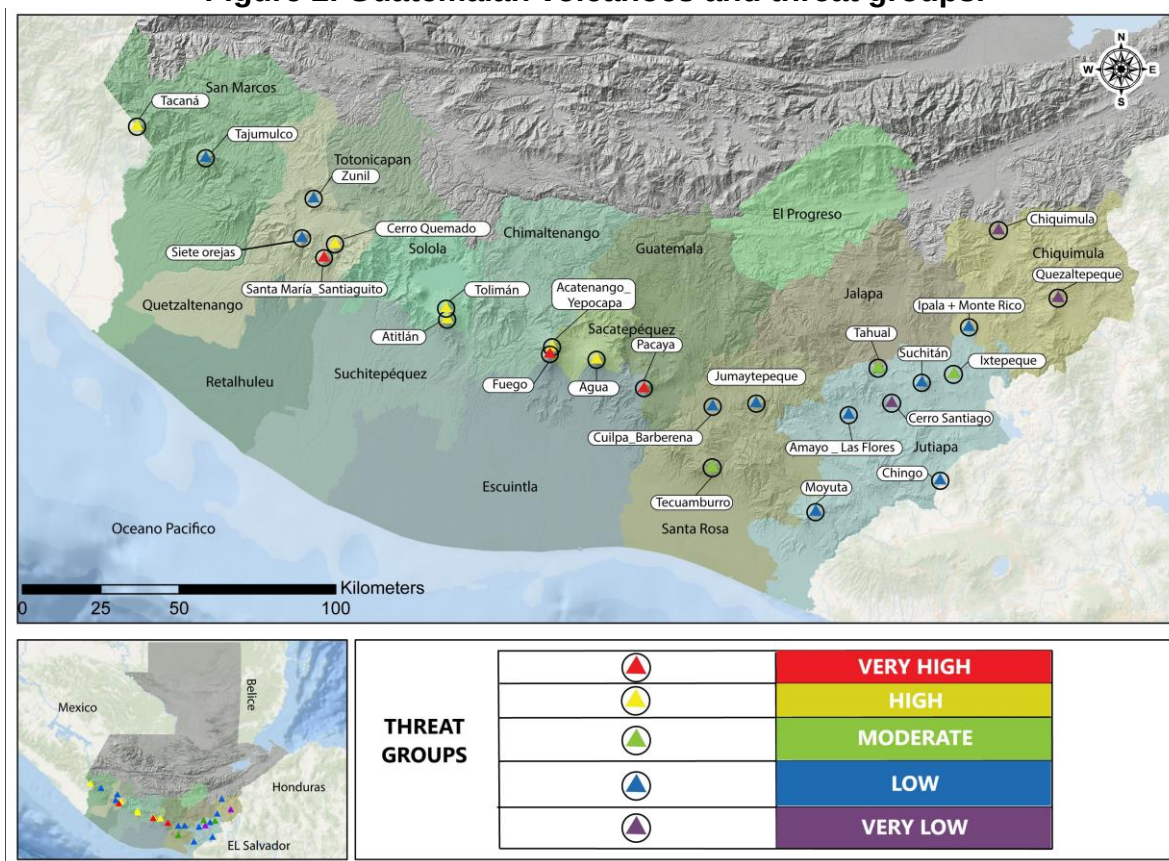
About the names shown for the volcanoes, the “/” indicates two volcanoes considered as a single complex, “-” indicates two different names for the same volcano, “&” indicates a volcano and a parasitic structure of it listed as a separate volcano on the Diccionario Geográfico Nacional by Gall (1976).

Table 5. Relative threat ranking results

POSITION	NAME	THREAT SCORE	THREAT GROUP	LAST ACTIVE
1	Santa Maria/Santiaguito	439	VERY HIGH	2020 CE
2	Fuego	392		2020 CE
3	Pacaya	371		2020 CE
4	Atitlán	304	HIGH	1856 CE
5	Cerro Quemado	295		1818 CE
6	Tacaná	291		1986 CE
7	Acatenango/Yepocapa	254		1972 CE
8	Tolimán	216		Unknown
9	Agua	181		Unknown
10	Tecuamburro	183	MODERATE	960 BCE
11	Tahual	143		Unknown
12	Ixtepeque	140		Unknown
13	Jumaytepeque	106	LOW	Unknown
14	Tajumulco	104		Unknown
15	Zunil	103		Unknown
16	Siete Orejas	103		Unknown
17	Suchitán	102		Unknown
18	Moyuta	100		Unknown
19	Ipala+Monte Rico	97		Unknown
20	Amayo-Las Flores	81		Unknown
21	Chingo	78		Unknown
22	Cuilapa Barberena	74		Unknown
23	Cerro Santiago-Jutiapa Group	28	VERY LOW	Unknown
24	Chiquimula Volcanic Field	28		Unknown
25	Quezaltepeque Volcanic Field	27		Unknown

The following map shows the geographical distribution of the 25 volcanoes in the ranking with their colors according to their threat group (very high: red, high: yellow, green: medium, blue: low, purple: very low).

Figure 2. Guatemalan volcanoes and threat groups.



The volcanoes with the very high threat classification happen to be the three currently active and monitored ones: Santa María/Santiaguito, Fuego and Pacaya. This three volcanoes not only have shown an explosive behavior with dome collapses, lateral blasts and pyroclastic flows, but also lahars and in the case of Pacaya, extensive lava flows, that all together have the potential to impact both large populations and productive land, as well as disrupting the air traffic. This volcanoes are currently the only ones included in the permanent monitoring program.

The group of the high threat volcanoes include six volcanoes: Atitlán, Cerro Quemado, Tacaná, Acateño/Yepocapa, Tolimán and Agua. These have been active in the last two centuries or less (except Agua), having shown at least one type of unrest since then, and all are located very close to popular tourist destinations and being tourist attractions themselves too. The only exception is Tacaná, split in half by the borderline between Mexico and Guatemala, in a remote location almost 200 km to the west of Guatemala City. Their recorded explosive behavior and lahar generation potential could also have a large impact in important areas, as the volcanoes in the first threat group. The volcanoes in this group are currently non-monitored. In the case of Atitlán and Tolimán volcanoes, both have the potential to generate a seiche in Lake Atitlán in case that a pyroclastic flow, lahar or a debris avalanche reaches the shores of such enclosed body of water.

The group of moderate threat comprise a group of three volcanoes: Tecuamburro, Tahual and Ixtepeque, all located in the southeast region of the country. The first of the three currently show a sustained hydrothermal activity, while the other two were last active during an unknown period in the Holocene. Stratovolcanoes with explosive behavior such as these could cause a larger disruption in case of an eruption, specially the obsidian domes of Ixtepeque, but their hazard and threat scores cannot be higher without knowing better the ages of their activity first.

The group of low threat comprise a group of ten volcanoes: Jumaytepeque, Tajumulco, Zunil, Siete Orejas, Suchitán, Moyuta, Ipala+Monte Rico, Amayo-Las Flores, Chingo and Cuilapa-Barberena. Consisting mainly of stratovolcanoes with suspected Holocene activity and stratovolcanoes of Pleistocene age with active hydrothermal manifestations, as well as a volcanic field with active hydrothermal systems, the volcanoes of this group are scattered through both the western and eastern regions of the country. Tajumulco, despite being the tallest volcano in Central America and the Caribbean, remains in this threat group mainly because of the complete lack of the basic knowledge about it: no geological map, ages or historical accounts of activity. Just like the volcanoes in the moderate threat group, this ten volcanoes are currently non-monitored as well.

The group of the very low threat comprise a group of three volcanic fields: Cerro Santiago-Jutiapa Group, Chiquimula and Quezaltepeque. Their eruptive history remain poorly understood and the explosivity associated to the cinder cones and lava flows produced is very low. The three volcanic fields are located in the eastern region of the country and are currently non-monitored.

Most of the scores given in this ranking are actually the minimum ones for many of the volcanoes outside the high and very high threat groups, given the fact that their basic geology, past behavior and ages of activity are poorly known. This is discussed in the results of the knowledge gap analysis.

It is important to make clear that the volcanoes threat ranking it is not a guide to the next volcano likely to erupt, but a tool to identify targets and elaborate work plans for the monitoring and research efforts of INSIVUMEH and collaboration partners.

Monitoring gap analysis results

The threat ranking analysis results allowed us to group the 25 active and potentially active Guatemalan volcanoes into the very high, high, medium, low and very low threat levels. Each of this threat level should be linked to a specific monitoring level, which translates into the type and number of instruments needed for each volcano.

The following table shows the required instruments for each of the monitoring levels, related to the threat score groups, following the suggestions from Moran et. al. 2008.

Table 6. Monitoring level required instruments

MONITORING LEVEL	THREAT LEVEL	REQUIRED INSTRUMENTS
LEVEL 1 MINIMAL MONITORING	VERY LOW THREAT	Five seismic stations within 200 km from volcano, including two located within 50 km. Occasional InSAR and GPS surveys. Baseline water chemistry/temperature measurements every 10-20 years. LAHARZ simulations for the volcano drainages. Daily scans of routinely collected satellite imagery data
LEVEL 2 LIMITED MONITORING FOR CHANGE DETECTION	LOW THREAT	Five seismic stations within 50 km from the volcano, including two within 10 km. Periodic (1-10 yrs) GPS and InSAR, one continuous mode GPS station within 10 km. Level 1 Hidrology surveys every 5-10 years. Level 1 remote sensing. Baseline fumarole measurements every 5-10 yrs, airborne plume measurements if plume exists, continuous measurements where appropriate.
LEVEL 3 BASIC REAL-TIME MONITORING	MEDIUM THREAT	Six to eight seismic stations within 20 km from the volcano, including two or three within 5 km (at least one broadband). Continuous (7-10) GPS stations and borehole tiltmeters (4-6) within 5-10 km, InSAR, GPS, leveling or microgravity surveys every 1-5 years. Level 2 hydrology plus lakes/springs/streams measurements every 3-5 years. Level 1 remote sensing plus one telemetered camera. Level 2 gas monitoring, plus fumarole and airborne measurements every 3-5 years.
LEVEL 4 WELL MONITORED	HIGH AND VERY HIGH THREAT	Twelve to twenty seismic stations within 20 km from the volcano, two or three within 5 km as well as six broadband stations with two of them within 5 km too. One strong motion station within 5 km and at least two infrasonic stations with two sensors per station. Continuous (16-20) GPS stations, eight of them and 5-10 borehole tiltmeters within 5-10 km, one continuous gravimeter near volcanic center, monthly InSAR surveys. Level 3 hydrology, plus lakes/springs/streams measurements every 1-5 years and continuous probes at two or three volcanoes. Level 1 remote sensing, plus two or three telemetered cameras and one low-light camera. Level 3 gas monitoring, plus fumarole measurements every 1-2 years, annual airborne measurements, long term deployment or measurement surveys at volcanoes with adequate degassing

The monitoring gap, which reflects how well or how poorly a volcano is monitored, is obtained by comparing the required and the current monitoring status of each volcano, based in the methodology proposed by Ewert et. al. 2005. A table with the names of the volcanoes, their threat level, required and current monitoring level, as well as the monitoring gap, is shown next.

As INSIVUMEH has instrumentation just for the three currently active volcanoes, the other 22 in the list have a full gap between the current and the required monitoring levels according to their threat group.

Table 7. Monitoring gap analysis results

NUMBER (GVP)	NAME	THREAT LEVEL	REQUIRED MONITORING LEVEL	CURRENT MONITORING LEVEL	MONITORING GAP
342030	Santa Maria/Santiago	VERY HIGH	4	2	2
342090	Fuego				
342110	Pacaya				
342060	Atitlán	HIGH		0	4
342040	Cerro Quemado				
341130	Tacaná				
342080	Acatenango/Yepocapa				
342070	Tolimán				
342100	Agua				
342120	Tecuamburro				
342141	Tahual	MEDIUM	3	0	3
342180	Ixtepeque				
342190	Ipala+Monte Rico				
342020	Tajumulco	LOW	2	0	2
342160	Suchitán				
342130	Moyuta				
342121	Jumaytepeque				
342800	Zunil				
342809	Siete Orejas				
342140	Amayo-Las Flores				
342170	Chingo				
342111	Cuilapa Barberena				
342150	Cerro Santiago-Jutiapa Group	VERY LOW	1	0	1
342200	Chiquimula Volcanic Field				
342210	Quezaltepeque Volcanic Field				

All of the high and very high threat volcanoes, Santa María/Santiago, Fuego, Pacaya, Atitlán, Cerro Quemado, Tacaná, Acatenango/Yepocapa, Tolimán and Agua, should have the instrumentation required to meet the criteria of a Level 4, Well monitored volcano, with the ability to track detailed changes in real-time and to develop, test, and apply models of ongoing and expected activity.

The volcanoes in the medium threat group should also be addressed, starting to reduce their monitoring gap, with the development of a regional network of seismic monitoring, or well, approach level 2 monitoring, with the installment of near-field seismic stations for this volcanoes. Low and very low threat volcanoes are not priorities at this time for instrumentation.

The instrumentation requirements described above are very unlikely to be met by INSIVUMEH in the short term, given that even if just the high and very high threat volcanoes (9 in total) were to be supplied in concordance with level 4 monitoring, exceeding the institution's capacity as well as the fellow cooperation agencies too.

In order to set a baseline to start from, Volcanology team at INSIVUMEH set a minimum/desired instrumentation requirement for the volcanoes of each of the threat/monitoring levels, from which the improvement/completion of instrumentation for each volcano following the requirements of Moran et. al. 2008 could be achieved in the mid to long term window frame. This desired or minimum instrumentation requirements is shown in the following table.

Table 8. Adapted monitoring levels required instruments

MONITORING LEVEL	THREAT GROUPS	REQUIRED INSTRUMENTS
LEVEL 1 MINIMAL MONITORING	VERY LOW: Cerro Santiago/Jutiapa Group, Chiquimula and Quezaltepeque Volcanic Fields	One three-component seismometer within 10 km of the volcano. Yearly gas-sampling campaigns. Equipment for yearly baseline water/fumarole physical and chemical parameters. Drones and computers for yearly DEM's, LAHARZ simulations and routinary satellite-images analysis to detect morphological changes.
LEVEL 2 LIMITED MONITORING FOR CHANGE DETECTION	LOW: Jumaytepeque, Tajumulco, Zunil, Siete Orejas, Suchitán, Moyuta, Ipala, Amayo-Las Flores, Chingo, Cuilapa Barberena	Two three-component seismometer within 10 km of the volcano. Portable Multigas station for monthly gas surveys. Equipment for semiannually baseline water/fumarole physical and chemical parameters. Drones and computers for semiannually DEM's, LAHARZ simulations and routinary satellite-images and INSAR analysis to detect morphological changes.
LEVEL 3 BASIC REAL-TIME MONITORING	MEDIUM: Tecuamburro, Tahual, Ixtepeque	One three-component seismometer within 20 km of the volcano and three within 10 km of it. 3 real-time GPS stations. Equipment for monthly baseline water/fumarole physical and chemical parameters. Portable Multigas station for monthly gas surveys and 2 real-time SCAN-DOAS. Two weather stations. One multiparametric station (seismic, webcam, infrasound, pluviometer) per watershed around the volcano for lahar monitoring. Drones and computers for monthly DEM's, LAHARZ simulations and routinary satellite-images (public and private) and INSAR analysis to detect morphological changes, ash dispersion and radiance estimations at eruptive vents. 2 webcams to aid with visual monitoring.
LEVEL 4 WELL MONITORED	HIGH AND VERY HIGH: Santa María/ Santiaguito, Fuego, Pacaya, Atitlán, Cerro Quemado, Tacaná, Acatenango/Yepocapa, Tolimán, Agua	Two three-component seismometer within 20 km of the volcano, three within 10 km and three within 5 km of it. Two six-sensors infrasound arrays in the locations of the two seismometers within 20 km of the volcano. 5 real-time GPS stations and one tiltmeter. Equipment for monthly baseline water/fumarole physical and chemical parameters. Portable Multigas station for monthly gas surveys and 3 real-time SCAN-DOAS, UV camera in real time. 4 weather stations. Two multiparametric station (seismic, webcam, infrasound, pluviometer) per watershed (high and low areas) around the volcano for lahar monitoring. Drones and computers for monthly DEM's (edifice and ravines), LAHARZ simulations and routinary satellite-images (public and private) and INSAR analysis to detect morphological changes, ash dispersion and radiance estimations at eruptive vents. 2 webcams to aid with visual monitoring and 2 thermal cameras in real time.

Knowledge gap analysis results

The geology and eruptive history are the fundamental basis for assigning hazard scores to the volcanoes in the relative threat ranking, as well as many other knowledge areas. For most of the volcanoes, the assigned scores are actually the minimum ones, derived from the fact that just the minimum set of data was available for them, from a series of limited sources.

This sources include a limited coverage of geological sheets with 1:50,000 scales or larger detail for most of the volcanoes, no hazard maps and eruptive history but for the historically active ones, and a disproportionate amount of scientific publications, abundant for a small group and almost non-existent for the rest of the volcanoes.

Table 9. Knowledge gap analysis results

NUMBER (GVP)	NAME	HAZARD SCORE	THREAT GROUP	KNOWLEDGE SCORE	KNOWLEDGE GAP
342030	Santa Maria/Santiago	19	VERY HIGH	25	26
342090	Fuego	17		28	18
342110	Pacaya	16		27	21
342060	Atitlán	14	HIGH	12	65
342040	Cerro Quemado	14		12	65
341130	Tacaná	14		14	59
342080	Acatenango/Yepocapa	12		11	68
342070	Tolimán	10		6	82
342100	Agua	8		10	71
342120	Tecuamburro	9	MEDIUM	6	82
342141	Tahual	7		3	91
342180	Ixtepeque	7		4	88
342121	Jumaytepeque	5	LOW	5	85
342020	Tajumulco	5		1	97
342800	Zunil	5		5	85
342809	Siete Orejas	5		4	88
342160	Suchitán	5		3	91
342130	Moyuta	5		3	91
342190	Ipala+Monte Rico	5		3	91
342140	Amayo-Las Flores	4		3	91
342170	Chingo	4		3	91
342111	Cuilapa Barberena	5		3	91
342150	Cerro Santiago-Jutiapa Group	2	VERY LOW	4	88
342200	Chiquimula Volcanic Field	2		4	88
342210	Quezaltepeque Volcanic Field	2		3	91

The table above shows the volcano's name, hazard score, threat group, knowledge score and the knowledge gap, calculated as the difference between the maximum score possible (34) and the knowledge score of each volcano. This gap is expressed as a percentage.

The scores obtained from this knowledge analysis show that there is a significant lack of the basic understanding about most of the Guatemalan volcanoes. Except for the three with ongoing eruptive activity, the knowledge gap is above 50% for all the other volcanoes. Those that haven't been active during historical times and/or where the age of last eruption is unknown or a detailed geological map does not exist can score as much as 97% of knowledge gap. A detailed table of the knowledge gap factors and their scores can be found in the appendixes.

The two apparently most complete knowledge areas are the petrology and geological maps for the volcanoes, with 84% and 61% of completion respectively, while the less complete are conceptual models, geodesy, event trees and emergency protocols, with 6, 5, 2 and 0 percent. The rest of areas remain below the 50% of completion.

Priority targets and future activities

The volcanoes in the very high, high and medium threat groups are the main targets in a short to medium term planning. The volcanoes in the low and very low threat groups does not represent an urgency but should be included in the long term planning to be incorporated into a monitoring and research program as well.

The highest priority targets three currently erupting and very high threat volcanoes, Santa María/ Santiaguito, Fuego and Pacaya. Actions should be taken in order to improve their instrumentation network (seismic, infrasound, webcams) in concordance with the required monitoring level and developing more disciplines as volcanic gas and deformation. Despite the high level of knowledge for this volcanoes, their conceptual models, event trees, hazard maps, remote sensing must be constantly updated.

Also as high priority targets, Atitlán, Cerro Quemado and Agua volcanoes, given their proximity to very populated and/or visited areas and the relatively easy access to installation sites for the instruments and the setup of data communication to INSIVUMEH headquarters. This volcanoes are ideal targets for research efforts that can improve the knowledge of them, not only by reconstructing their eruptive history but, by gathering valuable data needed to run simulations that will aid in the elaboration of modern hazard maps too.

Additional high priority targets include Tacaná, Acatenango/Yepocapa, Tolimán, Tecuamburro, Tuhual and Ixtepeque, but they will be addressed once that the research and monitoring capabilities are considerably improved.

INSIVUMEH priority targets are distributed and dispersed throughout Guatemala's territory. The creation of additional headquarters of INSIVUMEH in the western and eastern segments of the volcanic front would efficiently enhance the achievement of the monitoring requirements.

In order to carry out the research needed to improve the information about the geology and eruptive history of these volcanoes, as well to develop their instrumentation network and include them in a permanent and full operational monitoring program, investments should be made in increasing the professional, technological and financial capabilities of the volcanology workgroup at INSIVUMEH.

Eventually, the 25 volcanoes listed in this ranking should be incorporated in the monitoring program that includes not only the instrumental data acquisition, processing and storage, but also their individual and updated hazard assessments.

The results of the different analysis as well as the text presented in this report has to be reviewed and approved by the volcanology workgroup and the authorities at INSIVUMEH for its formal publication as well for the implementation of the work lines resulting from this initiative.

The implementation framework to approach the priority targets need to be discussed, designed and executed by the volcanology, geology and electronics sections of the Geophysical Research and Services department of INSIVUMEH, with the aid of the work groups from VDAP-USGS, OVDAS-SERNAGEOMIN, MichiganTech, Bristol, Liverpool and Edinburgh universities, as well with other institutions that could be approached by INSIVUMEH authorities to establish cooperation agreements.

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APPENDIX 1

HAZARD FACTORS SCORES AT THE GUATEMALAN VOLCANOES

NUMBER	NAME	LATITUDE	LONGITUDE	TYPE CODE	MAXIMUM VEI CODE	VEI≥3 IN LAST 500 YEARS	VEI≥3 IN LAST 5000 YEARS	ERUPTION RECURRENCE	HOLOCENE PDCS	HOLOCENE LAHARS	HOLOCENE LAVA FLOWS	HYDROTHERMAL EXPLOSION POTENTIAL	SECTOR COLLAPSE POTENTIAL	SEISMIC SOURCE	GROUND DEFORMATION	FUMAROLIC DEGASSING	HAZARD SCORE
342030	Santa Maria/ Santiaguito	14.756	-91.550	1	2	1	1	4	2	2	1	1	1	1	1	1	19
342090	Fuego	14.475	-90.880	1	1	1	1	4	2	2	1	1	1	1	0	1	17
342110	Pacaya	14.380	-90.600	1	1	1	0	4	1	2	2	0	1	1	1	1	16
342060	Atitlán	14.584	-91.186	1	1	1	0	3	2	2	1	1	1	0	0	1	14
342040	Cerro Quemado	14.797	-91.519	1	1	0	0	3	2	2	2	1	1	0	0	1	14
341130	Tacaná	15.131	-92.100	1	1	1	1	2	2	1	1	1	1	1	0	1	14
342080	Acatenango/ Yepocapa	14.500	-90.870	1	1	1	0	3	1	1	1	1	1	0	0	1	12
342070	Tolimán	14.613	-91.189	1	1	0	0	1	0	2	2	1	1	0	0	1	10
342100	Agua	14.465	-90.743	1	1	0	0	1	0	2	0	1	1	0	0	1	8
342120	Tecuamburro	14.156	-90.407	1	1	0	0	2	1	1	0	1	1	0	0	1	9
342141	Tahual	14.437	-89.905	1	1	0	0	1	1	1	1	1	0	0	0	0	7
342180	Ixtepeque	14.424	-89.684	1	1	0	0	2	1	0	1	1	0	0	0	0	7
342121	Jumaytepeque	14.340	-90.270	1	1	0	0	1	0	2	0	0	0	0	0	0	5
342020	Tajumulco	15.043	-91.904	1	1	0	0	1	0	0	0	0	1	0	0	1	5
342800	Zunil	14.740	-91.450	1	0	0	0	0	0	1	0	1	1	0	0	1	5
342809	Siete Orejas	14.815	-91.618	1	0	0	0	0	0	1	0	1	1	0	0	1	5
342160	Suchitán	14.399	-89.779	1	1	0	0	1	0	0	1	0	1	0	0	0	5
342130	Moyuta	14.030	-90.095	1	1	0	0	1	0	0	0	1	0	0	0	1	5
342190	Ipala+Monte Rico	14.556	-89.640	1	1	0	0	1	0	0	1	1	0	0	0	0	5
342140	Amayo-Las Flores	14.307	-89.996	1	1	0	0	1	0	0	1	0	0	0	0	0	4
342170	Chingo	14.118	-89.727	1	1	0	0	1	0	1	0	0	0	0	0	0	4
342111	Cuilapa Barberena	14.330	-90.400	0	0	0	0	2	1	0	1	1	0	0	0	0	5
342150	Cerro Santiago- Jutiapa Group	14.339	-89.870	0	0	0	0	1	0	0	1	0	0	0	0	0	2
342200	Chiquimula Volcanic Field	14.837	-89.549	0	0	0	0	1	0	0	1	0	0	0	0	0	2
342210	Quezaltepeque Volcanic Field	14.641	-89.373	0	0	0	0	1	0	0	1	0	0	0	0	0	2

Note: Values in shaded cells are equivalent to either No Data or assigned in function of volcano type.

TYPE CODE (0-1)

If volcano type is cinder cone, basaltic field, small shield, or fissure vents, score will be 0

If volcano type is stratocone, lava domes, complex volcano, maar or caldera, score will be 1

MAXIMUM VEI (0-3)

If maximum known VEI is equal or less than 2, score will be 0.

If maximum known VEI is 3 or 4, score will be 1.

If maximum known VEI is 5 or 6, score will be 2.

If maximum known VEI is 7, score will be 3.

If no maximum VEI is listed by GVP and if volcano type is 0, score will be 0.

If no maximum VEI is listed by GVP but volcano type is 1, score will be 1.

If no known Holocene eruptions and the volcano is not a silicic caldera system, score will be 0.

VEI≥3 IN LAST 500 YEARS (0-1)

If there is recorded explosive activity with a VEI equal or higher than 3 within the past 500 years, score will be 1; else will be 0.

VEI≥3 IN LAST 5000 (0-1)

If there is recorded explosive activity with a VEI equal or higher than 4 within the past 5000 years, score will be 1; else will be 0.

ERUPTION RECURRENCE (0-4)

Eruption interval is calculated by the division of the number of years from the oldest to the most recent eruptive event listed by GVP by the number of eruptive events listed by that same source.

For example: Oldest eruption at 100 years ago, most recent eruption this year, $N(\text{years})=100$;

number of eruptive events listed at 10, $N(\text{eruptions})=10$. Then eruptive interval would be

$EI=(N(\text{years})/N(\text{events}) = 100/10 = 10$. Eruption recurrence intervals are scored as follows:

If eruption interval is 1 – 99 years, score will be 4.

If eruption interval is 100 – 1,000 years, score will be 3.

If eruption interval is 1,000 to 5,000 years, score will be 2.

If eruption interval is 5,000 – 10,000 years, or if no Holocene eruptions but it is a large-volume restless silicic system that has erupted in the last 100,000 years, score will be 1.

If no known Holocene eruption, score will be 0.

HOLOCENE PDCS (0-2)

If there are records of Holocene pyroclastic density currents (PDC's) originating from the volcano, score will be 1.

If the PDC's traveled far enough to reach a currently inhabited place, score will be 2.

If no Holocene PDC's originated from the volcano, score will be 0.

HOLOCENE LAHARS (0-2)

If there are records of Holocene lahars originating from the volcano, score will be 1.

If the lahars traveled far enough to reach a currently inhabited place, score will be 2.

If no Holocene lahars originated from the volcano, score will be 0.

HOLOCENE LAVA FLOWS (0-2)

If there are records of Holocene lava flows originating from the volcano, score will be 1.

If the lava flows traveled far enough to reach a currently inhabited place, score will be 2.

If no Holocene lava flows originated from the volcano, score will be 0.

HYDROTHERMAL EXPLOSION POTENTIAL (0-1)

If the volcano has had Holocene phreatic explosive activity, and/or the volcano has thermal features that are extensive enough to pose a potential for explosive activity, score will be 1.

SECTOR COLLAPSE POTENTIAL (0-1)

If the volcano has produced a sector collapse in Quaternary time and has rebuilt its edifice, or, has high relief, steep flanks and demonstrated or inferred alteration, score will be 1.

SEISMIC SOURCE (0-1)

If there is recorded seismic unrest since the last eruption within 20 km of the volcanic edifice, score will be 1. If not, either because the records were lost or the volcano has never been monitored with seismic instruments before, score will be 0.

GROUND DEFORMATION (0-1)

If there is recorded ground deformation unrest since the last eruption, score will be 1. If not, either because the records were lost or the volcano has never been monitored with ground deformation instruments before, score will be 0.

FUMAROLIC DEGASSING (0-1)

If there are recorded heat sources and/or magmatic gases, or well, observed fumaroles since the last eruption, score will be 1. If not, either because the records were lost or the volcano has never been monitored with thermal or gas instruments before, score will be 0.

APPENDIX 2

EXPOSURE FACTORS SCORES AT THE GUATEMALAN VOLCANOES

NUMBER	NAME	LATITUDE	LONGITUDE	LOG10 OF POPULATION IN DISTAL AND PROXIMAL AREAS	HISTORICAL DEATHS	HISTORICAL EVACUATIONS	LOCAL AVIATION EXPOSURE	REGIONAL AVIATION EXPOSURE	ENERGY INFRASTRUCTURE	TRANSPORTATION INFRASTRUCTURE	MAJOR DEVELOPMENT OR SENSITIVE AREA	HAZARD SCORE
342030	Santa Maria/ Santiaguito	14.756	-91.550	12.010	1	1	2	4.102	1	1	1	23.112
342090	Fuego	14.475	-90.880	11.778	1	1	2	4.260	1	1	1	23.038
342110	Pacaya	14.380	-90.600	11.959	1	1	2	4.260	1	1	1	23.219
342060	Atitlán	14.584	-91.186	11.362	1	0	2	4.342	1	1	1	20.704
342040	Cerro Quemado	14.797	-91.519	11.759	0	0	2	4.334	1	1	1	21.093
341130	Tacaná	15.131	-92.100	10.680	0	1	2	4.089	1	1	1	20.769
342080	Acatenango/ Yepocapa	14.500	-90.870	11.867	0	0	2	4.260	1	1	1	21.127
342070	Tolimán	14.613	-91.189	11.231	1	0	2	4.342	1	1	1	21.573
342120	Tecuamburro	14.156	-90.407	11.061	0	0	2	4.250	1	1	1	20.311
342100	Agua	14.465	-90.743	12.362	1	0	2	4.260	1	1	1	22.622
342141	Tahual	14.437	-89.905	11.046	0	0	2	4.356	1	1	1	20.402
342180	Ixtepeque	14.424	-89.684	10.621	0	0	2	4.356	1	1	1	19.977
342121	Jumaytepeque	14.340	-90.270	10.936	1	0	2	4.322	1	1	1	21.258
342020	Tajumulco	15.043	-91.904	11.617	0	0	2	4.102	1	1	1	20.719
342800	Zunil	14.740	-91.450	11.352	0	0	2	4.342	1	1	1	20.694
342809	Siete Orejas	14.815	-91.618	11.498	0	0	2	4.102	1	1	1	20.600
342160	Suchitán	14.399	-89.779	11.050	0	0	2	4.356	1	1	1	20.406
342130	Moyuta	14.030	-90.095	10.718	0	0	2	4.314	1	1	1	20.032
342190	Ipala+Monte Rico	14.556	-89.640	10.023	0	0	2	4.356	1	1	1	19.379
342140	Amayo-Las Flores	14.307	-89.996	10.982	0	0	2	4.322	1	1	1	20.304
342170	Chingo	14.118	-89.727	10.078	0	0	2	4.348	1	1	1	19.426
342111	Cuilapa Barberena	14.330	-90.400	10.838	0	0	1	0.000	1	1	1	14.838
342150	Cerro Santiago- Jutiapa Group	14.339	-89.870	10.978	0	0	0	0.000	1	1	1	13.978
342200	Chiquimula Volcanic Field	14.837	-89.549	10.935	0	0	0	0.000	1	1	1	13.935
342210	Quezaltepeque Volcanic Field	14.641	-89.373	10.544	0	0	0	0.000	1	1	1	13.544

LOG10 OF POPULATION IN DISTAL AND PROXIMAL AREAS

Obtained from the numbers shown in appendix 4. When a municipality falls partially or completely inside the proximal and/or distal radius of a volcano, the whole population of the municipality adds to the sum of people living around the volcanic edifice. The numbers come from the results of the National Population and Household Census conducted in 2018.

HISTORICAL DEATHS (0-1)

If the eruptive and/or laharcic activity has resulted in fatalities, score will be 1. If not, score will be 0.

HISTORICAL EVACUATIONS (0-1)

If evacuations have been made at a volcano, due to an eruptive event and/or lahars, score will be 1. If not, score will be 0.

LOCAL AVIATION EXPOSURE (0-2)

If any type volcano is within 50 km of a jet-service airport, score will be 1; if a Type 1 volcano is within 300 km of a jet-service airport, score= 1; if a Type 1 volcano is within 300 km of a major international airport, score= 2; if none of these criteria are met, score= 0.

REGIONAL AVIATION EXPOSURE

This score is based on the log10 of approximate daily passenger traffic in each of the international airports that could be affected by the volcano, according to its type and the score obtained in the local aviation exposure.

ENERGY INFRASTRUCTURE (0-1)

Is there power infrastructure (power generation/transmission/distribution for electricity, oil, or gas) within 30 km from the volcano edifice, or in an area frequently downwind of the volcano and close enough to be considered at some risk? If yes, score will be 1, if not, will be 0.

TRANSPORTATION INFRASTRUCTURE (0-1)

Is there transportation infrastructure (port facilities, rail lines, major roads) within 30 km from the volcano edifice, or in an area frequently downwind of the volcano and close enough to be considered at some risk? If yes, score will be 1, if not, will be 0.

MAJOR DEVELOPMENT OR SENSITIVE AREA (0-1)

Are there major developments or sensitive areas threatened like national park facilities, flood control projects, government facilities, developed tourist/recreation facilities, manufacturing or other significant economic activity? If yes, score will be 1, if not, will be 0.

APPENDIX 3

KNOWLEDGE FACTORS SCORES AT THE GUATEMALAN VOLCANOES

NUMBER	NAME	GEOLOGIC MAP	HAZARD MAP	GIS DATABASE	ERUPTIVE HISTORY	CONCEPTUAL MODEL	GEOCHEMISTRY	TEPHRA STRATIGRAPHY	PETROLOGY	SEISMIC RECORD	GEODETTIC RECORD	REMOTE SENSING ANALYSIS	EVENT TREE	PUBLIC OUTREACH	EMERGENCY PROTOCOL	KNOWLEDGE SCORE	KNOWLEDGE AS (%)
342030	Santa Maria/ Santiaguito	3	2	2	2	1	2	2	2	4	1	2	0	2	0	25	3
342090	Fuego	3	2	2	2	2	2	2	2	4	1	3	1	2	0	28	3
342110	Pacaya	3	2	2	2	0	2	2	2	4	2	3	0	3	0	27	3
342060	Atitlán	3	2	0	2	0	1	2	2	0	0	0	0	0	0	12	3
342040	Cerro Quemado	3	2	1	2	0	1	1	2	0	0	0	0	0	0	12	3
341130	Tacaná	3	2	0	0	0	2	1	2	4	0	0	0	0	0	14	3
342080	Acatenango/ Yepocapa	2	1	0	2	0	1	2	2	1	0	0	0	0	0	11	2
342070	Tolimán	2	0	0	0	0	1	1	2	0	0	0	0	0	0	6	2
342120	Tecuamburro	3	0	0	1	0	2	1	2	1	0	0	0	0	0	10	3
342100	Agua	2	1	0	0	0	0	1	1	1	0	0	0	0	0	6	2
342141	Tahual	1	0	0	0	0	0	0	2	0	0	0	0	0	0	3	1
342180	Ixtepeque	1	0	0	0	0	1	0	2	0	0	0	0	0	0	4	1
342121	Jumaytepeque	2	0	0	0	0	0	1	2	0	0	0	0	0	0	5	2
342020	Tajumulco	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
342800	Zunil	1	0	0	0	0	2	1	1	0	0	0	0	0	0	5	1
342809	Siete Orejas	2	0	0	0	0	0	1	1	0	0	0	0	0	0	4	2
342160	Suchitán	1	0	0	0	0	0	0	2	0	0	0	0	0	0	3	1
342130	Moyuta	1	0	0	0	0	0	0	2	0	0	0	0	0	0	3	1
342190	Ipala+Monte Rico	1	0	0	0	0	0	0	2	0	0	0	0	0	0	3	1
342140	Amayo-Las Flores	1	0	0	0	0	0	0	2	0	0	0	0	0	0	3	1
342170	Chingo	1	0	0	0	0	1	0	1	0	0	0	0	0	0	3	1
342111	Cuilapa Barberena	2	0	0	0	0	0	0	1	0	0	0	0	0	0	3	2
342150	Cerro Santiago- Jutiapa Group	1	0	0	0	0	1	0	2	0	0	0	0	0	0	4	1
342200	Chiquimula Volcanic Field	2	0	0	0	0	1	0	1	0	0	0	0	0	0	4	2
342210	Quezaltepeque Volcanic Field	2	0	0	0	0	0	0	1	0	0	0	0	0	0	3	2

GEOLOGIC MAP (0-3)

No map at any scale, score will be 0. Map at 1:250,000 scale, score will be 1. Map at 1:50,000 map, score will be 2. Map at 1:25,000 or smaller scale, score will be 3.

HAZARD MAP (0-3)

No map, score will be 0. Map for at least one type of hazard, score will be 1. Map for multiple hazards, score will be 2. Map for multiple hazards updated to present state, score will be 3.

GIS DATABASE (0-2)

No database available, score will be 0. At least one dataset, score will be 1. Datasets containing all the needed vector and raster files, score will be 2.

ERUPTIVE HISTORY (0-2)

No data at all (but Holocene suspected), score will be 0. At least last eruption year is known, score will be 1. If the ages of the last and at least one of the prior eruptions are known, score will be 2.

CONCEPTUAL MODEL (0-2)

Nothing at all, score will be 0. At least one feature of the eruptive dynamics is known, score will be 1. If one or more models are proposed, score will be 2.

GEOCHEMISTRY (0-2)

No data, score will be 0. At least one study on rocks, water or gases, score will be 1. If there are full datasets on the geochemistry of it rocks, water or gases, score will be 2.

TEPHRA STRATIGRAPHY (0-2)

No reconnaissance of any product, score will be 0. Reconnaissance of products at regional level, score will be 1. Reconnaissance of products at local level, score will be 2.

PETROLOGY (0-2)

No data, score will be 0. General description of rock types, score will be 1. Detailed descriptions and analysis, score will be 2.

SEISMIC RECORD (0-4)

No data, score will be 0. Regional data, score will be 1. Data from short-lived surveys, score will be 2. Data from long-lived surveys, score will be 3. Data from real time "permanent" network, score will be 4.

GEODETTIC RECORD (0-3)

No data, score will be 0. Data from short-lived surveys, score will be 1. Data from long-lived surveys, score will be 2. Data from real time "permanent" network, score will be 3.

REMOTE SENSING (0-3)

No data, score will be 0. Available data, but not processed or published, score will be 1. Processed data, regardless of publication status, score will be 2. Processed and updated data, regardless of publication status, score will be 3.

EVENT TREE (0-2)

Never implemented, score will be 0. Implemented but not updated, score will be 1. Implemented and updated, score will be 2.

PUBLIC OUTREACH (0-3)

Not existing, score will be 0. Existed but not continued to date, score will be 1. Limited outreach to the community, score will be 2. Extended outreach to the communities around the volcano with periodical educational campaigns, score will be 3.

EMERGENCY PROTOCOL (0-1)

Nonexistent, score will be 0. If it exists for the specific volcano, score will be 1.

APPENDIX 4

POPULATION AROUND GUATEMALAN VOLCANOES

NUMBER	NAME	LATITUDE	LONGITUDE	HEIGHT (M.A.S.L.)	RELATIVE HEIGHT (METERS)	DISTAL RADIUS (KM)	PROXIMAL RADIUS (KM)	DISTAL POPULATION	PROXIMAL POPULATION
342030	Santa Maria/ Santiaguito	14.756	-91.550	3772	2400	20	15	1249472	818806
342090	Fuego	14.475	-90.880	3763	2600	20	15	897811	668625
342110	Pacaya	14.380	-90.600	2552	1300	20	10	2315906	392607
342040	Cerro Quemado	14.797	-91.519	3197	1300	20	10	1113071	515506
341130	Tacaná	15.131	-92.100	4092	1300	20	10	336395	142428
342080	Acatenango/ Yepocapa	14.500	-90.870	3976	2700	20	15	971976	756749
342060	Atitlán	14.584	-91.186	3597	2400	20	15	730201	315497
342070	Tolimán	14.613	-91.189	3150	1600	20	10	736802	230850
342120	Tecuamburro	14.156	-90.407	1840	1000	20	5	458276	251393
342100	Agua	14.465	-90.743	3766	2700	20	15	2109673	1091636
342141	Tahual	14.437	-89.905	1716	700	20	5	569336	195348
342180	Ixtepeque	14.424	-89.684	1292	400	20	5	446066	93633
342121	Jumaytepeque	14.340	-90.270	1815	800	20	5	554314	155791
342020	Tajumulco	15.043	-91.904	4220	3000	20	15	884543	467763
342800	Zunil	14.740	-91.450	3542	NA	20	5	1192584	188671
342809	Siete Orejas	14.815	-91.618	3370	NA	20	5	1189502	264448
342160	Suchitán	14.399	-89.779	2042	1300	20	10	442089	253591
342130	Moyuta	14.030	-90.095	1662	500	20	5	446175	117019
342190	Ipala+Monte Rico	14.556	-89.640	1650	800	20	5	272093	38766
342140	Amayo-Las Flores	14.307	-89.996	1600	600	20	5	569154	168590
342170	Chingo	14.118	-89.727	1775	800	20	5	284110	42100
342111	Cuilapa Barberena	14.330	-90.400	1458	NA	20	5	687207	100190
342150	Cerro Santiago- Jutiapa Group	14.339	-89.870	1260	NA	20	5	566096	167994
342200	Chiquimula Volcanic Field	14.837	-89.549	1192	NA	20	5	500723	171929
342210	Quezaltepeque Volcanic Field	14.641	-89.373	1200	NA	20	5	375278	93324

APPENDIX 5 SPECIFIC REFERENCES FOR EACH VOLCANO

2018 Population Census Results: <https://www.censopoblacion.gt/explo/TabA1.xlsx>

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