LATERAL FISSURE ERUPTIONS IN THE SOUTHERN ANDES OF CHILE

by

Yoshio KATSUI* and Hans R. KATZ**

(with 4 Text-figures and 1 Plate)

(Contribution from the Department of Geology and Mineralogy, Faculty of Science, Hokkaido University, No. 1062).

Introduction

After the great Chilean earthquake of May 21–22, 1960, it was rumoured that a new eruption took place in the high mountains near Puyehue volcano (2240 m a.s.l.), situated at Lat. 40° 35'S and Long. 72°08'W, in south-central Chile (Figs. 1 and 2). Bad weather and steepness of the mountain, however, prevented close examination. VEYL (1960) and SAINT AMAND (1961) gave some accounts of the eruption of Puyehue volcano based upon observations from the air. Brief reports also were made by CASERTANO (1961 and 1963) and TAZIEFF (1962).

During the following summer, March 16 to 18, 1961, one of the present authors (H.K.) visited Puyehue volcano. The first close observations on the 1960 activity was made, new lava was sampled, and detailed mapping was carried out based on new vertical aerial photographs at a scale of 1 :50,000 (Fig. 3). Another visit was made by the other author (Y.K.) in February 1965, in company with Prof. Oscar GONZÁLEZ F. of the Instituto de Geología of the Universidad de Chile. However, weather conditions allowed only a short reconnaissance along the south and eastern part of the volcano, where fresh pumice samples were collected.

The 1960 eruption of Puyehue volcano began with an explosive pumice ejection, which was followed by outpourings of lava from 28 crater pits aligned along new fissures extending a little over 14 km in total length. Altogether 0.2 km^3 of new lava and 0.06 km^3 of pumice were produced. A similar type of eruption, although slightly larger in scale, took place in approximately the same area in 1921–22 (HANTKE, 1940). This type of eruption appears to be similar to those of Icelandic volcanoes. However, the long fissures appeared in the flank of this stratovolcano, and the new lavas are not basalt but felsic andesite (or dacite), unlike those of Icelandic eruptions. Eruptions such as those manifested of Puyehue volcano

* Department of Geology and Mineralogy, Hokkaido University, Sapporo, Japan.
** Empresa Nacional del Petróleo, Santiago de Chile.

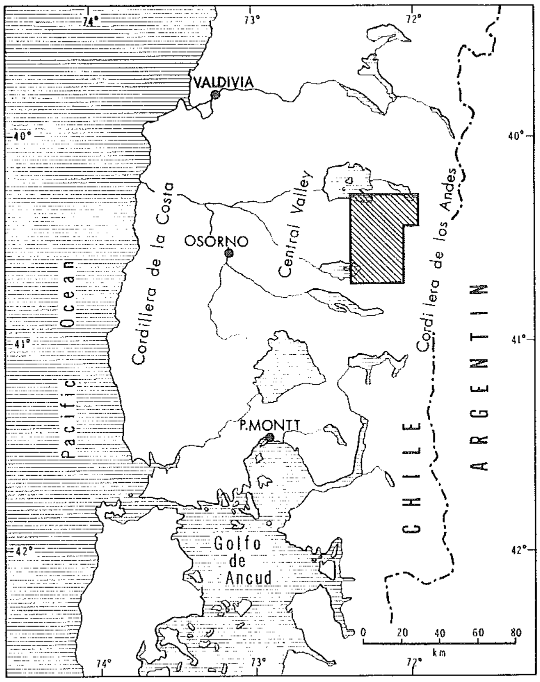

Fig. 1
Location map of Puyehue volcano, south-central Chile.

thus may be a comparatively uncommon phenomenon. In this report, the term " lateral fissure eruption " is tentatively used for this type of activity to distinguish it from the fissure eruption of the Icelandic type which commonly build lava plains and lava plateaus of basalt.

The 1960 eruption started about 48 hours after the main shock of the great earthquake, whose epicenter was situated about 300 km northwest of the volcano. The relationship between this earthquake and the volcanic eruption is also an interesting problem. This report gives a description of the 1960 eruption of Puyehue volcano and some geologic and petrologic considerations.

The authors wish to express their cordial thanks to Director Don Jorge MUÑOZ C. and Prof. Oscar GONZÁLEZ F. of the Instituto de Geología of the Universidad de Chile for their kind advice and aid in the field study. The authors are greatly indebted to Prof. Toshio ISHIKAWA of Department of Geology and Mineralogy, Hokkaio University, for helpful discussions of the work. Thanks are also due to Dr. Charles ROWETT of Department of Geology, University of Alaska, for reading the manuscript. Most of the laboratory work was performed at the Department of Geology and Mineralogy, Hokkaido University.

Regional geologic setting

The area covered by the geologic map shown in Fig. 2 forms a part of the Cordillera de los Andes adjacent to the low plain of the " Central Valley " in the west. Due to the scarcity of older sedimentary formations little is known about the geologic history of this mountain belt, but regional considerations suggest that the last main uplift occurred in the late Neogene, and probably continued to the Quaternary (KATZ, 1962).

Older rocks are divided into three units. Well bedded argillites, quartzites and some conglomerates which appear to be Palaeozoic in age crop out across Ranco Lake in the northwest. They are intensely folded and in general strike E-NE.

Northeast of Ranco Lake a complex of porphyritic effusive rocks (mainly andesite), volcanic breccias, and tuffaceous rocks are exposed at one locality. Both massive and faintly layered sequences occur, and intercalations of quartzose conglomerates, micaceous siltstones and black, coaly shales (KATZ, 1963, p. 1090). These rocks are comparable to the Cretaceous formations further to the north. They are strongly tectonized and faulted, and intruded by numerous granitic masses of the Andean batholith which forms the core of the Cordillera at this latitude. The granitic masses are intensely fractured and faulted and deeply eroded prior to the younger volcanic cycle. Their age is probably Cretaceous, at least on the Chilean side of the mountains, based on an absolute age of 90 to 117 m.y. (AGUIRRE and LEVI, 1964, p. 30), but further to the east several older complexes appear to exist (GERTH, 1955, p. 17–18).

Tertiary sediments, including Oligo-Miocene marine beds, apparently had an original distribution across the entire area, but are now restricted due to uplift and erosion in the Cordillera and occupy the down-faulted depression along Nahuel Huapi Lake in the east and the low land of the Central Valley to the west of the Cordillera.

Large-scale volcanism, characterized by eruption of andestic and basaltic magmas has occurred along the Cordillera de los Andes since Pliocene time, and probably is related to the general rise of this mountain range. Thick piles of subhorizontal lava flows, frequently interbedded with pyroclastic and volcanic mudflow deposits, cover an extensive area and are up to several hundred or even a thousand meters in total thickness. The eruption centers of these deposits are so close to each other that it is difficult to identify individual volcanoes.

Late Cenozoic volcanism continued into the Quaternary, and formed a number of large stratovolcanoes along the Andes. Among these, numerous small craters, cinder and tuff cones, maars and volcanic spines are sparsely distributed; ash, scoria, and pumice deposits are ubiquitous. The distribution of eruptive centers

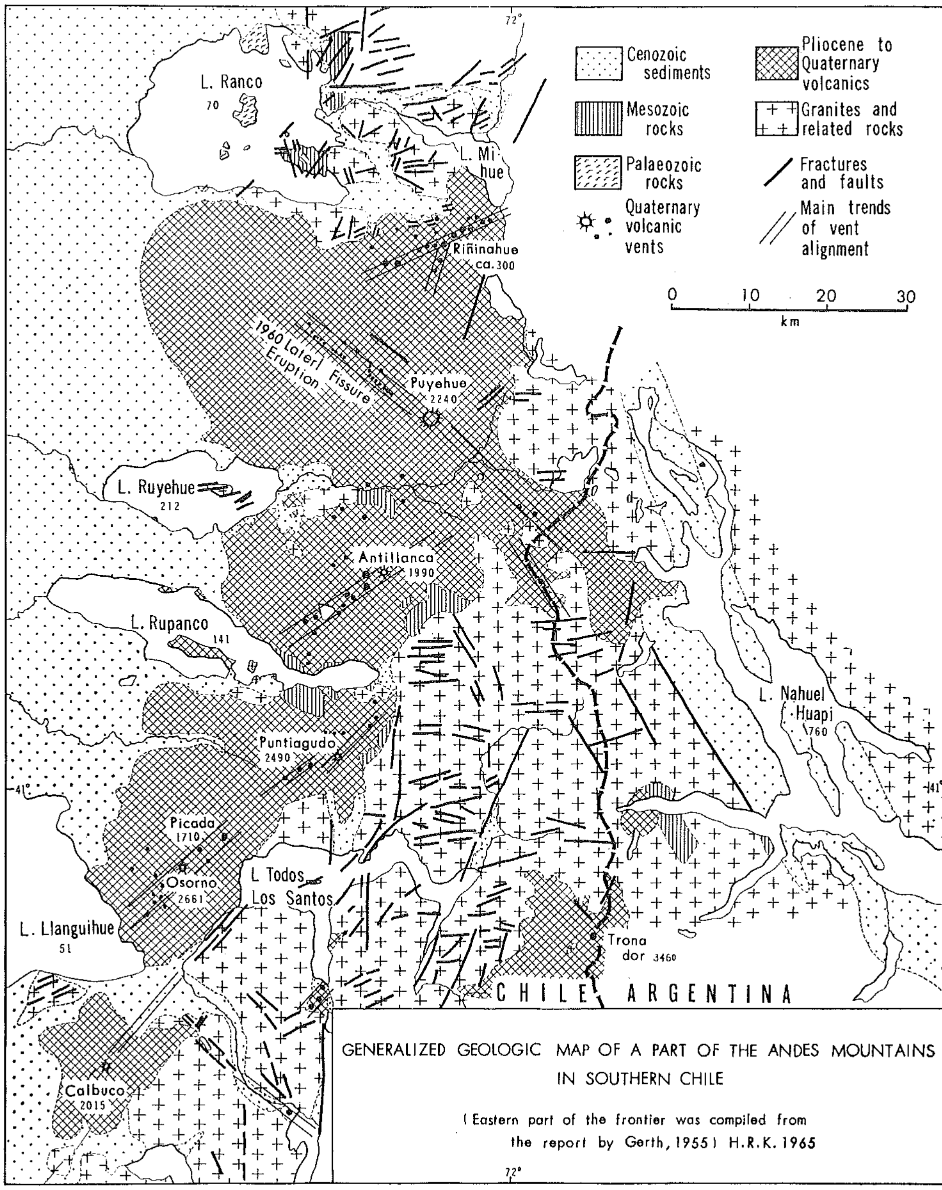

Fig. 2

indicates their alignments along older zones of weakness, many of which are considered to have remained active. Accordingly, a tectonic control of volcanic activity is evident throughout the area. Some stratovolcanoes have been partially destroyed by subsequent erosion, but still form impressive mountains such as Puntiagudo, Picada, and Cerro Toronador. The last named volcano, for instance, towers 1500 m above the general " roof " of the Andes, which is mainly composed of granite in this area (LARSSON, 1941). Other stratovolcanoes have been only slightly eroded. Of these, Osorno volcano (2660 m a.s.l.) which is covered by perennial snow and ice, is one of the most beautiful stratovolcanoes in the world. Although some volcanoes of this region exceed two thousand meters in elevation, each volcanic edifice is itself less than 1000 m in true height. Osorno volcano, for example, is composed of two units : a central cone and a somma built upon older volcanic rocks and elevated Andean batholith. The relief of either of these units does not exceed 1000 m.

As mentioned by STONE (1935), most of the volcanoes in this area seem to have entered their final stage. Their activity has in general become more explosive, while the effusion of lavas is less in both frequency and volume. When an effusion of lava takes place, it is always preceded by ash and pumice ejection. The 1955 activity that occurred in the valley of Río Niláhue (Volcan Carrán), is an example of a purely explosive type (COFRÉ, 1956 ; MÜLLER and VEYL, 1957 ; ILLIES, 1959). The eruption of Calbuco volcano from January to March, 1961, on the other hand, produced viscous lavas which flowed down the north and south flanks of the mountain, accompanyed by ash-falls at the beginning and end of the activity. Osorno volcano, however, is an exception ; fluid basalt and basaltic andesite lavas together with scoria, have been intermittently erupted within historic times (CASERTANO, 1963).

Puyehue volcano is also a large stratocone, resting on Pliocene lavas and volcanic conglomerates which have an elevation of 1300 m or more. Construction of the main cone probably took place during the Pleistocene to early Holocene. It is clear that some of the lavas represent a late stage of the main cone and flowed down the valley of Golgol which was formed by the final glaciation. The main crater appears to have been long inactive, and is slightly dissected. However, flank eruptions, mainly at the northwest foot of the volcano, continued into historic time. The main cone is composed of lavas and fragments of augite olivine andesite whose groundmass pyroxene is characterized by sole clinopyroxene (augite and pigeonite). These comprise a rock series of high alumina basalt, similar to the somma lavas of Calbuco and the interglacial lavas of Cerro Toronador. Recent lavas and ejecta of Puyehue together with those of Calbuco, however, subsequently became more felsic in composition, being highly oversaturated with silica. They are characterized by the presence of both rhombic and monoclinic pyroxenes in the groundmass, and included in the calc-alkali rock series.

1960 eruption of Puyehue volcano

About 48 hours after the main shock of the great earthquake of Sunday, May 22, a volcanic eruption occurred on a northwest-trending ridge which extends from the old, main volcano (Puyehue, also called Cauye). At 2 p.m. (local time) on May 24, an enormous eruption cloud was observed by the inhabitants of the farms far to the west. This ash-laden cloud rose to an altitude of approximately 9000 m. According to VEYL (1960), the eruption started at 1 p.m. of the same day and lasted for about 10 days (or several weeks, according to SAINT AMAND, 1961).

The location of the initial purely explosive activity was 5.5 km northwest of the crater rim of the main volcano, at an elevation about 1900 m. During the eruption west- and northwest-winds prevailed, so that a layer of pale yellowish gray pumice of the initial activity, was deposited in a fan-shaped area widening toward the ESE from its source; this ash layer decreases in thickness as well as in grain size with increasing distance from the source. Numerous pumice rafts appeared on Nahuel Huapi Lake in Argentina, about 100 km southeast of the volcano. No pumice, however, is found beyond 4 km northwest from the new crater. Near the crater, the thickness of the pumice deposit reaches 30–50 cm, with an average grain size of about 3–5 cm (max. 10–15 cm); in the frontier area between Chile and Argentina, 30 km ESE from the crater, the thickness of this deposit decreases to 10 cm, and the average grain size to 1 cm (max. 3 cm). It is evident that these deposits show good sorting.

Subsequent to the pumice ejection, black lava began to flow from a chain of small crater pits along fissures which had opened from the initial explosion crater in a northwesterly direction parallel to a high ridge which descends from about 1900 to 1400–1500 m in elevation. VEYL (1960) observed from the air a row of seven or eight such pits, extending over a distance of 4.5 km, from which black lavas were flowing down the ridge. As shown in Fig. 3, however, there are actually 28 openings from which lava extruded. These openings are aligned along fissures a little over 14 km in total length, and can be divided into three groups.

The first group, in the southeastern part of this area, consists of a fissure 4 km long, forming a practically straight line trending N50°W, from which lava extruded at 12 places and accumulated downslope both on the southwest and northeast sides of the ridge. From the northwestern end of this line, a branch fissure trands N20°W, and includes 6 lava effusion pits within a distance of 1.3 km. The area around the first group is mostly covered by an older pumice-fall deposit probably due to 1921–22 activity. Some long fissures were still observed on the older pumice terrain in March, 1961, from which small bodies of lava locally had extruded (Plate 53, Fig. 1). In several places, fumarolic activity was still continuing at that time. The other two groups of lava effusions are situated further to the northwest,

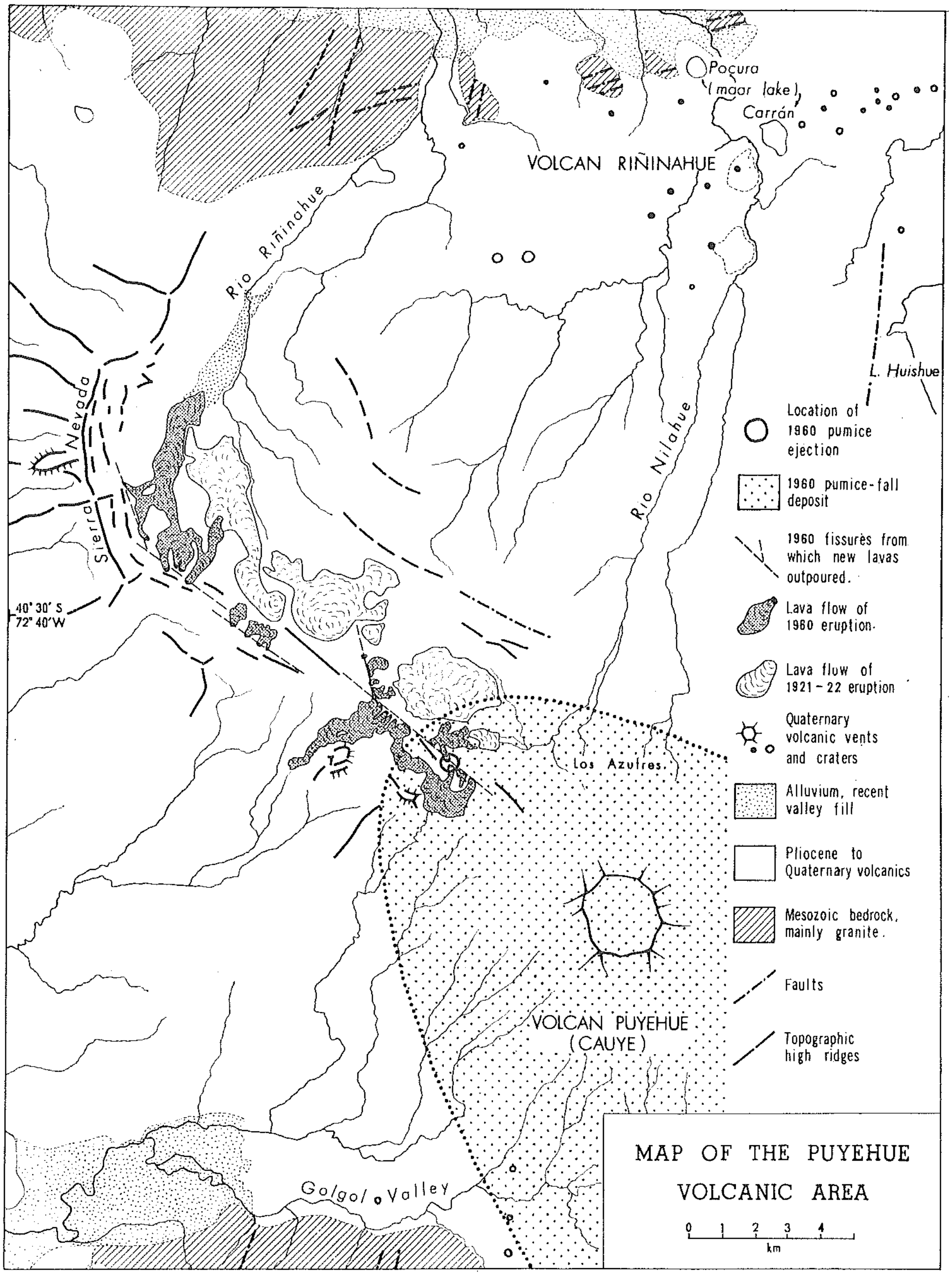
Pocura
(maar lake)
Carrán
VOLCAN RIÑINAHUE
Rio Riñinahue
Sierra Nevada
Rio Nilahue
L. Huishue
40° 30' S
72° 40' W
Los Azufres
VOLCAN PUYEHUE
(CAUYE)
Golgol Valley
Location of 1960 pumice ejection
1960 pumice-fall deposit
1960 fissures from which new lavas outpoured.
Lava flow of 1960 eruption.
Lava flow of 1921–22 eruption
Quaternary volcanic vents and craters
Alluvium, recent valley fill
Pliocene to Quaternary volcanics
Mesozoic bedrock, mainly granite.
Faults
Topographic high ridges
MAP OF THE PUYEHUE VOLCANIC AREA
0 1 2 3 4
km

Fig. 3

and aligned in similar directions.

Unfortunately, the exact time relationship of these events is not known. It seems possible, however, that immediately after the first explosive eruption in the extreme southeast, fissures opened and lava extrusion began in the southeast and extended progressively toward the northwest.

The new lavas are not widely distributed and commonly form steep-sided lava tongues. They have surface features typical of block lava and are fractured into polygonal blocks (Plate 53, Fig. 2). It is evident that these new lavas were rather viscous at the time of their eruption.

Toward the end of the activity, another explosive eruption occurred at the same site of the first explosition. New lava flows in the far southeast are partly covered by another pumice-fall deposit, which appears reddish at the base due to oxidation by contact with the hot lava. This second pumice is darker than the first, and is pale brown in color. The two phases of pumice eruption are also clearly established by the presence of two different layers exposed near hot sulphur springs (Los Azufres) at Río Niláhue, where they have an aggregate thickness of 50 cm (Plate 53, Fig. 3). It is probable that the cloud of the second explosion was not as high as the first one. Accordingly, distribution of the second pumice-fall deposit is limmited to an area near the crater, is fan-shaped, and widens toward the southeast.

The eruption of 1921–22

Although the 1921–22 eruption must have been one of the larger ones in recent history, no exact description is available in the literature. STEFFEN (1922), KRUMM (1923) and HANTKE (1940) are authors who mentioned it, while more recently ILLIES (1959) compiled some of the more important facts in his discussion of the Carrán explosion.

It is unfortunate that neither exact geographic location of the eruption nor the extension of the flows was established at that time. STEFFEN indicates an area close to the headwaters of Río Riñináhue (Fig. 3), from which two large lava masses flowed down the valley and buried existing vegetation and even dense forest. The eruption started on December 13, 1921, with an extraordinarily strong explosion. A huge mass of pumice and ash is said to have been ejected, which covered an area to the southeast; even as far as 100 km to the SE, near Bariloche at Nahuel Huapi Lake, pumice lumps mixed with lava fragments fell. Two weeks later, fine volcanic ash composed of glass and tiny plagioclase needles drifted as far as La Plata on the Atlantic side of the continent (KRUMM, 1923). According to KRUMM, the first phase of the cycle continued until December 19, 1921. A month later, E. VOLKMANN (from Valdivia) organized a trip into the area and found the front of one of lava flows still advancing (STEFFEN, 1922, p. 275). Although no crater had previously existed, a new large crater, several smaller ones, and fissures resulted from this eruption (STEFFEN, p. 274).

Study of new areal photographs now reveals that the 1921–22 eruption was even greater in scale and involved at least three large and possibly several smaller eruption centers. The area covered by lava includes more than 15 km², compared to 10 km² covered by the 1960 eruption (Table 1). It is notable that the centers of eruption are aligned in a chain 4 km long which is parallel to that of 1960, though slightly offset to the NE (Fig. 3). Thus it appears that both in the 1921 and the 1960 eruptions the same fissure system was responsible for the release of volcanic materials, both ejecta and lava.

Magnitude of the eruption

The thermal energy released by the 1960 eruption can be roughly calculated from the total mass of produced materials and estimated values of their specific heat and eruption temperature. The total mass of pumice and lava is given as 5.1×10^8 tons (Table 1), while 1000°C and 0.2 *cal/gr* may be taken as reasonable values of the eruption temperature and specific heat, respectively. Then, the thermal energy released by this eruption is obtained as follows:

$$E_{th} = 5.1 \times 10^{14}\,gr \times 1000°C \times 0.2\,cal/gr \times J\,ergs = 4 \times 10^{24}\,ergs$$

The kinetic energy which was released mostly in the form of ejection of pumice and ash is estimated by the following equation:

$$E_k = \tfrac{1}{2} M \times V_0^2$$

The mass (M) of the pumice-fall deposit is given in Table 1, and the initial velocity (V_0) of pumice ejection may be roughly estimated from the height of the ash-laden cloud (SAKUMA, 1957; KATSUI and MURASE, 1960). Based on a height of this ash-laden cloud of 6000 to 7000 m above the crater (VYEL, 1960; SAINT AMAND, 1961), this initial velocity must have been about 170 m/sec.

Table 1. Volume of lava and pumice of the 1960 Puyehue eruption

Lava flows:	Total area covered by lava flows from		
	28 crater pits		9.93 km²
	Thickness, 10–30m		20 m (mean)
	Total volume		0.2 km³
	Bulk specific gravity		2.4
	Total mass		4.8×10^8 tons
Pumice-fall deposit:			
	Thickness	Area	Volume
	50–30 cm	40 km²	0.016 km³
	30–10	80	0.016

10– 5	150	0.011
5– 1	290	0.009
1– 0	(1680)	(0.008)
Total volume		0.06 km^3
Bulk specific gravity		0.5
Total mass		3×10^7 tons

Table 2. Volume of lava and pumice of the 1921–22 Puyehue eruption

Lava flows:	Total area of lava flows	15.7 km^2
	Thickness of lava	75 m (mean)
	Total volume	1.2 km^3
	Bulk specific gravity	2.4
	Total mass	2.9×10^9 tons
Pumice-fall deposit:		
	Total volume	0.4 km^3
	Bulk specific gravity	0.6
	Total mass	2.4×10^8 tons

The kinetic energy is obtained as follows:

$$E_k = \tfrac{1}{2}\times3\times10^{13}\,gr\times(1.7\times10^4\,cm/sec.)^2\,ergs = 4\times10^{21}\,ergs$$

Compared with the thermal energy released by this activity, the kinetic energy is very small. This has been observed in other examples of volcanic activity accompanied by the eruption of magmatic materials (YOKOYAMA, 1957; KATSUI and MURASE, 1960). For this reason, it can be concluded that the greater part of the eruptive energy of the 1960 activity was released in the form of thermal energy derived from the molten magma itself.

Similar calculation can be made on the 1921–22 eruption of Puyehue volcano, based upon the total mass of produced material (Table 2):

$$E_{th} = 3.1\times10^{15}\,gr\times1000^\circ C\times0.2\,cal/gr\times J\,ergs = 2.6\times10^{25}\,ergs$$

A part of the energy of this eruption was also released by pumice ejection whose energy, however, is assumed to be less than 1/10 E_{th}. The total energy of the 1921–22 eruption may therefore be estimated at 2.8×10^{25} *ergs*.

The magnitude of the order of 10^{24} to 10^{25} *ergs* represents not only a large eruption but also a large earthquake. It therefore is pertinent to examine the energy of the preceding Chilean earthquake of 1960, whose epicenter was situated some 300 km northwest of the volcano. According to DUDA (1963), four large shocks exceeding a magnitude $7\frac{1}{2}$ occurred on May 21–22, 1960: the first shock occurred on May 21 (10h 02 m 50 s UT, $M=8.3$) and three shocks occurred within less than 16 minutes on May 22 (18 h 55 m 57 s, 19 h 10 m 37 s, and 19 h 11 m 17 s UT, respective $M=7.8$, 8.3, and 8.3). The total energy of these four shocks is calculated as 5.7×10^{24} *ergs* from the GUTENBERG and RICHTER's formula ($\log E = 11.8+1.5M$). Consequently, the total energy released by these shocks is closely comparable to that of the Puyehue eruption, which started two days later. This result is interesting inasmuch as these two catastrophic events thereby seem to be related to each other.

The large Chilean earthquake, however, is considered to be of tectonic origin, caused by fault displacements along the Pacific coast (SAINT AMAND, 1961; DUDA, 1963). It seems very likely that the earthquake shocks produced disturbances of the magma and opened fissures along the older NW-trending tectonic line. Thus, the earthquake appears to have initiated the beginning of the eruption. The magnitude of the eruption, however, must be considered to be independent to that of the earthquake shocks which were only responsible for triggering the eruption.

Petrography and chemistry of 1960 lava and pumice

Modal composition

Lava: The fractured surface of the new lava is smooth and black in color and has a brilliant luster similar to that of obsidian. Due to a linear arrangement of small gas pores and phenocrystic plagioclase, flow texture is generally well developed. The lava contains a few phenocryst of plagioclase, hypersthene, augite, and magnetite, but less than 7% of the total volume of the whole rock (Table 3). The groundmass exhibits a hyalopilitic texture. It is mainly composed of pale brown glass that includes small crystallites of plagioclase, monoclinic and rhombic pyroxenes, magnetite and apatite. The abundance of these minute crystallites in the groundmass seems to be responsible for the black color of the rock. Due to their extremely small size, the optical properties of the pyroxene could not be

Table 3. Modal composition* and optical properties of rock-forming minerals of 1960 lava, Puyehue volcano

Phenocrysts 6.9%	Plagioclase	3.1%	An 37 (core)——An 34 (rim) (after KAADEN, 1951) $2V_\alpha$=88° (core)——80° (rim)
	Hypersthene	1.5%	n_γ=1.709——1.710 $2V_\alpha$=60°——58° En 69 Fs 31——En 66 Fs 34 (after POLDERVAART, 1950) X=pale red, Y=pale yellowish brown, Z=pale green
	Augite	1.4%	$c \wedge Z$=43° (core)——40° (rim) $2V_\gamma$=51° (core)——48° (rim) n_β=1.693, pale green Wo 42 En 40 Fs 18 (after HESS, 1949).
	Magnetite	0.9%	
Groundmass 93.1%	Pale brown glass, n_D=1.503, including crystallites of plagioclase (An 22), monoclinic and rhombic pyroxenes, magnetite, and apatite.		

* Calculated without gas pores, which occupy 5% to 8% (volume) in compact lavas. Bulk specific gravity ranges from 2.40 to 2.46 in fairly compact lavas.

determined. The refractive index of the groundmass glass is $n_D = 1.503$, indicating a sliliceous composition.

Pumice: The pumice produced by the initial explosion is generally whitish and highly vesiculated. Its bulk specific gravity (apparent density) ranges from 0.20 to 0.67 which indicates a porocity of 72 to 92%, if the assumed true specific gravity is 2.4. A few phenocrysts of plagioclase, hypersthene, augite and magnetite are sparsely distributed in the vesciular glass; their optical properties are essentially the same as those of the phenocrysts in the lava. The groundmass consists of highly vesicular, clear and colorless glass which includes a very few crystallites of plagioclase, magnetite, and apatite. The refractive index of the glass is $n_D = 1.502$, which is nearly identical to that of the lava.

The pumice ejected in the final stage of the eruption is generally pale brown in color. This brownish coloration appears to be due to the abundance of tiny microlites of plagioclase, rhombic and monoclinic pyroxenes, and magnetite, which are suspended in the groundmass glass. Except for the abundant groundmass microlites, no remarkable difference was found between the pale brown and whitish pumice. Pale brown bands of this composition are rarely found in the whitish pumice of the initial stage.

Table 4. Chemical composition of 1960 pumice and lava of Puyehue Valcano, Chile (Analyst: Y. KATSUI)

Wt%	1 Pumice, pale yellowish gray	2 Lava	3 Pumice, pale brown	Norm	1′	2′	3′
SiO_2	68.30	67.34	67.18	q	24.44	26.45	25.97
TiO_2	.59	.75	.69	or	14.66	13.89	14.18
Al_2O_3	14.06	14.28	14.25	ab	38.93	31.73	32.32
Fe_2O_3	2.57	2.92	3.04	an	10.40	15.20	14.65
FeO	2.83	3.17	2.97	wo	.50	.60	.79
MnO	.10	.11	.11	en	3.04	3.54	3.59
MgO	1.22	1.42	1.44	fs	2.28	2.39	2.00
CaO	2.51	3.59	3.54	mt	3.73	4.23	4.41
Na_2O	4.60	3.75	3.82	il	1.12	1.42	1.31
K_2O	2.48	2.35	2.40	ap	.31	.44	.39
P_2O_5	.14	.20	.18	$H_2O(\pm)$	.96	.37	.43
$H_2O(+)$	.81	.23	.32	Total	100.37	100.26	100.04
$H_2O(+)$	.15	.14	.11				
Total	100.36	100.25	100.05	Color index	11.0	12.6	12.5

Chemical composition

Three representative products, 1) pumice of the initial stage, 2) lava, and 3) pumice of the final stage, were analyzed chemically, and are shown in Table 4 together with their Norms. They are generally felsic, oversaturated with silica, and can be termed felsic andesite (after KUNO's classification, 1954) or dacite (after WILLIAMS et al, 1954).

A slight compositional difference is noted between the pumice of initial (1) stage and other stages (2 and 3), although their difference is not clearly detectable under the microscope. The pumice of initial stage is more felsic than the others, and is characterized by its richness in silica and alkalies and poorness in iron and lime. No significant difference, however, can be seen between the lava and pumice of the final stage. Such compositional changes are in reverse order to the usual trend in magmatic differentiation, and will be discussed later.

Sequence of eruption and role of water in magma

The change in the manifestation of volcanic activity from the ejection of pumice to the emission of molten lava within a single cycle of eruption, as was observed during the short period of the 1960 activity of Puyehue volcano, is of particular interest. As mentioned above, a similar phenomenon also occurred during the 1921–22 activity of this volcano.

As stated by KENNEDY (1958), this sequence of eruption may be controled by volatile substances, mostly water, which are dissolved in the magma. The water is believed to diffuse and distribute itself within the magma chamber so that the chemical potential of the water becomes almost the same throughout the chamber. In this way, the water tends to be concentrated in the regions of lowest pressure and temperature in the magma reservoir. Consequently, initial volcanic activity is characterized by the highly explosive ejection of vesicular pumice and ash which originates from the apex of the magma reservoir. Due to the subsequent decrease of the vapor pressure in the magma, this form of activity is replaced by the outflow of molten lavas derived from deeper levels.

It has been noted that the initial explosion during the 1960 activity of Puyehue volcano took place at the highest point, situated at the southeast end of the fissure system. During the final stage of eruption, another pumice ejection, although much weaker than the first, also occurred at this point. It seems probable that vapor released from the ascending magma tended to be concentrated in the highest part of the magma reservoir.

Similar changes within a single cycle of eruption have been reported from all over the world (YAMASAKI, 1959; KATSUI, 1963). In a previous paper, KATSUI

(1963) pointed out that many of these show a compositional change in the products in an inverted order to the normal trend of magmatic differentiation as well as conversion of the form of eruption. This can be ascribed not only to gravitational crystallization-differentiation within a magma chamber, but also to the concentration of volatile components in its upper part (Fig. 4).

As noted above, the pumice of the initial explosion of the 1960 activity of Puyehue volcano is more felsic than others. It is suggested that during the some 40 years of quiescence preceding this activity differentiation of magma had taken place, probably due to concentration of volatile components together with alkalies and silica in the upper part of the magma reservoir.

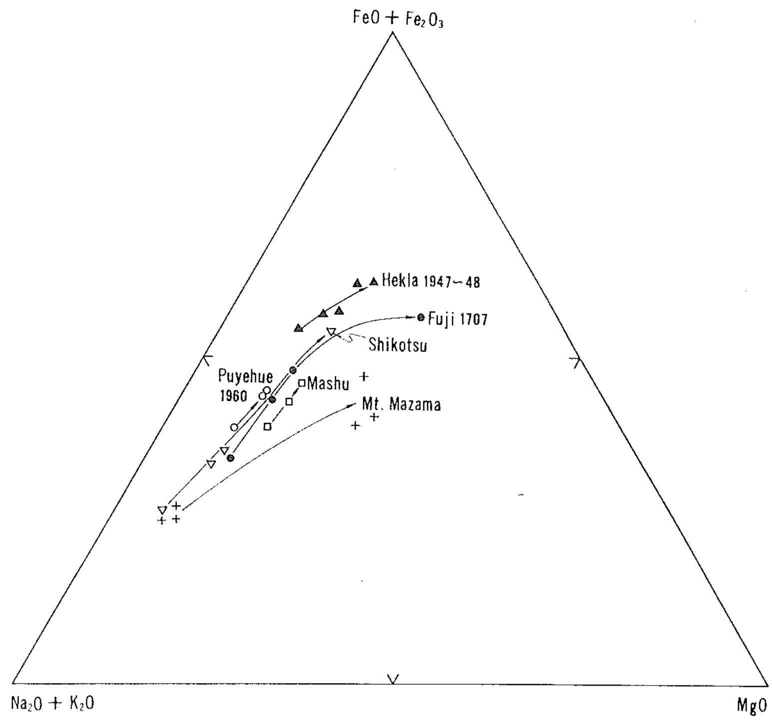

Fig. 4
MgO—FeO+Fe_2O_2—Na_2+K_2O diagram showing compositional change from the pumice of the initial stage to lava and pumice of the later stage produced by the 1960 activity of Puyehue volcano, together with similar changes of volcanic products within a single cycle of eruption of Hekla 1947–48 (rhyolite pumice to mafic andesite lava, THORARINSSON 1954), Fuji 1707 (rhyolite pumice to basalt scoria, TSUYA 1955), Shikotsu (rhyolite pumice-fall to felsic andesite pumice-flow, KATSUI 1963), Mashu (felsic andesite pumice-fall to andesite pumice-flow, KATSUI 1963), and Mt. Mazama (dacite pumice-fall to andesite scoria-flow, WILLIAMS 1942).

Conclusion

Two days after the main shock of the great Chilean earthquake of May 21–22, 1960, a lateral fissure eruption took place at the northwest flank of Puyehue volcano, south-central Chile. Following the initial explosive phase of pumice ejection, lava began to outpour from 28 crater pits aligned along new fissures trending in a NW direction and extending a little over 14 km in total length. Approximately 0.2 km^3 of new lava together with 0.06 km^3 of pumice was produced by this eruption. No sign of activity, however, was observed at the central crater of Puyehue volcano. The type of eruption appears to be similar to that of the Icelandic volcanoes, although the new lavas are felsic andesite or dacite (67.18–68.30% in SiO_2), and thus unlike the basalts of the Icelandic type of eruption. The magnitude of the entire eruption is calculated as 4×10^{24} *ergs*, which is comparable to that of the preceding earthquake. The earthquake, however, was responsible only for disturbing the magma reservoir and opening the fissures, which resulted in the beginning of eruption. Throughout the whole cycle of eruption, a compositional change in the volcanic products occurred in an inverted order to the normal trend of magmatic differentiation as well as conversion in the form of eruption. This phenomenon is attributed to the role of water in the magma. Similar lateral fissure eruptions, larger in scale, occurred in 1921–22 at nearly the same place. Eruptions along lateral fissure of such magnitude must be related to the regional tectonic pattern. The NW and NE trending fissures along which most Pliocene to Quaternary volcanism has taken place were developed in response to the uplift of the Andes and principally followed older tectonic lines.

Bibliography

AGUIRRE, L. and LEVI, B. (1964): Geología de la Cordillera de los Andes de las provincias de Cautín, Valdivia, Osorno y Llanquihue. Bol. Inst. Inv. Geol., **17**, Santiago.

CASERTANO, L. (1961): Bull. Volcan. Eruptions. Intern. Assoc. Volcan., **1**, 6, Tokyo.

CASERTANO, L. (1963): Catalogue of the active volcanoes of the World, Part 15, Chilean continent. Intern. Assoc. Volcan. Napoli.

COFRÉ, Z. C. (1956): Erupción del volcán Niláhue. Anal. Fac. Cienc. Fis. y Mat., Univ. Chile. **7**, 73–94, Santiago.

GERTH, H. (1955): Der geologische Bau der südamerikanischen Kordillere. Borntraeger, Berlin.

HANTKE, G. (1940): Das Vulkangebiet zwischen den Seen Ranco und Puyehue in Süd-Chile. Bull. Volcan., Sér. II, **7**, 75–83, Napoli.

ILLIES, H. (1959): Die Entstehungsgeschichte eines Maares in Süd-Chile. Geol. Rundschau, **48**, 232–247, Stuttgart.

ILLIES, H. (1960): Geologie der Gegend von Valdivia/Chile. N. Jb. Geol. u. Paläont.

111, 30–110, Stuttgart.

KATSUI, Y. (1963): Evolution and magmatic history of some krakatoan calderas in Hokkaido, Japan. Jour. Fac. Sci., Hokkaido Univ., ser. 4, **11**, 631–650, Sapporo.

KATSUI, Y. and MURASE, T. (1960): Some considerations on the activity of the Shikotsu volcano. Jour. Geol. Soc. Japan, **66**, 631–638, Tokyo.

KATZ, H. R. (1962): Fracture patterns and structural history in the sub-andean belt of southernmost Chile. Jour. Geol., **70**, 595–603, Chicago.

KATZ, H. R. (1963): Erdölgeologische Untersuchungen im chilenischen Längstal. Erdöl und Kohle, Erdgas, Petrochemie, **16**, 1089–1094, Hamburg.

KENNEDY, G. C. (1958): Some aspects of the role of water in rock melts. Geol. Soc. America, Special Paper 62, 489–504.

KRUMM, F. (1923): Topographische und geologische Nachrichten über die Gegend östlich des Ranco-Sees in Süd-Chile, im besonderen über den Jüngsten Vulkan-Ausbruch " Los Azufres " (Dezember 1921). Geol. Rundschau, **14**, 146–150, Berlin.

KUNO, H. (1954): Kazan oyobi Kazan-gan (Volcanoes and volcanic rocks, in Japanese), Tokyo.

LARSSON, W. (1941): Petrology of interglacial volcanics from the Andes of Northern Patagonia. Bull. Geol. Inst. Uppsala, **28**, 191–405, Uppsala.

MÜLLER, G. and VEYL, G. (1957): The birth of Nilahue, a new maar type volcano at Riñinahue, Chile. Proc. XX Session Intern. Geol. Congr., Sect 1-(II), 375–396, Mexico.

SAINT AMAND, P. (1961): Observaciones e interpretación de los Terremotos Chilenos de 1960. Com. Esc. Geol., Univ. Chile, **1**, 2, Santiago.

SAKUMA, S. (1957): Volcanic smoke, regarded as turbulent motion. Bull. Volcan. Soc. Japan, 2nd ser., **1**, 1–8, Tokyo.

STEFFEN, H. (1922): Nachrichten aus den Vulkangebieten der Kordilleren von Mittel-Chile. Z. Ges. Erdkunde, Berlin, 273–277.

STONE, J. B. (1935): The volcanoes of Southern Chile. Zt. f. Vulk., **16**, 81–97.

TAZIEFF, H. (1962): Quelques observations sur la crise séismovolcanique de mai 1960 au Chili central. Bull. Volcan. **24**, 84–86, Napoli.

THORARINSSON, S. (1954): The eruption of Hekla 1947–48, II, 3: The tephra-fall from Hekla on March 29th, 1947. Soc. Sci. Islandica, 1–68, Reykjavík.

TSUYA, H. (1955): Geological and petrological studies of Volcano Fuji, V. On the 1707 eruption of Volcano Fuji. Bull. Earthq. Res. Inst., **33**, 341–383, Tokyo.

VEYL, C. (1960): Los fenómenos volcanicos y sísmicos de fines de Mayo de 1960 en el Sur de Chile. Univ. Concepción, Inst. Central de Química, Dpto. Geol. Min.

WILLIAMS, H. (1942): The geology of Crater Lake National Park, Oregon. Carnegie Inst. Wash., Pub. 540, 1–157, Washington.

WILLIAMS, H. TURNER, F. J. and GILBERT, C. M. (1954): Petrography, San Francisco.

YAMASAKI, M. (1959): Role of water in volcanic eruption. Bull. Volcan. Soc. Japan, 2nd ser., **3**, 95–106, Tokyo.

YOKOYAMA, I. (1957): Energetics in active volcanoes (part 2). Bull. Earthq. Res. Inst., **35**, 75–98, Tokyo.

(Manuscript received January 31, 1967)

PLATE 53 AND EXPLANATION

Explanation of Plate 53

Fig. 1 New NW-trending fissures from which black lavas were emitted.

Fig. 2 A terminus of the 1960 lava-flow showing a surface features typical of block lava which is fractured into polygonal blocks.

Fig. 3 The 1960 pumice-fall deposit composed of two layers, deposited during the initial (B) and the final (A) stages. The dark-stained pumice-fall deposit (C) at the bottom was deposited during the 1921–22 activity. Length of the hammer is 40 cm.

Plate 53