SECCION

RIESGOS VOLCANICOS

PELIGROS VOLCANICOS

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VOLCANIC HAZARD

Resumen:

Los peligros volcánicos pueden ser evaluados utlizando: 1) Registros históricos, 2) el registro geológico, 3) a través del conocimiento del comportamiento general de los volcanes. Esta información es mejor presentada en mapas de zonificación de peligros volcánicos indicando peligros inmediatos y potenciales para flujos de lava y flujos piroclásticos, y otros tipos de erupciones volcánicas.

Los volcanes de pendientes moderadas presentan el riesgo más elevado porque sus productos son ampliamente dispersados durante sus erupciones. Los valles de los ríos pueden actuar como canales para lahares, permitiendo el transporte de los materiales fragmentarios más allá del área alrededor del volcán. Las erupciones de ignimbritas son el tipo de erupciones volcánicas más peligrosas debido a que causan la devastación de grandes áreas. Los volcanes que hacen erupción raramente ofrecen un problema especial porque por lo general no son observadas.

En Costa Rica hay muchas zonas de peligros: los volcanes Poás e Irazú han producido numerosos depósitos freáticos; San José y el Valle Central están cubiertos por ignimbritas y coladas de lava; depósitos de nubes ardientes se encuentran alrededor del Volcán Arenal. Existen numerosos volcanes jóvenes en Costa Rica, que como el Arenal, pueden reactivarse.

PART 1. VOLCANIC HAZARD IN GENERAL.

1. How is volcanic hazard assessed? There are three information sources.

(a) The historical record of eruptions of a volcano, as a guide to possible future activity. Generally this record covers only the past few hundred years.

(b) The record of eruptions of a volcano determined by stratigraphic mapping/volcanological interpretation of the volcanic products (each volcanic eruption leaves a layer which, when deciphered, reveals the characteristics of the eruption). Generally this record covers a much more extended period and is correspondingly a more reliable guide to possible future behaviour than (a).

(c) Knowledge of the behaviour of volcanoes in general.

To give an example of (a), the historical record of Irazu since 1700 is one of fairly frequent ash-producing explosive eruptions. The probability seems high that eruptions of a similar type and on a similar scale will take place at a comparable frequency in future. To give an example of (b), the

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record of the past ca. 40.000 years determined by stratigraphic study of pumice deposits from Taupo and Okataina rhyolitic volcanoes (New Zealand) reveals that major explosive eruptions occur roughly once per 1000 years, the latest being 700 and 1800 years ago, and similar infrequent but large explosive outbreaks may be expected in future. An example where general knowledge of volcanoes is helpful is Mt. St. Helens. In 1980 a bulge developed on the northern side of this steep cone and this side of the cone became mechanically unstable. The consequent failure and collapse of part of the cone had devastating consequences.

2. How is information on volcanic hazard presented ? The best method is by means of volcanic hazard zone maps which delineate areas liable to specific volcanic hazards, based in part on the past record of the volcano and in part on general knowledge of volcano behaviour. There is no unique type of hazard zone map. The simplest type delimit zones of greatest danger, requiring evacuation or restricted entry should an eruption be impending, or alternatively it shows areas which are judge to be most liable to be affected for example by pyroclastic flows, surges, lava flows, mudflows, or pyroclastic falls having a thickness greater than a specified threshold. Another type takes into account the frequency or recurrence interval of specific events or (derived from that) the probability that such events will happen within a given time period. Yet another type delineates zones which shows the probability, should an eruption occur, that given effects will be experienced. Thus at Taupo there is a 0.3 probability that when an eruption occurs, pyroclastic flows will develop extendig to a radius of 30 Km from the vent.

3 Two broad types of hazard may be distinguished: inmediate, and potential. Inmediate hazard is that which recurs relatively frequently (once or more than once per century); the probability therefore is high that people may experience a hazardous event in their lifetime. Potential hazard is that which recurs relatively rarely (less than once per century). the probability is therefore low that people will experience a hazardous event in their lifetime.

These two types of hazard should be treated differently. For volcanoes which present inmediate hazard, detailed hazard zone maps should ideally be prepared delimiting the probable extent and frequency of the hazard, a volcano observatory be established to monitor the volcano closely, contingency plans be drawn up should a volcanic emergency develop, and the people be educated regarding the volcanic hazards they may have to face. It might moreover prove desirable to restrict construction or development within certain hazard zones. An example where safety features have been incorporated into the design of a construction works is the provision of gates on intake tunnels at the hydroelectric power plants near Ruapehu volcano (New Zealand) which can be closed when lahars are approaching. Consideration might be given to no-cost/low-cost measures such as the construction of buildings with a steep-pitched roof in areas that may be susceptible to pyroclastic falls, and the building of simple volcano shelters (proof against nuees ardente or pyroclastic falls) as a possible alternative to evacuation in some volcanic areas. For volcanoes which present potential hazard it is more appropriate merely to do quiet research to establish the behaviour pattern of the volcano, and to set up some kind of simple monitoring system so as to avoid the possibility of an eruption breaking out without warning.

A few general comments should be made. First, it is a principle of volcanology that the more powuerful or violent (and hence more dangerous) a volcanic event, the less impressive or conspicuous is the resulting deposit when viewed on the scale of a rock outcrop (the converse is not necessarily true). It is only when the deposit is mapped and its far-reaching nature recognised that the extent of the threat may be assessed. An example is the 1902 nuée ardente which is recorded today by a deposit only 20 cm thick in the devastated town of St. Pièrre. Again the ash thickness is less than 10 cm thick over half of the forest blow-down area of May 18th. 1980 around Mt. St. Helens, and within a few years will probably be almost totally removed by erosion.

A second general comment is that steep volcanoes are steep because their eruptions are weak and their volcanic products are piled up inmediately around the vent. and flat volcanoes are flat because their eruptions are habitually powerful or violent so that the volcanic products become widely dispersed. However even small volcanic events on steep volcanoes may be amplified by gravity. operating on the high and steep slope, into potentially dangerous events.

A third comment is that lahars pose a especial hazard because. channelled as they are by river valleys, they may present a hazard far outside the area of the volcano. For example, some prehistoric lahars of Mt. Rainier are known to have travelled km from the volcano. Note that the distance travelled is probably a rather simple function of the lahar volume.

A fourth comment is that by far the greastest volcanic hazard is that arising from ignimbrite eruption. Such an event is probably the only type which is capable effectively of temporarily "knocking out" a country the size of Costa Rica, Guatemala, North Island, New Zealand, Kyusyu, or New Britain. Apart from the devastation caused by the ignimbrite itself, disruption would be caused over a great area by the accompanying fall of co-ignimbrite ash.

A final comment is that the most insiduous type of volcanic hazard is posed by volcanoes which erupt very rarely, at intervals say of 10^3 to 10^5 years. Such volcanoes are commonly regarded as extinct ———an example is Mt. Lamington (New Guinea) which erupted unexpectantly and with great violence in 1951 ———and will thus not be watched. Eruptions which follow a long repose period tend moreover to be particulary large, powerful or violent events———examples are the plinian outburst of Somma-Vesuvius in the year 79, and the ferocious eruption of Taupo in 186 A. D. which followed nearly 500 years of quiescence.

PART 2. VOLCANIC HAZARD IN COSTA RICA

The following discussion is based on impressions gained during a brief ten-day visit to Costa Rica and should not be regarded in any way a definitive account.

1. San Jose and the Central Valley. Extensive lava flows and ignimbrite are seen in many canyon exposures near San Jose I understand that these are of the order of a million years old. A pre-ignimbrite plinian pumice fall deposit underlying the ignimbrite thickens and coarsens towards the north and east consistent with a source underlying Barva. It is possible that these extensive lava flows and ignimbrite represent a long-past period of more vigorous volcanism that will not recur, but it seems better not automatically to assume that this is so and to regard similar eruptions in future as possible, posing a potential hazard.

Resting on these older volcanoes are very prominent mudflows, and the reality of the mudflow hazard is shown by the 1964 mudflows that ravaged Cartago. I visited the mudflow source area in the Reventado Valley and saw how extremely unstable it is. A high-intensity rainfall following a period of wet weather would readly activate major mudflows perhaps much bigger than the 1963 one. It seems desirable to attempt to stabilize this mudflow source area, although it would be very costly to do so.

2. The slopes of Poas and Irazu. Repeated central vent eruptions of Poas have produced many mud-rich phreatic deposits which are up to 0.5 m thick at 8 km radius, besides strombolian deposits and a pumice fall (probably of sub-plinian type) which is 1 m thick at 12 km radius. Irazu has had many strombolian and like eruptions; similar central vent eruptions may be expected in future. They pose a hazard to life only very near the eruptive vent, but have a serious if temporary effect on the farming community, exemplified by the 1963-65 ash-falls of Irazu. There is also a mudflow hazard. Poas and Irazu volcanoes have a broad shield-like form, and my impression was that lava flows are a major component of their broad edifices, and are now mostly covered by a thick volcaniclastic veneer. One lava flow (Formación Cervantes) covering 38 km^2 and extending 13 km from vent has however been mapped on the south side of Irazu and is reatively young.

3. Arenal. The 1968 and 1975 nuées ardent originated, as do all nuées ardente, on a steep cone and may be expected to develop in future eruptions. The stratigraphic study of the earlie products of the volcano is well in hand and should reveal the full capability of the volcano.

4. Guanacaste Province. I did not reach the andesite cones of Orosi, Rincón de la Vieja, and Miravalles, so I have no comments to make on the hazards they present. I did however visit the extensive ignimbrite field on the south-west side of these cones. A number of ignimbrite eruptions (at least 5) have occurred there, and it is clear that if one such eruption were to occur today it would have very serious effects. Stratigraphic mapping of the ignimbrite field and dating of the individual ignimbrites is a necessary prelude to assessing hazard from possible future eruptions.

5. Other volcanoes. There are many volcanoes in Costa Rica which are currently not classified as

active. The outburst of Arenal in 1968 serves as a reminder of how important it is to investigate "dormant" and "extinct" volcanoes as well as the "active" ones when assessing volcanic hazards.

SECCION

QUIMICA DE GASES

BALANCE DEL S Y CL PARA CUERPOS MAGMATICOS CALCALKALINOS POCO PROFUNDOS

William I. Rose.

S and Cl Budgets for Shallow Calc-Alkalic Magma Bodies.

Resumen

El presupuesto volátil de un volcán puede ser determinado de la siguiente forma:

(1) Midiendo volátiles en inclusiones de vidrio-vapor en minerales para determinar el contenido inicial de volátiles en el magma; (2) usando equipo de sensores remotos y aparatos de muestreo de gases para determinar la cantidad de volátiles liberados durante las emisiones de bajo nivel entre las erupciones; (3) el muestreo y análisis de los materiales eruptados para determinar la concentración de volátiles retenidos en los materiales eruptados; y (4) midiendo la cantidad de volátiles liberados durante una erupción, que es lo más difícil de estimar exactamente y tiene muchas fuentes de error.

Resultados iniciales muestran para erupciones recientes del volcán Fuego, Guatemala (1974) y el Monte Santa Elena (1980), que la gran mayoría del azufre y cloro fueron liberados del magma antes y durante la erupción, a pesar de esto una porción significativa de ambos gases se libera durante los períodos de emisión baja entre erupciones.

Los presupuestos gaseosos pueden ser usados para (1) estimar el tamaño de cuerpos magmáticos superficiales; (2) detectar el arrivo de nuevo magma; (3) determinar el grado de degasificación del magma superficial; y (4) determinar cambios en la temperatura y fugacidad del oxígeno en el magma

ABSTRACT

Particularly in the case of explosive magmas, it is almost never possible to directly obtain representative samples of magmatic gases: As a result we have limited understanding of the degassing of shallow magma bodies. If a program of selected geochemical and petrographic observations can be made on volcanic samples, however, it is possible to infer much about the magma inmediately below volcanic vents.

To make an interpretation of the volatile budget we need to know at least: 1) The initial volatile concentrations of magma when it reaches the shallow reservoir, 2) the amounts of volatiles released during eruptive activity, 3) the amounts released during low-level emissions between eruptions, 4) the concentrations of volatiles remaining in the lava and ash samples after eruption and solidification. Recent analytical methods allow us to make estimates of 1 by determination and interpretation of the chemical composition of glass inclusions trapped within phenocrysts by rapid skeletal growth. 3 can be measured by using remote sensing equipment and gas sampling. 4 can be estimated by sampling and analysis of materials erupted. 2 is the hardest to accurately estimate and the sources of error in its determination are numerous. Nevertheless because of atmospheric sampling of

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eruptive clouds in recent years and because os studies of fresh pyroclastics collected before and during fallout we have some primitive estimates.

Results so far have focused on S and Cl budgets for the recent eruptions of Fuego, Guatemala (1974) and Mount St. Helens, USA (1980). The magmas lose the vast majority of S and most Cl before and during eruption. There is considerable gas from intrusive magma which participates in explosive eruptions. Mafic magma may have higher S content. A significant portion of both gases is lost during low level emissions between eruptions. The compositions of emissions varies considerably with time.

Interpretation of the gas budgets of shallow magma bodies offers information of obvious value in forecasting of activity. 1) The sizes of shallow magma bodies may be estimated. 2) The arrival of new magma from depth may be detected. 3) The degree of degassing of the shallow magma may be inferred. 4) Changing temperature and oxygen fugacity conditions in the magma body may be inferred.

EMISION DE DIOXIDO DE AZUFRE Y OTROS GASES EN EL VOLCAN MASAYA, NICARAGUA

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Sulfur Dioxide and Other Gas Emission From Masaya Volcano, Nicaragua

El volcán Masaya se encuentra en un estado de alta emisión gaseosa, produciendo 1000 a 2000 toneladas de SO_2 por día. Estos estados ocurren aproximadamente a intervalos de 25 años y se extienden por un lapso de 5 años. Lluvia ácida con un PH de 2.5–3.5, se precipita de la pluma de gas del Masaya. Filtros especiales se han colocado en el cráter y en la dirección del viento para colectar SO_2, HCl, HF, HBr, SO_4, Cl y F (ver tablas). Estos datos combinados con los datos suministrados por un espectrógrafo de correlación permiten hacer estimaciones de la emisión de gases diaria. Un analizador de gas Intersca electroquímico de SO_2 fue usado para medir las concentraciones de SO_2 y HCl en la pluma de gases. Estos datos permiten evaluar los peligros ambientales derivados de la degasificación del volcán Masaya.

A group of scientists from Dartmouth College (Stoiber, R. E., S. N. Williams, and N. M. Johnson), University of Virginia (R. A. Parnell), Stanford University (William Winner), and Colorado College (B. Huebert) are studying the geology of the Masaya Caldera, Nicaragua with special attention to the gas emission from its crater, Santiago. We are now in the midst of a period of high emission, 1000 to 2000 tons per day SO_2 and often more. These periods have recurred at aproximately 25 year intervals and last about 5 years.

Gas is almost always at ground level as it passes over a ridge which is traverse to the prevailing wind direction, 15 km downwind from the crater Concentrations of up to 1 ppm SO_2 are found here. Measurements of SO_2 flux passing over the ridge were made in 93 instances in January to March 1981. At this time an average rate of 1300 tons was indicated.

There is a wide variations in emission, greater than we have measured at other volcanoes, wich quite surely reflects a changing output at the crater. Our collaborator Johnson finds strongly acid rain falls thru plume, pH 2.5–3.5. The soil reactions are under study. Winner is describing the deleterious effects of the gas on the coffee plants.

Special filters appropriate for the determination of certain gases have been placed in the gas plume both at the crater and downwind at Llano Pacaya. The 3 filters in each set allow the weight of

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SO_2, HCl, HF (and infrequently HBr) which passes through them to be measured. The filters also collect aerosols: $SO_4^{=}$, Cl^{-}, F^{-}. From these data gas ratios, aerosol ratios and gas to aerosol ratios have been calculated (Table 1).

Table 1

Average ratios of weights of gases and aerosols from filter samples

Sample Location	Gases			Aerosols		Gas to aerosol		
Santiago Crater	SO_2/HCl	HCl/HF	HCl/HBr	$SO_4^{=}$ /Cl $^{-}$	/Cl $^{-}$ /F $^{-}$	$SO_2/SO_4^{=}$	HCL/CL $^{-}$	HF/F
Masaya Volcano	3.4	>370	840	1.3	2.3	90.5	29.5	H .5 < .5
Llano Pacaya, 15 km	6.7	> 10	Not	1 0	3.4	10.8	1.77	H .68 < .68
downwind from Santiago			determined					

Our present data indicate that ratios from 3 filter collections, all on Llano Pacaya, all on the same day, are very similar. The major differences in these ratios are the contrast between ratios from filter collections at the crater and downwind as shown in Table 1. The aerosol component increases downwind. This is marked in the gas to aerosol ratios for $SO_2/SO_4^{=}$ and especially HCl/Cl^{-}. The gas aerosol ratio is greatest for SO_2, less for HCl and least for HF.

We have calculated the probable SO_2, HCl and HF flux at the crater using the ratios and the downwind correlation spectrometer average value. The ratios allow one to take account of the SO_2 loss due to aerosol production downwind from the crater and to include the amounts in aerosols at the crater (Table 2).

Table 2

Tons per day and per year of selected gases emitted from Santiago Crater

Rate of Emission	SO_2	HCl	HF	HBr*
Tons/day	1300	400	5	0.5
Tons/year	500000	150000	3300	180
* based on very few data				

Concentrations of SO_2 and HCl in the plume were measured using an Interscan electrochemical SO_2 gas analyzer at the crater and downwind. Because of the difficulty of sampling the most concentrated part of the plume, values (Table 3) must necessarily be viewed as minimum only.

The data relative to Masaya volcano degassing are being used in a continuing study of the environmental impact downwind from the Santiago crater. The study emphasis the importance of volcanic gas plumes as a volcanic hazard under certain conditions of winds and local topography.

Table 3

Concentrations (ppm by weight)

Method	Location	SO_2	HCl
Filter data Calculated)	Crater	96	30
	Llano Pacaya	2.8	0.7
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Interscan data	Crater	$\gg$ 10	
	Llano Pacaya	1	
	Aircraf traverse Over Llano Pacaya	0.5	
	20 km downwind ground level	0.4	

SECCION

SISMOLOGIA VOLCANICA

ANALYSIS OF VOLCANIC TREMOR FROM PAVLOF, FUEGO, PACAYA, SAN CRISTOBAL AND MASAYA VOLCANOES.

Steven McNutt[*].

Análisis de tremor volcánico de los volcanes Pavlof, Fuego, Pacaya, San Cristóbal y Masaya.

RESUMEN

Tremor volcánico estrechamente relacionado en el tiempo con la actividad eruptiva de cinco estratovolcanes de los arcos circumpacíficos fue analizado y comparado con señales de baja amplitud producidas por agua fluyendo a través de túneles de descarga de la represa Tarbela en Pakistán. Análisis de frecuencia fueron hechos para cada volcán usando los métodos de la discreta transformada rápida de Fourier y el análisis Burg de máxima entropía. La represa y los volcanes tienen resonancias de tubo de órgano, exhibiendo picos angostos e igualmente espaciados.

Usando la frecuencia de la vibración, una velocidad de 2 Km/sec para las ondas P en el magma, la longitud de onda puede ser determinada. De la longitud de onda, se puede calcular la longitud del conducto magmático (tabla 1), que es positivamente correlacionable con las alturas del volcán.

Alternativamente, si los conductos están abiertos en ambos extremos, en vez de ser solo en la parte superior como en el modelo anterior, los conductos serían más largos por un factor de 2. Si el magma contiene burbujas, entonces la velocidad de las ondas "P" decrecería reduciendo la longitud del conducto calculado por un factor hasta de 5.

Todos los casos estudiados aquí involucran trémores superficiales, que pueden representar un fenómeno de resonancia asociada con los conductos magmáticos en un edificio o macizo volcánico que pueden considerarse como una zona de la baja resistencia mecánica cuyos esfuerzos internos están gobernados por fuerzas de cuerpo (gravedad) en vez de ser por fuerzas tectónicas como en la profundidad.

Volcanic tremor is generally defined as continuous seismic ground oscillations associated with volcanic activity (Tokarev, 1981). Tremor has been classified in the literature in several ways, based upon: I) eruptive vs non-eruptive activity of the volcano; II) frequency content and seismic wave type; III) time duration (continuous or intermittent on a time scale of minutes to months); and IV) source mechanism, including closed vent mechanisms (jerky crack growth, continuous block motion, magma chamber oscillations), and open vent mechanisms (explosions, continuous gas and lava ejection, magma flow in conduits, gas oscillations) (Tokarev, 1981; Kubotera, 1974; Shimozuru, 1961, 1971). This study is concerned with tremor which is closely related in time to surface eruptive activity at five circum-Pacific island arc stratovolcanoes: Pavlof (Alaska), Fuego and Pacaya (Guatemala), San Cristóbal and Masaya (Nicaragua). Brief descriptions of tremor episodes at these volcanoes follow.

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Tremor at Pavlof volcano is observed as short bursts of 2-26 minutes time duration and also as continuous tremor of $1\ ^1/_2$ days duration accompanying major strombolian eruptions. At Fuego volcano, tremor episodes often begin with or are accompanied by large explosions from the summit crater; these episodes last from several hours to many days duration. Tremor from Pacaya volcano occurs during strong strombolian eruptions and is of several hours duration. At San Cristóbal volcano, tremor increased in amplitude gradually over a period of several days prior to a strong ash and steam eruption on March 10, 1976. Finally, continuous tremor of low amplitude is observed near the active lava lake of Masaya volcano.

Signals resembling volcanic tremor are also observed on seismograms from stations near Tarbela dam and reservoir in Pakistán. This signal is observed when water is flowing through the dam's outflow tunnels. Frequency analysis have been perfomed on the tremor from each volcano and on the Tarbela signals using two spectral analysis methods: Discrete Fast Fourier Transform (FFT) and Burg maximun entropy (MEM). The Tarbela signals are shown to be organ pipe resonances in the outflow tunnels, with both even and odd harmonics present (i. e., $\lambda = 1/4\ell, 1/2\ell, 3/4\ell\ \ell, 5/4\ell$, etc.). The observed spectra change with location around the reservoir and with the size of the outflow opening, which is gate controlled.

We infer that the volcanic tremor signals are also organ pipe resonances, presumably of a magma-filled conduit. The tremor spectra exhibit narrow, evenly-spaced speaks, similar to the Tarbela dam signals (Figure 1). We measure the frequency of the fundamental mode of vibration, and by assigning a velocity of 2.0 km/sec to P-waves in magma (Murase and McBirney, 1973), we are able to determine the wavelenght from the relation:

$$V = \lambda f \quad \text{or} \quad \lambda = V/f$$

where $V =$ velocity in km/sec, $\lambda =$ wavelength in km, and $f =$ frequency in Hz. Based on our results from Tarbela dam, we assume that both odd and even harmonics are present. We then calculate the lengh of the magma conduit based on the relation for the fundamental mode of vibration for an organ pipe with one open and one closed end.

$$\ell = \frac{\lambda}{4}$$

where $\ell =$ length in km, $\lambda =$ wavelength in km. Results are shown in Table 1. We note a rough positive correlation between the length determined by this method and the heigh of the volcano above its surroundigs.

We also note two possible sources of error in this type of analysis. It is possible that the fundamental mode of vibration is that for a pipe with two open ends; we cannot determine this unambiguously. If true, our lengths given in Table 1 should be multiplied by a factor of 2. There is also a large uncertainty in the value to assign for the velocity of P-waves in magma. Addition of even a few percent of bubbles to the magma drastically lowers the P-wave velocity, so our value of 2.0 km/sec is probably a maximum. Values as low as 0.3 km/sec have been measured in the field (Aki et al., 1978). Using this value reduces the lengths given in Table 1 by a factor of 6.

All the examples of tremor examined in this study appear to be of shallow origin. We speculate that tremors originating at shallow depths may represent a resonance phenomena associated with magma conduits within the volcanic pile, which can be regarded as a zone of relatively low mechanical strength whose internal stress field is largely governed by body forces (gravity) rather than tectonic forces at depth.

TABLE 1

Lengths of resonating structures
with $V = 2.0$ km/sec

Pavlof	1.6 ± 0.3 km
Fuego	1 0 ± 0.1 km
Pacaya	1.1 ± 0.2 km
San Cristóbal	0.7 ± 0.1 km
Masaya	0.5 ± 0.1 km

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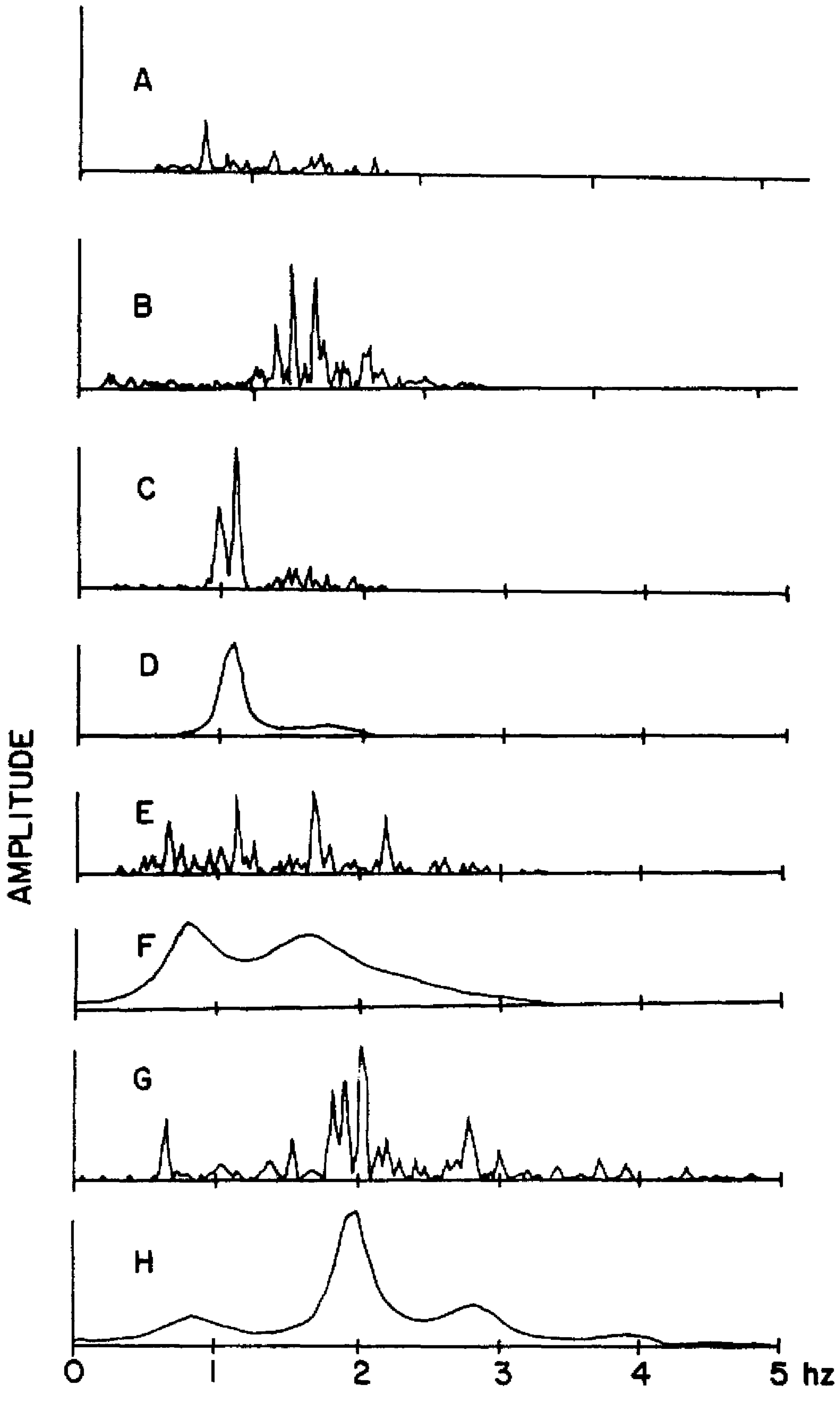

Figure 1

SECCION VOLCAN ARENAL

PETROLOGY OF ARENAL VOLCANO

M. Sc. Eduardo Malavassi R. *

ABSTRACT

Petrochemestry of Arenal volcano is similar to volcanic rocks of other circum-Pacific Continental margins, characterized by the presence of orogenic andesite and related rocks. The MgO, CaO, TiO_2 and total Fe contents decrease, and alkalis increase in these rocks with increasing SiO_2 (see figure 1).

Arenal volcano magmas show typical cal-alkalic trends in the AFM diagram with neither enrichment non empoverishment in the total Fe relative to MgO and total alkalies (see figure 2). Compositions of rocks from Arenal volcano plot in the calc-alkalic field in the total Fe versus total Fe/MgO, which differentiate between the calc-alkalic and tholeitic series of island arcs and active continental margins (see figure 3).

Based on chemical analyses most volcanic rocks from Arenal Volcano are basaltic-andesites or andesites. The exceptions are these dacitic lapilli layers, a basalt and several gabbroic accidental blocks.

Mineralogy and mineral proportions of Arenal tephra layers show the most contrasting composition variations. Juvenile ejects from these layers range from two pyroxene basalts, to two pyroxene basaltic-andesites, to one pyroxene hornblende andesite, to hornblende dacites. Texture ranges from hyalopilitic to trachytic.

Arenal volcano lavas are two pyroxene basaltic-andesites and andesites, gray to dark grey in color and hyalopilitic to pilotaxitic texture. Historic Arenal lavas (1968-present) are two pyroxene basaltic-andesites, porphyritic hyalopilitic texture; with exception of the first lava flow erupted in 1968 (Sáenz, 1977) which had hornblende phenocrysts.

Chemical trend of lavas erupted betweend 1968-1973 (Melson and Sáenz, 1973) reflects the extrusion of less differentiated lava with time. New chemical analyses of lavas erupted between 1974-1978 do not support a simple evolution toward less differentiated lavas with time since they have minor chemical variations, but generally are very similar and fairly basic for calcalkaline volcanic rocks (see figure 4).

PETROLOGIA DEL VOLCAN ARENAL

La petroquímica de las rocas del volcán Arenal es similar a la de las rocas volcánicas de otras márgenes continentales de la región circumpacífica, caracterizados por la presencia de andesita orogénica y rocas relacionadas. En las rocas del volcán Arenal el contenido de MgO, CaO, TiO_2 y Fe total decrece y el contenido de alcalis crece con el incremento en sílice, ver figura 1.

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Los magmas del volcán Arenal muestran típicas tendencias calcoalcalinas en el diagrama AFM sin incremento o decremento de Fe total relativo al MgO y alcalis totales, ver figura 2. Las rocas del volcán Arenal se ubican en el campo calco-alcalino en el gráfico Fe total contra Fe total/MgO, que permite diferenciar entre las series volcánicas calco-alcalinas y toleíticas de los arcos de islas y márgenes continentales activas, ver figura 3.

La petroquímica sugiere que la mayoría de las rocas del volcán Arenal son andesitas basálticas o andesitas. Las excepciones conocidas son tres eyectas juveniles dacíticas de las capas de tefra, un basalto y muchos bloques accidentales gabroides.

La mineralogía y proporciones minerales de las capas de tefra evidencian variaciones químicas contrastantes en composición. Las eyectas juveniles de estas capas gradan de basalto con dos piroxenos, a andesitas basálticas con dos piroxenos, a andesita con hornblenda y un piroxeno, a dacitas con hornblenda. Su textura grada desde hialopilítica hasta traquítica.

Las lavas del volcán Arenal son andesitas basálticas y andesitas de dos piroxenos, color gris oscuro a gris, y textura pilotaxítica a hialopilítica. Las lavas históricas (1968-presente) son andesitas basálticas con dos piroxenos y textura porfirítica hialopilítica; a excepción de la primera lava eruptada en 1968 (Sáenz, 1977) que contenía fenocristales de hornblenda.

Las tendencias petroquímicas de lavas eruptadas entre 1968-1973 (Melson y Sáenz, 1973) sugieren la extrusión de lavas menos diferenciadas con el tiempo. Nuevos análisis químicos de las lavas eruptadas entre 1974-1978 no respaldan una simple evolución hacia lavas menos diferenciadas, ya que ellas tienen sólo variaciones menores pero generalmente son muy similares y básicas para volcanes calcoalcalinos, ver figura 4.

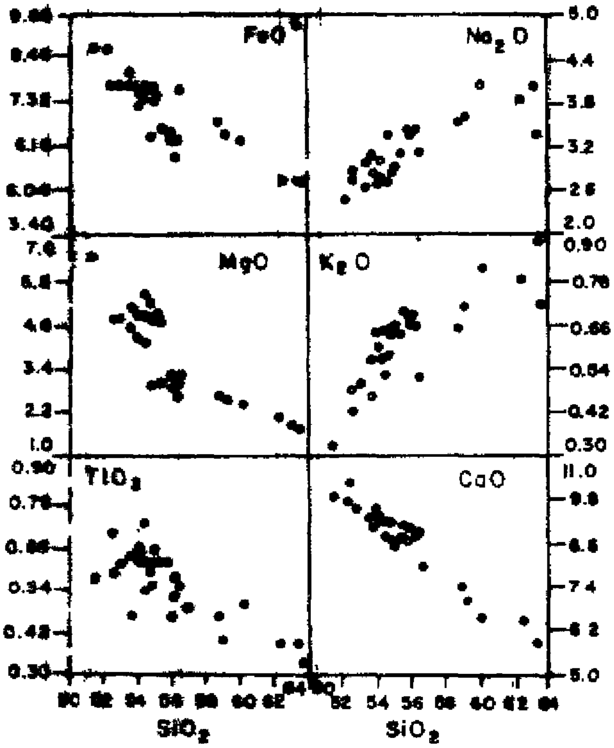
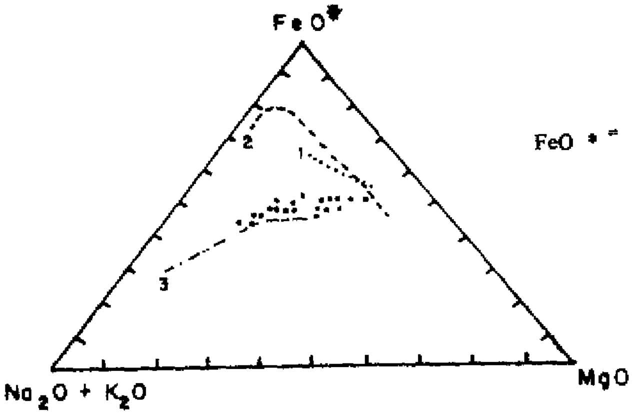


FIG: 1 DIAGRAMA DE VARIACION HARKER PARA LAS ROCAS DEL ARENAL

HARKER VARIATION DIAGRAMS FOR ARENAL ROCKS.



FeO * = Hierro total expresado como FeO
Total Iron as FeO

⁘	ROCAS DEL VOLCAN ARENAL	ARENAL VOLCANO ROCKS.
1	TENDENCIA TOFUA, SERIE TOLEITICA DE ARCOS DE ISLAS Y MARGENES CONTINENTALES ACTIVAS.	TOFUA TREND, TOLEIITIC SERIES OF ISLAND ARCS AND ACTIVE CONTINENTAL MARGINS ENVIRONMENT.
2	TENDENCIA INTRUSION SKAERGAARD (LIQUIDO) PROVINCIA TOLEITICA CONTINENTAL.	SKAERGAARD INSTRUSION (LIQUID) TREND CONTINENTAL THOLEIITIC PROVINCE
3	TENDENCIA VOLCAN ASAMA, SERIE CALCOALCALINA DE ARCOS DE ISLAS Y MARGENES CONTINENTALES ACTIVAS	ASAMA VOLCANO TREND, CALC-ALKALIC SERIES OF ISLAND ARC AND ACTIVE CONTINENTAL MARGINS ENVIRONMENT.

FIG: 2 DIAGRAMA AFM PARA ROCAS DE ARENAL

AFM DIAGRAMA FOR ARENAL ROCKS.

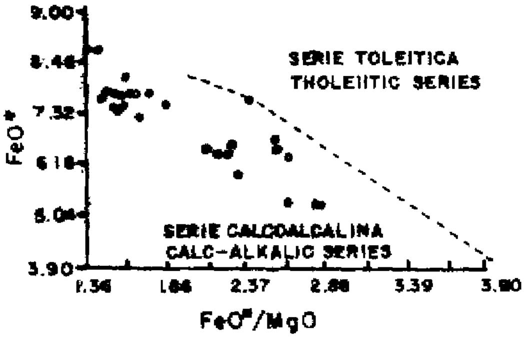


FIG. 3

GRAFICO DE HIERRO TOTAL EXPRESADO COMO FeO VERSUS LA RELACION FeO*/MgO. LINEA SEGUN MIYASHIRO, A. (1974). EL GRAFICO REUNE LAS SERIES VOLCANICAS CARACTERISTICAS DE LOS ARCOS DE ISLAS Y MARGENES CONTINENTALES ACTIVAS

PLOT OF TOTAL IRONS AS FeO VERSUS THE RATIO TOTAL IRONS AS FeO*/MgO. LINE AFTER MIYASHIRO, A. (1974). GRAPH REVIEW VOLCANIC SERIES OF ISLAND ARCS AND ACTIVE CONTINENTAL MARGINS ENVIRONMENT.

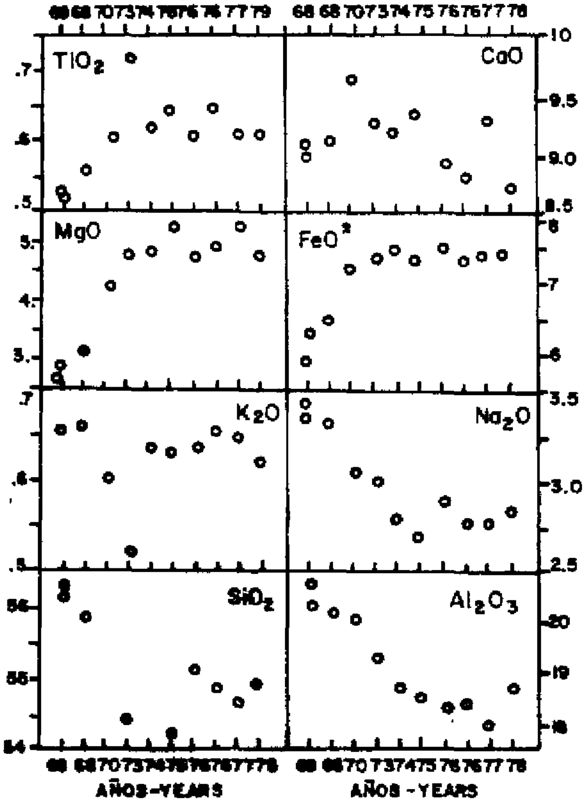


FIG. 4

VARIACION DE LA COMPOSICION VERSUS TIEMPO PARA LAS LAVAS HISTORICAS DEL VOLCAN ARENAL.

VARIATION IN COMPOSITION VERSUS TIME IN ARENAL VOLCANO HISTORIC LAVAS.