Studies on the Neogene subaqueous lavas and hyaloclastites in Southwest Hokkaido

Hiromitsu YAMAGISHI

Abstract: Southwest Hokkaido is situated in the extension of the inner belt of the North Honshu Arc and is dominated by the Neogene to Quaternary volcanic rocks. The Early Miocene volcanic rocks are mostly subaerial products, whereas the subsequent Neogene volcanic rocks are mainly submarine andesitic products diagnostic of island arcs.

They are divided into lavas and volcaniclastic rocks. The lavas are subdivided into pillow lobes, lava lobes, sheet flows and pseudo-pillow lavas. The volcaniclastic rocks are classified into hyaloclastites, pyroclastic rocks and epiclastic volcanic rocks. Particularly, the hyaloclastites occupy the large proportion of the Neogene volcanic rocks in Southwest Hokkaido.

The pillow lobes are cylinder or tubular and mostly andesitic. Their surface structures are recognized as ropy wrinkles, spreading cracks, tensional cracks and contraction cracks. The former three are formed during the growth of the pillow lobes, whereas the latter two are made after the emplacement. The ropy wrinkles are analogous to those on a subaerial pahoehoe lava. The corrugations are formed by internal convection or scratching. The spreading cracks are formed across or along the elongation of the pillow lobes, and play the most important role in their growth. The tensional cracks are produced by further supply of the interior magma even after stopping of the growth of the pillow lobes. The contraction cracks are formed by gradual cooling of the pillow lobes.

The internal structure of the pillow lobe is characterized by joints, crusts and vesicles. The joints correspond to the contraction cracks and are radial, irregular and tortoise-shell in shape. The crusts are produced by shear jointing during the growth of the pillow lobes. The vesicles are ellipsoidal to spherical. The inner vesicles are larger than the outer ones. Pipe vesicles develop in places along the boder zone of the pillow lobes. Microscopic features of the andesitic pillow lobes are intersertal or intergranular texture in the inner part, and quench crystal overgrowth on the phenocrysts or microphenocryst in the outer part.

The lava lobes are chracteristic of andesitic or rhyolitic subaqueous lavas. They are ellipsoidal a few meters across and are composed of crystalline cores and glassy margins grading outward into hyaloclastites. The cores are characterized by flow layers conformable to the outlines, and radial rude joints. Sheet flows and small lava lobes develop from the glassy margins. The lave lobes are formed by expansion of the sheet flows due to further supply of the internal magma.

The pseudo-pillow lavas are one of andesitic subaqueous forms. They consist of polyhedral blocks of tens centimeters to a few meters across. They are formed by development of quench joints.

The hyaloclastites are divided into (A) and (B) types. The (A) type is basaltic to andesitic monolithologic breccia and usually includes pillows (ellipsoids with quench glass). These pillows are formed by disintegration of pillow lobes or apophysis-like feeder dyke. Particularly, those concentrated at the margins of the apophysis-like feeder dykes are called concentric pillows. The (B) type is andesitic to rhyolitic monolithologic breccia. It is a product formed by brittle fracturing of the pseudo-pillow lava, lava lobe, massive feeder dyke, caused by quenching with water.

Massive hyaloclastites are accumulated around the lavas and feeder dykes, and grade laterally into stratified hyaloclastites which are foreset-beds showing a primary dipping of 20°—30°, in places overlain by topset-beds. Each foreset-bed displays reverse or reverse-to-normal grading, suggesting that it was formed by a debris flow.

The Neogene subaqueous lavas and hyaloclastites in Southwest Hokkaido are highly vesicular and in places associated with subaqueous pyroclastic rocks, such as scoriaceous agglomerates and pyroclastic pillow breccias, suggesting that they are the products of shallow submarine volcanism.

I INTRODUCTION

Subaqueous volcanic rocks involving lavas and volcaniclastic rocks are the products of underwater eruptions. They have notable characters different from subaerial volcanic rocks in many respects. Nature of underwater eruptions, effusive or explosive, is probably determined by the depth (pressure) of water-column, the composition and physical property of magma, and the extent of interaction between magma and water (McBirney, 1963 ; Moore, 1965, 1975 ; Moore and Schilling, 1973 ; Fisher and Schmincke, 1984 ; Kokelaar, 1986). Accordingly, subaqueous volcanic rocks would provide important information on the geologic environment as well as nature of volcanism.

Much information on subaqueous basaltic rocks, such as pillow lavas and hyaloclastite, has been obtained (e. g. Rittmann, 1962 ; Moore, 1975 ; Ballard and Moore, 1977). Compared with the basaltic rocks, however, subaqueous andesitic to rhyolitic rocks, which occur as important volcanic products in island arcs, have not received much attention. There are still unsolved problems in their recognition, classification, and process of formation.

Southwest Hokkaido is located in the northern extension of the inner belt of North Honshu Arc, and is characterized by extensive distribution of the Neogene to Quaternary volcanic rocks (Fig. 1). The Neogene system in Southwest Hokkaido has been divided into the Fukuyama, Yoshioka, Kunnui, Yakumo, Kuromatsunai, and Setana Formations, in ascending order (Nagao and Sasa, 1933, 1934 ; Geol. Surv. Hokkaido, 1980). Lavas and volcaniclastic rocks of the earlier Neogene formations, such as Fukuyama and Yoshioka Formations, are interbedded with terrestrial sediments. However, those of the subsequent formations are interbedded with marine sediments as a result of transgression.

These subaqueous lavas and volaniclastic rocks are considerably abundant, and are composed mainly of andesitic rocks which are characteristic of island arc, although basaltic and rhyolitic rocks are associated. Most of the Neogene subaqueous volcanic rocks preserve their primary structures because of their younger age. Thus, the Neogene Southwest Hokkaido may provide a clue to the problems of subaqueous volcanic rocks in island arcs.

Although detailed studies on the Neogene formations and associated ore deposits in Southwest Hokkaido have been made during last tens of years, these volcanic rocks have been scarcely studied, especially in the volcanological point of view.

Since 1973, the author has been engaged in the study of the Neogene subaqueous volcanic rocks in Southwest Hokkaido (Yamagishi, 1973, 1979, 1982, 1985 ; Yamagishi et al., 1979 ; Yamagishi and Dimroth, 1985). He has studied the classification, mode of occurrence, external

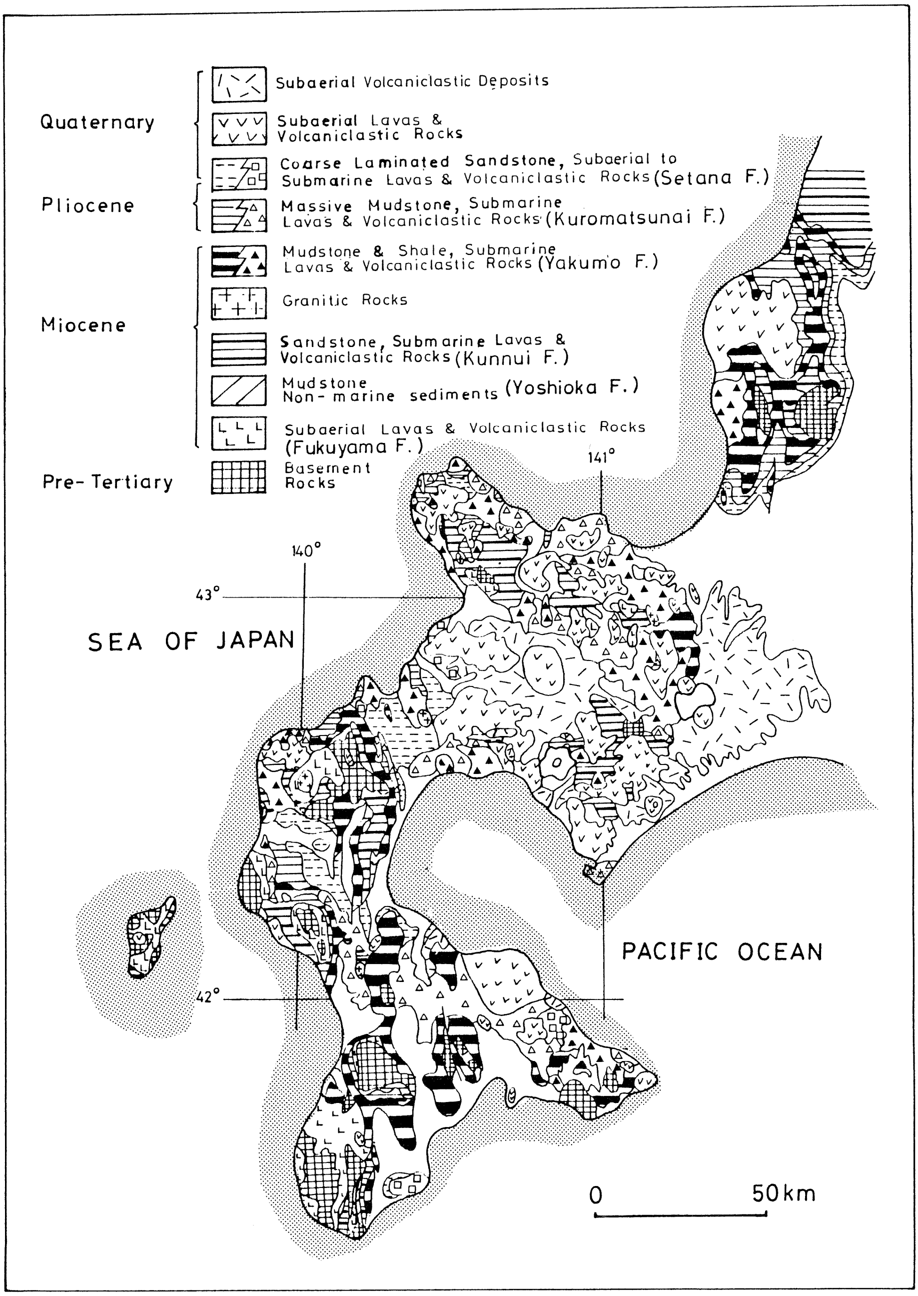

Fig. 1 Geological map of Southwest Hokkaido. Simplified from the Geological Map of Hokkaido, scale 1 : 600,000, Geological Survey of Hokkaido (1980).

and internal structures, and sedimentary structures of the Neogene subaqueous volcanic rocks,

The results will contribute to the better understanding of submarine volcanism in other island arcs as well as in Southwest Hokkaido.

In this paper, the author is concerned with classification and definition of subaqueous volcanic rocks on reference to the substantial results of studies on modern subaqueous volcanic products. Then, descriptions of the Neogene subaqueous lavas, hyaloclastites and associated pyroclastic rocks in Southwest Hokkaido are given on the basis of typical examples. Finally, the criteria for the recognition and the processes of formation of the subaqueous volcanic rocks are discussed.

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II CLASSIFICATION AND DEFINITION OF SUBAQUEOUS VOLCANIC ROCKS

Subaqueous volcanic rocks can be classified into subaqueous lavas and volcaniclastic rocks although there are transitions between them. This chapter is concerned with their classification and definition on reference to many previous works.

1. Subaqueous lavas

Pillow lavas of mafic compositions have been known as the most representative subaqueous lavas although those of intermediate to felsic rocks have been found (Lipple, 1972; Bevins and Roach, 1979; Cousineau and Dimroth, 1982).

There have been many arguments on the mechanism of formation of pillow lavas and the similarity to pahoehoe lavas (Macdonald, 1967; Truckle, 1979). However, a decisive solution on the mechanism of formation of pillow lavas was given by Moore (1975), who dived the shallow sea at Hawaii and observed a growing pillow lava for the first time in the world. In addition, recent submarine researches have provided abundant excellent pictures of pillow lavas (e. g. Ballard and Moore, 1977).

The observation and research on modern pillow lavas indicate that it is of importance to describe and to examine ancient pillow lavas in three dimensions, because observation only in two dimensions cannot distinguish pillow lavas from other forms, such as lava lobes and pseudo-pillow lavas.

Various modes of occurrence of intermediate to felsic subaqueous lavas have been described, e. g. submarine extruded domes (Pichler, 1965), pseudo-pillow lavas (Watanabe and Katsui, 1976), lava pods (Snyder and Fraser, 1963; De Rosen-Spence et al., 1980), lava lobes (Furnes et al., 1980) and silicic massive lavas (Cas, 1978).

Pichler (1965) described felsic viscous dome disintegrated in contact with water. Watanabe and Katsui (1976) reported pseudo-pillow lavas which are subaqueous dacite lavas disected into polyhedral blocks by water-chilling joints across flow layers. Snyder and Fraser (1963) described andesitic and dacitic lava pods showing equant or tabular bodies with concentric flow layers. De Rosen-Spence et al. (1980) reported Archean subaqueous felsic flows composed of pods, lobes and tongues. Furnes et al. (1980) described subglacial rhyolitic lobes consisting of lithic core, vesiculated zone, and obsidian rim grading outward into hyaloclastite. Cas (1978) described subaqueous massive lavas of felsic composition in Paleozoic flyschlike deposits.

In the Neogene Southwest Hokkaido, the author has recognized not only mafic pillow lavas, but also intermediate to felsic lava lobes and hyaloclastite in places containing pseudo-pillows. Furthermore, thin-tabular lavas defined as sheet flows (Ballard and Moore, 1977; Ballard et al., 1979) have been found in many places.

2. Subaqueous volcaniclastic rocks

The first systematic classification of volcaniclastic rocks was proposed by Wentworth and Williams (1932). Their classification is primarily based on shape, structure and size of fragments derived mostly from subaerial eruptions. This classification is even now available for the pyroclastic rocks which are expelled by explosion from volcanic vents at subaerial environment.

Subsequently, Blockhina et al. (1959) and Fisher (1961, 1966) have proposed classification schemes for volcaniclastic rocks involving various clastic rocks.

On the basis of the composition of cementing materials and the relative content of pyroclastic and sedimentary materials, Blockhina et al. (1959) divided volcaniclastic rocks into 1) lava breccias, 2) pyroclastic rocks, 3) tuffites, and 4) tuffogenic rocks, without regard to their origin or environment.

Fisher (1961) proposed a classification of volcaniclastic rocks based on the mechanism of fragmentation, i. e. 1) autoclastic volcanic breccias resulted from internal processes during movement of semi-solid or solid lava, 2) pyroclastic volcanic breccias produced by volcanic explosions, and 3) epiclastic volcanic breccias resulted from transport of loose volcanic materials by epigene geomorphic agents or gravity. In addition to the three categories, alloclastic volcanic breccias formed by subsurface volcanic activity, were added after discussion with Wright and Bowes (1963), and hyaloclastic breccias fragmented by contacting of magma with water were supplemented (Fisher, 1966).

On referring to the studies mentioned above, particularly those by Fisher (1961, 1966), the author has divided the Neogene subaqueous volcaniclastic rocks from Southwest Hokkaido into 1) hyaloclastites, 2) pyroclastic rocks, and 3) epiclastic volcanic rocks (Yamagishi, 1979).

2.1. Hyaloclastites

The term "hyaloclastite" was first defined by Rittmann (1962) as "deposits formed from the comminuted glassy shells of growing pillows". The term, therefore, involves originally deposits of fine-grained basaltic glassy fragments that are spalled off from the pillow rinds.

Subsequently, Pichler (1965) extended the term "hyaloclastite" to felsic rocks during his study on the geology of Island Ponza, Italy. Namely, he defined the term as "fine-grained to coarse-brecciated volcanoclastic materials in contact with water, ice or unconsolidated water-bearing country rocks. "He reported that the felsic hyaloclastite is formed by quick contraction and disintegration on the quenched margin of growing lava dome.

Moreover, Honnorez and Kirst (1975) discriminate hyaloclastite generated by non-explosive granulation which takes place when basaltic magma is quenched by water, from hyalotuff produced by phreatomagmatic and phreatic explosions at basaltic volcanoes in shallow water.

Hence, the author proposes to apply the term "hyaloclastite" to glassy fragmental rocks formed by non-violent processes which occur when lavas and dykes come in contact with water. Namely, he distinguishes the "hyaloclastite" from the "pyroclastic rock" which is produced by violent explosion.

He also proposes to divide the hyaloclastite into (A) and (B) types; the former involves ellipsoidal blocks enveloped with glassy rims (pillows), whereas the latter comprises polyhedral fragments without glassy rims.

The hyaloclastites commingled with sedimentary fragments are called peperites (Williams and McBirney, 1979; Brooks et al., 1982; Hanson and Schweickert, 1982). They are usually filling up feeder channels.

2.2. Pyroclastic rocks

The term "pyroclastic rocks" is applied to the rocks produced by explosive ejection of materilas from a volcanic vent (Wentworth and Williams, 1932). The pyroclastic rocks are divided into fall and flow deposits; the former are produced by showers of pyroclastic fragments while the latter by transport en masse from vents (Lajoie, 1984).

The author believes that the term is extended to the subaqueous equivalents. Criteria for recognition of the subaqueous pyroclastic fall deposits are quenching as evidenced by water-chilled essential fragments (Yamagishi, 1974), floating action forming reverse-grading, and resedimentation producing foreset-beds.

The subaqueous pyroclastic flows (Fiske, 1963, Fisher, 1984) found in the Neogene formations in Southwest Hokkaido are characterized by combination of lower massive part and fine-grained bedded top (Fisher, 1984), and by separation of lithic fragment from pumice and scoria in the massive part (Yamagishi, 1974).

The Neogene subaqueous pyroclastic rocks in Southwest Hokkaido comprise 1) volcanic breccias composed mostly of accessory and/or accidental blocks (>64 mm in diameter) ejected by explosion, 2) scoriaceous agglomerates consisting of water-chilled bombs (Yamagishi, 1974, 1982) in a matrix of scoriaceous lapilli tuff, 3) scoria- and pumice-tuffs, 4) pyroclastic pillow breccias defined as coarse-grained mafic phreatomagmatic tuff composed of quench glass and pillow fragments (Dimroth et al., 1985).

2.3. Epiclastic volcanic rocks

The term "epiclastic volcanic rocks" is applied to the rocks consisting dominantly of volcanic fragments transported by any epigene geomorphic agent (Fisher, 1961, 1966). Most of the heterolithologic volcaniclastic rocks in the Neogene formations in Southwest Hokkaido are included in this category. Epiclastic volcanic breccias, volcanic conglomerates and fine-grained epiclastic volcanic rocks are discernible.

3. Glossary of subaqueous volcanic rocks

Much information on subaqueous volcanic rocks has led to a proliferation of new terms and many varied redefinition of older ones. Hence, a glossary of subaqueous volcanic rocks is needed.

Agglomerate: A deposit consisting mostly of volcanic bombs. A subaqueous agglomerate is characterized by water-chilled bombs (cfr. page 87).

Asymmetric transverse spreading crack: A type of spreading crack on a pillow lobe. It is formed across the elongation of a pillow lobe when the toe of the older pillow breaks and a new pillow lobe drains. It is defined as tiny fault scarp (Yamagishi, 1983, 1985).

Apophysis-like feeder dyke : A feeder dyke showing apophytic intrusion into surrounding sediments (Yamagishi, 1982 ; Cucuzza Silvestri, 1963a).

Autoclastic volcanic breccia : A volcanic breccia (volcaniclastic rock) formed by fragmentation by mechanical friction or gaseous explosion during movement of lava, or gravity crumbling of spines and domes (Fisher, 1961 ; Fisher and Schmincke, 1984) ; e. g. subaerial block lava (Macdonald, 1953, 1967).

Close-packed pillow lava : A pillow lava consisting of pillow lobes which are closely fitted with each other (Carlisle, 1963 ; cfr. page 79).

Concentric joint : A joint pattern of feeder dyke or pillow. A top of massive dyke has, in places, joints along flow layers developed conformably to the curved surface. Most of the pillows associated with apophysis-like feeder dyke have concentric joints along the glassy margin (cfr. page 76).

Concentric pillow : An ellipsoidal block with concentric joints along the glassy margin (cfr. pages 76 and 84).

Constriction : A narrow neck formed when a new pillow lobe emerges through the crust of a pillow lobe (Yamagishi, 1985). Syn. reentrant selvedge (Hargreaves and Ayres, 1979).

Contraction crack : A nearly vertical fracture in hot materials formed by thermal contraction during cooling (American Geological Institute, 1980). The contraction crack of a pillow lobe is represented by tortoise-shell joints on the surface, which propagate inward into radial-columnar joints in cross section.

Corrugation : A wrinkle on the surface of a pillow lobe. It develops along the elongation of the pillow lobe. It is formed during the growth of pillow lobe.

Corrugation(A) : A kind of corrugation showing moderately waving wrinkles whose wavelength is a few centimeters (Yamagishi, 1983, 1985).

Corrugation(B) : A kind of corrugation showing V-shaped grooves with various width less than 1 cm (Yamagishi, 1983, 1985).

Crust : A solidified rim of a pillow lobe. It is a few centimeters thick and has distinct glass with tiny joints on both outer and inner margin (Yamagishi, 1985).

Epiclastic volcanic rock : A volcaniclastic rock consisting dominantly of volcanic fragments transported from essential volcanic debris by any epigene geomorphic agent (Fisher, 1961, 1966).

Fault sliver : A tiny ridge in a spreading crack of pillow lobe. It is formed during its growth. It is bounded by small normal faults of a few millimeters in displacement (Fuller, 1932 ; Moore, 1975).

Feeder channel : A channel through which a fluidal magma passes. Consequently, it is filled with a feeder dyke.

Feeder dyke : An auto-intrusive body which grades vertically into subaqueous lava and hyaloclastite. It acts as feeder from depth (Yamagishi, 1982). Syn. lava-dyke (Cucuzza Silvestri, 1963a).

Finger : A branch of apophysis-like feeder dyke, which protrudes surrounding sediments (cfr. page 84).

Flow-foot breccia : A foreset-bedded breccia formed by flowing of subaerial lava into water (Fuller, 1931 ; Jones and Nelson, 1970 ; Dimroth et al., 1985).

Flow-front breccia : A foreset-bedded breccia formed by deltaic progradation of hyaloclastite entirely in water (Dimroth et al., 1985).

Flow layer : A laminated structure marked by preferred orientation of vesicles or phenocrysts, indicative of flowage of a lava. Syn. fluidal structure (Macdonald, 1967).

Foreset-bedded breccia : A stratified volcaniclastic rock showing foreset bedding. Especially, it means a breccia produced by disintegration of lava/dyke and deltaic progradation (Fuller, 1931 ; Jones and Nelson, 1970). It is roughly parallel and has a primary dip of 20°—40°. It is covered or truncated by topset-bedded breccia.

Hyaloclastite : A glassy fragmental rock formed by fracturing and disintegration of lava/ dyke when they come in contact with water (Cucuzza Silvestri, 1963b ; Pichler, 1965 ; Maruyama and Yamazaki, 1978 ; cfr. page 76).

Hyaloclastite (A) : A kind of hyaloclastite formed by disintegration of pillow lobe, lava tongue and apophysis-like feeder dyke. It is commonly basaltic and pyroxene andesitic (cfr. page 76).

Hyaloclastite (B) : A kind of hyaloclastite formed by brittle fracturing of viscous lava and/ or dyke due to quenching (cooling-contraction granulation ; Kokelaar, 1986 ; cfr. page 78).

Hyalotuff : A volcaniclastic rock resulted from explosive interaction between basaltic magma and water (Honnorez and Kirst, 1975). Syn. pyroclastic pillow breccia (Dimroth et al., 1985) and scoria pillows and scoria lapilli/bomb breccia (Staudigel and Schmincke, 1984).

In-situ breccia : Monolithologic breccia produced by disaggregation of lava and/or dyke due to brittle fracturing during quenching with water (Kokelaar, 1986 ; De Rosen-Spence, 1980). Syn. subaqueous autobrecciated lava (Kuno, 1968).

Jigsaw breccia : A kind of in-situ breccia. Disaggregated small fragments assembled easily into a large block, resembling a jigsaw puzzle.

Lava lobe : A kind of intermediate to felsic subaqueous lava. It is ellipsoidal or elongated body of a few to ten meters in diameter. It consists of lithic core and glassy border zone which grades outward into hyaloclastite (Furnes et al., 1980 ; cfr. page 72).

Lava pod : A kind of subaqueous lava. It is equant or tabular body of concentrically layered igneous rock (Snyder and Fraser, 1963). It ranges in minimum dimensions from tens to many hundreds of feet and average several hundred feet in diameter. It is generally intimately associated with massive lave, pillowed lava and peperite. It is formed by the intrusion of andesitic and dacitic magma into semi-consolidated ocean-bottom muds.

Massive feeder dyke : A feeder dyke with columnar joints, in places, radially developed at the top. It feeds hyaloclastite (B) through in-situ brecciation along the margin (cfr. page 84).

Massive lava : A lava with rude columnar joints. A subaqueous massive lava has fragmented margin (Cas, 1978) and/or glassy margin grading outward into hyaloclastite or pillow lava (Dimroth et al., 1978).

Pahoehoe lava : A kind of basaltic subaerial lava represented by a smooth, billowy or ropy surface (Macdonald, 1953, 1967).

Palagonite : Altered basaltic glass (tachylite) of brown to yellow or orange in color. It is found in the interstitial materials or in amygdules of pillow lavas (American Geological Institute, 1980).

Peperite : A mixture of lava fragments and muddy or sandy materials. It is formed by decrepitation and thermal shattering of magma in contact with water during its surface intrusion (Snyder and Fraser, 1963 ; Williams and McBirney, 1979). The term was originally used by Scrope (1862) for basaltic tuffs and breccias in a light-colored marly to limy matrix.

Perlitic glass : A conchoidal-jointed glass formed by hydration and exfoliation of obsidian (Ross and Smith, 1955).

Pillow breccia : A breccia consisting of complete or broken pillows in a matrix of cogenetic basic tuff (Carlisle, 1963). Syn. pillow block breccia (Furnes and Friedleifsson, 1979), Pillow fragment breccia (Staudigel and Schmincke, 1984), Hyaloclastite (A) (cfr. page 76).

Pillow bud : A bud growing from cracks on the top or side of a pillow lobe, resembling paste squeezed from a tube (Moore et al., 1973).

Pillow lava : A general term for a lava with pillow structure formed in a subaqueous environment. Subaqueous equivalent of paheohoe lava (Truckle, 1979 etc.). A pillow lava is accumulation of pillow lobes.

Pillow lobe : A kind of mafic to intermediate subaqueous lava featured by cylinder or tube -shape. The surface is characterized by distinct glassy rind with ropy wrinkle, corrugation and spreading crack (Yamagishi, 1983, 1985).

Pipe vesicle : A tubular or cylinder-shaped vesicle arranged perpendicularly to the surface of a pahoehoe lava (Walker, 1987) or pillow lava (Moore and Schilling, 1973). This term was originally defined as a small tube projecting upward several centimeters from the base of a subaerial lava when the lava flows over wet ground, steam generates beneath the lava, and bubbles rise into the lava (Waters, 1960 ; Macdonald, 1967). However, the pipe vesicles in the pahoehoe lava are formed from magmatic gass exsolved from the interior of lava (Walker, 1987). The pipe vesicles in the pillow lobes are similarly produced by degassing from the interior of pillow.

Pseudo-pillow : A type of intermediate to felsic polyhedral block. It is characterized by even surface with tortoise-shell joints, which cross flow layers (Watanabe and Katsui, 1976). Commonly, the pseudo-pillow has not distinct glass margin, but tiny joints develop along the surface. Syn. pillow-like block (Yamagishi and Takahashi, 1975).

Pseudo-pillow lava : A type of intermediate to felsic lava consisting mostly of pseudo-pillows which are closely fitted with each other.

Pyroclastic pillow breccia : A coarse-grained mafic phreatomagmatic tuff composed of irregularly-shaped pillow fragments in a cogenetic matrix of vesiculated shards and granules (Dimroth et al., 1985). It is a product of phreatomagmatic pyroclastic activity. Syn. scoria pillows and scoria lapilli/bomb breccias (Staudigel and Schmincke, 1984). The fine-grained equivalent is defined as hyalotuff (Honnorez and Kirst, 1975) or scoriaceous vitric tuff (cfr. page 88).

Pyroclastic rock : A rock produced by explosive ejection of materials from a volcanic vent (Wentworth and Williams, 1932 ; Fisher, 1961, 1966).

Quench crystal : A microlite characteristic of the border zone of a subaqueous lava. It displays characteristic morphologies showing skeletal, dendritic and spherulitic forms (Dimroth and Lichtblau, 1979 et al.). It is formed by a crystal-liquid equilibrium (Lofgren, 1974) ; it grows rapidly in a large super-cooled viscous lava, combined with low-rate diffusion (Bryan, 1972).

Radial-columnar joint : A columnar joint arranged in a radial pattern. It is a kind of a cooling joint formed by contraction.

Ropy wrinkle : A surface structure diagnostic of subaerial pahoehoe lava. It is also found on a subaqueous pillow lobe (Yamagishi, 1983).

Scoria : A highly vesiculated juvenile fragment of mafic composition. It has dark brown or black color. Scoria ejected in subaqueous environment is fringed with distinct black glass covered with palagonite rind (Dimroth and Yamagishi, 1987).

Scoria pillow : A kind of irregular-shaped pillow, in places, with amoeboidal apophyses branching or mushroom-shaped protrusions (Staudigel and Schmincke, 1984).

Segregation vesicle : A vesicle in basalt lava lined with dark fine-grained material believed to represent residual melt which moved into early-formed vesicle before consolidation of the lava (Smith, 1967). Smith proposed that such vesicles are formed by increased confining pressure on a subaqueous lave flow moving into deeper water. However, Jones (1969) mentioned that there is no perceptible variation in development of the vesicles of Icelandic pillow lavas with depth, and that the expulsion of residual liquid into early-formed macrovesicles occurred during later vesiculation of the mesostasis.

Sheet flow : A thin-tabular lava formed by extremely rapid delivery of fluid lava in water (Ballard and Moore, 1977 ; Ballard et al., 1979).

Subaqueous pyroclastic rock : A pyroclastic rock formed by an explosion in a subaqueous environment (Dimroth and Yamagishi, 1987).

Subaqueous pyroclastic flow : A pyroclastic flow occurring in water. It is commonly composed of massive lower division and finer-grained bedded top. Three principal ways in which subaqueous pyroclastic flows are generated, are recognized (Fisher, 1984) ; a) hot pyroclastic flow entering from land into water (Francis and Howells, 1973 ; Yamada, 1973), b) pyroclastic flow developing from column collapse entirely in water (Fiske, 1963 ; Fiske and Matsuda, 1964). c) sediment gravity pyroclastic flows in water developed from slumping of unstable slopes consisting of pyroclastic debris.

Symmetric longitudinal spreading crack : A type of spreading crack of a pillow lobe. It displays several forms, such as V-shaped depression, fault sliver and minor graben. It is formed along the elongation and opens symmetrically (Yamagishi, 1985).

Symmetric transverse spreading crack : A type of spreading crack of a pillow lobe. The shape is similar to the symmetric longitudinal spreading crack. However, it is formed across the elongation of the pillow lobe (Yamagishi, 1985).

Spreading crack : Opening crack found on the solidified crust of a pillow lobe. It is formed during its growth (Moore, 1975 ; Moore and Lockwood, 1978 ; Yamagishi, 1983).

Subaqueous volcanic rock : A volcanic rock produced in subaqueous environment. It comprises not only lavas, but also fragmental rocks such as hyaloclastites, pyroclastic rocks and epiclastic volcanic rocks.

Subaqueous volcaniclastic rock : A clastic rock produced by subaqueous volcanic activity. It comprises hyaloclastite, pyroclastic rock and epiclastic volcanic rock.

Tensional crack : An open crack on the solidified crust of a pillow lobe. It is formed by inflation of the interior due to resupply of lava after cessation of the growth of the pillow lobe (Yamagishi, 1983).

Topset-bedded breccia : A primarily horizontal stratified breccia making up an upper deltaic complex ; it overlies or truncates foreset-bedded breccia (Dimroth et al., 1985 ; cfr. page 80).

Volcanic conglomerate : An epiclastic volcanic rock consisting mostly of rounded, coarse-grained volcanic materials (Fisher, 1961, 1966).

Volcaniclastic rock : A clastic rock consisting mostly of volcanic materials in whatever proportion (American Geological Institute, 1980). This term implies the entire spectrum of fragmental volcanic rocks formed by any mechanism or origin, and emplaced in any physiographic environment, or mixed with any other volcaniclastic type or with any non-volcanic fragment types in any proportion (Fisher, 1966).

V-shaped depression : A form of a spreading crack on a pillow lobe. It is a V-shaped groove with minor displacement (Fuller, 1932).

Vesicle : A cavity of variable shape in a lava. It is formed by entrapment of gas bubbles during solidification of the lava (American Geological Institute, 1980). The vesicles of pahoehoe lava and pillow lava are spherical or ellipsoidal. In contrast, those of of aa lava, concentric pillow, pseudo-pillow and lava lobe, are amoeboid or contorted (Macdonald, 1967 ; cfr. pages 70 and 77). This term is also used for bombs, scoriae, and other volcanic fragments.

Water-chilled bomb : A volcanic bomb showing characteristics of water quenching (Yamagishi, 1982 ; cft. page 87).

Water-chilled scoria : A scoria showing characteristics of water quenching (Dimroth and Yamagishi, 1987 ; cft. page 88).

III DESCRIPTIVE FEATURES OF THE NEOGENE SUBAQUEOUS LAVAS AND VOLCANICLASTIC ROCKS IN SOUTHWEST HOKKAIDO

This chapter is concerned with occurrence, morphological features and internal structures of subaqueous lavas and volcaniclastic rocks on the basis of the observations of typical examples at the localities shown in Fig. 2. The characteristic morphological features are summarized in Table 1.

Table 1 Morphological features of pillow lobe, concentric pillow, pseudo-pillow and lava lobe in the Neogene subaqueous volcanic rocks in Southwest Hokkaido

	PILLOW LOBE	CONCENTRIC PILLOW	PSEUDO-PILLOW	LAVA LOBE
ROCK TYPE	basalt, px andesite	basalt, px andesite	px andesite, ho andesite	px andesite, rhyolite
SIZE IN DIAMETER	a few tens cm to a few meters	a few tens cm	a few tens cm to a few meters	a few to ten meters
SHAPE IN THREE DIMENSION	cylinder, tube	ellipsoid, sphere	polyhedron, ellipsoid	ellipsoid
FEATURE OF SURFACE	ropy wrinkle corrugation, spreading crack	even	even, tortoise-shell joints	in-situ breccia
CHILLED MARGIN	thin glass, tiny joint	thin glass, concentric joint	tiny joint	thick glass, tiny joint
INNER JOINT	radial-columnar, tortoise-shell joint	none	radial-columnar, tortoise-shell joint	radial-columnar joint
FLOW LAYER	conformable to outer surface	none	oblique to outer surface	conformable to outer rim
AMOUNT OF VESICLES	abundant	common	rare or common	common
ARRANGE-MENT OF VESICLES	elongated, normal or in parallel to surface	sporadic, at random	oblique to outer surface	conformable to outer rim
SHAPE OF VESICLES	pahoehoe type	aa type	aa type	pahoehoe and aa types
ASSOCIATED HYALO-CLASTITE	(A)type	(A)type	(B)type	(A) and (B) types
ASSOCIATED FEEDER DYKE	apophysis-like type	apophysis-like type	massive type	lava lobe type

px: pyroxene, ho: hornblende

1. Subaqueous lavas

1.1. Pillow lobe

In Southwest Hokkaido, Neogene pillow lavas have been found in many places ; Oshoro (No. 5 in Fig. 2 ; Yamagishi, 1982), Furubiragawa (No. 8 in Fig. 2 ; Yamagishi, 1981), Kayanuma

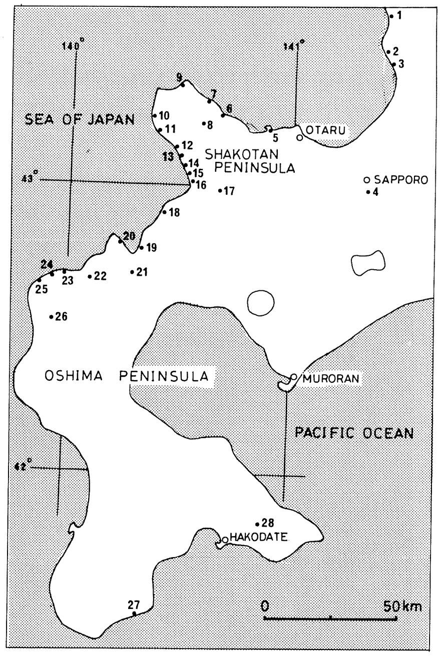

Fig. 2 Map showing localities and formation names of the Neogene subaqueous volcanic rocks in Southwest Hokkaido, described in this study. Name of formations is given with references.

1. Hamamasu, "Bishabetsu lava and agglomerate" of the Hamamasu Group (Hata and Yamaguchi, 1957), 2. Gokibiru, "Yasosuke agglomerate" of the Kita-Atsuta Group (Tsushima et al., 1956), 3. Ruran, Ibid., 4. Monami, the Monami Formation (Yamagishi and Takahashi, 1975), 5. Oshoro, "Upper agglomerate" of the Otaru Formation (Igi and Kakimi, 1954), 6. Seta-kamui, the Onenai Formation (Yamagishi, 1981), 7. Bikuni, Ibid., 8. Furubiragawa, the Furubiragawa Formation (Yamagishi, 1981), 9. Hizuka, the Onenai Formation, Ibid., 10. Kawashira, the Onenai Formation (Yamagishi and Ishii, 1979), 11. Sannai, the Volcaniclastic Rock Member of the Onenai Formation, Ibid., 12. Benzaima, the Kabuto Volcaniclastic Rock Member of the Tomari Group (Yamagishi et al., 1979), 13. Moiwa, Ibid., 14. Kabuto, Ibid., 15. Kayanuma, Ibid., 16. Tomari, Ibid., 17. Kunitomi, the Kunitomi Formation (Hasegawa and Osanai, 1978), 18. Raiden, the Raiden-misaki Volcanic Breccia Formation (Yamagishi et al., 1976), 19. Utasutsu, the Isoya Formation (Yamagishi, 1984), 20. Yamanaka, the Suttsu Formation (Suzuki et al., 1981), 21. Soibetsugawa, the Garogawa Volcanic Rocks (Yamagishi, 1984), 22. Guhnai, the Nagatoyo Formation (Suzuki et al., 1981), 23. Harauta, the Makomanai Volcanic Rocks (Yamagishi and Kurosawa, 1987), 24. Kimaki, the Kodanishigawa Formation Ibid., 25. Sakae-hama, Ibid., 26. Makomanaigawa, The Makomanai Volcanic Rocks, Ibid., 27. Iwabe, the Shiriuchi Volcanic Rocks (Yamaguchi, 1978), 28. Kakkumi, the Shiodomarigawa Formation (Suzuki et al., 1969).

(No. 15 in Fig. 2 ; Yamagishi et al., 1979), Kunitomi (No. 17 in Fig. 2 ; Hasegawa and Osanai, 1978), Yamanaka (No. 20 in Fig. 2 ; Suzuki et al., 1981), Soibetsugawa (No. 21 in Fig. 2 ; Yamagishi, 1984), Guhnai (No. 22 in Fig. 2), Harauta (No. 23 in Fig. 2 ; Yamagishi and Kurosawa, 1987), Kimaki (NO. 24 in Fig. 2 ; Yamagishi, 1983), Sakaehama (No. 25 in Fig. 2 ; Yamagishi, 1985), Makomanaigawa (No. 26 in Fig. 2 ; Yamagishi, 1983), and Kakkumi (No. 28 in Fig. 2 ; Baba, 1963).

The pillow lavas are usually a few to ten meters thick as mentioned by Yagi et al. (1976).

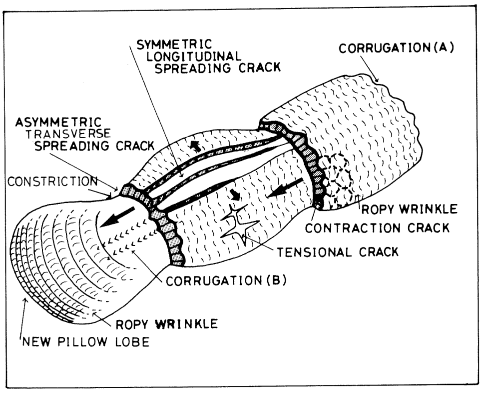

Fig. 3 Schematic model showing characteristic surface structures of pillow lobe. Arrows indicate spreading and flow directions.

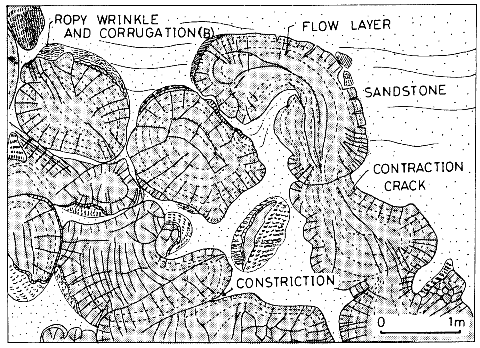

Fig. 4 Elongated pillow lobes exposed in three dimensions. Loc. Oshoro (No. 5 in Fig. 2). The surface is characterized by a combination of ropy wrinkle and corrugation (B), and constriction, while the interior by flow layers defined by vesicle arrangement, which is conformable to the surface of pillow lobe, and by contraction crack perpendicular to the surfaces.

Table 2 Chemical compositions of the Neogene pillow lobes in Southwest Hokkaido

	1	2	3	4	5
SiO_2	48.99	50.83	51.05	52.39	52.87
TiO_2	0.62	0.71	0.76	0.82	1.24
Al_2O_3	19.85	18.95	17.00	19.92	17.60
Fe_2O_3	3.91	3.87	1.74	3.24	4.13
FeO	4.87	5.46	5.79	4.90	4.07
MnO	0.10	0.14	0.11	0.12	0.14
MgO	3.66	3.90	8.44	3.16	3.39
CaO	11.48	11.29	6.01	9.27	8.47
Na_2O	2.23	2.14	5.28	2.50	3.57
K_2O	0.52	0.61	0.08	1.08	1.21
P_2O_5	0.12	0.19	0.13	0.25	0.37
$H_2O(+)$	1.57	1.14	3.38	1.20	1.95
$H_2O(-)$	2.05	0.87	1.00	1.41	1.22
Total	99.97	100.10	100.77	100.26	100.23

1. Basalt. Margin of pillow lobe. Loc. Nekodomari, Oshoro Penisnula (No. 5 in Fig. 2; Yamagishi, 1982), 2. Basalt. Core of pillow lobe. Loc. Nekodomari, Oshoro Peninsula (Ibid.), 3. Basalt. Pillow lobe. Loc. Kakkumi. (No. 28 in Fig. 2; Oba, Unpub.), 4. Pyroxene andesite. Core of pillow lobe. Loc. Oshoro Bay, Oshoro Peninsula (Yamagishi, 1982), 5. Olivine-bearing augite andesite. Pillow lobe. Loc. Yamanaka (No. 20 in Fig. 2; Okamura, 1986).

These lavas are overlain by, or intercalated with hyaloclastite and pyroclastic pillow breccia. They are basalt and basaltic andesite in chemical composition (Table 2).

The pillow lava is defined as accumulations of pillow lobes which are cylinder or tubular (Fig. 3 and 4). These pillow lobes are described in three dimensions as follows :

1.1.1. Surface structures

The surface structures characteristic of pillow lobes are represented by ropy wrinkle, corrugation, spreading crack, tensional crack and contraction crack (Figs. 3 and 5 ; Yamagishi, 1983). These surface structures are well preserved on the pillow lobes exposed in many localities.

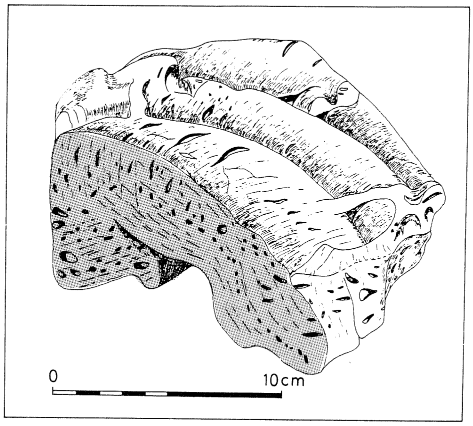

Fig. 5 Ropy wrinkles of a pillow lobe. Loc. Makomanai-gawa (No. 26 in Fig. 2). Tensional cracks are observed on the ropy ridge. Cross section displays pipe-vesicles near the margin.

Ropy wrinkle : It is characteristic of a subaerial pahoehoe toe (Macdonald, 1967). It has been pointed out that pahoehoe toe and pillow lobe have several common features and mode of formation (Jones, 1968 ; Truckle, 1979), and that pillow lobe is a subaqueous equivalent form of subaerial pahoehoe toe. The pillow lobe has, therefore, ropy wrinkles similar to those of pahoehoe toe (Fig. 3).

These wrinkles consist of convex-shaped ridges and V-shaped troughs which are less than a few centimeters in width and relief (Fig. 5). The ropy wrinkles are aligned almost

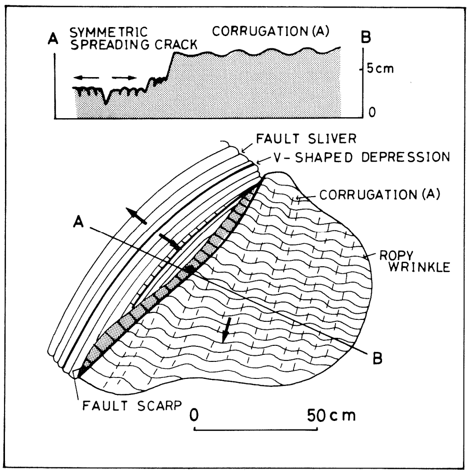

Fig. 6 Symmetric spreading crack on a pillow lobe. Loc. Oshoro (No. 5 in Fig. 2). It is composed of a V-shaped depression, fault slivers and fault scarp. The ropy wrinkle and corrugation (A) are arranged obliquely to the spreading crack. Arrows indicate spreading and flow direction.

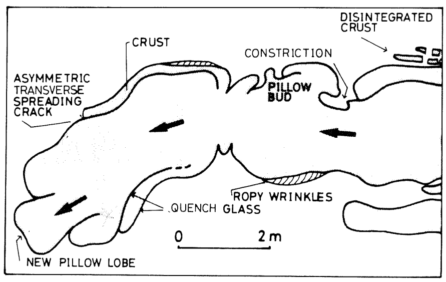

Fig. 7 Horizontal cross section of a pulsating pillow lobe. Loc. Sakaehama (No. 25 in Fig. 2). The pillow lobe is enveloped by crusts with quench glass on both inner and outer margins. Some of the crusts have been disintegrated. It is noted that constrictions develop in front of an asymmetric transverse spreading crack, and that a pillow bud and a new pillow lobe have grown through the crust. Ropy wrinkles develop perpendicularly to the elongation of the pillow lobe.

perpendicularly to the elongation of the pillow lobe (Figs. 6 and 7 ; Plates 1A and 2A). They slightly curve toward the front of the pillow lobe.

Corrugation : This is defined as wrinkles developing along the elongation of pillow lobe (Fig. 3 ; Moore, 1975). Apparently it is formed during the growth of a new pillow lobe.

Two types of the corrugations are observed on the Neogene pillow lobe ; one represents moderately waving wrinkles (Plate 1B), whose wavelength is usually a few centimeters ; whereas, the other has V-shaped grooves with various widths less than 1 cm (Plate 1C). The author defines the former and the latter as corrugation (A) and (B), respectively (Fig. 3 ; Yamagishi, 1983). Some pillow lobes show a combination of ropy wrinkles and corrugations, both of which are perpendicular to each other (Fig. 4 and 6 ; Plate 1D).

The corrugation (A) may be explained by convective roll of the fluid interior of the pillow lobe (Moore and Lockwood, 1978), whereas the corrugation (B) is scratching scars developed on a new pillow lobe, when lava drains through solidified crust.

Spreading crack : This is designated as opening crack formed on solidified crust of growing pillow lobe (Moore, 1975 ; Moore and Lockwood, 1978). In general, longitudinal and transverse types of spreading crack are recognized (Fig. 3 ; Yamagishi, 1985). The former develops along the elongation of the lobe, commonly showing minor grabens or V-shaped depressions (symmetric type), whereas the latter across the pillow lobe, displaying tiny fault scarps (asymmetric type) as well as minor grabens or V-shaped depressions (Yamagishi, 1983).

The spreading crack found on the Neogene pillow lobe at Oshoro is composed of V-shaped depression, fault slivers and tiny fault scarps (Fig. 6). It can be regarded as a longitudinal spreading crack because it is a symmetric spreading crack developed obliquely to the elongation of pillow lobe, which is defined by alignment of the corrugation (A).

Tensional crack : This is an opening crack formed on the solidified crust and caused by inflation due to resupply of the fluid interior after cessation of the growth of pillow lobe (Fig. 3 ; Yamagishi, 1973, 1983).

Some of the tensional cracks develop along or across the ropy wrinkles of the Neogene pillow lobes (Fig. 5), while the others are similar to bread-crust fractures (Fig. 8). The latter are represented by tiny grabens with quench glass at the bottom.

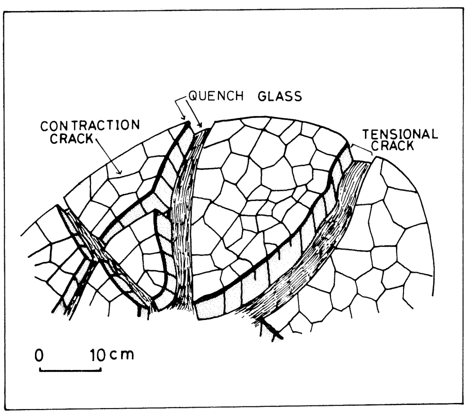

Fig. 8 Tensional and contraction cracks on a pillow lobe. Loc. Kimaki (No. 24 in Fig. 2). The former and the latter are defined by tiny grabens and tortoise-shell joints, respectively.

Contraction crack : This is represented by tortoise-shell joints on the surface of a pillow lobe (Figs. 3 and 8). The joints propagate inward into radial-columnar in joints cross section. It is formed by thermal contraction by water cooling after emplacement of a pillow lobe.

The contraction cracks on the surface of the Neogene pillow lobe are rare (Fig. 8) ; most of the cracks lie concealed under wrinkled rinds.

1.1.2. Internal structures

The joints, crust and vesicularity are the characteristic internal structure of pillow lobe.

Joint : The interior of most of the Neogene pillow lobes displays radial-columnar joints

(Fig. 4 and Plate 2B). Some of them, however, show irregular or tortoise-shell joints, and the others have not distinct internal joints as shown by pillow lavas from Kakkumi (Baba, 1963) and Furubiragawa (Yamagishi, 1981).

The margin of most of the pillow lobes is fringed with a layer of tiny joints developed perpendicularly to the surface.

Crust : Some pillow lobe shows a single crust or multiple ones on the margin (Yamagishi, 1985). Its crust is a few tens of centimeters thick and has distinct glass with tiny joints on both outer and inner margins.

As shown in Fig. 7, the single crust can be traced laterally for a few meters ; the end of the crust is marked by a tiny transverse scarp (asymmetric spreading crack). Some of the crusts have been separated from the pillow lobe, and has been disintegrated.

The multiple crusts envelope the interior of some pillow lobes (Plates 2A and B). One of the crusts has a surface with ropy wrinkles aligned perpendicularly to the elonation of the pillow lobe (Plate 2A).

Vesicularity : Pillow lobes have more or less vesicles in the interior. If other factors are

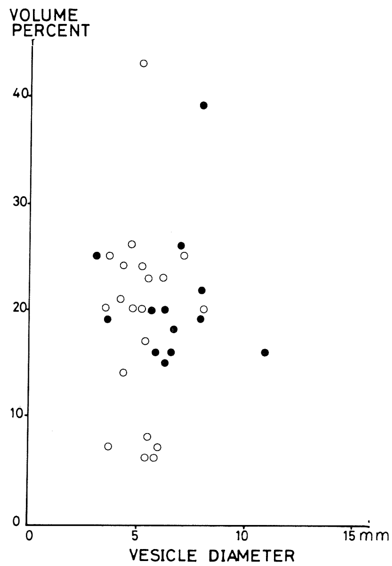

Fig. 9 Volume percent versus diameter of vesicles in pillow lobes and pillow fragments from the Suttsu Formation (Loc. Yamanaka, No. 20 in Fig. 2). Open circles : pillow lobes, solid circles : pillow fragments in hyaloclastite (A). Volume percent was measured by counting ca. 100 points by the use of a transparent plate with 5 mm grids. Diameter represents the average values of largest 10 vesicles. Spherical and ellipsoidal vesicles in the upper outer (5 cm from the surface of pillows) were measured, but pipe-vesicles were omitted.

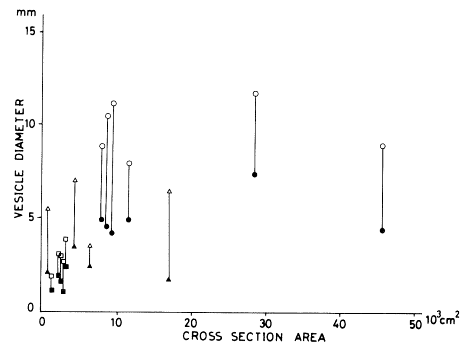

Fig. 10 Vesicle size versus cross section area of pillow lobes from Oshoro (circle ; No. 5 in Fig. 2), Kayanuma (triangle ; No. 15 in Fig. 2) and Harauta (square ; No. 23 in Fig. 2). Cross sections of pillow lobes nearly perpendicular to the flow direction were selected for measurement. The cross section area of a pillow lobe can be approximately obtained from π x 0.5 V x 0.5 H (V : Vertical axis, H : horizontal axis) if it is regarded as an ellipse. Solid symbols indicate the size of vesicles in the outer core of a pillow lobe ; open symbols that in the core. Lines connecting solid and open symbols indicate the same pillow lobe. The diameter represents the average values of 5 largest vesicles.

same, the extent of vesiculation depends largely on depth of water (Jones, 1969). Most of the Neogene pillow lobes in Southwest Hokkaido contain abundant vesicles. The arrangement of the vesicles defines flow layers of the interior, which are conformable to the surface of the pillow lobe (Fig. 4).

The vesicles in the core of the pillow lobe are spherical, whereas those in the outer core are ellipsoidal (pahoehoe type ; Macdonald, 1967). The size of the former is usually larger than that of the latter, whereas the number of the former is smaller than that of the latter.

The size of the vesicles in the outer core of the pillow lobes from Yamanaka (No. 20 in Fig. 2) is approximately 5—10 mm in diameter, while the volume of the vesicles ranges from 5 to 40% (Fig. 9). The vesicles in the core of the pillow lobes from Oshoro (No. 5 in Fig. 2), Kayanuma (No. 15 in Fig. 2) and Harauta (No. 23 in Fig. 2) reaches 12, 7 and 4 mm in diameter, respectively (Fig. 10). The diameter of the vesicles in both of the inner and outer core increases with size (cross section area) of the pillow lobe, suggesting that smaller pillow lobes are cooled too fast to permit sufficient coalescence of gas bubbles.

The pillow lobes exposed at Oshoro (No. 5 in Fig. 2) have abundant pipe-vesicles (Macdonald, 1967) in the outer core, which are arranged perpendicularly to the surfaces. The pipe vesicles measure 3—10 mm in width and 20—30 mm in length.

Microscopic petrography of pillow lobes : The Neogene pillow lobes in Southwest Hokkaido display aphyric or porphyritic texture. The aphyric pillow lobes are mostly basaltic and rarely distributed, although they are found at Furubiragawa, Kunitomi and Kakkumi. The margin of the pillow lobes is in places fringed with globules or shards, while the border zone of these pillow lobes shows varioritic texture. The core shows subophitic texture consisting of ceder-leave shaped crystals of pyroxene and plagioclase (Yagi et al., 1976).

Segregation vesicles (Smith, 1967) are observed in the basaltic pillow lobes from Furubiragawa (No. 8 in Fig. 2), Kunitomi (No. 17 in Fig. 2), Harauta (No. 23 in Fig. 2) and Makomanaigawa (No. 26 in Fig. 2).

The porphyritic pillow lobes are mostly andesitic and distributed dominantly in Southwest Hokkaido. They contain abundant phenocrysts of plagioclase and pyroxene. The groundmass ranges from intersertal or intergranular texture in the core, to hyalopilitic texture in the border zone of pillow lobes. Both of the core and border zone have microphenocrysts or microlites of lath-shaped plagioclase and grains of pyroxene.

Some of the microlites in the groundmass of the border zone occur as dendritic or fibrous overgrowths along the margin of microphenocrysts as shown in the pillow lobes from Guhnai (No. 22 in Fig. 2) and Yamanaka (No. 20 in Fig. 2 ; Plate 2C). These microlites are regarded as quench crystals (Bryan, 1972 ; Dimroth and Lichtblau, 1979). However, in the outer margin no such quench crystals are formed, but tabular-shaped microlites and microphenocrysts are set in a glass with curviplanar joints formed by contraction.

Most of the Neogene pillow lobes have more or less undergone palagonitization and/or hydrothermal alteration after emplacement. As a result of palagonitization, smectite clay has replaced the glass and filled some vesicles. Intense hydrothermal alteration has produced chrolite, epidote, calcite, quartz, zeolite, smectite and interstratified chrolite-montmorillonite. They have replaced particularly glass and mafic minerals and filled vesicles as shown in the pillow lobes from Furubiragawa (No. 8 in Fig. 2) and Harauta (No. 23 in Fig. 2) and Kunitomi (No. 17 in Fig. 2 ; Yagi et al., 1976) and Kakkumi (No. 28 in Fig. 2 ; Baba, 1963).

1.2. Lava lobe and pseudo-pillow lava

Other forms of the Neogene subaqueous lava in Southwest Hokkaido are represented by lava lobe (Furnes et al., 1980) associated with sheet flow (Ballard et al., 1979), and pseudo-pillow lava (Watanabe and Katsui, 1976).

Lava lobe : This form is one of characteristic occurrences of intermediate to felsic subaqueous lavas in Southwest Hokkaido. A typical lava lobe is composed of lithic core enveloped with glassy border zone which grades outward into hyaloclastite through in-situ breccia. The core has flow layers defined by arrangement of vesicles or phenocrysts, which are conformable to the glassy border zone. Three examples of the lava lobes are described here.

A remarkable exposure of subaqueous felsic lavas is found at Kawashira (No. 10 in Fig. 2). They intercalate hard shale beds of the Onenai Formation (Yamagishi and Ishii, 1979). These lavas comprise sheet flows and lava lobes, both of which are propagated from feeder dykes of elliptical-shape in plan view. These lavas are generated from glassy rims of the feeder dykes, and both of the lavas and feeder dykes are embedded in perlitic hyaloclastite (Plate 2D ; Figs. 11 and 12). The sheet flows and lava lobes grade outward into a perlitic hyaloclastite through a glassy in-situ breccia zone.

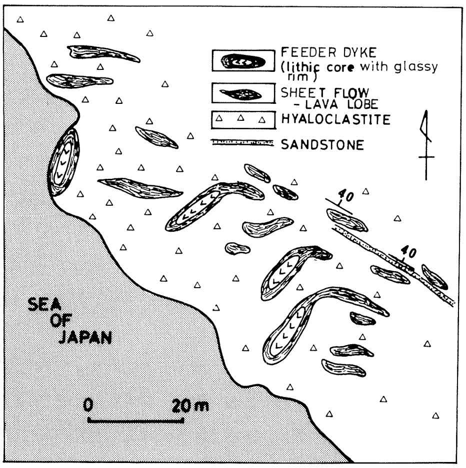

Fig. 11 Geologic sketch of an abrasion platform showing occurrence of rhyolitic subaqueous feeder dykes associated with sheet flows, lava lobes and hyaloclastites. Loc. Kawashira (No. 10 in Fig. 2).

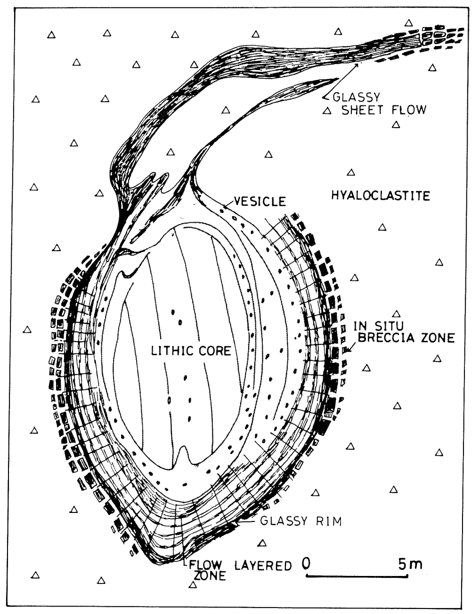

Fig. 12 Horizontal exposure of a rhyolite feeder dyke. Loc. Kawashira (No. 10 in Fig. 2). It is composed of lithic core, flow layer zone and glassy rim that grades outward into hyaloclastite through an in-situ breccia zone. Sheet flows are developed from the glassy rim.

The hyaloclastite intercalates sandstone beds and have a NW-SE strike which is regarded as a general trend in this area. On the other hand, the feeder dykes strike NE-SW (Fig. 11).

The feeder dyke consists of lithic core, flow layer zone, and glassy rim enveloped with the perlitic hyaloclastite. The lithic core has rude columnar joints and abundant large ellipsoidal vesicles.

Under the microscope, the lithic core includes 10% or more of plagioclase phenocrysts in a microfelsitic groundmass consisting of plagioclase and hypersthene, and interstitial anhedral quartz. The flow layer zone consists of alternation of obsidian and perlitic glass layers, and has radial joints. The glassy rim has undergone in-situ brecciation and is characterized by the presence of microlite needles in a glassy groundmass.

The perlitic hyaloclastite enclosing the feeder dykes consists of glassy fragments which are hydrated and partly replaced by clay minerals. The vesicles and perlitic cracks of the fragments, and interstices between the fragments, are filled with clay minerals and quartz grains. Columnar joints are in places observed in the hyaloclastite. This observation proves that the glassy fragments have been cemented at high temperature, since columnar joints can only form in a hot coherent material during its cooling.

Modal analysis of the feeder dyke and hyaloclastite shows decrease in microlites and increase in perlitic glass from the core to the hyaloclastite through the glassy rim, while phenocryst content remains almost constant (Fig. 13). Large phenocrysts of plagioclase in the core of the feeder dyke (A in Plate 3) are not fractured, but those in the flow layer zone (C in Plate 3) are weakly fractured. Plagioclase phenocrysts in the glassy rim (E in Plate 3) show in-situ brecciation, and further, those in the hyaloclastite are completely disaggregated (F in Plate 3).

Chemical compositions of the feeder dyke shown in Table 3 (Samples 3 to 5), indicate that it is classified as rhyolite and water content increases from the core to hyaloclastite through the glassy rim. When these compositions are recalculated on water-free basis, the glassy rim as well as hyaloclastite has been depleted in

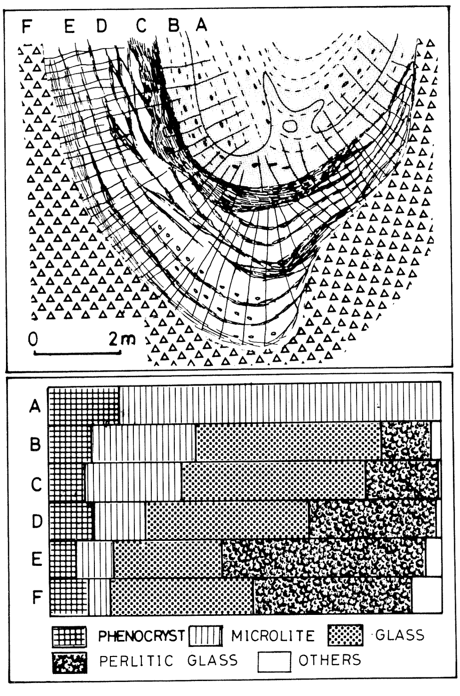

Fig. 13 Schematic sketch of a horizontal section of a rhyolite feeder dyke and modal compositions. Loc. Kawashira (No. 10 in Fig. 2). A: lithic core, B to E: flow layer zone and glassy rim, F: hyaloclastite. Approximately 500 points were counted on a thin section from each zone.

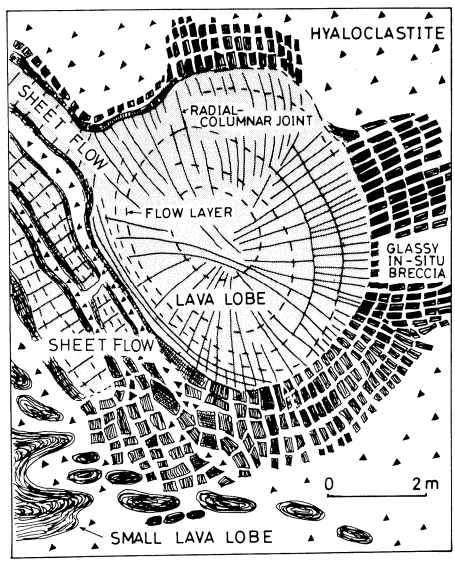

Fig. 14 Vertical exposure of a lava lobe of pyroxene andesite developed from a sheet flow. Loc. Ruran (No. 3 in Fig. 2). The core with radial-columnar joints grades outward into hyloclastite through glassy in-situ breccia.

silica and sodium, and slightly enriched in aluminium, manganese and iron, relatively to the lithic core of the feeder dyke.

High water content in the glassy rim and hyaloclastite is presumably caused by penetration of external water into felsic magma (Marshall, 1961 ; Ross and Smith, 1955 ; Taniguchi, oral comminucation).

The second example of lava lobe associated with sheet flows is exposed at Ruran, north of Atsuta (Fig. 14 ; No. 3 in Fig. 1). It is a part of subaqueous lavas and hyaloclastites corresponding to the "Yasosuke agglomerate" of the Kita-Atsuta Group (Tsushima et al., 1956).

Three steeply inclined sheet flows overlie splitted lava tongues which are arranged in a line of gentle dip. Each of the sheet flows has columnar joints and thick glassy margin, and is one meter thick. The toes of the lower two sheet flows have undergone in-situ brecciation, whereas the end of the upper one has been notably inflated into a lava lobe (Fig. 14).

The lava lobe shows elliptical shape in exposure and consists of a lithic core and glassy border zone. The lithic core is characterized by radial-columnar joints and flow layers conformable to the outer surface. The glassy border zone has undergone in-situ brecciation (glassy in-situ breccia) and grades outward into hyaloclastite. The matrix of the hyaloclastite has been partly altered into smectite clay.

Microscopically, the lava lobe is a porphyritic rock charged with abundant phenocrysts (30-40 vol. %) of plagioclase and pyroxene set in a hyalopilitic groundmass which contains

Table 3 Chemical compositions of the Neogene intermediate to felsic subaqueous lavas and hyaloclastites.

	1	2	3	4	5
SiO_2	57.40	57.06	74.54	69.65	66.35
TiO_2	0.71	0.64	0.28	0.31	0.33
Al_2O_3	15.74	15.61	12.96	14.09	14.69
Fe_2O_3	3.92	3.12	0.68	0.91	1.78
FeO	5.37	6.14	0.82	1.18	0.54
MnO	0.14	0.15	0.01	0.03	0.08
MgO	2.30	2.30	0.12	0.74	0.25
CaO	7.85	7.49	1.11	1.32	1.53
Na_2O	2.65	2.58	4.31	3.12	3.22
K_2O	1.20	1.17	3.82	2.70	3.29
P_2O_5	0.24	0.18	0.07	0.07	0.08
$H_2O(+)$	1.61	3.78	0.73	4.50	4.54
$H_2O(-)$	0.33	0.10	0.36	0.92	3.53
Total	99.46	100.32	99.81	99.81	100.21

1. Pyroxene andesite. Core of lava lobe. Loc. Ruran. (No. 3 in Fig. 2), 2. Pyroxene andesite. Glassy in-situ breccia of the lava lobe (Ibid.), 3. Rhyolite. Core (A zone) of the feeder dyke. Loc. Kawashira, No. 10 in Fig. 2), 4. Rhyolite. Glassy rim (C zone) of the feeder dyke (Ibid.), 5. Rhyolite. Hyaloclastite (F zone) enveloping the feeder dyke (Ibid.) Analyst; Y. Oba.

plagioclase needles, and pyroxene grains.

Chemical compositions of the lava lobe represent andesite (Samples 1 and 2 of Table 3). Water content increases from the core to the glassy in-situ breccia.

The third example of lava lobe crops out at Oshoro (Fig. 15 ; No. 5 in Fig. 1). It is a part of subaqueous lava of porphyritic pyroxene andesite, which corresponds to the "Upper agglomerate" of the Otaru Formation (Igi and Kakimi, 1954). The lava lobe is elongated, 5 m thick and 10 m across. It is characterized by rude columnar joints, and distinct flow layers conformable to the surface. The columnar joints propagate outward into glassy in-situ breccia which grades further into hyaloclastite. It consists of polyhedral and ellipsoidal blocks, and angular fragments.

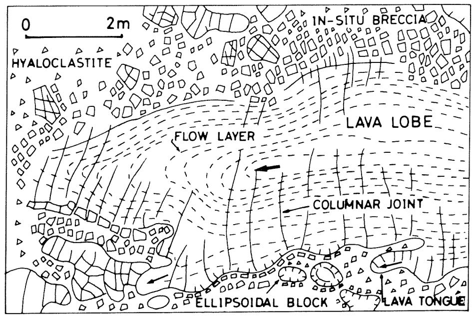

Fig. 15 Vertical exposure of a lave lobe of pyroxene andesite. Loc. Oshoro (No. 5 in Fig. 2). Note that flow layers are conformable to the surface and rude columnar joints develop perpendicularly to it, and that the margin grades outward into hyaloclastite. Lava tongues diverge from the base of the lava lobe into hyaloclastite. Arrows show flow direction.

The in-situ breccia grades from the upper surface of the lava lobe into the overlying hyaloclastite, and lava tongues (De Rosen-Spence et al., 1980) protrude down into the underlying hyaloclastite through in-sitû brecciation. The advance direction of the lava lobe can be determined by that of the lava tongues (Fig. 15).

Pseudo-pillow lava : The felsic lavas showing pseudo-pillow structure are rare in Southwest Hokkaido. An example of pseudo-pillow lava is found at Sannai (No. 11 in Fig. 2). It is andesite and included in the Volcaniclastic Rock Member of the Onenai Formation (Yamagishi and Ishii, 1979).

The pseudo-pillow lava consists of polygonal blocks of a few to several tens centimeters or more in size, and they grade upward into hyaloclastite (B) mentioned later. The large

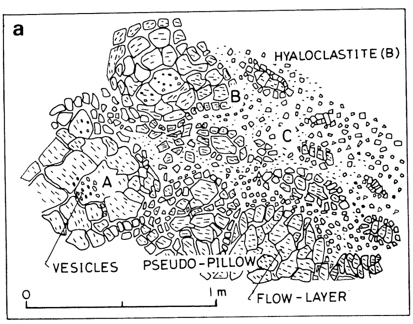

Fig.16a Vertical exposure of pseudo-pillow lava of andesite. Loc. Sannai (No. 11 in Fig. 2). Note that most of the polyhedral blocks are bounded by joints which obliquely cross the flow layers, although some blocks have conformable flow layers.

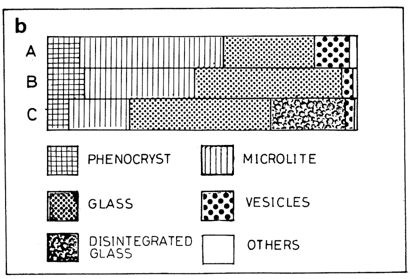

Fig. 16b Modal compositions of the left-handed pesudo - pillows. A : core, B : jointed margin, C : hyaloclastite. Approximately 500 points were counted on a thin section from each part.

polygonal blocks are closely fitted with each other, whereas the small ones are scattered in hyaloclastite (Fig. 16a).

This lava has flow layers defined by rows of elongated vesicles. Most of the flow layers are cut by joints, some of which outline the polygonal blocks. In places, some of the flow layers are conformable to the outline of the block. The interior of the block is characterized by tortoise-shell joints. The core of the block is dominated by spherical to ellipsoidal vesicles up to 1 cm across (A in Fig. 16a), while the margin by glass with tiny joints (B in Fig. 16a). The margin grades outward into the hyaloclastite.

The pseudo-pillow lava from Sannai contains a few phenocrysts (about 10 vol. %) of plagioclase in a hyalopilitic groundmass which consists of plagioclase and pyroxene microlites (20—40 vol. %) set in a palagonitized glass (Fig. 16b). Plagioclase and pyroxene microlites decrease in volume and glass increases from the core to hyaloclastite through the margin. Curviplanar cracks have disintegrated the margin resulted into formation of the hyaloclastite.

The subaqueous lava at Sannai is regarded as a pseudo-pillow lava with respect to jointing, although it occurs as a lava lobe enveloped with a glassy jointed margin which grades outward into hyaloclastite, and vesicles are concentrated in the core.

2. Hyaloclastites

Hyaloclastites occupy the largest part of the Neogene volcaniclastic rocks in Southwest Hokkaido. In particular, they predominate in the northen regions of the Oshima Peninsula.

The author divided them into hyaloclastites (A) and (B) ; the former consists mostly of ellipsoidal blocks with glassy rinds (pillows), while the latter comprises angular fragments (Yamagishi, 1979 ; Yamagishi et al., 1979).

2.1. Structural features of hyaloclastites

2.1.1. Hyaloclastite (A)

It is a monogenetic volcanic breccia which is massive or shows faint stratification with grading. It is composed of pillows and/or broken pillow fragments set in a matrix of fine-grained cogenetic tuff (Plate 4A). The volume of the pillows and their fragments is equal to or more than that of the matrix. The composition of hyaloclastite (A) is commonly basalt or pyroxene andesite.

Most of the hyaloclastites grade laterally into lava tongues or fingers of apophysis-like feeder dykes although some of the hyaloclastites occupy the top of a pillow lava sequence, as mentioned later. The pillows of the former hyaloclastites have concentric joints along the glassy margin, which are called concentric pillows (Yamagishi et al., 1979 ; Yamazaki and Shuto, 1986), while the latter ones have ropy wrinkles and/or corrugations on the surfaces, both of them are observed on a pillow lobe mentioned already.

The concentric pillow is ellipsoidal or spherical in shape and a few tens centimeters across. Contorted large vesicles (aa type ; Macdonald, 1967) are sporadically distributed in the interior (Fig. 17). They range in size from a few millimeters to 1cm, and have a tendency to increase in size with the pillow size (Fig. 18). The vesicles in the margin are rarely present and they are less than a few millimeters across. The concentric pillows from Benzaima (No. 12 in Fig. 2) are strongly porphyritic and contain abundant phenocrysts (30—40 vol.%) of plagioclase and pyroxene set in a hyalopilitic to intersertal groundmass. It shows a wide variation in crystallinity from lithic core to glassy margin. Namely, the content of quench crystals, such as fibrous and dendritic overgrowths on the microlites, increases toward the core. However,

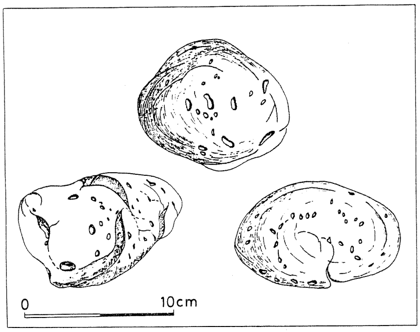

Fig. 17 Concentric pillows from hyaloclastite (A) of basaltic andesite. Loc. Benzaima (No. 12 in Fig. 2).

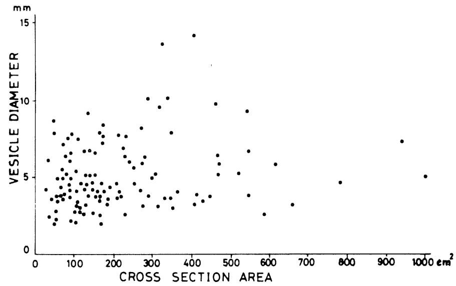

Fig. 18 Vesicle size versus cross section area of concentric pillows from various localities in Southwest Hokkaido. Localities: Oshoro (No. 5 in Fig. 2), Benzaima (No. 12), Moiwa (No. 13), Kabuto (No. 14), Kayanuma (No. 15 in Fig. 2) and Utasutsu (No. 19 in Fig. 2). The cross section area of a concentric pillow can be approximately obtained from π x 0.5 a x 0.5 b (a: long axis, b: short axis). The size of vesicles represents the average diameter of largest 5 vesicles for each hand specimen.

the content of phenocrysts remains almost constant throughout the concentric pillow. Small fractures appear in the glassy margin from which an in-situ breccia grades outward into fine-grained hyaloclastite. Large concentric pillows are similar to isolated small lava lobes mentioned above. The hyaloclastite containing small lava lobes, therefore, can be classified as (A) type.

A concentric pillow from Benzaima is pyroxene basalt in chemical composition (Sample 1 in Table 4).

Table 4 Chemical compositions of the Neogene mafic to intermediate hyaloclastites in Southwest Hokkaido

	1	2	3	4	5
SiO_2	51.22	56.86	56.94	59.81	61.68
TiO_2	0.87	0.95	0.91	0.66	0.62
Al_2O_3	16.89	17.55	17.01	17.31	16.25
Fe_2O_3	2.91	2.26	2.58	3.20	2.71
FeO	4.94	5.46	4.19	2.62	3.24
MnO	0.14	0.16	0.15	0.13	0.13
MgO	5.77	3.01	3.38	2.28	2.25
CaO	10.05	6.85	7.58	5.30	5.11
Na_2O	2.88	3.17	3.26	3.10	3.09
K_2O	0.90	1.64	1.68	2.30	2.32
P_2O_5	0.39	0.28	0.21	0.42	0.18
$H_2O(+)$	1.68	1.57	1.43	1.68	1.38
$H_2O(-)$	0.92	0.24	0.41	0.69	0.50
Total	99.56	100.00	99.73	99.50	99.46

1. Pyroxene basalt. Concentric pillow in a hyaloclastite (A). Loc. Benzaima (No. 12 in Fig. 2), 2. Pyroxene andesite. Angular block in a hyaloclastite (B). Loc. Kabuto (No. 14 in Fig. 2), 3. Pyroxene andesite. Pseudo-pillow in a hyaloclastite (B). Loc. Seta-kamui (No. 6 in Fig. 2), 4. Hornblende andesite. Pseudo-pillow in a hyaloclastite (B). Loc. Bikuni(No 7 in Fig. 2), 5. Hornblende andesite. Pseudo-pillow in a hyaloclastite (B). Loc. Hizuka (No. 9 in Fig. 2). Analyst; Y. Oba.

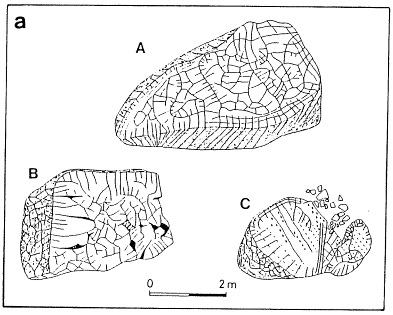

Fig. 19a Pseudo-pillows of hornblende andesite. A and B from Bikuni (No. 7 in Fig. 2) and C from Hizuka (No. 9 in Fig. 2).

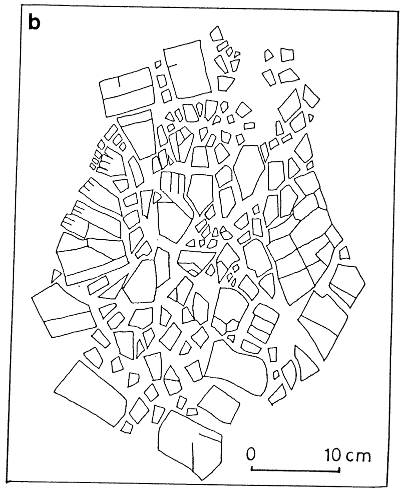

Fig. 19b Jigsaw breccia of hornblende andesite assembled into a pseudo-pillow. Loc. Tomari (No. 16 in Fig. 2). Neither flow layers nor chilled glass are observed.

The matrix of hyaloclastite (A) consists of lapilli- and ash-sized glassy fragments of polyhedral shape, most of which have vesicles and irregular joints. They are bounded by curved or curviplanar surfaces with disrupted vesicles. Microscopically, the fragments of the matrix have glassy groundmass with or without quench crystals. Most of the glass have been replaced by smectite clay due to palagonitization.

The fragments are similar in petrographical feature to the margin of the concentric pillows, suggesting that the fragments have been spalled off from the concentric pillows and disaggregated into fine-grained fragments by contraction jointing.

2.1.2. Hyaloclastite (B)

It is a monogenetic volcanic breccia which is massive or shows stratification with grading. It is associated with sheet flows, lava lobes and pseudo-pillow lavas. It consists of angular fragments in a cogenetic tuff (Plate 4B) and ocassionally includes pseudo-pillows (Fig. 19a). In places, the angular fragments can be assembled into a pseudo-pillow likely to a jigsaw puzzle (Fig. 19b). The content of the fragments is equal to or more than that of the matrix. It is commonly intermediate to felsic rock.

The pseudo-pillow is a polyhedral block of a few meters across, which is characterized by radial or columnar joints perpendicular to the surface (Fig. 19a). The margin has tiny joints developing also perpendicularly to the surface. Distinct glassy rim is usually absent. Tiny joints also develop along the radial or columnar joints which result in formation of small pseudo-pillows. The flow layers defined by arrangement of crystals and/or vesicles are commonly cut by the outer surface or inner joints. The surface of the pseudo-pillow is usually even and characterized by tortoise-shell joints which propagate into the radial or columnar joints in the interior ; it is regarded as the joint plane by which the pseudo-pillow is produced. Therefore, the surface of the pseudo-pillow is essentially different from that of the pillow lobe mentioned already.

Microscopically, the pseudo-pillows from Bikuni (No. 7 in Fig. 2) are porphyritic hornblende andesite and contain abundant phenocrysts of plagioclase, hornblende, pyroxene, quartz and biotite, set in a hyalopilitic groundmass composed of acicular to dendritic microlites of plagioclase in a perlitic glass. Some of the pseudo-pillows from Monami (No. 4 in Fig. 2; Yamagishi and Takahashi, 1975) are aphyric dacitic rocks, including acicular to dendritic microlites of plagioclase and pyroxene in a microfelsitic or quartzo-feldspathic groundmass.

The fragments of hyaloclastite (B) are classified as intermediate rocks in terms of chemical compositions (Samples 2 to 5 in Table 4).

The fine-grained fragments of the matrix have flat or curviplanar surface (Plate 4C; No. 19 in Fig. 2). Under the microscope, these fragments are more glassy than large fragments or pseudo-pillows.

2.2. Occurrence and sedimentary structure of hyaloclastite

The Neogene hyaloclastites in Southwest Hokkaido show characteristic occurrences and sedimentary structures. In this section, transition from pillow lava to hyaloclastite and common features of sedimentary structure of the hyaloclastite are described.

Transition from pillow lava to hyaloclastite: Hyaloclastites of basalt and basaltic andesite are often underlain by thin pillow lavas. The author has recognized several exposures showing transition from pillow lava to hyaloclastite at Yamanaka (Fig. 20; No. 20 in Fig. 2), Furubiragawa (Fig. 21a; Yamagishi, 1981), Kayanuma (Fig. 21b; Yamagishi et al., 1979), Sakaehama (Yamagishi and Kurosawa, 1987.) and Kakkumi (Baba, 1963).

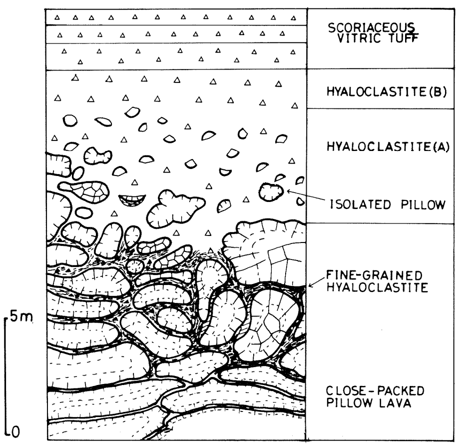

Fig. 20 A sequence from close-packed pillow lava to scoriaceous vitric tuff through hyaloclastites (A) and (B). Loc. Yamanaka (No. 20 in Fig. 2).

A typical example is exposed at Yamanaka where a vertical sequence from close-packed pillow lava (Carlisle, 1963) to scoriaceous vitric tuff through hyaloclastites (A) and (B) is observed (Fig. 20). This sequence corresponds to the Suttsu Formation (Suzuki et al., 1981).

The pillows in the lower portion of the close-packed pillow lava are considerably elongated and flattened, whereas those in the upper portion are ellipsoidal or spherical in shape, and those in the hyaloclastite (A) have been broken into watermelon-slice shaped fragments. The pillows in the pillow lava and hyaloclastite (A) have conspicuous ropy wrinkles and/or corrugations (Plate 2B). The size of the pillows remarkably decreases upward; the pillows in the close-packed pillow lava are up to a few meters across, whereas those in the hyaloclastite (A) are several tens centimeters across.

The hyaloclastite (B) overlying the hyaloclastite (A) consists of monolithologic breccia of the same rock type as the hyaloclastite (A) and pillow lava. The scoriaceous vitric tuff is parallel-laminated and consists mostly of lapilli- and ash-sized fragments and shards, all of which have abundant vesicles.

Similar transitional features are observed in the exposures at Furubiragawa (Fig. 21a) and Kayanuma (Fig. 21b). The former exposure shows transition from close-packed pillow lava to hyaloclastite (A), while, the latter consists of close-packed pillow lava, hyaloclastites

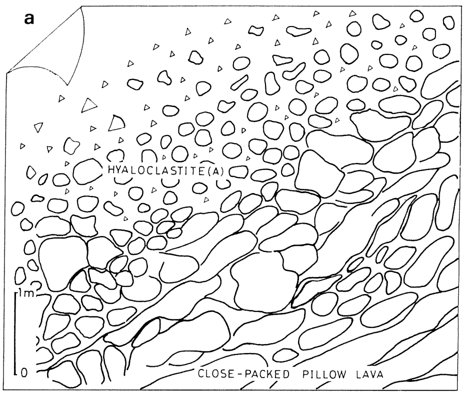

Fig. 21a Transition from close-packed pillow lava to hyaloclastite (A) of aphyric basalt. Loc. Furubiragawa (No. 8 in Fig. 2).

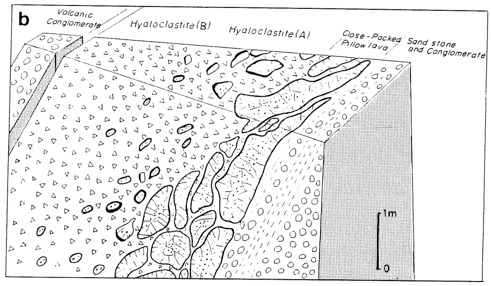

Fig. 21b Transition from close-packed pillow lava to hyaloclastite (B) through hyaloclastite (A) of porphyritic basaltic andesite. Loc. Kayanuma (No. 15 in Fig. 2).

(A) and (B) in ascending order.

Sedimentary structures of hyaloclastite: Several excellent exposures of hyaloclastite showing remarkable sedimentary structures are found at Hamamasu (No. 1 in Fig. 2), Kabuto (No. 14 in Fig. 2), Gokibiru (No. 2 in Fig. 2), Moiwa (No. 13 in Fig. 2) and Raiden (No. 18 in Fig. 2; Yamagishi, 1987) in Southwest Hokkaido.

Pyroxene andesitic hyaloclastite (B) of the "Bishabetsu lava and agglomerate" of the Hamamasu Group (Hata and Yamaguchi, 1957), exposed on a vertical cliff at Hamamasu (No. 1 in Fig. 2), is a subaqueous deltaic sediment (Fig. 22, Plate 4D; Dimroth et al., 1985). The hyaloclastite is divided into lower and upper parts. The lower part consists of stratified hyaloclastite beds dipping of 20°—30° N. Each bed is less than 1 m thick and shows remarkable reverse grading. Toward the south, the stratified hyaloclastite grades into massive one. The upper part is made up of disintegrated sheet flows (Ballard et al., 1979) associated with hyaloclastite. Toward the north, the sheet flows are disintegrated into hyaloclastite and rest on the underlying stratified hyaloclastite which shows steep inclination toward the north. The lower part of the exposure corresponds to foreset-beds, while the upper part to topset-beds (Fuller, 1931). Namely, these hyaloclastites are considered to be subaqueous deltaic deposits prograding toward the north.

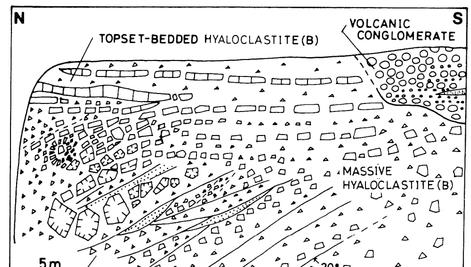

Fig. 22 Outcrop showing foreset-beds of hyaloclastite overlain by topset-beds of disintegrated sheet flow and hyaloclastite. Loc. Hamamasu (No. 1 in Fig. 2).

The Kabuto Volcaniclastic Rocks of the Tomari Formation (Yamagishi et al., 1979), which are well exposed at Kabuto Beach, Shakotan Peninsula (No. 14 in Fig. 2), represent a notable succession of pyroxene andesitic hyalolastite interbedded with layers of pyroclastic pillow breccia (Figs. 23 and 24). Several hyaloclastite beds make up a deltaic sequence unit that is discernible by difference of rock type, structural features and directions of strike. Each

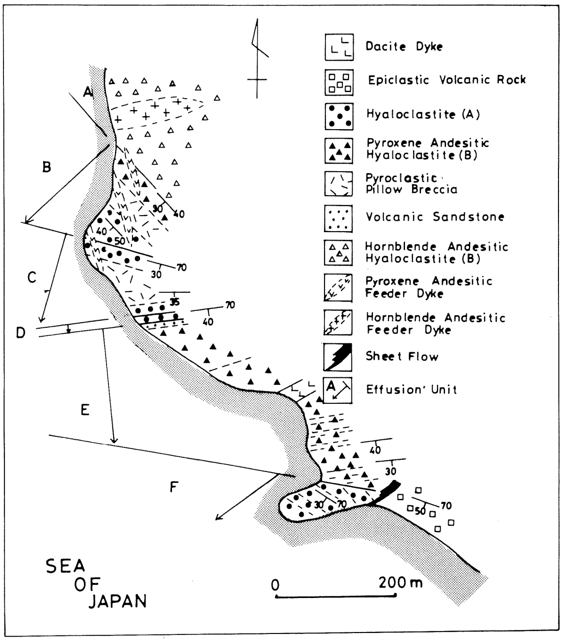

Fig. 23 Map showing an occurrence of hyaloclastites ineterbedded with pyroclastic pillow breccias and sheet flows. Deltaic sequence units (A to F) are discernible by difference in rock type, structural features and direction of strikes. Loc. Kabuto (No. 14 in Fig. 2). The columnar section is shown in Fig. 24.

hyaloclastite bed is a few meters to 10 m thick and shows reverse or reverse-to-normal grading. The deltaic sequence implies a pile of hyaloclastite beds formed by foreset bedding in one direction for a relatively short time.

The top of the succession (Units E and F in Figs. 23 and 24) is composed of hyaloclastite (B) (Unit E) and (A) (Unit F). The Unit E is made up of normal-graded hyaloclastite in the lower part, and parallel-laminated one in the upper part. The Unit F exhibits transition from massive hyaloclastite to foreset-bedded one.

The occurrence of Unit F is as follows. A sheet flow extruded from a feeder dyke overlies the massive hyaloclastite. Attenuated sheets and fingers diverge from the base of the sheet flow and then pass down into the massive hyaloclastite through in-situ breccia (Figs. 25 and 26a). The massive hyaloclastite grades laterally into the foreset-bedded one striking N40° W and dipping 40°S. Each foreset-bed is a few meters thick and shows reverse-to-normal grading. It scoured underlying bed one after another and was emplaced in an onlap manner ; it corresponds to a debris flow of hyaloclastite sweeping down on a slope. Laminated sandstone was deposited during the quiescence of the debris flow (Fig. 25 and 26b). The foreset-bedded hyaloclastite is overlain by topset-bedded hyaloclastite striking N70°W and dipping 30°S. Each topset-bed is more than 5 m thick and does not show distinct grading. The foreset-bedded hyaloclastite is underlain by a top of the Unit E, corresponding to parallel-laminated hyaloclastite (B) striking EW and dipping 20°S (Plate 5A).

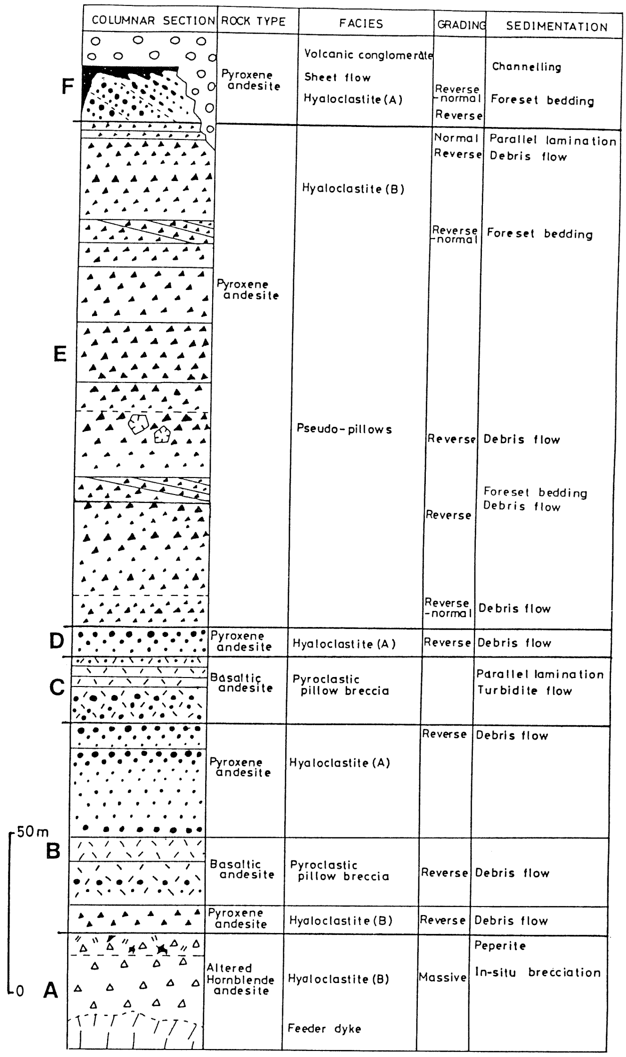

Fig. 24 A columnar section of the hyaloclastites interbedded with pyroclastic pillow breccias and a sheet flow shown in Fig. 23. Loc. Kabuto (No. 14 in Fig. 2). Capital letters indicate deltaic sequence units of the hyaloclastite.

Other examples are observed on vertical exposures of the "Yasosuke agglomerate" of the Kita-Atsuta Group (Tsushima et al., 1956) at Gokibiru (No. 2 in Fig. 2) and the Kabuto Volcaniclastic Rock Member (Yamagishi et al., 1979) at Moiwa (No. 13 in Fig. 2). Both of them are of pyroxene andesite, and show lateral transition from feeder dykes to foreset-bedded hyaloclastite through massive one. The foreset-bedded hyaloclastite steeply dips. Each hyaloclastite bed is up to 10 m thick and displays usually reverse grading (Plates 5B and C). The interstices among the large fragments at the top of each bed are filled with parallel-laminated sandstone. At Gokibiru, four feeder dykes are surrounded by massive and foreset-

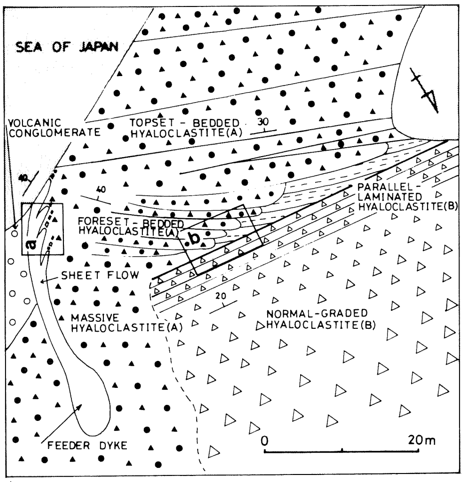

Fig. 25 Map showing a horizontal exposure of the deltaic sequence unit F in in Figs. 23 and 24. Loc. Kabuto (No. 14 in Fig. 2). Details of quadrangle areas (a) and (b) are shown in Fig. 26.

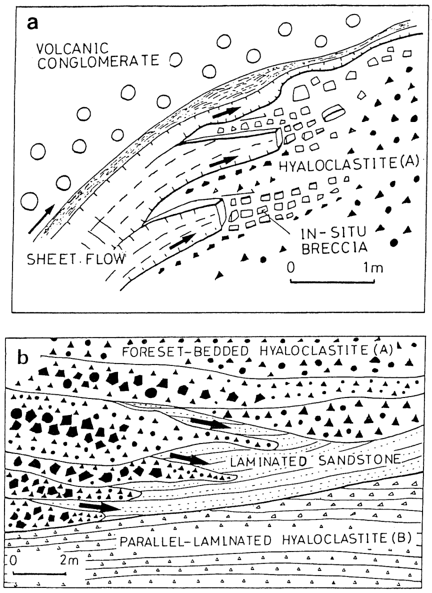

Fig. 26 Detailed sketch of Fig. 25. a : A sheet flow showing in-situ brecciation diverges into hyaloclastite. It is overlain by a volcanic conglomerate. b : Foreset-bed of hyaloclastite (A) scoured underlying bed one after another and was emplaced in an onlap manner ; each bed corresponds to a debris flow. Laminated sandstone was deposited during the quiescence of the debris flow. The piles of the foreset-bedded hyaloclastite (A) overlie parallel-laminated hyaloclastite (B). Arrows indicate the direction of flowing of the debris flow.

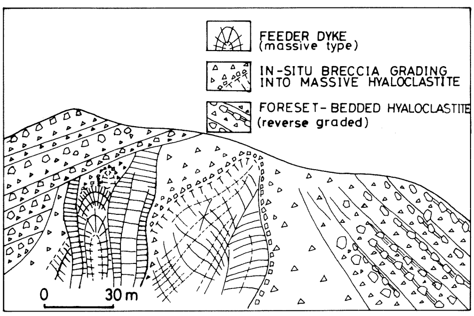

Fig. 27 Vertical exposure of a complex of feeder dykes and hyaloclastites (B). Loc. Gokibiru (No. 2 in Fig. 2). Note that the feeder dykes of massive type grade outward into massive hyaloclastite through in-situ breccia. The massive hyaloclastite grades further into foreset-bedded hyaloclastite. Another stratified hyaloclastite has truncated the complex. N : north, S : south.

bedded hyaloclastites (Fig. 27). The largest feeder dyke is inclined 10°—20° toward the south and grades outward into massive hyaloclastite through in-situ breccia. The massive hyaloclastite grades further into the foreset-bedded one which dips 40°—50° S. On the north side of the feeder dykes, the complex composed of the massive hyaloclastite and their feeder dykes has been truncated by another foreset-bedded hyaloclastite dipping 20°—30° N (Fig. 27).

The common features of the sedimentary structures of the andesitic hyaloclastites described in this section, are summarized as follows. a) There exists lateral transition from feeder dykes to a stratified hyaloclastite through massive one. b) Stratified hyaloclastites are made up of foreset-beds and in places topset-beds. They are, therefore, regarded as a subaqueous deltaic deposit. c) Each bed of the stratified hyaloclastite is a debris flow deposit as evidenced by reverse or reverse-to-normal grading.

3. Feeder dykes

The conduit through which magma passes from the magma chamber to some localized intrusion is a feeder dyke (American Geological Institute, 1980). The Neogene hyaloclastites in Southwest Hokkaido are commonly accompanied with feeder dykes of a few meters to 10 m across. They are divided into apophysis-like type, massive type, lava lobe type and clastic type.

3.1. Feeder dykes of apophysis-like type

The feeder dykes of apophysis-like type (Yamagishi, 1982) are mostly basaltic andesite and pyroxene andesite. They are meandering apophyseal intrusions from which lava tongues and fingers are propagated. They grade laterally and vertically into hyaloclastite (A) consisting mostly of concentric pillows. The feeder dykes of this type are exposed at Oshoro (No. 5 in Fig. 2), Kayanuma (No. 15 in Fig. 2), Iwabe (No. 27 in Fig. 2) and Utasutsu (No. 19 in Fig. 2 ; Yamagishi, 1984).

The feeder dykes exposed at Oshoro are accompanied with minor normal faults on both sides, which are conjugated with each other (Yamagishi, 1982). Some of the dykes were intruded forcibly into unconsolidated sediments along the faults (Fig. 28). They were subjected to disaggregation, inflation and bulbous budding during intrusion.

The feeder dykes found at Kayanuma (Fig. 29a) and Iwabe (Fig. 29b) are associated with lava tongues and fingers. Both of them have curved joints perpendicular or oblique to the elongation, by which they have been disintegrated into concentric pillows (Plate. 5D).

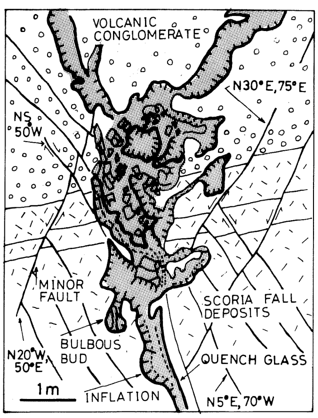

Fig. 28 Vertical exposure of an irregular-shaped feeder dyke of apophysis-like type, intruding forcibly along minor conjugated faults. Loc. Oshoro (No. 5 in Fig. 2). It shows bulbous budding and inflation in the lower portion and disaggregation in the middle.

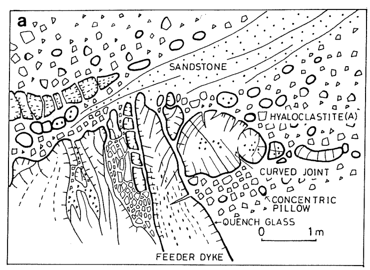

Fig. 29a Vertical exposure of a feeder dyke of apophysis-like type. Loc. Kayanuma (No. 15 in Fig. 2). Note that a lava tongue extended from the dyke has been splitted into concentric pillows.

3.2. Feeder dykes of massive type

The feeder dykes of massive type (Yamagish, 1982) are commonly pyroxene andesite and hornblende andesite. They are characterized by regular-shaped joints, which show columnar pattern, radial pattern (radial-columnar joint) or polyhedral pattern.

Examples of this type are exposed at Gokibiru (No. 2 in Fig. 2) and Tomari (No. 16 in Fig. 2). The feeder dykes exposed at Gokibiru have radial-columnar and concentric joints. The radial-columnar joints propagate across flow layers of the dyke, whereas the concentric joints develop along the flow layers (Fig. 30). The margin is tiny-jointed and grades outward into hyaloclastite (B) through in-situ breccia. The feeder dyke of massive type exposed at Tomari show polyhedral pattern composed of pseudo-pillows and jigsaw breccia (Fig. 31). It has apparently intruded into or has been overlain by a volcanic conglomerate.

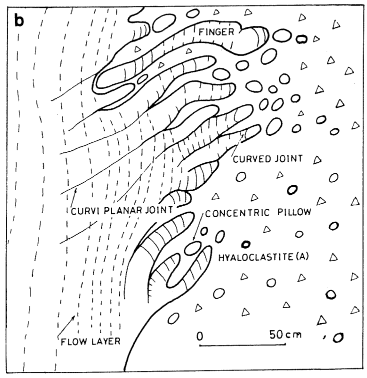

Fig. 29b Vertical exposure of a feeder dyke of apophysis-like type. Loc. Iwabe (No. 27 in Fig. 1). Fingers extended from the dyke have been disintegrated into concentric pillows.

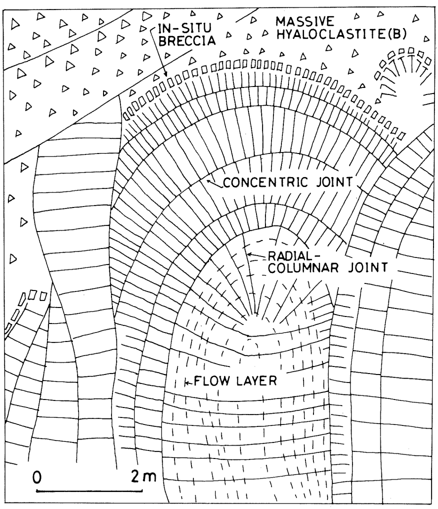

Fig. 30 Vertical exposure of feeder dykes of massive type with radial-columnar joints grading outward into hyaloclastites (B) through in-situ breccia zone. Loc. Gokibiru (No. 2 in Fig. 2).

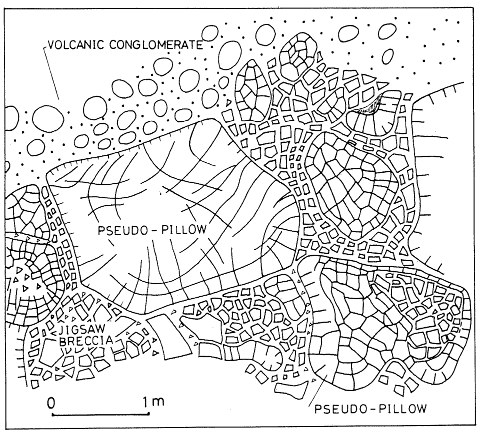

Fig. 31 Vertical exposure of a pyroxene andesitic feeder dyke of massive type, splitted into pseudo-pillows and jigsaw breccia. Loc. Tomari (No. 16 in Fig. 2).

3.3. Feeder dykes of lava lobe type

The feeder dyke equivalent to lava lobe, as mentioned already, is typically exposed at Kawashira (No. 10 in Fig. 2). It provides sheet flows and small lava lobes. (See page 72).

3.4. Feeder dyke of clastic type

The feeder dyke of clastic type (Yamagishi, 1982) is observed at Kabuto (No. 14 in Fig. 2) and Oshoro (No. 5 in Fig. 2). The feeder dyke of this type at Kabuto is composed of disaggregated angular fragments and polyhedral blocks (hyaloclastite (B) of pyroxene andesite ; Fig. 32). The lower portion is regarded as the feeder dyke of massive type. The feeder dyke at Oshoro consists of hyaloclastite (A) of basaltic andesite (Plate III, 1 of Yamagishi, 1982). The feeder dykes of clastic type from Kabuto and Oshoro intruded into stratified hyaloclastite (B) and fine-grained epiclastic volcanic rocks, respectively. Fragmentation took place probably by interaction between intruding dyke and water from the surrounding wet-sediments or sea.

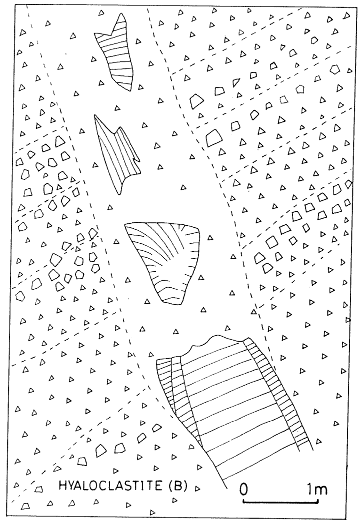

Fig. 32 Vertical exposure of a feeder dyke of clastic type. It consists of disaggregated angular fragments and polyhedral blocks of pyroxene andesite. Loc. Kabuto (No. 14 in Fig. 2). The top of the massive feeder dyke has been disintegrated into clastic rock within a feeding channel.

3.5. Peperite

Peperite occurs as a kind of feeder dyke of clastic type, consisting of hyaloclastite commingled with sedimentary rocks (Williams and McBirney, 1979). It is found in some places in Southwest Hokkaido, and an example of the peperite exposed at Moiwa (No. 13 in Fig. 2) is described here.

The peperite found in the Kabuto Volcaniclastic Rocks of the Tomari Formation is a massive breccia tens of meters across. The peperite is a mixture of altered aphyric andesite fragments and mudstone chips (Plate 6A). The andesite fragments are pale-green colored, lapilli-sized, and angular in shape. The fragments show hyalopilitc texture with a few phenocrysts of plagioclase, hornblende and pyroxene (Plate 6B). The interstices between the fragments are filled with amoeba-shaped chlorite and calcite as identified by X-ray diffraction. The mudstone chips are dark grey or black, up to a few centimeters across, and irregularly shaped. Some of the mudstone chips are penetrated by the andesite fragments, and the others are moulded fitting with interstitial spaces among the andesite fragments. The peperite includes sparsely subangular pebbles of pyroxene andesite.

The peperite grades laterally into in-situ breccia of porphyritic green-colored andesite containing phenocrysts of plagioclase, hornblende and pyroxene, all of which have been altered into chlorite, epidote, and calcite, in a hyalopilitic-textured groundmass. The in-situ breccia which is free from mudstone chips, grades downward into a columnar-jointed dyke.

The occurrence of the peperite described above suggests that interaction between aphyric andesite magma and unconsolidated mudstone, produced a peperite during intrusion of the magma. Subsequently, porphyritic andesite dykes intruded from the same magma chamber and formed in-situ breccia in contact with water from surrounding wet-sediments or sea. Therefore, the peperite of aphyric andesite and the associated porphyritic andesite may be regarded as a kind of composite dyke (Kuno, 1950).

4. Pyroclastic rock

Pillow lava and hyaloclastite (A) are in places overlain and/or underlain by pyroclastic rocks such as scoriaceous agglomerate, scoriaceous lapilli tuff, pyroclastic pillow breccia and scoriaceous vitric tuff.

4.1. Scoriaceous agglomerate

The scoriaceous agglomerates are exposed in places in Southwest Hokkaido. Most of them contain characteristic volcanic bombs showing quench features (water-chilled bombs, Yamagishi, 1974, 1982), lying in a matrix of lapilli-sized scoria and/or ash associated with accessory lapilli.

In Southwest Hokkaido, two types of agglomerate, pyroclastic fall and flow deposits in a broad sense, can be identified in terms of sedimentary structure (Dimroth and Yamagishi, 1987). An example of agglomerate consisting of pyroclastic fall deposit is exposed at Oshoro Peninsula (No. 5 in Fig. 2). This is a scoriaceous agglomerate which is well sorted, reverse or normal graded and characterized by monogenetic features. Ash-sized materials are absent. Fall unit boundaries can be traceable within a certain extent, and bomb sags are rarely recognized.

Most of the bombs are 5—10cm in diameter. Tiny and curved wrinkles with wave length of less than one centimeter, are characteristic of the surface of the bombs. They have abundant vesicles and chilled margins. The vesicles in the core are spherical to ellipsoidal in shape and a few centimeters in diameter, whereas those in the outer core and chilled margin, are elongated and a few millimeters in diameter. The long axes of the elongated vesicles are parallel to the surface of the bombs. The inner surfaces of the vesicles are fringed with smectite clay probably due to palagonitization. The chilled margin of the bomb is characteristically made up of black glass with a few tiny contraction cracks perpendicular to the surface. The black glass is enveloped by a film of palagonite of 0. 3 to 0. 5 mm thick. The core of the bomb exhibits several zonal-bands defined by difference in color; the outer core ranges in color from reddish brown to yellow (Fig. 33).

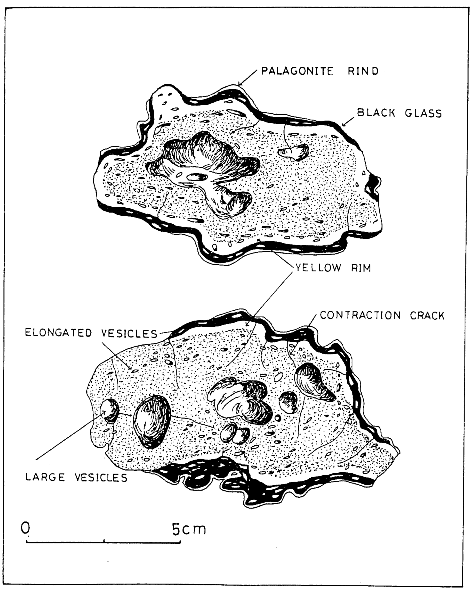

Fig. 33 Water-chilled bombs in a scoriaceous agglomerate (No. 5 in Fig. 2). Note that the inner core has large spherical - ellipsoidal vesicles, and the outer core small vesicles aligned conformably to the surface. The chilled margin consists of black glass enveloped by palagonite rinds.

4.2. Scoriaceous lapilli tuff

A typical example of scoriaceous lapilli tuff consisting of pyroclastic fall deposit exposed in Oshoro Peninsula (No. 5 in Fig. 2). This lapilli tuff is well sorted and monogenetic in lithology and comprises lapilli-sized water-chilled scoriae (Dimroth and Yamagishi, 1987). No interstitial ash-sized materials are present.

The water-chilled scoria shows remarkable zonation, varying in color from reddish brown in the inner core to black in the glassy margin, through yellow in the outer core (Fig. 34). The scoria has elongated vesicles in

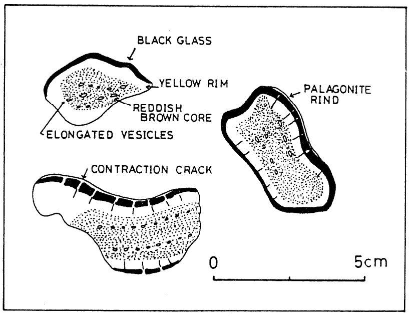

Fig. 34 Water-chilled scoriae in a lapilli-fall deposit (No. 5 in Fig. 2). Note that the core varies in color from reddish brown to yellow and the inner core is slightly vesiculated. The margin consists of black glass with tiny contraction cracks, and is enveloped with palagonite rinds.

the outer core, arranged conformable to the surface. The black glassy margin has tiny contraction cracks perpendicular to the surface and is fringed with palagonite rind.

The internal variation in color of the water-chilled bomb and scoria has been presumably caused by oxidation at the time of eruption (Walker and Croasdale, 1972). Both of the scoriaceous agglomerate and scoria lapilli tuff are probably products of Strombolian eruptions in subaqueous environment (Dimroth and Yamagishi, 1987).

4.3. Pyroclastic pillow breccia

Typical examples of pyroclastic pillow breccis are exposed at Harauta (No. 23 in Fig. 2) and Kabuto (No. 14 in Fig. 2).

The pyroclastic pillow breccia exposed in both localities contain a number of pillow fragments similar to water-chilled bombs in a matrix of high-vesiculated scoriaceous lapilli with vitric ash. The lapilli and ash have usually palagonite rinds formed by interaction with sea water at the time of eruption. The fine-grained matrix is characteristically much more abundant than the pillow fragments.

A depositional unit of the pyroclastic pillow breccia can be defined by recognition of the massive lower part and the fine-grained bedded top (Plate 6C). The massive lower part shows chaotic structure with faint normal or reverse grading. Total thickness of the unit is up to a few meters thick. The sedimentary structure of the pyroclastic pillow breccia suggests that the deposit is formed as the result of hydrovolcanic explosion immediately followed by turbulent flow.

4.4. Scoriaceous vitric tuff

A typical exposure of scoriaceous vitric tuff is found at Yamanaka. This vitric tuff consists mostly of lapilli-sized scoriae and vitric ash. The ash is angular in shape and has palagonite rinds (Plate 6D). This vitric tuff consists commonly of upper parallel-laminated part and lower massive part, suggesting that it was formed by turbulent flow. The total thickness of the unit is up to 10 m.

Microscopically, the scoriaceous vitric tuff from Yamanaka consists mostly of glass fragments associated with lithic fragments. Both of them have planar or curviplanar surfaces, suggesting that they were formed by fragmentation of a brittle or viscous material during hydrovolcanic explosion, such as Surtseyan eruption (Wohletz, 1983). Most of these fragments are enveloped with palagonite rinds. The glassy fragments have abundant small ellipsoidal vesicles and tiny joints. The glass fragments have no quench crystals, whereas the lithic fragments have a few large vesicles and abundant microlites and quench crystals. The glass fragments correspond to the quenched margin of essential material, whereas the lithic ones to the core.

IV MECHANISM OF FORMATION OF SUBAQUEOUS LAVAS AND HYALOCLASTITES

This chapter is concerned with mechanism of formation mostly of subaqueous lavas and hyaloclastites on the basis of description of typical examples of the Neogene subaqueous volcanic rocks in Southwest Hokkaido on referring to the occurrence of the ancient subaqueous volcanic rocks in the other regions (Yamagishi, 1983, 1985 ; Dimroth and Yamagishi, 1987).

1. Subaqueous lavas

1.1. Growth of pillow lobe

The process of formation of pillow lobe can be interpreted by means of analysis of the surface and internal structures in the light of much information of modern and ancient pillow lavas (Fig. 35 ; Yamagishi, 1983, 1985). Ropy wrinkles, corrugations and spreading cracks are important evidence for the interpretation of growth of pillow lobes.

Particularly, the spreading crack plays an important role in growth of a pillow lobe (Moore, 1975 ; Moore and Lockwood, 1978 ; Yamagishi, 1985). The symmetric longitudinal spreading crack opens on the top surface of lobe during growth, resulted into lateral diverging of two pillow lobes, while the asymmetric transverse spreading crack develops when interior liquid lava breaks a toe of the older pillow lobe, consequently a new pillow lobe drains from its interior. During the further growth of pillow lobe, constrictions are left in front of the asymmetric transverse spreading crack by budding and digital inflation of the new pillow lobe (Hargreaves and Ayres, 1979), and a solidified crust is formed by shear joint between the solidified margin and the liquid interior, resulted in penetration of water. Consequently, both of the outer and inner margins of the crust are quenched into glass (Fig. 35a, b and c).

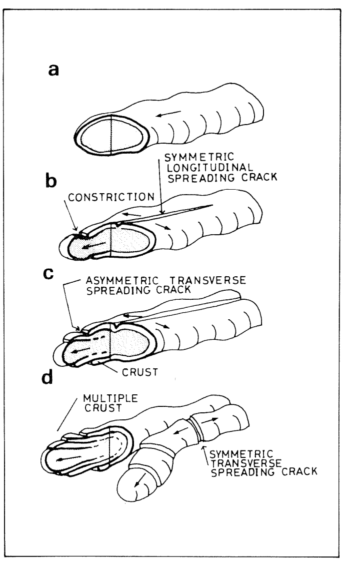

Fig. 35 Model of growth of pillow lobe. a : Pillow lobe is filled with liquid lava and enveloped by solidified crust due to quenching. b and c : Interior liquid lava breaks the toe, and a new pillow lobe emerges through crust. Simultaneously, water penetrates into shear joints between crust and interior, and constrictions are left at the end of crust by inflation of new pillow lobe. Symmetric longitudinal spreading crack opens on the top surface of lobe during growth. d. Multiple crusts are formed at the end of toe by repeated surge of liquid lava. Two pillow lobes diverge from the old single pillow lobe by formation of symmetric longitudinal spreading crack, and each pillow lobe advances by symmetric transverse spreading cracks. Arrows indicate spreading or flow direction.

Repeated draining forms multiple crusts, and each pillow lobe advances forming symmetric transverse spreading crack (Fig. 35d). Some crusts undergo disintegration due to quenching contraction, and the others grow into a pillow lobe by further supply of liquid interior.

The origin of the multiple crusts has been discussed by Fuller (1932), Snavely et al. (1973), and Kawachi et al. (1983). Fuller (1932) interpreted the multiple crusts (concentric bands) to be formed by the periodic advance of contraction cracks during growth. Snavely et al. (1973) suggested that they resulted from development of tension cracks beneath an initial skin during cooling, which was followed by injection of water into the cracks. Kawachi et al. (1983) interpreted the multiple crusts as a product of repeated implosion (Moore, 1975) of pillow. On the origin of the multiple crusts the author considers that they are formed through the following process, 1) repeated generation of shear joints between the outer solidified crust and the inner liquid interior during pulsating growth of pillow lobe and 2) water penetrates into the joints just after generation of the shear joints.

Tensional and contraction cracks are formed after cessation of growth of pillow lobe. The tensional crack is produced during further inflation of the toe of pillow lobe after the surface crust is solidified. It is analogous to bread-crust fracture of volcanic bomb (Macdonald, 1972). On the contrary, the contraction crack is formed by gradual cooling of the whole pillow lobe.

Macdonald (1967) mentioned that the interior of pillow lava gives general impression of radial structure, whereas that of pahoehoe lava shows concentric structure delineated by rows of vesicles. However, both the radial structure defined by contraction cracks and the conformable flow layers (concentric structure) are observed in some of the Neogene pillow lobes from Southwest Hokkaido (Fig. 4). In addition, some of the Neogene pillow lobes have tortoise-shell joints, while the others have not distinct radial joints. Hence, the radial structure is not always the best criterion for recognition of a pillow lobe.

1.2. Formation of lava lobe and pseudo-pillow lava

The process of formation of a subaqueous lava lobe can be interpreted satisfactorily in terms of Fink's (1983) model for the emplacement of subaerial rhyolite lava.

A lava extruded from the feeding fissure may be immediately quenched by water (Fig.

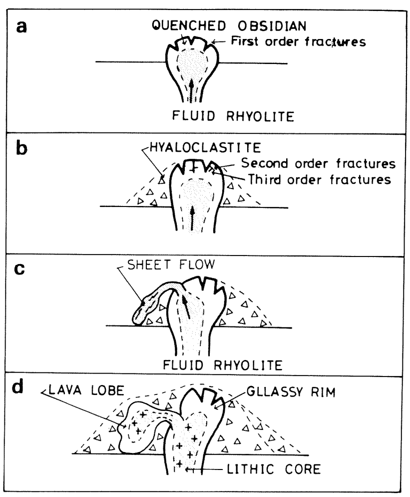

Fig. 36 Mode of the formation of lava lobe and associated hyaloclastite. a: The feeder dyke reaches the sea floor; its surface is quenched and contraction fractures are formed perpendicularly to it. b: Second- and third-order contraction fractures develop and the quenched surface layer undergoes in-situ brecciation. c: The first-order contraction fracture taps the fluid interior of the feeder dyke, and a sheet flow extrudes upon the surface of the rubble pile, d: The forward propagation of the sheet flow produces a lava lobe. Simultaneously its surface is quenched and disaggregated.

36a). The resultant glassy rim is thermally isolated from the hot interior of the feeder dyke, and confines volatile component to the interior. Consequently, a steep temperature gradient is formed across the margin of the feeder dyke. With decrease in temperature at the margin, contraction fractures may be produced perpendicularly to the surface and they propagate inward. Further propagation of the fracturing produces second- and third-order· cracks, resulting in formation of in-situ breccia along the margin of the dyke. Thus, massive hyaloclastites may be accumulated around the feeder dyke (Fig. 36b).

Thus, a sheet flow extrudes onto the surface of the massive hyaloclastite (Fig. 36c). The surface of the sheet flow also undergoes brittle fracturing. Finally, the sheet flow is inflated to form a lava lobe with further supply of magma (Fig. 36d). The inflation may be promoted by degassing of volatile components.

Furnes et al. (1980) and De Rosen-Spence (1980) described rhyolitic lava lobes of Quaternary and Archean age, respectively. Furnes et al. (1980) interpreted that the subglacial lava lobe was detouched from its parent lava flow by increasing in internal pressure due to further supply of volatile-rich magma. De Rosen-Spence (1980) reported that the Archean subaqueous rhyolite lavas including lava lobes are similar to subaqueous basalt flows in many respects.

The term "lava lobes" were originally defined for subglacial or subaqueous felsic lavas. The author points out, however, that the Neogene lava lobes in Southwest Hokkaido were formed from intermediate magma as well as felsic magma. They occur as not only lavas, but also feeder dykes with sheet flows and small lava lobes. They were probably formed by inflation of fluidal sheet flows by further supply of magma.

Pseudo-pillow lavas, which are splitting products of viscous lavas through quench jointing, were originally described for subaqueous felsic rocks (Watanabe and Katsui, 1976). However, most of the Neogene pseudo-pillow lavas or dykes in Southwest Hokkaido are andesitic in composition. In general, pseudo-pillow lavas and dykes are rare in Southwest Hokkaido, because most of them are probably disintegrated into isolated pseudo-pillows due to further disaggregation, by which angular fragments of hyaloclastite (B) are formed during flowage or intrusion.

1.3. Rheological interpretation of subaqueous lavas and feeder dykes

Pillow lobe : Field and laboratory studies on cooling of Hawaiian tholeiitic basalt by Shaw et al. (1968) and Shaw (1969) indicate that a rapid change occurs in viscosity and rheological behavior from a Newtonian fluid to a Bingham plastic at temperature below the liquidus.

Pillow lobes may occur as a Bingham plastic ; the interior of the pillow lobe behaves as an inner plug flow showing constant velocity as if it were a solid body undergoing no shear strain, whereas the border zone of the pillow lobe acts as a laminar flow having a velocity gradient and undergoing shear stress (Johnson, 1970 ; Peterson and Tilling, 1980). The inner plug flow provides a good condition for the growth of pipe vesicles to develop perpendicularly to the border zone. The laminar flow causes generally shear partings (Cas and Wright, 1987). Consequently it probably produces flow layers and shear joints.

Lava lobe and pseudo-pillow lava : The rheology of rhyolite lava was discussed by Fink (1983) based on the works of Shaw (1963, 1969), Shaw et al. (1968) and Friedman et al. (1963). It is generally believed that a lava behaves as a Newtonian fluid at temperatures above the liquidus ; high-temperature rhyolite lava has neither shear strength nor tensile strength. Its viscosity decreases with increasing temperature and water content (Friedman et al., 1963). Below the liquidus temperature, a lave acquires a non-Newtonian behavior in response to degassing, increase in viscosity and growth of quench crystals (Sparks and Pinkerton, 1978). The rheological behavior of a lava at temperatures below the liquidus can be approximated by a Bingham model. Flow layers of lava result from shear partings developed during laminar flow in a Bingham fluid (Cas and Wright, 1987). Further, the lava is fractured by brittle failure when the tensile stress caused by quench contractiton exceeds the tensile strength of the lava.

In general, highly porphyritic subaqueous lavas containing a high proportion of microlites in their quenched phase must have a high yield strength and viscosity, which result in formation of domes or short flows. Further, they are commonly disected into polyhedral blocks such as pseudo-pillows, or disaggregated into a monolithologic breccia by brittle fracturing. On the other hand, sparsely porphyritic lavas extruded at a near liquidus temperature, act as a Newtonian fluid and tend to form sheet flows even if they begin to change into a Bingham plastic during cooling and flowage. The margins undergo brittle fracturing due to quenching contraction.

Feeder dykes : Rheological interpretation can be also applied to feeder dykes. Flow layers in most of the feeder dykes are probably ascribed to laminar flow of a Bingham plastic. The flow layers of apophysis-like feeder dykes change into shear jointing during intrusion, which results into formation of lava tongues or fingers protruding into the surrounding unconsolidated sediments. It is probably promoted by fluidization of the sediments due to water vapor generated from wet sediment and hot magma interaction (Kokelaar, 1982). Subsequently, both lava tongues and fingers are disected into pillow fragments making up hyaloclastite (A).

Brittle fracturing occurs on the quenched margin of viscous feeder dykes of massive type, on a sea floor or within a feeding channel, which results in formation of monolithologic breccia such as hyaloclastite (B).

2. Hyaloclastites

The hyaloclastite (A) associated with pillow lavas in Southwest Hokkaido is similar to the "pillow breccia" (Carlisle, 1963), "pillow block breccia" (Furnes and Friedleifsson, 1979) and "Pillow fragment breccia" (Staudigel and Schmincke, 1984).

Carlisle (1963), Dimroth et al. (1978), Maruyama and Yamazaki (1978), and Furnes and Fridleifsson (1979) discussed the transition from pillow lava to "pillow fragment breccia". Carlisle (1963) explained that the upward increase in the ratio of matrix to pillow and in the proportion of small pillows, may be ascribed to increase in the amount of "violent globulation" with time. Dimroth et al. (1978) indicated that pillow size is in part controlled by supply of lava from a feeding vent and tube system. Accordingly to them, the pillow fragments at the top of massive or pillowed flows were formed at the waning eruption stage when the supply of lava decreased significantly. Maruyama and Yamazaki (1978) suggested that their "hyaloclastite layer" (hyaloclastite (A) in this paper) is a product formed either by decrepitation of glass due to rapid cooling, or by shattering and crushing of tumbling pillow blocks. Furnes and Fridleifsson (1979) reported that the transition from pillow lava to "pillow block breccia" may not be formed by breakage of individual pillows during their growth and incipient cooling, but by mechanical movements after congealation of the pillow lava.

Jones (1969), Moore and Fiske (1969), and Staudigel and Schmincke (1984) noted different lithologies of basaltic submarine volcanoes ; Jones (1969), and Moore and Fiske (1969) described the fragmental materials on the top of pillow lava piles in Iceland and ocean-bottom near Hawaii, respectively. Staudigel and Schmincke (1984) described a large-scale transitional sequence from effusive facies (pillow lavas) to clastic facies (pillow fragment breccias, and scoriaceous pillows and breccias) of the Pliocene seamount series of La Palma, Canary Island. They noted that upward decrease in pillow size even in the effusive facies is commonly observed, which suggests decrease in eruption rates.

A large-scale lithological difference between the lower and upper volcanic sequence, may depend also on the depth of water as suggested by McBirney (1963) and Moore (1965).

The transitional sequences found at Yamanaka (Fig. 20), Furubiragawa (Fig. 21a) and Tomari (Fig. 21b) are exposed in a small scale. Therefore, the upward decrease in pillow size may not be ascribed to the effect of depth of water, but mainly to the decrease in supply of lava with time, as suggested by Dimroth et al. (1978) and Staudigel and Schmincke (1984).

The pillow lobes roll down slope after their solidification and are disintegrated as shown by Maruyama and Yamazaki (1978), and Furnes and Fridleifsson (1979). The hyaloclastite (A) which is composed motsly of concentric pillows, exposed at Kayanuma and Iwabe, can be interpreted as follows.

The toes of lava tongues and fingers are further splitted into concentric-jointed pillows. The concentric joints are presumably formed by shear fracturing due to the difference in contraction rate between the outer and central portions of pillow. Concentration of large vesicles in the interior is probably caused by coalescence of gas bubbles in the interior since the quench glass margin prevent degassing from the interior (Yamagishi, 1982).

The hyaloclastite (B) in the Neogene volcanic rocks from Southwest Hokkaido is ineterpreted as a product of brittle fracturing of intermediate to felsic viscous lava and dyke by quench contraction (cooling-contraction granulation ; Kokelaar, 1986).

As observed at Yamanaka (Fig. 20) and Kayanuma (Fig. 21b), the transition from the hyaloclastite (A) to (B) can be explained by the increasing viscosity of magma toward the end of effusion ; i. e. fragmentation mechanism of lava may change with time from mechanical moving of solidified pillow lobes to brittle fracturing of viscous lava or dyke. The increase in viscosity seems to be caused by further decrease in eruption rate. The scoriaceous vitric tuff on the top of the sequence at Yamanaka is composed of fine-grained shards and lithic fragments enveloped with palagonite rinds, suggesting that it is a product of hydrovolcanic explosion (Wohletz, 1983 ; Kokelaar, 1986).

When a massive feeder dyke extruding through a feeding channel is quenched, contraction fractures develop perpendicularly to the surfaces and propagated inward. Propagation of the second- and third-order contraction fractures may produce angular fragments, which results in formation of hyaloclastite (B) around the dyke. In places, the top of the feeder dyke is disected into pseudo-pillows by planar or curviplanar contraction joints. The pseudo-pillow is again disintegrated into a jigsaw breccia which is further disaggregated during transportation.

The detail mode of occurrence of the hyaloclastites in the Neogene Southwest Hokkaido suggests that the difference in formation between the hyalocastite (A) and (B) depends largely on viscosity of magma; the former shows behavior of lower viscosity than the latter at the time of eruption. The hyaloclastite (A) may correspond to subaqueous equivalents of disintegrated pahoehoe and aa lavas, whereas the hyaloclastite (B) to block lava of Macdonald (1953).

Complete disaggregation of a feeder dyke within a feeding channel may provide a clastic dyke. Intrusion of a feeder dyke into water-logged and unconsolidated mudstone, may produce a peperite by interaction between the lava and water in the mudstone. Moulded- and irregular-shaped mudstone chips fitting with the lava fragments, are probably formed by fluidization of the mudstone owing to water vapor pressure generated during the interaction between hot magma and water (Kokelaar, 1982).

The loose hyaloclastite debris piled around feeder dykes tend to collapse, which may result in accumulation of stratified hyaloclastites consisting of foreset beds with primary dips of 20°—30° and topset beds with primary gentle inclination. Each hyaloclastite bed is considered to be a sediment of a matrix-supported debris flow of a few meters thick, judging from reverse or reverse-to-normal grading of block-sized fragments (Fisher, 1971 ; Fisher and Mattinson, 1968) and considerable amounts of interstitial matrix. The reverse-to-normal grading is evidence for the debris flow which transforms into turbulent flow in the upper portion (Fisher, 1971, 1983).

Repeated subaqueous debris flows yield a thick-pile of foreset- and topset-bedded hyaloclastite around their feeder dykes. Some of the debris flows scour and channelize underlying debris flow deposits or loose basement sediments. Deposition from suspension clouds of fine grained materials on the top of the debris flows forms parallel-laminated sandstone beds among the large fragments in the upper portion. Variable prograding direction of the foreset- and topset-bedded hyaloclastites for the deltaic sequence unit as shown at Kabuto (Fig. 25).

The in-situ breccias of sheet flows exposed at Hamamasu and Kabuto are similar to the "flow-foot breccia" of subaerial lava flowing into water (Jones and Nelson, 1970). However, Dimroth et al. (1985) suggested that these breccias were formed entirely in water as flow-front breccia.

3. Pyroclastic rocks

Scoriaceous agglomerates and scoria lapilli tuffs may be produced by Strombolian eruption from volcanic islands associated with pillow lavas and hyaloclastites. On the other hand, the pyroclastic pillow breccia and scoriaceous vitric tuff are considerable to be formed by hydrovolcanic explosions, commonly associated with effusion of pillow lavas and hyaloclastites.

4. Reconstruction of subaqueous volcanoes

A number of models for the reconstruction of subaqueous volcanoes have been presented during the last two decades (Table 5). Most of these models are concerned with submarine volcanoes consisting of mafic rocks in the oceanic regions, while those for the volcanoes of intermediate to felsic rocks common in island arcs are rather rare. The models provided in the Neogene Southwest Hokkaido, therefore, must be important for the study of submarine volcanoes in island arcs.

Detailed studies on the Neogene subaqueous volcanic areas enable the author to reconstruct different kinds of subaqueous volcanoes that is composed of subaqueous lavas, hyaloclastites and their feeder dykes. The models for the volcanoes of mafic to intermediate rocks (Fig. 37a) have been drawn on the basis of the data from Yamanaka (Fig. 20), Oshoro (Figs. 4 and 28), Hamamasu (Fig. 22), Gokibiru (Fig. 27), Kabuto (Fig. 25), Kayanuma (Fig. 29a), Iwabe (Fig. 29b) and Moiwa (Plate 12), while those for the volcanoes of intermediate to felsic rock (Fig. 37b) based on the data from Tomari (Fig. 31), Kawashira (Fig. 12), Ruran (Fig. 14), and Oshoro (Fig. 15).

Fig. 37a illustrates a reconstructed model for the submarine volcanoes produced by mafic and intermediate magma. In the earlier stage, intrusion of a feeder dyke of massive type into unconsolidated mudstone, followed by interaction of the dyke and mudstone, produced a

Table 5 Reconstruction of subaqueous volcanoes

ENVIRONMENT	AGE	LOCATION	ROCK TYPE	REFERENCE
Submarine	Modern	Cobb Seamount	basalt	Nayudu(1962)
	Miocene	Ponza Islands, Tyrrhenia Sea	rhyolite-quarztlatite	Pichler(1965)
	Modern	Surstey, Iceland	basalt	Kjartansson(1967)
	Modern	Hawaii	basalt	Moore and Fiske (1969)
	Quaternary	St. Helena & others	basalt	Cotton(1969)
	Miocene	Kosaka, Japan	dacite	Horikoshi(1969)
	Modern	Puna Ridge, Hawaii	basalt	Fornari et al. (1978)
	Miocene	Shakotan Peninsula, Japan	hornblende andesite, pyroxene andesite	Yamagishi et al. (1979)
	Miocene-Pliocene	Pentecost Island, New Hebrides	basalt	Neef(1980)
	Miocene	Low Layton, Jamaica	basalt	Wadge(1982)
	Pliocene	La Palma, Canary Islands	basalt	Stautigel and Schmincke(1984)
	Miocene	Kawashira, Japan	rhyolite	Yamagishi and Dimroth(1985)
Subglacial	Quaternary	Laugarvatn Region, Iceland	basalt	Jones(1969)
	Quaternary	Southwest Iceland	rhyolite	Furnes et al. (1980)

peperite (Fig. 37a, right). The top of the dyke underwent brittle fracturing to form massive hyaloclastite (B), which was followed by collapse to generate avalanche and debris flow. Consequently, foreset-bedded breccias showing reverse or reverse-to-normal grading were emplaced on the slope of the seamount. Further supply of the loose debris from the seamount produced topset-bedded breccias overlying the foreset-bedded breccias. Intrusion of feeder dykes of apophysis-like type caused effusion of pillow lobes, lava tongues or fingers, followed by mechanical movement and disintegration due to quenching to form hyaloclastite (A) (Fig. 37a, left). In places, pyroclastic pillow breccia were produced by hydrovolcanic explosion. Loose debris of the pillow lobes, hyaloclastites and pyroclastic pillow breccias collapsed and swept down as debris flow on the slope of the seamount. As a result, foreset- and topset-bedded hyaloclastites and pillow breccias were accumulated on the slope and foot of the seamount. Epiclastic volcanic rocks were produced by mass movement of the loose debris derived from the seamount or beach gravels. The mass movement scoured and channelized the slope.

Fig. 37b illustrates a model for the submarine volcanoes generated by intermediate to felsic magmas. Extrusion of a feeder dyke of massive type into sea water made a top of the dyke splitted into pseudo-pillows. They were further disintegrated into much smaller pseudo-pillows and angular fragments during transport by avalanche or debris flow (Fig. 37b, right). Finally, foreset- and topset-bedded hyaloclastites were deposited on the slope and foot of the seamount.

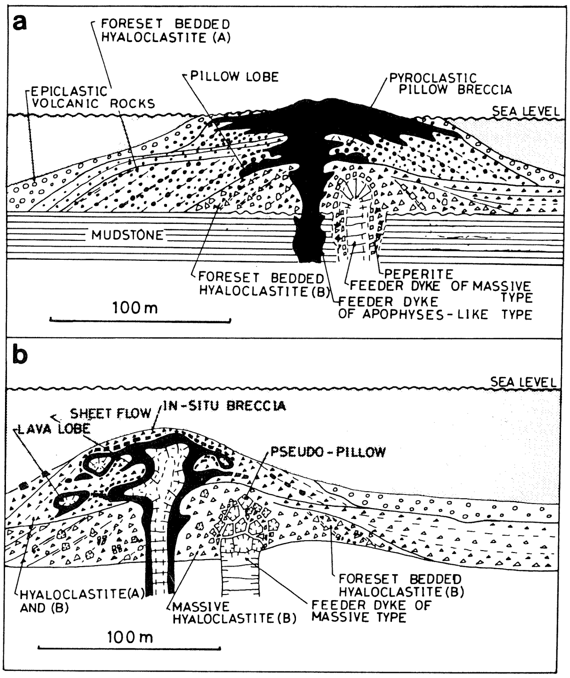

Fig. 37 Figures illustrate models of submarine volcanoes, compiled from the date of this study. a : A volcano of mafic to intermediate rocks which consist mainly of pillow lobes and hyaloclastites (A) and (B). Peperite is formed by intrusion of feeder dykes into unconsolidated mud. b : A volcano of intermediate to felsic rocks which consist of lava lobes associated with sheet flows, and hyaloclastite (B) containing pseudo-pillows.

A feeder dyke of lave lobe type intruded, which caused effusion of a sheet flow (Fig. 37b, left). The sheet flow expanded to form a lava lobe by further supply of interior fluid lava. Simultaneously, the surface of the sheet flow and lava lobe underwent in-situ brecciation by quench contraction to produce hyaloclastite (B). Small lava lobes were isolated from the main body and were commingled with the hyaloclastite (B). The loose debris of hyaloclastite flowed down the slope to form foreset- and topset-bedded hyaloclastites. Finally, epiclastic volcanic rock was deposited through erosion of the seamount.

In the Neogene Southwest Hokkaido, high vesiculation of pillow lavas and occasional association of pyroclastic rocks indicate that the submarine volcanism took place at the shallow sea bottom less than a few hundred meters to one kilometer deep (McBirney, 1963 ; Jones, 1969 ; Moore and Schilling, 1973 ; Fisher, 1984), although the degree of vesiculation of submarine lavas is largely a function of both volatile content and pressure (Moore, 1970).

V CONCLUSION AND SUMMARY

Although the subaqueous volcanic rocks are an important subject to elucidate the geologic development of Southwest Hokkaido, they have been scarcely studied until the author commenced an extensive work in this field. This paper is concerned with their mode of occurrence and genesis in the light of recent studies on subaqueous lavas and hyaloclastites. In order to avoid confusion of terminology, a glossary relating to subaqueous volcanic rocks has been prepared, which appears in the beginning of this paper.

Detailed descriptions of occurrence, morphological features, internal structures and sedimentary structures of the subaqueous lavas and hyaloclastites, and associated pyroclastic rocks from the representative localities were made, and their processes of formation were investigated. The results are summarized as follows:

1) The Neogene subaqueous volcanic rocks in Southwest Hokkaido can be classified into a)subaqueous lavas, b)hyaloclastites, c)pyroclastic rocks, and d)epiclastic volcanic rocks. In particular, the difference between the hyaloclastites and pyroclastic rocks is significant with respect to mechanism of fragmentation. The hyaloclastites associated with subaqueous lavas occupy the largest part of the Neogene subaqueous volcanic rocks in Southwest Hokkaido.

2) The Neogene subaqueous lavas show various morphologies; pillow lobe, lava lobe, sheet flow, and pseudo-pillow lava. The following features are important criteria for their recognition and diagnosis.

The pillow lobe is cylinder or tubular, and is characterized by surface structures, such as ropy wrinkles, corrugations, spreading cracks, tensional cracks and contraction cracks. The former three are formed during growth of the pillow lobes. Especially, the spreading cracks play an important role in their growth. On the other hand, the latter two are produced after cessation of the growth of pillow lobes.

The lava lobe is commonly composed of lithic core and glassy margin grading outward into hyaloclastite through in-situ breccia. The lava lobe is formed by expansion of fluid sheet flow by further supply of new lava, although both of them undergo in-situ brecciation on the quenched margins.

The pseudo-pillow lava consists of close-fitted polyhedral blocks (pseudo-pillows), which are formed by rude jointing of viscous lava or dyke due to quench contraction. The pseudo-pillow has a tendency to be separated from the lava and dyke during intrusion and to be disintegrated into angular fragments of hyaloclastite (B) during transport.

The cross sections of the pillow lobe, lava lobe, and pseudo-pillow, are similar to each other in having radial and concentric structures. Therefore, it is of importance to observe these morpholgical features in three dimensions.

3) Most of the Neogene subaqueous volcanic rocks in Southwest Hokkaido are intermediate in composition, although the mafic and felsic rocks are included. They occur mostly as hyaloclastites associated with subaqueous lavas and feeder dykes.

The hyaloclastites are defined as glassy fragmental volcanic rocks formed by a non-violent process when lavas or dykes come in contact with water. The author classified them into (A) and (B) based on the shape of fragment. The former is composed mostly of pillow fragments disintegrated from mafic to intermediate pillow lobes or feeder dykes of apophysis-like type, while the latter comprises angular fragments and in places pseudo-pillows, both of which are derived from intermediate to felsic viscous lavas and feeder dykes of massive type, and are produced in terms of brittle fracturing due to quench contraction.

4) Massive hyaloclastites piled around feeder dykes and subaqueous lavas commonly grade into stratified hyaloclastites. They are subaqueous deltaic deposits composed of foreset-beds and in places topset-beds. Each bed of the stratified hyaloclastite is a matrix-supported debris-flow deposit as evidenced by existence of a considerable amount of interstitial matrix and reverse or reverse-to-normal grading.

5) The Neogene subaqueous volcanic rocks in Southwest Hokkaido are the products of shallow submarine eruptions, evidenced by the high vesiculation of the subaqueous lavas and hyaloclastites, and by the occasional association of the subaqueous pyroclastic rocks indicating violent explosion.

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西南北海道における新第三紀水中溶岩およびハイアロクラスタイトの研究

山岸宏光

要旨：西南北海道は北本州弧の内帯の延長部に位置し，新第三紀～第四紀の火山岩類が広く分布する．前期中新世の火山岩類は主に陸成のものであるが，それ以降の新第三紀の火山岩類は，島弧を特徴づける主として安山岩質の海底火山噴出物である．

これらは溶岩と火砕岩とに区分できる．溶岩は pillow lobe，lava lobe，sheet flow，pseudo-pillow lava に細分される．また，火砕岩はハイアロクラスタイト，火山砕屑岩（pyroclastic rock）および epiclastic volcanic rock にわけられる．以上のうち，本地域には水中溶岩をともなうハイアロクラスタイトが最も広く分布する．

pillow lobe は直径数10cm～数 m の円筒～チューブ状で，玄武岩質のものに比べ，安山岩質のものが多産する．その表面構造には ropy wrinkle, corrugation, spreading crack, tensional crack, contraction crack が認められる．前三者は pillow lobe の成長時に形成され，後二者はその定着後に形成される．ropy wrinkle は陸上のパホイホイ溶岩に見られるものと同じであり，corrugation には内部の対流によって生じたものと，引っ掻き傷に相当するものとがある．spreading crack は pillow lobe の延びに平行なものと直交するものとがあり，pillow lobe の成長に最も重要な役割を果たす．tensional crack は pillow lobe の成長停止直後も内部の melt の再供給による膨張で生じた伸張割れ目であり，contraction crack は pillow lobe の成長停止後の徐冷による収縮割れ目である．

pillow lobe の内部構造としては節理，殻および気泡が特徴的である．節理は contraction crack の断面であり，放射状節理のほか不規則あるいは亀甲状割れ目もみとめられる．殻は pillow lobe の成長時に shear jointing によって形成され，外縁のみならず内縁も急冷ガラスとなっている．気泡は一般に楕円体～球で，内部が大きく外側は小さい．また，外形に直交してのびる pipe vesicle も認められることがある．

安山岩質 pillow lobe は鏡下では，内側はインターサータル～インターグラニュラーの組織を示すが，外側はハイアロピリティック組織の石基に樹枝状～束状の quench crystal が斑晶や微斑晶の周囲に成長している．

lava lobe は安山岩や流紋岩質の水中溶岩の一形態である．典型的な lava lobe は直径数 m の楕円形で，内部の結晶質のコアとそれをおおう急冷ガラス帯からなり，その外側へハイアロクラスタイトへ漸移する．コアは外形に平行な流理構造と放射状節理で特徴づけられる．ガラス帯から sheet flow の発達がみられる．lava lobe は sheet flow の先端に生じ，内部の melt の再供給により sheet flow が膨張したものである．

pseudo-pillow lava は安山岩に多い形態で，直径数10cm～数 m の多面体のブロックの積み重なりであり，急冷節理の発達によって形成される．

ハイアロラスタイトは（A）タイプと（B）タイプに区別される．

（A）タイプは玄武岩～安山岩質の monolithologic な角礫岩で，pillow（急冷ガラスを有する楕円体）を含む．この pillow は pillow lobe や apophysis-like feeder dyke の先端部の分離によって形成される．これには，pillow lava の上位に重なるものと，apophysis-like feeder の先端に集中するものとがある．前者は pillow lobe の破片であり，後者は concentric pillow とよばれ，lava tongue や finger がちぎれたものである．

（B）タイプは安山岩～流紋岩質の monolithologic な角礫岩片からなる．pseudo-pillow lava，lava lobe，massive feeder dyke などの brittle fracturing の産物である．

以上の溶岩や feeder dyke の周囲に，無層理のハイアロクラスタイトがとり囲み，それから側方へ，層理

を示すハイアロクラスタイトへ移化する.後者は初生的に20～30度の傾斜を有するforeset-bedsで,時々top-set-bedsにおおわれる.各foreset-bedは逆グレーディングないし逆～正グレーディングを示し，debris flowであることを示唆する.上記の水中溶岩やハイアロクラスタイトは気泡の発達が良く，水中火山砕屑岩(subaqueous pyroclastic rock) をともなうことから，浅海の海底火山活動の産物であることが示唆される.

Plate 1

A. Ropy wrinkles on a pillow lobe. Loc. Oshoro (No. 5 in Fig. 2)

B. Corrugation (A) on a pillow lobe. Loc. Soibetsugawa (No. 21 in Fig. 2). A camera-lens cap as a scale.

C. Corrugation (B) on a newly formed pillow lobe squeezed out through a crust. Loc. Oshoro (No. 5 in Fig. 2)

D. Combination of ropy wrinkles and corrugations (B) on a broken pillow lobe in a hyaloclastite (A). Loc. Yamanaka (No. 20 in Fig. 2)

Plate 1

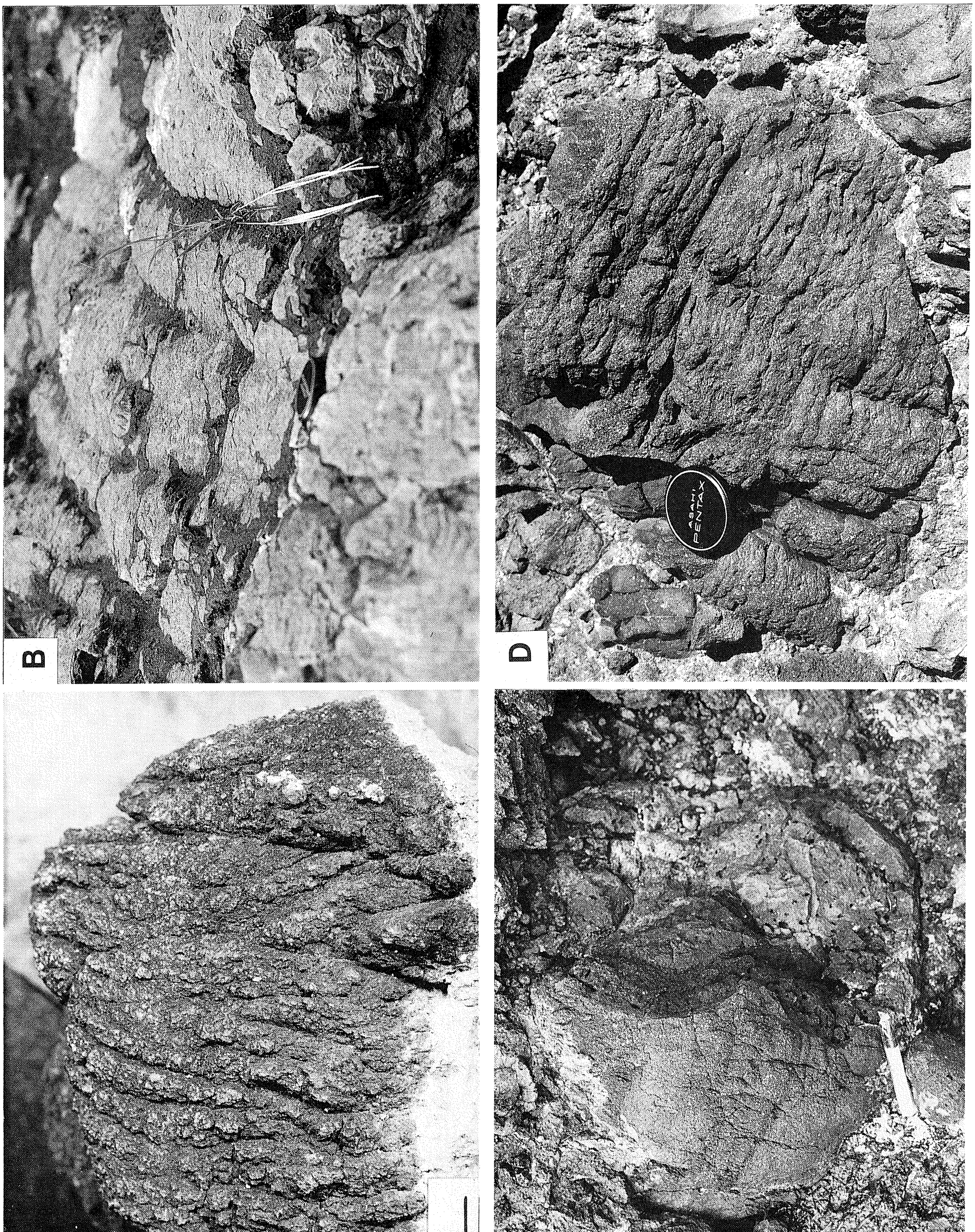

Plate 2

A. A pillow lobe enveloped with multiple crusts. Loc. Sakaehama (No. 25 in Fig. 2). The inner crust has ropy wrinkles curving toward the upper left of the picture, suggesting that the inner pillow lobe advanced toward this direction.

B. Vertical cross section of a pillow lobe showing radial-columnar joints and multiple crusts on a pillow lobe. Loc. Oshoro (No. 5 in Fig. 2). The end of each crust is marked by a tiny scarp outside the picture.

C. Photomicrograph of groundmass of the border zone of a pillow lobe. Loc. Yamanaka (No. 20 in Fig. 2). Fibrous and dendritic quench crystals have overgrown on the micro-phenocrysts. Parallel nicol.

D. An abrasion platform at Kawashira Beach (No. 10 in Fig. 2). Note feeder dykes (f) of rhyolite enveloped with perlitic hyaloclastite (h).

Plate 2

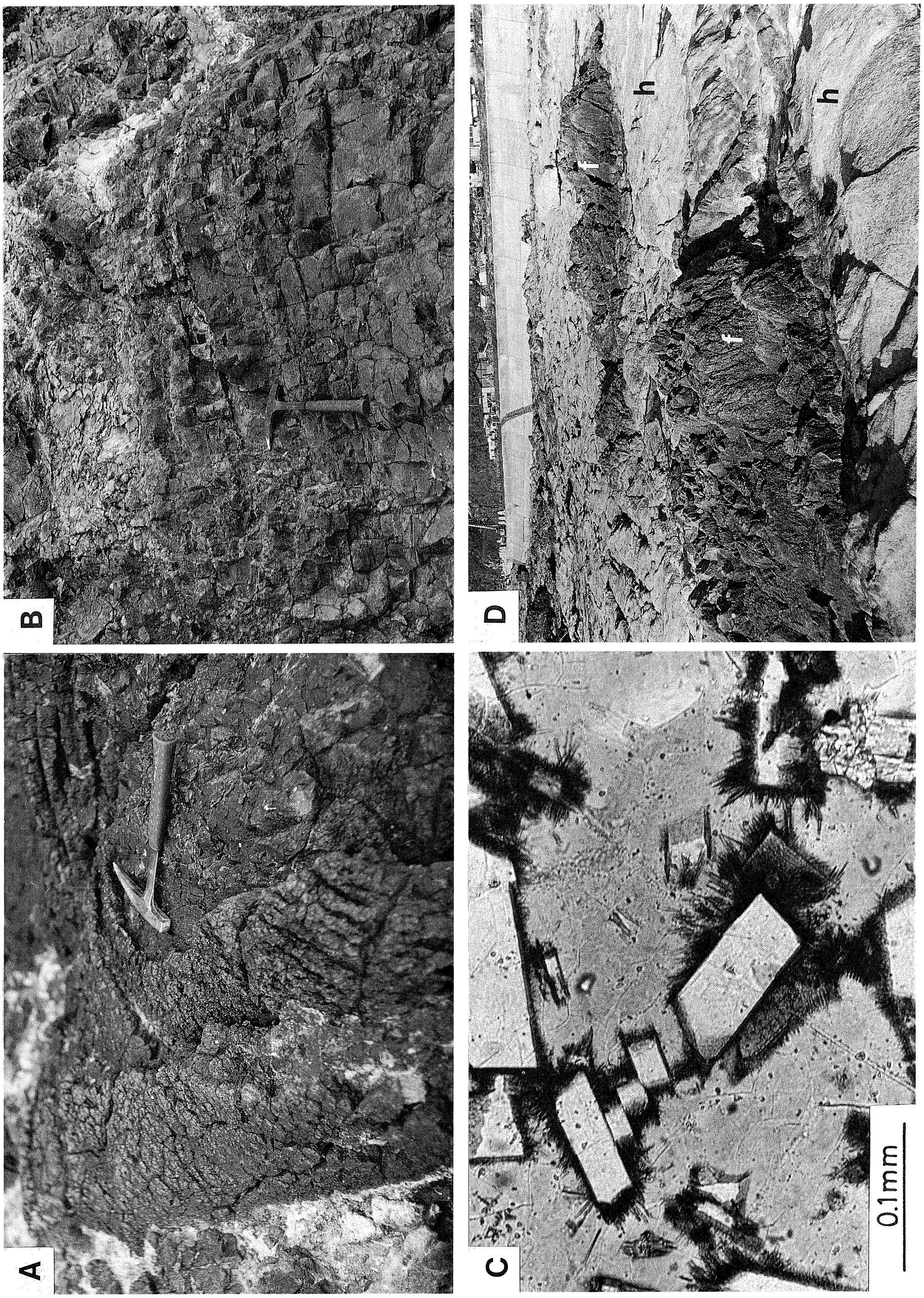

Plate 3

Photomicrograph showing a sequence of fracturing of plagioclase phenocrysts in a feeder dyke of rhyolite. Loc. Kawashira (No. 10 in Fig. 2). The capital letter refers to the respective portion of Fig. 13. Parallel nicol.

A: flawless phenocrysts at the core.

C: fractured phenocrysts in the flow layer zone.

E: partially broken phenocrysts at the obsidian rim.

F: completely broken phenocrysts in the hyaloclastite.

Plate 3

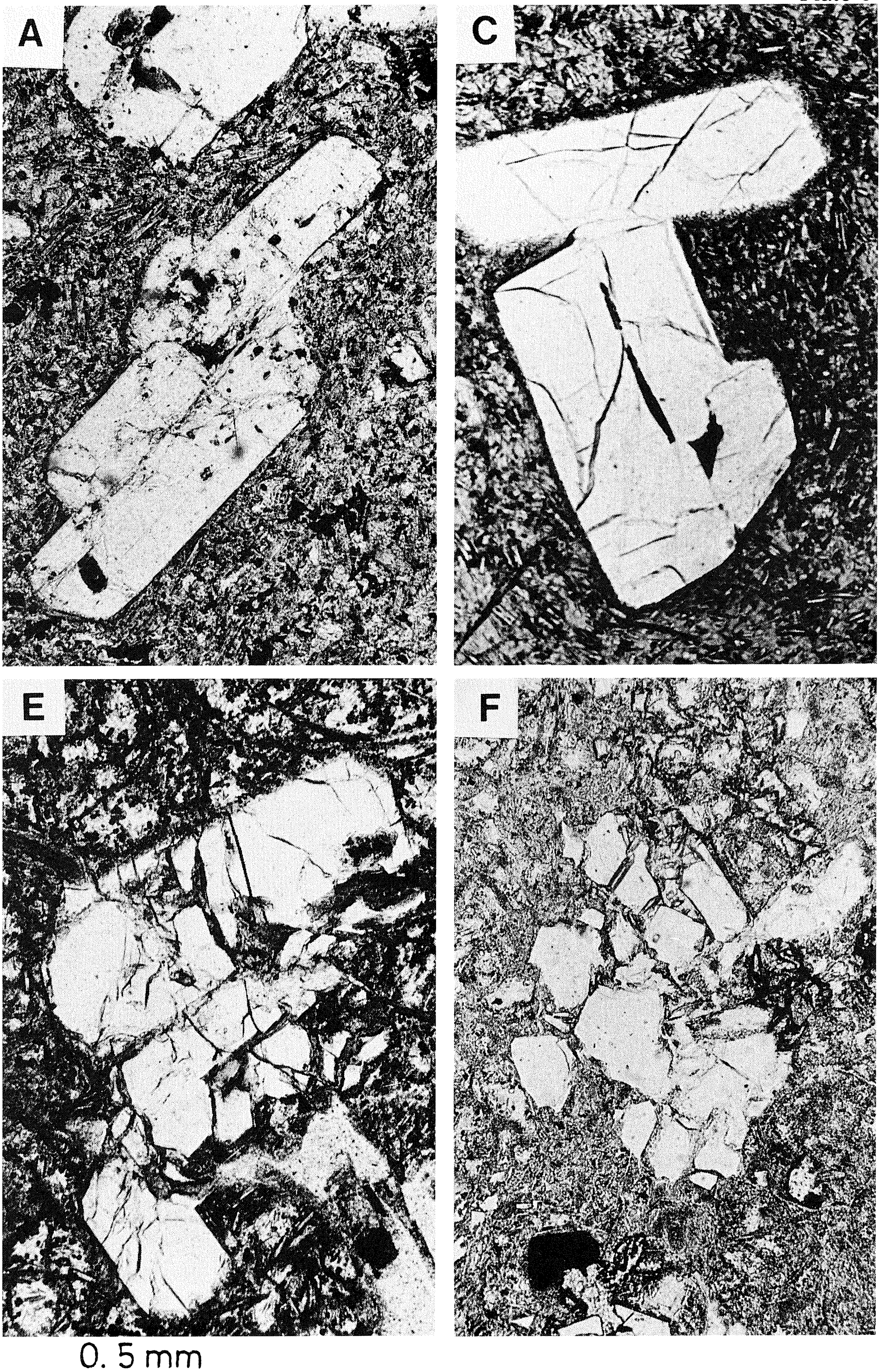

Plate 4

A. Hyaloclastite (A) of basaltic andesite composed mostly of concentric pillows. Loc. Benzaima (No. 12 in Fig. 2).

B. Hyaloclastite (B) of pyroxene andesite. Monolithologic angular blocks are set in a matrix of cogenetic vitric tuff. Loc. Kabuto (No. 14 in Fig. 2).

C. Photomicrograph of the matrix of hyaloclastite (B) of pyroxene andesite. Loc. Utasutsu (No.19 in Fig.2).

D. Foreset-bedded hyaloclastite (B) and topset-bedded disintegrated sheet flows associated with hyaloclastite. Loc. Hamamasu (No. 1 in Fig. 2).

Plate 4

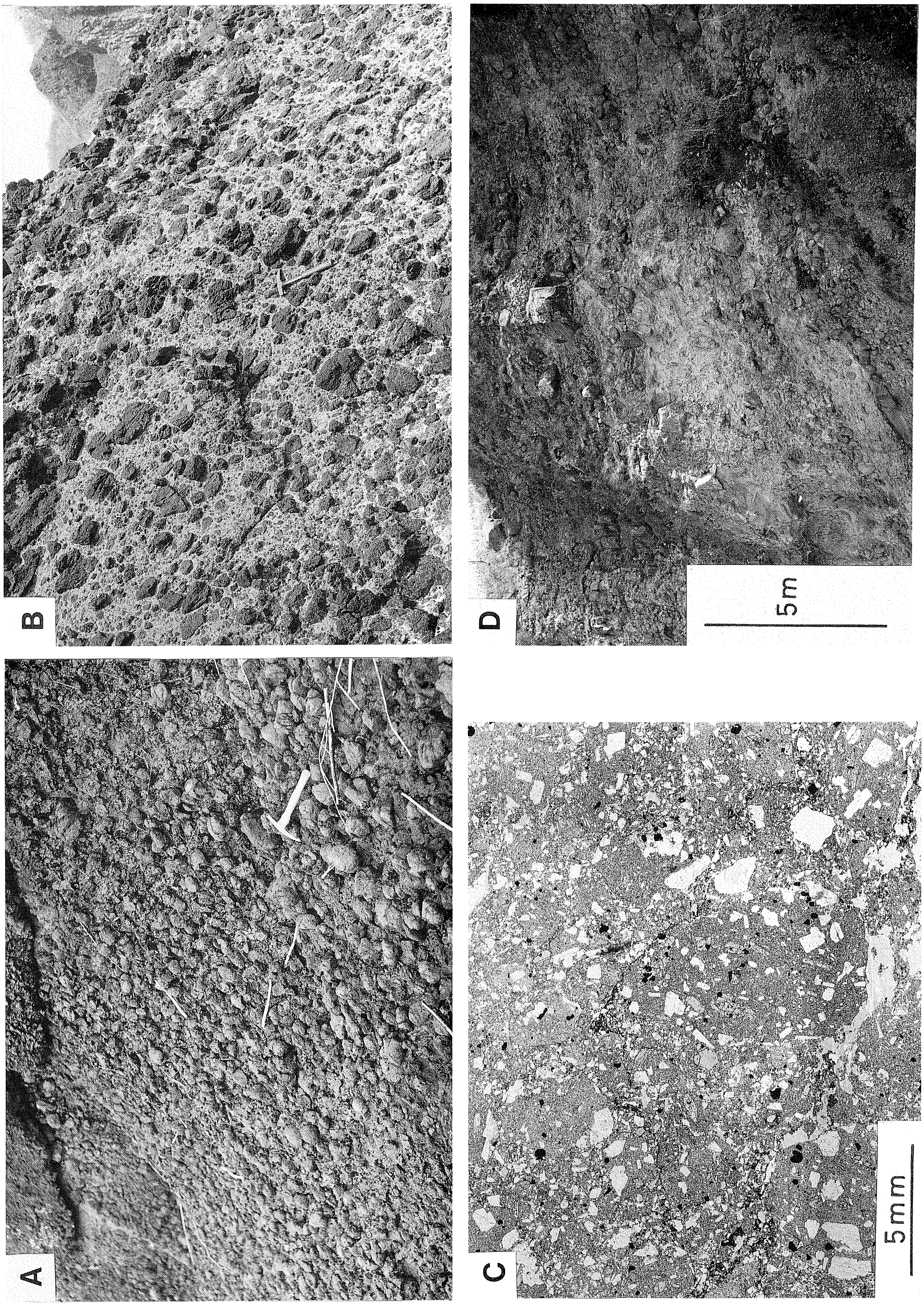

Plate 5

A. An abrasion platform at Kabuto (No. 14 in Fig. 2). Foreset-bedded hyaloclastite (A) overlies normal-graded hyaloclastite (B).

B. Foreset-bedded hyaloclastite (B) of pyroxene andesite. Each bed displays remarkable reverse grading. Loc. Gokibiru (No. 2 in Fig. 2).

C. Foreset-bedded hyaloclastite (A) of pyroxene andesite. Note faint reverse-grading. Loc. Moiwa (No. 13 in Fig. 2).

D. Lava tongue disintegrated into concentric pillows by curved joints to form hyaloclastite (A). Loc. Kayanuma (No. 15 in Fig. 2).

Plate 5

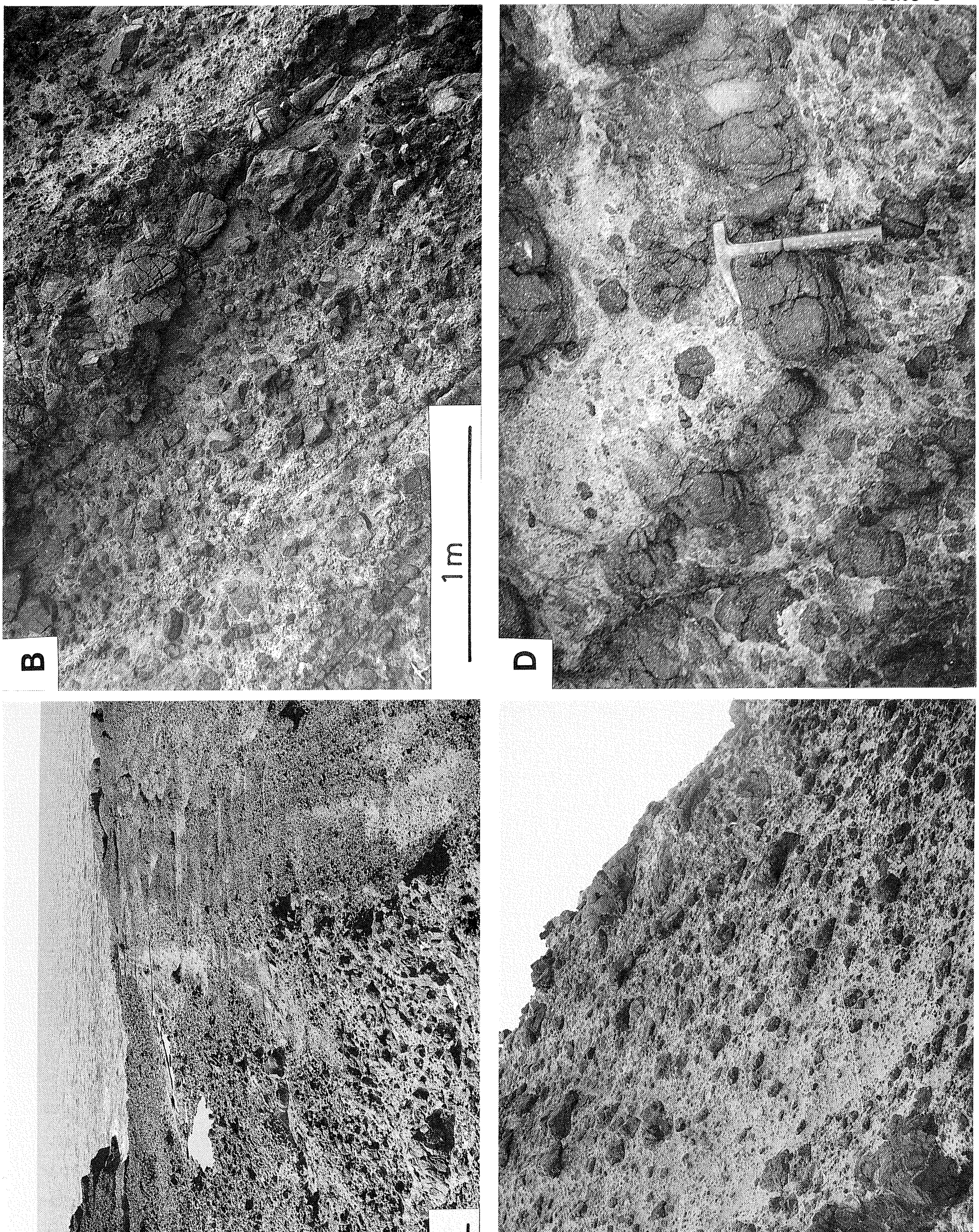

Plate 6

A. A polished handspecimen of peperite consisting of aphyric andesite fragments and mudstone chips. Loc. Moiwa (No. 13 in Fig. 2). a : andesite fragment, m : mudstone chip.

B. Photomicrograph of the same peperite as Plate 6A. a : andesite fragment, m : mudstone chip, p : plagioclase phenocryst. The mudstone is moulded fitting with the andesite fragments. Cross nicol.

C. Pyroclastic pillow breccia composed of scoria pillows set in a matrix of scoriaceous vitric tuff. Note several flow units showing reverse-grading. Large pillow fragments are concentrated to the top of each unit. Loc. Harauta (No. 23 in Fig. 2).

D. Lapilli tuff consisting of vesiculated scoriae enveloped with palagonite rinds. Loc. Yamanaka (No. 20 in Fig. 2).

Plate 6