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INTERNAL STRUCTURES AND FRACTURE NETWORKS IN A MIOCENE DACITE INTRUSION, REBUN ISLAND, HOKKAIDO, JAPAN

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ABSTRACT

Momo-iwa, Rebun Island, Hokkaido, Japan, is a dacite cryptodome (intrusive dome) 200-300 m across and 190 m high. The dome displays well preserved, primary internal structures in a cross-section and provides an excellent opportunity to describe the internal structures and fracture networks of a shallow-level intrusion. The internal structure of the dome is concentric, with a massive core, banded rim, and narrow brecciated border, all of which are composed of compositionally uniform feldspar-phyric dacite. Boundaries between each of the zones are distinct but gradational. The massive core consists of homogeneous coherent dacite and is characterized by radial columnar joints 60-200 cm across. The banded rim encircles the massive core and is 40 m wide. It is characterized by large-scale flow banding parallel to the dome surface. The flow banding comprises alternating partly crystalline and more glassy bands 80-150 cm thick. The banding is overprinted by radial columnar joints which are continuous with the radial columnar joints in the massive core. The columns in the banded rim are hexagonal and occasionally pentagonal in cross-section, and gradually decrease in diameter outward from 60-80 cm near the massive core to 40-60 cm at the margin of the banded rim. The outermost brecciated border is up to 80 cm thick, and consists of in situ breccia and blocky peperite. The in situ breccia comprises polyhedral dacite clasts 5-20 cm across and a cogenetic granular matrix. The blocky peperite consists of polyhedral dacite clasts 0.5-2 cm across separated by the host sediment (mudstone). The internal structures of the dome suggest endogenous growth involving a continuous magma supply during a single intrusive phase and simple expansion from the interior, and simple cooling history. Although much larger, the internal structures and fractures of Momo-iwa closely resemble those of smaller lobes (tens of metres across) in subaqueous felsic lobe-hyaloclastite lavas. Larger intrusions for HDR (Hot Dry Rock) geothermal electric power plants (such as granite intrusion) would have similar internal structures and fracture networks, if the intrusion had similar mode of growth and simple cooling history.

1. INTRODUCTION

In advanced geothermal heat extraction from HDR (Hot Dry Rock), one of the key technologies is the characterization of fracture networks and estimation of internal structures within a plutonic intrusion such as granite. It is highly desirable to estimate the basic characteristics of fractures, such as distribution, size and aperture in plutonic intrusions, and to infer the formation mechanism of the fractures. Detailed descriptions of fractures in exposed intrusions (such as granite mass exposed on the ground surface) are, however, rare in the literature, and this rareness may be due the lack of perfect, continuous, cross-section exposures of large plutonic intrusions. Thus, we have studied fractures and internal structures of a smaller silicic intrusion (several hundered metres across) which shows near-perfect, continuous exposure of the cross section.

A Miocene dacitic dome at Momo-iwa, Rebun Island, Hokkaido, Japan (Momo-iwa dome), displays well preserved, primary internal structures in a cross-section exposure along the seashore. Contacts with enclosing marine sedimentary formations are intrusive. Momo-iwa provides an excellent opportunity to describe the fracture networks and the internal structure of an intrusion as the basis for inferring mechanisms of dome growth. The objectives of this paper are (1) to describe in detail the internal structures and fracture networks of the dome, and (2) to infer the formation mechanisms of the internal structures and fracture networks. Internal structures of the Momo-iwa dome have been described by Goto and McPhie (1998), and we will introduce their work in this paper. We believe this description will give important constraints to the fracture networks and internal structures in larger silicic intrusions such as granites.

2. GEOLOGICAL SETTING

The Momo-iwa dome is located in the southern part of Rebun Island in the northeastern part of the Sea of Japan (Fig. 1). The main units present on the island are Cretaceous volcanic rocks of the Rebun Group, overlain by Late Miocene sedimentary rocks of the Motochi, Meshikuni and Hamanaka Formations, and several Late Miocene basaltic to dacitic intrusions (Fig. 1; Nagao et al., 1963). The Motochi Formation is the lowermost Late Miocene formation on the island, and is about 200 m thick. It comprises mudstone, sandstone and conglomerate, and dips gently westward. Lenticular coal seams, plant fossils and shallow marine mollusc fossils such as *Chlamis*, *Patinopecten*, *Serripes* and *Neptunea* have been reported from this formation (Nagao et al., 1963). The Motochi Formation is overlain by the Meshikuni Formation, which is about 200 m thick. The Meshikuni Formation consists of sandstone, mudstone, conglomerate and andesitic hyaloclastite, and dips gently northwestward. It includes shallow marine mollusc fossils such as *Glycymeris*, *Patinopecten* and *Ostrea* (Nagao et al., 1963). In the northern part of the island, the Meshikuni Formation is overlain by the Hamanaka Formation, which is more than 250 m thick. The Hamanaka Formation comprises alternating siltstone and mudstone, and dips gently westward or eastward. No fossils have been recorded from it. Along the western coast of the island, the Motochi, Meshikuni and Hamanaka Formations have been intruded by Late Miocene basaltic to dacitic sills, laccoliths and domes up to several hundred metres across (Fig. 1). The Momo-iwa dome is one such intrusion and was emplaced into the Motochi Formation. The dome has been dated as 13.0?1.6 Ma by the K-Ar method (Goto et al., 1995).

3. MOMO-IWA DOME AND HOST SEDIMENT

The Momo-iwa dome has been partly exhumed and is well exposed in three dimensions (Fig. 2). It is elliptical in plan view, ranging from 200 m (west - east) to 300 m (north - south) in diameter. In cross-section, it is hemispherical with very steeply sloping sides and an exposed height of 190 m. The enclosing Motochi Formation is only gently tilted and the dome itself shows no evidence of deformation or faulting after emplacement. The dome has probably retained its original shape, except that the western part has been eroded. On the large scale, the partly exhumed outer surface of the dome is smoothly curved and there are no deep indentations.

The host sediment (the Motochi Formation) of the Momo-iwa dome outcrops at the base and on top of the dome. At the base of the dome the host sediment dips 10^o-30^o westward and consists of alternating beds of pale grey sandstone 10-30 cm thick and dark grey mudstone 10-20 cm thick, associated with minor pebbly sandstone. Near the dome (within 5 m from the contact), the alternating sandstone and mudstone beds have been highly deformed and locally intermixed. The mixed part comprises amoeboid patches of sandstone 10-20 cm across embedded in massive mudstone. Details of the contacts between the dome and host sediment are described later. On top of the dome the host sediment outcrops in an area about 5m x 10m but no contacts with the dome dacite are exposed. There, the host sediment consists of pale grey, poorly sorted, non-stratified sandstone.

4. INTERNAL STRUCTURES AND FRACTURES OF THE MOMO-IWA DOME

The interior of the Momo-iwa dome is displayed in a remarkable north-south cross-section (Fig. 2). The internal structure is concentric and consists of three zones: a massive core, a banded rim and a brecciated border.

4.1. Massive core

In the exposed section, the massive core in the centre of the dome is about 150 m across. It comprises pale grey, massive, coherent dacite (or high silica andesite, $SiO2$=63 wt.%, Table 1) and is characterized by columnar joints radiating regularly from the core to the margins. The columns have hexagonal and occasional pentagonal or quadrangular outlines in cross-section and gradually decrease outwards in diameter, from 150-200 cm in the centre to 60-80 cm at the margin of the core.

The dacite is porphyritic, with 5 vol.% plagioclase phenocrysts (<1 mm long) and trace amounts of augite (<0.5 mm) and opaque (<0.5 mm) phenocrysts. The groundmass (95 vol.%) shows a pilotaxitic texture dominated by plagioclase microlites (82 vol.%), pale brown glass (7 vol.%), opaque minerals (3 vol.%), quartz (2 vol.%) and augite (1 vol.%). Although no macroscopic flow banding is present in the massive core, the plagioclase microlites are strongly aligned and define a flow texture that is deflected around the phenocrysts. No vesicles occur in the dacite of the massive core. The massive core passes outward into the banded rim with the gradual appearance of banding. There is no sharp contact or discontinuity between these two zones.

4.2. Banded rim

The banded rim encircles the massive core, and is about 40 m wide (Fig. 2). It comprises alternating pale grey and dark grey bands, both being 80 to 150 cm thick. Neither kind of band shows any systematic variation in thickness outward. The pale grey bands are more resistant to weathering and protrude, whereas the dark grey bands are recessive. The bands are parallel to the outer surface of the dome and in three dimensions are arranged concentrically like a series of shells. The banding is overprinted by radial columnar joints which are continuous with the radial columnar joints in the massive core. The columns in the banded rim are hexagonal and occasionally pentagonal in cross-section, and gradually decrease in diameter outward from 60-80 cm near the massive core to 40-60 cm at the margin of the banded rim.

The banded rim consists of partly crystalline dacite. The size, abundance and mineralogy of the phenocrysts in this zone are the same as in the massive core. However, the dacite in the banded rim is vesicular (5 vol.% vesicles) and more glassy than the dacite in the massive core. The vesicles are amoeboid and elongate in shape (1-3 mm across, 2-4 mm long), with long axes aligned parallel to the dome surface. In the pale grey bands, the groundmass (90 vol.% excluding vesicles) of the dacite shows a hyalopilitic texture comprising 50 vol.% plagioclase microlites and trace amounts of opaque minerals embedded in pale brown glass (40 vol.%). The plagioclase microlites are strongly aligned parallel to the dome surface. The dark grey bands consist of partly crystalline dacite which has more glassy groundmass than the pale grey bands. The groundmass (90 vol.% excluding vesicles) of the dark grey bands shows a hyalopilitic texture comprising 40 vol.% plagioclase microlites oriented parallel to the dome surface and small amounts of opaque minerals embedded in dark brown glass (50 vol.%). The glass is partially altered and replaced by clay minerals. The banded rim passes outward into the brecciated border with the gradual appearance of fractures in the outermost pale grey band. There is no sharp contact between these two zones.

4.3. Brecciated border

The outermost brecciated border is 5-80 cm wide and encircles the banded rim, extending to the margin of the Momo-iwa dome (Fig. 2). It consists of *in situ* dacite breccia and peperite that are well exposed only at the southern and southwestern margins of the dome. At the southern margin of the dome, the coherent dacite of the outermost pale grey band becomes increasingly fractured and brecciated outward into a zone of *in situ* breccia about 80 cm wide. The breccia comprises monolithologic, polyhedral dacite clasts 5-20 cm across and a cogenetic matrix consisting of angular dacite fragments up to 5 mm across. The breccia includes domains of jigsaw-fit and clast-rotated texture. The dacite clasts have the same mineral assemblage and texture as the dacite in the pale grey bands, although they are distinctly more vesicular (up to 20 vol.% vesicles). The vesicles are spheroidal in shape and up to 5 mm across. The contact with the host sediment is not exposed at this location.

The southwestern part of the dome is in contact with dark grey massive mudstone. The outermost pale grey band at the margin of the dome is fractured, brecciated and mixed with mudstone in a narrow zone of peperite 5-10 cm wide. The peperite comprises pale grey, polyhedral dacite clasts 0.5-2 cm across separated by indurated, dark grey massive mudstone. Some groups of dacite clasts show a jigsaw-fit texture. The dacite clasts have the same mineral assemblage and texture as in the in situ breccia, but are less vesicular (up to 5 vol.%, <1 mm across).

5. DISCUSSION

5.1. Environment of dome emplacement

Coal seams, plant fossils and shallow marine mollusc fossils in the Motochi Formation, and shallow marine molluscs in the immediately overlying Meshikuni Formation suggest deposition of the host sedimentary succession in a shallow marine environment. The presence of peperite in the brecciated border indicates that the host sediment (Motochi Formation) was wet and only weakly consolidated at the time of dome emplacement (Kokelaar, 1982).

The Momo-iwa dome is inferred to have been intrusive (ie. a cryptodome; cf. Minakami et al., 1951; McPhie et al., 1993) and did not break through the sediment cover because: (1) the dome is entirely surrounded by the Motochi Formation; and (2) no dacite clasts nor dacite-derived clastic facies are present in the adjacent or younger parts of the Motochi Formation. The sediment cover was probably thin because dacite clasts in the brecciated border zone are vesicular (up to 20 vol.%), indicating that the confining pressure was relatively low, but its presence could have influenced the dome morphology. Lateral spreading that accompanies emplacement of subaerial extrusive domes (e.g., Huppert et al., 1982; Fink and Bridges, 1995) would have been inhibited by the sediment, allowing the dome to maintain a high-aspect-ratio, hemispherical shape.

5.2. Formation of the internal structures in the Momo-iwa dome

The Momo-iwa dome is characterized by a concentric zonal structure consisting of a massive core, banded rim and brecciated border. These three zones are inferred to be genetically related internal structures that developed within a single intrusion and to not represent three discrete injections of magma, because the contacts between the zones are gradational: the massive core grades outward into the banded rim with the gradual appearance of the banding, and the banded rim grades into the brecciated border with the gradual appearance of fractures. In addition, phenocryst mineralogy, size and abundance are identical in all three zones and radial columnar joints in the massive core extend continuously through the banded rim.

The texturally uniform, coherent dacite of the massive core has the largest diameter columnar joints and highest groundmass crystallinity among the three zones. The dimensions of columnar joints depend chiefly on the temperature and rate of cooling, so that smaller columns develop in response to more rapid cooling (e.g., Grossenbacher and McDuffie, 1995). Groundmass crystallinity is also related to the rate of cooling, with slow cooling favouring more complete melt crystallization. Therefore, the massive core is interpreted to have formed by slow cooling of homogeneous dacite magma and the rate of cooling increased gradually outward.

The banding that characterizes the rim zone is overprinted by the radial columnar joints, and therefore formed before the joints. The bands are defined by variations in colour and groundmass crystallinity, pale grey, more crystalline bands alternating with dark grey, more glassy bands. Such textural variations are similar to those that define flow bands formed in response to laminar shear in viscous silicic lavas and intrusions (e.g., Christiansen and Lipman, 1966; McPhie et al., 1993). Although flow bands are typically sub-millimetre to centimetre in width, bands up to several metres wide have also been reported (Snyder and Fraser, 1963; Christiansen and Lipman, 1966). Therefore, the banded rim in the Momo-iwa dome is interpreted to be a large-scale flow banded zone preferentially developed at the margin of the dome.

The banded rim grades outward into the brecciated border with gradual appearance of fractures, suggesting that the brecciated border formed by fragmentation of the outermost part of the banded rim. The jigsaw-fit texture in the brecciated border indicates that brecciation was *in situ*. The polyhedral shape of the dacite clasts is consistent with brittle fragmentation, most likely in response to cooling contraction on contact with wet sediment and/or dynamic stressing of the rigid outer margin due to continued movement of the intruding dacite (cf. Brooks et al., 1982; Kokelaar, 1986).

At the time of intrusion, the host sediment immediately adjacent to the dome may have been fluidized by vaporization of pore water (Kokelaar, 1982; Busby-Spera and White, 1987; Brooks, 1995), more or less simultaneously with fragmentation of the dacite. The fluidised sediment invaded the newly created open fractures in the dacite in response to the pressure reduction as the fractures opened (Kokelaar, 1986; Brooks, 1995; Goto and McPhie, 1996). Open spaces between the clasts were thus completely filled with homogenised host sediment, resulting in the peperite texture. Escaping pore fluid also disrupted bedding and caused mixing of sand and mud layers up to 5 m from the contact.

5.3. Growth, cooling and fracturing of the Momo-iwa dome

In general, growth of lava domes is thought to be either endogenous or exogenous (Fink et al., 1990; Fink, 1993). When new lava is added to the outer surface of a dome, the style of growth is referred to as exogenous. If new lava is injected into the dome interior, the dome grows by internal inflation and the growth is endogenous (Fink, 1993). Styles of growth of subaqueous cryptodomes have not been well studied. The concentric internal structure of the Momo-iwa dome strongly suggests that the dome formed by endogenous growth involving uniform steady internal inflation.

The Momo-iwa dome is inferred to have grown by simple expansion in response to a continuous supply of magma during a single intrusive phase. A pulsatory magma supply and multiple injections of magma would have resulted in a more complicated internal structure comprising multiple domes or lobes (e.g., Hamasaki, 1994) with highly variable flow banding orientations and more complex arrangements of textural domains (glassy versus crystalline, vesicular versus dense).

During injection of magma, the margin of the dome close to the contact with wet sediment was cooled more rapidly than the interior. Once a chilled margin formed, it could have effectively insulated the interior, allowing continued injection of magma as the dome inflated. Only the more viscous chilled margin would be likely to fracture in a brittle fashion due to dynamic stressing as more magma was fed into the interior. In the rim zone, the magma was hotter and more ductile. As the dome expanded, large-scale laminar flow structure developed in the rim. The core comprises the final magma injected into the dome, which, being well insulated and hottest, remained unsheared and massive.

The mode of cooling of the Momo-iwa dome can be inferred from the geometry of the columnar joints. The radial columnar joints in the Momo-iwa dome are very regular in arrangement through the massive core to the banded rim. The diameter of the columns gradually decreases outward from the core, suggesting that the isothermal surfaces within the dome during cooling were concentrically parallel to the dome surface (Spry, 1962). Such concentric isothermal surfaces are consistent with dome growth by endogenous inflation as inferred above. Exogenous growth or multiple discrete injections of magma would have resulted in highly variable isothermal surfaces and more complicated joint patterns. The concentric isothermal surfaces also reflect the simple hemispherical shape of the dome.

Thus, emplacement of the Momo-iwa dome can be explained as follows: A lobe of dacitic magma intruded wet, poorly consolidated mud and sand in a shallow marine environment. Continued supply of new magma into the interior resulted in inflation to form a small dome. Additional expansion of the dome was accommodated by the weak, wet sediment. The margin of the dome was rapidly cooled due to contact with wet sediment. Blocky peperite formed along the margin of the dome in response to cooling contraction of the chilled dacite in contact with wet sediment and/or dynamic stressing due to continued growth of the dome. The rigid chilled margin and the enclosing sediment inhibited lateral spreading so that the dome height increased almost at the same rate as the dome width, the result being the high aspect ratio, almost hemispherical dome shape. Inside the chilled margin, large-scale flow banding developed in a zone subject to shear as more hot magma was fed into the core. Finally, the magma cooled simply from the outer surface inwards, and radial columnar joints that propagated perpendicular to the dome surface record progressively slower cooling rates inward to the massive core. Differential erosion of the softer host sedimentary succession compared with the harder dacite dome has resulted in near-perfect exhumation of the dome.

5.4. Similarity between the Momo-iwa dome and smaller silicic lava lobes

The internal structure of the Momo-iwa dome closely resembles the structure of subaqueous silicic lava lobes. These are in general characterized by the presence of concentric zonal structures and radial columnar joints. However, such lobes are only tens of metres across whereas Momo-iwa is ten times larger. De Rosen-Spence et al. (1980) described Pleistocene subglacial rhyolite lava lobes from Blahnukur, Iceland and Archean subaqueous rhyolite lava lobes from Quebec, Canada. The Icelandic lava lobes are up to 10 m across, and are commonly zoned, with a massive core, a flow banded rim and a brecciated border. The core consists of poorly vesiculated, microcrystalline rhyolite. The flow banded rim is 50 cm thick and consists of alternations of centimetre-thick bands of pumice, obsidian, and partly crystalline, poorly vesiculated rhyolite. The border is 10-50 cm thick and consists of intensely fractured obsidian that grades outwards into hyaloclastite. Similar internal zonation of structures was found in the Archean examples. Furnes et al. (1980) described Quaternary subglacial rhyolite lava lobes tens of metres across from several localities in Iceland. They recognised the same zonation in the lobes as those noted by De Rosen-Spence et al. (1980), but reported that the core commonly had well developed radial columnar joints. Yamagishi and Dimroth (1985) described Miocene subaqueous rhyolite lava lobes about 8 m across in Hokkaido, Japan, and noted that the lobes had a concentric zonal structure, with a massive core (5 m across), banded rim (1-3 m thick), and an outermost obsidian border that graded outward into hyaloclasite.

Lava lobes in subaqueous silicic lobe-hyaloclastite lavas are, in general, formed by simple expansion as magma is injected into the interior, and cool simply from the lobe surfaces (De Rosen-Spence et al., 1980; Furnes et al., 1980; Yamagishi and Dimroth, 1985). We thus infer that the similarity of the internal structures between the Momo-iwa dome and the lava lobes can be attributed to a similar mode of growth and similar cooling history.

5.5. Applications to larger silicic intrusions for HDR geothermal electric power plants.

Internal structures and fracture networks in granite intrusions are central in hot dry rock geothermal projects, and estimations of fractures within underground granites are important subjects for geothermal developments. Although petrology and geochemistry of granites have been well studied and discussed by many geoscientists (e.g. Chappell and White, 1974; Ishihara, 1977; Collins et al., 1982), there has been few descriptive studies of fractures in exposed granite intrusions(e.g. Segall and Pollard, 1983; Gerla, 1988; Bergbauer and Martel, 1999), and little has been known about fracture networks in granites.

Similarity between the Momo-iwa dome and smaller silicic lava lobes, described above, strongly suggests that independently of the size of intrusions, silicic intrusions generally have similar internal structures and thermal stress fractures, if the intrusions had a similar mode of growth and a simple cooling history. Recent studies (Segall and Pollard, 1983; Gerla, 1988; Bergbauer and Martel, 1999) indicate that thermal stress plays a key role in the formation of internal fractures of granite intrusions. We thus infer that larger silicic intrusions such as granite would have similar internal structures and fracture networks to the Momo-iwa dome, if the intrusion had a similar mode of growth and a simple cooling history.

It has to be stressed that our conclusion described above is limited to the basic structures and basic fracture networks within silicic intrusions. There may be many small differences between the fractures of small silicic domes and those of larger granite intrusions. For example, fractures in the Momo-iwa dome make hexagonal and pentagonal columns (columnar joints), whereas those in granites commonly show orthogonal or parallel systems. Such differences may be due to inhomogenity or plastic behavior of granite magma (cf. Lachenbruch, 1962), and should be further studied in detail.

We believe that descriptive studies of small silicic domes will be of great value in interpreting the basic structures and fracture networks in granite intrusions.

6. CONCLUSION

The Momo-iwa dome, Hokkaido, Japan is 200-300 m across and 190 m high. It consists of weakly porphyritic dacite. The dome is characterized by (1) concentric zonal structure consisting of a massive core, a banded rim, and a brecciated border; and (2) radial columnar joints extending through the massive core into the banded rim. Contact relationships indicate that Momo-iwa is a cryptodome which formed from intrusion of dacite into wet, poorly consolidated sediment in a shallow marine environment. The dome is inferred to have grown by steady inflation as magma was supplied continuously during a single intrusive phase. The banding in the rim zone is a kind of large-scale flow banding developed inside the more rigid, chilled and brecciated border zone as new, hotter magma was supplied in the core. The internal structures of the Momo-iwa cryptodome closely resemble those of much smaller (tens of metres across) lobes in subaqueous and subglacial lobe-hyaloclastite lavas. These structures appear to be characteristic of domes or lobes (or larger intrusions ?) that grow endogenously.

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REFERENCES

Bergbauer, S. and Martel, S.J. (1999). Formation of joints in cooling plutons. *Journal of Structural Geology*, Vol. 21, pp. 821-835.

Brooks, E.R. (1995). Palaeozoic fluidization, folding, and peperite formation, northern Sierra Nevada, California. *Can. J. Earth Sci.*, Vol. 32, pp. 314-324.

Brooks, E.R., Wood, M.W. and Garbutt, P.L. (1982). Origin and metamorphism of peperite and associated rocks in the Devonian Elwell Formation, northern Sierra Nevada, California. *Geol. Soc. Am. Bull.*, Vol. 93, pp. 1208-1231.

Busby-Spera, C.J. and White, J.D.L. (1987). Variation in peperite textures associated with differing host-sediment properties. *Bull. Volcanol.*, Vol. 49, pp. 765-775.

Chappell, B.W. and White, A.J.R. (1974). Two contrasting granite types. *Pacific Geol.* Vol. 8, pp. 173-174.

Christiansen, R.L. and Lipman, P.W. (1966). Emplacement and thermal history of a rhyolite lava flow near Fortymile Canyon, southern Nevada. *Geol. Soc. Am. Bull.*, Vol. 77, pp. 671-684.

Collins, W.J., Beam, S.D., White, A.J.R. and Chappell, B.W. (1982), Nature and origin of A-type granites with paerticular reference to southeastern Australia. *Contrib. Mineral. Perol.*, Vol. 80, pp. 189-200.

De Rosen-Spence, A.F., Provost, G., Dimroth, E., Gochanauer, K. and Owen, V. (1980). Archean subaqueous felsic flows, Rouyn-Noranda, Quebec, Canada, and their Quaternary equivalents. *Precambrian Res.*, Vol. 12, pp. 43-77.

Fink, J.H. (1993). The emplacement of silicic lava flows and associated hazards. In: *Active Lavas,* C.J. Kilburn and G. Luongo (Eds.), University College London Press, pp. 5-24.

Fink, J.H. and Bridges, N.T. (1995). Effects of eruption history and cooling rate on lava dome growth. *Bull. Volcanol.*, Vol. 57, pp. 229-239.

Fink, J.H., Malin, M.C. and Anderson, S.W. (1990). Intrusive and extrusive growth of the Mount St Helens lava dome. *Nature*, Vol. 348, pp. 435-437.

Furnes, H., Fridleifsson, I.B. and Atkins, F.B. (1980). Subglacial volcanoes - on the formation of acid hyaloclastites. *J. Volcanol. Geotherm. Res.*, Vol. 8, pp. 95-110.

Gerla, P.J. (1988). Stress and fracture evolution in a cooling pluton: an example from the Diamond Joe stock, Western Arizona, U.S.A. *J. Volcanol. Geotherm. Res.*, Vol. 34, pp. 267-282.

Goto, Y., Nakagawa, M. and Wada, K. (1995). Tectonic setting of the Miocene volcanism in the Northern Hokkaido district, Japan: Speculation from their K-Ar ages and major element chemistry. *J. Min. Pet. Econ. Geol.*, Vol. 90, pp. 109-123.

Goto, Y. and McPhie, J. (1996). A Miocene basanite peperitic dyke at Stanley, northern Tasmania, Australia. *J. Volcanol. Geotherm. Res.*, Vol. 74, pp. 111-120.

Goto, Y. and McPhie, J. (1998). Endogenous growth of a Miocene submarine dacite cryptodome, Rebun Island, Hokkaido, Japan. *J. Volcanol. Geotherm. Res.*, Vol. 84, pp. 273-286.

Grossenbacher, K.A. and McDuffie, S.M. (1995). Conductive cooling of lava: columnar joint diameter and stria width as functions of cooling rate and thermal gradient. *J. Volcanol. Geotherm. Res.*, Vol. 69, pp. 95-103.

Hamasaki, S. (1994). The internal structure of a rhyolite intrusion and the process of emplacement; an example from the Izumiyama porcelain stone deposit, Saga prefecture, southwestern Japan. *Bull. Volcanol. Soc. Japan*, Vol. 39, pp. 91-98.

Huppert, H.E., Shepherd, J.B., Sigurdson, H. and Sparks, R.S.J. (1982). On lava dome growth, with application to the 1979 lava extrusion of the Soufriere of St. Vincent. *J. Volcanol. Geotherm. Res.*, Vol. 14, pp. 199-222.

Ishihara, S. (1977). The magnetite-series and ilmenite-series granitic rocks. *Mining Geol.*, Vol. 27, pp. 293-305.

Kokelaar, B.P. (1982). Fluidization of wet sediments during the emplacement and cooling of various igneous bodies. *J. Geol. Soc. London*, Vol. 139, pp. 21-33.

Kokelaar, B.P. (1986). Magma-water interactions in subaqueous and emergent basaltic volcanism. *Bull. Volcanol.*, Vol. 48, pp. 275-289.

Lachenbruch, A.H. (1962). Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost. *Geol. Soc. Am. Bull. Spac. Paper*, No. 70, 69 pp.

McPhie, J., Doyle, M. and Allen, R. (1993). *Volcanic Textures: A Guide to the Interpretation of Textures in Volcanic Rocks.* Centre for Ore Deposit and Exploration Studies, University of Tasmania, Hobart, 198 pp.

Minakami, T., Ishikawa, T. and Yagi, K. (1951). The 1944 eruption of Volcano Usu in Hokkaido, Japan. *Bull. Volcanol.*, Vol. 11: 45-160.

Nagao, S., Akiba, M. and Omori, T. (1963). *Explanatory text of the geological map of Japan, ?Rebunto?, scale 1:50000.* Geological Survey of Hokkaido, Japan, 43 pp.

Segall, P. and Pollard, D.D. (1983). Joint formation in granitic rocks of the Sierra Nevada. *Geol. Soc. Am. Bull.*, Vol. 94, pp. 563-575.

Snyder, G.L. and Fraser, G.D. (1963). Pillowed lavas, I: Intrusive layered lava pods and pillowed lavas Unalaska Island, Alaska. *Geol. Surv. Prof. Paper.*, 454-B, pp. B1-23.

Spry, A. (1962). The origin of columnar jointing, particularly in basalt flows. *Geol. Soc. Aus. Jour.*, Vol. 8, pp. 191-216.

Tsuchiya, N., Shibata, T., Koide, Y., Owada, M., Takazawa, E., Goto, Y., Choi, J.H., Terada, S. and Hariya, Y. (1989). Major element analysis of rock samples by X-ray fluorescence spectrometry, using scandium anode tube. *Jour. Fac. Sci. Hokkaido Univ., Ser. IV*, Vol. 22, pp. 489-502.

Yamagishi, H. and Dimroth, E. (1985). A comparison of Miocene and Archean rhyolite hyaloclastites: Evidence for a hot and fluid rhyolite lava. *J. Volcanol. Geotherm. Res.*, Vol. 23, pp. 337-355.

SiO2	62.89
TiO2	0.89
Al2O3	17.00
Fe2O3*	5.99
MnO	0.13
MgO	2.18
CaO	5.68
Na2O	4.18
K2O	0.89
P2O5	0.23
Total	100.06
L.O.I.	1.97

Table 1. XRF major element chemical analysis of the Momo-iwa dome. Sample was taken from the massive core. Analytical method after Tsuchiya et al. (1989). Fe_2O_3*= total iron as Fe_2O_3; L.O.I.= loss on ignition.

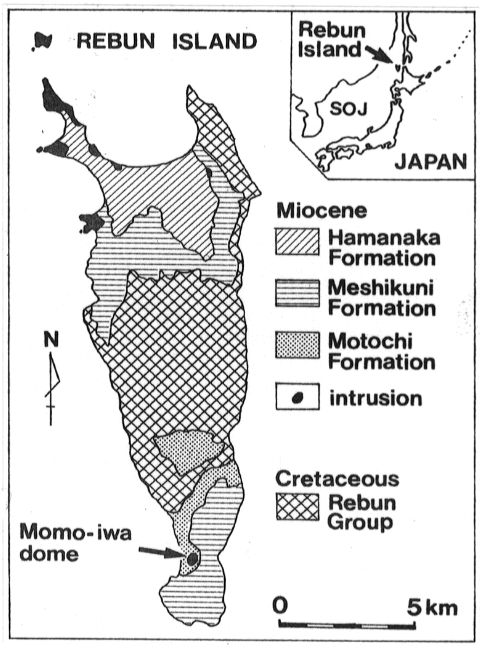

Figure 1. Simplified geological map of Rebun Island, Hokkaido, Japan, showing location of the Momo-iwa dome (solid arrow). Modified from 1:50000 geological map, Rebunto (Nagao et al., 1963). SOJ= Sea of Japan

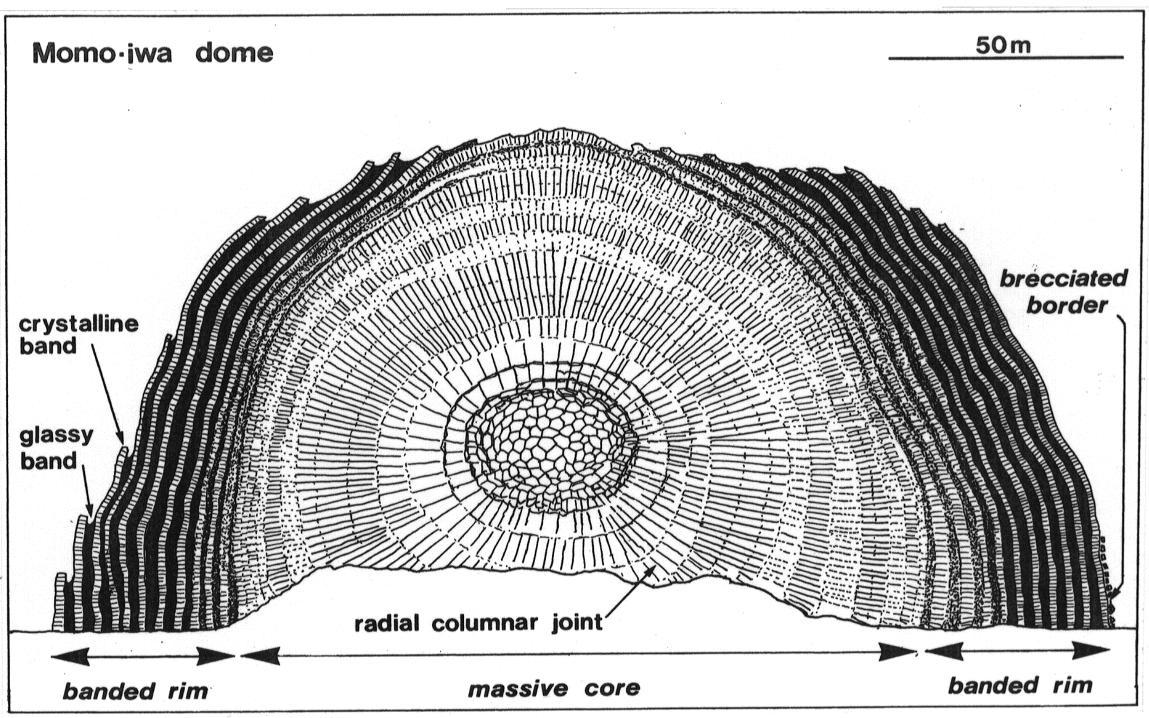

Figure 2. Sketch of the internal structure of the Momo-iwa dome, showing the concentric structure consisting of a massive core, banded rim and brecciated border. Radial columnar joints are well developed through the massive core to the banded rim.