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The Evolution of Arc Magmatism in the NE Honshu Arc, Japan

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Abstract : Recent geological and petrological studies for late Cenozoic volcanic rocks from the NE Honshu arc, Japan, revealed the presence of clear secular change of mode of magmatism. Three prominent periods of volcanic activity: continental margin (66-21 Ma), back-arc basin (21-13 Ma), and island-arc stage (13-0 Ma), are identical there. Each period has its unique pattern of lateral alkali variation that is closely related with the thermal structure of the uppermost wedge mantle. The island-arc stage can be divided into four phases: submarine volcanism (13-8 Ma), late Miocene caldera-forming phase (8-5 Ma), Pliocene caldera-forming phase (5-1.7 Ma) and compressional volcanic arc (1.7-0 Ma). These changes in the mode of igneous activity correlated with the stress regime mainly controlled by plate motion, and with the evolutional stage of arc magmatism.

Combined geological, petrological, and geophysical studies have become a valuable tool in revealing intra-crustal structures. The thermal structures seen in the crust of the present NE Honshu arc are closely related to the distribution of the late Cenozoic collapse calderas. High temperature plutons under cooling from the magma reservoirs must be exist now at middle crustal depths under the calderas, and probably observed as low-velocity bodies with many S wave reflectors. To clarify the close relations between the late Cenozoic calderas with unexposed plutons and the seismicity will become one of the main target for predicting hazardous events at volcanic arcs.

1. Introduction

Northeastern (NE) Honshu is an island arc with a back-arc marginal sea basin. Geological and petrological approaches with seismological images enable us to discuss the deep structures beneath island arcs including magma segregation and plumbing systems. In this report, the present status of understanding for the evolution of late Cenozoic arc magmatism in the NE Honshu arc based such viewpoints was reviewed. Recent studies for late Cenozoic volcanic rocks from the NE Honshu arc revealed the presence of clear secular change of mode of magmatism which closely related with the tectonic evolution of the NE Honshu arc. The resulted petrological models of the crust-to-mantle structures beneath the NE Honshu arc and the study of the evolutional history of arc magmatism are very useful to understanding recent activities of volcanoes and earthquakes.

2. NE Honshu Arc

The NE Honshu arc is a mature double volcanic arc with the most completely studied Cenozoic section. It is located on the convergent plate boundary at the northwestern Pacific. The volcanism in the NE Honshu arc is related to the westward subduction of the Pacific plate with a dip angle of about 30-degree. The age of the subducting plate is late Jurassic to early Cretaceous. The depth of trench is deeper than 7,000 m in NE Honshu. The thickness of the continental crust is nearly 30 km (Zhao *et al.*, 1990). This arc shows a zonal arrangement of geological and geophysical features from the trench to the back-arc side such as structure of crust, gravity anomalies, heat flow and seismic activity (Yoshii, 1979 ; Hasegawa *et al.*, 1994, 2000). There exists a double-planed deep seismic zone in the depth range from about 70 km to 150 km within the subducted slab beneath NE Honshu. The upper seismic plane of the double-planed deep seismic zone is characterized by down-dip compression and the lower seismic plane by down-dip extension (Umino and Hasegawa, 1975 ; Hasegawa *et al.*, 1978). The subducted slab is imaged as a high-velocity zone with a thickness of 80-90 km, and low-velocity zones are inclined toward the backarc side in the mantle wedge and are nearly parallel to the dip of the slab, assumed to ascending flow of subduction-induced convection in the mantle wedge (Hasegawa *et al.*, 1991, 1994 ; Zhao *et al.*, 1992).

3. Structure and Evolution of Magma Plumbing Systems

The NE Honshu arc is divided into four volcanic zones (Nakagawa *et al.*, 1986). The Sekiryo volcanic zone is an axial zone of arc volcanism in which the temperature of magma is the highest, and the eruptive materials are more voluminous than in the other zones. Trace elemental and isotopic data suggest that the associated medium-K calc-alkaline (CA) and low-K tholeiitic (TH) rock series in the Sekiryo zone were derived from different degrees of partial melting and/or different mantle sources (Yoshida, 1989). The difference of magma emplacement depth can also explain the diversity of CA/TH rock series in andesite compositions. At least four magma chambers, which existed at different depths, are of the requisite to explain the complex magma activities that occurred at Ontake and other volcanoes (Kimura and Yoshida, 1993, 1999).

The Quaternary volcanism showed both short-term and long-term spreading from volcanic front to back-arc side (Kimura, 1996). Simultaneous magma transport from the deeper reservoirs by tectonic pulse could be a cause of the synchronized volcanic activity. The systematic delay of back arc eruptions could have resulted from longer transfer times of the magma enroute to the surface. The long-term spreading of the volcanism to back arc side could relate to the expansion of the magmatic source region in the mantle (Kimura, 1996). The periodic magma eruption episodes at intervals of 50 to 100 thousand years synchronized with tectonic movements exists in the Norikura Volcanic Chain and the southern part of the NE Honshu arc (Kimura, 1996 ; Kimura and Yoshida, 1996). The climactic eruptions seem to match the timing of the eccentricity-

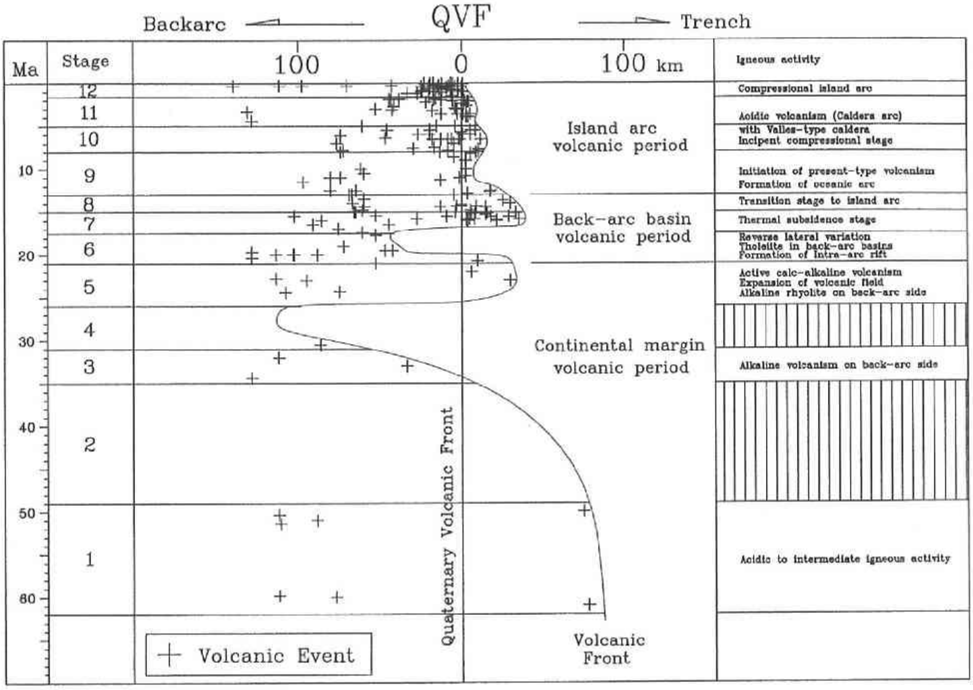

Fig. 1. Migration of volcanic front through the past 60 Ma.
This shows the migration of volcanic front through the past 60 Ma in the NE Honshu arc, Japan. In this figure the age of each volcanic event is plotted to the distance of the eruption center from the Quaternary volcanic front. In the continental margin volcanic period, the volcanic front moved to the back-arc side long distance. The field of Early Miocene volcanism from 25 to 21 Ma spreads to the trench side exceeding the Quaternary volcanic front. When the widest Neogene marine transgression initiated, the volcanic front began to shift to the present position. (Adapted from Yoshida *et al*., 1995.)
Stage: age group of igneous activity in NE Honshu.
QVF: Quaternary volcanic front.

maximum of the Earth's orbit around the Sun. The tidal forces could work supplementary to the compressive stress from the subducting plate (Kimura *et al*., 1995). The recent magnetic excursions are closely correlated with the eccentricity-maximums (Jacobs, 1994). These 'forced' reversals might be related with worldwide-synchronized volcanism by the periodic tidal deformation of the Earth (Yoshida *et al*., 1997).

4. Tectonic and Magmatic Evolutions of the NE Honshu arc

NE Honshu is characterized by wide distribution of late Cenozoic back arc sediments, which fill Miocene extensional basins. On the back arc side of NE Honshu, more than 5 km of late Cenozoic successions have accumulated (Sato, 1994). These represent a major cycle of sedimentation, changing from terrestrial to deep marine and back to terrestrial again. These Cenozoic section of NE Honshu can divided into three promi-

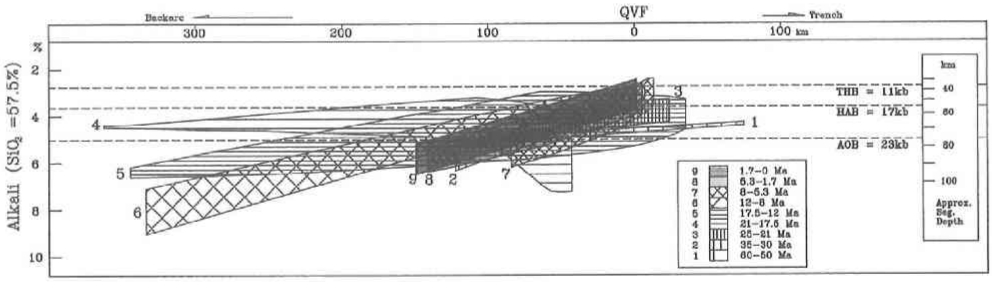

Fig. 2. Secular changes in depth of magma segregation.
Tatsumi *et al.* (1983) show the depth of segregation of magma change from shallow (11 kb) at the volcanic front to deep (23 kb) at the back-arc side with the change of magmatic composition from olivine tholeiite (THB) to high-alumina basalt (HAB) and alkali olivine basalt (AOB). The temperature of each magma at segregation from mantle source is very similar and nearly 1,320°C. The figure shows the secular change of estimated depth of magma segregation, that is, the thermal structure in the wedge mantle through the Cenozoic Era. (Adapted from Yoshida *et al.*, 1995.)

nent periods of volcanic activity: continental margin, back-arc basin, and island arc volcanic period (Ohguchi *et al.*, 1989; Yoshida *et al.*, 1995). Cenozoic continental margin volcanic period of 66–21 Ma is characterized by acidic volcanism at continental margin. The back-arc basin volcanic period of 21–13 Ma has bimodal volcanism under weak tension. The island arc volcanic period after 13 Ma is characterized by caldera-forming and andesitic volcanism under the neutral to compressional stress. Since the magmatic source regions are considered to be long-lived, they have a strong influence on the distribution and evolution of the volcanoes (Yoshida *et al.*, 1995).

Figure 1 shows the migration of volcanic front through the past 60 Ma in NE Honshu (Yoshida *et al.*, 1995). In this figure the age of each volcanic event plotted to the distance of the eruption center from the Quaternary volcanic front. In the continental margin volcanic period, the volcanic front moved to the back-arc side long distance. The field of early Miocene volcanism from 25 to 21 Ma spreads to the trench side exceeding the Quaternary volcanic front. When the widest Neogene marine transgression initiated, the volcanic front began to shift to the present position.

Tatsumi *et al.* (1983) showed the depth of segregation of magma changed from shallow (11 kb) at volcanic front to deep (23 kb) at back-arc side with the change of magmatic composition from olivine tholeiite (THB) to high-alumina basalt (HAB) and alkali olivine basalt (AOB). The temperature of each magma at segregation from mantle source is very similar and nearly 1,320°C. Figure 2 (Yoshida *et al.*, 1995) shows the lateral variation of alkali level and its secular change. Silica-normalized alkali contents of the Cenozoic volcanics were plotted to the distance of the volcanic center from the Quaternary volcanic front in Figure 2. The pattern of lateral alkali variation is not steady. In the continental margin volcanic period, the increment of alkali content was gentle toward the back-arc side, and higher in abundance. In the back-arc basin volcanic period, there was a minimum of alkali content at near Japan Sea coast. In

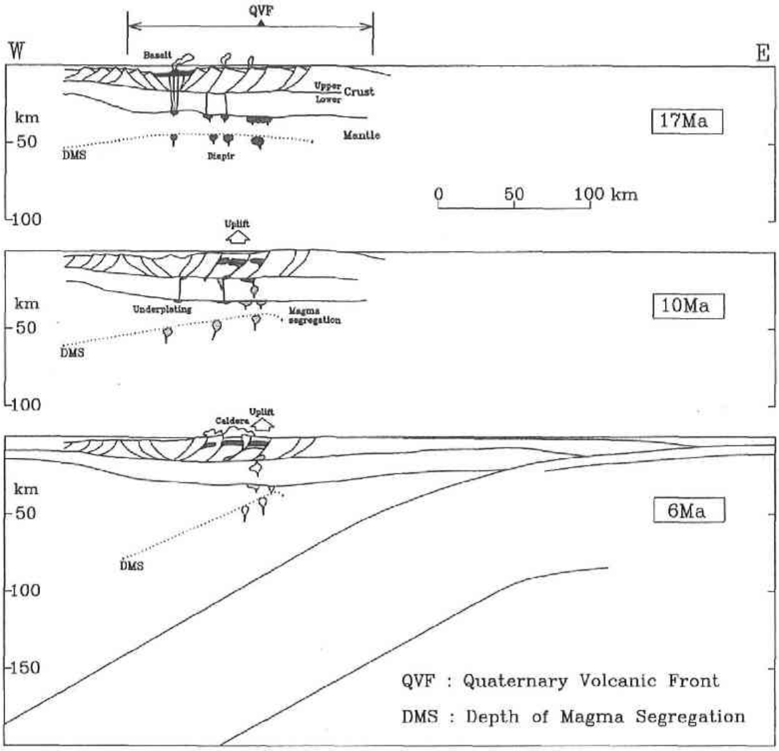

Fig. 3. Cross sections depicting the evolution of the NE Honshu arc, Japan, from middle to late Miocene (Sato and Yoshida, 1993 ; Yoshida *et al*., 1995).
In the back-arc basin volcanic period (17 Ma), the estimated isotherm of maximum temperature (1,320°C) was very flat. This means the increase of temperature at back-arc side in this period. In island arc volcanic period (10 Ma), the slope of the estimated isotherm deeper to back-arc side as the results of the cooling of back-arc mantle after back-arc basin opening.

island arc volcanic period, the incremental gradient of alkali content became steeper, and alkali abundance at the volcanic front were lower than the previous two periods. Each volcanic period has its unique pattern of lateral alkali variation. Figure 2 also shows the secular change of estimated depth of magma segregation from the experimental results of Tatsumi *et al*. (1983), that is, the thermal structure in the wedge mantle through the Cenozoic Era. The each pattern of the lateral alkali variations is closely related with the thermal structure of the uppermost wedge mantle.

Figure 3 (Sato and Yoshida, 1993) shows cross sections depicting the evolution of the NE Honshu arc, after middle Miocene. In the back-arc basin volcanic period (17 Ma), the estimated isotherm of maximum temperature (1,320°C) was very flat. This means the increase of temperature at back-arc side in this volcanic period. This increase of temperature at back-arc side may result from the back-arc opening and related updoming of mantle asthenosphere, and causing the generation of tholeiite from shallower mantle depth in the back-arc side. This back-arc opening was stopped at 15 Ma, and the slow subsidence of the back-arc region attributed to the cooling of the injected hot mantle and sub-arc lithosphere was started at 14.5 Ma (Yamaji, 1990). In island arc volcanic period (10 Ma) with normal lateral alkali variation, the slope of the estimated isotherm became deeper to back-arc side as the results of the cooling of back-arc mantle after back-arc basin opening.

5. Source mantle compositions in the Cenozoic NE Honshu arc

SiO_2-normalized compositions of incompatible elements of the Cenozoic volcanics were calculated using empirical equations (Yoshida and Aoki, 1992). All of the MORB-normalized patterns (Pearce, 1983) of the Cenozoic volcanics from the NE Honshu arc show the characteristics of subduction related magmas. The reciprocal data of the incompatible elements correlate inversely with SiO_2-normalized alkali contents. The isotopic and primitive magma compositions of these Cenozoic volcanic rocks from the NE Honshu arc suggest the presence of three types of source mantle ; the sub-continental and sub-arc lithospheric mantles, and the sub-arc asthenospheric mantle (Yoshida *et al.*, 1995). Strontium isotope data of volcanic rocks (Ohki *et al.*, 1994 ; Shuto *et al.*, 1995) show that depleted mantle source appeared late Miocene at the back-arc side of NE Honshu. This means that the deeper source is much more depleted in the back-arc mantle. The presence of mantle heterogeneity between the volcanic front side and the back-arc side was shown in the process identification diagrams for the volcanic rocks of the island arc volcanic period (Yoshida and Aoki, 1988). These two source mantles, that is, sub-arc lithospheric and asthenospheric mantles (Figure 4, adapted from Yoshida *et al.*, 1995) can be mineralogically heterogeneous, and vertically layered. Increasing segregation depth of basaltic magmas from the volcanic front to the back-arc side crosses the layer boundary resulting in lateral variations in incompatible elements. There is no need to add a slab component to the source of island arc volcanics from NE Honshu in order to explain their across-arc variations of isotopic and LILE compositions (Togashi *et al.*, 1992, Yoshida *et al.*, 1999a).

Recent geochemical investigations of Quaternary volcanic rocks show along-arc isotopic variations from enriched at southern section to depleted at northern section (Yoshida *et al.*, 1999a ; Kimura *et al.*, 2000). This change is paralleled with the same compositional changes in the basement granitic rocks. Yoshida *et al.* (1999a) have shown the mutual relations among the estimated magmatic segregation depth of Quaternary volcanics, schematic cross-section of NE Honshu showing partial melt zones and seismic Q structure. At the northern section (Figure 5), there is a clear gap of partial melt zone and seismic low-Q zone between the volcanic front side and the back-arc side. At the southern section, however, there is no clear gap. These are consistent with isotopic data of volcanic rocks showing lateral and vertical heterogeneity (Yoshida *et al.*, 1999a ; Kimura *et al.*, 2000). Yoshida *et al.* (1999a) have argued that a part of the estimated vertical and lateral heterogeneity of isotopic compositions in the source mantle may be derived by the injection of depleted mantle diapir to the enriched

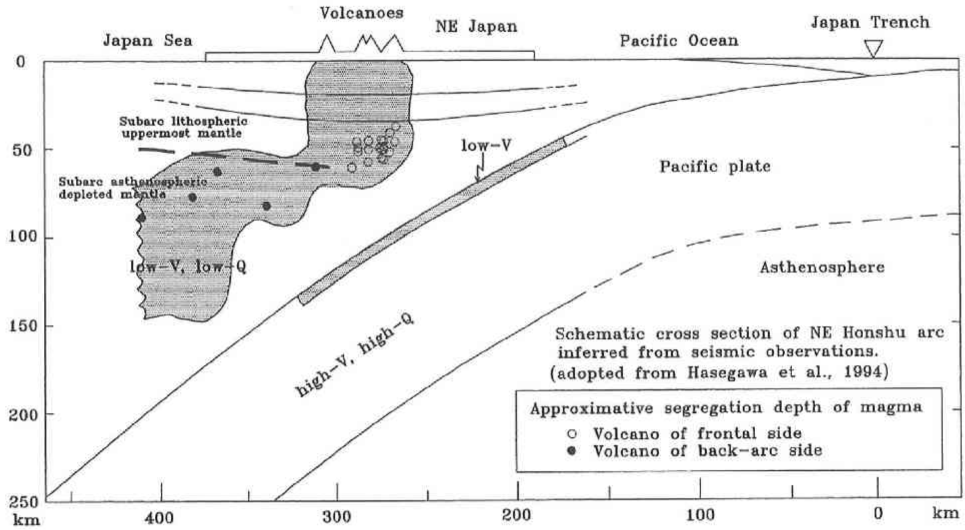

Fig. 4. Estimates of magmatic segregation depth of Quaternary volcanics (Yoshida *et al.*, 1995) and schematic cross-arc vertical section of the crust and the upper mantle in NE Honshu inferred from seismic observations (Hasegawa *et al.*, 1994). The magmas of frontal volcanoes with high-$^{87}Sr/^{86}Sr$ ratios are probably derived from the sub-arc lithospheric mantle (Ujike and Tsuchiya, 1993 ; Togashi *et al.*, 1992) located in the uppermost mantle of the NE Honshu arc. The magmas of back-arc volcanoes with low-$^{87}Sr/^{86}Sr$ ratios seem to have derived from the underlying sub-arc asthenospheric depleted mantle. The geochemically estimated layering in the upper mantle of the NE Honshu arc is closely related to the distribution of the low-velocity zones with the separated cores in the mantle wedge. (Adapted from Yoshida *et al.*, 1995.)

continental lithosphere during the Japan Sea opening.

6. Cross-arc vertical structure of the NE Honshu arc

Figure 4 (Yoshida *et al.*, 1995) shows the estimates of magmatic segregation depth of Quaternary volcanics and schematic cross-arc vertical section of the crust and the upper mantle in NE Honshu inferred from seismic observations (Hasegawa *et al.*, 1994) and petrological data. The magmas of frontal volcanoes with high-$^{87}Sr/^{86}Sr$ ratios are probably derived from the sub-arc lithospheric mantle (Ujike and Tsuchiya, 1993 ; Togashi *et al.*, 1992) located in the uppermost wedge mantle of the NE Honshu arc. The magmas of back-arc volcanoes with low-$^{87}Sr/^{86}Sr$ ratios seem to have derived from the underlying sub-arc asthenospheric depleted mantle. The geochemically estimated layering and heterogeneity (Figure 5, adapted from Yoshida *et al.*, 1999a) in the upper mantle of the NE Honshu arc are closely related to the distributions of the low-velocity partial melting bodies and the low-Q bodies with the separated cores in the mantle wedge (Zhao *et al.*, 1992 ; Sato and Hasegawa, 1996 ; Tsumura *et al.*, 2000), though the distribution patterns of these two bodies are not completely the same.

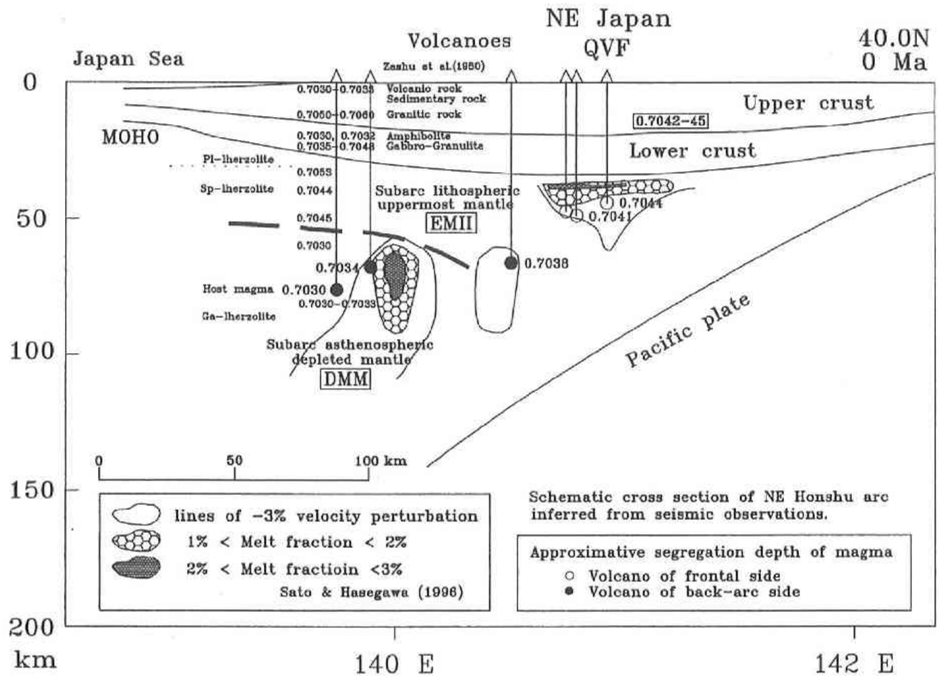

Fig. 5. Schematic cross section of the NE Honshu arc inferred from seismic and petrological observations (Zashu *et al.*, 1980 ; Sato and Hasegawa, 1996 ; Shibata and Ishihara, 1979 ; Yoshida *et al.*, 1995). (Adapted from Yoshida *et al.*, 1997.)

Petrological model for the crust and the upper mantle of the back-arc side is also shown in Figures 5 and 6 (Zashu *et al.*, 1980 ; Arai, 1980). Figure 6 shows geotherm (Kushiro, 1987) and rock types in the crust at Ichinomegata in NE Honshu, and some data relating the crustal temperatures (Arai, 1980 ; Yamada, 1988 ; Hasegawa *et al.*, 2000) are added in the figure. Stability fields of the different mineral assemblages and rocks (Wyllie, 1971) are also shown in Figure 6. Ichinomegata, Akita Prefecture is the most famous ultramafic to mafic xenolith locality in NE Honshu (Aoki, 1987). The pumice deposits of Megata volcano contain many xenoliths. They are classified as follows ; volcanics, granite to diorite, hornblende gabbro, amphibolite and hornblendite, pyroxene gabbro and granulite, wehrlite to pyroxenite, and lherzolite. Each rock type can clearly classify in the density to magnetic susceptibility relation (Yoshida *et al.*, 1998a ; Figure 7). Mantle rocks are much denser than crustal rocks, and have relatively small susceptibility. Recent seismic experiments in NE Honshu revealed a detailed P-wave velocity structure. Nishimoto *et al.* (2000) measured P-wave velocities of lower crustal xenoliths from Megata volcano to obtain better petrologic model for the lower crust of the NE Honshu arc. The measured P wave velocities of the hornblende gabbros and amphibolites are comparable to the range of the lower crustal layer of the seismic profile in the NE Honshu arc by Iwasaki *et al.* (1999). Their results support that the lower crust of the NE Honshu arc is mainly composed from amphibolites and/or hornblende

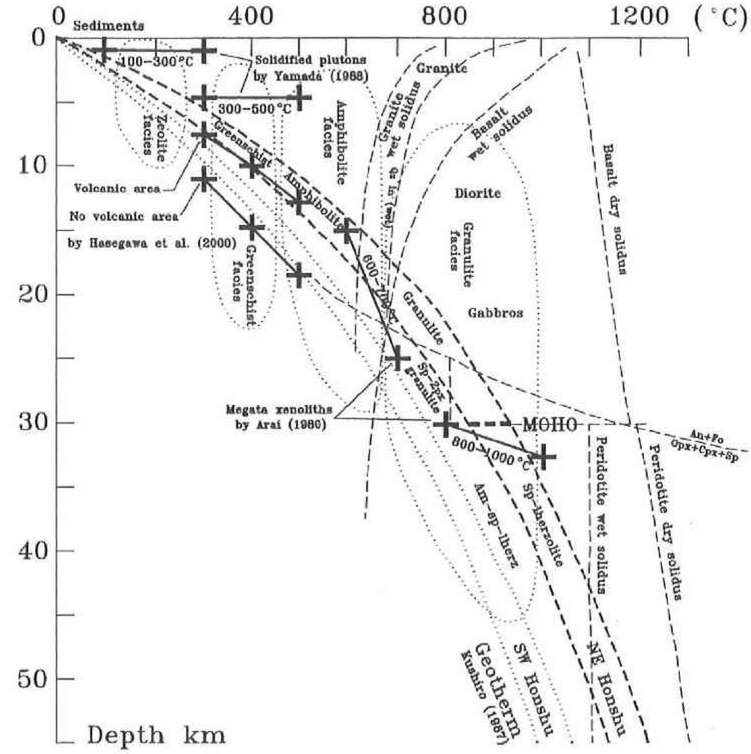

Fig. 6. Geotherms and rock types in the crusts modified from Kushiro (1987). Plus marks connected by tie-lines show each temperature ranges estimated from Megata xenoliths petrologically, from Onikobe hydrothermal systems for solidified plutons thermodynamically, and from velocity perturbations of P wave beneath volcanic and no volcanic areas in the NE Honshu crust by Arai (1980), Yamada (1988) and Hasegawa *et al.* (2000), respectively.
Stability fields of the different mineral assemblages and rocks (Wyllie, 1971) are also shown in the figure. The solidus of the water-saturated granitic magma (Robertson and Wyllie, 1971) is crossed with geotherm at around 20 km depth.

gabbros. Higher magnetic susceptibility of these amphibole-bearing lower crustal rocks can be used as a good indicator to distinguish from pyroxene gabbroic to granulitic lower crust.

7. Finding of many large calderas and study of caldera structures

There are many late Cenozoic calderas in the NE Honshu arc (Ito *et al.*, 1989 ; Sato and Amano, 1991 ; Sato and Yoshida, 1993). Recently, Yoshida *et al.* (1999b) estimated about 80 calderas through field and literature surveys. The collapse calderas are difficult to locate despite their large size because their relief is subdued and erosion of their soft ash beds adds to their cover-up. In recent years, hundreds of large calderas have been found in the North and South American continents by using remotely sensed

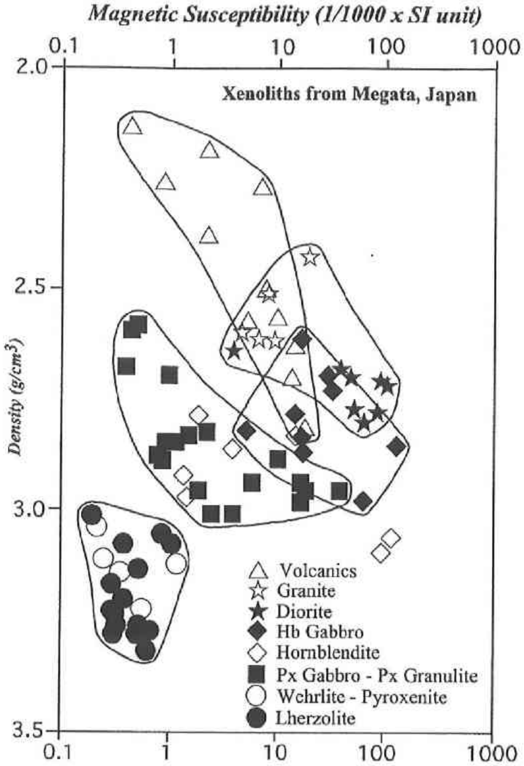

Fig. 7. Density to magnetic susceptibility relations of xenoliths from Megata volcano, Japan. (Adapted from Yoshida *et al.*, 1998a.)

data by satellite (de Silva and Francis, 1991). Some large calderas have been also found in Japan on satellite imagery (Muraoka and Hase, 1990). In Japan, however, the application of satellite imagery is sometimes limited because geological information is heavily disturbed by a variety of land use and vegetation.

The digital elevation model (DEM) of 50 m-mesh for Japan was issued from the Geographical Survey Institute, Japan, recently. In the analysis of caldera structures, digital image maps of slope and openness synthesized from the DEM of NE Honshu (Yokoyama *et al.*, 1999) are used conveniently besides regular topographical and geological maps (Yoshida *et al.*, 1999c). In the maps synthesized, topographical features such as ridges, slopes, valleys, etc are relevantly detected. Those digital image maps of slope and openness are convenient to interpret geomorphological and geological features, were effectively used to identify boundaries of different geological properties (Kanisawa and Yokoyama, 1999; Yokoyama *et al.*, 2000).

Many of the late Cenozoic calderas are the large-scale collapse calderas of the piston-cylinder type (Yamamoto, 1992; Sato and Yoshida, 1993). Calderas of piston-cylinder type consist of collapsed volcanic basin surrounded by arcuate ring faults or array of vents and the surrounding pyroclastic flow deposits (Yoshida, 1984; Yoshida *et*

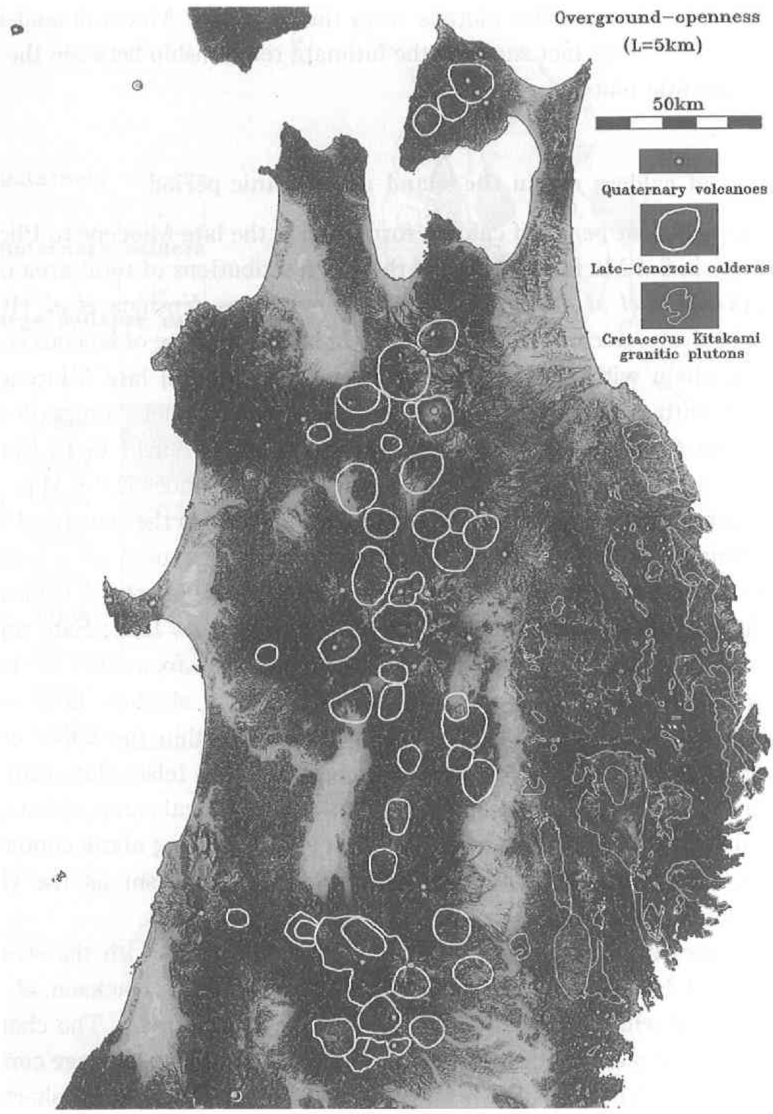

Fig. 8. Topographic and morphological features of late Cenozoic calderas and Cretaceous Kitakami granitic plutons. (Adapted from Yoshida *et al.*, 1999c and Yokoyama *et al.*, 1999, 2000.)

al., 1993). The distribution and morphology of the calderas are very important in understanding their genesis. The topographic and morphological features of these calderas are analyzed by using these digital image maps (Fig. 8 ; Yoshida *et al.*, 1999c ; Yokoyama *et al.*, 1999, 2000). The calderas distributed in the NE Honshu arc show the average diameter of about 10 km and aspect ratio of 1.24. According to size, they are divided into three groups, about 5 km, 10 km, and over 14 km of diameters. Yoshida *et al.* (1999b) found that the spatial and size distributions of calderas are comparable with those of the Cretaceous granitic plutons from the Kitakami Mountainland in the NE Honshu arc (Fig. 8). This fact suggests the intimate relationship between the genesis of calderas and granitic plutons.

8. Formation of caldera arc in the island-arc volcanic period

There are two clear peaks of caldera formation in the late Miocene to Pliocene with short dormancy in 5-4 Ma in the figure of the age distributions of total area of calderas in each Ma (Yoshida *et al.*, 1999b). From these evidences, Yoshida *et al.* (1998b) have divided the island-arc volcanic period after 13 Ma into four phase of igneous activity : (1) oceanic island chain with submarine volcanism (13-8 Ma) ; (2) late Miocene caldera-forming phase with weak updoming of the central mountainous range (8-5 Ma) ; (3) Pliocene caldera-forming phase under weak compressional field (5-1.7 Ma) ; and (4) highly compressional volcanic arc with andesitic stratovolcanoes (1.7-0 Ma).

In the phase (2) to (3), felsic volcanism was concentrated in the structural high of the central mountainous range, and nearly eighty piston-cylinder type (Valles-type) calderas were formed under a condition of neutral to weak compressional stress fields associated with gentle uplift of the central mountainous range (Ito *et al.*, 1989 ; Sato and Amano, 1991 ; Sato and Yoshida, 1993 ; Yoshida *et al.*, 1999b). The formation of these large-scale felsic collapse calderas suggests the emplacements of shallow, large-scale felsic magma reservoirs, that is, volcano-plutonic complexes within the upper crust. The dome-like structures around caldera centers suggest that the felsic plutonism contributed to the uplift of the central mountainous range. The chemical composition of volcanic rocks erupted during these stages shows a tendency to increasing alkali contents toward the back-arc side characterizing subduction-related magmatism as the Quaternary andesitic volcanism (Yoshida *et al.*, 1998b).

These changes in the mode of igneous activity correlated with the stress regime mainly controlled by plate motion (Jackson and Shaw, 1975 ; Jackson *et al.*, 1975 ; Masuda, 1984), and with the evolutional stage of arc magmatism. The change in the motion of the Pacific plate that occurred at about 4 Ma introduced a large component of compression normal to the Japan trench (Pollitz, 1986). Resulted crustal shortening that occurred in the age between 3.5-1.0 Ma is attributable to the change in volcanic activity from felsic piston-cylinder type (Valles-type) calderas to andesitic stratovolcanoes (Moriya, 1983 ; Sato and Yoshida, 1993). The Quaternary andesitic stratovolcanoes locate the peripherals of the clusters of late Cenozoic piston-cylinder type calderas and low-velocity partial melting zones (Zhao *et al.*, 1992 ; Sato and Hasegawa, 1996) in the upper mantle (Figure 9, adapted from Yoshida *et al.*, 1997).

9. Distribution of unexposed plutons and the present subsurface thermal structures

Combined geological, petrological, and seismological studies have become a valuable tool in revealing intra-crustal structures beneath volcanoes (e.g., Kimura *et al.*, 1999).

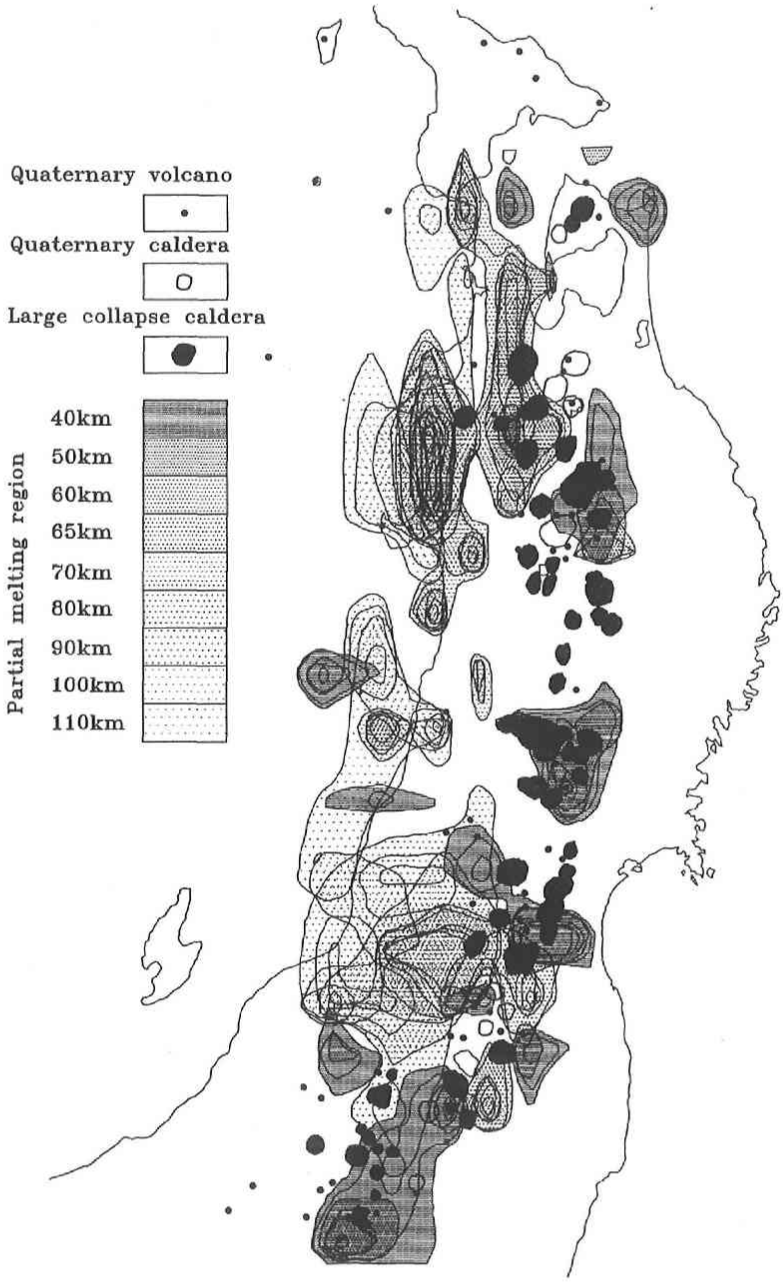

Fig. 9. Distribution of large-scale collapsed calderas in 8-0 Ma (Ito *et al.*, 1989; Sato, 1994), the Quaternary volcanoes, and partial melting zones (Zhao *et al.*, 1992; Sato and Hasegawa, 1996) in the upper mantle depth beneath NE Honshu, Japan. (Adapted from Yoshida *et al.*, 1997.)

As mentioned above, there are many late Cenozoic calderas in the NE Honshu arc. The locations of crustal low-velocity areas, high seismic areas, and focal mechanisms of inland earthquakes are closely related with the distributions of these calderas of piston-cylinder type in the central mountainous range (Onodera *et al.*, 1998 ; Umino *et al.*, 1998). Active magmas in super-solidus and even in sub-solidus states can be detected as low-Vp bodies in both the lower and upper crusts, and the derived fluid infilling cracks can act as seismic reflectors beneath the volcanoes (Kimura *et al.*, 1999).

The subsurface thermal structure beneath the Japanese islands should provide important information about many geophysical and geological activities occurring at convergent plate boundaries (e.g., Tanaka and Yoshida, 2000). Hasegawa *et al.* (2000) estimated the temperature distribution within the crust of the NE Honshu arc from P wave velocity perturbations, and clarified the temperature in the crust varies significantly not only in the vertical but also in the horizontal direction. The resulted isotherms become locally shallow beneath the volcanic areas. The thermal gradient under the Sekiryo volcanic areas is in good agreement with the petrological estimate from Megata xenoliths (Fig. 6, Arai, 1980 ; Kushiro, 1987). This means that the estimate is one of the sub-volcanic thermal gradients. The gradients from no volcanic areas are lower than volcanic areas and the same order of SW Honshu. Unexposed sub-volcanic plutons just solidified at Onikobe caldera are several hundred degrees higher in temperature than the regional thermal gradient of the volcanic areas (Yamada, 1988). Therefore, some plutonic bodies can still remain at high temperature, and possibly correlate with large low-Vp bodies in the area. Kimura and Yoshida (1999) considered that the low-Vp body correlated with the remnant large acid magma chamber. Intensive water discharge occurs in rhyolites during solidification of water saturated magmas (Kimura *et al.*, 1999). Intracrustal seismic reflectors correlated with "trapped fluid" discharged from the molten magma or plutonic body (Gianelli *et al.*, 1988).

Yano *et al.* (1999) have compiled the borehole temperature data and studied the shallow thermal structure in Japan. They made the contour maps of geothermal gradient, Curie point depth, temperature of thermal water and subsurface temperatures estimated from borehole temperature data and heat flow data. The distribution of high-temperature areas in their maps coincides well with the distribution of the late Cenozoic calderas in the NE Honshu arc. Especially, the distribution of high-temperature areas of the hot spring water (Tanaka, 1999 ; Tanaka and Yano, 2000) just coincides with the dense distribution of the calderas (Yoshida *et al.*, 2000). In the NE Honshu arc, high temperature plutons which solidified from the caldera-forming magma reservoirs, probably exist now at comparatively shallow depths under the calderas in the crust, and high temperature hydrothermal systems have been formed above the plutons (Yamada, 1988 ; Yoshida *et al.*, 1999b). The thermal structures seen in the upper crust of the present NE Honshu arc are closely related to and must be controlled by the distribution of unexposed deep-seated plutonic bodies which formed the late Cenozoic collapse calderas.

Anderson (1936) presumes that in a magma chamber of circular shape, the magma column oscillates in height, pushing upward and subsiding and causing tension cracks in the surrounding rocks. The geometry of the sheets originates in the upward push of the magma (Yoshida, 1970). S wave reflectors distributing beneath and around the caldera complex (Hori *et al.*, 1999) are presumed to be the fracture systems filled with high temperature hydrothermal fluids. Close spatial relations between caldera structures and the distributions of low S wave velocity, high Vp/Vs ratio area, and the estimated thermal structures together with S wave reflectors support those models. The distribution pattern of S wave reflectors is systematically changed with the depth (Hori *et al.*, 1999) and suggests that it is controlled by the unexposed plutons under the caldera structures (Umino *et al.*, 1998 ; Yoshida *et al.*, 2000). The solidus of the water-saturated granitic magma (Robertson and Wyllie, 1971) is crossed with geotherm at around 20 km depth (Fig. 6). This means wet granitic magmas and the related plutons are stable at middle crust during it hold H_2O and will live long time as low-velocity bodies with surrounding cone sheets of S wave reflectors.

10. Concluding Remarks

Recent advancements in seismic tomography have enabled crust and mantle imaging beneath the NE Honshu arc. The across-arc profile of magmatic temperature and heterogeneity of mantle compositions inferred from petrological data correlate to the seismic velocity structure in the NE Honshu arc. The major vertical and lateral heterogeneity in the magmatic source area of wedge mantle may be formed by the injection of depleted mantle diapir to the enriched continental lithosphere during the Japan Sea opening.

Seismic low-velocity areas, high seismic areas, and their focal mechanisms are closely related to the distributions of the late Cenozoic calderas in the central mountainous range parallel with the volcanic front. The distribution of high-temperature areas of the hot spring water coincides well with the dense distribution of the late Cenozoic calderas. The thermal structures seen in the present NE Honshu arc is closely related to the distribution of the late Cenozoic collapse calderas with unexposed deep-seated plutonic bodies. These evidences imply that high temperature plutons under cooling from the magma reservoirs must be exist now at middle crustal depths under the calderas, and probably observed as low-velocity bodies with many S wave reflectors.

Hasegawa *et al.* (2000) argued that the fluid- or magma-filled reflectors, together with a lower strength and a locally thin brittle seismic zone above them, will allow more contractile deformation in the low-velocity areas, resulting in crustal shortening, land elevation, and mountain ranges. And, they concluded that magmatic underplating or intrusion from low-velocity and low-Q mantle diapirs raises the crustal temperature and may have contributed not only to the crustal weakening but also to the formation of the topographic highs. To clarify the close relations between the late Cenozoic calderas with unexposed plutons and the seismicity will become one of the main target for predicting hazardous events at volcanic arcs.

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