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Quaternary Volcanism Along the Volcanic Front in Northeast Japan

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1. Introduction

Northeast Japan parallels a subduction zone where the Pacific plate converges against the North American plate. The axial part of Northeast Japan is composed of an uplifted mountain range called the Ou Backbone Range, along which a number of Quaternary volcanoes are distributed. The eastern margin of these volcanoes defines part of the Quaternary volcanic front of Northeast Japan (Fig. 1). The chemical composition of the volcanic rocks indicates a strong across variation in the alkali content and other incompatible elements, which are lower along the volcanic front and gradually increase rearward (Nakagawa et al., 1988; Yoshida, 2001). The Sr isotope compositions also indicate across-arc variation; the fore-arc volcanoes have higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.704-0.705) than the rear-arc volcanoes (around 0.703) (Notsu, 1983; Kumura & Yoshida, 2006). Such variations can be ascribed to heterogeneous subcontinental lithosphere and/or additional of components from the subducted slab (e.g., Sakuyama & Nesbitt, 1986; Tatsumi & Eggins, 1995). This trench-parallel chemical zonation in Northeast Japan has been established since ca. 12 Ma (Yoshida, 2001).

The late Miocene to Quaternary evolution of the volcanic arc of Northeast Japan has been accompanied by some remarkable features. These include (1) Late Miocene to Pliocene caldera-forming volcanism phase, under a direction of maximum compression oblique to the arc and (2) Quaternary andesite stratovolcano-forming volcanism phase, under orthogonal convergence settings (Acocella et al., 2008). A compressive stress regime under orthogonal convergence is unfavourable to facilitate caldera-forming volcanism requiring the formation of a large magma reservoir at shallow depth (Yoshida, 2001). The predominance of stratovolcanoes is reconciled with compressional tectonic settings in the present-day subduction system. Nevertheless, it remains obscure as to when the andesite stratovolcano-forming volcanism has been established under Quaternary orthogonal convergence in Northeast Japan.

In general, characteristics of volcanism such as distribution of volcanoes, type of eruptions, magma discharge rate are closely associated with tectonics surrounding the volcanoes. It is very important to examine the relationship between them for better understanding magmatism in various tectonic settings. In this chapter, the temporal changes in the distribution, type and magma discharge rate of the volcanoes near the volcanic front (i.e., Nasu Volcanic Zone) during the last 2.0 m. y. were clarified based on the age and volume...
data of the Quaternary volcanoes in Northeast Japan presented by Martin et al. (2004). In addition, we examine the relationship between variations in Quaternary volcanism and tectonics specifically with regard to faulting and uplifting.

Fig. 1. Distribution of volcanic centers in Northeast Japan since 2.0 Ma. Solid triangle and open square represent stratovolcano and large-scale caldera volcanoes, respectively.

2. Volcanism during the last 2.0 million years

Thirty four Quaternary volcanoes have been recognized along the volcanic front between Mutsuhiuchi-dake volcano and Nasu volcano (Ono et al., 1981), and their eruptive volumes were calculated (Aramaki & Ui 1978). To refine the sequence of volcanism during the last 2.0 million years, Umeda et al. (1999) subdivided individual volcanoes into as small a unit as possible, and estimated their active periods from radioactive age and stratigraphic data, and calculated their eruptive volumes. Recently, Martin et al. (2004) revised the database of Umeda et al. (1999) using the “Catalog of Quaternary volcanoes in Japan” of Committee for Catalogue of Quaternary Volcanoes in Japan eds. (1999) and other new radiometric age data for each volcano along the volcanic front in Northeast Japan. Martin et al. (2004) refers to “Volcanic Event” that is defined as multiple eruptions from the same conduit occurring over several tens to hundreds of thousands of years (Table 1). By defining the highest points of the individual stratovolcanoes or the geometrical centers of the calderas as volcanic centers (the main vents) for each volcanic event, the locations, magma volume and eruption styles were evaluated to clarify the temporal change in volcanism.

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### Quaternary Volcanism Along the Volcanic Front in Northeast Japan

| Volcano Complex | Volcanic event | Location | Age (Ma) | Volume (km$^3$, DRE) |
|-----------------|----------------|----------|----------|---------------------|
| Mutsuhiuchi-dake | Older Mutsuhiuchi-dake | 41.437, 141.057 | ca.0.73 | 5.9 |
| Mutsuhiuchi-dake | Younger Mutsuhiuchi-dake | 41.437, 141.057 | 0.45 | 0.2 | 3.6 |
| Osorezan | Kamabuse-yama | 41.277, 141.123 | ca.0.8 | 11.4 |
| Hakkoda | Hakkoda P.F.1st | 40.667, 140.897 | 0.65 | 17.8 |
| Hakkoda | South-Hakkoda | 40.600, 140.850 | 0.65 | 0.4 | 52.4 |
| Hakkoda | Hakkoda P.F.2nd | 40.667, 140.897 | 0.4 | 17.3 |
| Hakkoda | North-Hakkoda | 40.650, 140.883 | 0.16 | 0 | 30.4 |
| Okiura | Aoni F. Aonigawa P.F. | 40.573, 140.763 | ca.1.7 | 17.6 |
| Okiura | Aoni F. Other P.F. | 40.573, 140.763 | 1.7 | 0.9 | 3.7 |
| Okiura | Okogawasawa lava | 40.579, 140.759 | 0.9 | - | 0.65 | 0.9 |
| Okiura | Okiura dacite | 40.557, 140.755 | 0.9 | - | 0.7 | 2.1 |
| Ikarigaseki | Nijikai Tuff | 40.500, 140.625 | ca.2.0 | 20.2 |
| Ikarigaseki | Ajarayama | 40.490, 140.640 | 1.91 | - | 1.89 | 2.1 |
| Towada | Herai-dake | 40.450, 141.000 | | | |
| Towada | Ohanabe-yama | 40.500, 140.883 | 0.4 | - | 0.05 | 8.9 |
| Towada | Hakka | 40.417, 140.867 | | | 1.4 |
| Towada | Towada Okuse | 40.468, 140.888 | 0.055 | 4.8 |
| Towada | Towada Ofudo | 40.468, 140.888 | 0.025 | 22.1 |
| Towada | Towada Hachinohe | 40.468, 140.888 | 0.013 | 26.9 |
| Towada | Post-caldera cones | 40.457, 140.913 | 0.013 | - | 0 | 14.4 |
| Nanashigure | Nanashigure | 40.068, 141.112 | 1.06 | - | 0.72 | 55.5 |
| Moriyoshi | Moriyoshi | 39.973, 140.547 | 1.07 | - | 0.78 | 18.1 |
| Bunamori | Bunamori | 39.967, 140.717 | 1.2 | - | 0.1 |
| Akita-Yakeyama | Akita-Yakeyama | 39.963, 140.763 | 0.5 | - | 0 | 9.9 |
| Nishimori/Maemori | Nishimori/Maemori | 39.973, 140.962 | 0.5 | - | 0.3 | 2.6 |
| Hachimantai/Chausu | Hachimantai | 39.953, 140.857 | 1 | - | 0.7 | 5.5 |
| Hachimantai/Chausu | Chausu-dake | 39.948, 140.902 | 0.85 | - | 0.75 | 13.7 |
| Hachimantai/Chausu | Fuenoyu | 39.953, 140.857 | ca.0.7 | - | 0.2 |
| Hachimantai/Chausu | Gentamri | 39.956, 140.878 | | - | 0.2 |
| Yasemori/Magarisaki-yama | Magarisaki-yama | 39.878, 140.803 | 1.9 | - | 1.52 | 0.3 |
| Yasemori/Magarisaki-yama | Yasemori | 39.883, 140.828 | | 1.8 | 0.9 |
| Kensomori/Morobidake | Kensomori | 39.897, 140.871 | ca.0.8 | - | 0.8 |
| Kensomori/Morobidake | Morobi-dake | 39.919, 140.862 | 1 | - | 0.8 | 2.5 |
| Volcano Complex         | Volcanic event                    | Location   | Age (Ma) | Volume (km³, DRE) |
|-------------------------|-----------------------------------|------------|----------|------------------|
| Kensomori/ Morobidake   | 1470m Mt. lava                    | 39.909     | 140.872  | 0.1              |
| Kensomori/ Morobidake   | Mokko-dake                        | 39.953     | 140.857  | ca.1.0 0.5       |
| Tamagawa Welded Tuff    | Tamagawa Welded Tuffs R4          | 39.963     | 140.763  | ca.2.0 83.2      |
| Tamagawa Welded Tuff    | Tamagawa Welded Tuffs D           | 39.963     | 140.763  | ca.1.0 32.0      |
| Nakakura/ Shimokura     | Obuka-dake                        | 39.878     | 140.883  | 0.8 — 0.7 2.9    |
| Nakakura/ Shimokura     | Shimokura-yama                    | 39.889     | 140.933  | — — 0.4         |
| Nakakura/ Shimokura     | Nakakura-yama                     | 39.888     | 140.910  | — — 0.4         |
| Matsukawa               | Matsukawa andesite                | 39.850     | 140.900  | 2.6 — 1.29 11.6  |
| Iwate/ Amihari          | Iwate                             | 39.847     | 141.004  | 0.2 — 0 25.1     |
| Iwate/ Amihari          | Amihari                           | 39.842     | 140.958  | 0.3 — 0.1 10.6   |
| Iwate/ Amihari          | Omatsukura-yama                   | 39.841     | 140.919  | 0.7 — 0.6 3.3    |
| Iwate/ Amihari          | Kurikigahara                      | 39.849     | 140.882  | — — 0.2         |
| Iwate/ Amihari          | Mitsuishi-yama                    | 39.848     | 140.900  | 0.46 — 0.6 0.6   |
| Shizukuishi/ Takakura   | Marumori                          | 39.775     | 140.877  | 0.4 — 0.3 2.4    |
| Shizukuishi/ Takakura   | Shizukuishi-Takakura-yama         | 39.783     | 140.893  | 0.5 — 0.4 5.2    |
| Shizukuishi/ Takakura   | Older Kotakakura-yama             | 39.800     | 140.900  | 1.4 — 2.7        |
| Shizukuishi/ Takakura   | North Mikado-yama                 | 39.800     | 140.875  | — — 0.3         |
| Shizukuishi/ Takakura   | Kotakakura-yama                   | 39.797     | 140.907  | 0.6 — 0.5 1.8    |
| Shizukuishi/ Takakura   | Mikado-yama                       | 39.788     | 140.870  | ca.0.3 — 0.2     |
| Shizukuishi/ Takakura   | Tairagakura-yama                  | 39.808     | 140.878  | ca.0.3 — 0.1     |
| Nyuto/ Zarumori         | Tashirotai                        | 39.812     | 140.827  | 0.3 — 0.2 0.6    |
| Nyuto/ Zarumori         | Sasamori-yama                     | 39.770     | 140.820  | 0.23 — 0.1 0.4   |
| Nyuto/ Zarumori         | Yunomori-yama                     | 39.772     | 140.827  | ca.0.3 — 0.5     |
| Nyuto/ Zarumori         | Zarumori-yama                     | 39.788     | 140.850  | 0.56 — 0.9       |
| Nyuto/ Zarumori         | Nyutozan                          | 39.802     | 140.843  | 0.58 — 0.5 5.0   |
| Volcano Complex | Volcanic event | Location | Age (Ma) | Volume (km$^3$, DRE) |
|-----------------|---------------|----------|----------|---------------------|
| Nyuto/Zarumori  | Nyuto-kita    | 39.817   | 140.855  | ca.0.4              | 0.1 |
| Akita-Komagatake| Akita-Komagatake | 39.754  | 140.802  | 0.1                | 1.7 | 0  | 2.9 |
| Kayo            | Kayo          | 39.803   | 140.735  | 2.2                | 1.17| 5.9 |
| Kogyromori      | 39.828        | 140.787  | 0.94     | 0.3                |
| Kayo            | Akita-Ojiromori| 39.839  | 140.788  | 1.7                | 1.7 | 1.7 | 0.3 |
| Innai/Takahachi | Takahachi-yama| 39.755  | 140.655  | 1.7                | 1.7 | 1.7 | 0.0 |
| Innai/Takahachi | Innai        | 39.692   | 140.638  | 2                 | 1.6 | 0.5 |
| Kuzumaru        | Aonokimori andesites | 39.543  | 140.983  | 2.06               | 0.3 |
| Yakeishi        | Yakeishidake  | 39.161   | 140.832  | 0.7                | 0.6 | 9.5 |
| Yakeishi        | Komagatake    | 39.193   | 140.924  | ca.1.0             | 7.6 |
| Yakeishi        | Kyoizukayama  | 39.178   | 140.892  | 0.6                | 0.4 | 5.7 |
| Yakeishi        | Usagimoriyama | 39.239  | 140.924  | 0.07               | 0.04| 2.3 |
| Kobinai         | Kobinai      | 39.018   | 140.523  | 1                  | 0.37| 2.3 |
| Takamatsu/      | Kabutoyama Welded Tuff | 39.025 | 140.618  | 1.16               | 3.2 |
| Kabutoyama      | Kabutoyama   | 39.025   | 140.618  | 0.30               | 5.1 |
| Takamatsu       | Takamatsu    | 38.965   | 140.610  | 0.3                | 0.27| 3.8 |
| Takamatsu       | Futsutsuki-dake | 38.961  | 140.661  | ca.0.3             | 0.8 |
| Kuriroma        | Tsurugi-dake | 38.963   | 140.792  | 0.1                | 0   | 0.2 |
| Kuriroma        | Magusa-dake  | 38.968   | 140.751  | 0.32               | 0.1 | 1.5 |
| Kuriroma        | Kuriroma     | 38.963   | 140.792  | 0.4                | 0.1 | 0.9 |
| Kuriroma        | South volcanoes | 38.852 | 140.875  | ca.0.5             | 0.3 |
| Kuriroma        | Older Higashi Kuriroma | 38.934 | 140.779  | ca.0.5             | 2.2 |
| Kuriroma        | Younger Higashi Kuriroma | 38.934 | 140.779  | 0.4                | 0.1 | 0.7 |
| Mukaimachi      | Mukaimachi   | 38.770   | 140.520  | ca.0.8             | 12.0|
| Onikobe         | Shimoyamasato tuff | 38.830  | 140.695  | 0.21               | 0.21| 1.0 |
| Onikobe         | Onikobe Central cones | 38.805  | 140.727  | ca.0.2             | 1.1 |
| Onikobe         | Ikezuki tuff  | 38.830   | 140.695  | 0.3                | 0.2 | 17.3|
| Naruko          | Naruko Central cones | 38.730  | 140.727  | ca.0.045           | 0.1 |
| Naruko          | Yanagizawa tuff | 38.730  | 140.727  | ca.0.045           | 4.8 |
| Naruko          | Nizaka tuff   | 38.730   | 140.727  | ca.0.073           | 4.8 |
| Funagata        | Izumigatake  | 38.408   | 140.712  | 1.45               | 1.14| 2.3 |
| Funagata        | Funagatayama | 38.453   | 140.623  | 0.85               | 0.56| 19.0|
| Yakuraisan      | Yakuraisan   | 38.563   | 140.717  | 1.65               | 1.04| 0.2 |
| Nanatsumori     | Nanatsumori lava | 38.430 | 140.835  | 2.3                | 2   | 0.5 |
| Nanatsumori     | Miyatoko Tufts | 38.428 | 140.793  | ca.2.5             | 6.1 |
| Nanatsumori     | Akakuzure-yama lava | 38.433 | 140.768  | 1.6                | 1.5 | 1.5 |
| Nanatsumori     | Kamikadajin lava | 38.447  | 140.772  | 1.6                | 1.5 | 0.8 |
| Shirataka       | Shirataka    | 38.220   | 140.177  | 1                  | 0.8 | 3.8 |
| Volcano Complex | Volcanic event | Location | Age (Ma) | Volume (km$^3$, DRE) |
|-----------------|---------------|----------|----------|---------------------|
| Adachi          | Adachi        | 38.218   | 140.662  | ca.0.08             |
| Gantosan        | Gantosan      | 38.195   | 140.480  | 0.4                 |
| Kamuro-dake     | Kamuro-dake   | 38.253   | 140.488  | ca.1.67             |
| Daito-dake      | Daito-dake    | 38.316   | 140.527  | 1.1                 |
| Ryuzan          | Ryuzan        | 38.181   | 140.397  | 1.1                 |
| Zao             | Central Zao 1st. | 38.133 | 140.453  | 0.32                |
| Zao             | Central Zao 2nd. | 38.133 | 140.453  | 0.03                |
| Zao             | Suggigamine   | 38.103   | 140.462  | 1                   |
| Zao             | Higashi Azumasan | 37.710 | 140.233  | 0.7                 |
| Azuma           | Azuma Kitei lava | 37.733 | 140.247  | 1.3                 |
| Azuma           | Nishi Azumasan | 37.730   | 140.150  | 0.6                 |
| Azuma           | Naka Azumasan | 37.713   | 140.188  | 0.4                 |
| Nishikarasugawa | Nishikarasugawa andesite | 37.650 | 140.283  | 1.5                 |
| Adatara         | Adatara Stage 1 | 37.625 | 140.280  | 0.55                |
| Adatara         | Adatara Stage 2 | 37.625 | 140.280  | 0.03                |
| Adatara         | Adatara Stage 3a | 37.625 | 140.280  | 0.2                 |
| Adatara         | Adatara Stage 3b | 37.625 | 140.280  | 0.12                |
| Sasamori-yama   | Sasamari-yama andesite | 37.655 | 140.391  | 2.5                 |
| Bandai          | Pre-Bandai    | 37.598   | 140.075  | ca.0.7              |
| Bandai          | Bandai        | 37.598   | 140.075  | 0.3                 |
| Nekoma          | Old Nekoma    | 37.608   | 140.030  | 1                   |
| Nekoma          | New Nekoma    | 37.608   | 140.030  | 0.5                 |
| Kasahi/ Oshiromori | Kasahi       | 37.184   | 139.973  | 0.1                 |
| Kasahi/ Oshiromori | Oshiromori  | 37.199   | 139.970  | 0.7                 |
| Kasahi/ Oshiromori | Matami-yama | 37.292   | 139.886  | 0.3                 |
| Kasahi/ Oshiromori | Naka-yama    | 37.282   | 139.899  | 0.0                 |
| Shirakawa       | Kumado P.F.   | 37.242   | 140.032  | 1.31                |
| Shirakawa       | Tikachi A.F. tuffs | 37.242 | 140.032  | 1.31                |
| Shirakawa       | Ashino P.F.   | 37.242   | 140.032  | 1.2                 |
| Shirakawa       | Nn3 P.F.      | 37.242   | 140.032  | 1.2                 |
| Shirakawa       | Kinshoji A.F. tuffs | 37.242 | 140.032  | 1.2                 |
| Shirakawa       | Nishigo P.F.  | 37.252   | 139.869  | 1.11                |
| Shirakawa       | Tenei P.F.    | 37.242   | 140.032  | 1.06                |
| Nasu            | Futamata-yama | 37.244   | 139.971  | 0.14                |

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Table 1. List of volcanoes along the volcanic front in Northeast Japan (after Martin et al., 2004)

| Volcano Complex | Volcanic event | Location | Age (Ma) | Volume (km$^3$, DRE) |
|-----------------|----------------|----------|----------|---------------------|
| Nasu            | Kasshiasahi-dake | 37.177, 139.963 | 0.6 | 12.3 |
| Nasu            | Sanbonyari-dake  | 37.147, 139.965 | 0.4 | 5.5 |
| Nasu            | Minami-gassan    | 37.123, 139.967 | 0.2 | 8.7 |
| Nasu            | Asahi-dake       | 37.134, 139.971 | 0.2 | 4.6 |
| Nasu            | Chausu-dake      | 37.122, 139.966 | 0.04 | 0.3 |
| Hakkoda         | South-Hakkoda    | 41.437, 141.057 | ca.0.73 | 5.9 |
| Hakkoda         | Hakkoda P.F.2nd. | 41.437, 141.057 | 0.45 | 3.6 |
| Hakkoda         | North-Hakkoda    | 41.277, 141.123 | ca.0.8 | 11.4 |
| Okiura          | Aoni F. Aonigawa P.F. | 40.667, 140.897 | 0.65 | 17.8 |
| Okiura          | Aoni F. Other P.F. | 40.600, 140.850 | 0.65 | 52.4 |
| Okiura          | Okogawa-sawa lava | 40.667, 140.897 | 0.4 | 17.3 |
| Okiura          | Okiura dacite    | 40.650, 140.883 | 0.16 | 30.4 |
| Ikarigaseki     | Nijikai Tuff     | 40.573, 140.763 | ca.1.7 | 17.6 |
| Ikarigaseki     | Ajarayama        | 40.573, 140.763 | 1.7 | 5.7 |
| Towada          | Herai-dake       | 40.579, 140.759 | 0.9 | 0.9 |
| Towada          | Ohanabe-yama     | 40.557, 140.755 | 0.9 | 7.1 |
| Towada          | Hakka            | 40.500, 140.625 | ca.2.0 | 20.2 |
| Towada          | Towada Okuse     | 40.490, 140.600 | 1.91 | 2.1 |
| Towada          | Towada Ofudo     | 40.450, 141.000 | 5.1 |
| Towada          | Towada Hachinohe | 40.500, 140.883 | 0.4 | 8.9 |
| Towada          | Post-caldera cones | 40.417, 140.867 | 1.4 |
| Nanashigure     | Nanashi-gure     | 40.468, 140.888 | 0.055 | 4.8 |
| Moriyoshi       | Moriyoshi        | 40.468, 140.888 | 0.025 | 22.1 |
| Bunamori        | Bunamori         | 40.468, 140.888 | 0.013 | 26.9 |
| Akitaya         | Akitaya-Yakeyama | 40.437, 140.913 | 0.013 | 14.4 |
| Nishimori/Maemori | Nishimori/Maemori | 40.068, 141.112 | 1.06 | 0.72 |
| Hachimantai/Chausu | Hachimantai     | 39.973, 140.547 | 1.07 | 18.1 |
| Hachimantai/Chausu | Chausu-dake     | 39.967, 140.717 | 1.2 |
| Hachimantai/Chausu | Fuenoyou        | 39.963, 140.763 | 0.5 | 9.9 |
| Hachimantai/Chausu | Gentamri        | 39.973, 140.962 | 0.5 | 2.6 |
| Yasemori/Magarisakiyama | Magarisakiyama | 39.953, 140.857 | 1 | 5.5 |

2.1 Number of volcanoes and volcanic regions

The volcanoes are clustered near the volcanic front. Seven volcanic regions (V.R.) can be identified as along the arc and named as follow: the Osore V.R., the Hakkoda-Towada V.R., the Sengan V.R., the Kurikoma-Onikobe V.R., Zao-Funagata V.R., the Bandai-
Adatara V.R. and the Aizu V.R. Each volcanic region is consists of a number of small- to medium-sized stratovolcanoes, typically measuring less than 10 km$^3$ in magmatic eruption (DRE). This feature of volcano clustering was first pointed out by Umeda et al. (1999) and re-pointed out by Tamura et al. (2002). However, several volcanic centers have produced large-sized stratovolcanoes or large-scale felsic pyroclastic flows, attaining as much as tens of cubic kilometers in DRE volume. Along the volcanic front in Northeast Japan, 139 volcanic events are recognized (Fig. 1). 113 are stratovolcano-forming events, and the rest are caldera-forming.

### 2.2 Temporal change in magma discharge rate and eruption style

In order to elucidate temporal variations in the long-term magma discharge rate all over the NE Japan arc, the magma volume erupted every 100 kilo years (long-term discharge rate of magma) was calculated for each volcano during the last 2.0 million years. In the case of South-Hakkoda eruptive episode between 0.65 and 0.40 Ma (million years ago) belonging to Hakkoda volcano (Table 1), the erupted volume was estimated to be 52.4 km$^3$ magma from which 10.5 km$^3$, 21.0 km$^3$ and 21.0 km$^3$ magmas can be allocated to the periods of 0.7 to 0.6 Ma, 0.6 to 0.5 Ma and 0.5 to 0.4 Ma, respectively.

![Fig. 2. Temporal changes in eruptive volume (A) and cumulative eruptive volume (B) per 100 ky along the volcanic front in Northeast Japan.](image)

To identify when andesite stratovolcano-forming volcanism was initiated all over the volcanic arc, instead of felsic caldera-forming volcanism, the temporal change in the amount of magma discharged from all the volcanoes is shown in Fig. 2. The figure shows that erupted magma volume increased after 1.2 Ma and more than 50 km$^3$ of magma per 100,000 years were steadily erupted along the volcanic front.

On the one hand, the temporal change in the amount of erupted magma associated with stratovolcanoes and calderas is shown in Fig. 3. Felsic caldera-forming volcanism with large-scale pyroclastic flows is occurred intermittently since 2.0 Ma, and possible hiatuses of several one hundred thousand years exist during the Quaternary. Andesite stratovolcano-forming volcanism is recognized in the early Quaternary time, and note that it intensified after 1.1 Ma. Thus, Quaternary volcanism along the volcanic front changed in erupted...
magma volume and eruption style around 1.2 to 1.1 Ma. It can be characterized in two stages: stage 1 (before ca. 1.2 Ma), dominated by felsic caldera-forming volcanism; stage 2 (ca. 1.2 Ma onwards), was characterized by the predominance of andesite stratovolcano-forming volcanism, and marked by a significant increase in erupted magma volume.

Fig. 3. Temporal changes in eruptive volume for each type of volcanism. (A) is stratovolcano-building volcanism associated with stratovolcanoes, and (B) is felsic caldera-forming volcanism.

2.3 Temporal change in distribution of volcanic centers
The distribution of volcanic centers identified in the two stages discussed above is shown in Fig. 4. Stage 1 volcanism is only recognized in the Hakkoda-Towada V.R., the Sengan V.R., the Zao-Funagata V.R., the Bandai-Adatara V.R. and the Aizu V.R. In contrast, additional volcanic centers in stage 2 emarged in the Osore V.R. and the Kurikoma-Onikobe V.R. in the frontal arc. All seven volcanic regions and the volcanic front in Northeast Japan have only been established since ca.1.2 Ma. Moreover, the distribution of volcanic centers indicates that the northern part of the volcanic front has shifted about 10 to 20 km toward the trench side around 1.2 Ma.

3. Overview of cenozoic tectonism, Northeast Japan
So far, a great deal of effort has been made to obtain information about the Cenozoic tectonism in Northeast Japan (e.g., Sato, 1994; Acocella et al., 2008) and the published results are summarized as follows. The Cenozoic tectonic sequence is directory associated with the separation of the present-day Northeast Japan arc from the Asian continental margin due to the subduction of the Pacific plate and the opening of the Japan Sea rifted. Main rifting started at ~ 23 Ma, and from 21 to 18 Ma, was accompanied by significant counterclockwise rotation of the Northeast Japan arc (Jolivet et al., 1994). Owing to the cessation of the opening of the Japan Sea, the extensional stress field changed at about 13 Ma. In the Middle Miocene to the Pliocene, the tectonics is characterized by very weak crustal deformation under the moderate regional stress field related to the convergence of the Pacific plate (Sato, 1994). The maximum horizontal stress oriented in the NE or ENE direction was manifested during this period. This is one of the reasons why the SW migration of the Kuril sliver due to the oblique convergence along the Kurile arc results from a NE or ENE trending maximum compression (e.g., Otsuki., 1990).
The tectonic shortening became apparent in an E-W direction of compression around the Pliocene to Quaternary boundary, which may be associated with the increase in the motion of the Pacific plate between 5 and 2 Ma (Cox and Engebretson, 1985; Pollitz, 1986). In contrast, the crustal shortening of Northeast Japan might be triggered by the eastward motion of the Amur plate including in the Eurasian plate in the Quaternary (Taira, 2001). This is the reason why the Amur plate is considered to have initiated an incipient subduction on the eastern margin of the Japan Sea (Nakamura, 1983, Tamaki & Honza, 1985). A compressional stress field during the Quaternary is responsible for the development of two narrow uplift zones oriented in the N-S direction, in the Northeast Japan arc: the Ou Backbone Range (fore-arc) and the Dewa Hills (rear-arc). They appear to be an active pop-up structure bounded by opposite-facing reverse faults accommodating < 5 mm/y. of E-W shortening across the range (Hasegawa et al., 2005). Based on the subsurface geology and deformation of river terraces, the initiation time of reverse faulting was estimated at several sites in the Northeast Japan. These results suggest that reverse faulting started in the rear-arc side between 3.4 and 2.4 Ma (Awata and Kakimi, 1985), and in the fore-arc side between 0.9 and 0.5 Ma (Otsuki et al., 1977), corresponding to the onset time of uplift of the Dewa Hills and the Ou Backbone Range. The compressional regime have reactivated normal faults related to the extensional back-arc rifting until 18 Ma as reverse faults and accommodate much of the ongoing shortening across the arc (e.g., Sato, 1994).

Fig. 4. Distribution of volcanic centers for stage 1 (2.0 – 1.2 Ma) and stage 2 (1.2 – 0 Ma).
4. Quaternary volcano-tectonic relationships

Quaternary volcanism and tectonism along the volcanic front are related to each other temporally and spatially. In Northeast Japan, the N-S trending folds and faults have evolved under E-W compression during the Quaternary. Around 1.0 Ma, faulting in the frontal side (Ou Backbone Range), caused the concentrated crustal shortening there. Some contemporaneous changes occurred in volcanism as well; Around 1.2 to 1.1 Ma, felsic caldera-forming volcanism changed to andesite straovolcano-bulding volcanism. Moreover, the total erupted magma volumes along the volcanic front have notably increased since ca. 1.1 Ma. At the same time, magma underwent a systematic change in chemical composition. A significant volume of medium-K andesite has been erupted along the Ou Backbone Range since 1.0 Ma to 0.7 Ma, together with subordinate low-K andesite (Ban et al., 1992). Thus some synchronization between volcanism and tectonism is apparent.

To examine the spatial connections between volcanism and tectonism, the distribution of volcanic centers is compared to those of active faults, amplitudes of uplift and subsidence. Faulting along the volcanic front was initiated around 1.0 Ma and has been intensely activated all over the Ou Backbone Range since 0.5 Ma. The uplift of the mountain range might be accelerated due to resulting in reactivation of more faults. Based on these results, the distribution of volcanic centers along the volcanic front before and after 0.5 Ma, in stage 2, is shown in Fig. 5. The figure indicates that the volcanically active areas became localized near the volcanic front (shifted to the eastern margin of the Ou Backbone Range) after 0.5

Fig. 5. Distribution of volcanic centers for stage 2a (1.2 –0.5 Ma) and stage 2b (0.5 – 0 Ma).
Ma, and the alignment of volcanic centers exhibits a weak N-S trend in each volcanic region.
Thus, volcanism in stage 2 can be divided into two sub-stages: stage 2a (1.2 to 0.5 Ma),
marked by volcanism extended over a wide area and stage 2b (0.5 to 0 Ma), dominated by
volcanic centers localized near the volcanic front.

Fig. 6. Distribution of volcanic centers for each stage of Quaternary volcanism
(Cross : Stage 1, Open circle : Stage 2a, Solid triangle : Stage 2b) and active faults.

The distribution of active faults in Northeast Japan (Research Group for Active Faults in
Japan, 1991) and volcanic centers formed in the respective stages are shown in Fig. 6. It
indicates that the volcanic centers in stage 2b were located in a restricted area between
active faults running along the eastern and western margins of the Ou Backbone Range,
whereas the volcanic centers in stage 2a are found outside the above area. Fig. 7 shows the
uplift and subsidence during the Quaternary (Research Group for Quaternary Tectonic
Map, 1968) and the distribution of volcanic centers in the respective stages. Fig. 7 indicates
that the volcanic centers formed in stage 2b tend to be distributed more in uplifted areas
than those formed in stage 2a. However, there is no active fault near the Hakkoda-Towada
V.R. and the Kurikoma-Onikobe V.R., where large-scale felsic pyroclastic flows were
erupted in stage 2b and the amount of uplift is less than in other districts. Thus, the distribution of volcanic centers and eruption styles are closely related to the distribution of active faults and amplitudes of uplift suggesting a spatial connection between volcanism and tectonism (Fig. 8).

Fig. 7. Distribution of volcanic centers for each stage of Quaternary volcanism (Cross : Stage 1, Open circle : Stage 2a, Solid triangle : Stage 2b) and amounts of Quaternary uplift and subsidence. Contour interval of uplift/subsidence is 200 m for solid line, and 100 m for broken line.
5. Discussion

In view of the temporal and spatial connections between volcanism and tectonism discussed above, notable changes in eruption style and magma discharge rate occurred around 1.2 Ma. Generally, the crustal stress regime is thought to reflect the eruption style. Caldera formation suggests a tectonic environment facilitating the emplacement of shallow, large-scale felsic magma reservoirs. Therefore, Yoshida et al. (2001) suggested that an intermediate stress field allowing the alternation of weakly compressive and tensile fields is more favourable than a strongly tensile field to develop such a tectonic environment. Similarly, Takahashi (1995) pointed out that the accumulation of a large amount of felsic magma requires a relatively stable tectonic environment with a low crustal strain. In contrast, in stage 2, the crustal stress along the volcanic front is inferred to have changed to a strong compressive stress field with a high crustal strain rate which is favourable for stratovolcano-building volcanism. Although compressive components in the crustal stresses have gradually increased toward the fore-arc side since the Pliocene, the patterns of crustal stress are concordant with the eruption styles in stage 1 and stage 2.

Fig. 8. Summary of volcanism and tectonism since 2.0 Ma along the volcanic front in the Northeast Japan arc.
However, it seems to be difficult to interpret a significant increase in erupted magma volume since ca. 1.2 Ma on account of compressional stress regime in fore-arc side. Because, in compressional settings, it is considered that magma cannot ascend so easily, for the reason of magma expanding along horizontal fractures perpendicular to the least principal stress ($\sigma_3$) equal to vertical stress ($\sigma_v$) (Hubbert and Willis, 1957). For this apparent contradiction, one of the plausible interpretations for this contradiction may be the increase in magma generation in the wedge mantle. Numerical simulations considering fluid migration and melting in the mantle wedge above a subducting plate indicate that melt production rates increase with increasing convergence rate (Cagnioncle et al., 2007). In the Cascade volcanic arc, the convergence rate of the Juan de Fuca plate to the North American plate is thought to control the change in eruption rate (Priest, 1990). Therefore, despite the overall compressive setting along the NE Japan arc, the increase of magma erupted could be interpreted to be due to the product of partial melting in the wedge by significantly faster subducting Pacific slab.

In addition, it is necessary to examine the effect of local crustal stress along the volcanic front on volcanism in stage 2. Local changes in crustal stress are attributable to: 1) the heterogeneity of differential stress caused by thermal structures (Watanabe et al., 1999); 2) a change in crustal stress near the faults caused by faulting (Yoshioka and Suzuki, 1997); and 3) the gravitational instability generated in uplifted mountain blocks (Moriya 1983; Molnar 1986).

5.1 Heterogeneity of differential stress caused by thermal structures

Watanabe et al. (1999) pointed out that the heat spreading from magma reservoirs can produce a horizontal stress heterogeneity which could be lowered locally around the reservoirs, so that the regional crustal stress could be maintained at some distance from the reservoir. In fact, a S-wave reflection horizon correlative to a magma reservoir at a depth of 7 to 12 km below the Kiso-Ontake Volcano has been recognized (Inamori et al., 1992). The focal mechanisms of swarm earthquakes generated near this horizon indicate that $\sigma_{\text{Hmax}}$ is always equal to $\sigma_1$, whereas the vertical stress ($\sigma_v$) is unstable switching from $\sigma_2$ to $\sigma_3$ (Hori et al., 1982). A stress field with $\sigma_v = \sigma_2$ could lead to the intrusion of a dike and permit vertical migration of magma. Thus, even though the regional stress field is compressive, magma could still ascend if the adjacent differential stress is lowered by the heat spreading from magma itself. Moreover, it is probable that dikes, conduits for magma are combined with horizontal sheets to form a complicated plexus as indicated by Takahashi (1994). Thus, the local lowering of differential stress by thermal effects is thought to be a factor in magma ascent.

5.2 Change in crustal stress near the faults caused by faulting

It has been noted that the crustal stress around faults changes before and after faulting. According to Yoshioka and Suzuki (1997), when a dislocation is generated by a fault, a reverse fault type of stress field with $\sigma_v = \sigma_2$ develops on upward and downward extensions of the fault plane, whilst a normal fault type of stress field with $\sigma_v = \sigma_1$ occurs immediately above and below it. As mentioned above, active fault systems exist that are believed to reach the lower crust beneath the volcanic front and contribute to the uplifting of the Ou Backbone Range. Dislocations along these faults give rise to a normal fault type of stress field that facilitates the ascent of magma around faults. Therefore, it is probable that the faulting activated all over the Ou Backbone Range since 0.5 Ma resulted in the concentration of
volcanic centers in the area between western and eastern marginal active faults during stage 2b.

5.3 Gravitational instability generated in the uplifted mountain block
The uplift of the volcanic front is believed to have been accelerated by the activation of faults all over the Ou Backbone Range since 0.5 Ma. The uplift-related gravitational instability in the mountain blocks in turn is expected to have generated a tensile stress field normal to the elongation of the mountain range (Moriya 1983; Molnar 1986). Based on the fact that the focal mechanism of earthquakes below the volcanoes on the uplifted mountains differs at depth from one another, Takahashi (1994) estimated that the local tensile stress field generated by the gravitational instability may extend down to several km below the mountain top. These facts show that the more severely uplifted areas form a favourable environment for magma ascent due to the local tensile stress field, and provide a reasonable explanation for the increase in eruptive volume and the concentration of volcanic centers in such uplifted areas in stage 2b (Fig. 7). Furthermore, the N-S alignment of volcanic centers in stage 2b might reflect the E-W tensile stress field generated by gravitational instability. Thus, the faulting and uplifting have presumably generated local lowering of differential stress or the tensile stress field along the volcanic front during stage 2, which in turn affected the amount of magma erupted and the alignment of volcanic centers. In the areas (e.g., the Hakkoda-Towada V.R, the Kurikoma-Onikobe V.R.) where volcanism associated with large-scale felsic pyroclastic flows occurred in stage 2b, a tectonic environment characterized by weak compression and a low crustal strain might have prevailed despite the lack of active faults and uplift.

6. Conclusions
From a compilation and analysis of stratigraphy, radiometric age and eruptive magma volume data for 139 volcanic events along the volcanic front, notable changes in eruption style, magma compositions, variation in eruptive volume, and distribution of volcanic centers can be recognized around 1.2 Ma. Before ca. 1.2, felsic caldera-forming volcanism are thought to occur in regions of neutral stress regime with low crustal strain rate. From ca. 1.2 Ma to the present-day, the crustal stress regime seems to have changed to compression yielding the formation of stratovolcanoes all the volcanic front. It has become apparent that stratovolcanoes lie along major thrust faults associated with uplift of the Ou Backbone Range since the Middle Pleistocene. Although it is widely assumed that magma cannot rise so easily in compressional setting, the increase of erupted magma volume since ca. 1.2 Ma may have been caused by an increase in subduction rate of the Pacific plate between 5 and 2 Ma. In addition, the lowering of differential stress by thermal effects is also thought to facilitate the ascent of magma. On the other hand, the distribution of volcanic centers formed since 0.5 Ma, controlled mostly by the local extensional stress regime in the upper crust, was locally influenced by fault dislocations and gravitational instability.

7. Acknowledgment
The author thanks Drs. R. I. Tilling, S. J. Day and S. Hayashi for many comments that helped us to improve the original manuscript, and Dr. A. J. Martin for editing this manuscript.
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Koji Umeda and Masao Ban (2012). Quaternary Volcanism Along the Volcanic Front in Northeast Japan, Updates in Volcanology - A Comprehensive Approach to Volcanological Problems, Prof. Francesco Stoppa (Ed.), ISBN: 978-953-307-434-4, InTech, Available from: http://www.intechopen.com/books/updates-in-volcanology-a-comprehensive-approach-to-volcanological-problems/quaternary-volcanism-along-the-volcanic-front-in-northeast-japan
