THE LATE QUATERNARY TEPHRA LAYERS FROM THE CALDERA VOLCANOES IN AND AROUND KAGOSHIMA BAY, SOUTHERN KYUSHU, JAPAN

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Abstract The Aira, Ata and Kikai calderas of Kagoshima Bay have erupted more than twenty silicic tehra formations including more than fifty tephra falls and flows (about 1,000 km^3 in total volume) in the last 150 ka. On the basis of the sequence of eruptive phases which have many kinds of eruption types, the eruptive cycles of these caldera volcanoes are grouped into three types: 1) a plinian cycle (composed of a single plinian phase, or a plinian phase and a moderate-scale pyroclastic flow phase); 2) a large-scale pyroclastic flow cycle (composed of a plinian phase followed by phreatomagmatic, phreatoplinian, moderate-scale pyroclastic flow phases, and then a large-scale pyroclastic flow phase); and 3) a moderate-scale pyroclastic flow cycle (composed of a single moderate-pyroclastic flow phase). A "multi-cycle" lasts for about 50 ka, and consists of several plinian cycles first preceded a large-scale pyroclastic flow cycle, which is followed by a couple of moderate-scale pyroclastic flow cycles. The multi-cycle suggests evolution of a large magma chamber; the plinian cycles resulted from pressure of magma filling the chamber, and the large-scale pyroclastic flow cycle caused the pressure to decrease rapidly. The low magma pressure generated a few moderate-scale pyroclastic flow cycles.

Key words: caldera volcanoes, tephra layers, eruptive cycles, late Quaternary, Kagoshima Bay

1. Introduction

Kagoshima Graben (Tsuyuki, 1969) in southern Kyusu includes the Kakuto, Kobayashi, Aira, Wakamiko, Ata, Ikeda, and Kikai Calderas, and other unidentified depressions (Fig. 1). From these depressions, many tephra layers have been erupted and thickly deposited around the graben during the Quaternary period. The late Quaternary tephra

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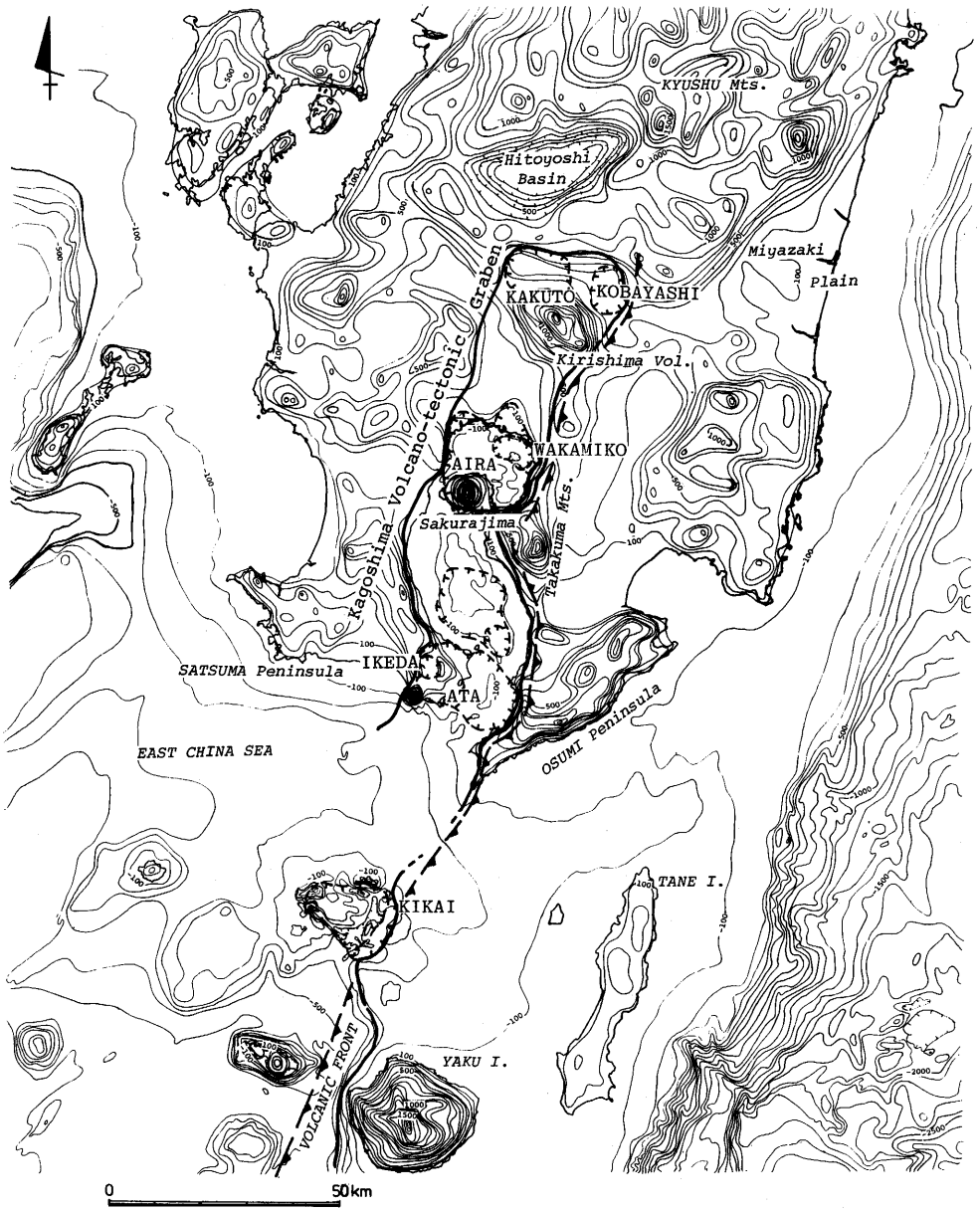

Fig. 1 Geomorphological map of southern Kyushu
The summit level map on land after unpublished data by Professor T. Okayama
Contour interval is 100 m

includes several large-scale pyroclastic flows and pumice falls which erupted from the Aira, Ata and Kikai Calderas in Kagoshima Bay in the southern half of the graben. Kagoshima Bay and its environs are therefore a significant region to study the nature of explosive caldera-forming volcanism.

Previous works

Preliminary studies on the identification of the calderas and their deposists

Yamaguchi (1937, 1938a, b) published a series of reports on petrography of "Hai-ishi" and "Shirasu" deposits around Kagosima Bay. Matumoto (1943) discovered the three gigantic calderas, Aira, Ata, and Kikai, and described "mud-lavas" (the "Hai-ishi" and "Shirasu" deposits) erupted from the calderas. Taneda (1954, 1957) and Taneda *et al.* (1957) interpreted the "Hai-ishi" and "Shirasu" deposits as the deposits of nuées ardentes or pumice flows (pyroclastic flows) on the basis of grain-size analysis.

Stratigraphical studies on pyroclastic flow deposits and caldera-filling sediments

Kuwano *et al.* (1959), Gohara and Komori (1960, 1961, 1962), Ota (1963), Ota and Kawachi (1965), and Ota and Kino (1965) provided descriptions and stratigraphy of two late Pleistocene large-scale pyroclastic flow deposits: Aira (Ito) and Ata pyroclastic flow deposits on the Osumi Peninsula. Sawamura (1956), Ota (1966, 1967), Taneda and Miyachi (1969), Aramaki (1969), and Ui (1967, 1971) reported on several pyroclastic flow deposits underlying the Ito and Ata pyroclastic flows around Kagoshima Bay.

Aramaki and Ui (1976), and Aramaki (1977) correlated many pyroclastic flow deposits in southern Kyushu by means of the Ca-Mg-Fe ratios of the specific phenocrysts, and identified more than fifty stratigraphic units. Miyachi (1987) also correlated the pyroclastic flow deposits on the basis of their assemblage of phenocrysts and the refractive indexes of glass and some phenocrysts.

Oki and Hayasaka (1970), Oki (1974), Otsuka and Nishiinoue (1980) and Hase *et al.* (1987) described pyroclastic flow deposits of the late Pliocene to Pleistocene period and interbedded marine formations in the coastal area north of Kagoshima Bay.

Hayasaka and Oki (1971) inferred that several faults extending in N-S direction cut the basement rocks knows as the Shimanto Supergroup, at the western margin of Kagoshima Graben, based upon the data from columnar sections of wells. Shibata *et al.* (1978) estimated from the K-Ar age of a pyroclastic flow deposit cut by the faults that large-scale pyroclastic flow eruptions and downfaulting began about 3 Ma ago in Kagoshima Graben.

The Kikai Caldera in the East China Sea was first surveyed by Matumoto (1937). Recently, Machida and Arai (1978) interpreted the caldera to be the source volcano of an exceptionally far-reaching, thin pyroclastic flow called the Koya pyroclastic flow (Ui, 1973), and a wide-spread ash called the Akahoya ash. Ono *et al.* (1982) gave a detail geologic description of the caldera.

Studies on emplacement modes of pyroclastic flows

The formation and emplacement modes of pyroclastic flows were studied by volcanologists after the stratigraphic framework was established. Aramaki and Ui (1966b), Yokoyama (1970, 1972), and Aramaki (1969, 1983, 1984) studied the Ito pyroclastic flow and its related deposits, and Aramai and Ui (1966a, b), and Suzuki and Ui (1981, 1982, 1988) studied the Ata pyroclastic flow. Yokoyama (1972) thought that the Ito pyroclastic flow spread radially as a fluidized bed more than 1000 m thick. Walker *et al.* (1984), Ui *et al.* (1984) showed that the Koya pyroclastic flow (Ui, 1973), unlike Ito pyroclastic flow, was a strongly fluidized, streaky sheet-like thin body.

Identification of co-ignimbrite ash fall deposits

Machida and Arai (1976) traced a thin vitric ash layer 22-21 ka old on the basis of the refractive index of volcanic glass and phenocrysts, and determined that the ash, called the Aira-Tn ash, was erupted from the Aira Caldera and was generated from the upper part of eruptive column simultaneous with the Ito pyroclastic flow. Machida and Arai (1978, 1983) discovered other "co-ignimbrite ash fall deposits" (Sparks and Walker, 1977), the Akahoya and Kikai-Tozurahara ashes from the Kikai Caldera. These widely spread ash falls are good marker beds to correlate the Quaternary system in Japan.

Purposes of this study

Previous studies have contributed to the understanding of pyroclastic flow deposits from Kagoshima Graben. This paper also concentrates on the study of fallout tephra. The following problems are addressed in this paper:

1) Stratigraphy and features of late Quaternary tephra fall layers from the Aira, Ata, and Kikai Calderas.

Studies on tephra falls are far behind those of pyroclastic flows in southern Kyushu. A detailed tephro-stratigraphy including tephra fall layers is established in order to reconstruct the history of explosive volcanism.

2) The nature of the explosive volcanism in the calderas from which the various tephra layers erupted.

3) Relationships between gigantic eruptions and caldera formation.

2. Outline of Geologic History in and around Kagosima Graben

Geomorphological and geological setting

Kagoshima Graben is a trough-shaped volcano-tectonic depression 120-130 km long × 20-30 km wide and is trending NNE-SSW direction across the southernmost part of Kyushu Island starting from Kakuto Basin (caldera) and continuing to the East China Sea (Aramaki, 1984; see Fig. 1). The northern half of the graben is thickly buried with magmatic material erupted from the Aira Caldera and Kirishima Volcano. The trough-shaped southern part forms Kagoshima Bay. The graben appears to extend southward to the Kikai Caldera about 50 km SSW of the mouth of Kagoshima Bay.

Kagoshima Graben is in the northern end of the Ryukyu Arc, and its eastern rim corresponds to the Quaternary volcanic front. Quaternary volcanism has occurred within the 20-30 km wide graben, west of the volcanic front. The concentration of the volcanic centers is interpreted to result from steep subduction of the Philippine Sea Plate at the Ryukyu Trench east of the graben and from steep gradient of the Benioff Zone demonstrated by Seno (1977) and Shiono *et al.* (1980).

In the graben, there are five major calderas from north to south; the Kakuto, Kobayashi, Aira, Ata, and Kikai Calderas (Fig. 1). All of these features include small-scale calderas and post-caldera cones. Each caldera, about 15-20 km in diameter, is confined within the width of the graben.

Basement of Kagoshima Graben

The northern end of Kagoshima Graben corresponds to the Hoku-satsu Convex Structure (Hashimoto, 1984), where the Shimanto Supergroup (Mesozoic to Paleogene sedimentary rocks) changes its strike from NE-SW to N-S (Fig. 2). The convex structure was formed in the early Miocene (Hashimoto, 1984), by the clockwise rotation of Southwest Japan (Otofuji and Matsuda, 1983; Torii *et al.*, 1985), and by the formation of the Rukyu Arc and the collision between the South-west Japan Arc and the Kyushu-Palau Ridge (Hashimoto, 1984).

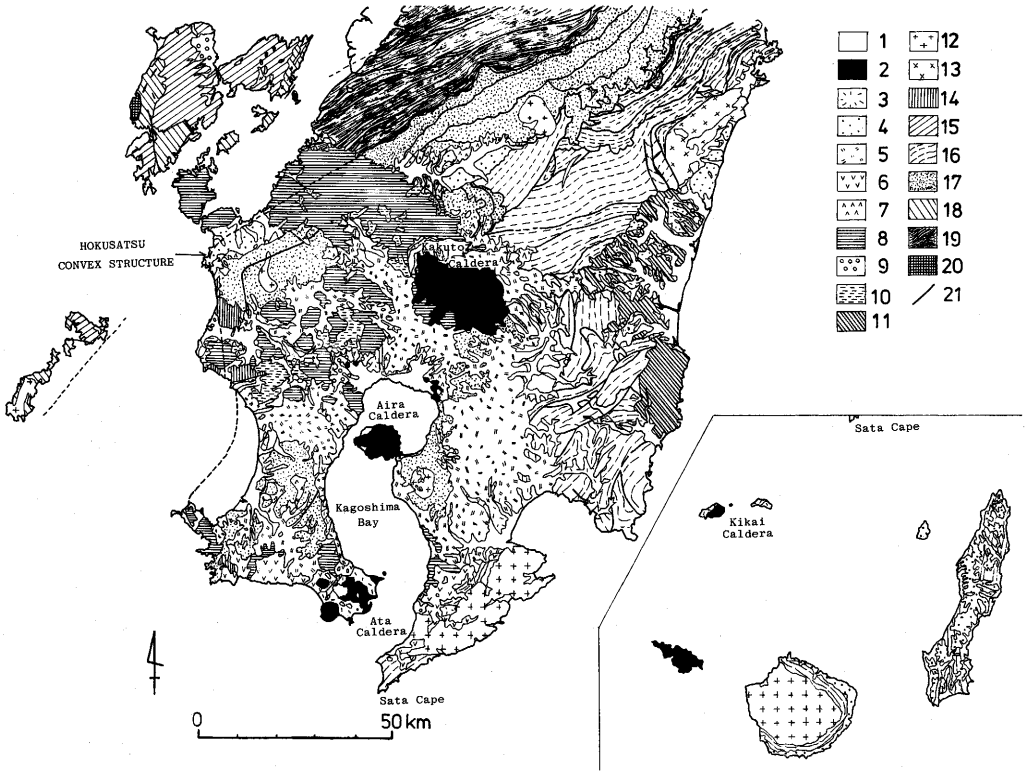

Fig. 2 Geological map of southern Kyushu (simplified from Geological Survey of Japan, 1953, 1980)
1: Alluvium; 2: Late Quaternary stratovolcano; 3: Holocene pyroclastic flows; 4: Pleistocene terrace deposits; 5: Ito pyroclastic flow; 6: Ata pyroclastic flow; 7: Pliocene to middle Pleistocene pyroclastic flows; 8: Hisatsu andesite; 9: Early Pleistocene sedimentary rock; 10: Upper Hokusatsu Group; 11: Miyazaki Group; 12: Miocene granite; 13: Miocene quartz porphyry; 14: Lower Hokusatsu Group; 15: Eocene sedimentary rock; 16: Upper Shimanto Supergroup; 17: Lower Shimanto Supergroup; 18: Himeura Group; 19: Paleozoic to Mesozoic formations; 20: Crystalline schist; 21: Fault

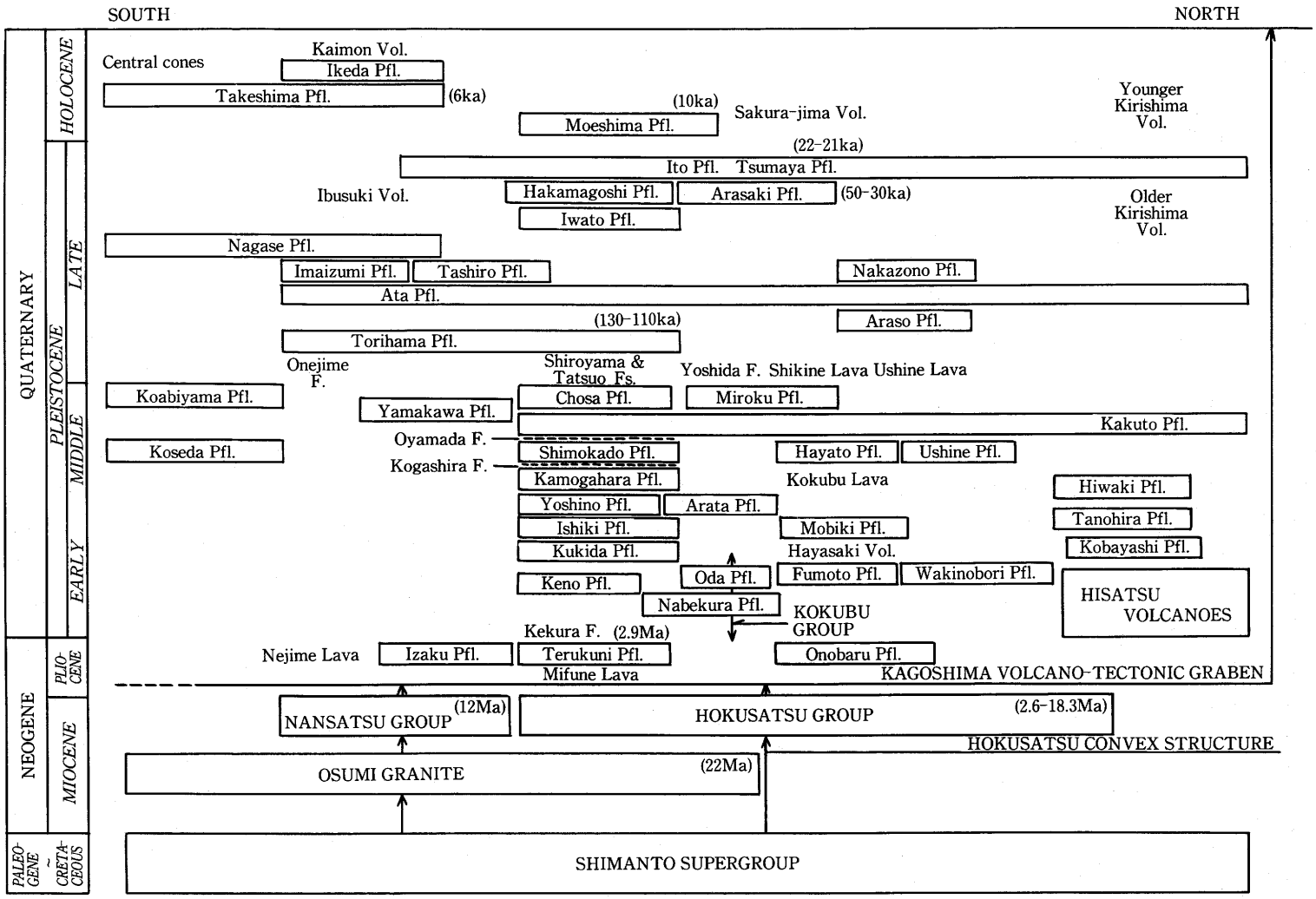

Fig. 3 Block diagrams showing the geologic history of Kagoshima Graben

After the formation of the Hoku-satsu Convex Structure, the Nan-satsu and Hoku-satsu Groups composed of andesite lava and tuff were formed in the Satsuma Peninsula and Hoku-satsu region in the middle Miocene to Pliocene period. During the period from the late Pliocene to the early Pleistocene, Hisatsu Andesite was erupted and formed a wide lava plateau in the Hoku-satsu region. Some of the lava flows erupted in Kagosima Graben, which started spreading in the late Pliocene.

Formation of Kagoshima Graben and its volcanism

Kagoshima Graben is formed in the northern zone of the Shimanto Supergroup. The process of graben formation is unknown in detail, but it probably involves the subduction of the Philippine Sea Plate.

At the western side of the Aira Caldera, the Shimanto Supergroup is broken by step-faulting and overlain by a densely welded pyroclastic flow deposit, the Terukuni pyroclastic flow deposit (Hayasaka and Oki, 1971) which is about 2.9 Ma old (Shibata *et al.* 1978). This means that Kagoshima Graben has been down-faulted in the last 2.9 Ma since the late Pliocene.

The explosive volcanism of silicic magma was almost simultaneous with the beginning of down-faulting of the graben. Many large-scale pyroclastic flows, including the Terukuni, Izaku, Onobaru, Fumoto, Mobiki, Hayato, Nabekura and Yoshino pyroclastic flows (Aramaki and Ui, 1976; Aramaki, 1977; Kaneoka *et al.*, 1984), erupted from the norhtern Kagosima Bay during the period from the late Pliocene to the middle Pleistocene (Aramaki, 1983; see Fig. 3). In the northern end of the graben, the Kobayasi, Tanohira and Kakuto pyroclastic flows (Aramaki and Ui, 1976; Tajima and Aramaki, 1980) erupted, forming the Kobayashi and the Kakuto Calderas in the middle Pleistocene.

Around Kagoshima Bay, these pyroclastic flow deposits alternate with marine and lacustrine deposits, the Kekura, Kogashira, and Oyamada Formations (Oki and Hayasaka, 1970) and the Kokubu Group (Ida *et al.*, 1950; Otsuka and Nishiinoue, 1980). This suggests that the southern part of the graben was a bay or a lake during the period from the early Pliocene to the middle Pleistocene. The Shiroyama and Tatsuo Formations (Oki and Hayasaka, 1970), the Yoshida Shell Bed (Otsuka and Nishiinoue, 1980), and the Onejime Formation (Gohara and Komori, 1961, 1962) were deposited in the bay during the Last Interglacial Stage.

Afterward, during the last 100 ka, the gigantic Ata, Nagase, Ito, and Takeshima (Koya) pyroclastic flows occurred, and the Aira, Ata, and Kikai Calderas were formed. Sakurajima and Kirishima Volcanoes, post-caldera stratovolcanoes in the Aira and Kakuto calderas, have been active in historic times.

3. Late Quaternary Volcanism of the Aira Caldera

Geomorphology

The Aira Caldera (Matumoto, 1943) occupies the northern end of Kagoshima Bay (Fig. 1). The caldera is about 20 km in diameter. Its bottom is 130 to 200 m below sea level. The top of the caldera wall is 500 to 900 m above the submarine bottom.

The northeastern quarter of the caldera is the deepest part of the depression more than 200 m below sea level. This depression is called the Wakamiko proto-caldera by Kuwashiro (1964). Vigorous submarine fumarolic activity is currently present there (Aramaki, 1977). The vents of late Pleistocene eruptions are also concentrated in the caldera. This part of the caldera was as active as Sakurajima Volcano during the late Quaternary period.

The western half of the caldera has a flat bottom at 140 m below sea level. It is covered by unconsolidateded ash, as well as non-volcanic sand and silt (Hayasaka, 1983, 1987). Deltaic deposits from the Amori and Beppu Rivers bury the northern end of the caldera, forming the Kokubu Plain. The southeastern quarter consists of the Shimanto Super-

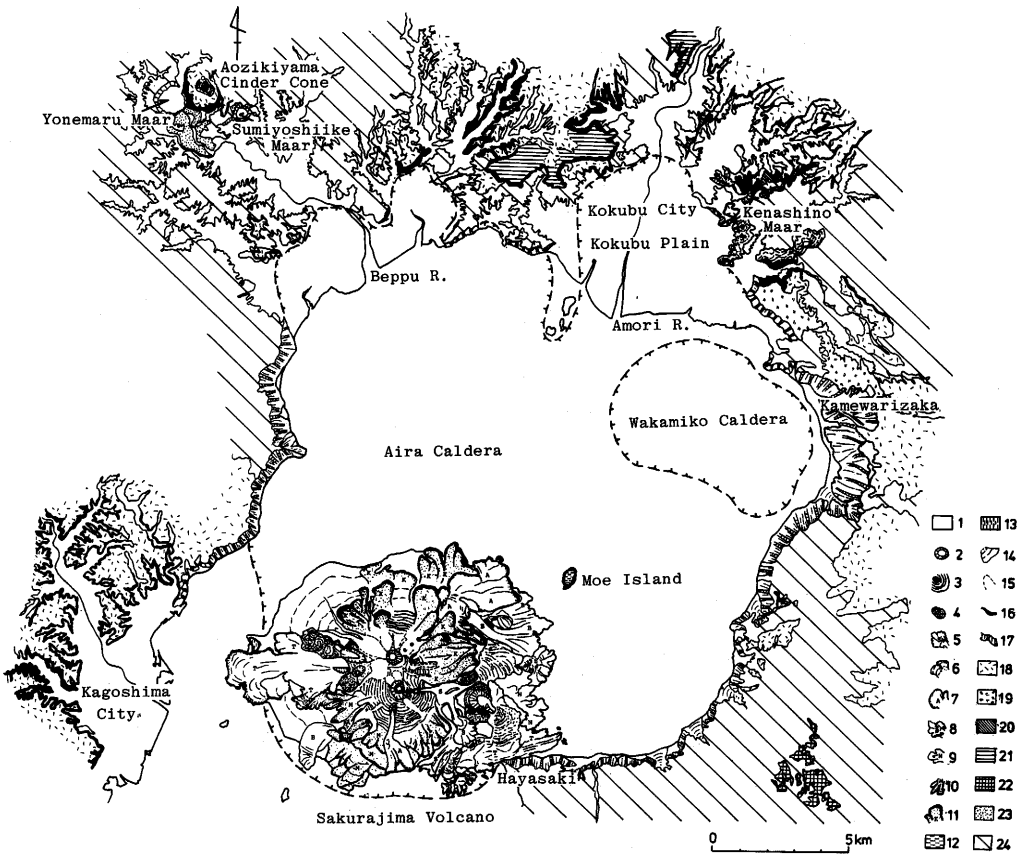

Fig. 4 Geomorphological map of the Aira Caldera
1: Alluvial plain; 2: Crater; 3: Conical volcano; 4: Lava dome; 5~11: Lava flow; 12: Moeshima pyroclastic flow surface; 13: Hakamagoshi pyroclastic flow surface; 14: Fluvial fan; 15: Landslide; 16: Cliff; 17: Caldera wall; 18: Ito pyroclastic flow surface; 19: Kamewarizaka breccia surface; 20: Iwato pyroclastic flow surface; 21: Kakuto pyroclastic flow surface; 22: Mobiki pyroclastic flow surface; 23: Pyroclastic surge deposit surface; 24: Hill and mountain. Geology of Sakurajima after Fukuyama, (1978) and Kobayashi (1982)

group (Hayasaka, 1983).

The eastern and western caldera walls are better exposed and higher than the northern and southern walls, exposing the Shimanto Supergroup and Pleistocene lava flows. According to Aramaki (1983), the western wall continues southward from the channel with a bottom of 40 m below sea level between Sakurajima and Kagoshima City through southern rim of Sakurajima Volcano, and to Cape Hayasaki in the Osumi Peninsula (Fig. 4). The northern wall is eroded away since it was mainly composed of soft pyroclastic flow deposits.

Sakurajima Volcano (Fig. 4), a post-caldera cone, is one of the most active stratovolcanoes in the recent history of Japan. There are some parastic volcanoes; Yonemaru, Sumiyoshiike, and Kenashino maars, and Aozikiyama cinder cone, which are located on the northern caldera rim (Fig. 4).

Outline of volcanism

The first eruptions of north Kagoshima Bay produced the 2.9 Ma old (Shibata *et al.*, 1978) Terukuni pyroclastic flow (Hayasaka and Oki, 1971) in the late Pliocene. Since that time, many pyroclastic flows (Aramaki and Ui, 1976; Aramaki, 1977; Kaneoka *et al.*, 1984) have erupted, occasionally accompanied by lava flows (Fig. 3).

The period from 400-200 ka when the Kakuto pyroclastic flow erupted (Miyachi, 1983), to 80 ka, was a relatively quiet time, with no large explosive eruptions. However, this time included the effusive eruptions of the Shikine andesite lava flow (Aramaki, 1969) and the Ushine rhyolite and basalt lava flows (Kobayashi *et al.*, 1977; Kaneoka *et al.*, 1984) at the northeastern and southeastern rims of the caldera.

Explosive volcanism reopened with the Fukuyama plinian eruption in 70-80 ka (Fig. 5). During 60-30 ka, the Iwato, Otsuka, Fukuminato, and Arasaki plinian eruptions intermittently occurred in the eastern half of the caldera, sometimes followed by moderate-scale pyroclastic flows (Nagaoka, 1984).

The plinian eruptions were followed by the largest eruption in the late Quaternary history of the Aira Caldera, the 22-21 ka event with is called the "Aira" eruption in this paper. The eruption consisted of the Osumi pumice fall, the Tsumaya pyroclastic flow and the Ito pyroclastic flow (Aramaki, 1969, 1983, 1984). The Ito pyroclastic flow covered a wide area of southern Kyushu, and its co-ignimbrite ash fall, the Aira-Tn ash (Machida and Arai, 1976), reached northeastern Japan more than 1,000 km far from the source.

Construction of Sakurajima Stratovolcano started at the southern margin of the caldera about 13 ka (Fukuyama and Ono, 1981). The first active center was Kita-dake and recently Minami-dake became the active center (Fukuyama, 1978; Kobayashi and Fukuyama, 1984). Lava flows from parastic craters and fissures on Sakurajima frequently occurred (Fukuyama, 1978; Kobayashi, 1986).

The Moeshima pyroclastic flow (Aramaki and Ui, 1976; Takano base surge in Kobayashi, 1986) was erupted from the Wakamiko Caldera (Kuwashiro, 1970) at about 10 ka (Aramaki, 1983, 1984) or 12-13 ka (Kobayashi, 1986). A phreatomagmatic eruption: Satsuma eruptive cycle, including pumice fall and base surge, took place beneath Sakurajima Volcano about 11 ka (Kobayashi, 1986). About 6 ka, two phreatomagmatic eruptions took place successively producing Yonemaru and Sumiyoshiike maars north-

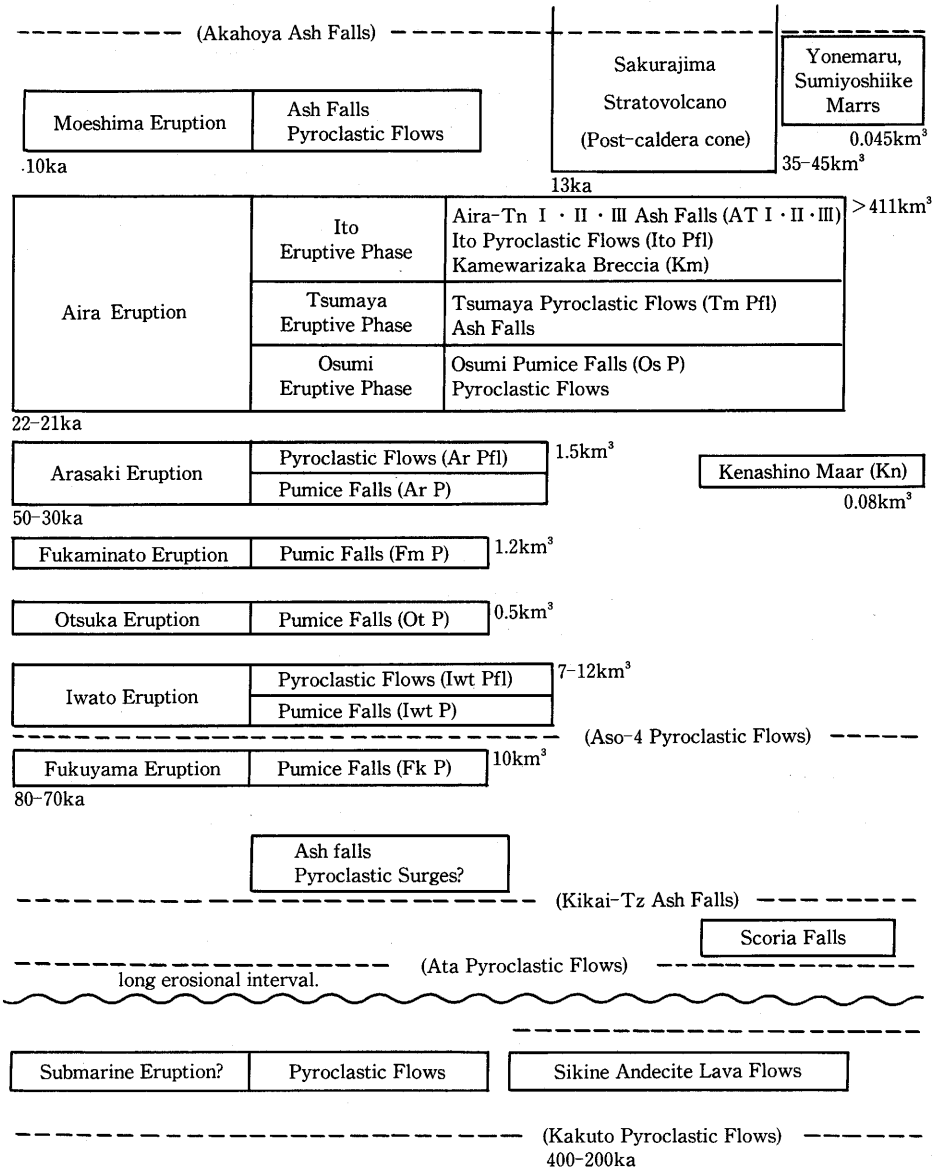

Fig. 5 Block diagrams showing the late Quaternary geologic history of the Aira Caldera

west of the caldera (Moriwaki *et al.*, 1986).

Late Pleistocene tephra layers older than the Aira eruptive cycle

In this section, late Pleistocene marker tephra layers 80-30 ka are described. These tephra layers are composed of six formations of Fukuyama to Arasaki eruptions (Fig. 5) interbedded with thin weathered layers representing quiescent time (Figs. 6 and 7). The

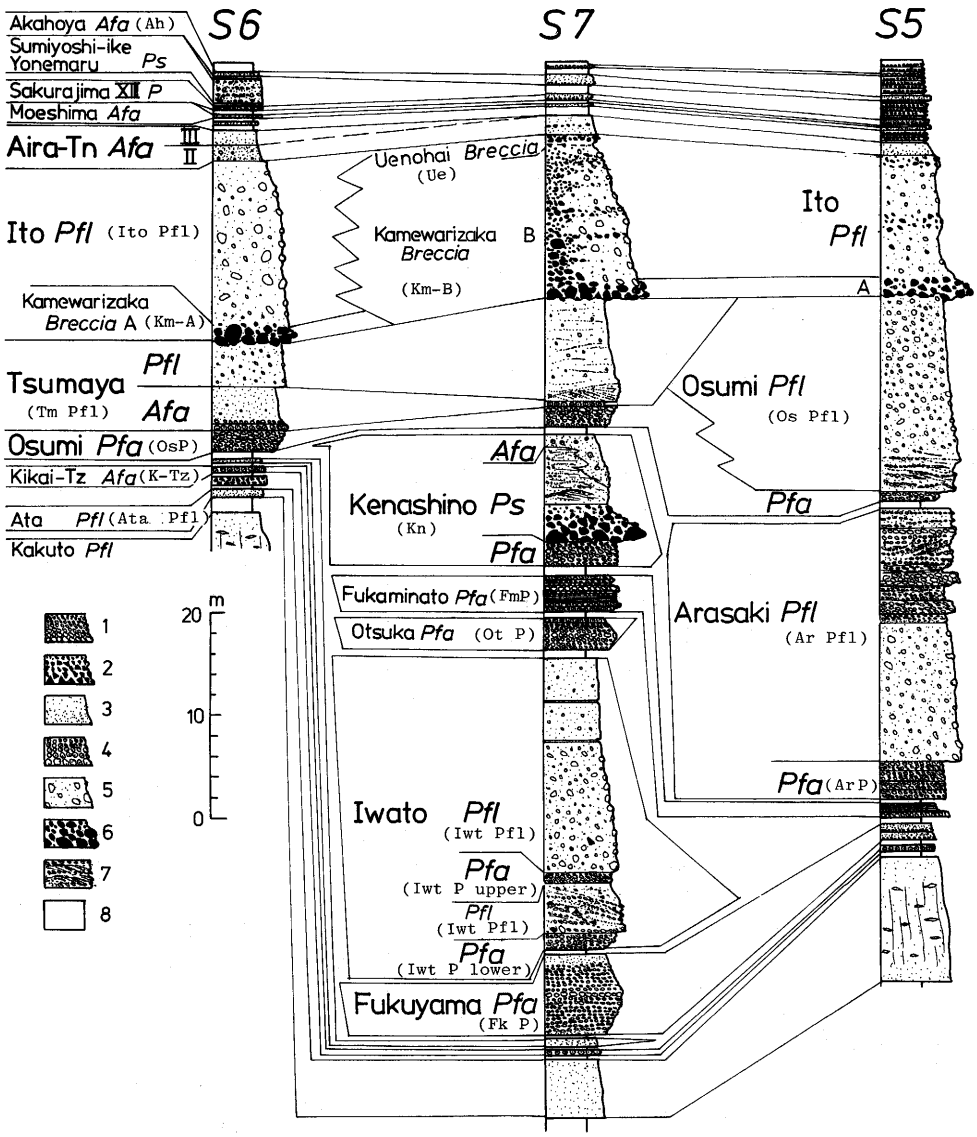

Fig. 6 Idealized columnar sections for the late quaternary tephra layers around the Aira Caldera
S6: Hayato area, the northern rim of the caldera; S7: Kokubu and Fukuyama area, the northeastern rim; S5: Tarumizu area, the southeastern rim; Pfa: Pumice fall; Afa: Ash fall; Pfl: Pyroclastic flow; Ps: Pyroclastic surge; 1: Pumice; 2: Scoria; 3: Ash; 4: Accretionary lapilli; 5: Pyroclastic flow; 6: Volcanic breccia; 7: Laminated bed; 8: Weathered volcanic ash

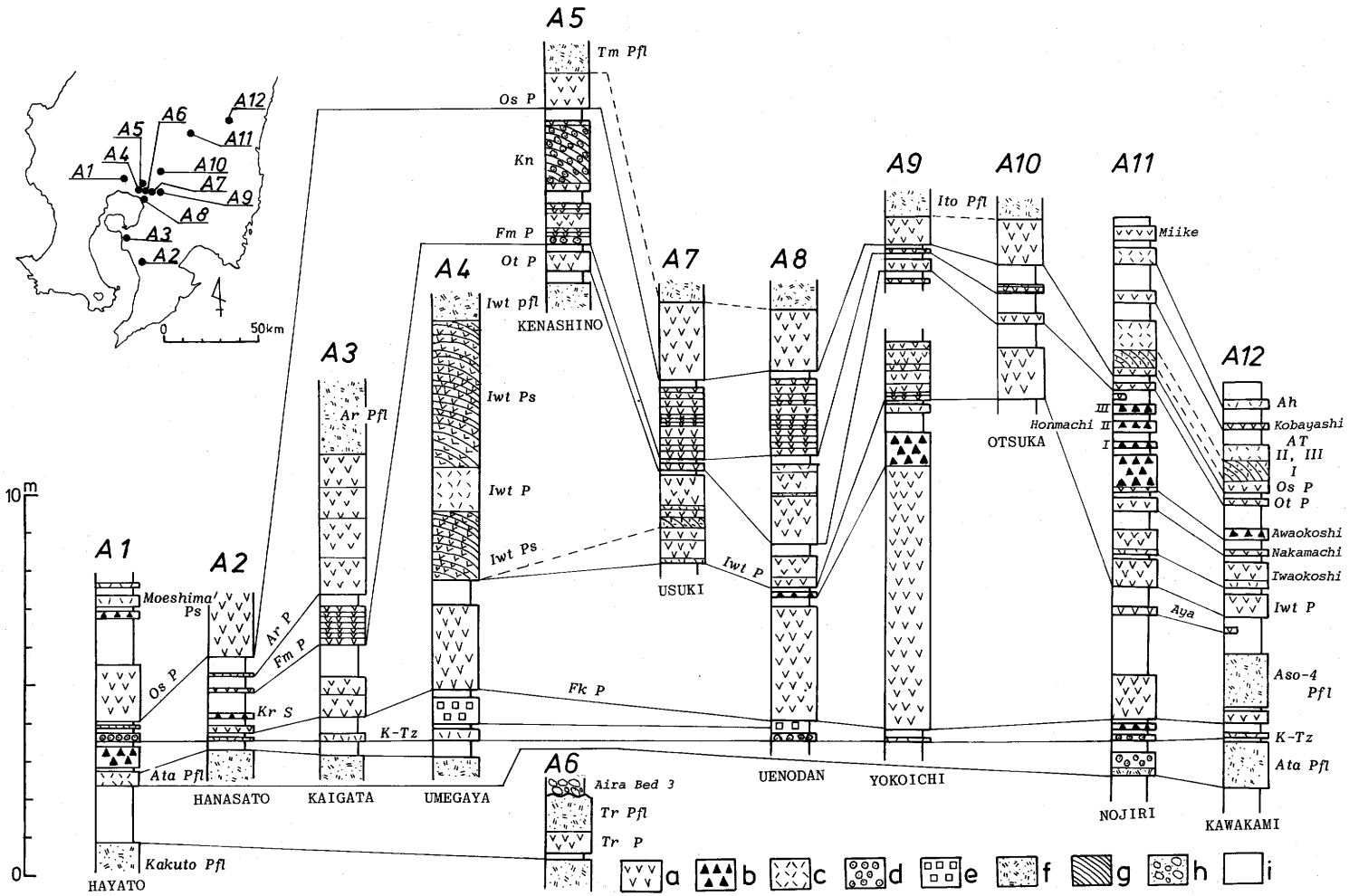

Fig. 7 Columnar sections for the late quaternary tephra layers around the Aira Caldera
a: Pumice fall; b: Scoria fall; c: Ash fall; d: Accretionary lapilli; e: Lithic fragments; f: Pyroclastic flow; g: Laminated bed (including pyroclastic surge); h: Sand and gravel; i: Weathered ash

formations consist of more than ten members containing pumice falls, ash falls, pyroclastic flows and pyroclastic surges. A formation is composed of a single member, or a few members without interbedded soil layers. While a formation is interpreted to represent an eruptive cycle defined by Nakamura *et al.* (1963), a member is formed by an eruptive phase defined by Fisher and Schmincke (1984). Descriptions of formations and members are given in ascending order.

Fukuyama pumice fall deposit **(Fk P)**

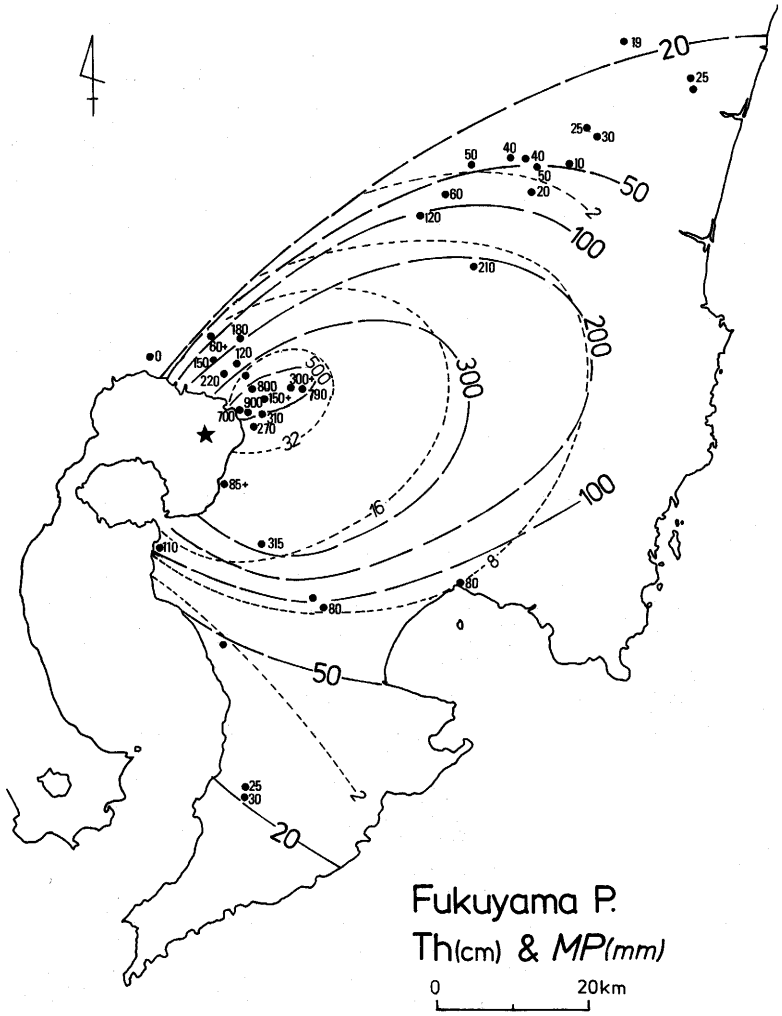

Fig. 8 Dispersal map of the Fukuyama pumice fall deposit
A thick broken line: Thickness (in cm); A thin broken line: Maximum pumice size (in mm); The vent position is shown by a star.

The formation comprises a single pumice fall member. Aramaki (1969) first described that the pumice fall deposit erupted in the Iwato cycle including the Iwato pyroclastic flow. Aramaki and Ui (1976) gave the pumice the name of Fukuyama to distinguish it from the products of the Iwato cycle.

At Kamewarizaka, on the northeastern rim of the Aira Caldera, Fk P overlies the about 75 ka old Kikai-Tozurahara ash fall (Machida and Arai, 1983), and has a maximum thickness of more than 800 cm. The Fk P layer is composed of one or two fall units which are well sorted and normally graded. Pumice fragments, 7.5 cm in maximum diameter, are light yellow and poorly vesicular. Phenocrysts of pumice contain many hornblende particles, a useful key to distinguish the Fk P from other tephra layers from the Aira Caldera. There are few lithic fragments.

Fk P is distributed among the area more than 3,500 km^2 from the Osumi Peninsula to the Miyazaki Plain (Fig. 8). The orientation of the dispersal axis is ESE. The vent position is estimated from the variation of maximum pumice sizes (Fig. 8) to be in the northeastern part of the caldera, the volume is about 10 km^3, calculated by isopach map (Fig. 8). The age of Fk P is about 80-70 ka because it is covered by the 70 ka old (Machida *et al.*, 1985) Aso-4 pyroclastic flow (Ono *et al.*, 1977) directly in the Miyazaki Plain (Nagaoka, 1984, 1986).

Iwato pumice fall deposit **(Iwt P)** *and Iwato pyroclastic flow deposit* **(Iwt Pfl)**

Iwato eruptive cycle is represented by pumice fall and pyroclastic flow members, Iwt P and Iwt Pfl.

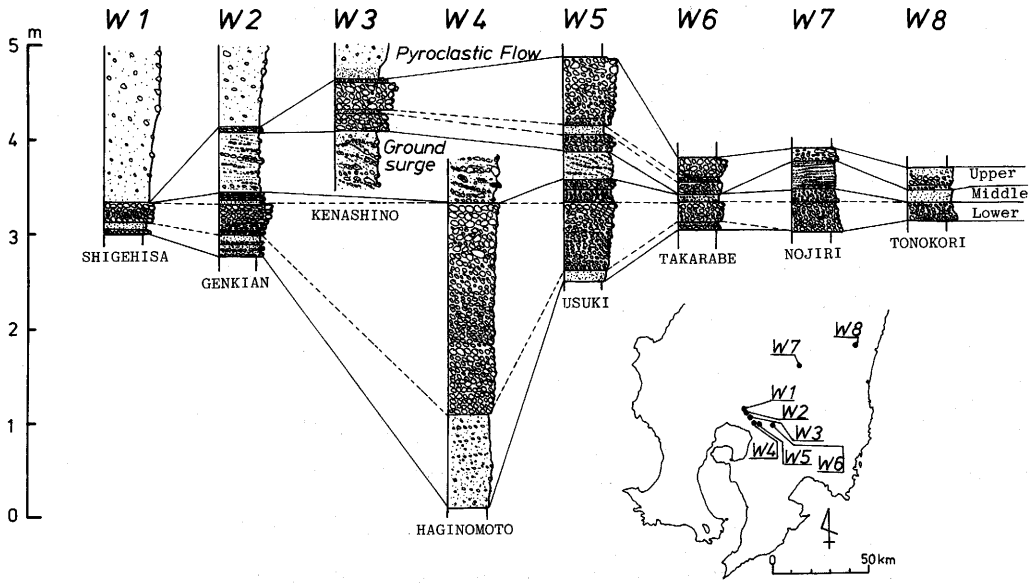

Fig. 9 Columnar sections for the Iwato pumice fall deposit
Symbols are the same as in Fig. 6.

Iwt P Iwt P is a product of a plinian phase preceding the pyroclastic flow. The pumice is correlated with the Dai-san Orange pumice (Endo *et al.*, 1962) in the Miyazaki Plain by Arai and Machida (1980), and Nagaoka (1984).

At Usuki (Loc. W5, Fig. 9), Kokubu City, Iwt P has a thickness of 220 cm and is composed of the three main units as follows in ascending order:

100 cm lower unit: moderately vesicular light yellow pumice (maximum diameter: 9.3 cm).

20-30 cm middle unit: cross-laminated crystal-rich ash.

95 cm upper unit: fairly vesicular light yellow pumice with brown scoria.

The lower unit corresponds to a pumice fall layer underlying Iwt Pfl around Kokubu City (Fig. 9). The upper unit is correlative with pumice layer intercalated in the lower part of Iwt Pfl (Fig. 9), because both layers include scoria. The middle unit can be equivalent to the lowermost part of Iwt Pfl which locally exhibits cross-bedding (Fig. 9). The last phase of Iwt P was probably synchronous with the earliest phase of Iwt Pfl.

The Iwt P covers the area of 1,800 km^2 from the eastern foot of Kirishima Volcano to the Miyazaki Plain (Fig. 10). The dispersal fan extends to the ENE. The vent position is estimated to be located in the Kukubu Plain, northeastern end of the Aira Caldera from the maximum pumice size variation (Fig. 10). The volume is calculated to be 3-5 km^3.

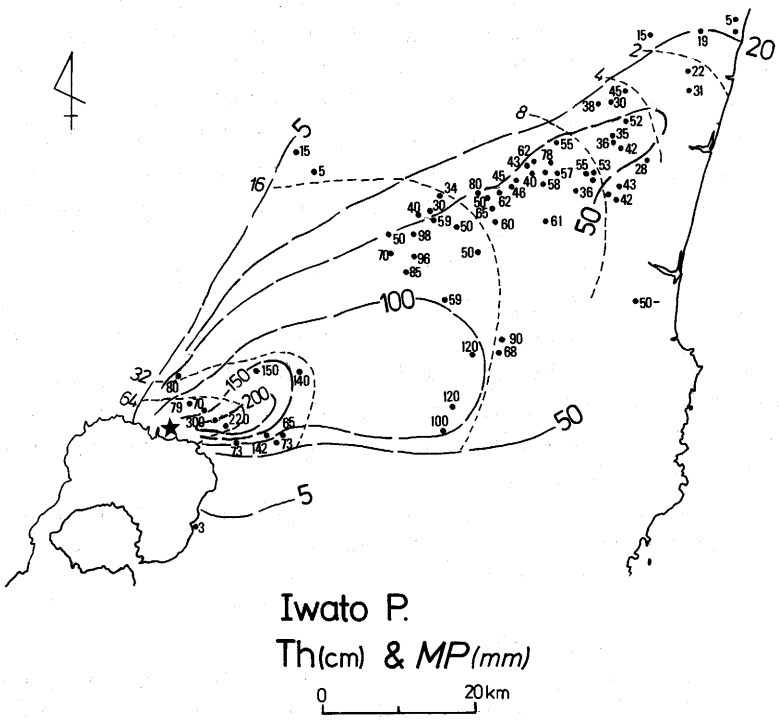

Fig. 10 Dispersal map of the Iwato pumice fall deposit
Symbols as Fig. 8.

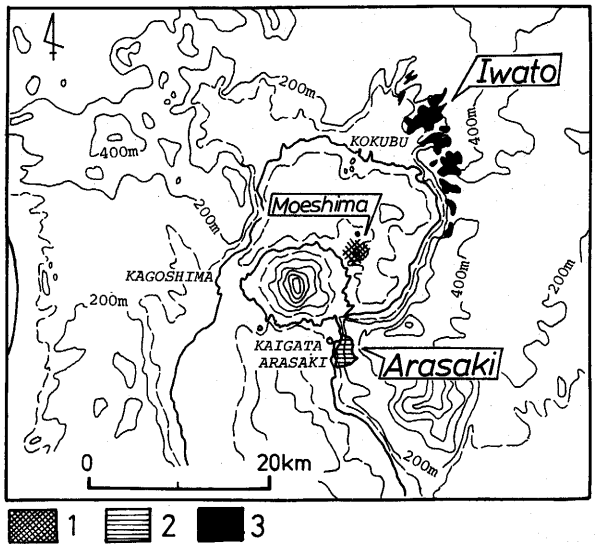

Fig. 11 Distribution of remaining parts of the Iwato, (Arasaki) and Moeshima pyroclastic flow deposits
1: Moeshima Pfl; 2: Arasaki Pfl; 3: Iwato Pfl. Iwt Pfl after Aramaki (1969, 1977)

Iwt Pfl Iwt Pfl corresponds to the Iwato pumice flow deposit (Sawamura, 1956; Ota *et al.*, 1967) and the Iwato pyroclastic flow deposit (Aramaki, 1969).

Iwt Pfl is distributed under the plateau around Kokubu City (Fig. 11). The Maximum thickness is more than 100 m. Iwt Pfl has at least four flow units separated by three air fall deposits including the Iwt P upper unit and two thin ash layers. The lowermost unit exhibits cross-bedding, which indicates strong turbulent flow occurring by friction at the bottom of the pyroclastic flow. The second unit from the bottom is the thickest among four units and is weakly welded. Others are non-welded. All units are mainly composed of poorly vesicular pumice up to 50 cm across and matrix of crystal-rich ash. Scoria and banded pumice are frequently found in the lower two units. The volume is calculated to be 5-10 km^3.

Otsuka pumice fall deposit **(Ot P)**

Ot P represents a single eruptive cycle. It is intercalated in the Aira bed 4 (Aramaki, 1969), lacustrine and fluvial sediments, and was described by Nagaoka (1984).

At Uenodan (Loc. A8, Fig. 7) in Kokubu City, Ot P, 200 cm thick, is composed of two fall units exhibiting reversed grading. Pumice fragments are white and very vesicular. There are few lithics in the deposit.

The narrow dispersal fan extends to NE (Fig. 12). The variation of maximum pumice size indicates that the vent was in the northeastern quarter of the caldera (Fig. 12). The volume is calculated to be about 0.5 km^3.

Fukaminato pumice fall deposit **(Fm P)**

This formation is made up of a single pumice fall member. Fm P was first described by Aramaki (1977) Fm P is 210 cm thick, and is composed of more than twenty thin fall units at Usuki (Loc. A7, Fig. 7) in Kokubu City. The pumice is light yellow and poorly vesicular, and has a maximum diameter of 90 cm in the lowermost unit.

In Kenashino (Loc. A5, Fig. 7), 5 km west of Usuki, Fm P has accretionary lapilli layer 30 cm thick at the base of Fm P. This layer suggests that a small phreatomagmatic eruption preceded the main plinian eruption.

The dispersal shape is almost round (Fig. 13). Its major axis is not clear, because Fm P consists of many thin fall units which have different dispersal fans and axes. The variation of the maximum pumice size (Fig. 13) suggests that the vent position is in the northeastern part of the caldera. The volume is calculated to be about 1 km^3.

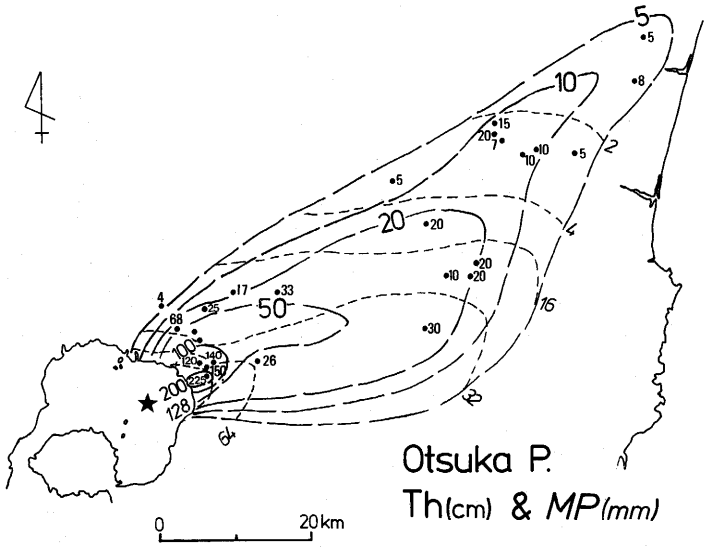

Fig. 12 Dispersal map of the Otsuka pumice fall deposit
Symbols as Fig. 8.

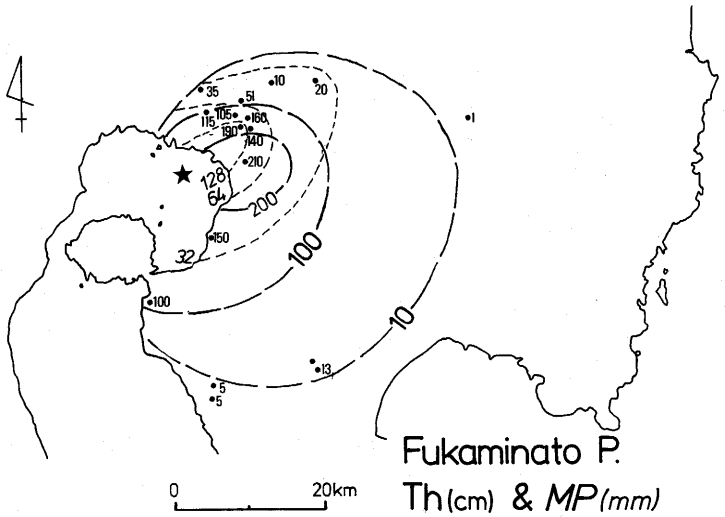

Fig. 13 Dispersal map of the Fukaminato pumice fall deposit
Symbols as Fig. 8.

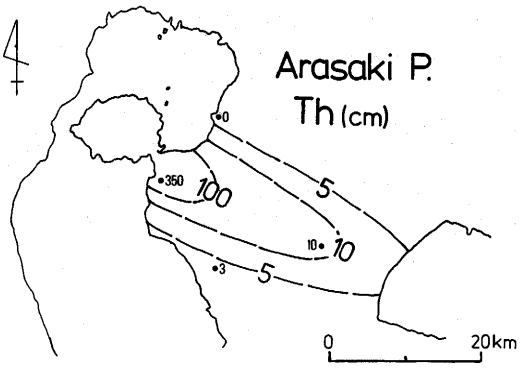

Fig. 14 Isopach map of the Arasaki pumice fall deposit

Arasaki pumice fall deposit **(Ar P)** *and Arasaki pyroclastic flow deposit* **(Ar Pfl)**

This cycle is represented by two members, Ar P and Ar Pfl.

Aramaki and Ui (1976) reported the Arasaki pumice fall deposit in the southwestern part of the Aira Caldera. Afterward, Nagaoka (1984), however, interpreted the deposit as a pyroclastic flow deposit, and renamed it the Arasaki pyroclastic flow deposit (Ar Pfl). Nagaoka (1984) found another pumice fall sheet underlying Ar Pfl, and called it the Arasai pumice fall deposit (Ar P).

Ar P Ar P is 350 cm thick and contains poorly-vesiculated light yellow pumice of 2 cm in maximum diameter at Kaigata Hot Spring (Loc. A3, Fig. 7) in Tarumizu City.

Ar P is scattered in the small area of the middle Osumi Peninsula (Fig. 14). The orientation of dispersal axis is ESE. The source is estimated to be in the southern part of the caldera. The volume is less than 1 km^3.

Ar Pfl Ar Pfl covers a small area around Kaigata Hot Spring (Fig. 11). At Loc. A3 in Fig. 7, Ar Pfl is a non-welded pyroclastic flow deposit 30 m thick. The lower two thirds of the 20 m in thickness is poor-sorted mixture of pumice and ash, and the upper one third, is composed of rounded coarse pumice exhibiting cross-bedding. The volume is less than 0. 5 km^3. The ages by fission track dating range from 41 ka to 31 ka (Sato *et al.*, 1972).

Kenashino maar deposit **(Kn)**

Kn was first described by Nagaoka (1984b). Kn erupted from small Genkian basin 500 m west of Kenashino, in Kokubu City, 1 km NNE of the Aira Caldera, and is deposited around the basin (Fig. 15). A good section of Kn is exposed at a road-cut at east wall of Genkian basin. The stratigraphy is as follows in ascending order:

30-100 cm: alternating beds of lithic fragments, coarse ash and pumice fragments (fall-out deposits).

600 cm: white pumice layer, 10 cm in maximum pumice size (fall-out deposits).

300-700 cm: poor-sorted explosion breccia including abundant obsidian chips (fall-out deposits).

700-800 cm: laminated pumice and ash layer (base surges).

The uppermost laminated layer changes into a vitric ash fall layer rich in accretionary lapilli in the distal area. Accretionary lapilli and obsidian chips suggest that the magma

was rapidly chilled in contact with water and that a phreatomagmatic eruption took place. The total volume of Kn is less than 0.1 km^3.

Kn, Ar P, and Ar Pfl are all covered with the Osumi pumice fall deposit (Figs. 6 and 7). But the stratigraphical relationship between Kn and Ar P-Ar Pfl is unknown because the distributions of the two formations do not overlap each other.

Tephra layers in the Aira eruptive cycle

About 22-21 ka, a cycle of large-scale eruptions occurred. The total magma erupted during this cycle is estimated to have been up to 100 km^3 in total volume before vesiculation (Aramaki, 1983). The series of eruptions is described in detail by Aramaki (1983, 1984). A summary of Aramaki's work follows and a few of author's new data are added.

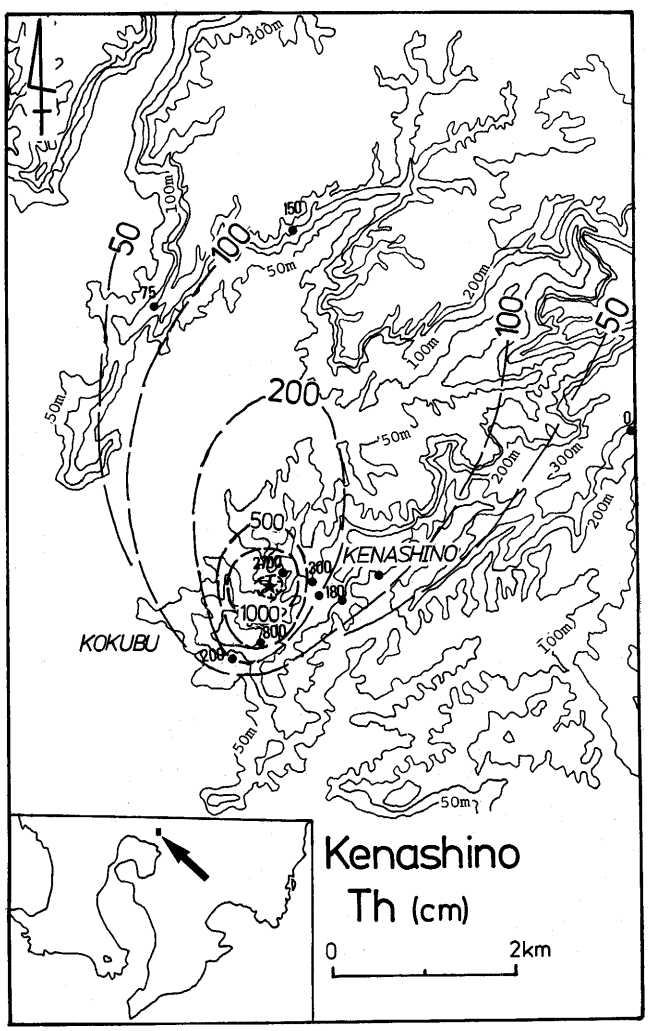

Fig. 15 Isopach map of the Kenashino maar deposit

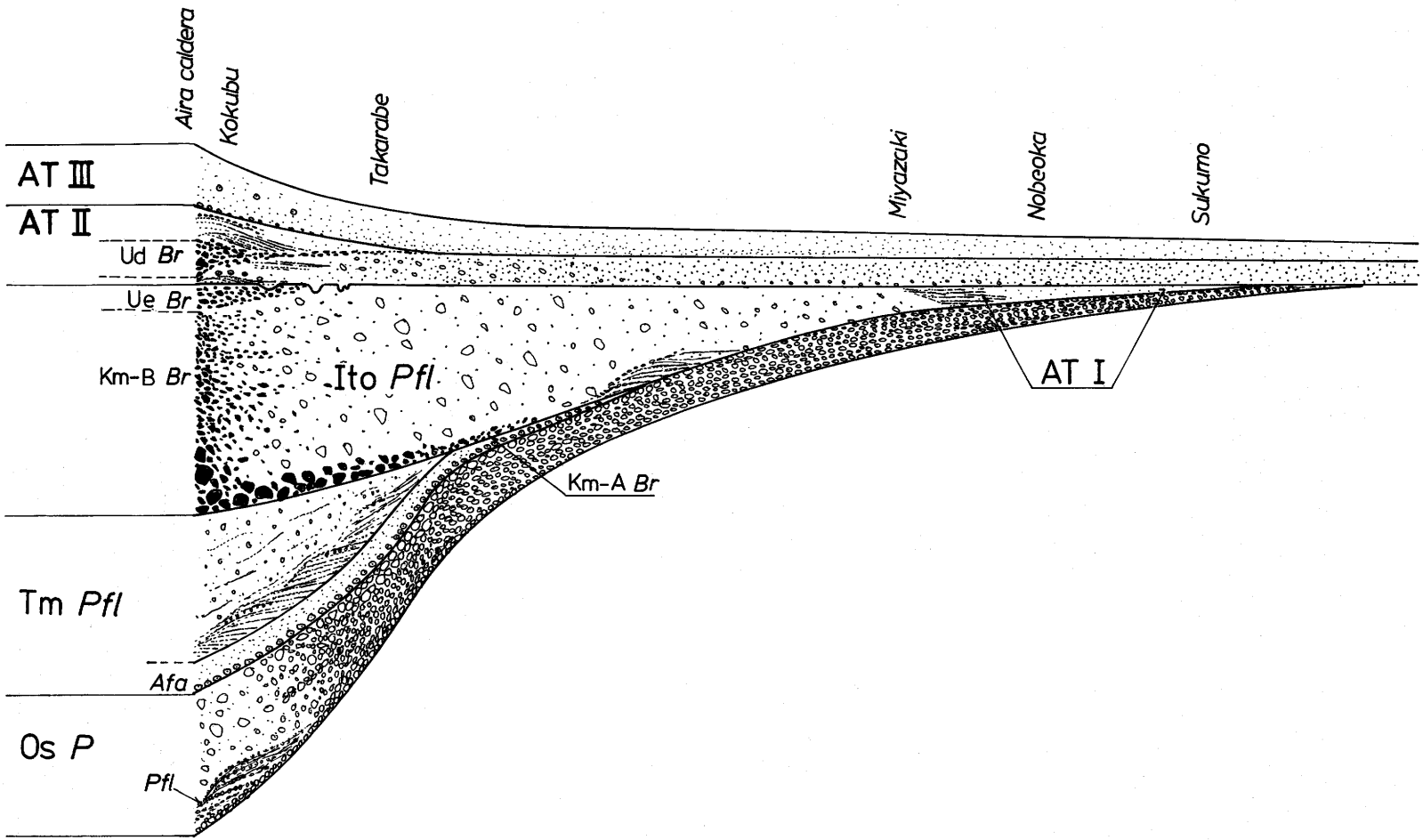

Fig. 16 Idealized crossection for the tephra layers of the Aira eruptive cycle
Symbols as Fig. 6.

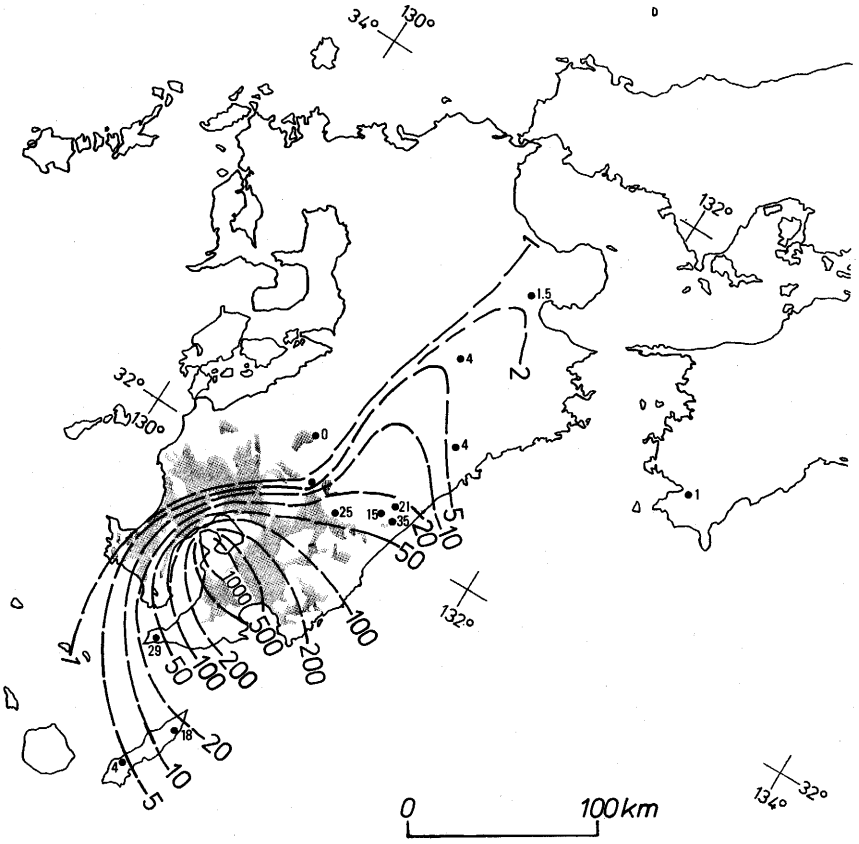

Fig. 17 Isopach map of the Osumi pumice fall deposit (in cm), modified from Kobayashi *et al.* (1983)

Osumi pumice fall deposit **(Os P)**

The cycle started with a large-scale plinian phase which formed the Osumi pumice fall deposit, Os P (Fig. 16) which may be as much as 90 km^3 in volume (Kobayashi *et al.*, 1983). The Os P erupted from a vent located at the present site of Sakurajima Volcano (Aramaki and Ui, 1966b; Kobayashi *et al.*, 1983).

The main dispersal axis of Os P extends to the ESE, but its wide-spread dispersal fan covers the southeastern half of Kyushu (Fig. 17). Os P consists of a layer of rhyodacitic gray-white pumice fragments. The deposit generally lacks stratification and nearly homogeneous except for an overall reverse grading. These features indicate the brevity and simplicity of the sequence of this plinian eruption (Aramaki, 1984).

Plots of area enclosed by isopachs against thickness of some late Quaternary tephra falls in southern Kyushu are given in Fig. 18a. The volume of Os P is much larger than other plinian phases. The size of the dispersal area of tephra is principally a function of the height reached by the eruptive column (Walker, 1973). Figure 18b indicates that the eruptive column of Os P was much higher than others. Os P phase had therefore high discharge rate of magma.

In near-source areas, along the eastern shore of the caldera within 20 km southeast of the vent (Fig. 19), there are many small-scale pyroclastic flow layers forming lower part of low-angle cross-bedding with a wavelength of up to 30 m (Kobayashi, 1981). Most of them appear to have been generated synchronously with the plinian eruption. This suggests that there were times when the southern part of the plinian eruption column collapsed.

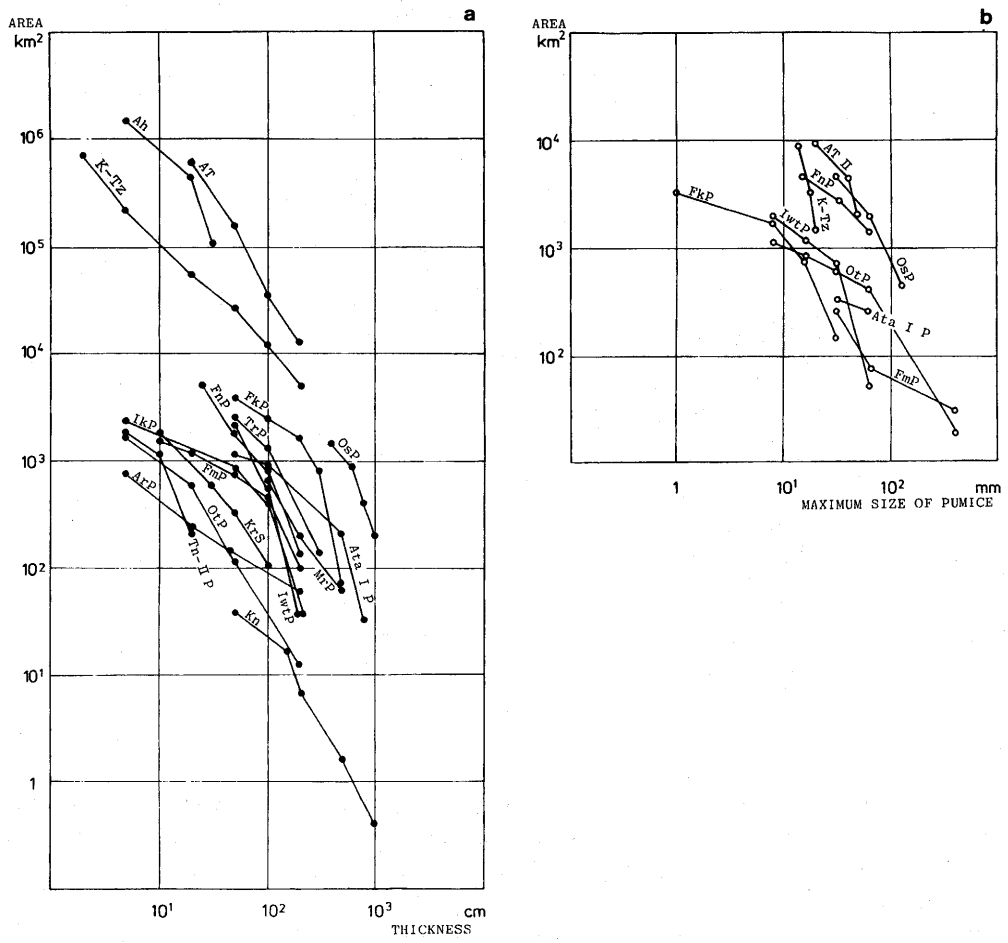

Fig. 18 Plots of the areas enclosed by isopachs a) against the thickness (left), and b) against the maximum size of pumice and scoria (right), for the subaerial fallout tephra layers from some caldera volcano in southern kyushu
AT: Aira-Tn ash from Aira caldera, Ah: Akahoya ash from Kikai caldera, K-Tz: Kikai-Tz ash from Kikai, Os P: Osumi pumice fall (pfa) from Aira, Fk P: Fukuyama pfa from Aira, Iwt P: Iwato pfa from Aira, Fm P: Fukaminato pfa from Aira, Ot P: Otsuka pfa from Aira, ArP: Arasaki pfa from Aira, Kn: Kenashino maar deposit, Tr P: Torihama pfa from Ata caldera. Ata P: Ata pfa from Ata, Mr P: Marumine pfa from Ata, Ik P: Ikeda pfa from Ikeda caldera, Kr S: Karayama scoria fall from Karayama volcano in Ata caldera, Fn P: Funakura pfa from Kikai caldera, Tn-II P: Tane II pfa from Kikai, Os P adapted from Kobayashi *et al.* (1983), Fn P from Walker *et al.* (1984)

Tsumaya pyroclastic flow deposit **(Tm Pfl)**

The Os P eruptive phase was followed by the oxidized, fine-grained Tsumaya pyroclastic flow (Tm Pfl), 13 km^3 in volume, which was erupted from the same vent as Os P (Aramaki, 1984). Its distribution is completely confined within the caldera (Fig. 19). Tm Pfl buries very rugged topography, and has a maximum thickness of up to 100 m (Aramaki, 1984).

Tm Pfl consists of a pale pinkish brown glassy matrix containing a small amount of pumice and lithic fragments. In the lower part of the flow, low-angle cross-beds occur in many places. An ash fall layer rich in accretionary lapilli, which probably formed in a phreatomagmatic eruption, was discovered at the base of Tm Pfl around the Aira Caldera. These features suggest that the earlier eruption of Tm Pfl was very violent and phreatic one.

Aramaki (1983, 1984) estimates that repeated phreatomagmatic eruptions occurred from a large crater when an amount of uniformly oxidized magmatic material repeatedly rose and fell in the crater, and that a moderate explosion expelled the finer-grained portion out of the vent to form Tm Pfl.

Ito pyroclastic flow deposit **(Ito Pfl)**

After a very short pause, a violent explosive ejection of the basement rock fragments and pumiceous materials occurred and gradually changed into a huge eruption column which rapidly collapsing to form the Ito pyroclastic flow deposit (Ito Pfl), about 300 km^3 in volume (Aramaki, 1984). It covers the land within a circle of 50 to 80 km radius (Fig. 20) of the caldera. Ito Pfl has a maximum thickness of more than 180 m, burying pre-Ito

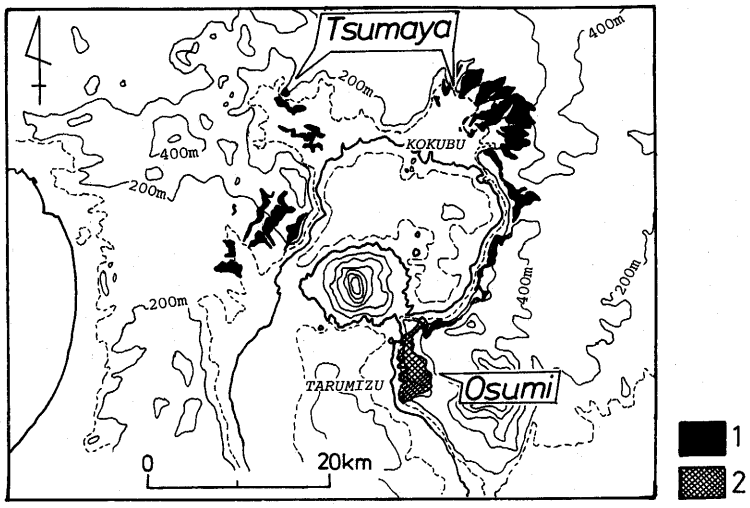

Fig. 19 Distribution of remaining parts of the Osumi and Tsumaya pyroclastic flow deposits (after Aramaki (1969), Oki and Hayasaka (1970), Oki (1974), Otsuka and Nishiinoue (1980), and Kobayashi (1981))
1: Tsumaya Pfl; 2: Osumi Pfl

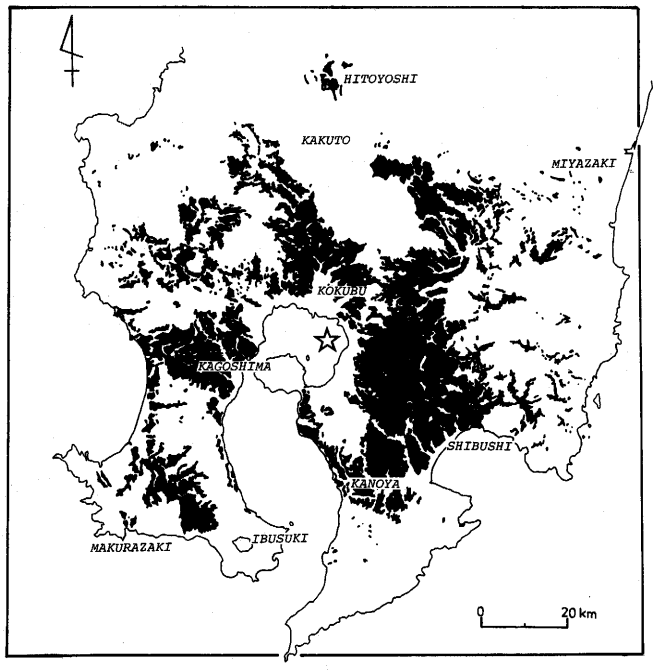

Fig. 20 Distribution of remaining parts of the Ito pyroclastic flow deposit, after Aramaki (1984)
The star indicates the vent position estimated from new data of the Kamewarizaka B-type breccia.

Pfl basins and valleys.

Ito Pfl consists of gray-white coarsely vesicular pumice blocks up to 1 m across, subangular lithic fragments derived from the basement, and finer particles of glass and phenocrysts. The deposit is homogeneous in color and grain-size distribution. Flow units interfaces cannot be distinguished by visual inspection. No systematic vertical or lateral variations in chemical and mineral compositions of pumice are confirmed. These features indicate that the main part of Ito Pfl consists of a single flow unit (Aramaki, 1983, 1984).

The Kamewarizaka breccia (Aramaki, 1969) and the Aira-Tn ash fall (Machida and Arai, 1976) occurred simultaneously with Ito Pfl. Description about these deposits is followed after new data.

Kamewarizaka breccia **(Km)**

The earliest phase of Ito Pfl eruption produced the Kamewarizaka breccia (Km). It is distributed to the caldera rim and is full of basement fragments (Aramaki, 1969, 1984). Aramaki and Ui(1966b) and Ota *et al.* (1967) first described Km overlying Os P at Kamewarizaka at the northeastern rim of the Aira Caldera. Two different facies of Km, A-type (Km-A, in this paper) and B-type (Km-B) facies, were lithologically distinguished by Aramaki (1969). A-type deposit is interpreted as the product of a certain kind of a

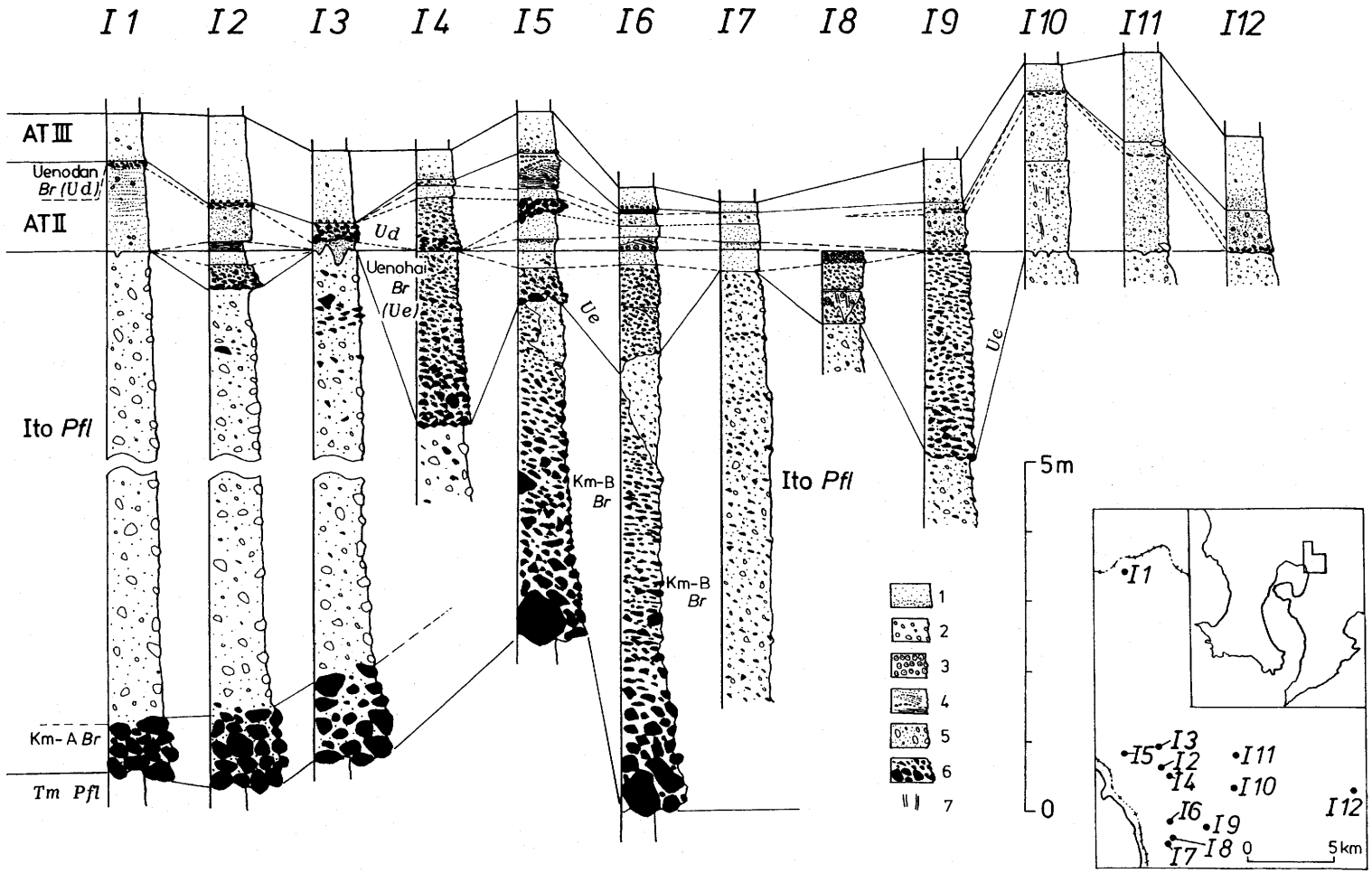

Fig. 21 Columnar sections for the Ito pyroclastic flow deposit, the Kamewarizaka breccia, and the Aira-Tn ash fall deposits
1: Ash; 2: Pumice; 3: Accretionary lapilli; 4: Laminated layer; 5: Pyroclastic flow deposit; 6: Degassing pipe

particle flow, like a pyroclastic flow of gas-solid mixture, and B-type as the product of a shower, probably a fallout, of mixtures of lithic and pumice fragments directly deposited on the ground (Aramaki, 1984). Another breccia, Uenohai breccia **(Ue)**, is found in the uppermost part of Ito Pfl.

Km-A The distribution of Km-A encloses the caldera rim. Km-A is overlain by Ito Pfl and eroded underlying Tm Pfl (Fig. 21). The breccia is more than 10 m in maximum thickness, and is composed primarily of poorly-sorted subangular lithic fragments of up to 2 m in maximum diameter. The fragments have their origins in the sedimentary rock of the Shimanto Supergroup, andesite, and Tm Pfl. Away from the caldera rim, the grain size and thickness exponentially decrease, and the ashy matrix increases. These features suggest, as Aramaki (1984) concluded, that Km-A was emplaced by a pyroclastic flow and is an extreme facies of basal concentration zone of Ito Pfl.

Km-B Km-B is distributed to environs of Kamewarizaka on the northeastern rim (Fig. 22). Km-B, less than 20 m in thickness, is matrix-free stratified angular gravel, better sorted than Km-A, and includes few particles less than 1 mm across. Lithic fragments are more angular than those of Km-A, and their lithology is the same kind as Km-A.

Aramaki (1984) showed that Km-B is covered with Km-A. But the author's work shows that the distributions of Km-A and Km-B do not overlap (Fig. 22). Km-A covers the proximal flat plateau of basement where Ito Pfl could not emplace (Figs. 22 and 23). On the other hand, Km-A occurs at the base of Ito Pfl filling depressions and valleys behind the plateau covered with Km-B (Figs. 22 and 23). Lenses of Ito Pfl are intercalated in the upper half of Km-B at the caldera rim (Locs. 15 and 16; Fig. 21). Many angular lithic fragments, lithologically corresponded to Km-B, are scattered with Ito Pfl at southern caldera rim of Kamewarizaka (Loc. 17, Fig. 21).

These features indicate that Km-A is the proximal facies of Ito Pfl and is laterally continuous with the Ito Pfl. Km-B can be identified with a co-ignimbrite lag fall deposit (Wright and Walker, 1977) which fell down from column and was left behind in the proximal area by a pyroclastic flow. Aramaki (1983, 1984) suggests that Km-B was formed from a lithic-laden gas jet in the earliest phase of Ito Pfl (Fig. 29-2).

Aramaki (1984) estimated from the variation of sizes of the largest clasts in Km-A that probably the vent position of the Ito eruption was located at the center of the Aira Caldera. But, the ballistic and fall deposits of Km-B provide better evidence to determine the vent position. The distribution of Km-B (Fig. 22) indicates that the eruptive center was in the north quarter (the Wakamiko Caldera) of the Aira Caldera.

Ue The Ue is less than 2 m thick, and is intercalated in the uppermost part of Ito Pfl at Loc. I4 (Fig. 21) 3 km north of Kamewarizaka. Ue consists of the same kinds of lithics as Km without unconsolidated sediments. Lithic fragments are less than 30 cm across, and are armored with very fine pinkish white ash similar to the matrix of Ito Pfl. Ue is better-sorted than Km-B, normally graded, and sometimes contains accretionary lapilli. It covers the small area of northeast part of the caldera rim (Fig. 22). Ue is interpreted, based on these features, as a fall or a ballistic deposit derived from water-and-lithic laden jets. A phreatic or phreatomagmatic explosion probably took place in the latest Ito Pfl phase when discharge of magma weakened (Fig. 29-3).

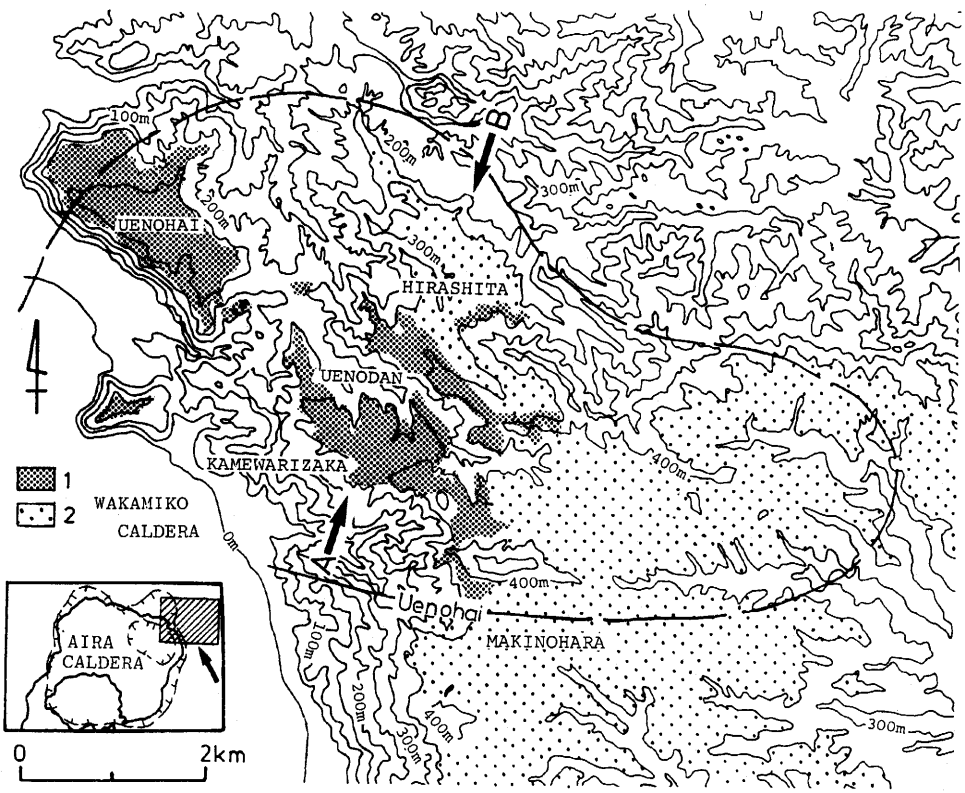

Fig. 22 Distribution of the Kamewarizaka A- and B-type breccia, and the Uenohai breccia
1: Kamewarizaka B-type breccia; 2: Kamewarizaka A-type br.; A broken line: Uenohai br.

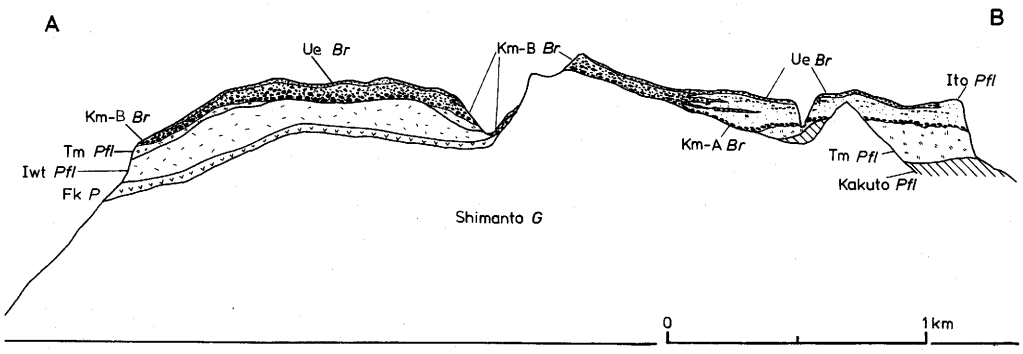

Fig. 23 Geological cross-section of northeastern rim of the Aira Caldera
Locality is in Fig. 22.

AT The Aira-Tn ash fall deposit (AT; Machida and Arai, 1976), a fine-grained counterpart of Ito Pfl, covers a wide area of more than 1,000 km from the Aira Caldera (Fig. 24), and is one of the most useful marker tephra layers in the late Quaternary of Japan. AT is interpreted as a co-ignimbrite ash fall deposit defined by Sparks and Walker (1977). But, the stratigraphical relationships between AT and Ito Pfl are not clear in southern Kyushu. The features and stratigraphy of AT of the proximal area in southern Kyushu are described in this paper.

In the central Miyazaki Plain, where there is no Ito Pfl, 80 km NNE of the Aira Caldera, the AT overlying Os P is subdivided into three units; AT I, AT II, and AT III in ascending order (Fig. 16), on the basis of grain sizes and grain shapes. AT II and AT III directly overlie Ito Pfl in the area where Ito Pfl is distributed (Fig. 16). In the most proximal area, on the northeastern rim of the Aira Caldera, AT II includs lithic-rich

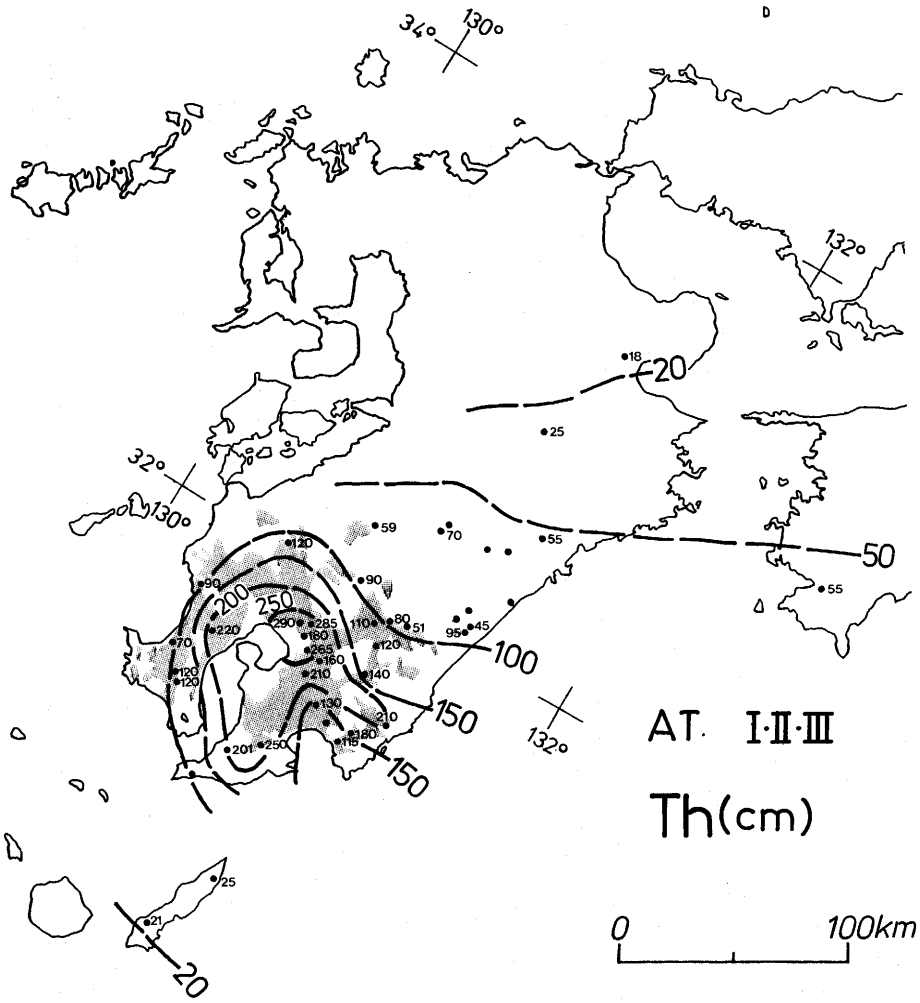

Fig. 24 Isopach map for total thickness of the AT I, II, and III units (in cm)
Shaded area shows the distribution of the Ito pyroclastic flow deposit.

layer, Uenodan breccia **(Ud)**, which overlays Ue.

AT I In the central Miyazaki Plain, AT I, about 10 cm thick, is yellowish brown and well-sorted vitric ash. The ash is finer-grained than AT II, and contains more glass shards of pumice type than bubble-walled type. Cross-bedding is sometimes displayed in the marginal areas of Ito Pfl, the central Miyazaki Plain, and the southern Osumi Peninsula.

AT I is distributed among the region NE to SE out of Ito Pfl (Fig. 25). AT I cannot be found in the area covered with Ito Pfl. Probably, AT I laterally changes into Ito Pfl (Fig. 16).

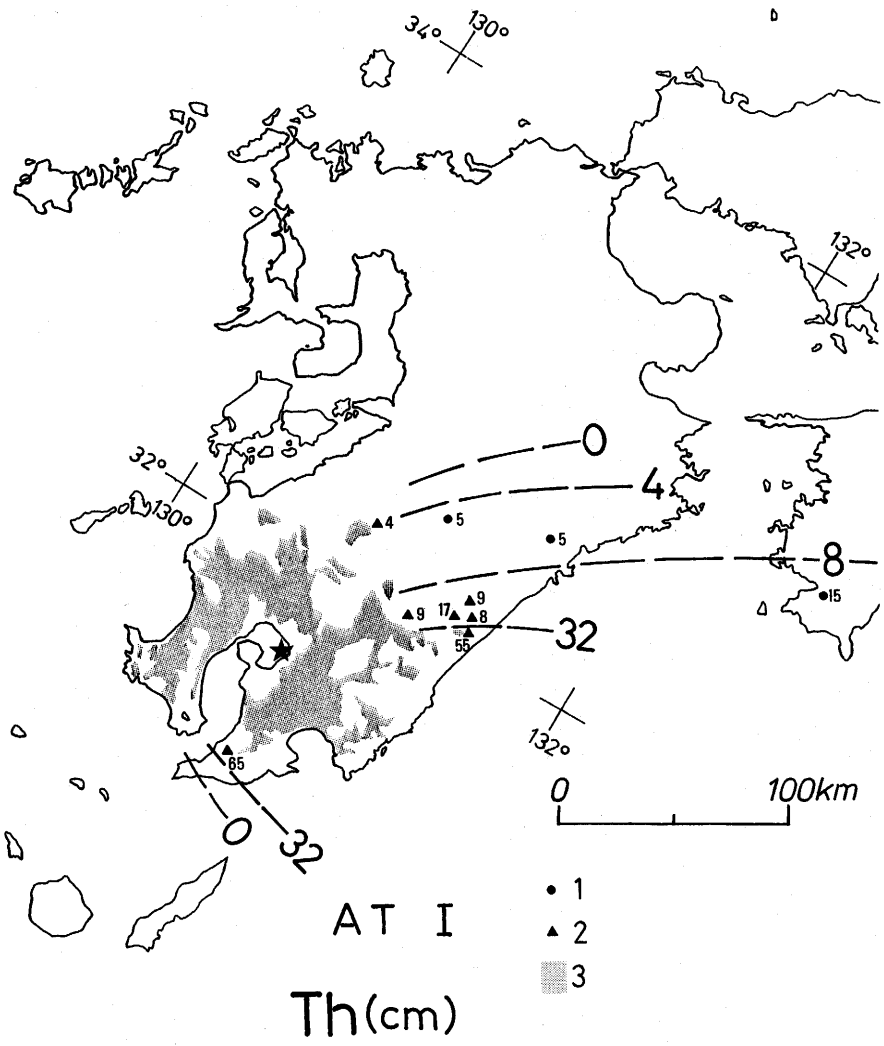

Fig. 25 Isopach map of the Aira-Tn I unit (in cm)
1: AT I ash fall; 2: AT I pyroclastic (ash-cloud) surge; 3: Ito pyroclastic flow

These features suggest that AT I was formed as an ash-cloud surge (Fig. 29-3) from the upper part of Ito Pfl and the more distal part of AT I is co-ignimbrite ash, the wind-blown lateral equivalent of ash-cloud surge.

AT II AT II is 20-40 cm thick, and is yellowish-brown, well-sorted medium-grained, and locally stratified vitric ash that includes small pumice grains less than 1 cm across in the lower part in the central Miyazaki Plain. The ash contains more bubble-walled type glass shards than pumice type shards.

AT II is Coarse vitric ash of 50-180 cm in thickness, and is more poorly-sorted and richer in pumice in the area covered with Ito Pfl than in the area free from Ito Pfl. The yellow pumice fragments have a maximum diameter of up to 5 cm in the most proximal area near caldera rim, and vesiculation is well developed. Sometimes, accretionary lapilli of 0.5 to 1.5 cm across are found in the matrix of ash. These facies indicate that AT II

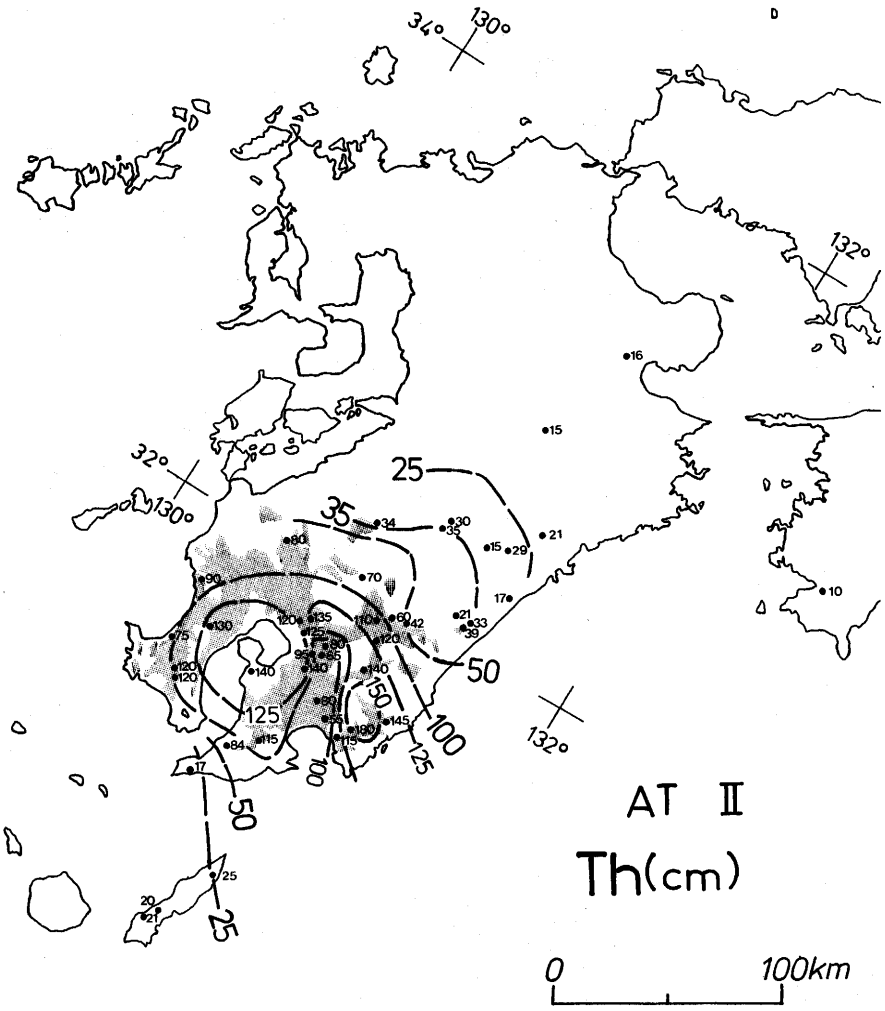

Fig. 26 Isopach map of the Aira-Tn II unit (in cm)
Symbols as Fig. 24.

was emplaced by fallout mixing magmatic materials of various sizes in the proximal area (Fig. 29-4).

The upper surface of Ito Pfl around the Aira Caldera is cut by steep-sided gullies which are several tens centimeters deep (Locs. I1, I3, I10 and I11; Fig. 21). The gullies are infilled with AT II. This erosion probably resulted from the run-off of rain shower before

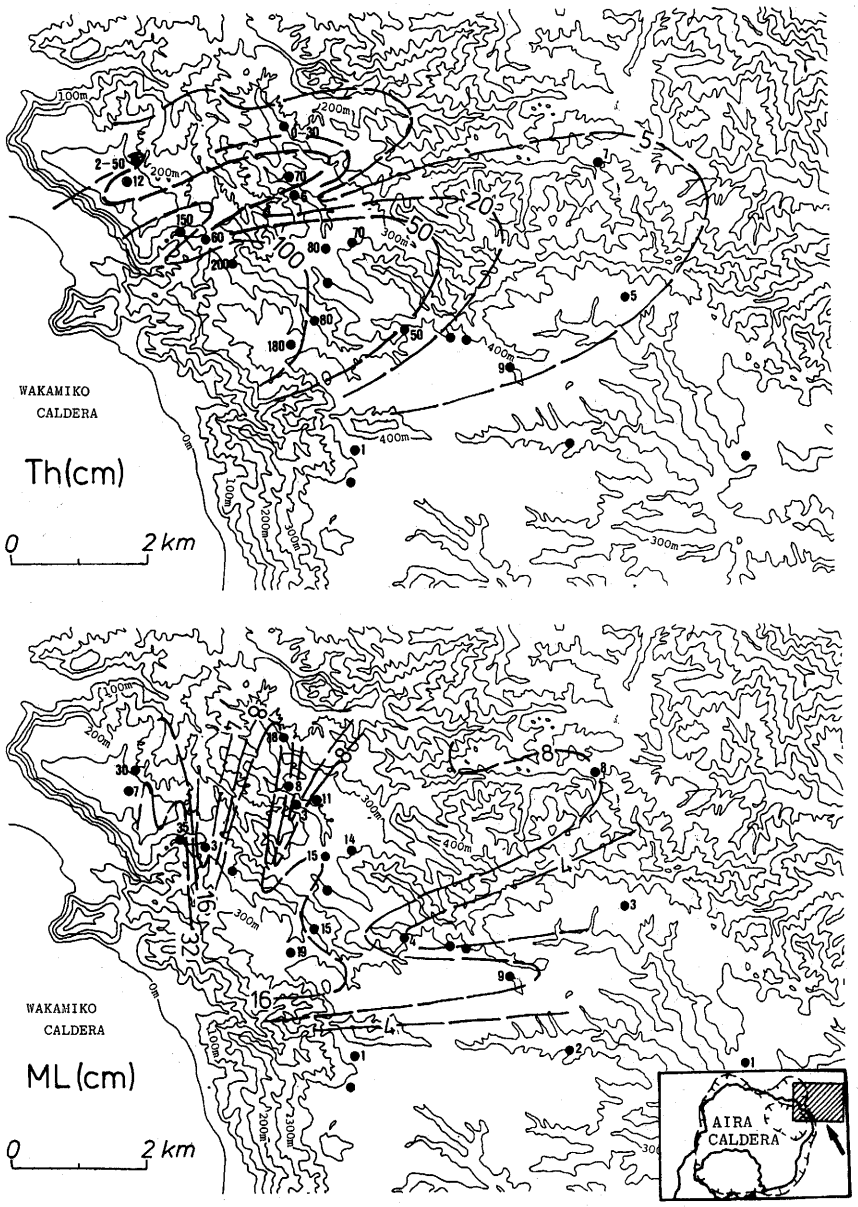

Fig. 27 Dispersal map of the Uenodan breccia
Th: Thickness (in cm); ML: Maximum lithic size (in cm)

or simultaneous with the fall of the AT II ash.

AT II is widely distributed in the western half of Japan (Fig. 26). The orientation of major dispersal axis is E to ESE, with minor axis of NE and SSE orientations (Fig. 26).

Ud A lithic-rich layer, Uenodan breccia (Ud), is intercalated in AT II and exhibits low-angle cross-bedding at Uenodan and its environs on the northeastern rim (Locs. I1 ~I7 and I9; Fig. 21). Ud is less than 150 cm thick and consists of angular lithic fragments, 35 cm in maximum diameter, mainly derived from shale and sandstone of the Shimanto Supergroup. The breccia is moderately sorted and occurs in matrix of the same yellowish brown vitric ash as AT II. Locally, when the deposit is lacking in matrix, lithic fragments are armored with fine vitric ash. There are block-sag structures; Ud depresses the lower part of AT II at Loc. I5 in Fig. 21.

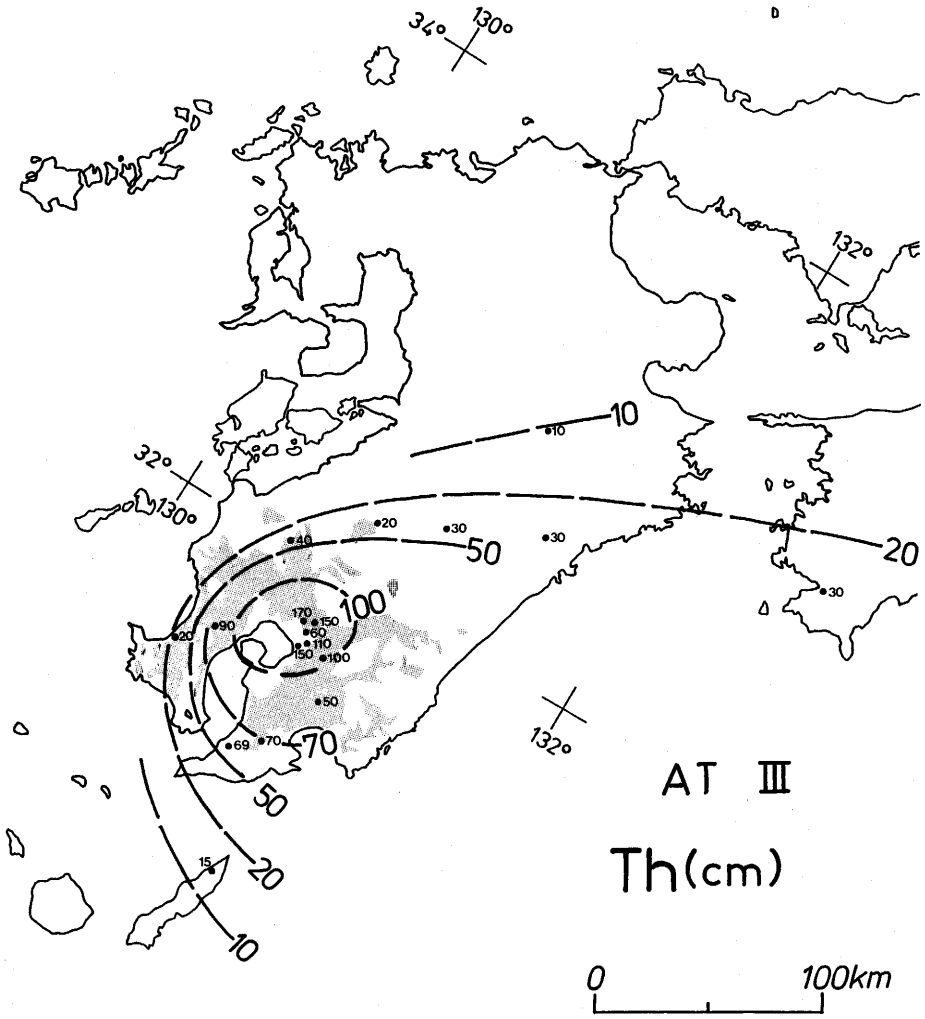

Fig. 28 Isopach map of the Aira-Tn III unit (in cm)
Symbols as Fig. 24.

Ud is scattered like a handprint within 5-6 km radius of the northeastern rim of the Aira Caldera (Fig. 27 above: Th). The vent position is estimated from the variation of maxmum lithic size (Fig. 27 below: ML) to be in the northeastern part (the Wakamiko Caldera) in the Aira Caldera.

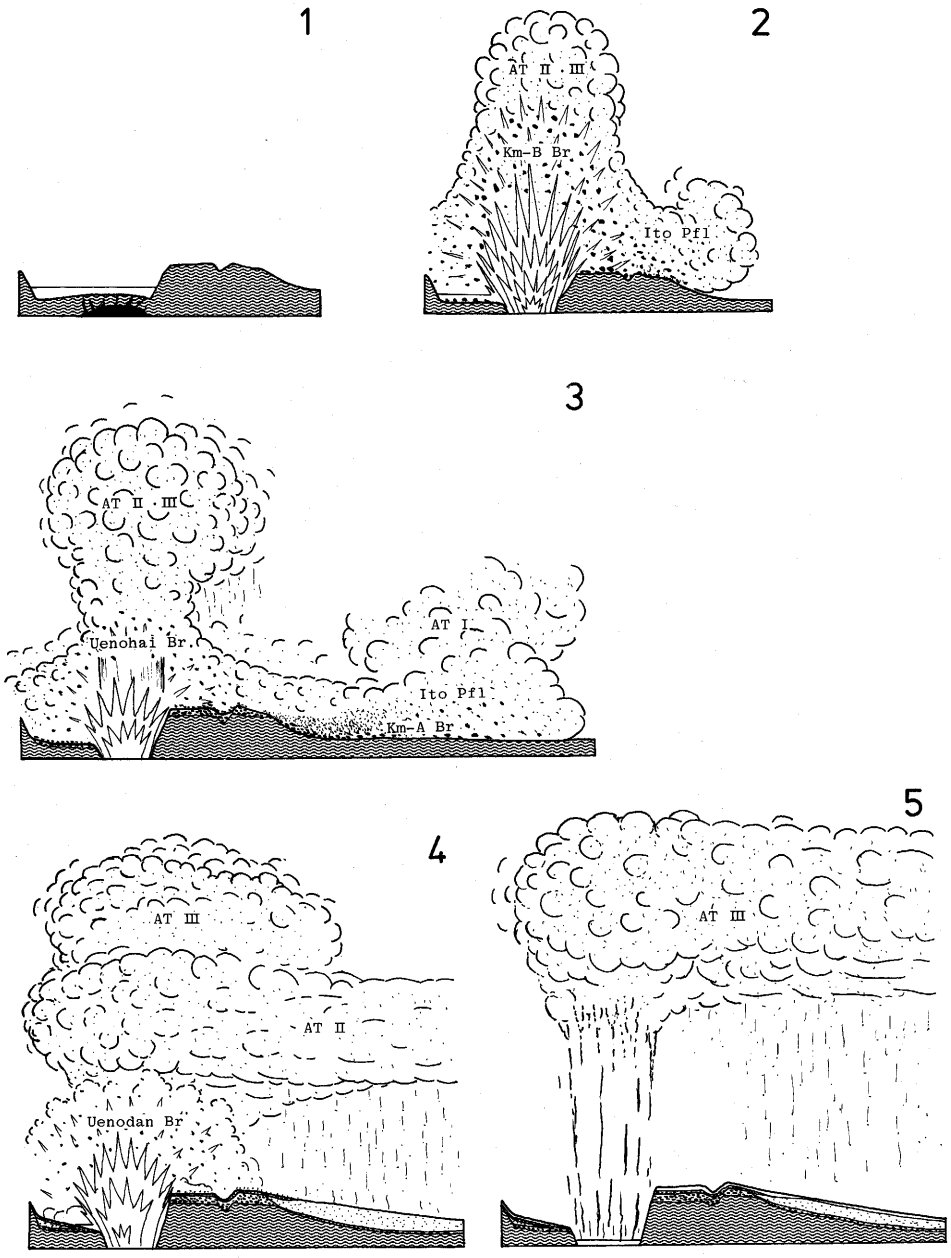

Fig. 29 Cartoons showing the Ito pyroclastic flow phase

These features indicate that Ud was ballistically transported through the AT II shower by lithic-and-water laden jets. Phreatic explosions probably occurred in the last time of the Ito phase, when the discharge of magma ended and a large amount of sea or lake water entered into the still-hot vent (Fig. 29-4).

AT III AT III, 30 cm thick, is the fine-grained and best-sorted ash layer in the three units of AT, and is abundant in glass shards of bubble-wall type. The ash is dispersed eastward (Fig. 28). Finer grains rose to the uppermost part of column penetrating troposphere, forming AT III (Fig. 29-5).

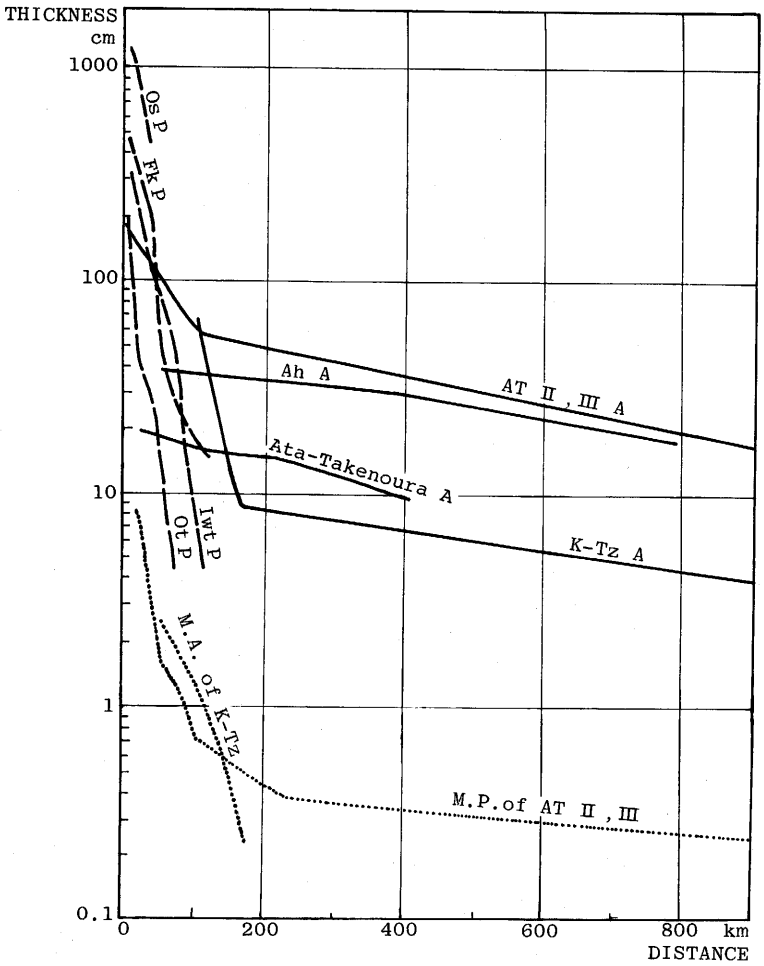

Fig. 30 Variations in thickness and maximum grain sizes of co-ignimbrite ash falls and some Plinian pumice fall deposits in southern Kyushu with distance
AT, Ah, and Os P adapted from Machida and Arai (1976, 1978), and Kobayashi *et al.* (1983). A solid line: Co-ignimbrite ash fall; a broken line: Pumice fall; a dotted line: Maximum sizes of pumice or accretionary lapilli

Figure 18b shows that the eruptive column of AT (AT II) are as high as that of Os P. The grain size and thickness of AT II and III decrease with distance less than the plinian pumice falls (Fig. 30). But, within 100 km, they decrease much more rapidly than the region far from 100 km. In the proximal part, the AT II and III may fall as accretionary lapilli with rain drops (Fisher and Schmincke, 1984). The distal part of AT II and III may have fallen as porous clusters like snowflakes by mechanical interlocking and electoric attraction (Sorem, 1982).

4. Late Quaternary Volcanism of the Ata Caldera

Geomorphology

The Ata Caldera (Matumoto, 1943) is 15 km × 20 km wide at the mouth of Kagoshima Bay (Figs. 1 and 31). The bottom is 100 m below sea level. The western wall is 200 m high

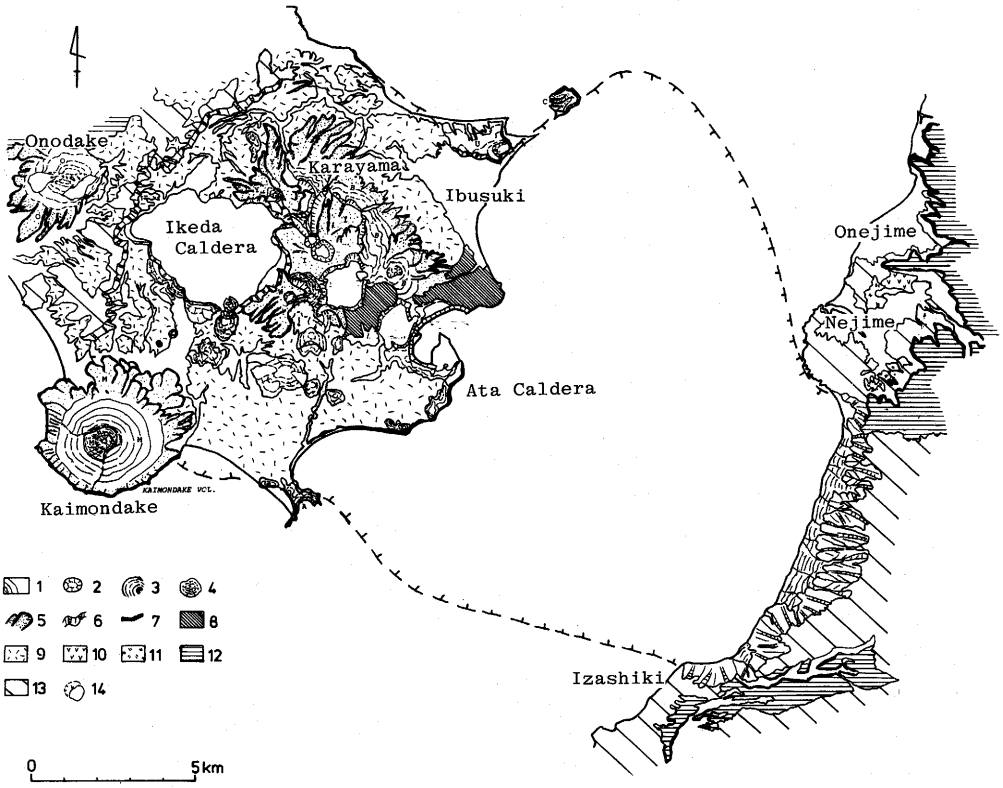

Fig. 31 Geomorphological map of the Ata Caldera
1: Alluvial plain and fan; 2: Crater; 3: Conical volcano; 4: Lava dome; 5: Lava flow; 6: Caldera wall; 7: Cliff (including fault scarps); 8: Pyroclastic surge deposit surface; 9: Ikeda pyroclastic flow surface; 10: Ito pyroclastic flow surface; 11: Tashiro pyroclastic flow surface; 12: Ata pyroclastic flow surface; 13: Mountain and hill; 14: Landslide

and the eastern wall is 900 m high. The northern and southern walls are probably submerged beneath the sea or eroded away (Fig. 31).

The western half of the caldera is buried with a large amount of ejecta of post-caldera volcanoes; stratovolcanoes of Ibusuki, Karayama and Kaimon-dake, lava domes of Washio-dake, Takeyama, Nabeshima-dake, and maars of Ikezoko, Namazuike, Narukawa, Yamakawa, and Kagamiike, a parastic stratovolcano of Ono-dake. The Ikeda Caldera, 3 km × 4 km wide, is located in the center of this volcanic area.

In central Kagoshima Bay, there is a caldera-like depression 14 km × 19 km wide and 200 m below sea level in contact with north of the Ata Caldera (Hayasaka, 1983, 1987; Fig. 1).

Outline of volcanism

There is little knowledge about when the explosive silicic volcanism started in southern Kagoshima Bay. The Torihama pyroclastic flow deposit (Ui, 1971) is one of the oldest tephra layers (Figs. 32 and 33) in this region. Its age is determined to range from 0.17 Ma to 0.10 Ma (Fukuoka, 1974; Sawada *et al.*, 1984).

Several plinian-eruption cycles, including the Marumine (Sakaguchi and Ui, 1979) cycle, occurred intermittently for 10^4 years after the Torihama cycle. These events were followed by the Ata cycle of 90-80 ka that generated a cataclysmic large-scale pyroclastic flow which covered a wider area of southern Kyushu than Ito Pfl (Aramaki and Ui, 1966a; Machida *et al.*, 1983; Nagaoka, 1984).

After the Ata eruption, the Imaizumi pyroclastic flow (Ui, 1967) (Im Pfl) formed in the northern part of the caldera and the Tashiro pyroclastic flow (Sakaguchi and Ui, 1983) (Ts Pfl) in the northeastern quarter of the caldera. Because they underlay the roughly 75 ka old Kikai-Tozurahara ash: K-Tz (Machida and Arai, 1983a; see Fig. 32 and Locs. B3 and B5 in Fig. 34), their ages are estimated to be about 80 ka. They cover small area along southern Kagoshima Bay (Fig. 36).

The period ranging from 70 ka to 40-30 ka was quiet. The evidence for quiescence is the strongly eroded tops of the non-welded part of the Ata and Tashiro pyroclastic flow deposits that produced a high-angle unconformity under Os P, Ito Pfl and the Karayama scoria fall deposit (Kr S).

Kr S was first called the Karayama volcanic ash by Nakamura (1980). Kr S erupted about 25 ka from Karayama Stratovolcano which is one of the oldest of the post-caldera cones (Nakamura, 1980), and covers the southern Osumi Peninsula.

After the construction of Karayama and Ibusuki stratovolcanoes, several lava domes and lava flows, including Take-yama Kiyomi-dake and Washio-dake, were formed. This andesitic volcanism ceased before the Aira eruption of 22-21 ka (Naruo and Kobayashi, 1983).

A moderate-scale rhyolitic eruptive cycle, the Ikeda cycle, occurred about 5 ka in the center of the post-caldera volcanoes, and formed the Ikeda Caldera. The cycle was composed of the Ikezoko phreatomagmatic phase (an ash fall and projectile), the Osagari scoria fall phase, the Ikeda pumice fall phase, the Ikeda pyroclastic flow phase, and a pyroclastic surge phase (Ui, 1967; Naruo and Kobayashi, 1983, 1984). The pyroclastic flow and surge deposits, 2-3 km^3 in volume, covered the western half of the Ata Caldera.

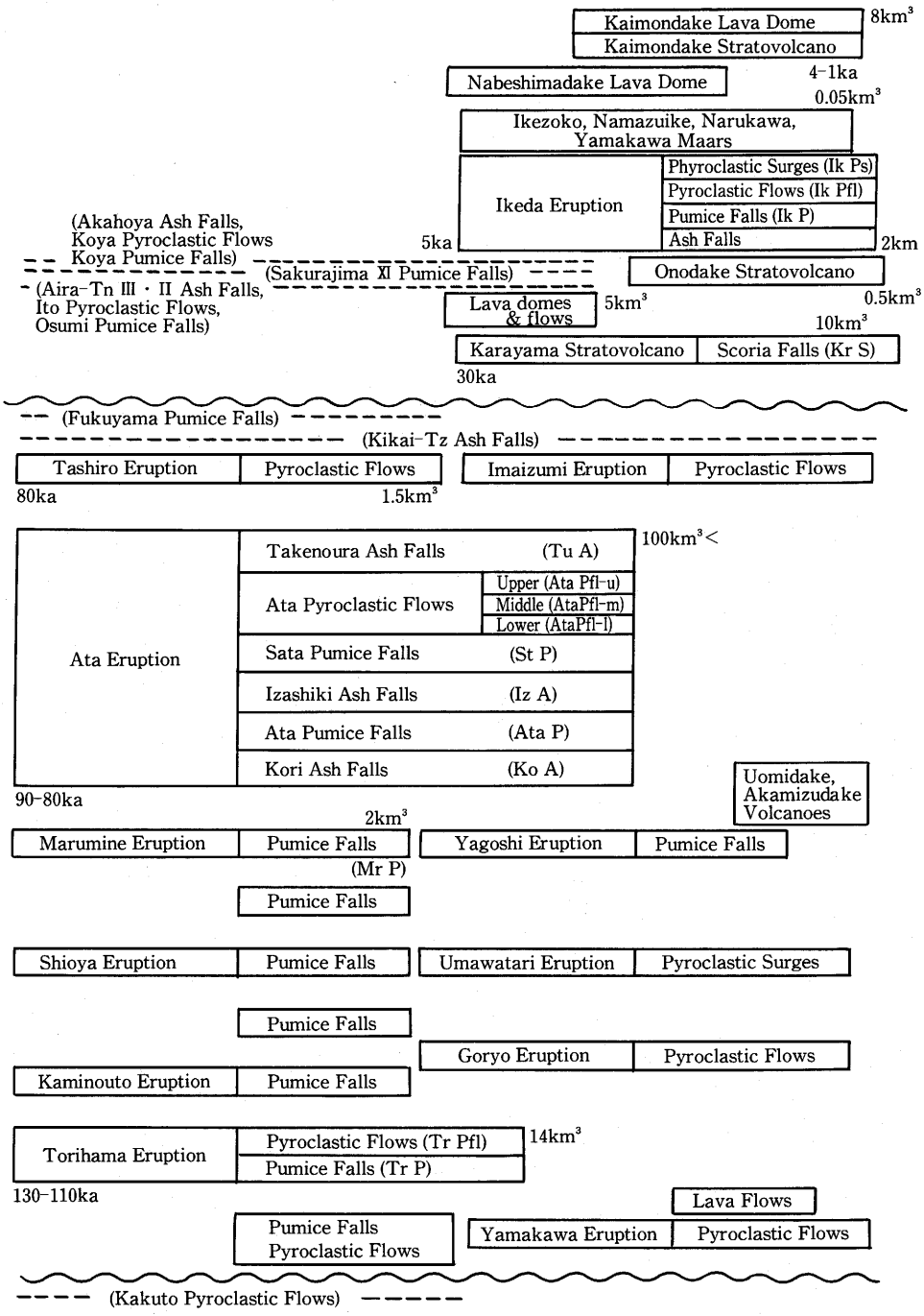

Fig. 32 Block diagrams showing the late Quaternary geologic history of the Ata Caldera

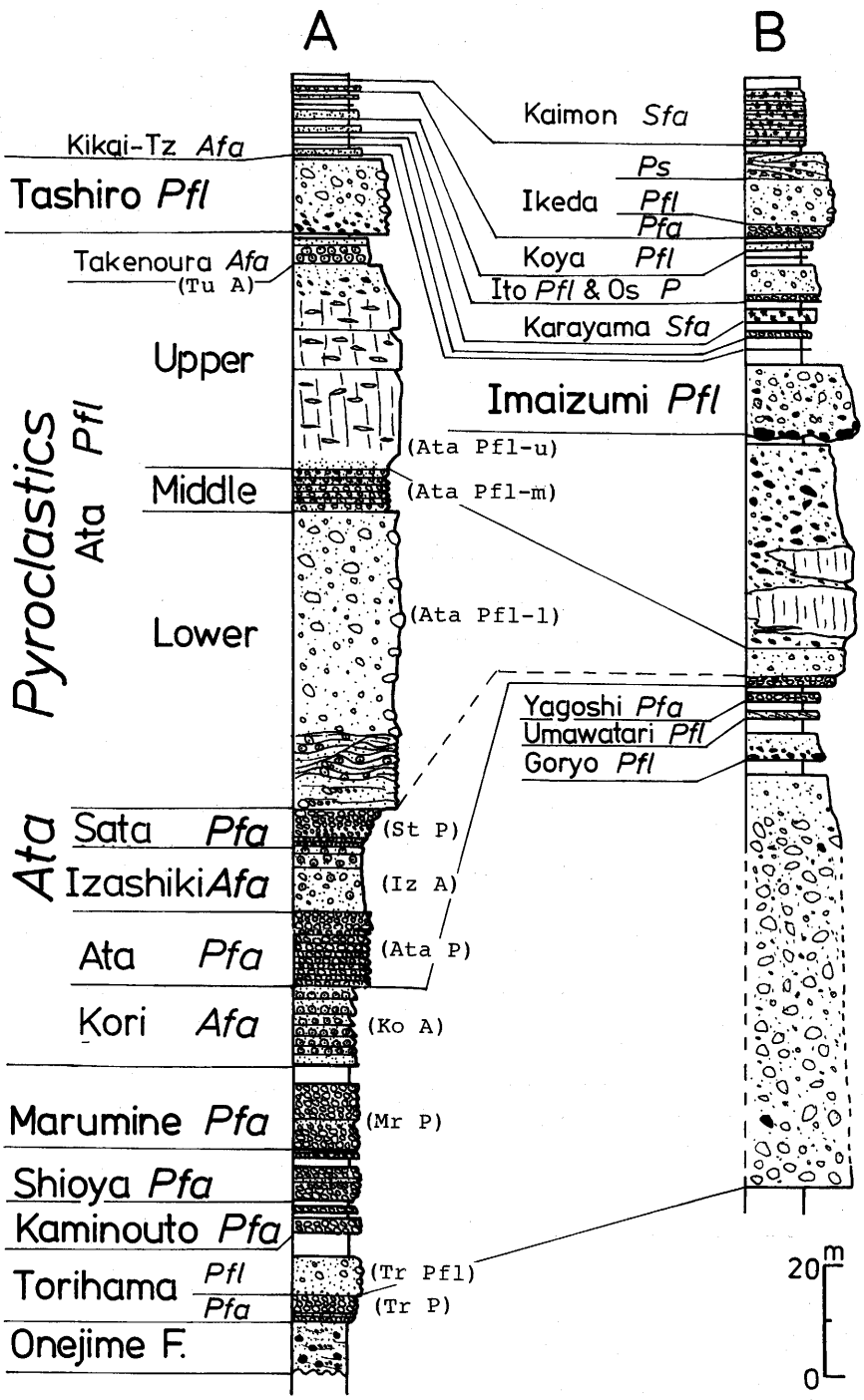

Fig. 33 Idealized columnar sections around the Ata Caldera
A: Onejime area, the Osumi Peninsula; B: Yagoshi area, the Satsuma Peninsula
Symbols as Fig. 6.

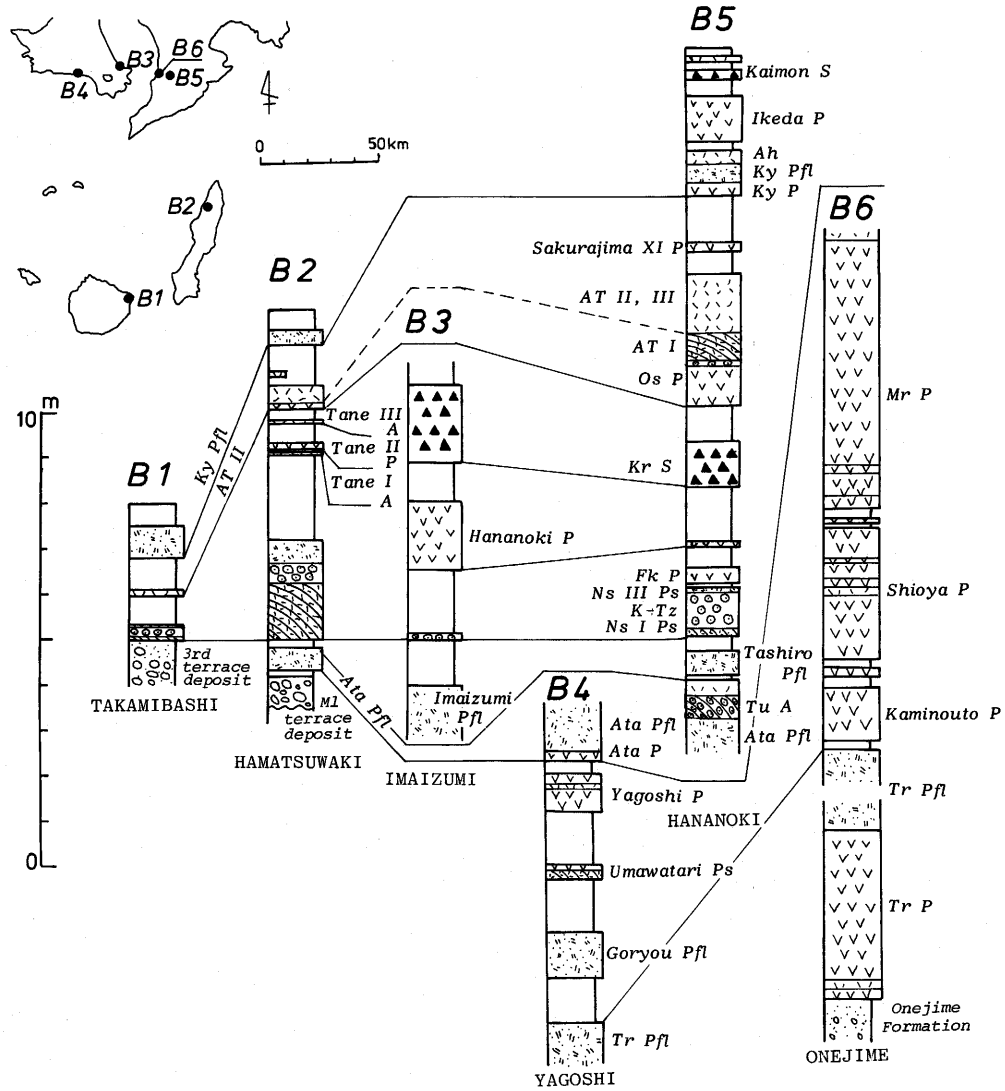

Fig. 34 Representive columnar sections for the late quaternary tephra layers around the Ata and Kikai Calderas
3rd terrace by Nakata (1968), M_1 terrace by Machida (1969). Symbols as Fig. 7.

Small-scale phreatomagmatic eruptions followed the Ikeda eruption just east of the Ikeda Caldera, and produced four maars; the Ikezoko, Namazuike, Narukawa, and Yamakawa, southeast from the caldera (Naruo and Kobayashi, 1983).

Kaimon Stratovolcano started to be constructed at the south of the Ikeda Caldera about 4 ka, and erupted many lava flow sheets, scoria and ash fall layers (Nakamura, 1967, 1971). Then, after the southern half of the high stratovolcano collapsed by a phreatic explosion, a lava dome formed in the crater at the peak of the last stage (Nakamura, 1971). The activity has been quiet in the last 1 ka (Nakamura, 1967, 1971).

Tephra layers older than the Ata eruptive cycle

In this and next sections, the Torihama and Ata pyroclastic flow deposits and their related fall deposits (Fig. 33) are described in detail. Because most of these tephra layers were formed about 150-80 ka, some of them are useful to correlated late Pleistocene marine terraces in southern Kyushu (Machida *et al.*, 1983).

Torihama pumice fall deposit **(Tr P)** *and Torihama pyroclastic flow deposit* **(Tr Pfl)**

The Torihama cyle, consists of a plinian pumice fall and a following pyroclastic flow. They uncomformably cover the Onejime formation (Kuwano *et al.*, 1959), near the coast at Onejime and Nejime in southern region of the Osumi Peninsula. Phenocrysts in pumice fragments contain abundant quartz and hornblende crystals which are used as a key for the identification of the units among other tephra layers from the Ata Caldera. However, the assemblage of phenocrysts is similar to that of tephra from the Ikeda eruption (Fig. 50).

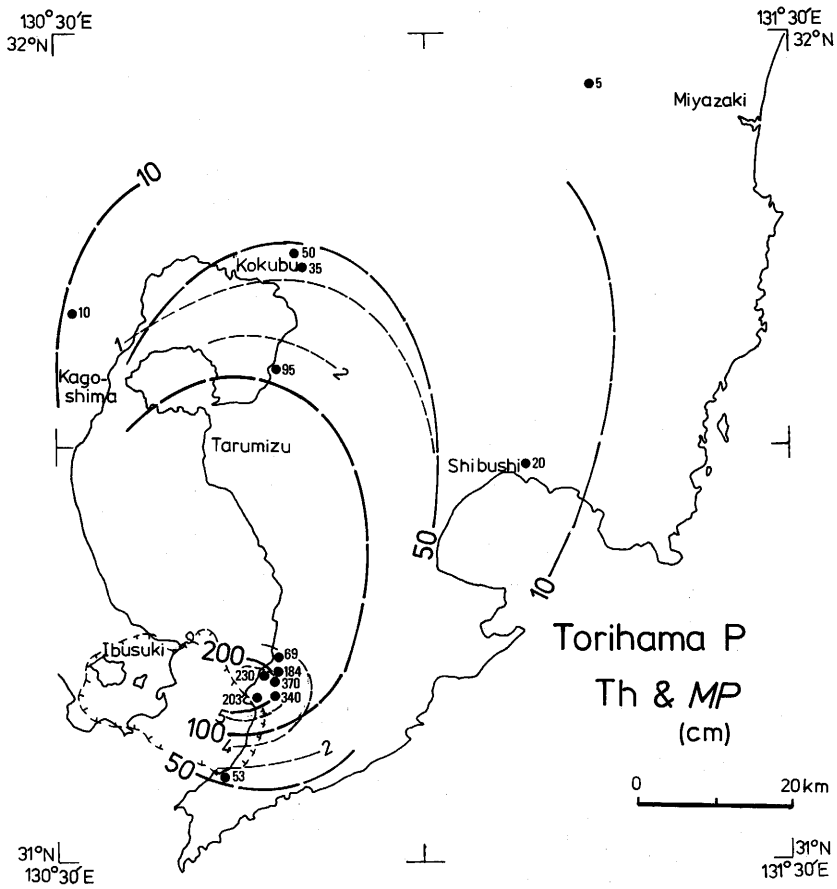

Fig. 35 Dispersal map of the Torihama pumice fall deposit
Symbols as Fig. 8.

Tr P Tr P was first described by Sakaguchi and Ui (1979). At Onejime (Loc. B6, Fig. 34; Loc. R7, Fig. 37) along the southwestern coast of the Osumi Peninsula, Tr P is 370 cm thick, and has five fall units. The third unit from the bottom with 300 cm of thickness is the thickest, and includes coarse-grained pumice fragments more than 6 cm across. The pumice is white and moderately vesicular. There are few lithic fragments.

The deposit covers the whole of the Osumi Peninsula (Fig. 35). The orientation of the dispersal axis is due north. The vent was located in the northwestern half of the Aira Caldera, estimated from the isopleth of maximum pumice size (Fig. 35). The volume is about 5 km^3.

Tr Pfl Tr Pfl was first described by Ui (1971) around Onejime in the southern Osumi Peninsula, and was afterward found under the Nan-satsu Upland in the southern end of

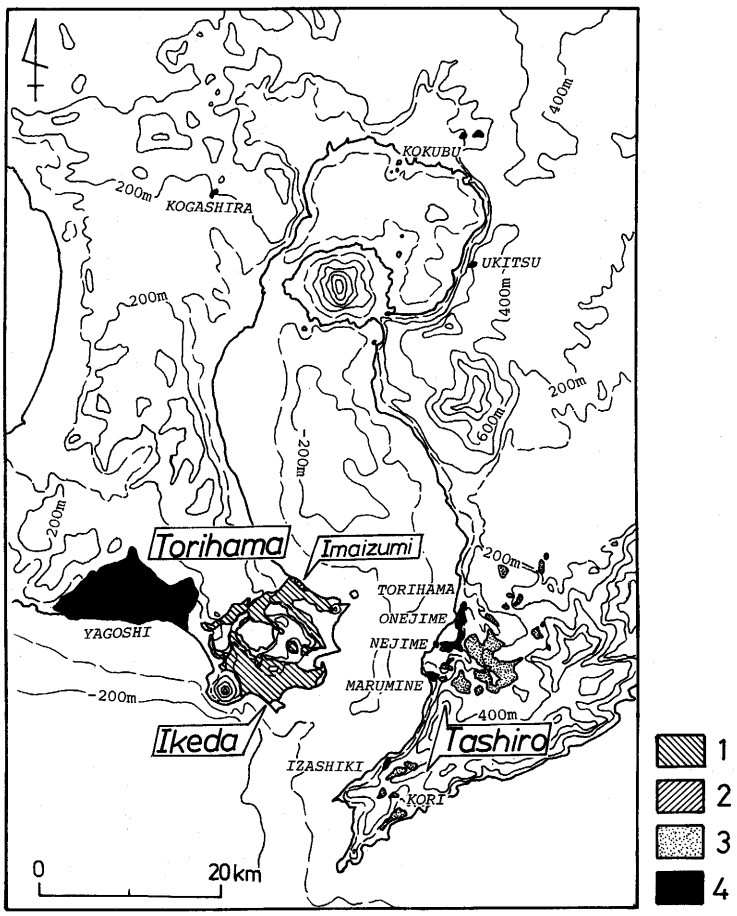

Fig. 36 Distribution of remaining parts of the Torihama Imaizumi, Tashiro and Ikeda pyroclastic flow deposits, adapted from Ui (1967), Terashima *et al.* (1979), and Sakaguchi and Ui (1983).
1: Ikeda Pfl; 2: Imaizumi Pfl; 3: Tashiro Pfl; 4: Torihama Pfl

the Satsuma Peninsula by Terashima *et al.* (1979). Tr Pfl corresponds to the Ukitsu pyroclastic flow deposit described by Aramaki (1977) in the northern Osumi Peninsula.

The most part of Tr Pfl is exposed in the southern parts of the Satsuma and Osumi Peninsulas (Fig. 36), and a thinner layer reaches Kogashira in Kagoshima City, Ukitsu in Tarumizu City and Umegaya in Kokubu City around the Aira Caldera (Fig. 36).

At the foot of cliff (Loc. B6, Fig. 34) behind Nejime town in the southern Osumi Peninsula, non-welded Tr Pfl is less than 5 m thick, composed of a mixture of white pumice and vitric ash. Pumice fragments are less than 10 cm across and are moderately vesicular. Tr Pfl, more than 10 m thick, includes many unsorted lithic fragments, more than 150 cm across in maximum diameter, at Matsugasaki (Loc. R7, Fig. 37), south of Onejime.

Tr Pfl is more than 60 m thick under the Nan-satsu Upland in the Satsuma Peninsula (Terashima *et al.*, 1979). The deposit, at the sea cliff of Yagoshi south of the upland (Loc. B4, Fig. 34; Locs. R1~R4, Fig. 37), contains a large amount of coarser-grained pumice, more than 50 cm across. The age of Tr Pfl is determined to be 145,000±27,000 y.B.P. by ionium dating (Fukuoka, 1974) and 110,000±20,000 y.B.P. by E.S.R. dating (Sawada *et al.*, 1984).

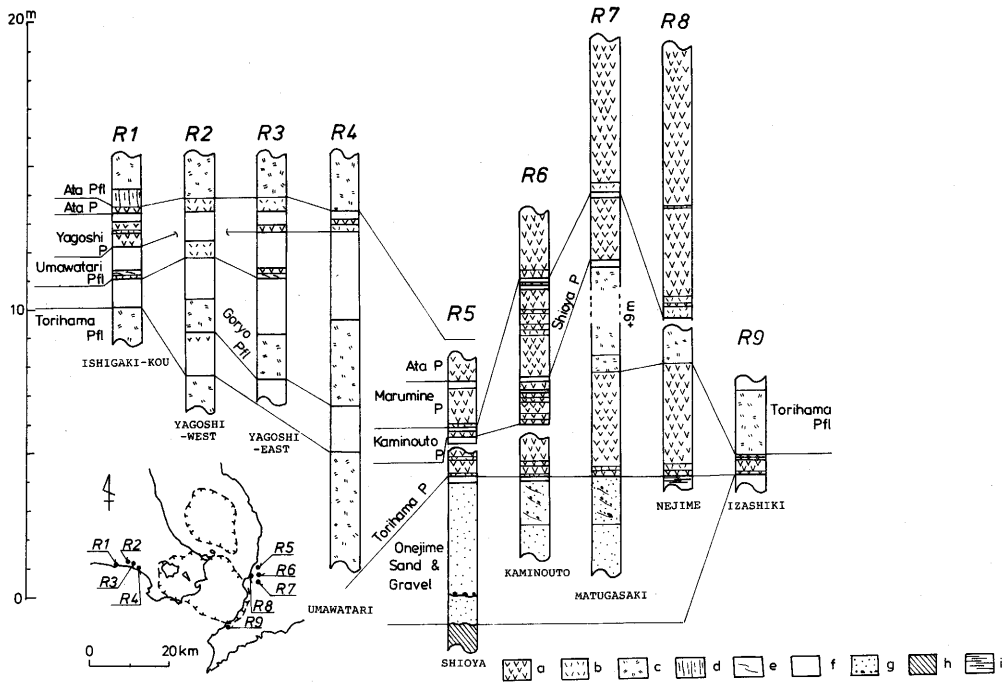

Fig. 37 Columnar sections of older tephra layers than the Ata pyroclastics around the Ata caldera
a: Pumice falls; b: Ash; c: Non-welded pyroclastic flows; d: Welded pyroclastic flows; e: Pyroclastic surges; f: Weathered tephra; g: Sand and gravel; h: Base rock; i: Silt

The pumice fall deposits covering Tr P and Tr Pfl

Tr P and Tr Pfl are overlain by several pumice fall deposits, more than 15 m in total thickness at Onejime (Loc. B6, Fig. 34; Locs. R5~R8, Fig. 37). The tephra formations consist of five pumice fall layers interbedded with soil. Three pumice fall layers are conspicuously thicker than other two, and are called Kaminouto, Shioya, and Marumine pumice fall deposits in ascending order (Fig. 33). Shioya, Kaminouto and other thin pumice layers are not found outside of the Onejime region.

The Marumine pumice fall deposit (Mr P; Sakaguchi and Ui, 1979) is the most widespread and the thickest of the five pumice falls. It has a maximum thickness of more than 750 cm at Nejime (Loc. R8, Fig. 37), and consists of poorly vesiculated yellowish white pumice. The lower part of Mr P is rich in lithic fragments. Mr P covers the southern Osumi Peninsula (Fig. 36). The volume on land is more than 2 km^3. The vent position is estimated from the isopach map to be in the northern half of the Ata Caldera (Fig. 38).

At Yagoshi (Loc. B4, Fig. 34; Loc. R1~R4, Fig. 37), two thin pyroclastic flow sheets and one pumice fall deposit (the Goryou pyroclastic flow deposit, the Umawatari pyroclastic flow deposit, and the Yagoshi pumice fall deposit in ascending order) are intercalated in the weathered tephra layers more than 5 m thick that overlying Tr Pfl. The stratigraphical relationship between these tephra layers and the pumice falls including Marumine on the Osumi-Peninsula is uncertain.

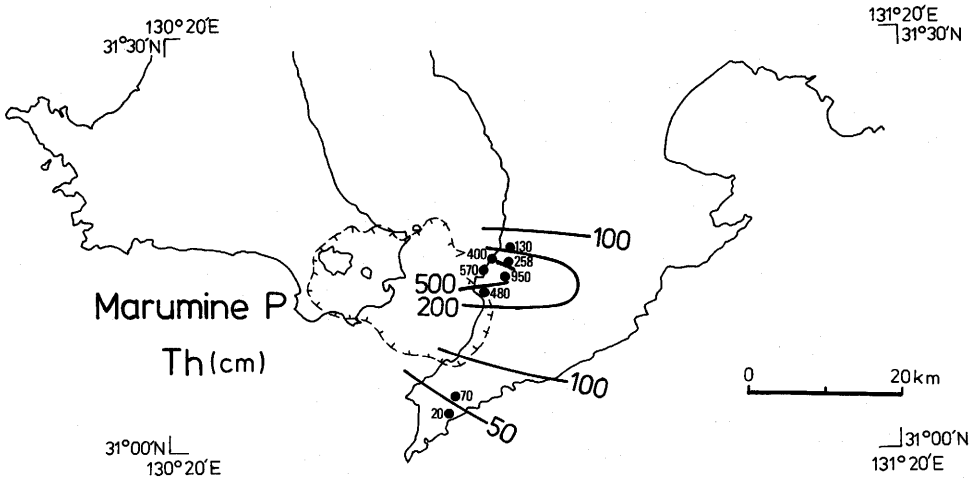

Fig. 38 Isopach map of the Marumine pumice fall deposit (in cm)
Symbols as Fig. 8.

Tephra layers in the Ata eruptive cycle

The Ata pyroclastic flow deposit (Aramaki and Ui, 1966a; Ata lava, Matumoto, 1943) is one of the largest Quaternary pyroclastic flow deposits in Japan. The volume of erupted magma was originally estimated to be 30-50 km^3 from the distribution around Kagoshima Bay (Aramaki and Ui, 1966a), but new estimates are that the total volume exceeds 100 km^3. Miyachi (1987) calculated 146 km^3. The estimates are based on new

data which shows that the Ata pyroclastic flow deposit is much more extensive than originally thought, and reaches Hitoyoshi Basin, the Miyazaki Plain and Tane Island more than 100 km away from the Ata Caldera (Machida *et al.* 1983; Watanabe, 1985; Nagaoka, 1984). The Ata pyroclastic flow deposit is 85-80 ka old (Machida *et al.*, 1983).

In Onejime of the southern Osumi Peninsula, the type region, the Ata pyroclastic flow deposit is described by Gohara and Komori (1962), Taneda and Irisa (1966), and Ota *et al.* (1967). Ui (1971) subdivided the deposit into six members, including three pyroclastic flow deposits and three airfall tephra layers. Suzuki (1988), and Suzuki and Ui (1981, 1982, 1988) discussed the modes of transport and emplacement of the Ata pyroclastic flow.

The latest data show that the Ata cycle was complex one consisting of several plinian and phreatomagmatic or phreatoplinian phases alternated with each other just before the cataclysmic pyroclastic flow phase. Tephra layers in the cycle can be lithologically subdivided into eight members (Figs. 33, 39a, b and c). The mineral assemblages of the essential material in each member are similar, containing feldspar, clinopyroxene, orthopyroxene, magnetite, and small amount of hornblende (Fig. 50).

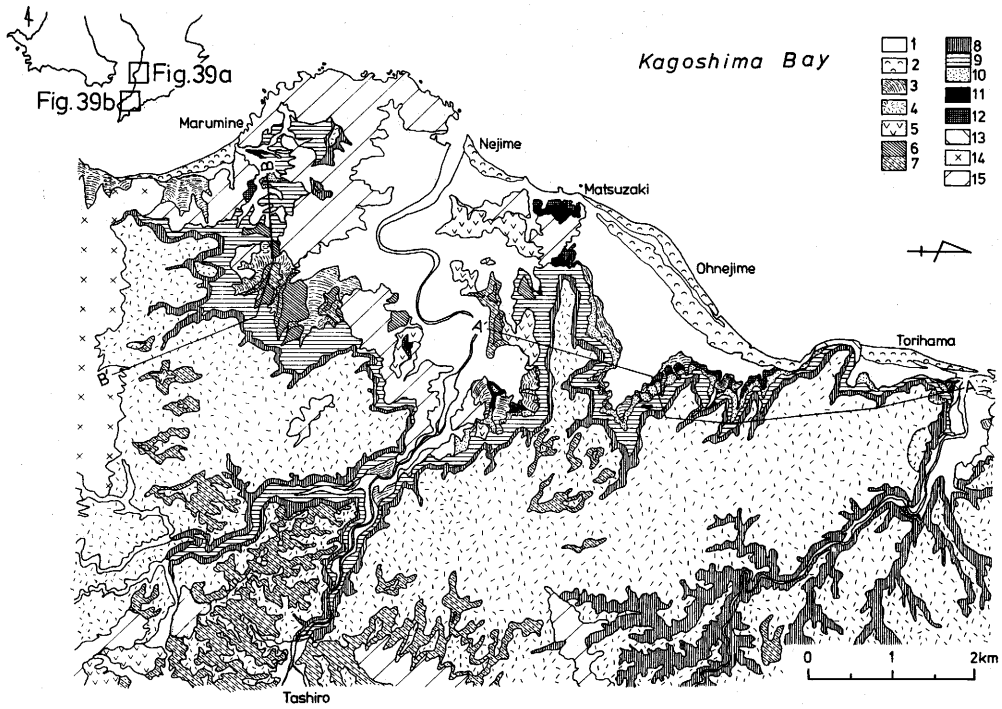

Fig. 39a Geological map of the Onejime region
1: Alluvium; 2: Deposit of sand ridges; 3: Tallus and alluvium fan deposits; 4: Tephra layers younger than the Tashiro pyroclastic flow deposit; 5: Ito pyroclastic flow deposit; 6: Tashiro pyroclastic flow (welded); 7: Tashiro pyroclastic flow deposit (non-welded); 8: Ata pyroclastic flow deposit upper; 9: Ata pyroclastic flow deposit middle & lower, and Ouchiyama-toge pyroclastic surge deposit; 10: Sata and Ata pumice fall deposits, Izashiki and Kori ash fall deposits, 11: Marumine and other pumice fall deposits; 12: Torihama pyroclasic flow and pumice fall deposits, and Onejime sand & gravel; 13: Early Quaternary andesitic lava; 14: Granite; 15: Shimanto supergroup

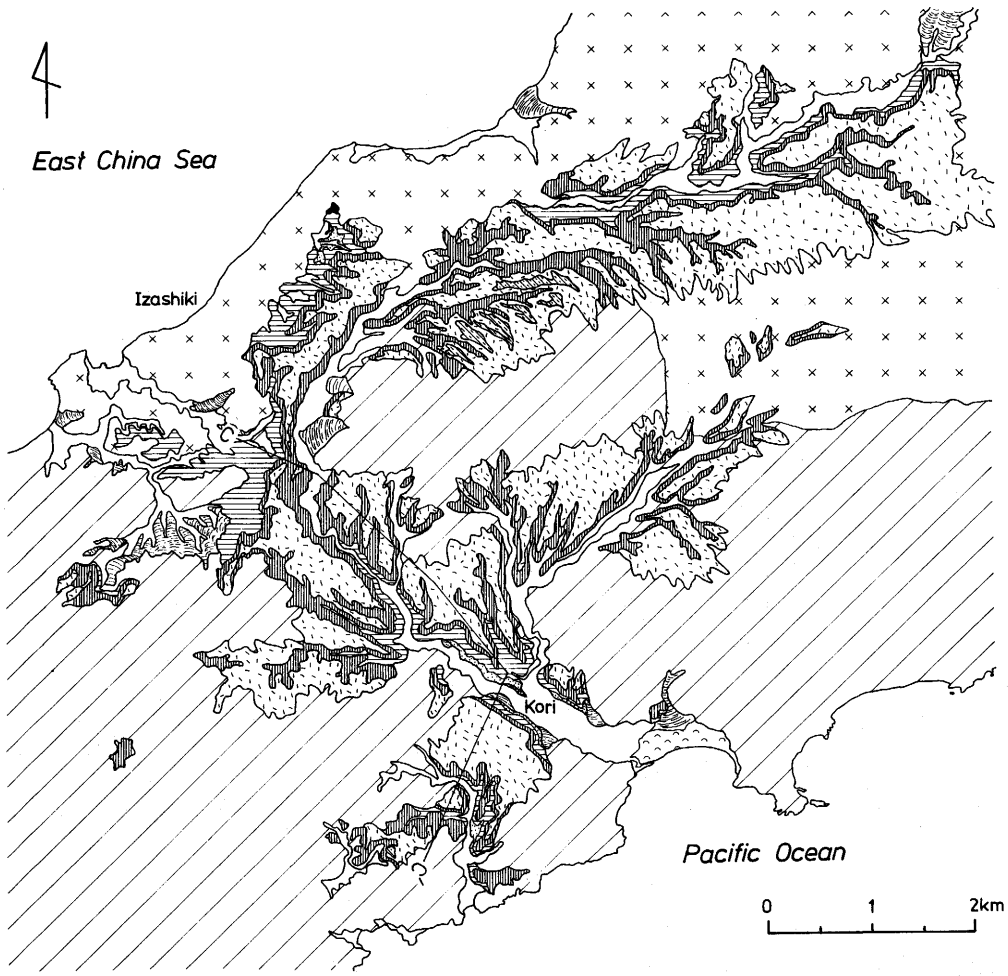

Fig. 39b Geological map of Izashiki region
Symbols as Fig. 39a.

Kori ash fall deposit **(Ko A)**

Ko A is 750 cm thick at Kori (Loc. T3, Fig. 40) in the southern end of the Osumi Peninsula. The ash consists of eight fall units which are normally graded. Each unit is composed of a matrix of fine-grained pumice-type glass shards and spherical accretionary lapilli. The accretionary lapilli, up to 1.5 cm in maximum diameter, have several thin concentric layers surrounding cores such as small pumice grains.

Ko A is dispersed in the southern end of the Osumi Peninsula. The vent position is unknown.

The accretionary lapilli and the fine-grained facies of Kori A suggest that it was formed from a violent silicic phreatomagmatic phase, probably a phreatoplinian eruption (Self and Sparks, 1978), that resulted from the explosive mixing of vesiculating magma with sea water in the vent.

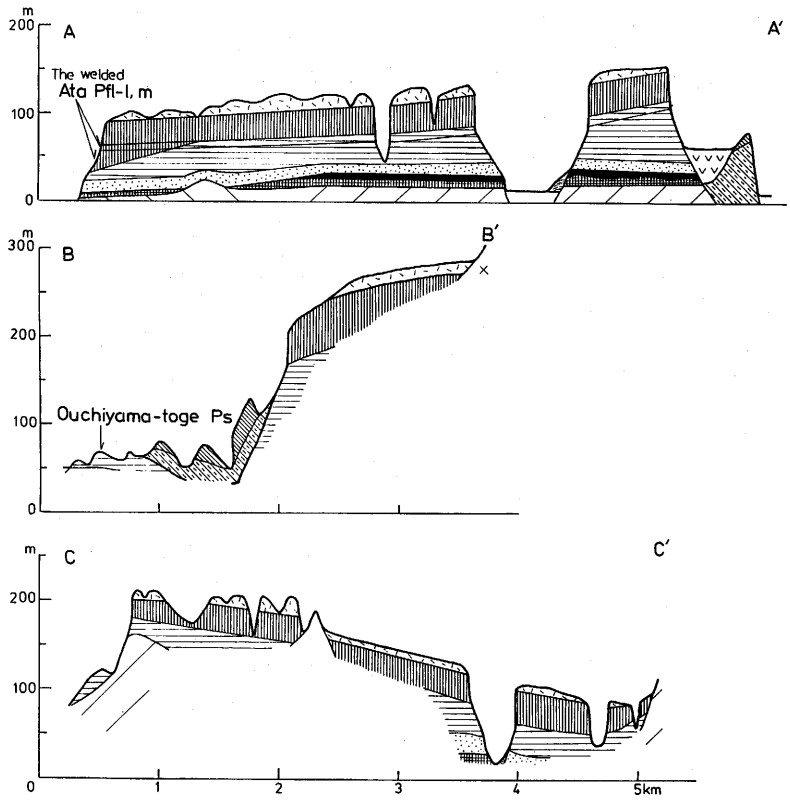

Fig. 39c Geological cross sections
Positions are in Figs. 39a and b.

Ata pumice fall deposit **(Ata P)**

Ata P was formed in the earliest plinian eruptive phase, and corresponds to the Ata pumice fall (Aramaki and Ui, 1966b) and the Ata I air-fall pumice (Ui, 1971). The boundary between Ko A and Ata P is commonly a small-scale high-angle unconformity formed by erosion. Since no humic soil or water-laid sediments are found on the unconformity, the time interval between Ko A and Ata P was geologically very short.

In Onejime (Loc. T8, Fig. 40), Ata P is more than 8 m thick and has more than eighteen fall units. The deposit includes moderately vesicular pumice fragments of 8 cm in maximum diameter. Scoria is found in the lower part.

Ata P covers the southern region of the Osumi Peninsula (Fig. 41). The orientation of the dispersal axis ranges from E to ESE. The vent position is estimated from the isopleth map of maximum pumice size (Fig. 41) to be in the northern end of the Ata Caldera near the position inferred by Aramaki and Ui (1966a). The volume on land is about 5 km^3.

Izashiki ash fall deposit **(Iz A)**

Ata P is covered with a yellowish gray to white gray fine-grained vitric ash layer, *i. e.* Iz A, which is 4 m thick, at Kori (Loc. T3, Fig. 40). The ash is composed of many

accretionary lapilli and vitric ash matrix. Iz A can be subdivided into two units. The upper unit shows crude mantle-bedded structure and normally graded bedding. The lower unit is more poorly sorted than the upper, and locally valley-ponded on a very small scale since the unit was locally reworked at Kosato (Loc. T1, Fig. 40).

Outcrops of Iz A are limited along the southern end of the Osumi Peninsula (Fig. 41). The eruptive center is unknown because few outcrops remain.

Many accretionary lapilli of Iz A suggest that the eruptive column and cloud were very moist. Probably, a slicic phreatomagmatic eruption like Kori phase occurred again.

Sata Pumice fall deposit **(St P)**

St P erupted in the second plinian phase of the Ata cycle.

At Torihama (Loc. T10, Fig. 40), St P with a thickness of 340 cm consists of four major reversely graded fall units. The units include poorly vesiculated yellowish gray pumice fragments which are 6 cm in maximum diameter.

St P is distributed among the southern half of the Osumi Peninsula (Fig. 41). The thickness data suggests that the eruptive center appears to be in the northern half of the Ata Caldera.

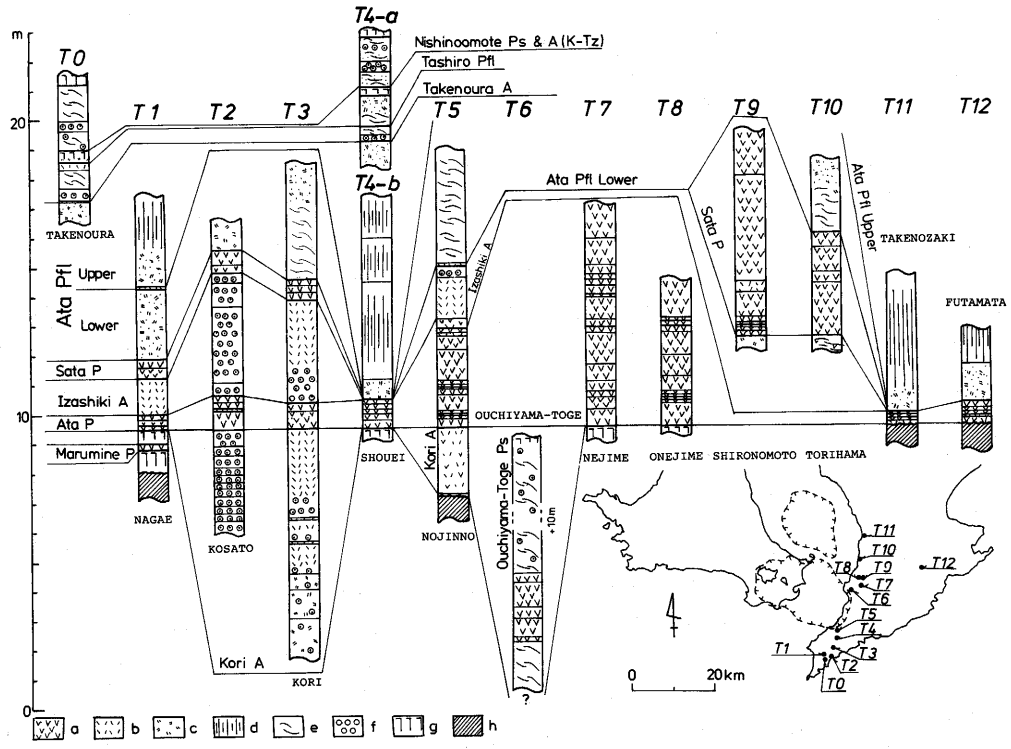

Fig. 40 Columnar sections for tephra layers from the Ata eruptive cycle
a: Pumice falls; b: Ash falls; c: Non-welded pyroclastic flows; d: Welded pyroclastic flows; e: Pyroclastic surges or laminated pyroclastics; f: Accretionary lapilli; g: Weathered tephra; h: Base rock

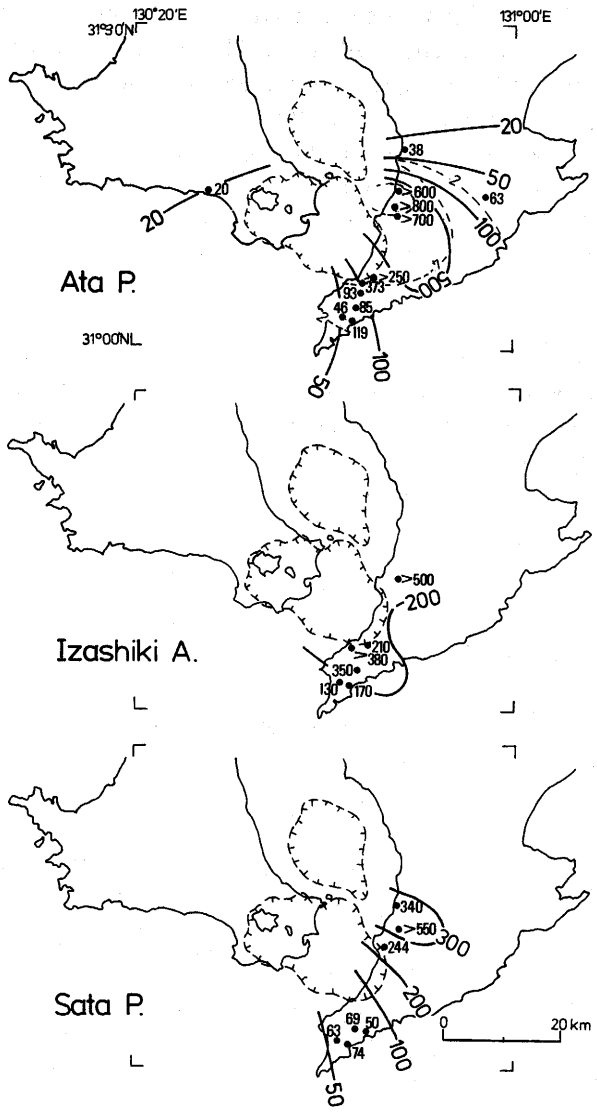

Fig. 41 Isopach maps of the Ata pumice fall, the Izashiki ash fall and the Sata pumice fall deposits (in cm)
Symbols as Fig. 8.

Ouchiyama-Toge pyroclastic surge deposit **(Oc Ps)**

Oc Ps is found only at Ouchiyama Pass, south of Nejime in the Osumi Peninsula. Though the stratigraphical relationships between Oc Ps and other Ata pyroclastics are unknown in detail, the deposit is probably older than Ata P.

At Ouchiyama pass (B-B′ section, Fig. 39c; Loc. T6, Fig. 40), Oc Ps is 15 m thick. The lower part is pumice-rich ash exhibiting planar and low-angle cross bedding, and it grades upward into accretionary-lapilli-rich ash with anti-dune structures. The wavelength of the dunes ranges from 4 m to 12 m, and the height from 1 m to 5 m. The pumice fragments are grayish white and moderately vesicular. Oval and spherical accretionary lapilli are 1.5 cm in maximum diameter, having thin concentric layers which consist of

fine-grained glass shards. These features suggest that Oc Ps is generated by strong pulsating explosions in a more explosive silicic phreatomagmatic eruption and is a proximal faces of the Ko A or Iz A phases.

Ata pyroclastic flow deposit lower **(Ata Pfl-l)**

The earlier phases repeating plinian and phreatomagmatic eruptions, were followed by three pyroclastic flow phases. The first phase formed Ata Pfl-l, which corresponds to the Ata I pyroclastic flow of Ui (1971). The deposit has many valley-ponds in the southern Osumi Peninsula, 20 km E-SSE of the northern end of the caldera.

At Nejime (Fig. 39a), Ata Pfl-l has a maximum thickness of 50-60 m, and is a non-welded pyroclastic flow deposit that is composed of a single flow unit. The deposit is a poorly sorted mixture of pumice and vitric ash. The pumice fragments are more than 50 cm across, and are grayish white and moderately vesicular. The matrix ash consists of glass shards and crystal grains. The lower part of Ata Pfl-l, less than 10 m in thickness, is well cross-stratified.

At the north end of Torihama (Fig. 39c), Ata Pfl-l is densely welded and consists of a single cooling unit. At the southern margin of the flow in Kori (Fig. 39b), the non-welded Ata Pfl-l is thinner and richer in the matrix vitric ash than in the northern part of the deposit. The deposit contains many accretionary lapilli and imbricated pieces of charcoal. The accretionary lapilli indicate that the collapsed eruption column was very moist.

Ata pyroclastic flow deposit middle **(Ata Pfl-m)**

Ata Pfl-m crops out locally from Torihama to Nejime 5 km E-ESE of the northern part of the Ata Caldera.

The flow deposit has a maximum thickness of 15 m, and is composed of twelve thin flow units which are partially welded at Onejime. Single flow units range from 50 cm to 200 cm in thicknss. The pumice fragments are inversely graded, and the lithic fragments are normally graded in each unit. The white-gray pumice fragments have a maximum diameter of more than 20 cm, and are moderately vesicular. At Torihama, Ata Pfl-l is densely welded (Fig. 39c) and displays platy jointing.

Ata pyroclastic flow upper **(Ata Pfl-u)**

Ata Pfl-u corresponds to the Ata II pyroclastic flow of Ui (1971). The distribution of Ata Pfl-u is so extensive that the deposits cover the whole of the Osumi and Satsuma Peninsulas, and can be traced to Hitoyoshi Basin, the Miyazaki Plain, and Tane Island 100-130 km far from the Ata Caldera (Fig. 42).

Ata Pfl-u is thickest in the southern part of the Osumi Peninsula. It ranges from 15 m to 50 m in thickness, and buries valleys and basins, forming plateaus. The deposit is densely welded and consists of two or three cooling units. The color is dark gray-reddish purple, which is a good key for distinguishing the deposit from other pyroclastic flows in southern Kyushu. Pumice is horizontally stretches and lineated in the dark gray-reddish purple welded part.

The uppermost part is less than 15 m in thickness and is non-welded in the central part of the plateau east of Onejime. But, the non-welded parts are strongly eroded away by

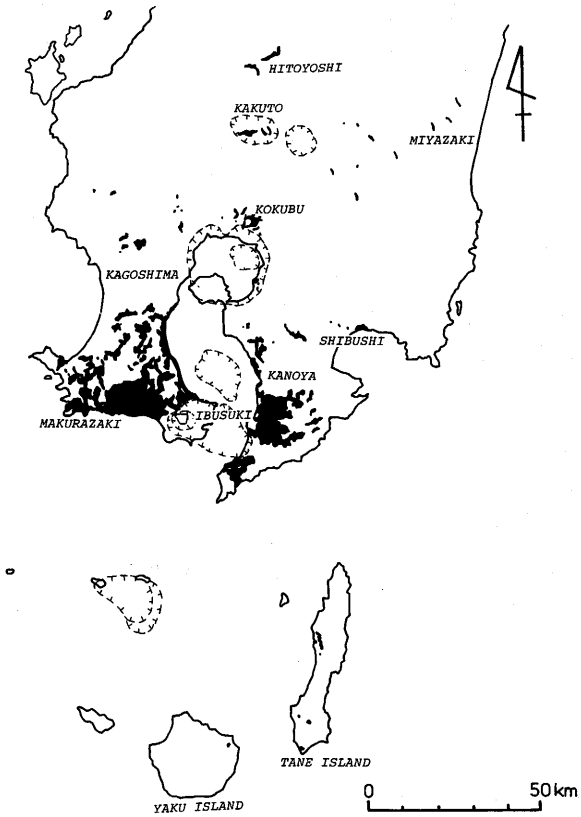

Fig. 42 Distribution of the remaining parts of the Ata IX pyroclastic flow deposit upper, after Oki and Hayasaka (1973), Suzuki and Ui (1981), Nagaoka (1984), and Watanabe (1985)

running water at the margins of the plateau.

In the distal area more than 30 km from the Ata Caldera, Ata Pfl-u is generally non-welded. It also contains more purple fine-grained vitric ash than in the proximal areas.

Takenoura ash fall deposit **(Tu A)**

Tu A overlies the uppermost non-welded part of Ata Pfl-u. The ash layer is 200 cm thick, and is subdivided into two units, at Takenoura and Shouei (Loc. T0, T4-a; Fig. 40) in the southern Osumi Peninsula. The lower unit is composed of pinkish white, very fine-grained vitric ash which includes many oval accretionary lapilli. The unit displays prominent cross-and planar bedding, as a ash cloud surges. The upper unit consists of orange fine-grained vitric ash that contains abundant bubble-wall type glass shards, and its very good sorting suggests that it is an ash fall deposit. The ash is probably the co-ignimbrite ash fall deposit of Ata Pfl-u, because it contains a large amount of bubble-wall type glass shards which are included in the matrix of the non-welded Ata Pfl-u.

5. Late Quaternary Volcanism in the Kikai Caldera

Geomorphology and geology

The Kikai Caldera (Matumoto, 1937), 20 km × 17 km wide, is located in the East China Sea 30 km southwest off Cape Sata at the south end of the Osmi Peninsula (Figs. 1 and 43). Most of the caldera is now submerged beneath the sea. The subaerial parts of the caldera are the northern caldera rim, Take-shima, and two main post caldera volcanoes, Iwo-jima and Shin-Iwo-jima. The caldera bottom is 300 m to 500 m below sea level.

The caldera rims are composed of the pre-caldera volcanoes which consist of two groups, basalt and andesite subaerial stratovolcanoes and rhyolite and dacite subaerial

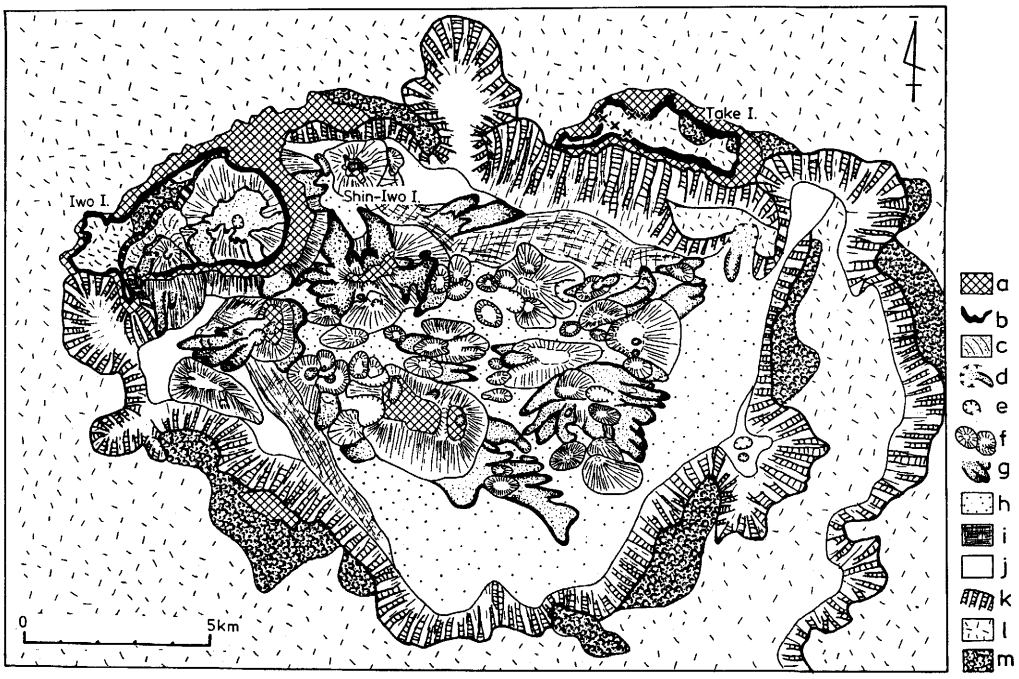

Fig. 43 Geomorphological map of the Kikai Caldera on land and beneath the sea
a: Abrasion platform and wave cut bench; b: Sea cliff; c: Fluvial fan; d: Slumping; e: Crater; f: Central cones (conical volcanos, mounds of pyroclastics or lava dome); g: Lobes of lava or pyroclastics; h: Surface of marine sediments or pyroclasitics from central cone; i: Slope; j: Caldera bottom; k: Caldera wall; l: Surface of pyroclastics of caldera-forming stage and marine sediments; m: Pre-caldera volcano

lava flows (Ono *et al.*, 1982). The rocks are all younger than 0.7 Ma (Ono *et al.*, 1982).

The deposits of the caldera-forming stage are composed of three major rhyolite and dacite pyroclastic flows accompanied by pumice falls and an alternation of thin ash and scoria fall beds (Ono *et al.*, 1982; see Figs. 44 and 45). These deposits thickly cover Take-shima and Iwo-jima.

Iwo-dake, Inamura-dake, Shin-Iwo-jima, and Asase are post-caldera volcanoes and tops of the submerged stratovolcanoes under the sea. Most of submarine post-caldera volcanoes are geomorphologically interpreted on the basis of bathymetric maps to be cones of hyaloclastite and lava domes (Fig. 43). Formation of them started after about 6 ka (Ono *et al.*, 1982).

Tephra layers in the caldera-forming stage older than the Takeshima eruptive cycle

The Kikai Caldera was probably formed by three or more silicic pyroclastic flow cycles: the Koabiyama, Nagase, and Takeshima (Ono *et al.*, 1982; see Figs. 44 and 45). In this and next sections, tephra layers in the caldera-forming stage are described.

The pyroclastic flow deposits older than the Nagase pyroclastic flow deposit

The Koabiyama pyroclastic flow deposit **(Ka Pfl)** is the oldest deposit in the stage (Ono *et al.*, 1982). Ka Pfl is less than 100 m thick, and covers Take-shima and Iwo-jima. It consists of many thin flow units that are densely welded. A thin pumice fall layer is found at the base of Ka Pfl.

The Koseda pyroclastic flow deposit (Machida, 1977) **(Ks Pfl)** probably erupted from the Kikai Caldera, and underlies the middle Pleistocene marine terrace deposits in Tane and Yaku Islands 35-50 km away from the caldera. Ks Pfl is a weathered, non-welded, rhyolite pyroclastic flow deposit containing phenocrysts of quartz and hornblende. Ka Pfl and Ks Pfl are both underlie the Nagase pyroclastic flow, but the stratigraphical relationship between Ka Pfl and Ks Pfl is unknown.

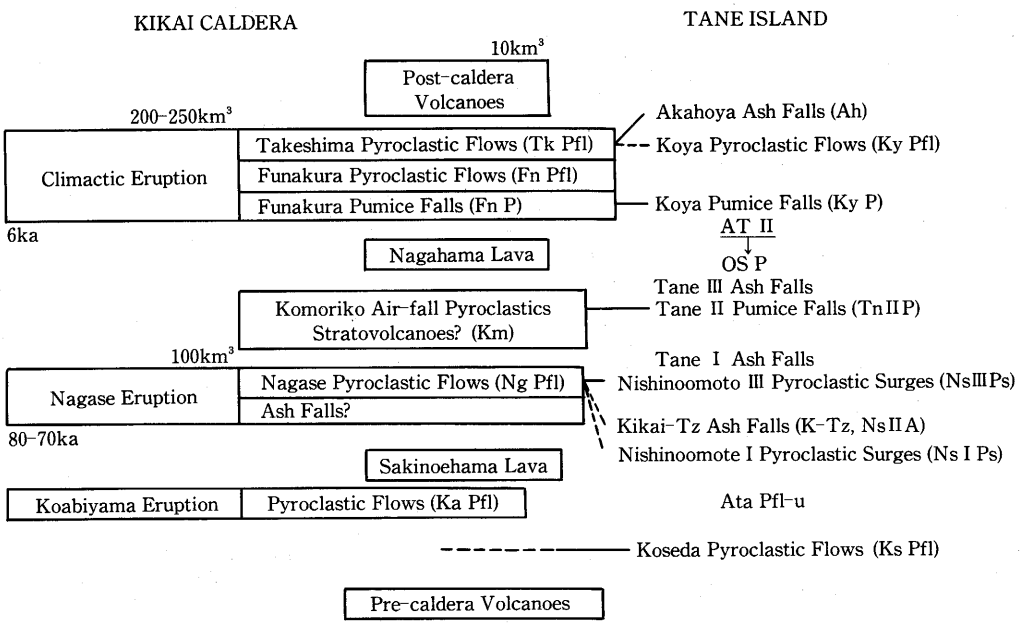

Fig. 44 Block diagrams showing the late Quaternary geologic history of the Kikai Caldera, after Ono *et al.* (1982) and Kobayashi and Hayakawa (1984)

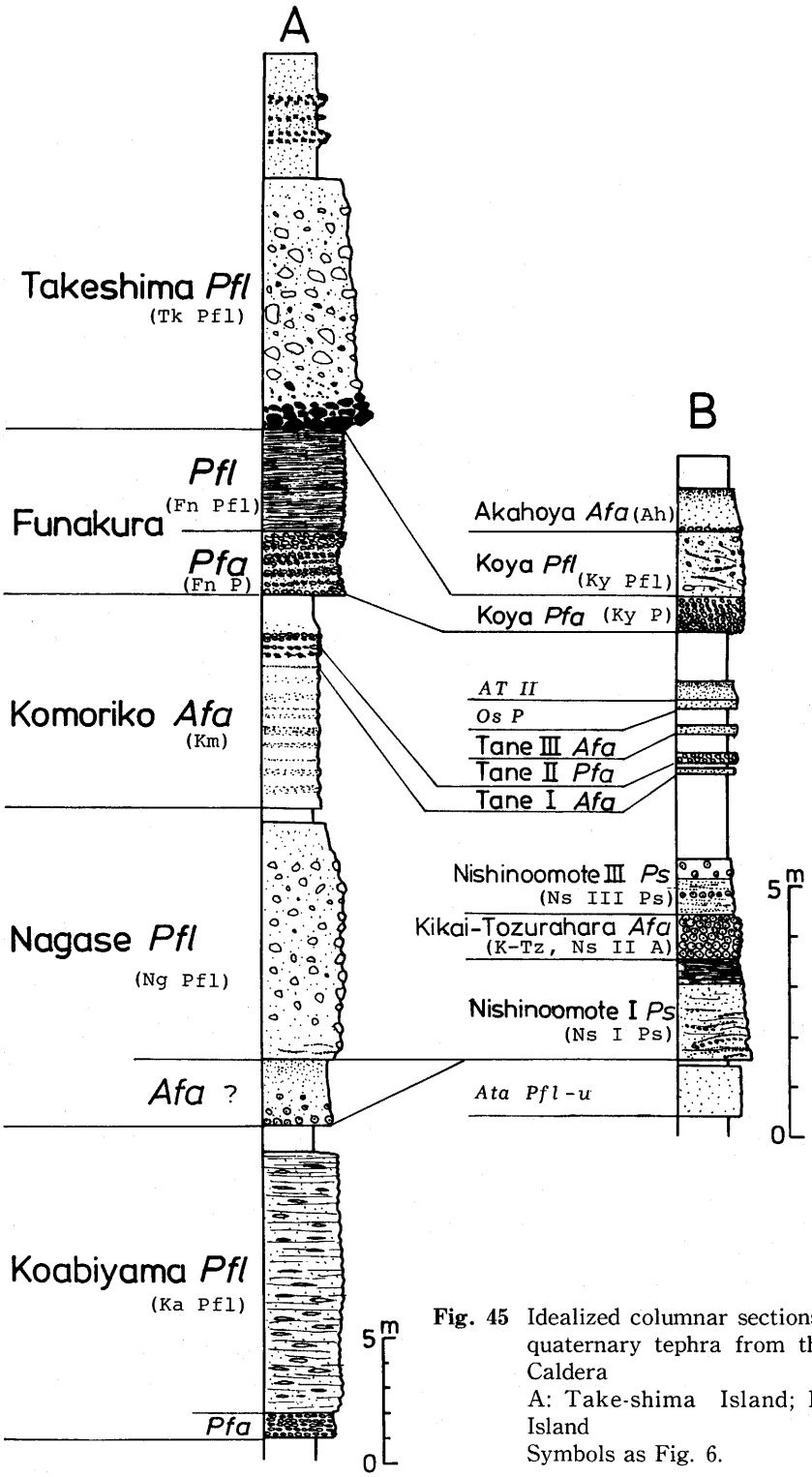

Fig. 45 Idealized columnar sections for the quaternary tephra from the Kikai Caldera
A: Take-shima Island; B: Tane Island
Symbols as Fig. 6.

Nagase pyroclastic flow deposit **(Ng Pfl)** *and its related deposits*

The Nagase pyroclastic flow (Ono *et al.*, 1982) (Ng Pfl) was erupted in the early late Pleistocene. Ng Pfl is a non-welded pyroclastic flow deposit, more than 10 m thick, and includes valley-ponds in the western half of Take-shima. It is composed of moderately vesiculated white rhyolite pumice in a matrix of white vitric ash. The pumice contains quartz, orthopyroxene, and clinopyroxene phenocrysts which are used as a key for distinguishing the deposit from other tephra layers from the Kikai Caldera (Fig. 50). At the base of the flow deposit, there is a coarse-grained ash fall layer, 100-200 cm thick, which contains accretionary lapilli as much as 3 cm across. The layer indicates that the Nagase cycle started with a silicic phreatomagmatic eruption.

Kikai-Tozurahara ash fall deposit **(K-Tz,** *Nishinoomote II ash fall deposit:* **Ns II A** in Nagaoka, 1988)

Kikai-Tozurahara ash fall deposit (K-Tz), a co-ignimbrite ash falls of Ng Pfl (Machida and Arai, 1983), is distributed as far as central Japan (Fig. 46) and the eruption date is estimated at about 75 ka (Machida *et al.*, 1983). In the Osumi Peninsula, and Tane and Yaku Islands, K-Tz contains a large amount of spherical accretionary lapilli, in which thin concentric layers are composed of fine-grained bubble-wall type glass shards.

K-Tz fell from the upper part of the high eruptive column because the deposit has many large accretionary lapilli, more than 2 cm across. The formation of the large accretionary lapilli needed long time for suspending in the air. This indicates that the upper part of eruptive column was so abundant in fine-grained glass shards and so moist that many accretionary lapilli formed in it. The vent was probably submerged beneath the sea and the Nagase cycle might be of a phreatomagmatic or phreatoplinian type.

Nishinoomote I and III pyroclastic surge deposits **(Ns I, III Ps)**

K-Tz is intercalated between two thin orange-colored fine-grained pyroclastic surge deposits (Fig. 45), the Nishinoomote I and III pyroclastic surge deposits (Ns I and III Ps; Nagaoka, 1988), in Yaku and Tane Islands and at the southern end of the Osumi Peninsula (Figs. 34 and 47) 30-70 km away from the Kikai Caldera. Ns I and III Ps are less than 150 cm thick and exhibit prominent low-angle cross-stratification. They are moderately sorted and consist of pumice below 2 cm across as well as fine-grained glass shards and crystal grains. Lithics are very few. Accretionary lapilli and vesicles are frequently found in the matrix of ash.

Ns I and III Ps are much farther-reaching, thin, finer-grained, and lithologically different from parent pyroclastic flow deposit: Ng Pfl which is petrographically correlated with the pyroclastic surge deposits. Ns I and III Ps were probably generated from the margin or ash cloud of Ng Pfl when the flow entered into the sea (Nagaoka, 1988).

The total volume of tephra in the Nagase cycle is about 100 km^3.

Komoriko ash and scoria fall deposits **(Km)**

Ng Pfl is unconformably covered with the Komoriko ash and scoria fall deposits (Km) in Take Island. These deposits coincide with the Komoriko air-fall pyroclastics in Ono *et al.* (1982). Km is less than 10 m thick, and is made up of alternation of thin scoria and ash layers. It is probably the product of strombolian and vulcanian eruptions at subaerial

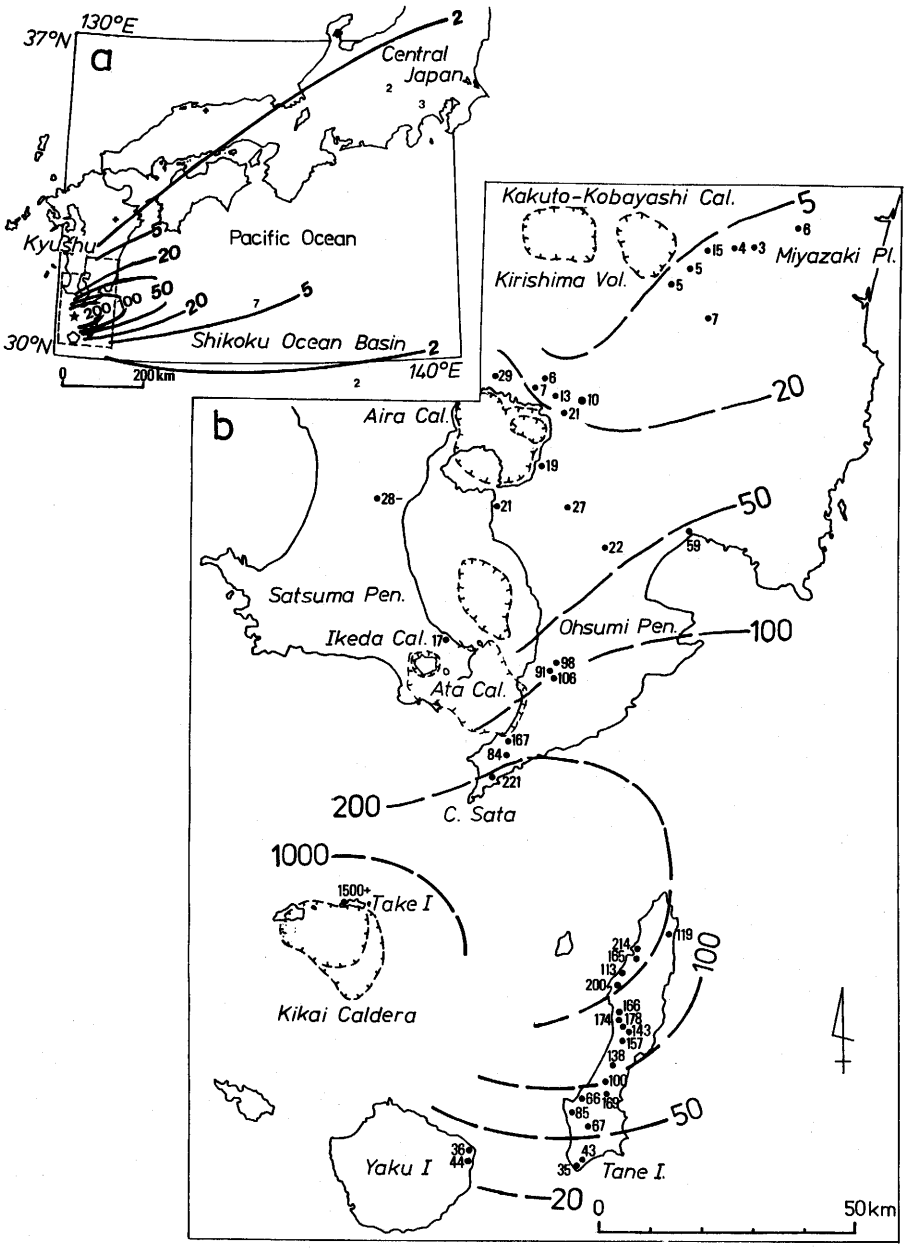

Fig. 46 Total thickness of the Nagase pyroclastic flow, Nishinoomote I and III pyroclastic surges and Kikai-Tz (Nishinoomote II) ash fall deposits (in cm)
Abyssal data from Arai and Machida (1983).

stratovolcanoes.

In Tane Island (Loc. B2, Fig. 34), weathered volcanic ash between K-Tz and Os P includes three marker tephra layers, the Tane I ash falls (In I A), the Tane II pumice falls (In II P), and the Tane III ash falls (In III A) in ascending order (Fig. 45). Tn I A and Tn II P are intercalated in the upper part of Km on Take Island (Fig. 45).

Tephra layers in the Takeshima eruptive cycle

A climactic eruptive cycle, called the Takesima eruptive cycle in this paper, of the caldera-forming stage took place about 6 ka (Ono *et al.*, 1982).

Funakura pumice fall deposit **(Fn P)**

The cycle started with a large plinian phase, and formed the Funakura pumice fall deposit (Ono *et al.*, 1982) (Fn P) which corresponds to the Koya pumice fall deposit (Ui, 1973; Machida and Arai, 1978) (Ky P) on the Osumi Peninsula. Many thin fall units in Fn P indicate the eruptive column was pulsating. Fn P covered the Osumi Peninsula and Tane Island with a dispersal axis of NE (Walker *et al.*, 1984).

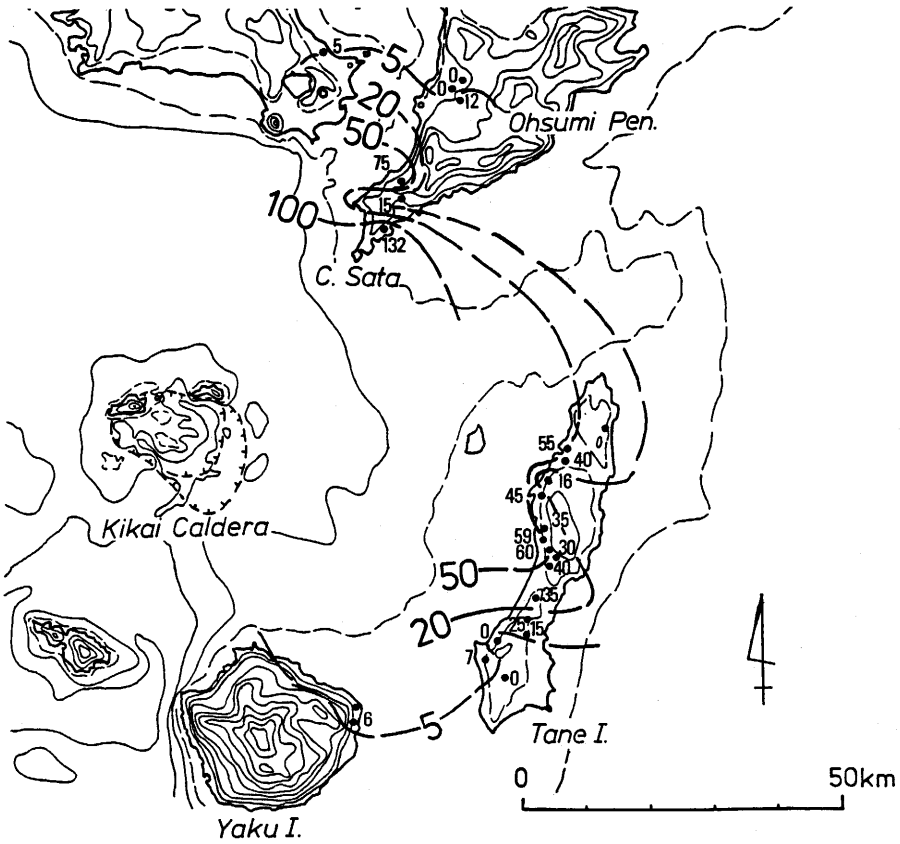

Fig. 47 Isopach map of the Nishinoomote I pyroclastic surge deposit (in cm)

Funakura pyroclastic flow deposit **(Fn Pfl)**

The Funakura pyroclastic flow deposit (Ono *et al.*, 1982) (Fn Pfl) overlies Fn P on the caldera rims. Fn Pfl is a dark-gray weakly-welded and well-stratified pyroclastic flow deposit, composed of fine-grained vitric ash. The plinian column of Fn P was probably collapsed to form Fn Pfl since the uppermost part of Fn P is interbedded with the lowermost of Fn Pfl.

Takeshima pyroclastic flow deposit **(Tk Pfl)** *and Koya pyroclastic flow deposit* **(Ky Pfl)**

The last phase of the cycle generated the Takeshima pyroclastic flow deposit (Ono *et al.*, 1982) (Tk Pfl). Tk Pfl on the caldera rims, Iwo-jima and Take-shima, more than 10 m thick, contains valley-ponds and is a non-welded pyroclastic flow deposit. It is composed of a mixture of excellently vesiculated gray-white pumice in a gray vitric ashy matrix, accompanied by a basal zone containing a concentration of coarse-grained lithics.

The Koya pyroclastic flow deposit (Ui, 1973) (Ky Pfl) is an exceptionally thin and extensively distributed deposit that covers Tane and Yaku Islands, and the southern half of the Satsuma and Osumi Peninsula. Ky Pfl is regarded as a low-aspect ratio ignimbrite (Walker *et al.*, 1981, 1984). Ky Pfl is the distal facies of Tk Pfl. Tk Pfl left large lithic and pumice fragments on the sea and changed into gas-and fine-particle rich pyroclastic flow, Ky Pfl, on the sea.

Akahoya ash fall deposit **(Ah)**

The Akahoya ash fall deposit (Ah; Machida and Arai, 1978) reaches central Japan 1, 000 km far away from the Kikai Caldera, and is a co-ignimbrite ash fall deposit, probably derived from Tk Pfl. Ah displays prominently normal-grading in comparison with other co-ignimbrite ash falls in southern Kyushu. It consists primarily of bubble-wall type glass shards. In southern Kyushu, there are pumice fragments, armored lapilli and accretionary lapilli concentrated at the base of Ah (Fig. 45). The ash-laden cloud and particles of Ah were drier than K-Tz and AT because Ah is more normally graded and has less accretionary lapilli than K-Tz and AT.

The total volume of the tephra in Takeshima cycle is about 150 km^3 (Machida and Arai, 1978).

6. Characteristics of the Eruptive Sequence of Caldera Volcanoes

Eruptive sequence of a single cycle

The tephra layers produced by a single eruptive cycle conformably superpose each other, and do not include layers that represent weathering breaks (Nakamura *et al.*, 1963). One of the several tephra layers in a cycle may be interpreted to represent a single eruptive phase defined by Fisher and Schmincke (1984).

Eruptive cycles in Kagoshima Graben are grouped into following types, based on the sequence of eruptive phases.

Plinian-eruptive cycle

Table 1 Sequences of eruptive phases during the Aira, Ata, Nagase and Takeshima large-scale pyroclastic flow eruptive cycles

CYCLE NAME	Aira	Ata	Nagase	Takeshima
ERUPTIVE CENTER	Aira caldera	Ata caldera	Kikai caldera	Kikai caldera
AGE	21ka-22ka	80ka-90ka	70ka-80ka	6ka
ERUPTIVE SEQUENCE OF A SINGLE CYCLE	Phreatic explosion (Ud) ↑ Phreatic explosion (Ue) ↑ Large-scale pyroclastic flow eruption (Km —A · —B, Ito Pfl, AT I · II · III) ↑ Moderate-scale pyroclastic flow eruption (Tm Pfl) ↑ Phreatomagmatic eruption (Tm A) ↑ Plinian eruption (Os P)	Large-scale pyroclastic flow eruption (Ata Pfl-u, Tu A) ↑ Small-scale pyroclastic flow eruption (Ata Pfl-m) ↑ Small-scale pyroclastic flow eruption (Ata Pfl-l) ↑ Plinian eruption (St P) ↑ Phreatomagmatic eruption (Iz A) ↑ Plinian eruption (Ata P) ↑ Phreatomagmatic eruption (Ko A)	Large-scale pyroclastic flow eruption (Ng Pfl, NsI · III Ps K-Tz A) ↑ Phreatomagmatic eruption (ash fall?)	Large-scale pyroclastic flow eruption (Tk Pfl, Ah) ↑ Small-scale pyroclastic flow eruption (Fn Pfl) ↑ Plinian eruption (Fn P)
TOTAL VOLUME	450km^3	+100km^3	100km^3	150km^3

This cycle consists of a single plinian (including subplinian) phase which is sometimes followed by a moderate-scale pyroclastic flow phase. The pyroclastic flows occur when the plinian columns gravitationally collapse. Total volume of ejecta in the cycle is less than 50 km^3.

Examples include the Fukuyama (Fk P), Iwato (Iwt P and Iwt Pfl), Otsuka (Ot P), Fukaminato (Fm P), and Arasaki (Ar P and Ar Pfl) cycles of the Aira Caldera; Torihama (Tr P and Tr Pfl), Marumine (Mr P), and Ikeda (Ik P, Ik Pfl, and Ik Ps) cycles of the Ata Caldera (Table 2).

Large-scale pyroclastic flow eruptive cycle

The cycle is characterized by a large-scale pyroclastic flow phase of up to 100 km^3 in volume. The phase is frequently preceded by various phases, including plinian, small-and

Table 2 Characteristics of eruptive multi-cycles

	STAGE	SEQUENCE OF A CYCLE	Vc (km^3)	Vs (km^3)	ERUPTIVE CYCLE (DEPOSIT)		
					AIRA	ATA	KIKAI
MULTI-CYCLE	PLINIAN STAGE	P P-MF	1-20	50	Fukuyama (Fk P) Iwato (Iwt P, Iwt Pfl) Otsuka (Ot P) Fukaminato (Fm P) Arasaki (Ar P, Ar Pfl) 80-30 ka	Torihama (Tr P, Tr Pfl) Marumine (Mr P), 130-90 ka Ikeda (Ikp, Ikpfl, Ikps, etc.) 5ka	
	LARGE-SCALE PYROCLASIC FLOW STAGE	P-MF-LF P-H-MF-LF H-LF	100<	100<	Aira (Os P, Tm Pfl Ito Pfl, AT) 22-21 ka	Ata (Ko A-Ata Pfl) 90-80 ka	Nagase (Ng Pfl, Ns I, II Pfl, K-Tz) 75 ka Takeshima (Fn P, Fn Pfl Tk Pfl, Ah) 6 ka
	MODERATE-SCALE PYROCLASTIC FLOW STAGE	MF	1-10	20>	Moeshima (Me Pfl, Me A) 10 ka	Tashiro (Ts Pfl) Imaizumi (Im Pfl) 80-70 ka	
	POST-CALDERA STAGE	S, V, P, H, L, SF, etc.	0, 1>	50>	Sakurajima 13 ka~	Ibusuki, Karayama Washiodake Onodake, etc. 40-30 ka Kaimondake 4-2 ka	Komoriko (Km) 60-40 ka Iwodake Inamuradake, etc. 6 ka~

LF: Large-scale pyroclastic flow phase; MF: Moderate-scale pyroclastic flow phase; SF: Small-scale pyroclastic flow phase; P: Plinian phase; H: Phreatomagmatic (including phreatoplinian) phases; V: Vulcanian phase; S: Strombolian phase; L: Lava flow; Vc: Total volume of tephra during a cycle; Vs: Total volume of tephra during a stage

moderate-scale pyroclastic flows, phreatomagmatic, and phreatoplinian phases (Table 1). A single cycle forms a large amount of tephra, generally more than 100 km^3. Examples include the Aira (composed of Os P, Tm Pfl, and Ito Pfl phases), Ata (Ko A, Ata P, Iz A, St P, Ata Pfl-1, Ata Pfl-m, Ata Pfl-u phases), Nagase (Ng Pfl phases), and Takeshima (Fn P, Fn Pfl, and Tk Pfl phases) cycles (Table 1).

Moderate-scale pyroclastic flow eruptive cycle

This cycle is composed of a single phase of a moderate-scale pyroclastic flow (1~50 km^3 in volume). Examples are the Moeshima pyroclastic flow cycle of the Aira Caldera, and the Tashiro and Imaizumi pyroclastic flow cycles of the Ata Caldera.

Cycles of small-scale eruption

The cycles include small-scale vulcanian, strombolian and phreatomagmatic eruptive phases, for example, Kenashino, Yonemaru, Sumiyoshiike, the recent eruptions of Sakurajima, and the eruptions of other post-caldera cones and lava domes including Kaimondake, Ibusuki and Karayama. The volume in the single cycle is less than 1 km^3.

Eruptive multi-cycle (long-term eruptive sequence)

The Aira Caldera

In the Aira Caldera, there was a period of quiescence for 10^5 years before the Fukuyama cycle in 70-80 ka (Fig. 48), because prominent reddish soil and a large high-angle unconformity are found at the boundary between Fk P and the Shikine lava or the Kakuto pyroclastic flow deposit 0.2-0.4 Ma old (Miyachi, 1983).

Late Quaternary explosive volcanism, resulting from eruptions of rhyolite and dacite magma, started with the Fukuyama cycle in 70-80 ka, and finished with the Moeshima cycle about 1 ka, or may still be continuing with the historic period being a time of quiescence and with other eruption types of post-caldera stratovolcano, Sakurajima. The history of volcanism contains several eruptive cycles. The intervening period between eruptive cycles is probably less than 10^4 years, based on the ages of tephra layers. The long-term eruptive unit is thought to be a kind of a eruptive epoch (Fisher and Schmincke, 1984), and in this paper, it is defined as "a eruptive multi-cycle", which is composed of several eruptive cycles with intervening intervals of quiescence for 10^3 years (Fig. 48; Table 2). The time interval between two multi-cycles (between Fk P and the Shikine lavd, and the Kakuto pyroclastic flow) may be 10^5 years.

Five plinian eruptive cycles, Fukuyama, Iwato, Otsuka, Fukaminato, and Arasaki, occurred intermittently during 80-30 ka in the last multi-cycle of the Aira Caldera (Fig. 48). This period is called a "plinian stage". The stage produced about 50 km^3 of pumiceous material.

This stage was followed by the Aira large-scale pyroclastic flow cycle 22-21 ka. The single large-scale pyroclastic flow cycle composes a stage, which is named a "large-scale pyroclastic flow stage". This stage of just one cycle formed eighty percent of volume of tephra which erupted from the Aira Caldera during one multi-cycle (Fig. 49).

After the large-pyroclastic flow stage, a moderate-scale pyroclastic flow cycle, the Moeshima pyroclastic flow, took place about 10 ka. A "moderate-pyroclastic flow stage" is defined as the period which consists of a few moderate-scale pyroclastic cycles after a large-scale pyroclastic flow cycle. This stage produces no pumice fall deposit. The total volume of tephra produced in the stage is less than 10 km^3. The stage overlaps with the period of post-caldera cone activity at the andesitic Sakurajima Volcano (Fig. 48).

The Ata Caldera

The Ata Caldera has a eruptive multi-cycle similar to the Aira Caldera (Fig. 48; Table 2). The multi-cycle began with the Torihama cycle 0.13-0.11 Ma, which had a plinian phase and exceptionally large-scale pyroclastic flow phase. The plinian stage is composed of several plinian cycles, including the Torihama and Marumine cycles, and continued to 90 ka (Fig. 48). The Ata cycle of 90-80 ka corresponds to the large-scale pyroclastic flow stage. The multi-cycle probably finished with a moderate-scale pyroclastic flow stage consisting of the Imaizumi and Tashiro cycles in 80-70 ka, because there was a long quiescence for about forty to fifty thousands years between the Imaizumi-Tashiro cycles and the opening of Karayama and Ibusuki post caldera stratovolcanoes.

Tephra of the Ikeda cycle 5 ka ago is petrologically similar to Tr P and Tr Pfl of the Torihama cycle at the beginning of the multi-cycle (Fig. 50). The Ikeda cycle may indicate that another young multi-cycle was opening.

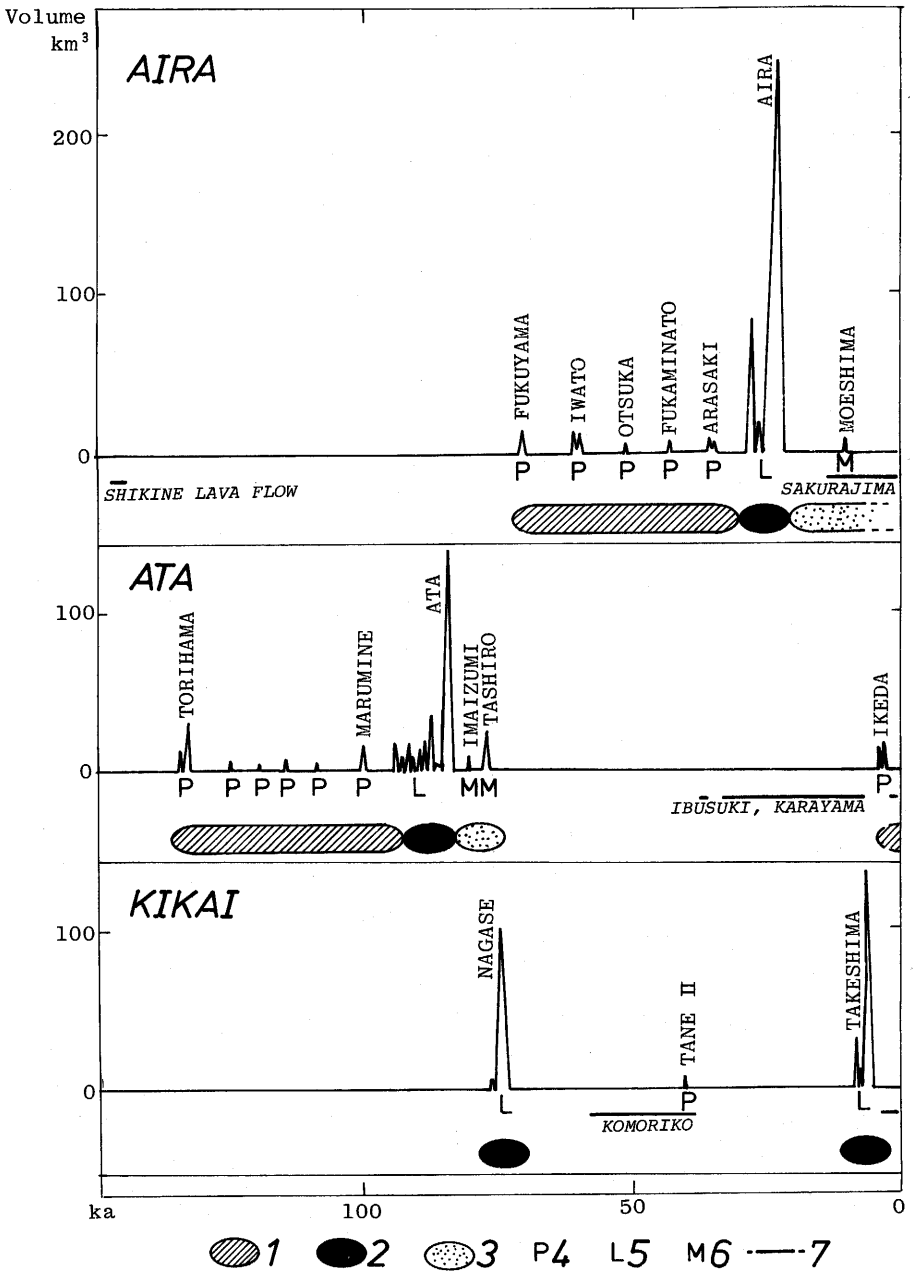

Fig. 48 Late Quaternary multi-cycles of the Aira, Ata, and Kikai Caldera Volcanoes
1: Plinian stage; 2: Large-scale pyroclastic flow stage; 3: Moderate-scale pyroclastic flow stage; 4: Plinian-eruptive cycle; 5: Large-scale pyroclastic flow eruptive cycle; 6: Moderate-scale pyroclastic flow eruptive cycle; 7: Post-caldera volcanism

Multi-cycle representing evolution of magma chamber

In the multi-cycles of the Aira and Ata Calderas, the volume percentage of pumice fall to the total volume of tephra of individual cycles shows a tendency to decrease rapidly after a plinian stage (Fig. 50). Ashy material rapidly increases during a large-scale pyroclastic flow cycle (Fig. 50). The tendency probably represents variation of pressure in a large silicic magma chamber. The plinian cycles probably resulted from pressure of magma filling the chamber, and the moderate-pyroclastic flow cycles resulted from low magma pressure which was rapidly lessened by a large-scale pyroclastic flow cycle (Fig. 51).

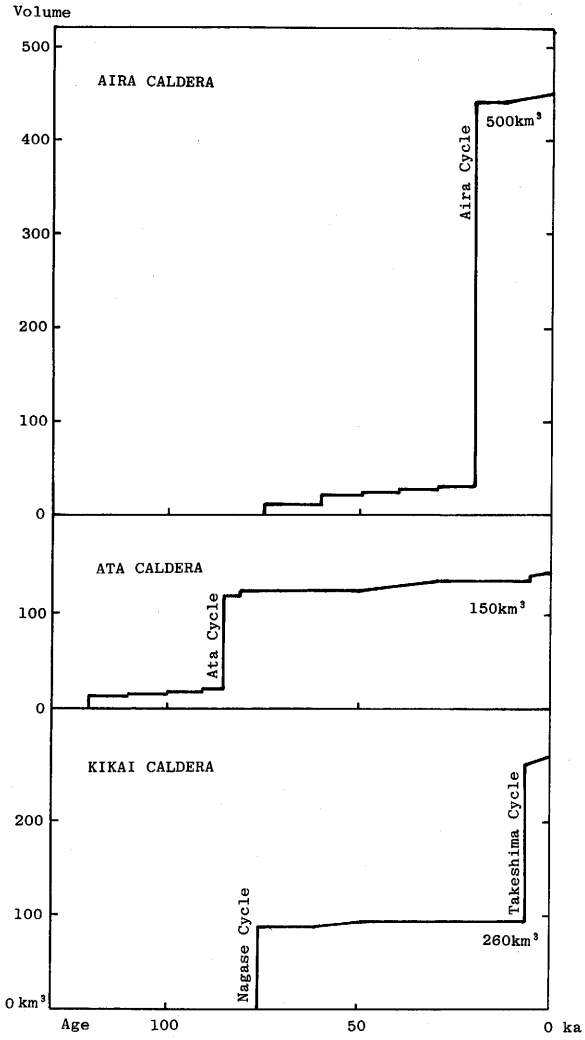

Fig. 49 Cumulative volume plotted against time for all magmatic materials erupted from the Aira, Ata and Kikai caldera volcanoes

The Ideka (the Ata caldera) and Moeshima (the Aira Caldera) cycles, predominantly rhyolite and dacite magma, overlap in time with the andesite activity of post-caldera volcanoes. Post-caldera volcanoes should be governed by another small andesite magma chamber.

The Kikai Caldera has no plinian or moderate-scale pyroclastic flow cycles (Fig. 48; Table 2). High water pressure on the vent submerged under the deep sea may prevent small-and moderate-scale eruptive columns penetrating the sea.

Relationships between large-scale eruptions and caldera formations

Caldera formation by repetition of large-scale pyroclastic flow cycles

The problem addressed in this section is: how have the calderas evolved during multi-cycles?

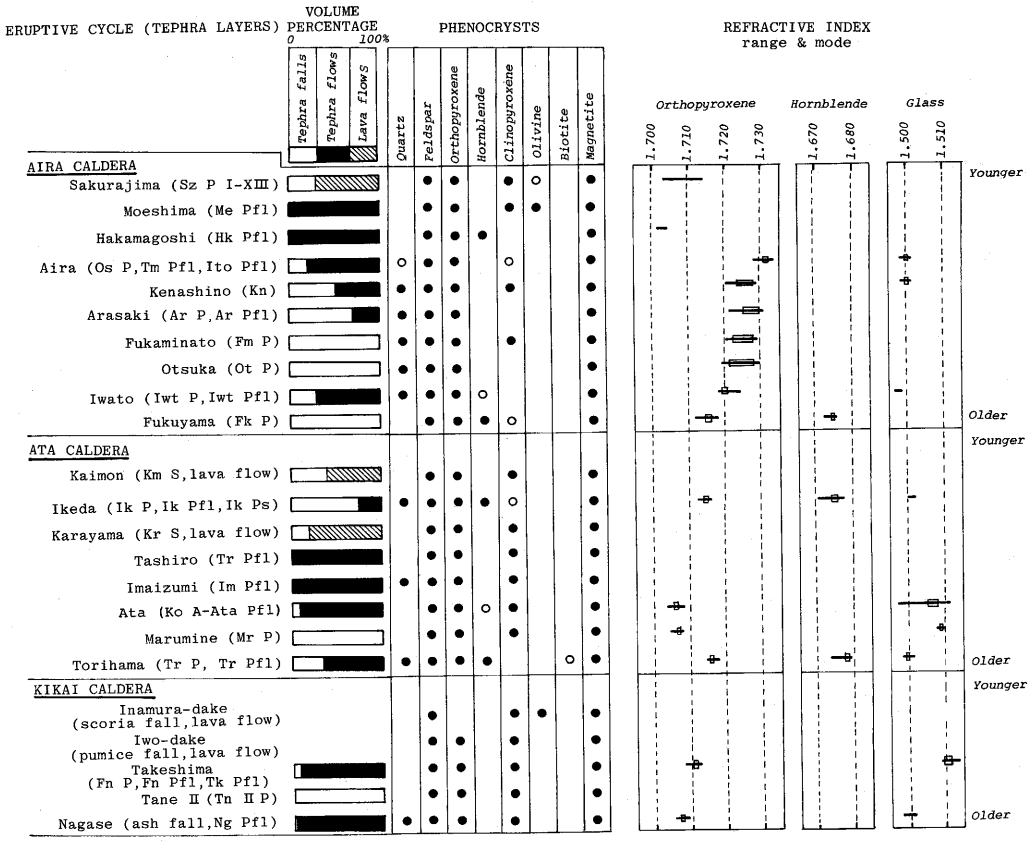

Fig. 50 Volume percentage and petrographic characteristics of tephra layers and lava flows of the late Quaternary eruptive cycles, from the Aira, Ata, and Kikai caldera volcanoes (adapted from Aramaki and Ui, 1976: Fukuyama, 1978; Arai and Machida, 1978; Ono *et al.*, 1982; and Nagaoka, 1984)
Tephra falls include pumice falls, scoria falls and ash falls without co-ignimbrite ash falls. Tephra flows include pyroclastic flows, pyroclastic surges and co-ignimbrite ash falls.

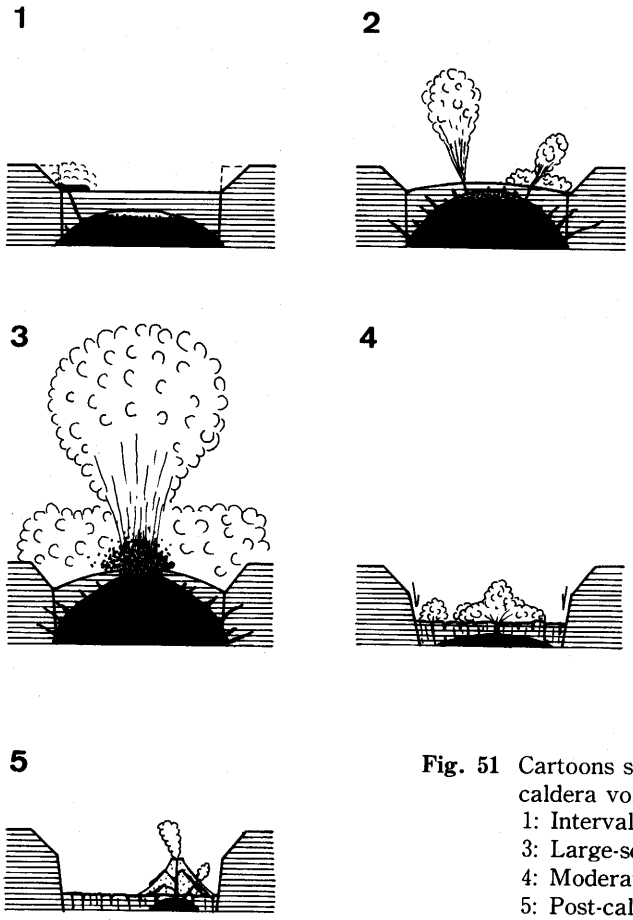

Fig. 51 Cartoons showing an eruptive multi-cycle of a caldera volcano
1: Interval of quiescense; 2: Plinian stage; 3: Large-scale pyroclastic flow stage; 4: Moderate-scale pyroclastic flow stage; 5: Post-calera stage

As mentioned in chapter 2, Kagoshima Graben started to downfault in 2.9 Ma, and has erupted many large-scale pyroclastic flows during the Quaternary times (Fig. 3). This suggests that an original caldera has existed before the Aira eruptive cycle of 22-21 ka.

The gentle inner slope of the eastern wall of the Aira Caldera is frequently covered with older pyroclastic flow deposits than Ito Pfl, including the Iwato, Ata, Kakuto, and Mobiki pyroclastic flow deposits (Fig. 52). Pleistocene marine and lacustrine sediments, including the Kekura Formation and the Kokubu Group, thickly bury the caldera bottom and valleys cutting the caldera wall. The evidence strongly indicates that a caldera, or caldera-shaped depression existed in the middle Pleistocene at least. The Aira Caldera must have evolved during several large-scale pyroclastic flow cycles, including Terukuni, Mobiki, Onobaru, Fumoto, Hayato, Nabekura, Yoshino, and Aira, during the Quaternary times. Moreover, the caldera has been also formed gradually by moderate-scale cycles between large-scale pyroclastic flow cycles.

Mode of caldera formation

The eastern caldera wall is the youngest in the Aira Caldera, because the eruptive centers of the last 80 ka concentrate on the eastern half of the caldera. The eastern wall

is morphologically divided into the lower and upper parts. The upper part of the wall, 300-800 m high, is gentler and more dissected by valleys than the lower part, and has segmentated profiles (Fig. 52). Because the upper part is covered with Ito Pfl, it was formed before the Aira cycle (Fig. 51). The lower part, less than 300 m high, is much steeper and less eroded than the upper part. The lower part is not covered with Ito Pfl. From this evidence, it is inferred that the upper part is the caldera wall older than Ito Pfl and that the lower part was mainly formed during the Aira cycle.

A tentative model of caldera-forming in the late Quaternary is as follows: before the

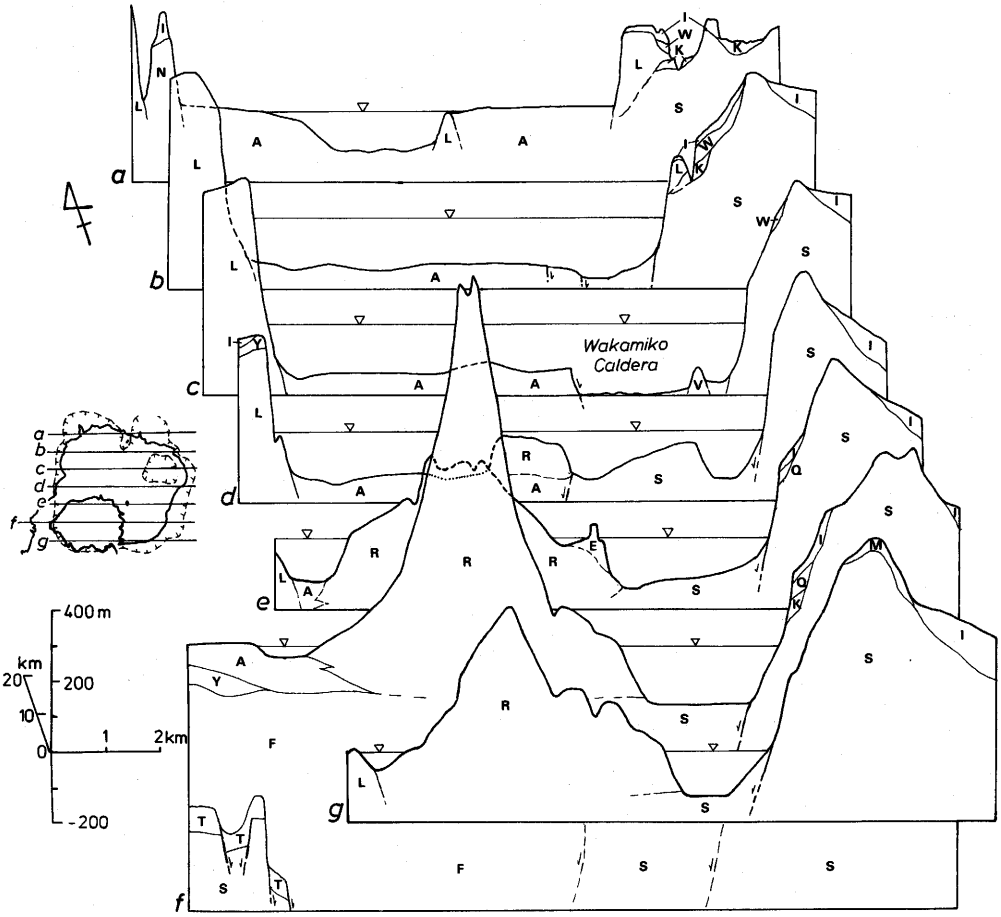

Fig. 52 Geological cross-sections of the Aira Caldera, adapted from Aramaki (1969, 1977, 1983, 1984), Chujo and Murakami (1976) Oki and Hayasaka (1970), Hayasaka and Oki (1971), Hayasaka (1982), and Otsuka and Nishiinoue (1980) A: Alluvium; R: Ejecta of Sakurajima Volcano; V: Lata Pleistocene to Holocene lava dome; E: Moeshima pyroclastic flows; I: Tsumaya and Ito pyroclastic flows; W: Iwato pyroclastic flows; Q: Ata pyroclastic flows; K: Kakuto pyroclastic flow; L: Early to middle Pleistocene lava; Y: Yoshino pyroclastic flows; M: Mobiki pyroclastic flows; N: Nabekura pyroclastic flows; F: Kekura Formation; T: Terukuni pyroclastic flows; S: Shimanto Supergroup

Aira cycle, the caldera bottom was higher than the present but lower than break-in-slope between upper and lower slopes (Fig. 51-1 and -2), The bottom subsided although the eastern wall did not withdraw horizontally during the Aira cycle (Fig. 51-3 and -4). The terraced slopes of upper part may represent intermittent subsidence of caldera bottom during the early to middle Pleistocene.

The steep western wall, composed of thick lava, may have been withdrawn during the Aira cycle, because it is not covered with the pyroclastic flow deposit.

The frequent subsidences of the Aira Caldera have probably taken place in the same area during the Quaternary. The position and the size of the caldera may be determined by the geological structure of the graben.

7. Conclusions

1) The calderas of Kagoshima Graben have generated a large amount of tephra-fall and tephra-flow deposits during the late Quaternary (Fig. 53). More than twenty tephra-fall members are identified. They are composed of both pumice fall and ash fall layers. Most of eruptive centers of the late Quaternary are concentrated in the eastern half of the Aira Caldera and in the northern half of the Ata Caldera.

2) The silicic volcanism is characterized by: (a) Large-scale pyroclastic flows and the associated co-ignimbrite ash falls occurred as a result of rapid supply of a large quantity of magmatic material, and of the formation of eruptive columns more than 30 km high. The eruption of pyroclastic material is an important factor in the formation of calderas. (b) Tephra layers were generated during phreatomagmatic and phreatoplinian eruptive phases which preceded large-scale pyroclastic flow phases. The evidence for interaction with water suggests that a caldera-like depression filled with water had been formed before the last large-scale pyroclastic flow cycle.

3) The eruptive cycles in the late Quaternary are classified into four types: (a) plinian cycles (composed of a single plinian phase, or a plinian phase followed by moderate-scale pyroclastic flow phases), (b) large-scale pyroclastic flow cycles (composed of plinian, phreatomagmatic, moderate-scale pyroclastic flow, and large-scale pyroclastic flow phases), (c) moderate-scale pyroclastic flow cycles (composed of a single moderate-scale pyroclastic flow phase), and (d) small-scale cycles (composed of vulcanian, strombolian, and lava flow phases). In the Aira and Ata Calderas, several plinian cycles occurred intermittently for 10^5 years preceding large-scale pyroclastic flow cycles. The large-scale pyroclastic flow cycle is followed by a few moderate-scale pyroclastic flow cycles for 10^4 years. Small-scale cycles then take place at post-caldera volcanoes. These cycles compose a eruptive multi-cycle that continues for 5-8 $\times$ 10^4 years. During a large-scale pyroclastic flow cycle, the volume percentage of pumice fall deposits relative to the total volume of tephra shows a tendency to decrease rapidly. The tendency may suggest evolution of a magma chamber; the pressure of magma gradually increases in plinian cycles and rapidly decreases at a large-scale pyroclastic flow cycle. The Kikai Caldera, which is deeply submerged, is an exception to the general pattern, and has no plinian or moderate-scale pyroclastic flow cycles because of high hydraulic pressure on the vents.

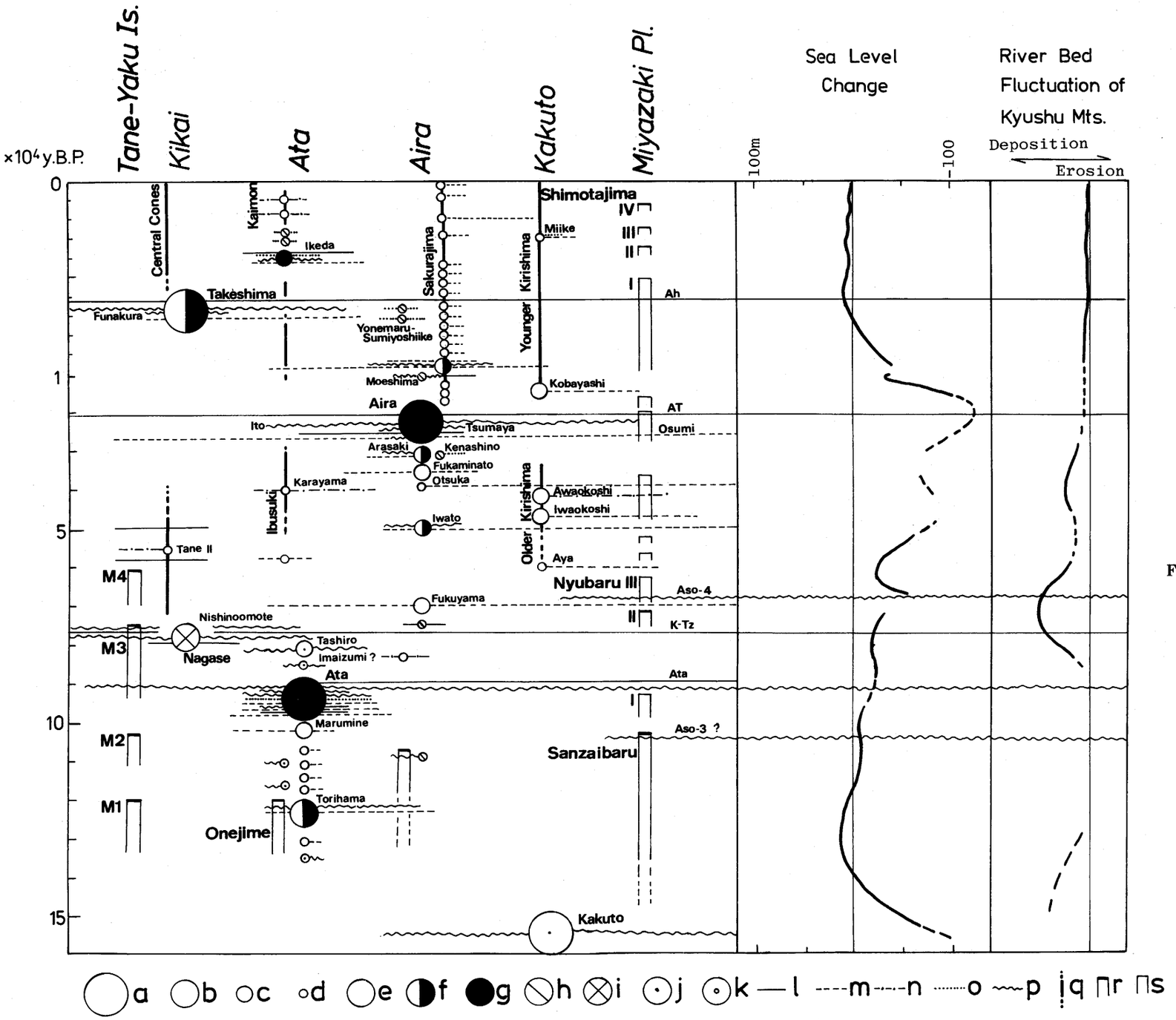

Fig. 53 Chronology of the late Quaternary in southern Kyushu
(Total volume of an eruptive cycle) a: >100km³; b: 100−10km³; c: 10−1km³; d: <1km³; (Types of the eruptive phases) e: Plinian phase; f: Plinian and moderate-scale pyroclastic flow phases; g: Plinian, moderate-scale pyroclastic flow, phreatomagmatic, and large-scale pyroclastic flow phases; h: Phreatomagmatic phase; i: Phreatomagmatic and large-scale pyroclastic flow phases; j: Pyroclastic flow phase; k: Plinian and phreatomagmatic eruptions; (Deposits) l: Ash falls; m: Pumice falls; n: Scoria falls; o: Pyroclastic surges; p: Pyroclastic flows; q: Post-caldera cone (stratovolcano); r: Marineterrace; s: Fluvial terrace

4) The calderas in Kagoshima Graben were not generated by only one large-scale pyroclastic flow cycles, but have been formed by several cycles and multi-cycles. There is good evidence that the Aira Caldera existed before the Kakuto pyroclastic flow cycle of 40-20 ka. A late Quaternary multi-cycle in the Aira Caldera caused primarily subsidence of the bottom of the caldera. A slight withdrawal of the wall also occurred.

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(* : in Japanese, * * : in Japanese with English abstract)