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Tephra Stratigraphic Approach to the Eruptive History of Pacaya Volcano, Guatemala

Shigeru KITAMURA and Otoniel MATÍAS[1)]

Abstract Pacaya Volcano, one of the most active volcano in the world, is situated in the principal area of Guatemala. To mitigate the volcanic hazard to the area, the information of the mode and timing of the eruption is important This study aims at revealing the tephra stratigraphy of the Pacaya-El Patrocinio scoria group (Kitamura, 1995) to demonstrate the major part of the eruptive history of Pacaya Volcano in the latest eruptive stage.

Fifteen scoria-falls are identified around El Patrocinio Village and they are distributed to the west of Pacaya Volcano, hardly traceable to the northeast. Every scoria layer is caused by a cycle of eruption, most of which are composed of several eruption phases forming fall-units or a unit of falls. The 2nd, the 3rd, the 7th, the 12th and the 14th eruption are large comparatively in the fifteen eruptions; The 1st, the 4th, the 5th, the 6th and the 13th eruption are small comparatively, and the 11th and the 15th eruption are extremely small. The scoria erupted at the 7th eruption intercalates the debris avalanche deposit and the overlying blast deposit, so that volcanic edifice collapse occurred during the scoria eruption. The 10th eruption appears to continue longer period because the erupted scoria comprises a basal scoria-fall unit and overlying numerous ash-fall units including accretionary lapilli.

Three radiocarbon dates suggest that the latest eruptive stage causing the fifteen scoria-falls initiated about 1,500 yr. B.P (NU-735) and that several latest eruptions occurred since the 16th century (NU-733 & 734).

Key words: Pacaya Volcano, Guatemala, eruptive history, tephra, scoria-fall

1 Introduction

Pacaya Volcano, one of the most active volcano in Central America, is situated only 30 km south of Guatemala City, the capital of the Republic of Guatemala. A principal road passes by the volcano and a number of coffee plantations are also located around it. They expose themselves to volcanic hazard, which can be assessed on the basis of the eruptive history of the volcano. However, the detail eruptive

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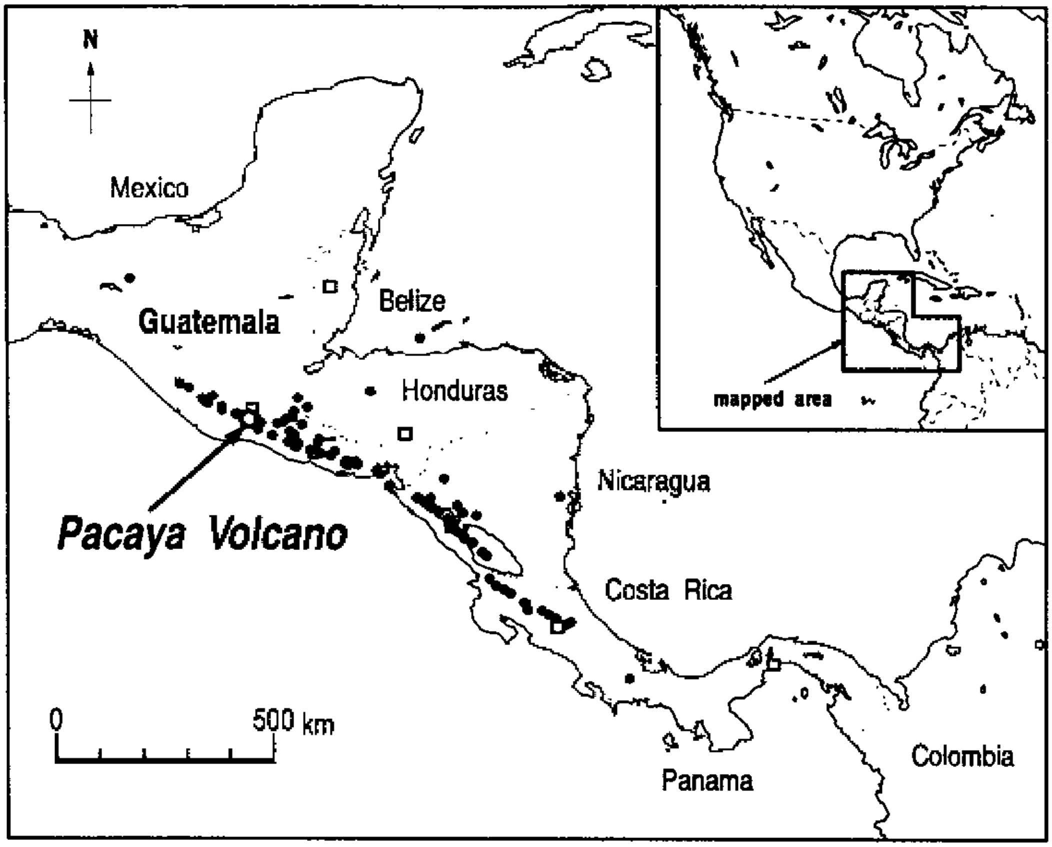
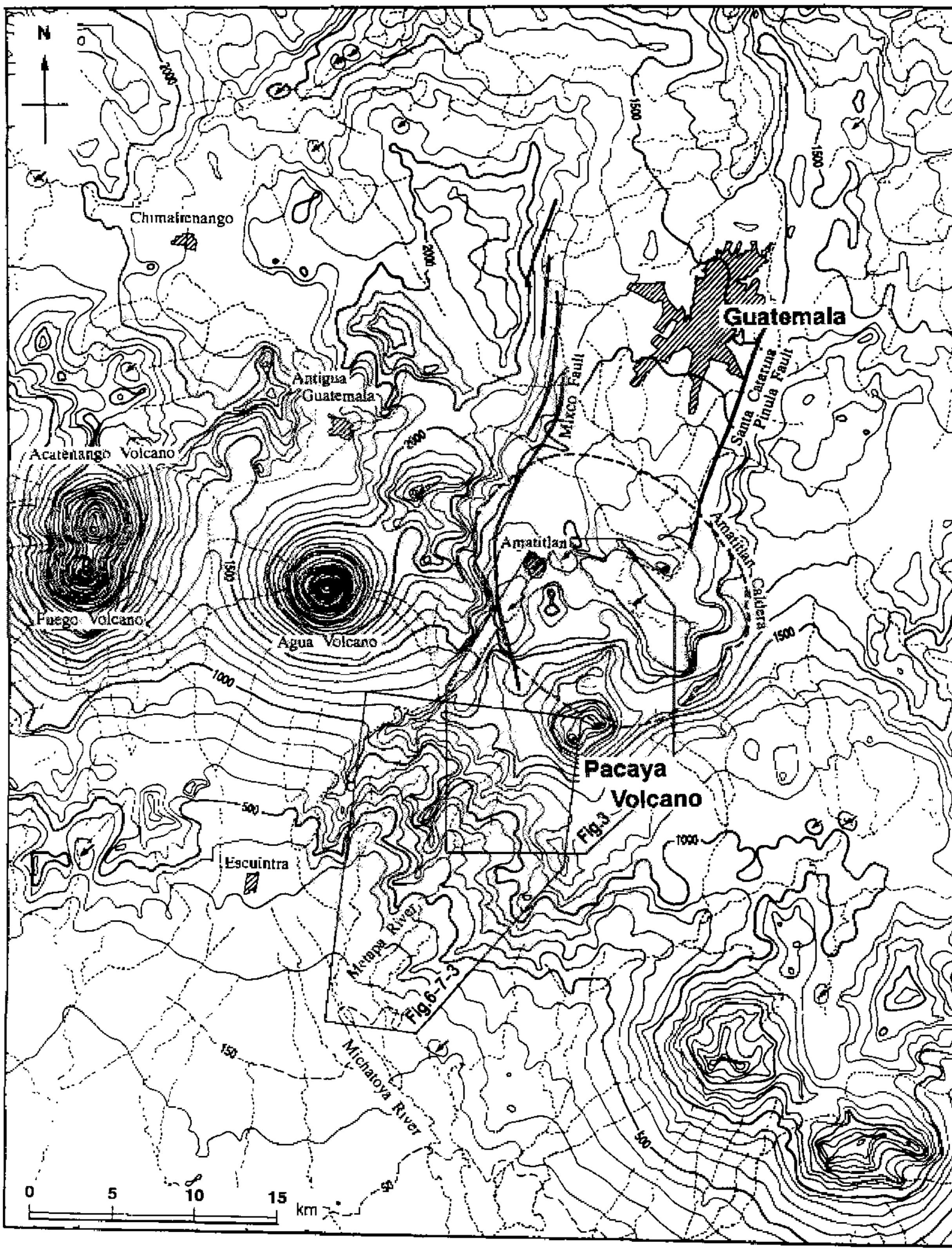


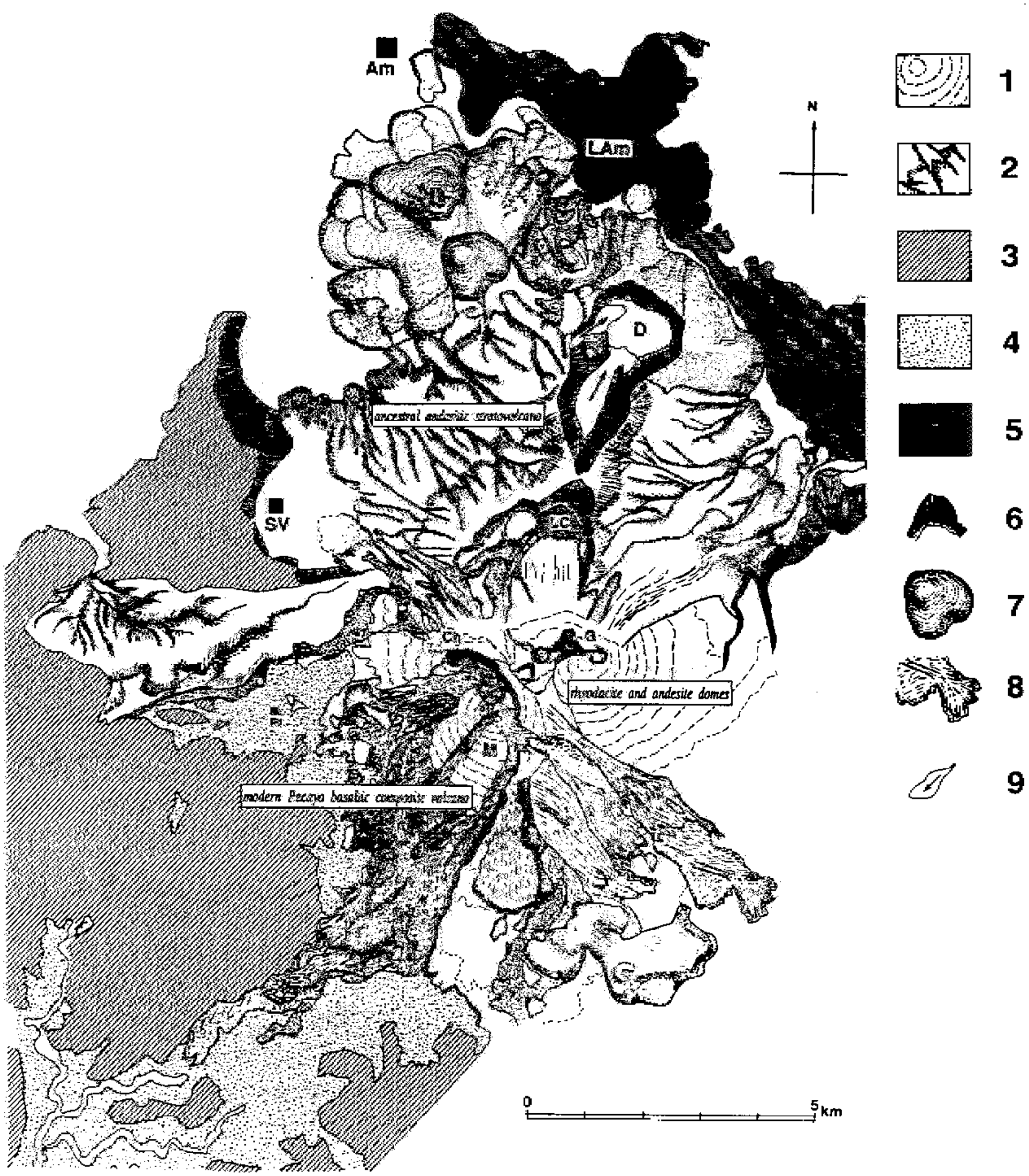
Fig. 1 Volcanic chain in Central America.
Solid circle shows volcano active in Holocene (Simkin *et al.*, 1981), and open square shows capital. Pacaya Volcano, shown in open circle, is located in the north of the volcanic chain.

history of Pacaya Volcano remains uncertain although some information about the eruption is obtained from previous geological study and historical documents since the 16th century.

The eruptive history of Pacaya Volcano since 23,000 yr. B.P. is divided into three stages by Kitamura (1995). This study aims at revealing the stratigraphy of tephra layers around the volcano in order to demonstrate a major part of the eruptive history in the latest stage, which will better enable us to mitigate hazards.

Fig. 2 Locality map of the central and south of Guatemala.
Solid (partly break) contour line shows sumit level of the landform, and other symbols, as follows; Hatched area, urban district; break line, river channel; thick solid line, active fault forming Guatemala Graben, thick break line, caldera rim of Amatitlan Caldera. Mepped areas of Fig. 3 and Fig. 6-7-3 are shown as polygons in this figure.


N
Chimaltenango
Antigua Guatemala
Acatenango Volcano
Fuego Volcano
Agua Volcano
Guatemala
Mixco Fault
Santa Catarina Pinula Fault
Amatitlan
Amatitlan Caldera
Pacaya Volcano
Fig.3
Escuintra
Metapa River
Fig.6-7-3
Michatoya River
2000
1500
1000
500
150
50
0 5 10 15 km


Am
LAm
D
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M
ancestral andesitic stratovolcano
rhyodacite and andesite domes
modern Pecaya basaltic composite volcano
N
1
2
3
4
5
6
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8
9
0
5 km

2 Previous studies

Pacaya Volcano is a large volcanic complex situated on the southern boundary fault zone of the Amatitlan Caldera (Koch & McLean 1975 ; Wunderman & Rose 1984), 30 km south of Guatemala City (Fig. 1 & 2). The Pacaya volcanic complex comprises an ancestral andesitic Pacaya stratovolcano, rhyodacite and andesite domes, and the modern Pacaya basaltic composite volcano (Eggers 1971MS ; Eggers 1975). It is the modern Pacaya composite volcano that is very active and has caused eruptions repeatedly in historic age. It has a horseshoe-shaped caldera open to the southwest, which is a result of the volcanic edifice collapse. The volcanic debris avalanche and the following blast produced by the collapse were emplaced the south and the west of the volcano (Vallence *et al.* 1988 ; Kitamura 1995). A post-caldera cone called the MacKenney cone has been developed in the caldera, and a small parasitic cone named Cerro Chino lies on the north rim of the caldera (Fig. 3).

From geological survey and petrological analysis, Eggers (1971MS) divided Quaternary volcanism in the Amatitlan quadrangle into three eruptive phases. Andesitic ancestral volcano was formed in the Phase I and voluminous eruptions of dacite pumice and domes are included in the Phase II. The volcanism in the latest phase continues today and has formed the modern Pacaya basaltic composite volcano. It is divided into three subphases as initial, historic and modern. From the paleomagnetic data of the lava, Conway (1992) showed that the volcanism from initial to historic subphase is strongly episodic and the durations of eruptive episodes and repose periods are the order of less than 100 to as much as 300 years and 300 to 500 years, respectively. Vallence *et al.* (1988) proposed that Pacaya Volcano collapsed and the horseshoe-shaped caldera was formed about 400 to 2,000 yr. B.P., based on the thickness of the soil underlain by the debris avalanche deposit. Kitamura (1995) divided the eruptive history of Pacaya Volcano into three stages based on the findings of three tephra groups above the B tephra (23 ka ; Peterson & Rose 1985 ; Koch & McLean 1975). The volcanism in the latest stage causing the Pacaya-El Patrocinio scoria group is inferred to initiate 700-3,000 years ago after a repose period of 1,000 to 2,000 years, on the assumption of a constant depositional rate of volcanic ash soil (Kitamura 1995).

Fig. 3 Landform of Pacaya Volcano

Legend : 1 ; cone and dome, 2 ; gentle slope (mostly dissected edifice of ancient Pacaya stratovolcano), 3 ; steep slope (mostly Tertiary rock area), 4 ; hummocky terrain or gravel land (debris avalanche deposit), 5 ; water, 6 ; scarp or crater rim, 7 ; lava dome, 8 , lava flow, 9 ; landslide, solid square ; city and town.

Abbreviatitn : M ; MacKenny cone, Ch ; Cerro Chino, G ; Cerro Grande, D , El Durazno Crater. LC ; Laguna de Calderas, LAm ; Amatitlan lake, Am ; Amatitlán, SV ; San Vicente Pacaya, Pt ; El Patrocinio

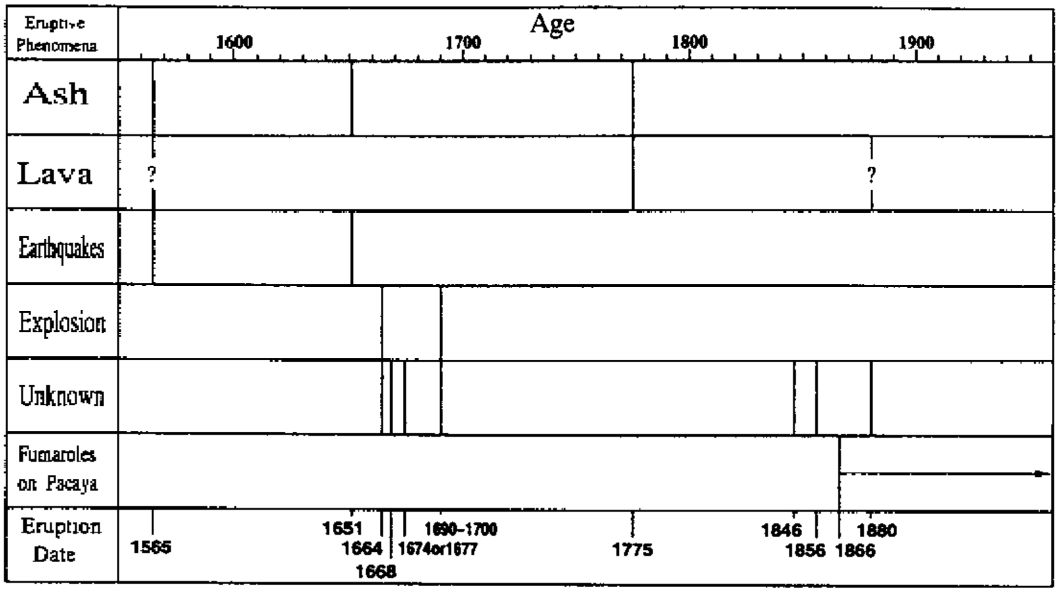


Fig. 4 Historically recorded eruption of Pacaya Volcano (Eggers, 1971MS; Meyer-Abich, 1956)

Since the 16th century, many eruptions are recorded. Meyer-Abich (1956) compiled the records of eruption in Guatemala and El Salvador, and Meyer-Abich (1958) condensed it to a short description and a table. Eggers (1971MS) also summarized it to a simple figure (Fig. 4), which shows that the Pacaya Volcano has two eruptions and two eruptive decades before the 20th century.

The first eruption accounted in historical documents occurred in 1565. Heavy ash-fall caused great damage in Antigua Guatemala, about 30 km west of the Pacaya Volcano. Eggers (1971MS) suggested that the lava extending from Cerro Chino to the west was erupted in 1565, based on Dollfus & Mont-Serrat (1868). Next eruption causing ash-fall occurred at 1651, and several small eruptions followed after that during the late half of the century. In 1775, another strong eruption caused heavy ash-fall and darkness for several days in Antigua Guatemala. A woodcut of the Archivos de Seville describes that the eruption occurred at the Cerro Chino crater and erupted lave flowed down to the south (Eggers 1971MS). In the middle of the 19th century, several small eruptions occurred, but they were not known in detail. Since 1880, the volcano had been quiet until 1960 except fumarolic emissions. In 1961, the volcano became active again, and lava flow has been erupted repeatedly since then. Stronger eruptions causing significant ash-fall occurred in 1987 and 1991.

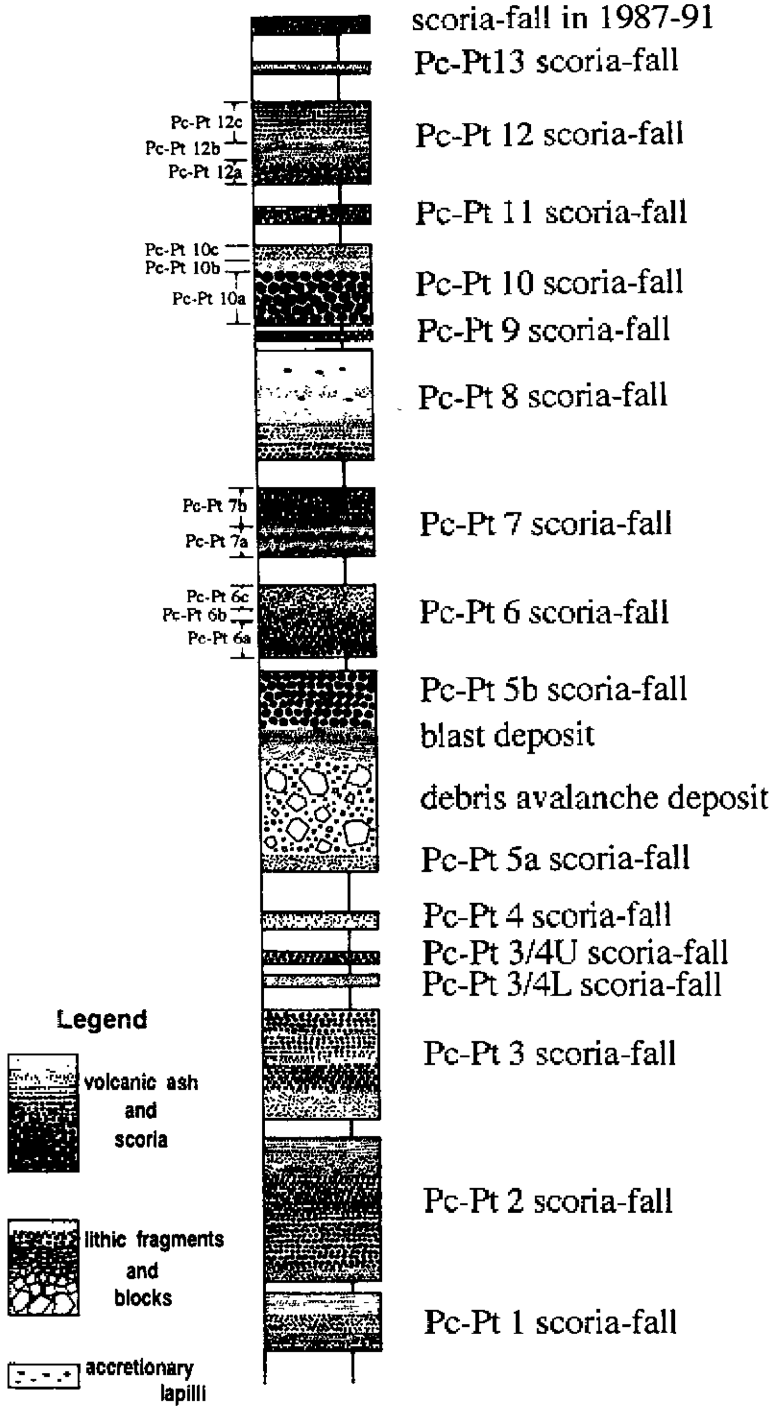


Fig. 5 Stratigraphy of tephras erupted in the latest stage of Pacaya Volcano.

3 Stratigraphy

Around Guatemala City, easterly winds predominate from June to October and southerly and westerly winds predominate from December to February (Mercado *et al.* 1988), suggesting that volcanic material erupted from Pacaya Volcano tends to be dispersed to the west or to the northeast. However, any tephra layer in the latest stage is not observed in the area to the northeast of the volcano. The most tephra layers are observed mainly in the area to the west.

Around El Patrocinio Village (Fig. 2), fifteen scoria layers in the latest stage, the debris avalanche deposit and the blast deposit are observed (Fig. 5). They are interlayered among dark-colored sandy soil. The scoria layers are also identified in the north of the Cerro Chino cone. Twelve layers of the fifteen have been already reported by Kitamura (1995) as the Pc-Pt1, the Pc-Pt2, . . . , the Pc-Pt12 scoria-falls. Other two layers are discovered between the Pc-Pt3 and the Pc-Pt4, and the other, above the Pc-Pt12, in this study. They are called the PcPt3/4L, the Pc-Pt3/4U and the Pc-Pt13 scoria-fall, respectively, according to the stratigraphic relationship.

(1) The Pc-Pt1 scoria-fall

The Pc-Pt1 scoria-fall is thinly bedded, several centimeters thick at most of the outcrops, but it accumulates to a thickness of 10 to 19 cm in the area to the southwest of El Patrocinio, suggesting that the dispersal axis trends to the SW from the volcano. The detail dispersal area, however, is not obtained because the deposit is hardly traceable to the further southern area that is covered by the debris avalanche deposit (Fig. 6-1). This scoria layer contains gray to light gray, occasionally yellowish light gray, volcanic ash, the particle size of which is equivalent to fine to medium sand in the size grade scale of Udden-Wentworth (described as "medium-sand-sized" in the following). It is laminated intercalating coarser dark scoria where it is thick. A basal thin unit rich in coarser and darker grain of scoria is observed at many outcrops.

The Pc-Pt1 scoria layer is the lowermost member of the Pacaya-El Patrocinio scoria group. Other scoria layer in the previous stage (San Vicente Pacaya scoria group ; Kitamura 1995) is observed 53 cm under the Pc-Pt1 scoria layer at the outcrop to the north of El Patrocinio. Between them, organic dark soil and brown loamy volcanic soil occupy the upper and the lower half, respectively.

(2) The Pc-Pt2 scoria-fall

This scoria-fall is thickly layered, and its maximum thickness is 96 cm. It comprises several units, most of which are composed of black to dark bluish gray or reddish gray, coarse scoria lapilli. In some places, two minor units composed of fine-grained scoria are observed at the base. The upper unit of the two, 1 to 2 cm thick, contains black scoriaceous fine-sand-sized volcanic ash as well as altered orange one, and the underlying unit, several centimeters thick, consists of fine scoria lapilli whose diameter is several millimeters or smaller. To the south of El Patrocinio, other minor unit, several to 20 cm thick, is also observed on the top of the layer and it is composed of medium- to coarse-sand-sized volcanic sand.

The Pc-Pt2 scoria fall layer lies several centimeters above the Pc-Pt1 scoria-fall and organic black sandy soil is laid between them as well as among other scoria layers of the Pacaya-El Patrocinio scoria group (Fig. 7). The Pc Pt2 scoria-fall is mostly distributed to the NW from the modern Pacaya composite volcano (Fig. 6-2) although every unit has its respective trend of dispersal axis which slightly differs from others' trend.

(3) The Pc-Pt3 scoria-fall

This scoria layer comprises several units, most of which are composed mainly of black to dark pale gray or reddish gray coarse scoria lapilli and free crystal of white plagioclase ; the scoria is 1 to 3 cm, or less, in diameter, and the crystal, several millimeters. To the south of El Patrocinio, a thin unit of brown volcanic ash is observed at the base of the layer.

This layer is observed several centimeters above the Pc-Pt2 scorai-fall (Fig. 7). It accumulates to a thickness of 89 cm at a outcrop about 2 km south of El Patrocinio, indicating that its dispersal axis trends to the southwest (Fig. 6-3). But detail areal distribution of the deposit is not obtained because it is hardly traceable to the further southern area where it was lost by volcanic edifice collapse.

(4) The Pc-Pt3/4L scoria-fall

This layer is not described in Kitamura (1995). It is composed mainly of black to dark bluish gray, coarse volcanic ash and fine scoria lapilli, whose maximum diameter is about 1 cm. It is thinly bedded, and its maximum thickness is only 4 cm. It is observed in a restricted area to the southwest of El Patrocinio (Fig. 6-4). The south limit of the dispersal area is not obtained because the layer is hardly traceable to the further southern area where it was lost by the collapse. This layer lies several centimeters above the Pc-Pt3 scoria layer (Fig. 7).

(5) The Pc-Pt3/4U scoria-fall

This layer is not described in Kitamura (1995). It is mainly composed of black to dark bluish gray scoria lapilli ranging from a couple of millimeter to ca. 2 cm in diameter, and abundantly contains free crystal of plagioclase. It is laid 3 to 4 cm above the Pc-Pt3/4L scoria layer. Although it is thinly bedded and its maximum thickness is only 8 or 9 cm, it is dispersed widely and its dispersal lobe extends to the

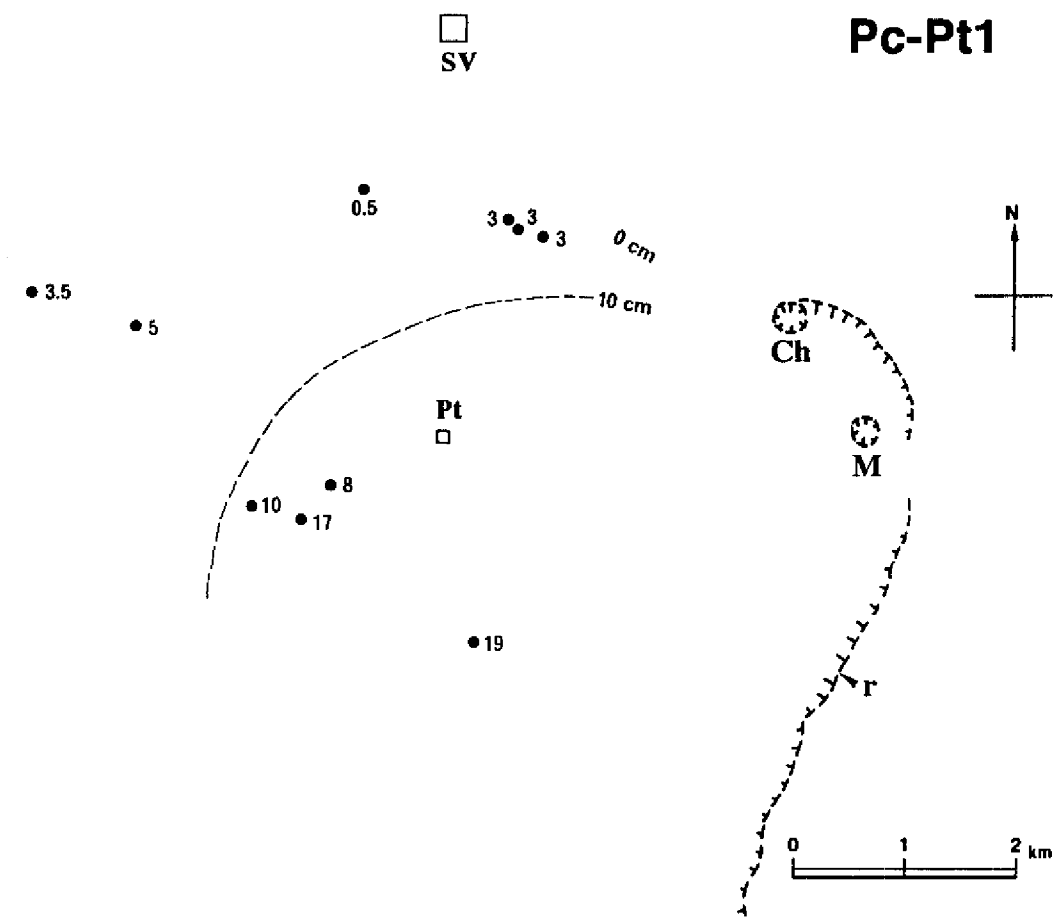


Fig. 6-1 Isopach map of the Pc-Pt1 scoria-fall (unit : cm)
Abbreviation. M, crater of present MacKenny cone; Ch, crater of present Cerro Chino, r, caldera rim; SV, San Vicente Pacaya; Pt, El Patrocinio

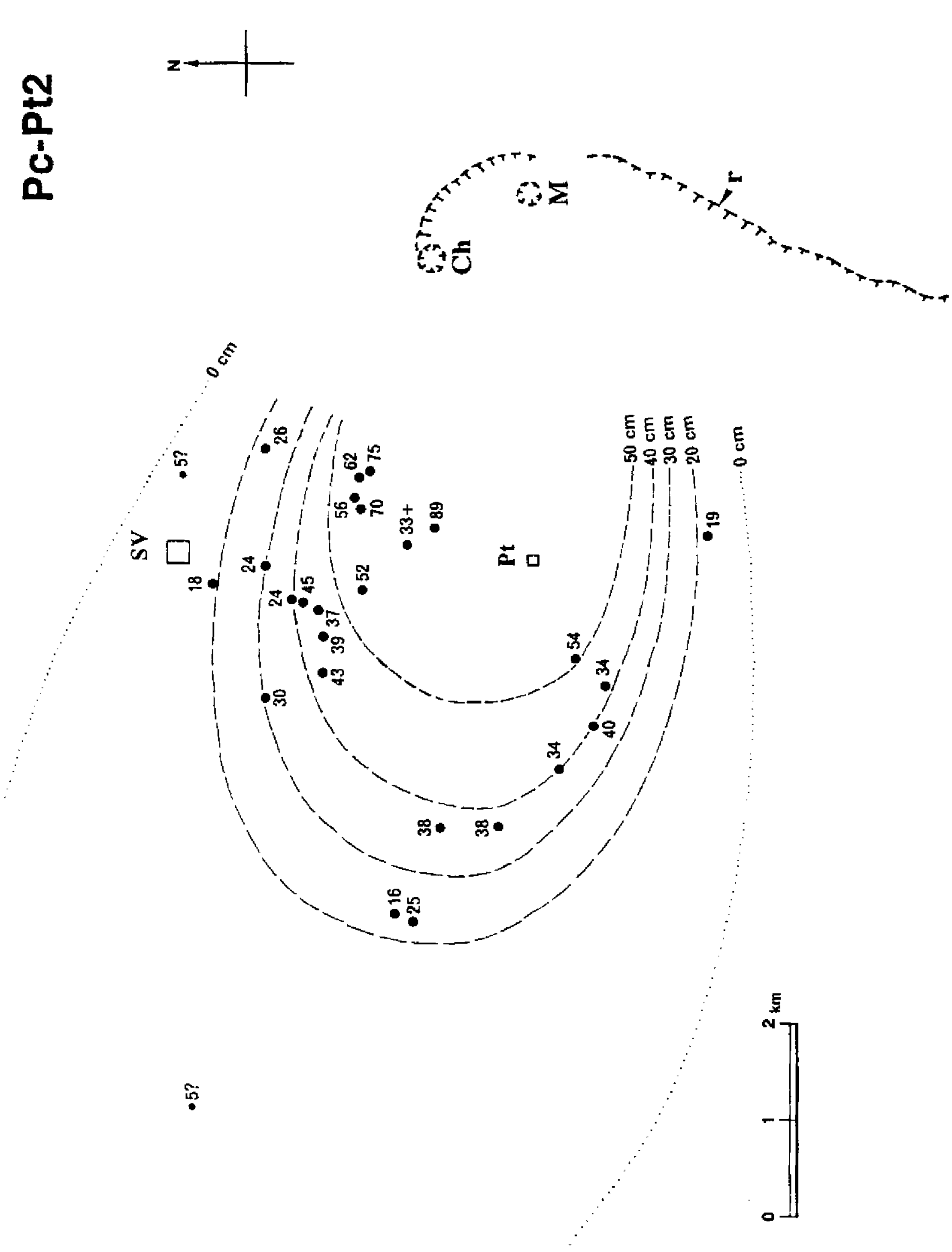


Fig. 6-2 Isopach map of the Pc-Pt2 scoria-fall (unit : cm). Abbreviations are the same as Fig. 6-1.

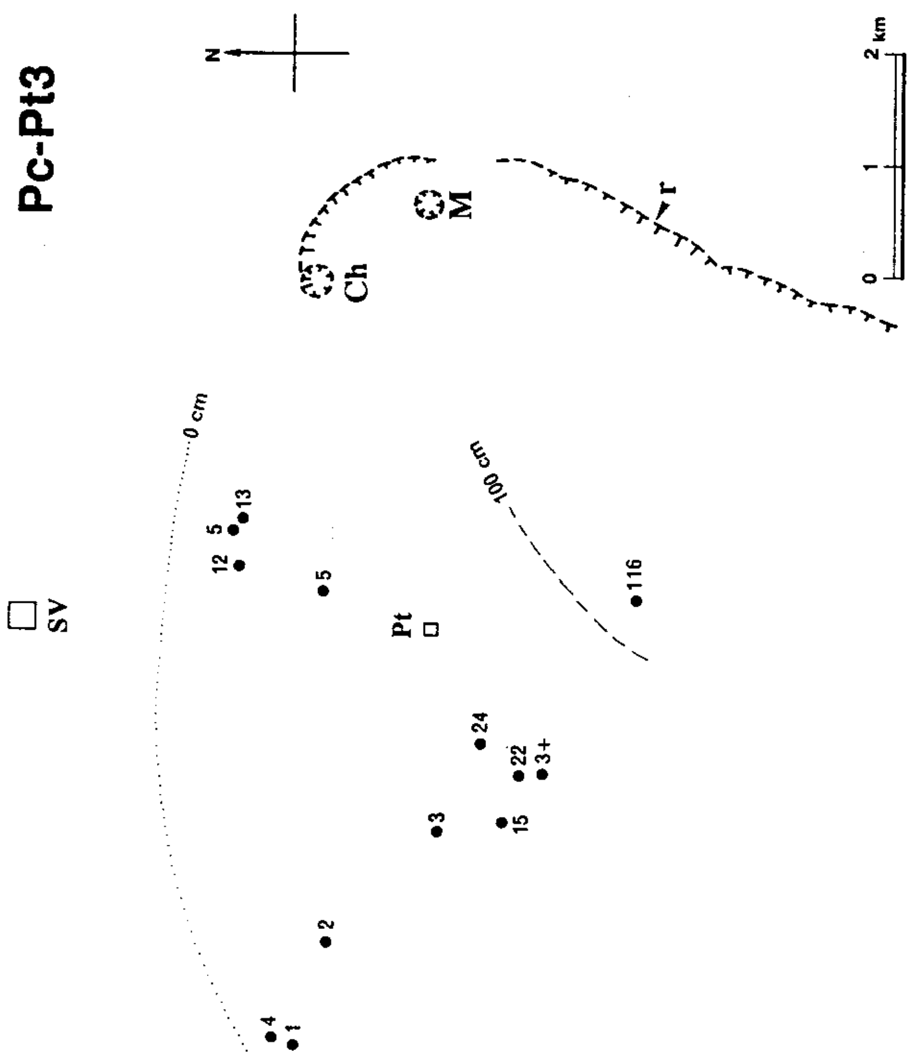


Fig. 6-3 Isopach map of the Pc-Pt3 scoria-fall (unit : cm). Abbreviations are the same as Fig. 6-1.

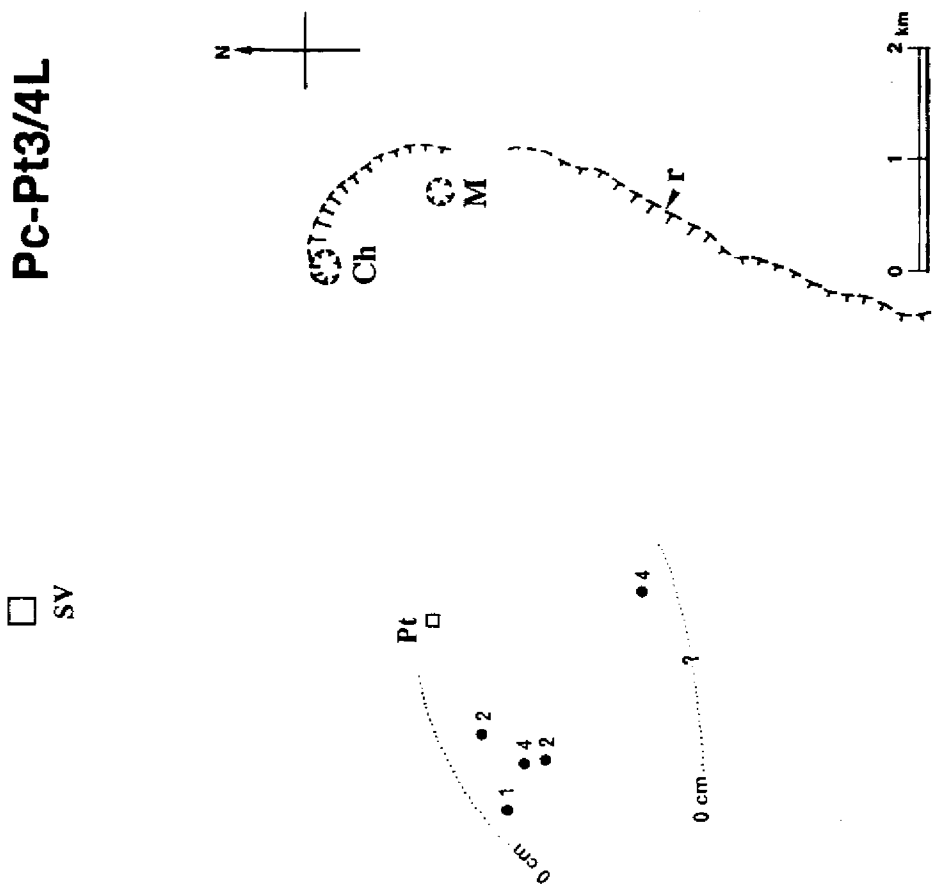


Fig. 6-4 Isopach map of the Pc-Pt3/4L scoria-fall (unit : cm). Abbreviations are the same as Fig. 6-1.

west from the volcano (Fig. 6-5).

(6) The Pc-Pt4 scoria-fall

This layer is composed mainly of several-millimeter-sized fine scoria lapilli, including coarse scoria lapilli as much as ca. 2 to 3 cm in diameter. Most of the scoria lapilli is black or dark gray, and dark red or reddish brown scoria lapilli is also included. It is laid 3 to 5 cm above the Pc-Pt3/4L scoria layer (Fig. 7). It is thin and its maximum thickness is only 9 cm. The dispersal axis trends to the west, or slightly more northerly, from the volcano (Fig. 6-6).

(7) The Pc-Pt5 scoria-fall, the debris avalanche deposit and the blast deposit

The Pc-Pt5 scoria layer are divided into two units ; The lower thin unit, Pc-Pt5a, contains faintly bluish dark gray fine scoria lapilli whose diameter is several millimeters ; The overlying thick unit, Pc-Pt5b, is composed of black coarse scoria lapilli ranging from 2 to 5-6 cm in diameter, and its lower part predominates scoria lapilli with brown clay skin. The Pc-Pt5b unit contains comparatively well-vesiculated scoria in the members of the Pacaya-El Patrocinio scoria group. Both scoria units are dispersed widely to the west of the volcano, although scoria of the Pc-Pt5b unit was much more voluminous than that of the Pc-Pt5a unit (Fig. 6-7-1 & -2).

The Pc-Pt5a unit is laid 8-10 cm above the Pc-Pt4 scoria layer (Fig. 7). It is overlain by the Pc-Pt5b unit in contact, in the northwestern area of the volcano, where both of the blast deposit and the debris avalanche deposit are absent. It is never observed in the area underlain by the debris avalanche deposit. In other area, it is overlain by the blast deposit in contact. The Pc-Pt5b unit overlies in contact not only the Pc-Pt5a unit but also the blast deposit underlain by the debris avalanche deposit, and the blast deposit is observed to be intercalated between Pc-Pt5a and Pc-Pt5b scoria in the area to the west and north of El Patrocinio. In some places, the Pc-Pt5b overlies the debris avalanche deposit without any deposit or any other evidence to indicate time-gap between them. These facts indicate that both of the debris avalanche deposit and the overlying blast deposit are intercalated between the Pc-Pt5a and the Pc-Pt5b units (Fig. 7).

The debris avalanche deposit contains lithic blocks, ranging from several centimeters to a couple of meters in diameter, with loamy to sandy matrix. In some places, it includes partly pebble- to cobble-sized pumice shards, and in some places it is composed mainly of them. The debris avalanche was generated by the collapse of the volcano that formed the horseshoe-shaped caldera open to the southwest (Vallence *et al.* 1988). The debris avalanche deposit is observed on the south and the west of the volcano (Fig. 6-7-3). In the south, it can be identified as the terrain characterized by numerous hummocks traceable from the volcano to an area about 3 km south of Las

Chapernas along the Metapa River (Río Metapa) valley for 25 km (Vallence *et al.* 1988). It accumulates thickly, especially in its upper valley, causing a terrace-like landform occupied by the hummocks on the top. In the west flank of the volcano, the debris avalanche deposit is observed at many outcrops and its distributed area extends to an valley neck, ca. 2 km west of El Patrocinio, on a tributary of Marinala River (Río Marinalã). Hummocks are also located in the area, but they are less distinct than in the southern area. Although the debris avalanche deposit cannot be traced from the south to the west by field observation, it is interpreted to be continuous between these areas by the following geomorphological feature ; The terrace-like landform, mentioned above, extends along the Guachipilin Stream (Riachuelo Guachipilín), a tributary of the Metapa River, up to the 3 km upper from the junction with the Metapa River ; The top of the terrace is continuous between the river valleys (Fig. 6-7-3), indicating that the debris avalanche not only flowed down to the south along the Metapa River but also flowed down over the west flank into the Guachipilin Stream because it hardly passes over the ridge among the valleys (Kitamura 1995)

The blast deposit overlies in contact the hummocky terrain in the south of the volcano (Vallence *et al.* 1988) as well as the debris avalanche deposit in the west (Kitamura 1995). It is traceable for at least 12 km from the origin on the dispersal axis trending to the SW (Fig. 6-7-3). To the south of the volcano, the blast deposit is exposed as a thick, stratified or laminated bed at most of the outcrops and massive in some places. It is poorly sorted, light brown to reddish brown silt or sand with many lithic fragments. In the west, about 2 km southeast of El Patrocinio, the blast deposit, 100 to 150 cm thick, is exposed as poorly-sorted loamy deposit with many pebble-sized fragments. It is laminated, partly cross-bedded, and has also wavy or dune-like bed form. In the area close to El Patrocinio, the blast deposit is thinly bedded to be only 10 to 20 cm thick, but has laminated structure. It occasionally intercalates a thin layer of coarse scoria lapilli in the upper part. To the west and north of El Patrocinio, the blast deposit is observed as, brown, more sorted, loamy to sandy deposit. It is thinly bedded and poorly laminated or almost massive, although it has laminated structure in the case of good reservation.

(8) The Pc-Pt6 scoria-fall

The Pc-Pt6 scoria-fall is laid only 3 cm above the Pc-Pt5b or avalanche deposit (Fig. 7). It also covers the weathered surface on the debris avalanche deposit. Although it is exposed as a bed thicker than 30 cm in a place, it is thinly bedded to as much as 20 cm in the major area.

This scoria layer comprises three units. The lowermost Pc-Pt6a unit is composed mainly of well-vesiculated scoria lapilli ranging from several millimeter to 2 cm in size, from dark gray to metallic black in color. This unit contains small volume of

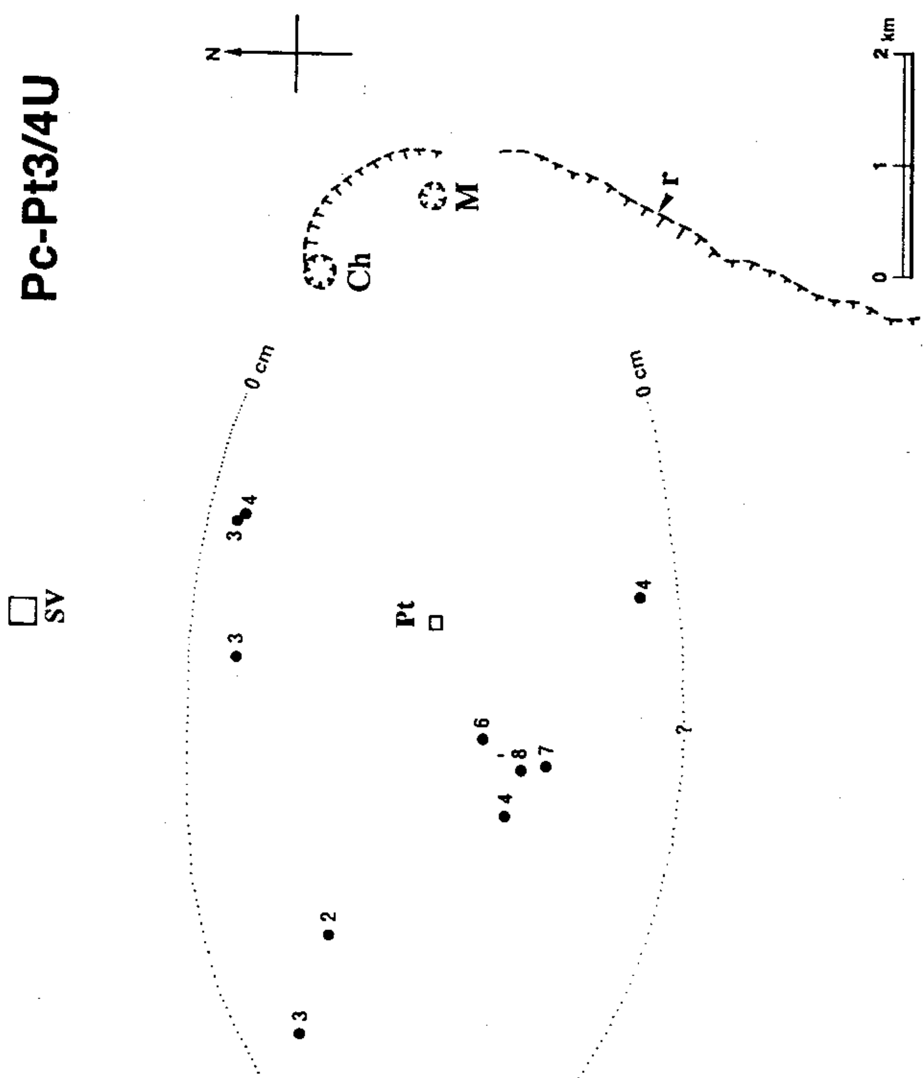


Fig. 6-5 Isopach map of the Pc-Pt3/4U scoria-fall (unit : cm). Abbreviations are the same as Fig. 6-1.

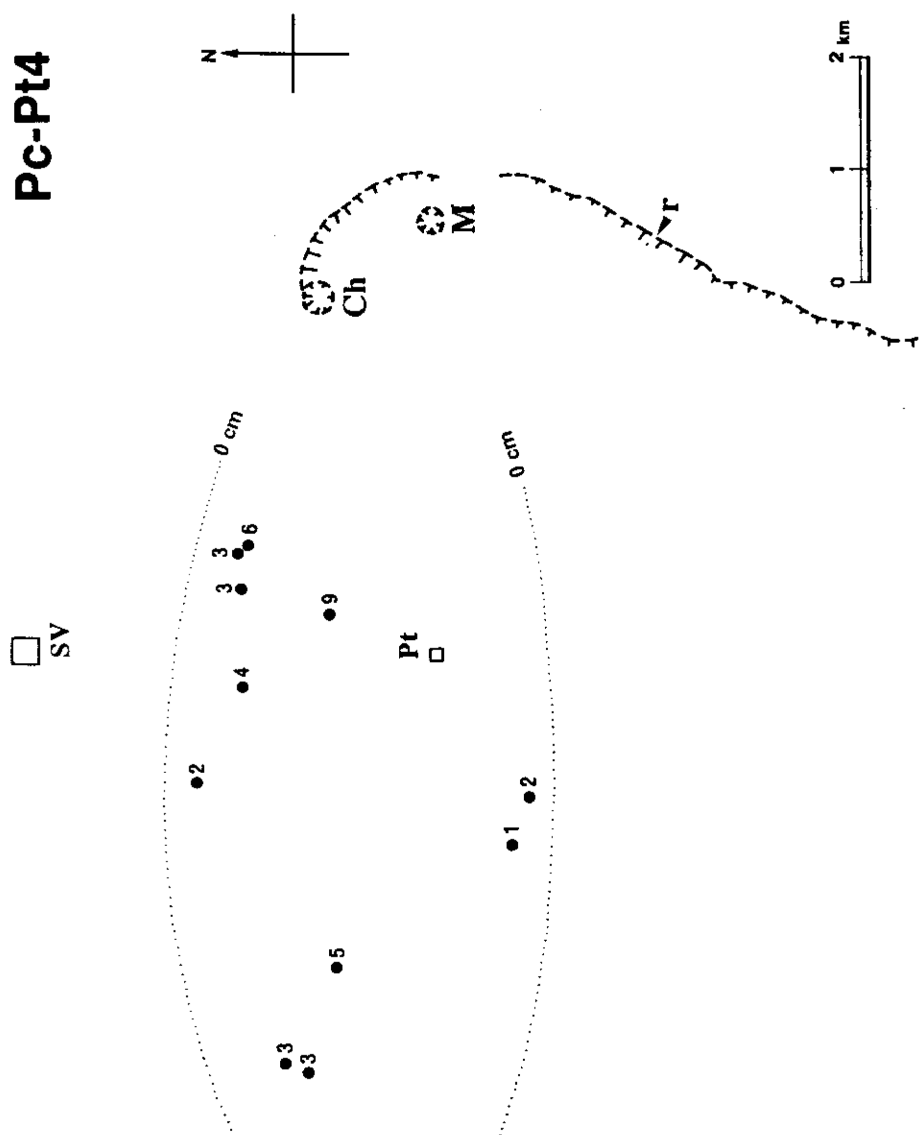


Fig. 6-6 Isopach map of the Pc-Pt4 scoria-fall (unit : cm). Abbreviations are the same as Fig. 6-1.

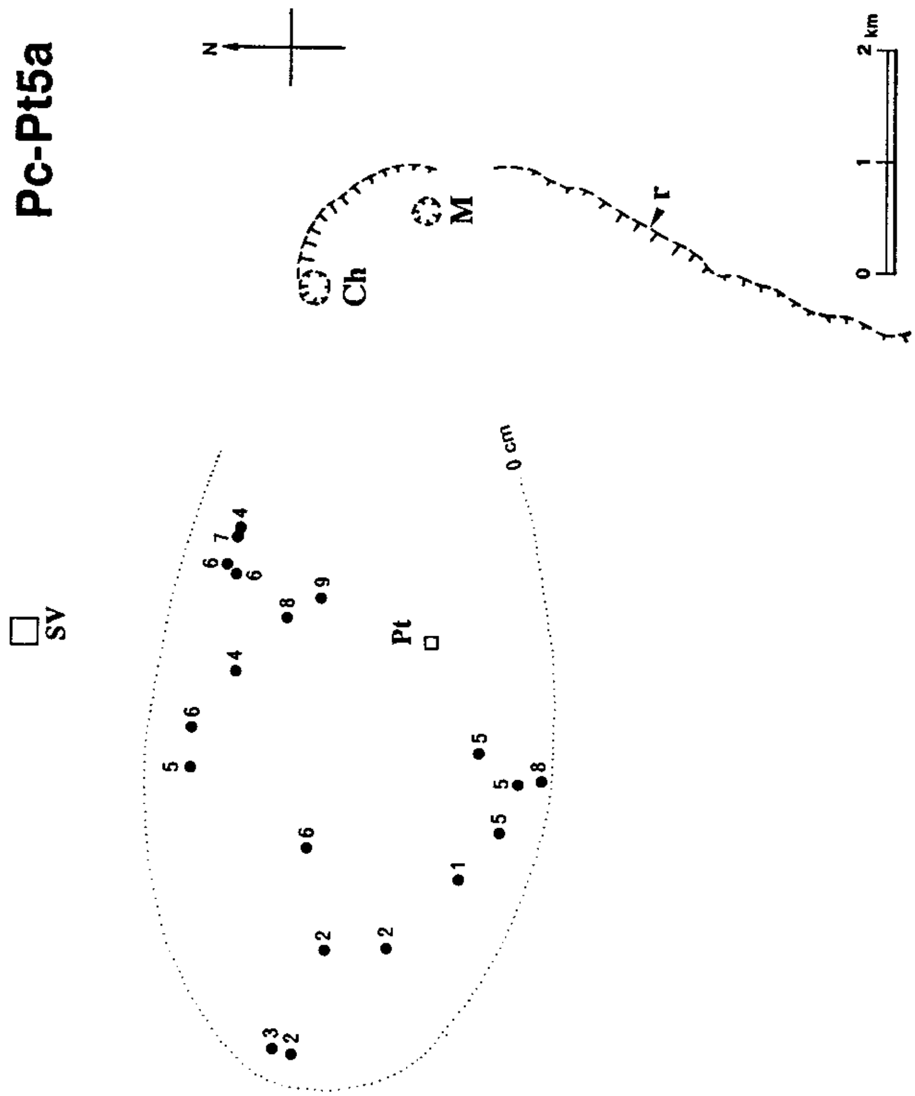


Fig. 6-7-1 Isopach map of the scoria-fall of the Pc-Pt5a unit (unit : cm). Abbreviations are the same as Fig. 6-1.

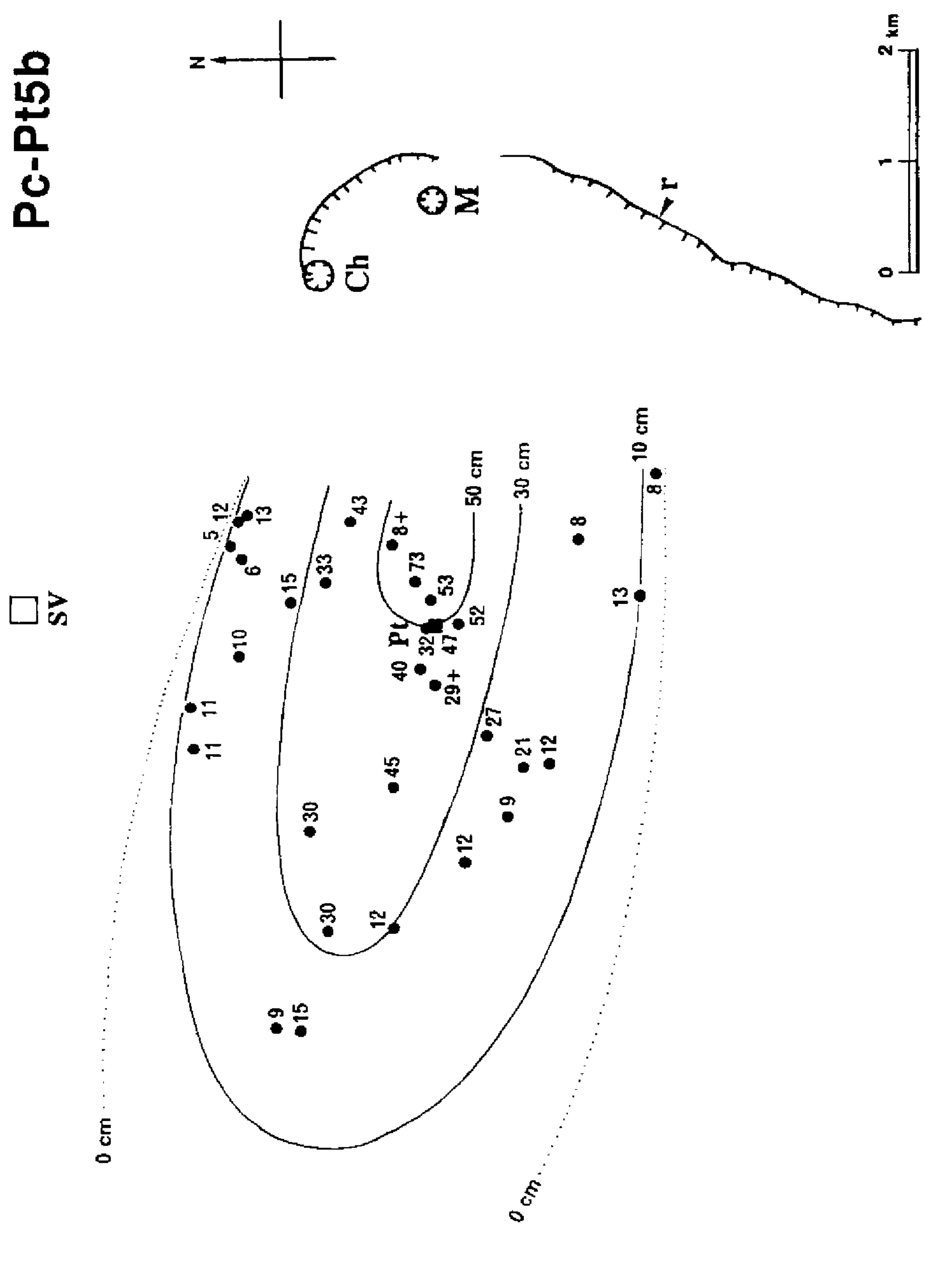
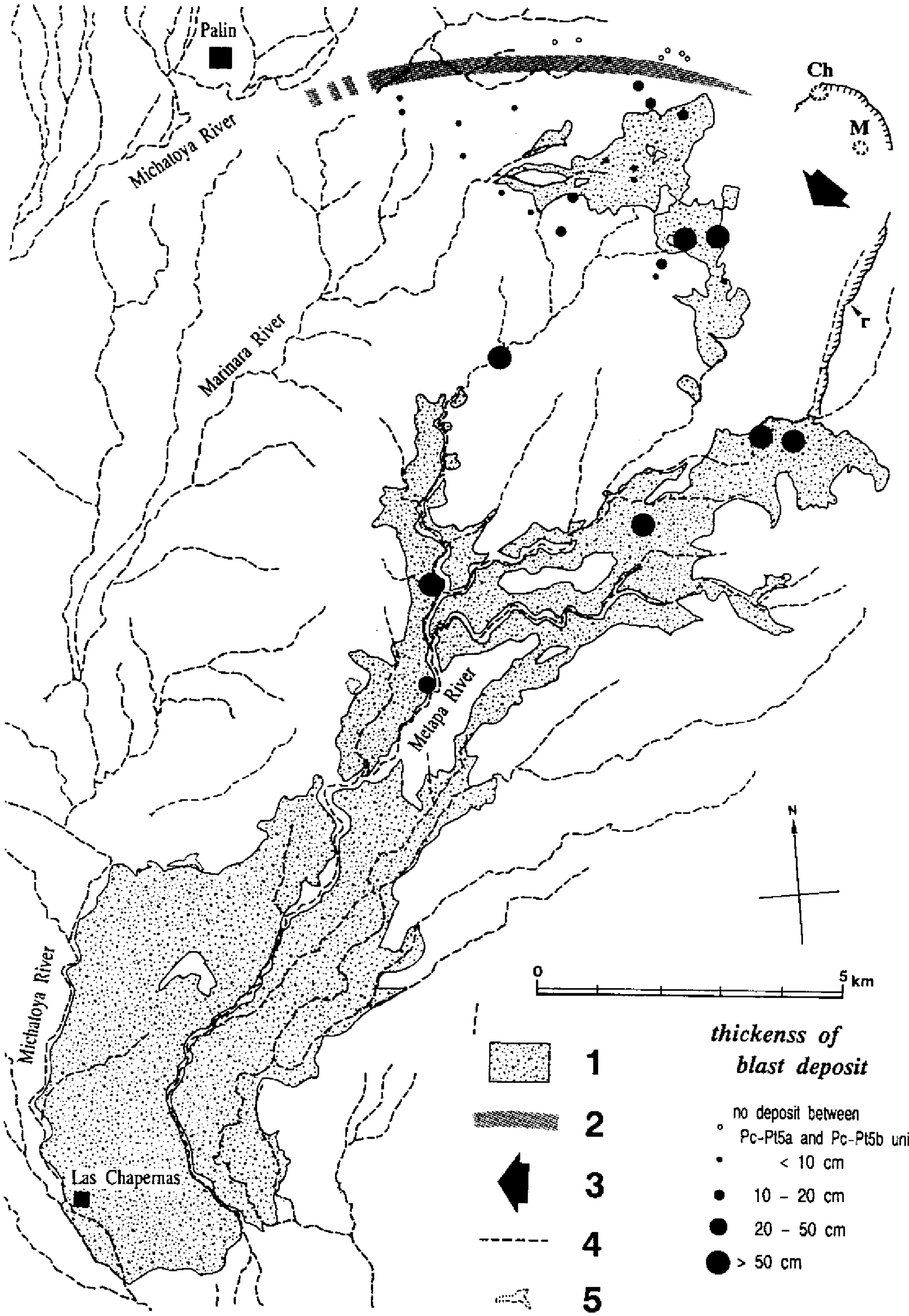


Fig. 6-7-2 Isopach map of the scoria-fall of the Pc-Pt5b unit (unit: cm). Abbreviations are the same as Fig. 6-1.


Palin
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Marinara River
Metapa River
Michaloya River
Las Chapernas
r
N
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5 km
1
2
3
4
5
thickenss of
blast deposit
no deposit between
Pc-Pt5a and Pc-Pt5b unit
< 10 cm
10 - 20 cm
20 - 50 cm
> 50 cm

large free crystal of plagioclase covered by gray skin of volcanic glass. It is distributed around El Patrocinio and its north (Fig. 6-8-2), and its maximum thickness is 9 cm. The overlying Pc-Pt6b unit is composed of poorly vesiculated fine scoria, as much as several millimeter in diameter, and includes small lithic fragments whose surface is weathered to yellowish brown, also several millimeter in diameter. It is as much as several centimeters thick although it accumulates to a thickness of 16 cm in a place at a slope. The uppermost Pc-Pt6c unit is composed of poorly vesiculated fine scoria and lithic fragments, whose maximum size is several centimeter in diameter. On the slope underlain by debris avalanche deposit at the south flank of the volcano, this unit accumulates a thickness of more than 10 cm, but most of the distributed area, it is less than 10 cm thick. The Pc-Pt6b and the Pc-Pt6c unit is distributed more southerly than the underlying Pc-Pt6a unit, their dispersal axes trend to the SW from the volcano (Fig. 6-8-3).

(9) The Pc-Pt7 scoria-fall

The Pc-Pt7 scoria-fall is laid several centimeters above the Pc-Pt6 scoria-fall (Fig. 7) Its dispersal lobe extends to the WSW (Fig. 6-9). It is observed as a thicker layer around El Patrocinio and to the south, its maximum thickness is more than 30 cm. This layer comprises two units. The lower stratified unit, Pc-Pt7a, is composed of coarse scoriaceous ash and scoria lapilli ranging from several millimeters to 2 cm in diameter, and multiply graded. In some places, the stratified structure is not clear or varies to be massive, so that it is observed as a unit composed of finer and less sorted grain than that of the overlying unit. The upper unit, Pc-Pt7b, is composed of vesiculated coarse scoria lapilli, about 2 to 3 cm in diameter. The scoria is originally metallic black, but changes to dark gray or yellowish dark gray in many outcrops. Large free crystals of plagioclase with gray skin of volcanic glass, ca 2-3 cm in size, are contained abundantly in the unit.

(10) The Pc-Pt8 scoria-fall

The Pc-Pt8 scoria-fall comprises a number of fall units, A basal unit rich in scoria observed commonly in most of the outcrops and overlying other units of ash hardly identifiable correlatively among the outcrops. The basal unit is thinly bedded to a thickness of several centimeters, and composed of dark gray scoria lapilli ranging from several millimeter to 2 cm in size in the major part of the area. On the north of the Cerro Chino cone, however, it is thick, ranging from about 20 cm to 85 cm, and its maximum particle size is more than 4 cm. The overlying units predominates well-

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Fig. 6-7-3 Areal distribution of the debris avalanche and the blast deposit. 1 ; debris avalanche deposit, 2 ; dispersal limit of blast deposit, 3 ; direction of blast, 4 ; river, 5 ; pond. Other abbreviations in the map are the same as Fig. 6-1.

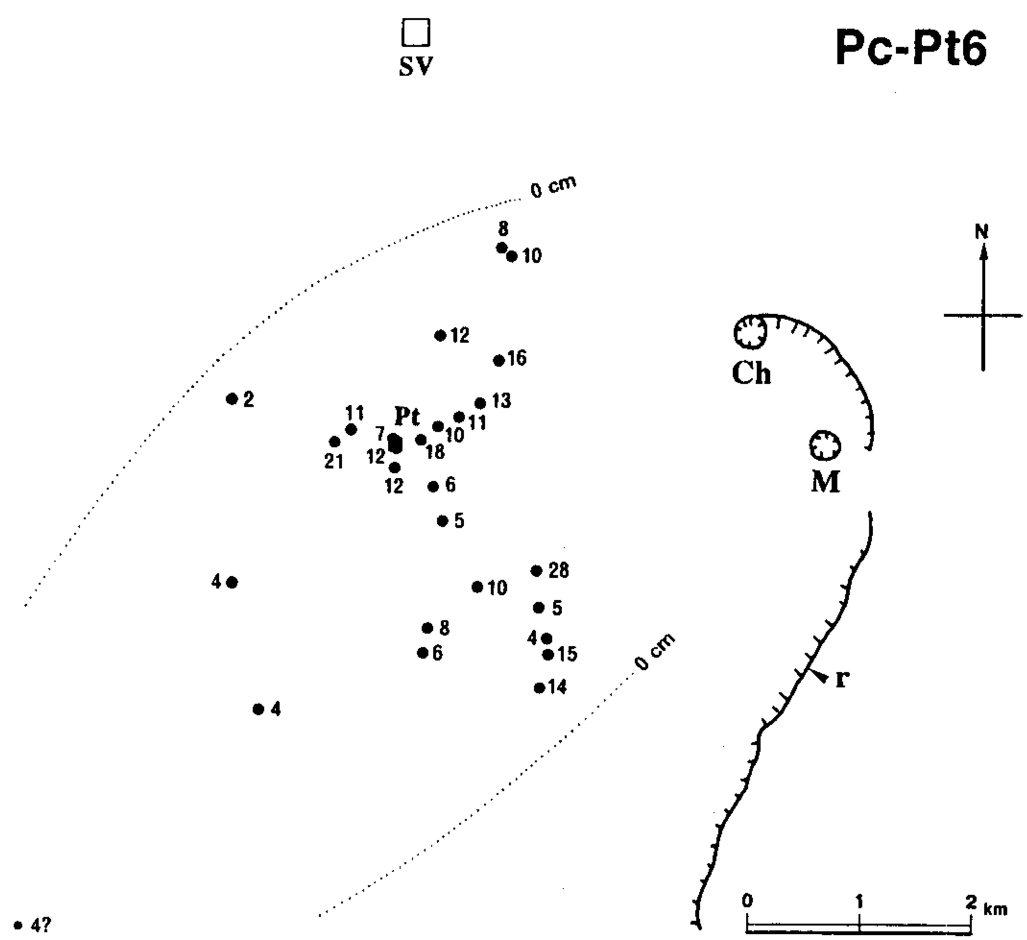

Fig. 6-8-1 Isopach map of the Pc-Pt6 scoria-fall (unit: cm). Abbreviations are the same as Fig. 6-1.

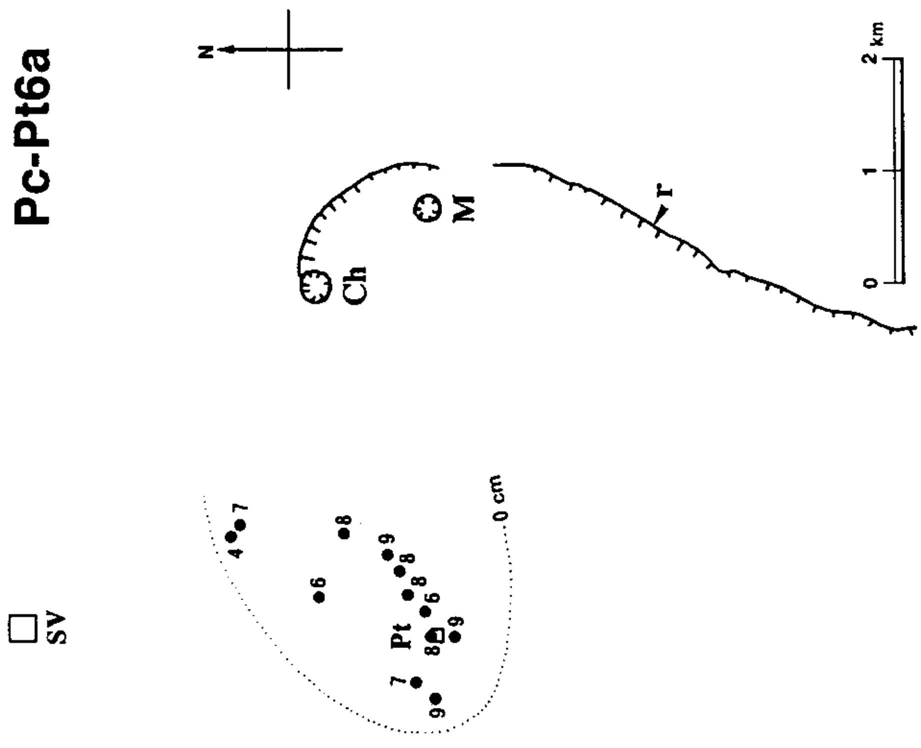

Fig. 6-8-2 Isopach map of the scoria-fall of the Pc-Pt6a unit (unit : cm). Abbreviations are the same as Fig. 6-1.

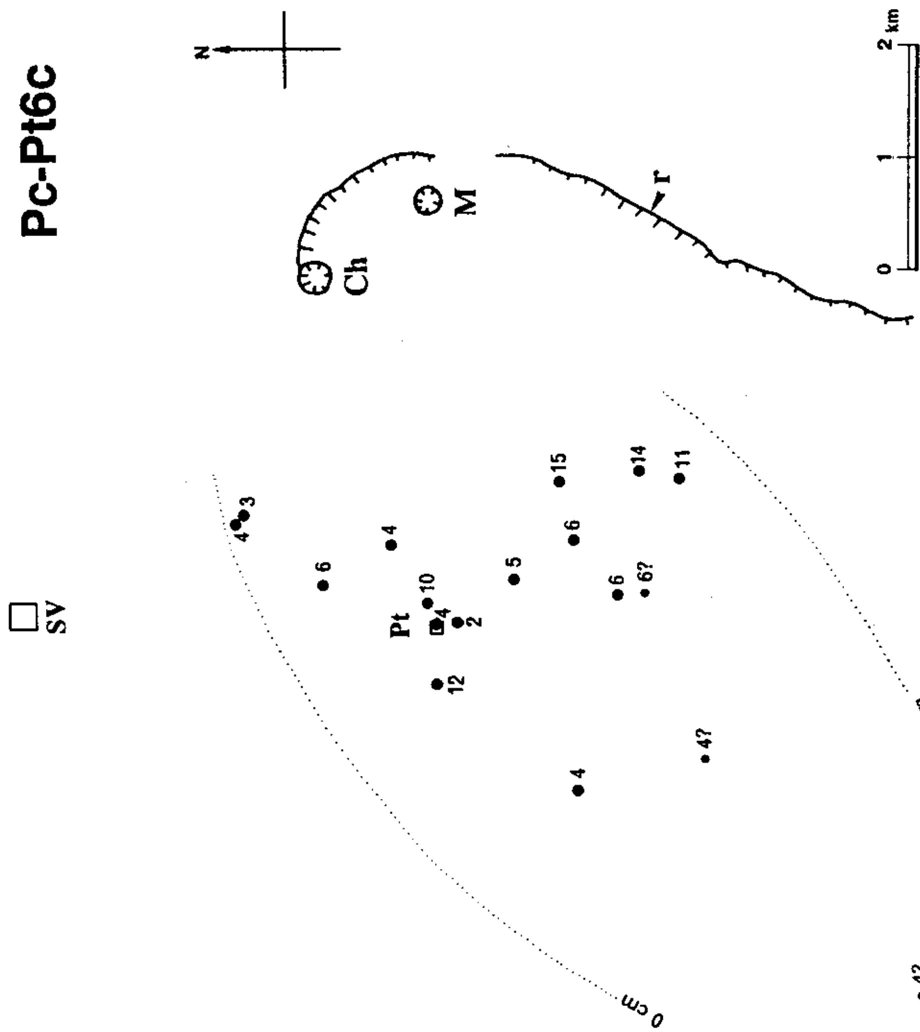

Fig. 6-8-3 Isopach map of the scoria-fall (unit : cm) of the Pc-Pt6c unit (unit : cm). Abbreviations are the same as Fig. 6-1.

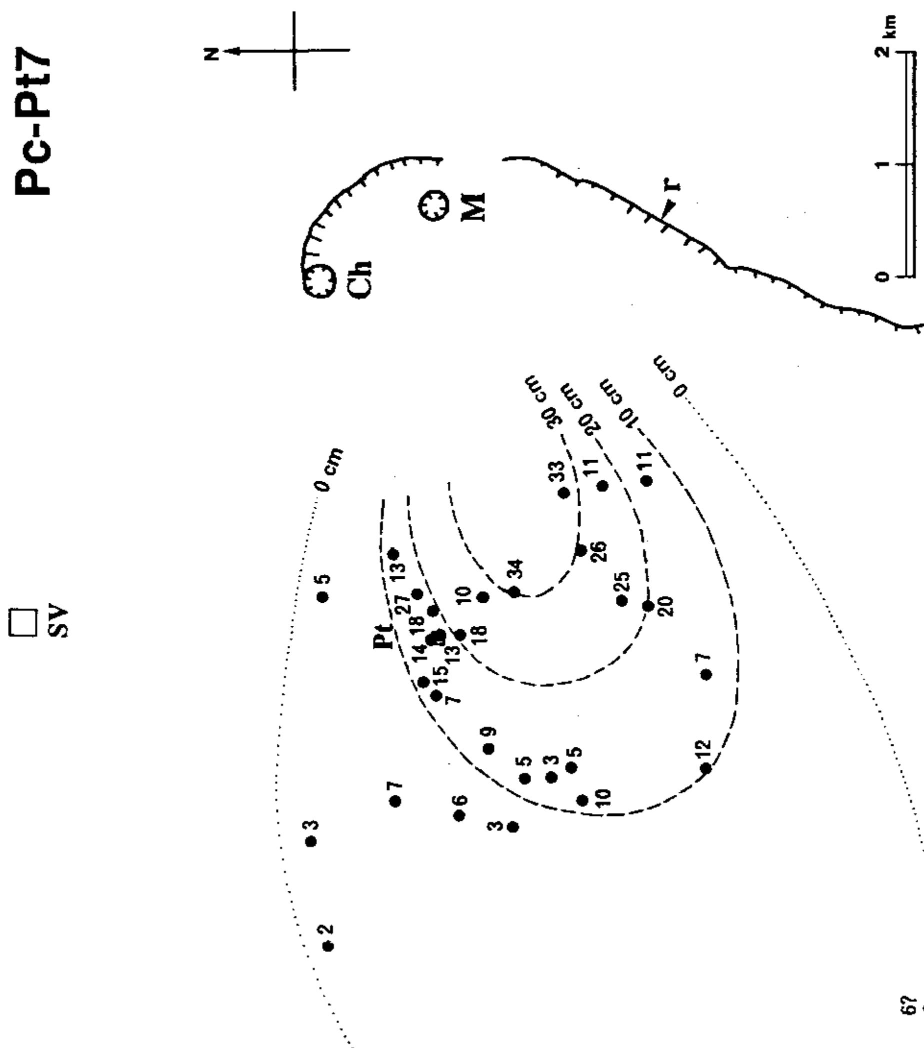

Fig. 6-9 Isopach map of the Pc-Pt7 scoria-fall (unit : cm). Abbreviations are the same as Fig. 6-1.

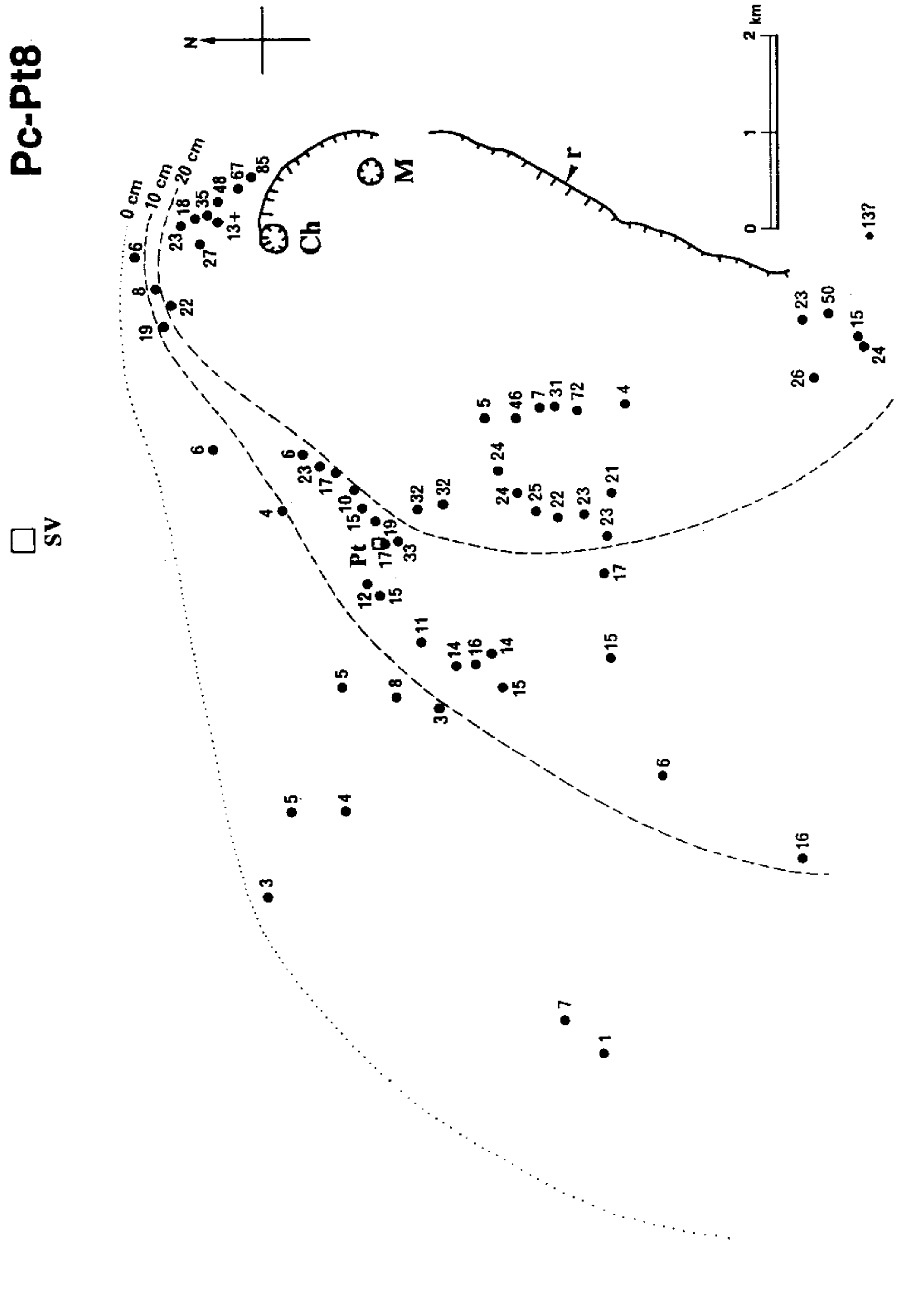

Fig. 6-10 Isopach map of the Pc-Pt8 scoria-fall (unit : cm). Abbreviations are the same as Fig. 6-1.

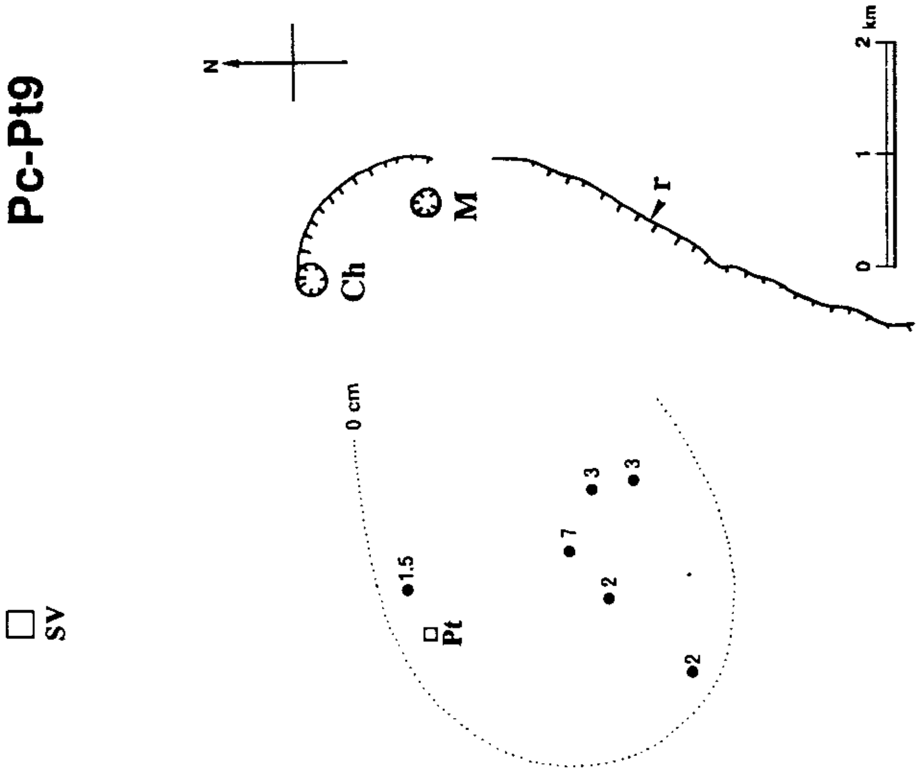

Fig. 6-11 Isopach map of the Pc-Pt9 scoria-fall (unit : cm). Abbreviations are the same as Fig. 6-1.

sorted, sand-sized volcanic ash. Some units of them are dark gray, fine- to coarse-sand-sized ash, occasionally including reddish brown coarse-grained volcanic ash or several-millimeter-sized gray accretionary lapilli. Others are light brown to light gray finer ash, occasionally including larger accretionary lapilli, several millimeter to 1 cm. Upward variation in facies from dark sand to light brown or light gray ash appears twice, or more, at the same outcrop.

The Pc-Pt8 scoria-fall is laid 4 to 10 centimeters above the Pc-Pt7 scoria layer (Fig. 7). The black to dark brown organic soil, or occasionally brown volcanic ash soil, is observed between them. Small pieces of charcoal are observed under the layer in many places. The dispersal axis of the Pc-Pt8 layer mostly trends to the south from the Cerro Chino crater (Fig. 6-10).

(11) The Pc-Pt9 scoria-fall

The Pc-Pt9 scoria-fall is composed of dark gray to bluish dark gray scoria lapilli ranging from several millimeter to 1-2 cm in diameter. It is thinly bedded, and its maximum thickness is only 4 cm It is distributed restrictedly to the SW from the volcano (Fig. 6-11). It is laid several centimeters, or less, above the Pc-Pt8 scoria layer (Fig. 7).

(12) The Pc-Pt10 scoria-fall

The Pc-Pt10 scoria-fall is laid several centimeters above the Pc-Pt9 scoria-fall (Fig. 7). It comprises a major unit and overlying other two minor units.

The lowermost Pc-Pt10a unit accumulates thickly but consists of single fall unit It is composed of bluish black to dark gray coarse scoria lapilli ranging from 1 to several centimeters in diameter, in most of the area In the outcrop 3 km west-southwest of the MacKenney cone, it is deposited to a thickness of 92 cm and contains scoria blocks, whose maximum size is 16 cm. Most of the scoria consist of dark red colored, vesiculated inside part, and blackish colored, poorly vesiculated outside part. Large free crystals of plagioclase with gray skin of volcanic glass, whose maximum size is 3 cm, are contained abundantly in the unit. The scoria is dispersed over 10 km in distance to the WSW from the volcano (Fig. 6-12).

The overlying Pc-Pt10b unit is composed of medium-sand-sized, altered reddish brown and dark gray colored, scoriaceous volcanic ash. It is only 2 to 3 cm thick The uppermost Pc-Pt10c unit is composed of coarse-sand-sized dark gray scoriaceous ash and its thickness varies from several to 10 centimeters. The upper two minor units are observed around El Patrocinio and traceable along the dispersal axis of the Pc-Pt10a

(13) The Pc-Pt11 scoria-fall

The Pc-Pt11 scoria-fall is composed of black to dark gray finer scoria lapilli ranging from several millimeters to a couple of centimeters in diameter. It is laid several centimeters above the Pc-Pt10 scoria-fall. It is a thin bed and its maximum thickness is only several centimeters. At several outcrops, however, it can be divided into two units by the presence of interlayered black or dark brown sandy soil. The dispersal lobe of the whole layer extends to the west from the volcano (Fig. 6-13).

(14) The Pc-Pt12 scoria-fall

The Pc-Pt12 scoria-fall comprises three units. The lowermost Pc-Pt12a unit is composed of well-vesiculated fine scoria lapilli ranging several millimeter to 2 cm in diameter, the color of which is bluish black to dark gray. In a few places, this unit intercalates a lamina of orangish brown ash in the middle. The overlying Pc-Pt12b unit comprises several beds; alternating thin beds of orangish brown finer ash including accretionary lapilli and coarse-sand-sized scoriaceous ash containing orangish brown and dark gray grain, overlain by brown, poorly sorted volcanic ash including accretionary lapilli. Although these stratified structure is clear around the El Patrocinio, the unit changes to be massive, orangish brown or brown loamy weathered ash, away from the distribution axis. The uppermost Pc-Pt12c unit is composed of black to dark gray finer scoria lapilli, as much as 2 cm in diameter, whose degree of vesiculation is medial. This unit comprises many fall units.

In the area close to the Cerro Chino crater, the thickness and the grain size of the scoria is markedly large (Fig. 6-14-1, -2 & -3), and amount of large ballistic bombs more than 2 m in size are observed on the ground. These facts indicate that the origin of the Pc-Pt12 scoria is the Cerro Chino crater. The dispersal lobe of the Pc-Pt12a unit extends to the WSW from the Cerro Chino crater (Fig. 6-14-2) and the dispersal trend of the Pc-Pt12c unit appears to vary from the WNW to the SW (Fig. 6-14-3). The layer is laid several centimeters above the Pc-Pt11 layer (Fig 7).

At a outcrop on the road from Los Rios Village to Finca Los Jazmines, the whole layer of the Pc-Pt12 scoria-fall is covered by the lava extending from the Cerro Chino to the WSW for 5 km (Fig. 7), and its bedform is transformed irregularly. On the other hand, the lava is covered by the pyroclastic deposit of the Cerro Chino cone. Consequently, this lava is concluded to have been produced at the eruption of the Pc-Pt12 scoria-fall, probably during the scoria eruption of the Pc-Pt12c unit. The lava was supposed to flow so slowly that it reached there after the fallout of the Pc-Pt12c scoria, and frictional force at the base of the lava flow transformed the bedform of the Pc-Pt12 layer.

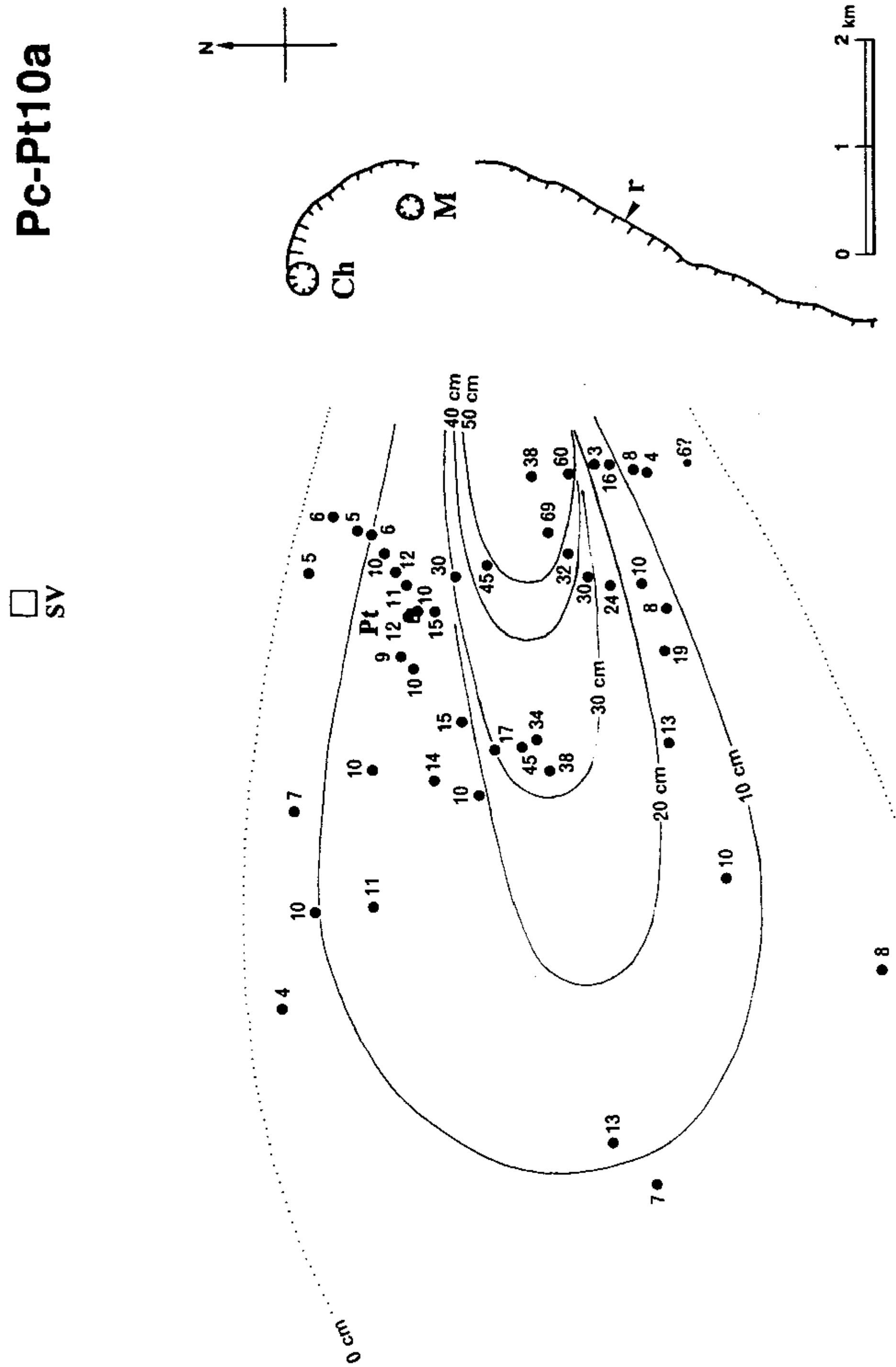

Fig. 6-12 Isopach map of the Pc-Pt10 scoria-fall (unit : cm). Abbreviations are the same as Fig. 6-1.

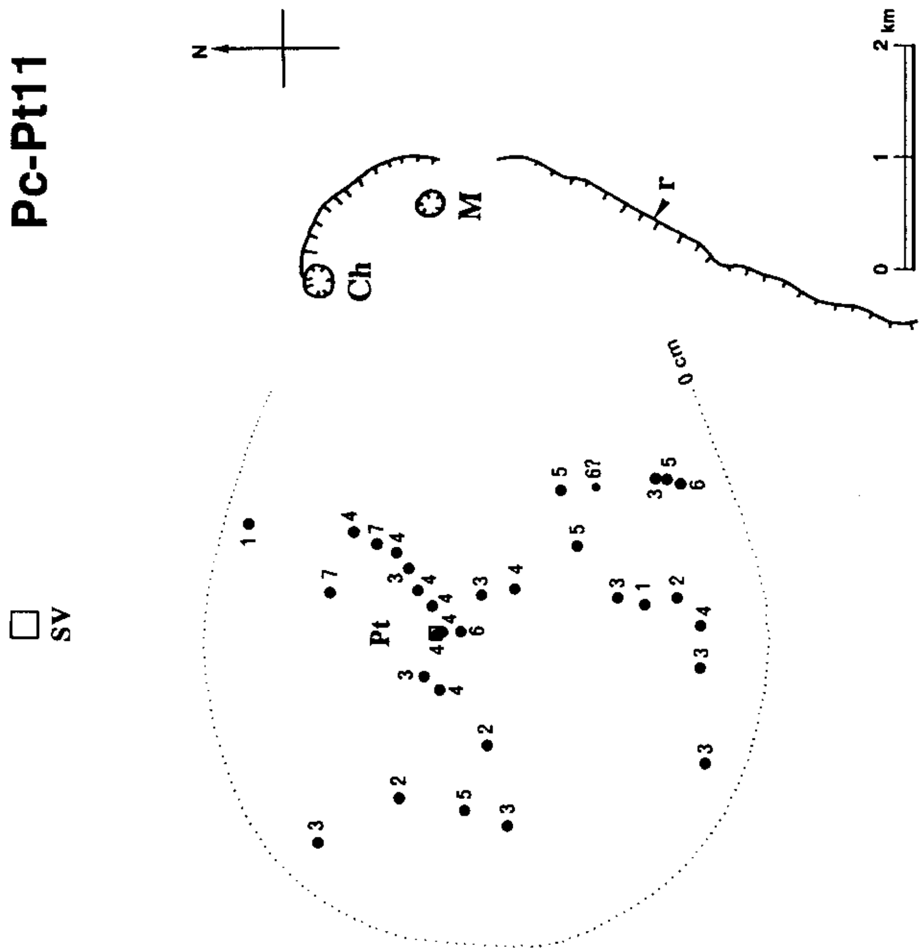

Fig. 6-13 Isopach map of the Pc-Pt11 scoria-fall (unit : cm). Abbreviations are the same as Fig. 6-1.

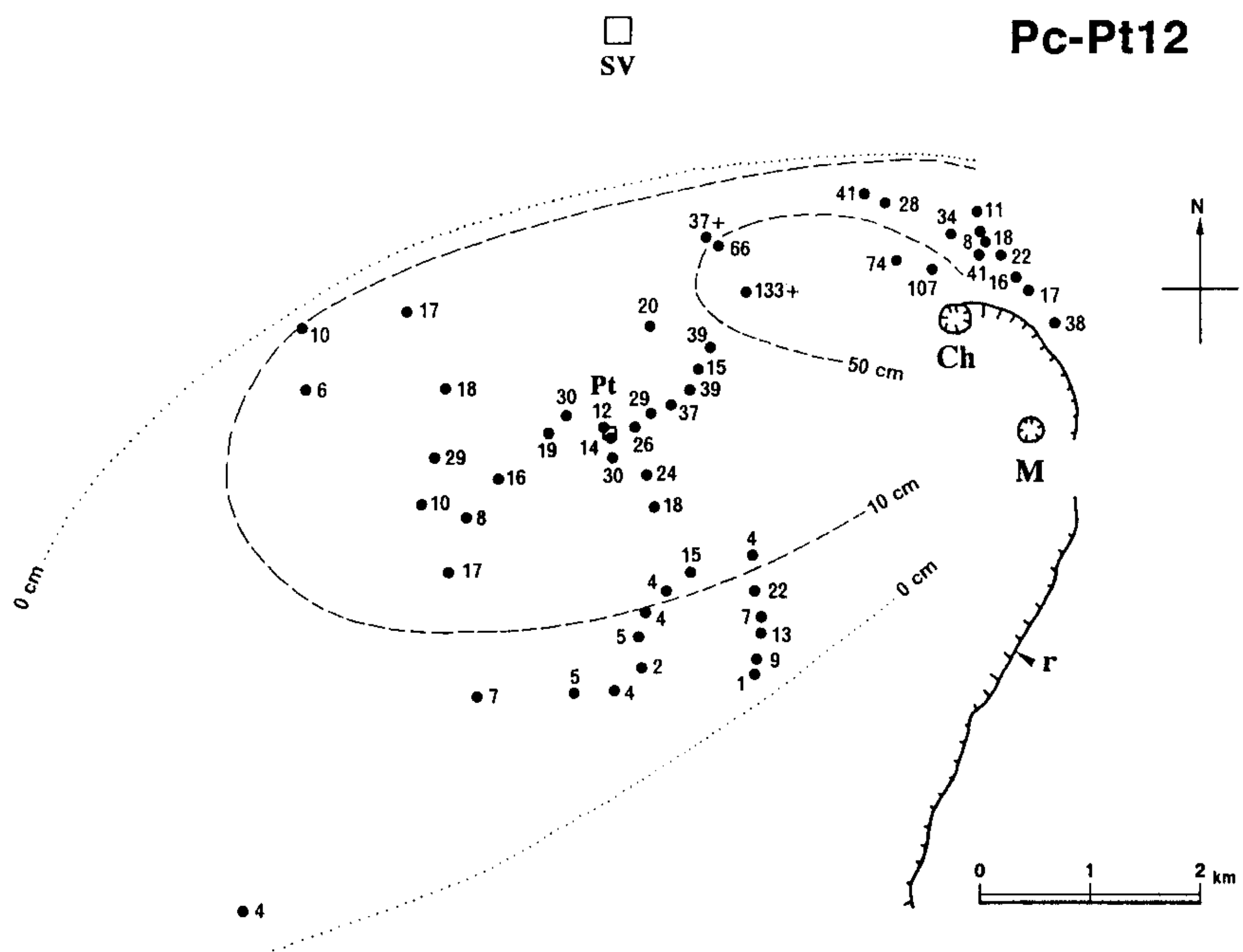

Fig. 6-14-1 Isopach map of the Pc-Pt12 scoria-fall (unit : cm). Abbreviations are the same as Fig. 6-1.

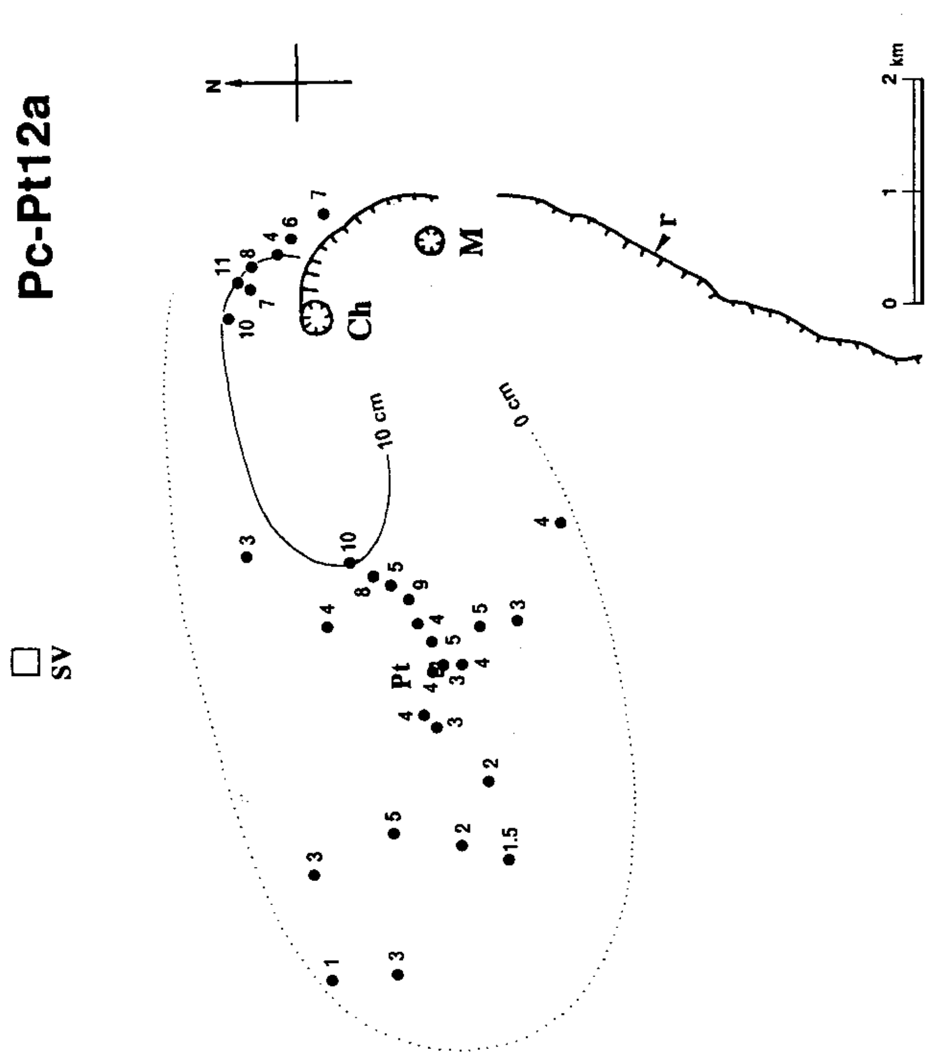

Fig. 6-14-2 Isopach map of the scoria-fall of the Pc-Pt12a unit (unit: cm). Abbreviations are the same as Fig. 6-1.

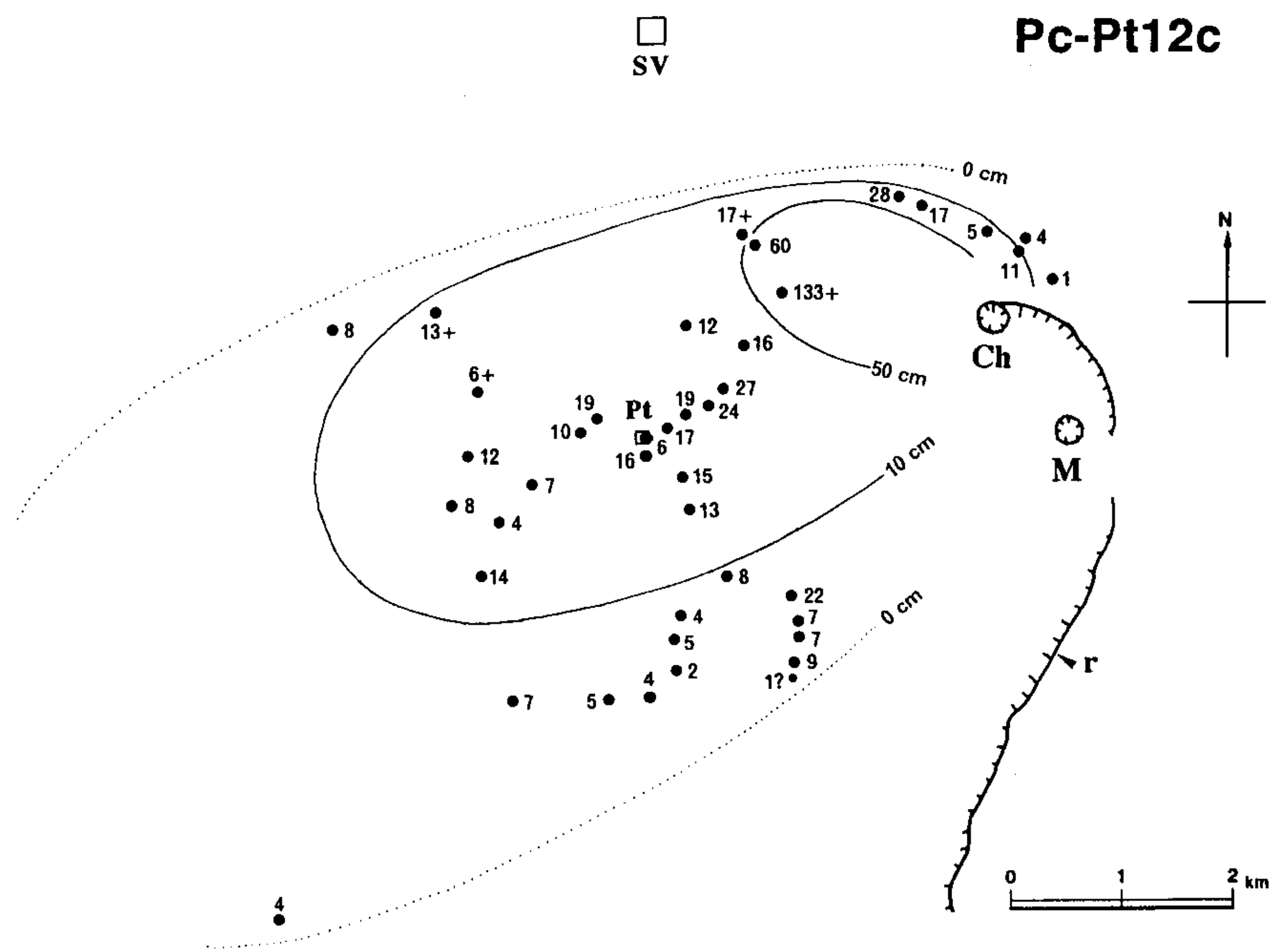

Fig. 6-14-3 Isopach map of the scoria-fall of the Pc-Pt12c unit (unit : cm). Abbreviations are the same as Fig. 6-1.

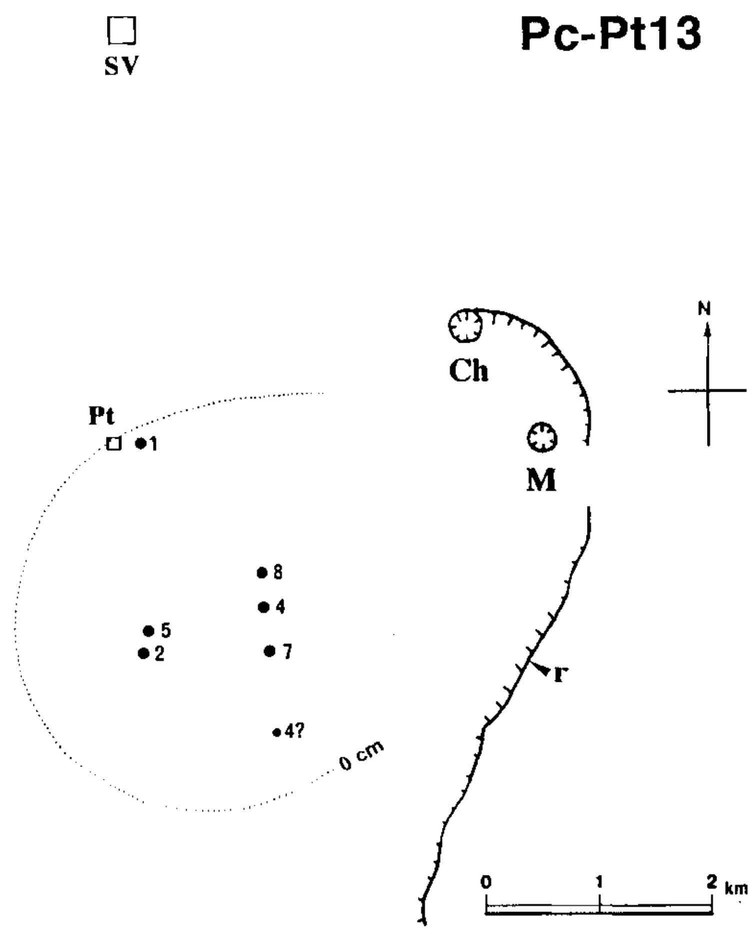

Fig. 6-15 Isopach map of the Pc-Pt13 scoria fall (unit : cm). Abbreviations are the same as Fig. 6-1.

(15) The Pc-Pt13 scoria-fall

The Pc-Pt13 scoria-fall is thinly layered, and its maximum thickness is only 7 cm. It is fine-sand-sized dark gray fine ash underlain by a lamina of coarser scoria lapilli as much as several millimeters in diameter. It is laid 5 to 15 cm above the Pc-Pt12 and 4 to 13 cm under the ground (Fig. 7). Its dispersal area, south of the El Patrocinio, is very small (Fig. 6-15).

(16) Scoria-fall in the 20th century

In 1987 and 1991, explosive eruption occurred at the top of the MacKenney cone. Bluish black scoria lapilli, ranging from one to several centimeters in diameter, is deposited to a thickness of several to 20 cm. Although this deposit originates from two or more eruptions, it is difficult to identify their events at outcrops. The layer is observed in the area to the west and the southeast of the volcano. The dispersal axis trends to the WSW, not extends to the SE.

4 Eruption date

This paper reports three radiocarbon ages of charcoal samples, which suggest depositional ages of the Pc-Pt1, the Pc-Pt8 and the Pc-Pt10 scoria-fall, respectively, as shown in table 1. The chronological order of the Pc-Pt8 scoria and the Pc-Pt10 scoria is reverse to their stratigraphic relationship.

A radiocarbon date to the Pc-Pt1 scoria-fall (NU-735) suggested that the initiation of the latest eruptive stage is ca 1,500 yr B.P., which is not inconsistent with the date proposed by Kitamura (1995).

The geological data indicate that an eruption from the Cerro Chino crater caused the Pc-Pt12 scoria-fall and a lava flow extending from the origin to the west. Eggers (1971MS) described it to have occurred in A D. 1565, based on the historical interpretation of Dollfus & Mont-Serrat (1868). The radiocarbon age of the Pc-Pt10 (NU-733) appears to support it. Any distinct layer, however, is not discovered above the Pc-Pt12 scoria layer, although the 1775 eruption was accounted in historical documents as another large eruption since 1565. The eruptive scale of the Pc-Pt13 scoria-fall is too small to cause the heavy ash-fall reaching the area 30 km away from the volcano The present geological observation indicates that the scales of the latest four eruptions causing the Pc-Pt10, the Pc-Pt11, the Pc-Pt12, the Pc-Pt13 scoria-falls are comparatively large, small, large and much small, respectively This sequence approximately agrees with the context of the historical eruptions in 1565, the 17th century, 1775 and the 19th century, although the Pc-Pt10 scoria-fall was not necessarily supposed to be erupted from the Cerro Chino. Moreover, the brown loamy volcanic ash soil above the Pc-Pt12 scoria layer is too thin to have been deposited since 1565; It should

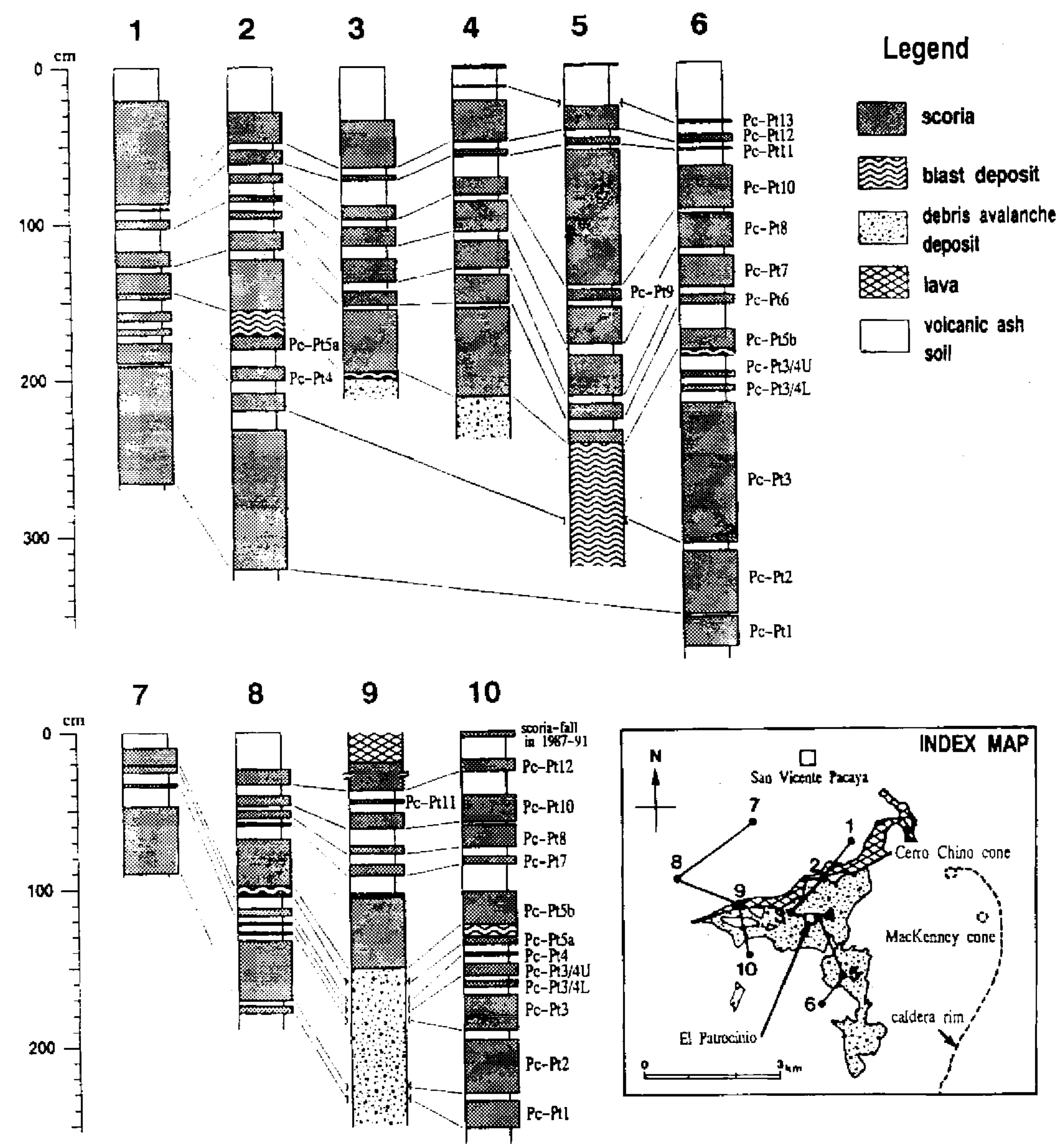

Fig. 7 Stratigraphic sections observed around El Patrocinio.
Note that the relationship among debris avalanche deposit, blast deposit, and Pc-Pt5a and Pc-Pt5b scoria-fall.

accumulate more thickly if depositional rate of volcanic ash soil between the Pc-Pt1 and the Pc-Pt8 scoria layer could be assumed to be constant (Table 1).

5 The eruptive history of the modern Pacaya composite volcano

From grain size, depositional structure and distribution of tephra obtainable by

Table 1. Radiocarbon dates of scoria layers around the Pcacaya Volcano.

Dating No.*	Age (yr. B.P.)	Cal. Age (cal. yr. B.P.)**	Sampling Location
NU-733	745±70	733 (669) 574	under the Pc-Pt10 scori-fall
NU-734	595±70	657 (619, 605, 556) 523	under the Pc-Pt8 scoria-fall
NU-735	1,555±80	1,534 (1,412) 1,313	under the Pc-Pt1 scoria-fall

* Determined by Dr K. Omoto at Nihon University
** Calibrated by the method of Stuiver & Becker (1992).

the field observation, framework of eruptive history can be reconstructed; Grain size of a bed or unit of tephra layer is an indicator of the mode of an eruption phase and stratigraphic sequence of units of a tephra layer indicates transition of an eruption, normally comprising many eruption phases and lasting for several hours to several years, occasionally several decades; Scale of an eruption is obtained from distribution of tephra. In this report, the major part of the eruptive history of the Pacaya volcano is demonstrated as follows by the present field observation.

After the longer repose period as long as 1,000 to 2,000 years, the activity of Pacaya Volcano entered into an eruptive stage and many eruptions occurred repeatedly to form the fifteen scoria layers of the Pacaya-El Patrocinio scoria group (Kitamura 1955). A radiocarbon date (NU-735) suggests that this stage initiated about 1,500 yr. B.P.

The first eruption of the eruptive stage is small, comprises many eruption phase and fluctuates between a magmatic, partially phreatomagmatic, phase and a magmatic phase, emplacing stratified fine ash and scoria lapilli. These eruption caused the Pc-Pt1 scoria-fall layer.

The second eruption is comparatively large in the fifteen eruptions in the latest stage. It consists of many eruption phases, mostly magmatic but partially phreatomagmatic in the end of the eruption, which caused the thick and stratified Pc-Pt2 scoria layer. It was supposed to continue for longer period because all fall-units are not distributed to the same direction.

The eruption causing the Pc-Pt3 scoria-fall is also large and comprises many eruption phases. The sequence of eruption phase and distribution, however, are not known in detail, because this scoria was eroded by the collapse of the volcano or capped by the debris avalanche in most of its distributed area.

The eruptions emplacing the Pc-Pt3/4L, the Pc-Pt3/4U and the Pc-Pt4 scoria-falls are magmatic and small. The Pc-Pt4's eruption is supposed to be accompanied with preceding tiny eruption phases or explosions that produced amount of altered reddish scoria in the vent.

The eruption of the Pc-Pt5 scoria is accompanied with the collapse of the volcanic edifice. The first magmatic eruption phase is not large, and emplaced the scoriaceous ash of the Pc-Pt5a unit. Next eruption phase collapsed the upper part of the volcano. The gigantic block moved down to the southwest, fractured and transformed to be debris avalanche. The avalanche flowed over the south and the west of the volcano into the Metapa River valley, the Guachipilin Stream valley and an upper tributary of Marinala River. It formed hummocky terrain not only at the foot of the volcano but also along the former two valleys. Blows of the directed blast to the southwest, generated by phreatic explosions, followed the collapse. A small and magmatic eruption occurred in the late stage of the explosions and emplaced very coarse scoria lapilli interlayered at the upper part of the blast deposit. Following large and effusive magmatic eruption phase emplaced coarse scoria of the Pc-Pt5b unit. In the early stage of the phase, not only scoria but also clayey material that originates from the debris avalanche and the blast were erupted, and scoria with clay skin was formed.

Next eruption producing the Pc-Pt6 scoria-fall comprises three phases. The first magmatic eruption phase emplaced vesiculated coarse scoria lapilli to the west. The eruption changed to be more phreatomagmatic, and finer scoria containing small lithic fragments, whose surface was altered to yellowish color, were dispersed to the SW.

The Pc-Pt7 scoria-fall was also deposited in the several eruption phases. In the early phases of the eruption, the eruption energy fluctuated and multiply graded structure was formed in the lower part of the Pc-Pt7. In the late half of the eruption, the eruption became much more effusive and emplaced vesiculated coarse scoria lapilli.

The Pc-Pt8 layer was produced by a number of eruption phases. At first, vesiculated coarse scoria lapilli was scattered to the WSW from the Cerro Chino crater by small and magmatic eruption. A number of small phreatic explosions and small phreatomagmatic, or occasionally magmatic, eruptions occurred repeatedly to emplace a large volume of sand-sized scoriaceous ash or gray to yellowish brown fine ash. The stratified many fall units of the Pc-Pt8 layer suggests that this eruptive activity continued for a longer period.

Very small and magmatic eruption emplaced the Pc-Pt9 scoria-fall, which was followed by the eruption of the Pc-Pt10 scoria-fall with short repose.

Major part of the Pc-Pt10 scoria-fall was formed by a single magmatic eruption phase. It was very large, so that the very coarse scoria lapilli was widely dispersed. Two magmatic eruption phases followed but these were very small. The earlier eruption phase of the two is probably accompanied with preceding tiny eruption phases or explosions to generate reddish scoriaceous ash in the vent.

The Pc-Pt11 scoria layer was caused by small magmatic eruption. Its eruption probably contains two or more eruption phases because the layer is observed to be divided into two units at several outcrops.

The Pc-Pt12 scoria-fall originates from the Cerro Chino crater because the thickness and the grain size increase markedly toward the crater. The first eruption phase was magmatic, so that vesiculated scoria lapilli was dispersed to the WSW. The next eruption phase varied from magmatic to phreatic, emplaced deposit ranges from sand-sized scoriaceous ash containing reddish scoriaceous grain to yellowish brown ash with small accretionary lapilli. The last eruption phase is magmatic, scattering out a large volume of less vesiculated finer scoria widely. The energy of this phase fluctuated, so that multiply graded scoria layer was formed. The lava flow also occurred in this eruption, and extended to the WSW.

The last eruption before the 20th century is very small. A magmatic eruption emplaced the fine scoria and following magmatic or partially phreatomagmatic eruption produced overlying scoriaceous fine ash.

Three radiocarbon dates are obtained in this study. A date suggests that the latest eruptive stage initiated 1,500 years before present. The others propose that the uppermost several scoria-falls have been erupted since the 16th century. Further radiocarbon dating, historical eruption record and archeological data are needed to determine depositional date of each scoria-fall in more detail.

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