SEDIMENTARY FACIES OF THE MIO-PLIOCENE
VOLCANOTECTONIC DEPRESSIONS ALONG THE VOLCANIC
FRONT IN NORTHEAST HONSHU, JAPAN

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Abstract. Since the Late Miocene, a number of depressions were formed within a narrow terrane along the volcanic front of the Japanese Arc-Trench System. Most of them are a type of caldera called “volcanotectonic depressions” (VTDs) which were probably formed under the control of regional tectonics. The characteristic rocks forming VTDs are basal pumice flows, lacustrine tuffaceous beds, mid-caldera volcanioclastics, and slump-, talus- and sliding-deposits. In general, these rocks originally contained a large amount of vitric materials, which were altered to zeolites and related minerals under high geothermal gradient conditions.

The eruption of basal pumice flows was probably the main cause of the original depressions on land. The deposits are thick and partly welded. Lacustrine tuffaceous beds are the main sediments filling VTDs; these strata contain a large amount of reworked vitric materials. The other four sedimentary facies have recorded episodes relating to volcanic and tectonic movements.

1. Introduction

In the Late Miocene, several isolated islands appeared within a narrow terrane along the volcanic front of the Japanese Arc-Trench System. The terrane was later uplifted to form the backbone zone of northern Honshu. During this process, a number of depressions were formed within this terrane. They were filled by characteristic sediments containing a large amount of volcanioclastic and reworked vitric materials. Ito (1956) first described the Motojuku caldera, northern Kanto, which is very similar in geologic setting to the depressions under consideration here. Recently others have reexamined the stratigraphy, geologic structure, volcanism, sedimentation and alteration of these depressions and clarified that most of them belong to a type of caldera called a “volcanotectonic depression” (VTD).

In this paper, the writers will focus on the characteristic sedimentary facies relating to the development of a VTD.

2. General Description of Volcanotectonic Depressions

2.1 Time and space

As shown in Fig. 1, a number of calderas of late Cenozoic age occur along a narrow
terrane in northern Honshu. They can be divided into three stages, according to fission-track ages. Roughly speaking, Stage I ranges from 7 to 5 Ma, Stage II from 5 to 2 Ma, and Stage III from 2 to the present. All VTDs were formed during Stages I or II; Crater Lake and Kilauea types of volcanic centers were formed during Stage III.

2.2 Morphology and dimensions

VTDs are characteristically surrounded by faults with trends that are concordant with the regional geologic structure. For instance, the external shape of the Sanzugawa caldera is nearly rectangular, reflecting the control of regional geologic structures with trends of N-S and NE-SE.

VTDs are roughly $n \times 10^2$ km$^2$ in area, and the thickness of caldera-filling sediments is $n \times 10^2$ m on average. Therefore, they originally had pancake-like shapes.

2.3 Stratigraphy

Generalized geologic columns of three typical VTDs are shown in Fig. 2. Generally speaking, the lowest formation consists of thick pumice flow deposits which unconformably cover the basement rocks. The main part of the caldera-filling formation consists of lacustrine sediments containing a large amount of reworked vitric material. Occasionally, these strata intercalate thick pumice flows or thin layers of volcaniclastic fall. They also
Fig. 2. Generalized stratigraphic columns of the Oyu, the Sanzugawa and the Shirasawa calderas.
intercalate slump and sliding deposits and interfinger with talus deposits along marginal zones. Lava flows and dike rocks are found in various horizons, as described in the igneous activity section below. In some cases, the formation can be divided into two or three members, each having a sedimentary cycle; local unconformities between them were probably caused by movements relating to volcanic activities, such as eruptions of mid-caldera pumice flows. Total thicknesses of caldera-filling formations range from several tens to several thousand meters.

2.4 Geologic structure

The geologic structure of VTDs is unique and characterized by composite graben-horsts. Many fault blocks are bounded on both sides by gravity faults with definite trends; this structure seems to have been developed through all stages. Though the original shapes of VTDs have generally been modified, they can be roughly estimated by the distribution of lacustrine sediments. The abutting relationship between the basal pumice flow and lacustrine sediments may indicate the margin of the original caldera. A visible fault cannot always be recognized in that area. Block movement at the mid-caldera stage is often demonstrated by the existence of talus deposits along newly-formed fault scarps; the faults of the post-caldera stage are well recognized in all VTDs. At present, most caldera-filling sediments remain in the depression surrounded by these faults, which roughly correlates to that of low Bouguer anomalies. On the other hand, the horst surrounded by these faults correlates to that of high Bouguer anomalies. An example of the geologic structure of a VTD is shown in Fig. 3.

Fig. 3. Simplified figure showing geologic structure of the Sanzugawa caldera.
2.5 **Igneous activity**

Igneous rocks relating to the VTDs under consideration are divided into three types, according to stages of igneous activity.

The pre-caldera igneous activity seems to have been less important for the formation of VTD structures. Thin flows of felsic lava are locally found below the basal pumice flow; however, they probably had little influence on the formation of the depression.

Eruption of the basal pumice flow, the volume of which is extraordinarily large, may have been genetically related to the original depression on land. A brief petrographic description will be given in the following section. Various kinds of lava flows are intercalated with caldera-filling lacustrine sediments, ranging from rhyolitic to basaltic in composition. Most lava flows are thin. Various kinds of dikes and sills intrude into the sediments locally and are often accompanied by hydrothermal alternations. Among them, a clot of vent breccias is notable, an example of which is found in the northern depression of the Sanzugawa caldera. As shown in Fig. 4, the vents were intruded into the black shales of the basement and brecciated themselves and the surrounding rocks.

Post-caldera igneous rocks are widely distributed in and around the caldera, usually occurring as lava flows or lava domes. They range from felsic to intermediate in composition. Lava flows and welded pumice flows cover a wide area inside and outside a typical VTD; however, intrusive rocks are distributed only inside a caldera.

![Diagram](image)

**Fig. 4.** Distribution and three sketches of vent breccias at Takinohara in the Sanzugawa caldera.
2.6 Alteration

The rock alterations appearing in the caldera formations are grouped into caldera-type alterations and hydrothermal alterations.

*Caldera-type alteration:* This alteration is characterized by the regional appearance of zeolites, which are listed in Table 1. Among zeolites, wairakite appears rather rarely. Its appearance, however, is significant as an indicator of high-temperature and low pressure conditions. Laumontite is pervasive, while analcime occurs only locally. Clinoptilolite and mordenite are very common. The clinoptilolite-mordenite zone is further subdivided into clinoptilolite-predominant and a mordenite-predominant subzones. The volcanic glass zone is also subdivided into a fresh glass subzone (in the strict sense) and a weakly altered subzone in which zeolites are absent.

The mode of occurrence of zeolites and related minerals in higher-grade zones is similar to that in the corresponding zone of hydrothermal alteration, while that in lower-grade zones is similar to that of the diagenetic alteration zone.

Alteration zones are mainly distributed in the caldera formations. They do not always surround an intrusive mass or specific feeder. The boundaries between the zones are usually oblique to the stratigraphy. Thus, caldera-type alteration is unique in its manner of zonal distribution among other zeolitizations. It is noteworthy that most economic mordenite deposits in Japan were formed by this type of alteration. The high quality of mordenite from these deposits is caused partly by the high content of vitric materials in caldera formations and partly by moderate temperature conditions under high geothermal gradients.

*Hydrothermal alteration:* Various alteration zones of hydrothermal origin appear locally in the caldera, divided into three groups according to their chemistry of reacting solutions, as listed in Table 2. Hydrothermal alterations are often superimposed upon caldera-type alterations. They mainly appear near actual or estimated faults and around intrusive masses. As an example, Fig. 5 shows the distribution of alteration zones in the Sanzugawa caldera. This indicates that caldera-type alterations are found in all of the

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**Table 1.** Mineral assemblages of the zones of caldera-type alteration. Solid lines denote common occurrence, dashed lines denote rare occurrence.
Table 2. Division of the zones of hydrothermal alteration (after Utada, 1980).

![Table 2 Diagram]

Fig. 5. Simplified figure showing distribution of alteration zones in the Sanzugawa caldera.

caldera formations, and that three hydrothermal alterations are superimposed upon them near an actual fault and an estimated fault zone.

3. Sedimentary Facies

3.1 Basal pumice flow

A basal pumice flow is an essential constituent of all of the VTDs under consideration. It generally unconformably covers various rocks of the basement formations, and is distributed not only in the present structural depressions but also in the surrounding
areas. Talus deposits or thin layers of lacustrine deposits are occasionally found below the basal pumice flow.

Pumice tuff is composed of pumice, various kinds of breccia, phenocrystalline minerals and varying amounts of vitric matrix. The pumice is highly vesicular, and it occurs as fibrous fragments with tabular, subparallel vesicles. The composition of the breccia is aphanitic or porphyritic dacite, green rock or black shale from the basement formations. The phenocrysts are euhedral high quartz, fragmental plagioclase, common hornblende, orthopyroxene, biotite and accessory minerals. The vitric matrix contains bubble-wall shards and fine ash. The above-mentioned constitution suggests that the basal pumice flow is felsic on average. However, the constitution of each pumice flow is variable from place to place, and from layer to layer. In some cases, the basal pumice flow consists of only a few layers, and the total thickness ranges from several to several tens of meters. On the other hand, the basal flows of the larger VTds consist of many cooling units which are further constituted of several flow units. The total thickness reaches 500 m in the Sanzgawa caldera. Part of a thick cooling unit is often welded (Point A in Fig. 2 and Plate 1a), changing gradually to non-welded. Non-welded massive beds are rather common and contain breccias of various sizes.

3.2 Lacustrine tuffaceous beds

Lacustrine tuffaceous beds are of the most characteristic sedimentary facies of VTds. Tuffaceous conglomerate to coarse sandstones conformably overlie the basal pumice flow. It is fairly difficult to discriminate these lithologies in the field; both have almost the same constitution of gravel, crystal grains and matrix. However, the pumice grains in the lacustrine tuffaceous beds are well-rounded and sorted, as shown in Plate 1b (from Point b in Fig. 2).

The main part of a lacustrine tuffaceous bed consists of alternations of sandy and muddy sediments. The sandy sediments are mainly composed of rounded pumice grains, as shown in Plate 1c (from Point C in Fig. 2) which are very similar in mode of occurrence to those in Plate 1b. They contain rather small amounts of quartz, plagioclase, biotite, hornblende, magnetite and pyroxine grains, as well as breccias of volcanic rocks, black shale, green rocks and others. The matrix is mostly composed of fine-grained vitric or clayey materials.

The muddy sediments contains fewer crystal grains and more vitric materials than the sandy sediments. They are usually finely laminated, as shown in Plate 1d.

The sandy beds occasionally exceed one meter in thickness, while the muddy beds are usually thinner; both beds alternate in various ways. Grading is found in comparatively thick beds only. Very fine lamination is common, composed of coarse- and fine-grained layers less than several millimeters thick. A typical outcrop consisting of sandy and muddy beds in the Sanzgawa caldera is shown in Plate 2. A "tuffite" is usually found at the top of the sedimentary cycle, as at Point G in Fig. 2. It is massive and fairly thick, and mostly composed of very fine-grained vitric materials, as shown in Plate 1c. Phenocrystalline minerals and breccias are rarely found, except for very small amounts of fragmental pumice. The total amount of vitric materials was measured as exceeding 95%, by means of microscopic examination and X-ray diffraction. There is no evidence that this tuffite is primary ash fall or fallback sediments. Vitric materials were probably concentrated by a sedimentary process, such as wave action in an enclosed caldera-lake.

Generally speaking, each sedimentary cycle in caldera formations is characterized by a fining-upward sedimentation, which seems to have been interrupted and renewed several times by mid-caldera volcanic and tectonic activities, as described in the next section.
Plate 1. 1a: Microscopic photograph of welded tuff from the basal pumice flow showing welded pumice grains, the Sanzugawa caldera (polarizer only). 1b: Microscopic photograph of pumice-concentrated part of tuffaceous conglomerate, showing well-rounded and sorted pumice grains, the Sanzugawa caldera (crossed nicols). 1c: Microscopic photograph of tuffaceous sandstone, mainly composed of reworked pumice grains, the Sanzugawa caldera (polarizer only). 1d: Microscopic photograph of laminated tuffaceous mudstone, the Sanzugawa caldera (crossed nicols). 1e: Microscopic photograph of very fine massive tuffite showing glass shards which altered to clinoptilolite and mordenite, the Sanzugawa caldera (crossed nicols). 1f: Microscopic photograph of the basal part of mid-caldera pumice flow overlying laminated tuffaceous mudstone, the Sanzugawa caldera (crossed nicols). The photograph shows that the former was deposited immediately after deposition of the latter.
Plate 2. Photograph of the outcrop where a lava flow interfingers with a slump deposit. They are overlain by alternations of tuffaceous sandstone and siltstone.

Fossil animals have been rarely reported in lacustrine tuffaceous beds, in spite of the existence of bioturbation. On the other hand, plant fossils have been reported, and several flora have been established (Murai, 1962; Huzioka and Uemura, 1973, 1974).

The total thickness of the lacustrine tuffaceous beds averages several hundred meters, and the duration of sedimentation may be several million years. Therefore, the sedimentation rate is estimated as about 1 mm/year.

3.3 Mid-caldera volcanioclastics

Various kinds of mid-caldera volcanioclastics are interlayered with the lacustrine tuffaceous beds. It is very difficult to discriminate a thin layer of ashfall from tuffaceous muddy sediments. However, ash fall generally contains a small amount of phenocrystal plagioclase and/or quartz, while well-sorted fine tuffite rarely contains these, as mentioned in the former section. Pumice falls can be more easily discriminated from clastic pumiceous sediments by a difference in the pumice shape. Furthermore, the former contains more abundant vitric materials in its matrix. Base surge deposits can barely be
discriminated from tuffaceous muddy sediments, because both have similar parallel or cross lamination, grading and other bed forms.

Pumice flows are most significant among mid-caldera volcanioclastics, from the tectonic viewpoint. In some cases, the mid-caldera pumice flow is thicker and more widely distributed than the basal pumice flow. The eruption of the former may have caused tectonic movements and interrupted sedimentation in the caldera-lake. One example is the Yoshinaga Tuff of the Sanzugawa caldera, which exceeds 600 m in thickness at its center. The eruption of this pumice flow seems to have caused the formation of a new graben-horst structure within the original caldera. In some cases, a mid-caldera pumice flow covered a fairly wide area, containing several calderas and the surrounding terrane. An example is found in the Tobe Tuff, consisting of several combinations of pumice flow and ash fall: it covered three calderas in northernmost Honshu—the Tobe, the Oyu and probably the Nurukawa—as well as the surrounding area, as shown in Fig. 6.

The mineralogical and chemical compositions of mid-caldera volcanioclastics generally range from felsic to intermediate. Welding is rather rare in mid-caldera pumice flows, the basal part of one of which is shown in Plate 1f.
3.4 Slump deposits

Slump deposits are occasionally intervened as an episode in lacustrine tuffaceous sediments. Usually, slump deposits are composed of subangular or subrounded gravels and a small amount of coarse matrix; the gravel is usually composed of various rocks derived from the basement formations. Sometimes, however, it is composed of only one kind of volcanic rock, which occurs with a tongue of lava flow interfingered with the slump deposit. A typical outcrop of the latter type is shown in Plate 2 (Point E of Fig. 2). Roughly speaking, a slump bed seems to be conformable with the underlying and overlying beds, but in detail, it fills small-scale troughs cutting the upper surface of the underlying bed. A single slump bed is several centimeters to several meters in thickness, and is useful as a key or correlation of strata in a caldera, because of its lithological character and wide distribution.

3.5 Marginal talus deposits

A talus deposit is often found near cliffs which were mainly formed at mid-caldera stage. It has customarily been called “unsorted breccia” (AKITA PREF., 1981, 1982). Characteristically, a talus deposit contains intraclasts of caldera-forming sediments from an earlier stage, which may be evidence of block movement at mid-caldera stages. The intraclasts vary in size and in shape; they are larger and more angular near the cliff. Total thickness attains several tens of meters there, but is negligible at the margin.

3.6 Sliding deposits

A sliding deposit is often distributed near the border of a caldera. An example is the “Akagawa unsorted breccia” which is found locally at the eastern margin of the Sanzugawa caldera. The sliding deposit is mainly composed of brecciated blocks of the basement rocks. The maximum thickness of the deposit exceeds 500 m, judging from drill hole data (MMAJ, 1975).

4. Sedimentology Relating to the Development of VTDs

The VTD under consideration is fairly unique, as the sedimentary environment and sedimentary facies are genetically related to the development of the VTD. Figure 7 is a schematic figure illustrating the relation between the deposition of caldera-forming sediments and the development of a VTD.

A basal pumice flow is essential for the VTD under consideration. The eruption of a large amount of pumice flow was probably the main cause of formation of the original depression (Stage I in Fig. 7); the volume of erupted pumice flow may have roughly controlled the dimensions of the depression. Actually, large VTDs accompany larger basal pumice flows more often than other types of calderas.

The original depression seems to have developed by flexure after eruption of the basal pumice flow. Simultaneously, the deposition of lacustrine tuffaceous sediments may have begun (Stage II in Fig. 7). Their extraordinarily high content of vitric materials can be well explained by assuming that the depression was mostly enclosed by basal pumice flow deposits, and that sediments were mainly derived from these. Judging from the sedimentary facies, sedimentation in this caldera-lake was probably similar to that in a present day, normal fresh-water lake.

However, several characteristic episodes are involved in the sedimentary history of VTDs. One is mid-caldera volcanic activities which contributed volcaniclastic, especially large-scale pumice flows (Stage III in Fig. 7). Significant tectonic movements seem to have
Stage I  Eruption of Basal Pumice Flow

Stage II  Flexure and Formation of Depression

Stage III  Eruption of Mid-caldera Pumice Flow

Stage IV  Block Faulting and Subdivision of Depression

Stage V  Eruption and Intrusion of Post-caldera Igneous Rocks

Fig. 7. Schematic figure showing development of a volcanotectonic depression and deposition of caldera-forming sediments.
occurred in and around the VTDs, closely related to the eruption of the mid-caldera pumice flows. The original depression was subdivided into several by block movement (Stage IV in Fig. 7), and a fairly thick talus deposit was piled up on the pumice flow near the border of the subsiding blocks. On the other hand, the deposition of lacustrine sediments was interrupted on the uplifting blocks. It is an important fact that the talus deposit contains intraclasts of lacustrine sediments of earlier stages, as evidence of mid-caldera tectonic movement. Sliding deposits were also probably formed in relation to mid-caldera tectonic movement; they are found only near the depression border. The formation of slump deposits may have been related to a volcanic or tectonic movement, as mentioned earlier. As a whole, the frequent appearance of these deposits may indicate that sedimentation in VTDs had progressed under the influence of more intense volcanic and tectonic activities than those in other lake environments.

These activities may have continued until the post-caldera stage. The former produced welded pumice flows, lava flows, lava domes and dikes, while the latter produced swarms of gravity faults (Stage V in Fig. 7).

The rock alteration appearing in the caldera-forming sediments is very significant, because it indicates a high geothermal gradient condition, probably related to the rise of magma to shallow depths. This detail will be discussed in another paper now in preparation.

As a whole, the sequence of VTD formation is quite similar to that of typical Valles-type calderas and their resurgent cauldrons, which was demonstrated by SMITH and BAILEY (1968). The formation of VTDs, however, may have been strongly controlled by regional tectonics. Therefore, the VTDs under consideration do differ, especially in morphology and dimension, from Valles and other types of caldera.

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