VOLCANIC GEOLOGY OF CHICHIJIMA, THE BONIN ISLANDS (OGASAWARA ISLANDS)

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Abstract Chichijima in the Bonin (Ogasawara) Islands consists mostly of submarine effusive rocks of Eocene age unconformably overlain by Oligocene to early Miocene foraminifer limestone (Minamizaki Formation). The volcanic rocks are divided into the Marubewan, Asahiyama and Mikazukiyama Formations in ascending order on the basis of both lithology and modes of occurrence.

The stratigraphic relationships indicate that the activity of boninite preceded those of bronzite andesite and dacite followed by the period during which the three volcanic rocks were concurrently effused. The activity of dacite continued after the activities of the other two ceased. There was a repose period between the activities of dacite and quartz dacite. The two-pyroxene andesite in the Mikazukiyama Formation is distinct from other volcanic rocks in the lower formations. It is a product of different volcanism on or around the Bonin Ridge.

Radiolarian fossils found in the lower portion of Mikazukiyama Formation indicate early Middle Eocene, while a K-Ar age for the two-pyroxene andesite is Middle Oligocene (29 Ma), and those for boninite and dacite are Middle Eocene (39–43 Ma). Two cases are considered. (1) Volcanism in Chichijima is not younger than the activities of island arc tholeiite and andesite in Hahajima. The fossil age suggests the existence of subduction before 43 Ma when the Pacific Plate moved towards NNW. (2) Volcanism of boninite was at 43 Ma and was contemporaneous with or slightly later than volcanism in Hahajima. These volcanisms were related to the subduction caused by the change in plate motion.

Introduction

The Bonin Ridge which extends from 25°N to 30°N is on the eastern edge of the Philippine Sea Plate and is in contact with the Pacific Plate by the Izu-Ogasawara Trench (Fig. 1). Quaternary volcanic islands (Volcano Islands on the Shichito Ridge) are located 260 km west of the trench. The Bonin Trough more than 4000 m in depth separates these two ridges. Extremely high free-air gravity anomaly up to 380 mgal on the Bonin Ridge suggests two possibilities: (1) the crust beneath the Bonin Ridge is as thin as 8 km or (2) the crust is composed of dense material such as gabbro if the thickness of the crust

beneath the ridge is 12 km, which is obtained from the analysis of seismic refractivity measurements at 32°N (HOTTA, 1970; ISHIHARA *et al.*, 1981).

There are three clusters of islands which rest on the 200 m deep shallow on the ridge from 26°35'N to 27°40'N. They are composed of Tertiary volcanic rocks and are called the Mukojima, Chichijima and Hahajima Islands from north to south. The Mukojima and Chichijima Islands yield boninite whereas Hahajima Islands do not (KURODA & SHIRAKI, 1975; SHIRAKI & KURODA, 1977; KURODA *et al.*, 1978; SHIRAKI *et al.*, 1979; SHIRAKI *et al.*, 1980; KOMATSU, 1980). Boninite is dredged from the western side of a seamount 85 km eastsoutheast of Hahajima (ISHII & KOBAYASHI, 1982) and also from the landward side of the Mariana Trench (DIETRICH *et al.*, 1978). On Leg 60 of Deep Sea Drilling Pro-

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Fig. 1 Regional topographic map of the sea floor in the vicinity of the Bonin Islands.

ject is recovered highly magnesian basaltic andesite similar to boninite, but it is clearly distinguished from boninite in major

elements (HICKEY & FREY, 1982; KUSHIRO, 1982; MEIJER, 1980; MEIJER *et al.*, 1982; NATLAND, 1982; SHARASKIN, 1982; WOOD

et al., 1982).

Boninite is proposed to be a candidate for primary magmas because of its high MgO, NiO and Cr₂O₃ contents and carrying magnesian, nickeliferous olivine (Fo₉₀, NiO 0.4%) and Cr-rich spinel (KURODA & SHIRAKI, 1975; SHIRAKI & KURODA, 1977; KURODA *et al.*, 1978). Magnesian bronzite andesite and dacite associated with boninite in Chichijima are thought to be fractional crystallization products of boninite (KURODA & SHIRAKI, 1975). These volcanic rocks occur as pillow flows and volcanic breccia intruded by numerous parallel dikes of the same lithologies. However, both petrological and geological relationships among boninite, bronzite andesite and dacite are still unclear. This paper describes the geological relationships and modes of occurrence of these rocks. Petrology of boninite and other rocks will be discussed elsewhere.

Geology

A geologic map and geologic cross sections of Chichijima are shown in Figs. 3 and 4 respectively. Figure 5 exhibits locations of sites which will be mentioned below. Chichijima is composed mainly of the products of submarine volcanism and a small amount of limestone. The limestone of Oligocene to early Miocene (MATSUMARU, 1976) is the stratigraphically youngest among the Tertiary rocks and unconformably overlies the volcanic rocks. The lowest part of the volcanic rocks is predominated by pillow flows and volcanoclastic rocks of boninite (GR-I), bronzite andesite (GR-II) and dacite (GR-III). The top of the lowest part consists of well-stratified heterolithic volcanic breccia and sandstone. The middle part consists mainly of sheet-like lava flows of quartz dacite (GR-IV). The structure of the lowest part is oblique to that of the middle part. The uppermost part of the volcanic rocks is composed of heterolithic volcanic breccia. On the basis of the above mentioned differences in both the lithology and modes of occurrence as well as stratigraphic relationships, these Tertiary rocks are divided into four formations;

Fig. 2 Diagram showing stratigraphic relationships of the four formations. The Asahiya Formation overlies the Marubewan Formation and the Mikazuki Formation overlies the both formations. The structure of the Mikazuki Formation intersects the underlying formations. Radiolarian fossils from the Mikazuki Formation indicate early Middle Eocene, although K-Ar age of Oligocene time is obtained for the two-pyroxene andesite from this formation. The age of this formation is unclear. The Minamizaki Formation unconformably overlies the Marubewan Formation.

the Marubewan (the lowest part), Asahiya (the middle part), Mikazuki (the uppermost part) and Minamizaki (limestone) Formations in ascending order (Fig. 2).

Marubewan Formation

This formation is mainly composed of pillow flows, volcanic breccia and sandstone, a few quantities of sheet-like lava flows and lava domes. The volcanic beds dip 30°WSW in the east, gently ENE in the west and 10°–20° NE in the southwest (Figs. 3, 4).

The lowest portion of this formation is exposed in the east and consists of pillow flows and volcanoclastic rocks of boninite. The thickness of pillow piles is up to 300 m of more than 400-m total thickness in the vicinity of Hatsuneyama (Loc. 1, Fig. 5). Pillow flows of bronzite andesite and dacite intercalate with pillow flows and volcanoclastics of boninite in the middle part of the formation. Bronzite andesite also occurs as sheet flows

Fig. 3

Fig. 4 Geologic cross sections cutting from northeast to southwest. Locations of sections are shown in Fig. 3.

among pillow flows and volcanic sandstone and breccia of boninite on the coast east of Manjumisaki (Locs. 2, 3). A sheet flow of the same lithology is observed among poorly stratified volcanic breccia of boninite to the north of Tsutsujiyama (Loc. 4). The upper part of the formation is predominated by pillow flows of dacite and yields no lava flows of boninite and bronzite andesite. The thick-

ness of dacite pillows exceeds 220 m near Kamenokubi (Loc. 5).

Asahiyama Formation

This formation consists of quartz dacite sheet-like lava flows and associated hyaloclastite. The thickness exceeds 100 m in Asahiyama (Loc. 6) and 200 m in Ten'noura (Loc. 7). Each flow unit varies in thickness from a few decimeters to more than 100 m. Most of the sheet flows exposed on an 80 m high cliff north of Asahiyama are composed of 1–2 m thick and 40–50 m long platy massive lava underlain by 10–20 m thick flow breccia, which suggests that they were extremely fluidal in spite of their high silica contents (65–75%). Some are thin, short flows extending only for several meters and some are 5–10 m thick massive lavas of several tens of meters in length. One of the largest flows is 20 m thick and 250 m long with 20–30 m thick basal breccia. The massive lava has no distinct glassy selvages. The breccia consists of lapilli- to block-sized angular fragments. The largest one exceeds 2 m in diameter. Smaller fragments less than a decimeter are very glassy.

Mikazukiyama Formation

This formation is restricted in distribution to Mikazukiyama area and consists of alternating beds of volcanic breccia, slump breccia

Fig. 3 Geologic map of Chichijima. 1. Quaternary sediments; 2. Minamizaki Formation (limestone); 3. Mikazukiyama Formation (alternating beds of volcanic breccia and sandstone); 4. Asahiyama Formation (mainly consisting of sheet-like lava flows of quartz dacite); 5–11. Marubewan Formation (5. Bedded volcanic sandstone and breccia mainly consisting of dacite but small amounts of boninite and bronzite andesite being also included; 6. Pillow flows of dacite; 7. Lava domes of dacite; 8. Bedded volcanic sandstone and breccia mainly consisting of boninite and bronzite andesite; 9. Pillow flows of bronzite andesite; 10. Pillow flows of porphyritic boninite; 11. Pillow flows of aphyric boninite); 12. Dikes of quartz dacite; 13. Dikes of boninite, bronzite andesite and dacite; 14. Faults; 15. Fault scarps formed by recent landslide; 16. Dips and strikes

Fig. 5 Map showing the localities in Chi-chijima. Dikes of boninite, bronzite andesite, dacite and quartz dacite are also shown. Symbols are the same as those in Fig. 3.

and sandstone. The structure of the Mikazukiyama Formation is oblique to that of underlying formations.

The breccia is heterolithologic and contains blocks of sandstone and siltstone, rock fragments of boninite (GR-I), bronzite andesite (GR-II), dacite (GR-III), quartz dacite (GR-IV), porphyritic two-pyroxene andesite (GR-V) and microdiorite (GR-VI) in a matrix of coarse sandstone. Two-pyroxene andesite (GR-V) and microdiorite (GR-VI) are characteristic to the Mikazukiyama Formation. The breccia sometimes exhibits graded bedding and intercalates medium- to coarse-grained sandstone. Load cast and flame

structure are observed between the overlying breccia and underlying sandstone.

The volcanic breccia laterally grades into slump breccia consisting of large blocks of bronzite andesite pillow lava more than 20 m across and blocks of hyaloclastite of porphyritic andesite. Underlying sandstone is frequently eroded by the overlying slump breccia.

The sandstone develops cross lamination and graded bedding and sometimes intercalates 10 to 50 cm thick siltstone. Slump fold and cross bedding are commonly observed. The sandstone occasionally contains fine sandstone and siltstone lenses.

Minamizaki Formation

This formation is exposed in Minamizaki, on the southwest of Chichijima, and in Minamijima Island, 1 km west of Minamizaki. It is composed of fossiliferous limestone yielding abundant foraminifers, corals, and other fossils. The age of larger foraminifers is Oligocene to early Miocene (MATSUMARU, 1976). This formation has a gentle, nearly horizontal dip and a minimum thickness of 60 m. It unconformably overlies dacite pillows and dikes of the Marubewan Formation. The unconformity is exposed on the coast of Kinshihama (Loc. 8).

Modes of occurrence of volcanic rocks

Pillow flows

(1) Boninite (GR-I)

Pillow flows of boninite have large exposures along the coast from Miyanohama (Loc. 9) to Tatsumijima (Loc. 10), along the coast of Nishikaigan (Loc. 11) and Marubewan (Loc. 12) (Fig. 5). They are also intercalated with well-stratified sandstone associated with pillow and sheet flows of bronzite andesite along the coast near Manjumisaki (Loc. 3). Boninite pillow flows are overlain by volcanic breccia and sandstone consisting of boninite and dacite in the vicinity of Ogiura (Loc. 13).

According to BALLARD & MOORE (1977), a pillow flow consists of four units: (1) flow foot rubble composed of extremely angular fragments of pillows at the base, (2) a thick layer of forset-bedded elongate pillows plunging at 30°–45°, (3) a master feeding tube inclined gently downhill from the vent, (4) a top layer composed of bulbous pillows, in ascending order. These four units are identified in pillow flows of boninite, though flow foot breccia at the base of a flow unit is not always recognizable because of its uneven thickness and distribution.

The lower part of a pillow flow is well observed on the cliff in Tsurihama (Loc. 14). The flow foot breccia is divided into three units. The upper layer is composed of angular rock fragments a few centimeters to several decimeters across including whole pillows and coarse matrix. The middle layer is composed of well-sorted volcanic breccia consisting of 5–20

cm fragments of pillows. Some of them take typical sliced-watermelon shape. The middle layer thins out 150 m southwards. Downwards the middle layer increases in matrix and grades into the lower layer composed of both lithic and glassy fragments with a diameter from a millimeter to a few decimeters averaging 1 cm, showing reversed grading. The upper layer may be the primary flow foot rubble formed by slumping of the steep flow front and breakage of pillows during growth. The piles of blocks are unstable and easy to crumble down the slope to form reversely graded deposit. Underlying two layers may also be a talus deposit at the base of steep scarps exposing pillows.

Flow foot breccia is overlain by tangled, cylindrical tubes with necks and knobs arranged roughly parallel to each other. Almost all the pillows exposed are these elongate pillows. Only an appropriate exposure exhibits their tendency to elongate. More than 20 m thick piles of elongate pillows in a same direction are observed on the cliff facing Ten'noura (Loc. 15, Plate I-a). Each tube swells and pinches between 30 and 60 cm and can be traced for more than 10 m and sometimes changes in direction every two to three meters.

A master feeding tube is a kind of elongate pillows with a larger diameter and a longer life, resulting in complicated structures and cooling history. A large tube 2 to 5 m across underlain by elongate pillows more than 20 m thick is exposed on the sea cliff in Nishikaigan (Loc. 11). The tube pinches and swells and changes its direction like small elongates. It is partly composed of smaller tubes and many concentric layers with glassy selvages. A thin layer of pillows fed from the top of the tube is overlain by alternating beds of coarse breccia and lapillistone.

(2) Bronzite andesite (GR-II)

Pillow flows of bronzite andesite are exposed on a road cut south of Miyanohama (Loc. 16), on the western coast of Tsurihama (Loc. 17), in the vicinity of Nagasaki (Loc. 18, 19), in and around Kominato (Loc. 20), on the coast east of Manjumisaki (Locs. 2, 3), along the Minamifukurozawa (Loc. 21), and

Fig. 6 Some pillow flows of both dacite and bronzite andesite grade into sheet-like flows and hyaloclastite. The larger master tube sometimes branches into two, feeding forset bedded smaller elongate pillows and sheet-like lava flows which break into glassy fragments. Some sheet-like lavas penetrate into the hyaloclastite layers showing their autointrusive nature.

on the sea cliffs facing Marubewan (Loc. 12).

They are mostly composed of closely packed pillows as boninite but occasionally accompanied by hyaloclastite and sheet-like lavas similar to 'broken flow breccia' of SOLOMON (1969). Road cuts around the loop tunnel (Loc. 19, Plate II-a, b) expose sheets of lava and pillows set in a massive matrix of cognate glass. The pillows are 1–2 m across and larger than boninite pillows. Well defined bedding is composed of thin lenticular sheets of lava with glassy selvages and discrete ellipsoidal to elongate pillows. Some of the sheets are seen to connect with closely packed pillow tubes. The discrete pillows are plausibly fed from the master tube and tumble down the slope. The matrix is of angular fragments of cognate glass from a few decimeters to tens of centimeters presumably formed by quenching and shattering of hot fluid lava contact with water.

(3) Dacite(GR-III)

Dacite forms both typical close-packed pillows and 'broken flow breccia' as bronzite andesite. Most of close-packed pillows are

elongate pillows showing forset bedding. Elongate pillows of dacite with presumable main feeder tubes crop out on the cliff in Ten'noura (Loc. 22, Plate I-c, d). At least four units are identified by different directions of forset-bedded elongate pillows and existence of large master tubes at the top of each unit of elongates. The thickness of each unit is 30–50 m. The elongate tubes are 1–2.5 m in diameter and most of them are very glassy from the core to the rim. At close sight, they appear to be 'in situ breccia' composed of angular fragments varying in size from a few millimeters to some 20 cm (Plate I-b). Each fragments are slightly or not offset against one another. Fragmentation occurred during the cooling and after the emplacement of pillows.

Close-packed elongate pillows frequently grade into forset-bedded coarse breccia similar to broken flow breccia (SOLOMON, 1969). Large tubes 2 to 3.5 m in diameter and sheet-like lavas are set in a cognate matrix on the coast north of Mikazukiyama (Loc. 23; Fig. 6). The sheets of lava with glassy selvages

are tens of centimeters in thickness and several tens of centimeters to some 10 m in length and arranged subparallel defining bedding planes. Some of them are clearly fed from larger tubes and some are detached lenses in a cross section. Their three dimensional shapes are not well known, though, a few outcrops cut parallel to their surfaces show their tongue- or ameba-like shapes. SOLOMON (1969) thought that all of these lenses of lava were detached and of intrusive origin. Considering their shapes, however, some of the lenses of lava lying on the same bedding plane may be not always detached but parts of a larger sheet of lava. The matrix consists of glass fragments from a few millimeters to a few decimeters across. The master tubes can be traced from within close-packed pillows to within the breccia. They pinch and swell, abruptly change in direction and sometimes divide, indicative of pillow tubes.

The lowest part of dacite pillow flows is exposed from Kinshihama (Loc. 8) to John Beach (Loc. 24), where numerous dikes cutting close-packed pillows grade into large master tubes consisting of many concentric layers.

Little is known on the dimensions of one definite flow unit of pillow flows because of incomplete outcrops. In Tsurihama (Loc. 14), a 5—30 m thick pillow flow of monolithologic boninite can be traced along the cliff for a distance of 250 m. To the northeast of Asahi-yama (Loc. 19), one flow of several meters thick extends for more than 150 m. Layers of boninite pillow flows interbedded with volcanic sandstone are exposed around Hatsuneyama (Loc. 1). In each layer, there is no abrupt change in direction of elongate pillows and large master tubes suggestive of different flow units within a layer. However, many of the layers consist of pillows with several kinds of microphenocryst assemblages, indicative of different flow units. The largest layer of monolithologic pillows which is considered to be a single flow unit is exposed to the south of Hatsuneyama. It extends up to 1.3 km along the general trend of dike swarms and 300 m in width normal to the trend. Bronzite andesite pillows are exposed in an area of $300 \times 800 \text{ m}^2$ in Kominato (Loc. 20). These

pillows are 5—30 m in thickness, monolithologic and contain no intercalated sediments. They may consist of one flow unit. The maximum volume is estimated to be $(300 \times 800 \times 20 =) 4.8 \times 10^6 \text{ m}^3$. These pillow flows tend to be larger parallel to the general trend of the dikes than normal to the trend. The largest dimension of a pillow flows is more than $1 \text{ km} \times 300 \text{ m}$. However, recent pillow flows observed in mid-ocean ridges have a little larger dimensions up to a few kilometers along the fissures and a kilometer normal to the fissures (BALLARD *et al.*, 1981; CRANE & BALLARD, 1981; VAN ANDEL & BALLARD, 1979). Considering incomplete outcrops and lost portions by erosion, the sizes of pillow flows of both boninite and bronzite andesite would not be much different from those of MORB pillow flows.

Non-pillowed flows

Non-pillowed flows are sheet-like lava flows less channelized than pillow flows and are formed by mechanics quite different from pillow budding. Both pillow and non-pillowed flows are commonly associated with various amounts of volcanoclastic rocks. The ratio of clastic rocks to massive lava has rough relation to the rock groups, or the compositions of lava.

Boninite and bronzite andesite occur as typical sheet flows which are found on the ocean floor. "Sheet" is a descriptive term meaning only the surface form of the flow and does not denote the mechanics of flow (BALLARD & MOORE, 1977; BALLARD *et al.*, 1979). Several kinds of sheet flows are recognized based on the surface forms such as flat lobate, folded, rippled and whorly sheet flows. Some sheets are covered by glassy blocks caused by autobrecciation of the surfaces and are called jumbled flows (BALLARD *et al.*, 1979; LONSDALE & SPIESS, 1980). Pillows are frequently observed to be fed through cracks in the surfaces of sheet flows, and the sheet flows commonly change into pillows at their distal ends. Sheet and pillow flows are thought to be subaqueous equivalent to unchannelized surface-fed and highly channelized tube-fed pahoehoe respectively. Change

Fig. 7 Sheet flows and pillow flows of bronzite andesite intercalated with volcanic sandstone of boninite.

from sheet to pillows is interpreted as channelization of the flow with diminishing eruption and/or enlarging flow fronts (BALLARD *et al.*, 1979).

Non-pillowed flows of dacite and quartz dacite commonly consist of sheet-like lava and glassy blocks. Both drastic chilling by water and movement of lava caused fragmentation of the flowing lava to glassy fragments. These lava flows could be called subaqueous auto-brecciated lava flow (KUNO, 1968).

The Marubewan Formation occasionally contains sheet-like lava flows of boninite, bronzite andesite and dacite associated with pillow flows of the same lithology. The most typical sheet flows very close to those found on the ocean floor are exposed on the steep sea cliff north of Manjūmisaki (Loc. 2; Fig. 7). The cliff rises 30–100 m above the sea for a distance of about 300 meters. The upper part of the cliff consists of pillow flows of dacite and the lower half is of several sheet flows and pillow flows intercalated with well-stratified volcanoclastic sandstone containing little amounts of siltstone. These sheet flows vary in thickness from a few meters to more than 20 m. They are of bronzite andesite most of which are strongly altered. The only fresh samples obtained from the upper glassy

surfaces are porphyritic olivine-augite-bronzite andesite (type II) carrying Cpx microlites and plagioclase as groundmass minerals.

Figure 7 shows a schematic view of the southern half of the cliff exposing two sheet flows. The lower flow (SH-I) up to 10 m in thickness develops columnar jointing in the lower part. The flow rests on coarse volcanoclastic sandstone containing interbedded thin siltstone and is overlain by pillow lavas. In some places pillows are seen to be connected with underlying sheet lava. The pillows are both bulbous and interconnected elongate pillows. Recent sheet flows which fed pillows on the top and along their margins are observed in the Galapagos rift (BALLARD *et al.*, 1979). This fact suggests that most of the pillows in this area may be secondary lava flows fed from the sheet flows.

The upper flow (SH-II) varying in thickness from 16 to 20 m overlies pillows and 40-cm thick alternating beds of volcanoclastic sandstone and siltstone deposited in the lows between the adjacent highs of pillows. Columnar jointing is developed in the lower 4.5–6 m and partly in the upper 1.5 m. The uppermost 5 m thick portion of the sheet displays a distinctive layering parallel to the surface. Each layer is 20 to 70 cm thick and

is bounded by several-centimeter-thick glassy layers which may result from drastic chilling by the water. Layered sheet flows just described above are discovered on the inward facing walls of the rift valley in the FAMOUS area (CRANE & BALLARD, 1978). These may be thin discrete sheet flows piled on top of one another without any sediments, suggestive of short intervals between the emplacement of the layers.

The top surface of the flow is overlain by pillows so that the structure of the top surface cannot be observed. Fortunately, however, the bottom surface is exposed where underlain by clastics. The lava is poorly vesiculated, less than a few percent. The vesicles are in the range of 0.5—5 mm in diameter averaging 1 mm, almost spherical though slightly elongated. Towards the bottom surface the lava becomes finer grained but not so glassy as the top surface of the flow or as the glassy rinds of pillows. The surface is moderately smooth except for small spots with 0.5—5 mm of diameter and less than one millimeter of relief. The most remarkable fact is that the surface is composed of a relatively regular train of corrugations a few centimeters in height similar to folding on the surface of ropy pahoehoe flows (Plate III-a). Individual rope occasionally divides along its length. The smallest folds are 1—2 cm in wave length and 2 cm in height. These folds are tightly appressed fold with cusps between them. The axial planes of folds are arranged nearly parallel to each other and overturned towards the same direction. The underlying laminated claystone exhibits parallel lamination and is not disturbed except for a centimeter or so from contact with the lava, where clay fills the interstices between the folds (Plate III-b, c). Between 3 and 5 cm above the bottom are weak streaks parallel to the surface, suggestive of shear strain. These facts suggest that thin bottom crust was plastic and able to be deformed without breakage when the inner part was molten. Load structure is developed by the emplacement of dense, heavy molten lava on light, water-saturated clay. The crust was dragged by the flowing inner lava resulting in the folding.

Dacite sheet-like lava flows are small in dimensions and associated with pillows. Some of them are already described. Several sheet-like flows with forset-bedded basal breccia are exposed in Manjumisaki (Loc. 25). The massive lava is several decimeters in thickness and is traceable for a distance of more than 70 m. The underlying breccia is 2—3 m thick and composed of a coarse matrix and angular blocks ranging from a few centimeters to tens of centimeters across defining forset bedding.

Volcaniclastic rocks

Volcaniclastic rocks mainly consisting of boninite are widespread interbedded with lava flows. Flow foot breccia and talus deposits consisting of isolated pillows and coarse pillow fragments occupy only a small part of them. Most of them are finer-grained volcanic sandstone and breccia not always associated with pillow flows. Volcaniclastics intercalated with boninite pillows in the eastern area are composed of massive volcanic sandstone and fine volcanic breccia containing some intercalated coarse volcanic breccia and siltstone. The constituent rock and glass fragments are of boninite. Small isolated pillows and irregular-shaped pillow-like blocks with lobate smooth surfaces of glass are sometimes intercalated with massive fine volcanic breccia. These volcaniclastic rocks become very thick around Hatsuneyama (Loc. 1) and Toriyama (Loc. 26) up to 200 m. These deposits are characterized by the existence of abundant fine lithic fragments about the size of a millimeter, small isolated pillows and irregular-shaped blocks with glassy selvages and ill sorting. These features may be interpreted by phreato-magmatic origin of the volcanic sandstone and breccia.

Well-stratified sandstone and siltstone containing intercalated volcanic breccia are distributed in the east of Toriyama (Loc. 26) and from the east of Manjumisaki (Loc. 3) to Marubewan (Locs. 12). The volcanic sandstone intercalates pillow flows and sheet flows of boninite andesite and boninite to the east of Manjumisaki (Locs. 2, 3) and overlies pillow flows of dacite from John Beach (Loc. 24) to

Kinshihama (Loc. 8) and pillow flows of boninite in Marubewan (Loc. 12). Most constituents are rock and glass fragments of boninite. Agglomerated bronzite crystals up to 4 cm across and large single bronzite crystals are sporadically contained in a coarse sandstone. Isolated pillows of boninite and bronzite andesite up to several decimeters across are rarely scattered in the volcanic sandstone. The sandstone and breccia occasionally exhibit both normal and reverse grading. Convolution lamellae, load structure, cross lamination and small-scale slumping fold are observed within the sandstone. Imbrication, cross bedding and forset bedding within the sandstone indicate a flow direction from southeast to northwest.

Well-bedded volcanic breccia and sandstone exposed from Kominato (Loc. 27) to Ogiura (Loc. 28) contain blocks of both boninite and dacite. Forset bedding and multiple graded bedding are observed in the volcanic breccia and sandstone. Coarse sandstone sometimes exhibits cut and fill structure.

Alternating beds of breccia and sandstone mainly consisting of dacite frequently occur at the top of the Marubewan Formation. The distribution is basically dominated by the ancient topography and the thickness changes from a few meters to more than 100 m. The well-bedded breccia and sandstone abut the underlying pillows of dacite and boninite and are overlain by the Asahiya Formation. Cross bedding is commonly observed.

Dikes

Dikes of boninite and a small amount of bronzite andesite are mostly exposed along coast from Miyanohama (Loc. 8) to Toriyama (Loc. 26), trending WNW in the north and NNW in the east. Many of the simple dikes are several decimeters to 2 m in thickness. Multiple dikes are commonly observed. Boninite and bronzite andesite dikes are rare in other areas, probably because erosion has not proceeded to stratigraphically lower horizons where boninite dikes are present.

Dacite dikes are largely exposed in Kinshihama (Loc. 8) and on the western cliff of Yagiya (Loc. 29). They are also visible in the

northern to eastern coast but lesser in amount than boninite dikes. Each dike varies in thickness from several decimeters to more than 10 m and thicker than boninite dikes in general. They trend nearly parallel to boninite dikes, WNW in the north and NNW in other areas.

Dikes of quartz dacite are distributed in the north and east of Chichijima. Their trend is NW to WNW, slightly oblique to those of boninite and dacite. Most dikes range in thickness from 10 m to 20 m and thickest ones exceed 40 m.

The total thickness of boninite, bronzite andesite and dacite dikes is 144 m within 620-m distance from Hatsuneyama (Loc. 1) to Ishiura (Loc. 30). There are many shore reefs composed of dikes presumably of boninite, bronzite andesite and dacite exposed on the sea surface for a distance of 2 km between Ishiura and Higashijima to the east of Chichijima. These dikes are more than 100 m in thickness per a distance of 612 m. However, there seem to be many dikes below the sea level. If we assume that the intensity of dikes (the thickness of dikes within a definite distance) is about the same as that in Ishiura, the total thickness of dikes in the sea would be some 150 m. Dikes exposed in the central part of Chichijima are little in amount and exceed 60 m. Dacite dikes and stocks which grade into pillows are exposed on the coast of Kinshihama (Loc. 8), around John Beach (Loc. 24) and on the cliffs of Yagiya (Loc. 29). These dikes are more than 70 m in thickness. The total thickness of these dikes is more than 370 m (+50 m below the sea level). If the intensity of dikes of both boninite and bronzite andesite which may exist but are not exposed between Hatsuneyama and Takayama is similar to that (144/620) in Ishiura, the thickness of dikes would be as much as 1100 m. The amount of crustal extension by the intrusion of boninite, bronzite andesite and dacite dikes would be 1500 m at most.

The thickness of quartz dacite is 130 m within a distance of 300 m in Nagasaki (Loc. 18), 108 m within a distance of 390 m around Toriyama (Loc. 26) and 110 m in the other

areas. The total thickness is up to 630 m.

Petrography of igneous rocks of Chichijima

Igneous rocks of Chichijima are classified into 7 rock groups on the basis of mineralogy and texture: (1) boninite (2) bronzite andesite (3) dacite (4) quartz dacite (5) two-pyroxene andesite (6) microdiorte (7) norite.

(1) Boninite (GR-I)

The term "boninite" is defined here as a feldspar-free andesite carrying bronzite as a phenocryst and/or microphenocryst. Boninite is a compact, black grey rock and has abundant glass more than 20% even in the core of a pillow and a dike, showing a vitreously lustered fracture. Boninites are divided into two major groups on the basis of modes of phenocrysts; porphyritic boninites (phenocryst mode >1%) and aphyric boninites (phenocryst mode ≤1%).

Besides bronzite, olivine and clinoenstatite are commonly present as phenocrysts and/or microphenocrysts. Augite rarely occurs as a phenocryst. Small amounts of minute chrome spinel grains are found as an inclusion in phenocrysts and microphenocrysts of olivine and pyroxenes, and in the matrix glass. Groundmass consists of clinopyroxene microlites and abundant glass.

Olivine occurs as euhedral crystals up to 2 mm, showing hollow or skeletal shapes surrounded by clinoenstatite and bronzite and also by clinopyroxene microlites. Anhedral olivine phenocrysts are sometimes enclosed in clinoenstatite or bronzite phenocrysts. Glass inclusions are commonly found.

Clinoenstatite phenocrysts occur as euhedral or subhedral prisms 0.2—2 cm in length frequently rimmed by bronzite crystals and clinopyroxene microlites. Microphenocrystic clinoenstatite occurs as long prisms up to 1 mm in length and 0.1 mm in width and commonly makes composite crystals with bronzite showing parallel growth texture.

Bronzite phenocrysts occur commonly as euhedral thick prisms up to 5 mm long, though corroded anhedral crystals are not rare. Euhedral crystals with corroded cores are also recognized. Some of corroded bronzite phe-

nocrysts are surrounded by olivine microphenocrysts. Frequent tiny glass inclusions arranged subparallel to the crystal outline are observed. Bronzite microphenocrysts are of thin prisms up to 1 mm long, some of which show skeletal shapes. Clinopyroxene lamellas commonly exsolve in both phenocrysts and microphenocrysts of bronzite.

Clinopyroxene phenocrysts are often corroded and surrounded by clinopyroxene microlites and bronzite grains. Microphenocrystic clinopyroxene occurs as rims of bronzite and less commonly as euhedral prisms. Clinopyroxene microlites are acicular crystals with a hexagonal cross section and develop cracks perpendicular to the long axis.

SiO₂ and MgO contents of whole rocks range from 56% to 60% and 20% to 8%, respectively, and the FeO*/MgO ratios are less than unity.

(2) Bronzite andesite (GR-II)

Bronzite andesite is similar to boninite in mineral assemblages but carries plagioclase as a groundmass mineral. Hypersthene, augite and plagioclase occur as microphenocrysts and/or groundmass minerals. Olivine, clinoenstatite, bronzite, hypersthene, augite and plagioclase occur as phenocrysts, though, some bronzite andesites lack some or most of these phenocrysts. Magnetite occurs as a microphenocryst and rarely as a phenocryst. Olivine phenocrysts are of anhedral grains frequently enclosed in bronzite or clinoenstatite phenocrysts. Clinoenstatite occurs as euhedral crystals frequently rimmed by bronzite. Clinoenstatite rimmed by Ca-rich clinopyroxene is also commonly observed. Bronzite phenocrysts are generally euhedral crystals with frequent rims of hypersthene. Hypersthene, augite, plagioclase phenocrysts are subhedral to anhedral grains which frequently occur as crystal clots with or without magnetite. Interstitial glass is present between crystals of the clots.

Bronzite andesites are divided into two types: type I; those with phenocrystic plagioclase, type II; those without phenocrystic plagioclase. Type I is more restricted in distribution than type II and found as pillow flows near Kominato and along the Fukuro-

zawa river east of Takayama.

SiO₂ and MgO contents of bronzite andesite range from 57% to 64% and 12% to 5%, respectively. The FeO*/MgO ratio ranges from 0.71 to 1.60, though most bronzite andesites have FeO*/MgO ratio higher than unity.

(3) **Dacite (GR-III)**

Dacite changes in color from black to grey with increasing crystallinity. Dacite pillows are very glassy and the crystallinity changes slightly from the rim to the core. Dacite forming dikes and thick massive lava flows has high crystallinity and tends to be silicified to become blue green.

Dacite carries small (<1 mm in length) phenocrysts of hypersthene, augite, plagioclase and magnetite. Some dacites have few or no hypersthene. Modal amount of phenocrysts is less than 5% in general and 10% at most. Groundmass consists of clinopyroxene, plagioclase, magnetite and glass. The phenocrysts occur both as euhedral discrete crystals and as crystal clots with interstitial glass, giving a glomeroporphyritic texture. Plagioclase phenocrysts are frequently riddled with glass inclusions.

SiO₂ content of dacite ranges from 62% to 73% and MgO content is less than 4.5%. Anorthite contents of plagioclase phenocrysts are An₆₇₋₈₅ and the most magnesian dacite carries calcic plagioclase up to An₈₉, which corresponds to the most An-rich plagioclase in crystal clots of bronzite andesite. Two pyroxene geothermometer (WELLS, 1977) indicates 1052 °C for augite and hypersthene pairs in the most Mg-rich dacite.

(4) **Quartz dacite (GR-IV)**

Quartz dacite is similar to dacite but carries quartz as a phenocryst. Phenocrysts are of hypersthene, augite, magnetite, plagioclase and quartz. Groundmass consists of tiny laths of plagioclase, magnetite, clinopyroxene microclots, glass and microspherulites. Hypersthene, augite, magnetite and plagioclase phenocrysts are euhedral to subhedral and commonly form crystal clots. Some plagioclases are riddled with glass inclusions. Quartz phenocrysts occur as subhedral grains commonly agglomerated each other. Some of them are resorbed and

enclosed with fibrous aggregates of silica mineral which is similar to spherulites.

SiO₂ content of quartz dacite ranges from 65% to 76% and some specimens have high SiO₂ contents as much as rhyolite. However, "rhyolite" is not used because of the lack of alkali feldspar.

(5) **Two-pyroxene andesite (GR-V)**

Two-pyroxene andesite is black to dark brownish grey and hard and compact with few vesicles. It is a porphyritic andesite containing abundant (<10%) large augite phenocrysts. Phenocrysts are of plagioclase, augite, hypersthene, olivine and magnetite in decreasing amount and are set in a fine-grained groundmass consisting of plagioclase, clinopyroxene, magnetite and orthopyroxene(?). Plagioclase phenocrysts are subhedral to anhedral and riddled with glass inclusions. Some of them are resorbed. Augite phenocrysts are subhedral prisms to anhedral grains up to 5 mm long. They frequently enclose plagioclase, augite, hypersthene and magnetite, giving a poikilitic texture. Glass inclusions are common. Hypersthene phenocrysts are euhedral to subhedral prisms enclosing fine grains of plagioclase, magnetite and glass. Clear orthopyroxene rims with low birefringence are sometimes observed on euhedral prisms of hypersthene. Olivine occurs as anhedral grains with reaction corona of small clinopyroxene grains. Tiny chrome spinel inclusions are common. Magnetite phenocrysts are frequently resorbed occurring both as discrete grains and as inclusions in augite and hypersthene. Plagioclase, augite and hypersthene also occur as small discrete anhedral fragments with sharp edges. Some crystal clots consisting of subhedral to anhedral grains of augite, hypersthene, plagioclase, olivine and magnetite are observed. Magnetite occurs as interstices between the crystals in clots and also as irregularly shaped fine blebs in augite and hypersthene. Fine-grained noritic inclusions are occasionally found.

(6) **Microdiorite (GR-VI)**

Microdiorite rarely occurs as blocks in heterolithologic breccia of the Mikazukiyama Formation. Microdiorite is brecciated and comprises fragments from a few millimeters to

Fig. 8 Relationships between the active periods of boninite, bronzite andesite, dacite, quartz dacite and porphyritic two-pyroxene andesite. The K-Ar ages of boninite and dacite in the Marubewan Formation are 39–43 Ma, however radiolarian fossils obtained from the lower portion of the Mikazukiya Formation indicate the early Middle Eocene.

a centimeter in diameter and interstices. Each fragments are sharply edged and scarcely moved each other after fragmentation. The fragments consist of granular green hornblende less than 0.1 mm across and plagioclase laths 0.1–0.2 mm long and lesser amounts of granular magnetite. The interstices consist of aggregate of finer-grained hornblende, plagioclase and magnetite.

(7) Norite (GR-VII)

Fine-grained norite inclusions are found rarely in boninite (GR-I) and frequently in two-pyroxene andesite (GR-V). The inclusions consist of abundant granular hypersthene including dendritic and irregularly shaped magnetite and small amounts of plagioclase.

Age and stratigraphic relationships of volcanic rocks

Correlation of the active periods of each volcanic rocks is shown in Fig. 8. Volcanism of Chichijima may have taken place with the eruption of boninite followed by bronzite andesite, dacite and quartz dacite. There is no information of pre-boninite volcanism in Chichijima. Field evidences are suggestive of a period of concurrent activity of boninite, bronzite andesite and dacite. These are; (1) A boninite dike intrudes into dacite hyaloclastite 400 m to the northeast of Tsutsujiyama (Loc. 20). (2) A pillow flow of boninite underlain by a pillow flow of dacite is observed on the northern coast of Nishikaigan (Loc. 11). (3) A boninite pillow flow overlain by sheet flows of quartz dacite overlies

well-stratified breccia of dacite in Sakaiura (Loc. 31). (4) Dacite xenoliths are found in a sheet flow of boninite in a small valley to the north of Tsutsujiyama (Loc. 4). (5) Boninite pillow flows overlie bronzite andesite pillow flows around loop tunnel (Loc. 19) and Tsurihama (Loc. 17). (6) Volcaniclastic rocks mainly composed of boninite with intercalated pillow flows of both boninite and bronzite andesite overlie dacite pillows and dikes on the coast near John Beach (Loc. 32). (7) A boninite dike intrudes into a pillow flow of bronzite andesite on the western coast of Tsurihama (Loc. 17). (8) A bronzite andesite pillow flow is underlain by well-bedded dacite breccia near Kominato (Loc. 20). (9) Dacite pillows in Ten'noura have inclusions of bronzite andesite. The inclusions have obscure outlines and are irregular in shape, slightly finer grained in the rim and vesiculated in the core. The groundmass of the inclusions is of clinopyroxene and glass in the rim and plagioclase occurs in the core. These facts suggest that bronzite andesite was liquid when engulfed by dacite magma, *i. e.*, both bronzite andesite and dacite magmas were active at the same time.

The activity of dacite continued after those of boninite and bronzite andesite had ceased. A period of quiescence between the activities of dacite and quartz dacite is suggested by the existence of well-stratified breccia at the top of the Marubewan Formation. No evidence indicative of coactivity of dacite and quartz dacite is found, which suggests that

differentiation of the dacite magma proceeded during the repose period.

Porphyritic two-pyroxene andesite (GR-V) and microdiorite (GR-VI) are distinct from other rock types and restricted in distribution to the Mikazukiyama Formation, the uppermost volcanic formation in Chichijima. These igneous rocks would be derived from different volcanism to boninite on or around the Bonin Ridge. The two-pyroxene andesite is also found in Anijima to the north of Chichijima. Heterolithologic volcanic breccia with close resemblance to the Mikazukiyama Formation composes the upper part of Yomejima some 50 km north of Chichijima. These facts suggest that the volcanism which yielded hyaloclastite and pillow flows of porphyritic two-pyroxene andesite took place on or around the Bonin Ridge. The volcanic products were transported to topographic lows on the Bonin Ridge and formed slump deposits in the Mikazukiyama Formation and Yomejima. The volcanism would have taken place before the sedimentation of the fossil-bearing rock, or almost at the same time with its sedimentation.

K-Ar whole rock ages are reported to be 39 Ma and 43 Ma for pillow lava of dacite and 41 Ma for pillow lava of boninite (TSUNAKAWA, 1983). Two-pyroxene andesite (GR-V) in slump breccia of the Mikazukiyama Formation gave a K-Ar date of 29 Ma (SHIBATA *et al.*, 1984). However, early middle Eocene fossils, indicative of a little older age than the oldest radiometric age, are found in the lowest portion of the Mikazukiyama Formation (TAKAYANAGI, personal communication). TSUNAKAWA (1983) suggests that post-boninite volcanism or some thermal disturbance occurred during the Miocene time in the Bonin Islands. Moreover, boninite and dacite are highly glassy (mode of glass exceeds 20%) and the glassy portions are in general more or less altered. Alteration may have given younger K-Ar ages than the fossil age. However, the Mikazukiyama Formation is largely composed of slumping deposits, so that the possibility of reworking of the fossils cannot be thoroughly excluded. The activity of boninite is, therefore, at least as old as

middle Eocene.

Problems on tectonic setting of Chichijima

SHIRAKI & KURODA (1977) argued that boninite magma had high-water contents because of high-water contents in boninites (5%), lack of plagioclase phenocrysts and presence of abundant vesicles. SHIRAKI & KURODA (1977) and KURODA & SHIRAKI (1975) proposed that boninite magma is a primary, hydrous partial melting product of mantle peridotite and that subduction is necessary for such a process. SHIRAKI *et al.* (1978) presented a model for a petrological evolution of Tertiary Izu—Mariana arc. The model consists of three stages: (1) Generation of tholeiite through sea-floor spreading in early Eocene time. (2) Beginning of subduction and generation of island arc tholeiites as those found in Hahajima by introduction of a little amount of water in late Eocene and early Oligocene time. (3) Production of calcalkalic andesite such as boninite by introduction of a larger amount of water in late Oligocene to early Miocene time.

In Chichijima, there are parallel dike swarms with a minimum total thickness of 1050 m and abundant multiple dikes. Vertically elongated vesicles in the selvages of dikes indicate that the magmas came from downwards. These facts indicate that Chichijima was under a relatively large differential stress which could be related to sea-floor spreading. However, the parallel dike swarms could also be interpreted as parts of huge radial dikes as those in Hawaii. Consequently, it is not known whether the volcanic activity of Chichijima was related to the spreading of the Bonin Ridge.

The Pacific plate changed its direction of movement from NNW to WNW at about 43 Ma (CLAGUE & JARRARD, 1973; DALRYMPLE & CLAGUE, 1976). At about this age, Izu—Mariana trench turned from a transform fault to a subduction zone (UYEDA & BEN-AVRAHAM, 1972; BUTLER & CONEY, 1981). However, the genetic relationship between the beginning of subduction and the change of plate motion is still unclear. UYEDA & BEN-

AVRAHAM (1972) thought that the plate motion change of the Pacific plate at 43 Ma resulted in the subduction along the Izu—Mariana trench. On the contrary, BUTLER & CONEY (1981) suggests that the initiation of subduction of the Pacific plate along its southwestern margin resulted in change in absolute plate motion, and that a time lag between these two events was expected.

Radiolarian fossils and *Nummulites* found in the Mikazukiyama Formation indicate early middle Eocene age which is older than the age of change in direction of plate motion. However, two-pyroxene andesite in this formation gives a far much younger K—Ar age of 29 Ma, and dacite and boninite from the lower formation give slightly younger K—Ar ages of about 40 Ma. As is already discussed, lack of confirmative reliance on both fossil and radiometric ages prevents us from defining the age of the volcanism and leads to following possibilities. (1) Hahajima yields Biarritzian and Lutetian foraminifers (older than 44 Ma: UJIE & MATSUMARU, 1977) among island-arc-type volcanic rocks. If the fossil age indicates the age of boninite volcanism, the volcanism in Chichijima is not younger than that in Hahajima. The two-pyroxene andesite (GR—V) in the Mikazukiyama Formation could be preceeding activity of the volcanism in Hahajima because of its lithological similarity to volcanic rocks in Hahajima. The fossil age also supports BUTLER & CONEY (1981). Subduction of the Pacific plate under the Philippine Sea plate produced boninite magma and was followed by the change in plate motion at 43 Ma. (2) Volcanism of boninite was at 43 Ma and was almost contemporaneous with or slightly later than that in Hahajima. These ages of volcanism coincide with the age of the change in plate motion within an error, which could be explicable by the model of UYEDA & BEN-AVRAHAM (1972). The pyroxene andesite (GR—V) could be related to the volcanism of Hahajima, or it might indicate post-quartz-dacite volcanism around the Bonin Ridge in Oligocene time.

Future studies on this problem should include: (1) Determination of the age of volcanism on the Bonin Ridge by fossils among

lava flows of boninite and related rocks (GR—I, II, III, IV) as well as by more reliable radiometric dating such as Ar—Ar method on boninite and related rocks, GR—V volcanic rocks from the Mikazukiyama Formation and Yomejima. (2) Petrological studies on boninite and related rocks, GR—V and volcanic rocks from Hahajima to clarify petrochemical characteristics and genetic relations among these rocks.

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〈地名〉

Anijima	兄島	Kinshihama	金石浜	Ogiura	扇浦
Anijimaseto	兄島瀬戸	Kohiyama	珈琲山	Sakaiura	境浦
Asahiya	旭山	Kominato	小港	Takayama	高山
Chichijima	父島	Manjumsaki	饅頭岬	Tatsumijima	巽島
Chuoizan	中央山	Marubewan	円縁湾	Ten'nohana	天之鼻
Fukurozawa	袋沢	Meshimoriyama	飯盛山	Ten'noura	天之浦
Futamiko	二見港	Minamizaki	南崎	Toriyama	鳥山
Hahajima	母島	Minamifukurozawa	南袋沢	Tsurihama	釣浜
Hakohama	箱浜	Mukojima	顰島	Tsutsujiyama	躑躅山
Hatsuneura	初寝浦	Nagasaki	長崎	Yagiyama	野羊山
Hatsuneyama	初寝山	Nakakaigan	中海岸	Yoakeyama	夜明山
Higashikaigan	東海岸	Nakotoshijima	中通島	Yomejima	嫁島
Ishiura	石浦	Nakodojima	媒島		
Kamenokubi	亀之首	Nishikaigan	西海岸		

(要 旨)

UMINO, S., 1985 : Volcanic geology of Chichijima, the Bonin Islands (Ogasawara Islands). *Jour. Geol. Soc. Japan*, **91**, 505-523. (海野 進, 1985 : 小笠原諸島父島の火山地質. 地質雑, **91**, 505-523)

小笠原諸島父島は始新世中期の海底火山噴出物とこれらを不整合で覆う漸新世～中新世初期の有孔虫石灰岩(南崎累層)から成る。火山岩類は岩質・産状により下位から円縁湾, 旭山, 三日月山累層に分けられる。層序及び岩脈の貫入関係の示す各火山岩類の活動時期は, 無人岩→無人岩+古銅輝石安山岩+デイサイト→デイサイト→(休止期)→石英デイサイトであり, 三日月山累層に特徴的な斑状輝石安山岩は無人岩類と異なる火山活動に由来する。

三日月山累層の放散虫化石(中期始新世初期)は下位火山岩の K-Ar 年代(43 Ma) より古い。これより2つの解釈が可能である。(1)化石年代の示す通り, 太平洋プレートが進行方向を転換する 43 Ma 以前に小笠原海嶺付近に存在した沈み込みが無人岩類の活動をもたらしした。(2)沈み込み帯は太平洋プレートが方向転換した時に生じた。母島の火山活動もほぼ同時期に起きた。

Explanation of Plates

- I-a Forset-bedded elongate pillows of boninite exposed on a cliff facing Ten'noura.
- I-b Close-up view of large close-packed pillows of dacite. Each pillow develops many cracks and appears to be in situ breccia. Fragmentation must have occurred after the emplacement of pillows. The scale in the bottom left is one meter long.
- I-c, d Dacite pillow flows overlain by quartz dacite sheet-like lava flows. Pillow flows are composed of elongate pillows and in both upper right and lower left portions are shown cross sections cut parallel to the direction of elongate pillows. In both upper left and lower right portions pillows are arranged perpendicular to the surface of the outcrops. Thus at least four flow units can be identified. A massive lava body seen in the middle of the right portion is the master feeding tube which fed pillows of the lower right.

I-c

I-d

I-a

I-b

II-a

II-b

II-a Sheets of lava tongues and elongate, lenticular masses of bronzite andesite in cognate matrix composed of fragments from a millimeter to a few centimeters across. (Looped tunnel to the northeast of Asahi-yama)

II-b Close-up view of Plate II-a showing irregular shaped masses of lava associated with pillows of bronzite andesite.

III-b

III-a

III-c

III-a Bottom surface of sheet flow II showing folding just as that onropy pahoehoe flows. The scale in the upper right is 20 centimeters long.

III-b, c Boundary between sheet flow II and underlying claystone.