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Thermal Monitoring of the Lithosphere by the Interaction of Deep Low-Frequency and Ordinary High-Frequency Earthquakes in Northeastern Japan

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Abstract: Deep low-frequency earthquakes (LFEs) are known to occur in dehydration phenomena from the subducting hydrous slab and in magmatic phenomena beneath Quaternary volcanoes in Japan. To realize the spatial and temporal characteristics of the magmatic deep low-frequency earthquakes, their hypocenters along with those of ordinary overhead high-frequency earthquakes are analyzed beneath six volcanic fields in northeastern Japan. This trial clarifies the rising basaltic magma conduits and rheological profiles of the lithosphere. Deep low-frequency earthquakes tend to form three vertical clusters corresponding to the rheological strength peak of the peridotite upper mantle, gabbroic lower crust, and granitic upper crust. Interactive aseismic gaps between low- and high-frequency earthquakes reveal the brittle–plastic transition as an isothermal indicator in the lithosphere. This relationship provides a tool to monitor the thermal evolution of the lithosphere and to explore sustainable geothermal resources with basaltic magma replenishment systems.

Keywords: deep low-frequency earthquake; high-frequency earthquake; aseismic gap; brittle–plastic transition; seismicity; lithosphere; basaltic magma conduit; thermal monitoring; geothermal exploration

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1. Introduction

A current high-sensitivity seismograph network enables us to observe deep, low-amplitude, and low-frequency earthquakes in Japan [1–3]. These deep low-frequency earthquakes (LFEs) are derived from a so-called aseismic layer beneath the seismogenic layer. The LFEs defined here are 50–1 km deep, have a magnitude of <2.5, and a frequency of 2–8 Hz [4]. These LFEs are distinguished from extremely shallow volcanic tremors (<1 km) that might be caused by the two-phase flash of shallow groundwater, as observed in fumaroles. An LFE zone over 600 km along the subducting Philippine Sea Plate at a slab surface depth interval of 35–45 km was discovered as a dehydration phenomenon from the subducting hydrous slab in Figure 1 [1]. These LFEs are categorized as tectonic LFEs [2]. The distinctive nature of the tectonic LFE cluster is that it is laterally almost continuous, similar to a curtain, indicating an isothermal and/or isobaric phenomenon controlled by the subduction depth interval.

Other LFE clusters in Japan are associated with Quaternary volcanoes, as shown in Figure 1 [2,3]. They are categorized as volcanic LFEs [2], but in this paper, they are referred to as "magmatic LFEs" because of their deep origins in the upper mantle. Magmatic LFEs provide key information on the ascent and replenishment of basaltic magma from the upper mantle to upper crustal subvolcanic magma chambers. This aspect was already identified in Hawaii 40 years ago [5]. Most of the previous LFE studies, however, focused on the focal mechanism of LFEs themselves. The spatial and temporal relationships of LFEs along with their overhead ordinary high-frequency earthquakes (HFEs) have seldom been investigated. The distinctive nature of the magmatic LFE cluster is that it is laterally discontinuous and sporadic, similar to a diapir, implying a magma rising phenomenon.

The next generation of deep geothermal resources are being investigated. For example, the New Energy and Industrial Technology Development Organization (NEDO) in Japan is promoting the use of supercritical water for geothermal power generation under the research project "Research and Development of Supercritical Geothermal Resources." In this context, deep geothermal exploration techniques that overcome the depth greater than the conventional geothermal reservoir depths such as 2 km or 3 km are anticipated. From this perspective, this study tries to plot hypocenters of the magmatic LFEs and their overhead HFEs beneath six volcanic fields in northeastern Japan for the purpose of identifying deep magmatic conduits and monitoring thermal conditions of the lithosphere.

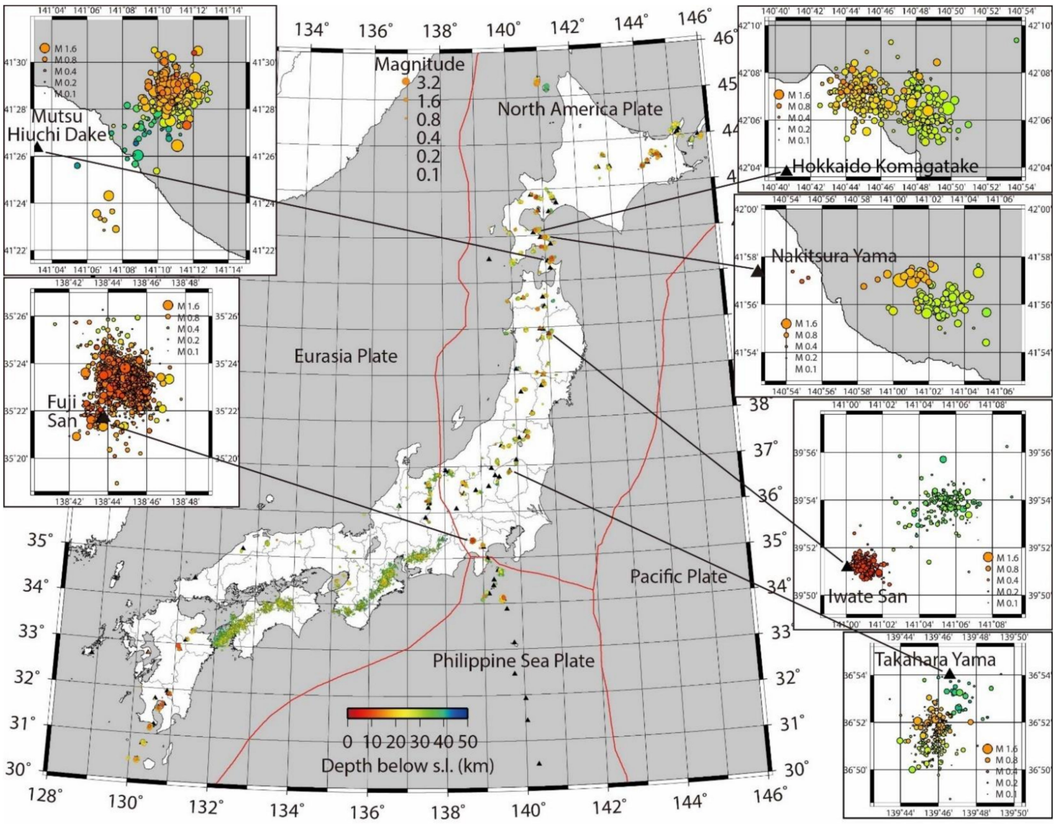

Figure 1. Distribution of 46,657 epicenters of deep low-frequency earthquakes (LFEs) on the plan views in the main part of Japan quoted from the earthquake catalog of the Japan Meteorological Agency (JMA) from the year 2000 to 2016. Solid triangles show the Quaternary volcanoes. Plan views of epicenters of LFEs of six volcanic fields are enlarged in insets.

2. Study Areas and Magmatic LFEs Swarms

Figure 1 shows the distribution of 46,657 epicenters of LFEs in a plan view in the main part of Japan. The hypocenter data were taken from the earthquake catalog of the Japan Meteorological Agency (JMA) during the 17 years from the year 2000 to 2016. The LFEs have been distinguished by the band-pass filter 2–8 Hz regardless of their mechanism by JMA since 1997 [2–4]. The earthquake catalog of JMA provides 96 columns of information for each earthquake event as a hypocenter record format. The LFEs can be distinguished from HFEs in the 61st column since 1997, but this procedure has been more improved since 2000 [3]. Fumarole-type LFEs that were shallower than 1 km were excluded from this study. Magmatic LFEs are generally associated with Quaternary volcanoes as swarms. Swarms of magmatic LFEs in six volcanic fields—Hokkaido Komagatake, Nakitsura Yama, Mutsu Hiuchi Dake, Iwate San, Takahara Yama, and Fuji San—are shown as insets in Figure 1.

Some magmatic LFE clusters consist of only a few to several events, and the six volcanic fields were chosen from the magmatic LFE clusters with relatively large numbers of events. These magmatic LFEs generally form isolated clusters with diameters ranging from 7 km to 15 km (Figure 1). It should be noted that most of the LFEs tend to appear toward the east or northeast of the nearest Quaternary volcanoes' summit at a distance of 2 km to 15 km away (Figure 1). The only exception is the LFE cluster in the Takahara Yama volcanic field, but if this cluster is connected to the next nearest volcano, the Nyoho-Akanagi volcano in the southwestern area, then the LFE clusters are situated in the northeastern direction from a Quaternary volcano, which is the same as the other five volcanic fields.

Recently, the Moho discontinuity beneath the Japanese Islands was investigated by three-dimensional seismic tomography [6]. Consequently, the depth of the Moho discontinuity is estimated to be more than 30 km in most of northeastern Japan, and partly more than 35 km along the volcanic front.

3. Depth Profiling

Figure 2 shows the distribution of hypocenters of LFEs and HFEs on the cross sections of the six volcanic fields. It is important to note that the HFEs are distributed in the two depth intervals in the six volcanic fields, namely, 0.00–29.49 km and 113.10–148.47 km in Hokkaido Komagatake; 0.00–29.49 km and 98.69–147.81 km in Nakitsura Yama; 0.81–25.89 km and 90.98–157.43 km in Mutsu Hiuchi Dake; 0.07–11.37 km and 92.83–108.71 in Iwate San; 1.08–30.65 km and 101.07–137.89 km in Takahara Yama; and 0.00–28.81 km and 154.20–207.81 km in Fuji San. These deeper intervals of the HFEs indicate subduction zone earthquakes in a broad sense including intra-slab earthquakes, but only shallower intervals of the HFEs are treated in this study for the geothermal purpose (Figure 2). The frequency of HFEs is larger than 8 Hz, and the largest magnitude of the HFEs among the six volcanic fields was 5.3 in Nakitsura Yama. Since the magnitude of the LFEs is defined to be 2.5 or less, the HFEs tend to be slightly larger in magnitude (Figure 2).

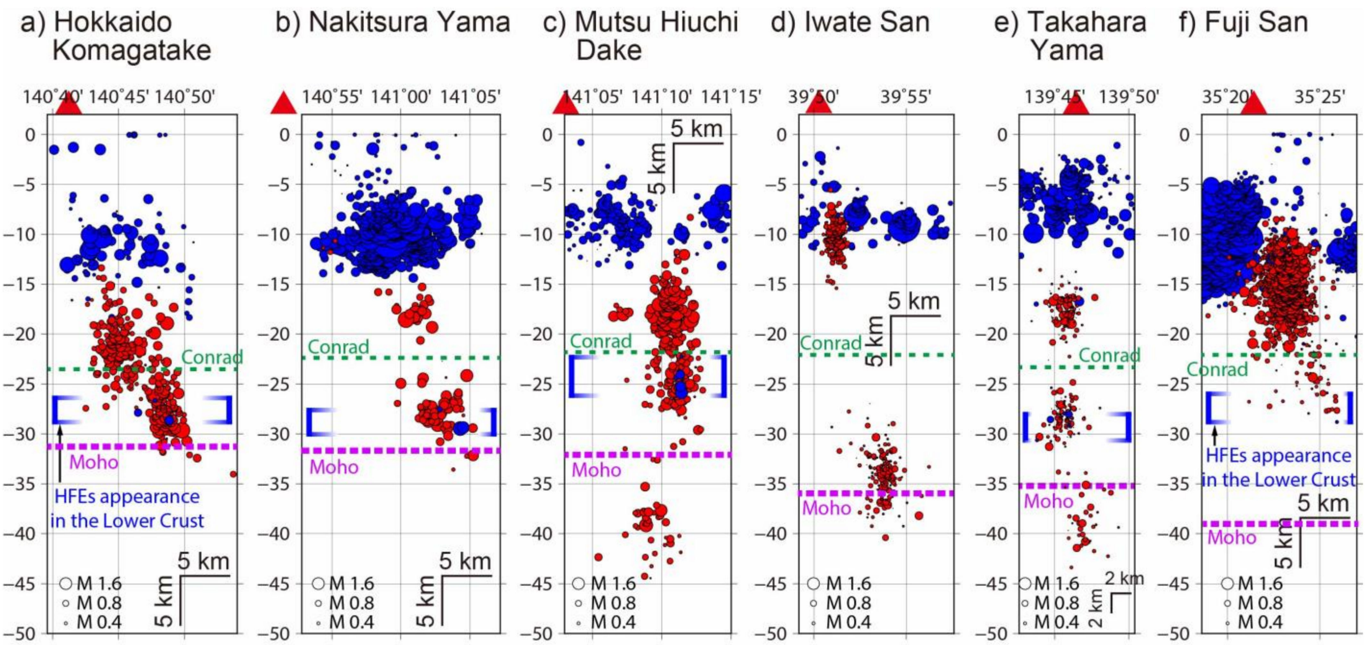

Figure 2. Hypocenter distribution of deep low-frequency earthquakes (LFEs, red circle) and ordinary high-frequency earthquakes (HFEs, blue circle) on the four E–W cross sections (Hokkaido Komagatake, Nakitsura Yama, Mutsu Hiuchi Dake, and Takahara Yama) and on the two N–S cross sections (Iwate San and Fuji San) in the same areas of insets as in Figure 1. A few HFEs are observed in the depth of 31–22 km of the lower crust in the five volcanic fields.

The depths of the Moho discontinuity in the six volcanic fields in Figure 2 were given from the depth contour map by seismic tomography [6]. The LFEs vertically tend to form three clusters on the cross sections showing the three depth intervals, 45–31 km in the uppermost of the upper mantle, 39–22 km in the lower crust, and 22–5 km in the upper crust. Compared to the Moho discontinuity, the depth of the Conrad discontinuity is not well demonstrated. For this reason, the depths of the Conrad discontinuity were simply speculated by the cluster boundaries of the LFEs in the six volcanic fields in Figure 2. The upper mantle clusters can only be recognized in the three volcanic fields—Mutsu Hiuchi Dake (Figure 2c), Iwate San (Figure 2d), and Takahara Yama (Figure 2e). Lower crust clusters and upper crust clusters can be observed in all six volcanic fields (Figure 2). The LFE clusters of the upper crust in Iwate San and Fuji San form vertically elongated ellipsoids, suggesting subvolcanic magma chambers and their peripheral plastic host rock envelopes. The ellipsoidal LFE clusters are surrounded by steep walls of the HFE clusters. The three-level clustering is possibly ascribed to the rheological difference of the lithological composition, such as the peridotite upper mantle, gabbroic lower crust, and granitic upper crust including quartz-feldspar dominant sedimentary rocks. Notably, a few HFEs are almost ubiquitously detected in the depth interval 31–22 km in the five volcanic fields except in Iwate San (Figure 2). The depth interval corresponds to the upper-middle of the lower crust. There are only four events of HFEs in Hokkaido Komagatake (Figure 2a), four events in Nakitsura Yama (Figure 2b), six events in Mutsu Hiuchi Dake (Figure 2c), seven events in Takahara Yama (Figure 2e), and two events in Fuji San (Figure 2f) in the lower crust. With decreasing depth of LFE hypocenters, two or three vertical LFE clusters tend to move laterally from the ENE to the WSW direction by 2 km to 15 km toward the summit of the nearest Quaternary volcanoes. Aseismic gaps are always recognized between the magmatic LFE cluster and its overhead HFE cluster throughout the six volcanic fields, although the aseismic gap is almost vertical in Iwate San and Fuji San because of the high angle relationships between the LFE and HFE clusters. When the top of the magmatic LFE cluster is wedge-shaped, as observed in Iwate San and Fuji San, its overhead HFE cluster interactively shifts further to the shallower sides, forming an umbrella-shaped envelope.

4. Chronological Depth Variations

Figure 3 illustrates the chronological depth variations of the LFE and HFE hypocenters in all six volcanic fields shown in the inset areas of Figure 1, from 2000 to 2016 (Figure 3a–f). Most of the vertical LFE clusters are stable and active at all depth intervals from the upper mantle to the upper crust throughout the 17-year period (Figure 3a–f). The aseismic gaps between the LFE and HFE clusters are recognized with scarce depth overlaps in Figure 3a–c,e, but the high-angle contacts of clusters inevitably overlap in Iwate San and Fuji San (Figure 3d,f). To quantitatively draw their chronological changes, curves of two-year moving averages are drawn for the LFE and HFE clusters, respectively. HFEs occur in the so-called seismogenic layer or brittle layer. Hence, LFEs might occur in the so-called aseismic layer or plastic layer. Therefore, a brittle–plastic transition is expected between the two curves. However, the LFEs generally extend in the wide depth interval from 45 km to 5 km and the HFEs extend in the narrow depth interval from 15 km to 0 km. Using this depth extent ratio of 0.73:0.27, a curve for the brittle–plastic transition can be drawn between the LFE and HFE curves, as shown in Figure 3. These curves are consistent with the boundary between the LFE and HFE clusters. During the 17-year period, two large-scale earthquakes occurred in the region—one was the 2003 Tokachi-Oki Earthquake M8.0 on 26 September 2003, and the other was the 2011 Tohoku-Oki Earthquake M9.0 on 11 March 2011. The latter is also known as the Great East Japan Earthquake, as the name of a historical natural calamity. The timings of the two earthquakes are shown in Figure 3.

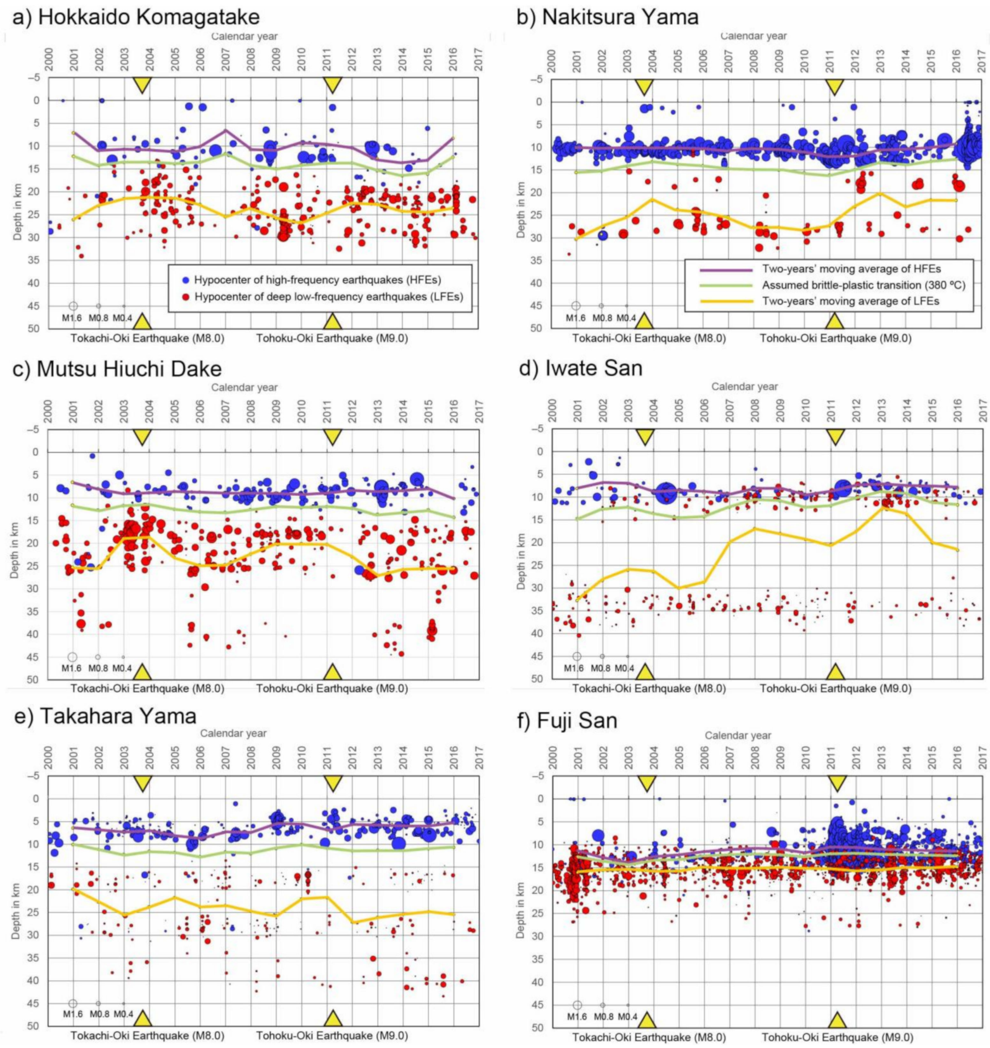

Figure 3. Chronological variations of the hypocenter depth of the deep low-frequency earthquakes (LFEs) and ordinary high-frequency earthquakes (HFEs) in the six volcanic fields, (**a**) Hokkaido Komagatake, (**b**) Nakitsura Yama, (**c**) Mutsu Hiuchi Dake, (**d**) Iwate San, (**e**) Takahara Yama, and (**f**) Fuji San.

5. Discussion

5.1. Perspective on the Deep Geothermal Energy Developments

One of the obvious historical trends in geothermal energy development is earnestly extending objective fields to the greater depth of the earth's crust. For example, deeper geothermal wells in Japan were drilled down to a depth of 1.5 km by 1970 but rapidly extended to 2.5 km by 1980 and to 3.0 km by 1985 [7]. It is reasonable that geothermal development is seeking high enthalpy energy resources induced by the geothermal gradient. However, permeability conversely decreases with depth in general. Then, the engineered geothermal system (EGS) including the artificial hydrofracturing technique has come to be of great interest to geothermal engineers and researchers in the last two decades.

When we consider geothermal development that address greater depths of the earth's crust, exploration technology becomes increasingly challenging. Deep exploratory wells can rarely be attained due to the extremely higher costs. Active geophysical exploration methods are higher in costs and close to a limit of the observed depth. Then, passive geophysical exploration methods such as natural earthquake observation are one of the efficient techniques for greater depths. Most active tectonic regions have stationary seismograph networks and the seismic data are usually open to the public for the mitigation of earthquake hazards. Therefore, most seismic data are distributed at no cost. This study is one of the efforts in this direction to the future deep geothermal energy developments.

As the application of magmatic LFEs to the magma conduits in the greater depths was achieved in Hawaii 40 years ago [5], this method can be applied in the world, even if a dense seismograph network is necessary.

5.2. Spatial Characteristics of Clusters of the Magmatic LFEs

Based on the above observations, four aspects are discussed. The LFEs tend to form clusters in the three depth intervals—the upper mantle, lower crust, and upper crust (Figure 4). These lithological units consist of peridotite rocks, gabbroic rocks, and granitic-sedimentary rocks divided by the Moho discontinuity at about 35 km depth and by the Conrad discontinuity at about 22 km depth (Figure 4a). The clustering can be reasonably explained by the strength envelope model of the continental lithosphere (Figure 4b). The power creep law of wet dunite in the upper mantle was drawn by [8,9], the power creep law of wet granulite in the lower crust was drawn by [10,11], and the Byerlee's law of the brittle layers in the lower and upper crusts was drawn by [12] under the strain rate condition of 10^{-14} s^{-1}. The temperature assumption was 800 °C at a depth of 35 km and 380 °C at a depth of 15 km.

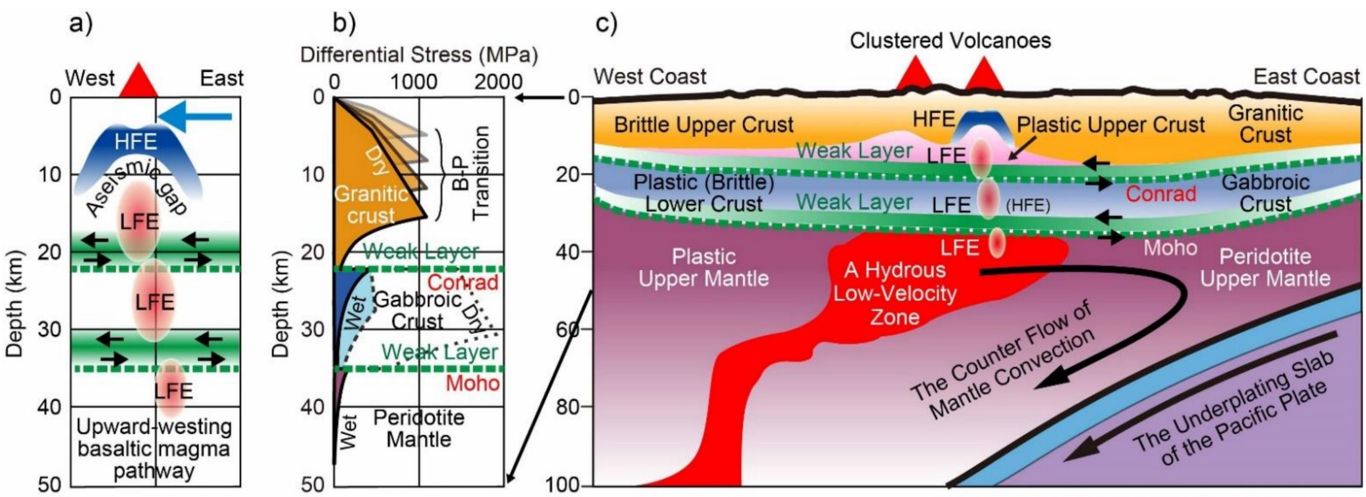

Figure 4. A model of the distribution of the LFEs and HFEs in volcanic fields, northeastern Japan. (**a**) Simplified spatial distributions of the LFEs and HFEs in volcanic fields in northeastern Japan. (**b**) Vertical three LFE clustering are explained by the strength envelope models in the three lithological layers. (**c**) A model of the basaltic magma replenishment systems to the subvolcanic magma chambers beneath the volcanic fields where the counter flow of the mantle convection to the underplating Pacific Plate results in the small lateral deviation of the basaltic magma conduits from the ENE to WSW directions as the LFEs move to shallower depths.

The three vertical LFE clusters seem to occur at the maximum strength depth in the upper crust, lower crust, and upper mantle, respectively (Figure 4b). The stress is generally concentrated in the stronger layers in the multi-layer systems, and then the fault rupture tends to disconnect the stronger layers rather than the weaker layers [13]. Consequently, the HFE ruptures prefer the maximum strength layers in the multi-layer systems. Whether the geneses of the magmatic LFEs also prefer the maximum strength layers or not is still open to questions. The magmatic LFEs occur in a plastic layer, and their focal mechanisms are estimated to be the compensated linear vector dipole type by the study of the 38 events in western Japan [2,14]. The directions of the dipoles are systematically controlled by the regional stress field [2]. Therefore, even if the magmatic LFEs occur in a plastic layer, it seems possible that they are also preferably clustered in the maximum strength depth of the three lithologic units—the upper mantle, lower crust, and upper crust. A few but ubiquitous numbers of HFEs are detected in the depth interval of 31–22 km. They appear exactly in the lower crust LFE clusters. This fact strongly supports that the LFEs preferably appear at the maximum strength depth in a similar manner to the HFEs.

The LFE clusters tend to appear in the ENE direction from the volcanic summits at 2 km to 15 km. In other words, lateral deviations of the LFE clusters are detected from the ENE to WSW directions at 2 km to 15 km as the LFEs move to shallower depths. This phenomenon could be ascribed to the effect of the counter flow in the wedge mantle to the Pacific Plate subduction (Figure 4c). Particularly, this movement can efficiently occur in the bottoms of the lower crust and upper crust because these horizons correspond to the weakest strength envelopes (Figure 4b). The total lateral deviation of the LFEs with depths of 2 km to 15 km can easily be detected in Figure 2. However, when we observe Figures 2 and 3, the vertical deviation or tilting has been stable in the depth from 45 km to 5 km throughout the 17 years. Therefore, although basaltic magma intrusions were quickly ascending, their deviated conduits themselves are controlled under the dynamic equilibrium by the velocity gradient of the counter flow of the wedge mantle to the Pacific Plate subduction.

5.3. The Magmatic LFEs as Rising Basaltic Magma Conduits

The tectonic LFE cluster in the subducting Philippine Sea Plate at a slab surface depth interval 35–45 km laterally forms an almost continuous zone over 600 km in the along-arc direction of southwestern Japan (Figure 1). This suggests that the tectonic LFE cluster is derived from isothermal and/or isobaric dehydration reactions controlled by the subduction depth interval [1]. This is also consistent with the fact that the tectonic LFE cluster is situated far more on the fore-arc side rather than the volcanic front of southwestern Japan, showing non-magmatic events. On the contrary, the magmatic LFE clusters in northeastern Japan are associated with the Quaternary volcanoes. They are laterally discontinuous and sporadic. Seismic tomography detected a distinctive low-velocity zone parallel to the subducting deeper slab of the Pacific Plate beneath northeastern Japan [15] (Figure 5). The low-velocity zone itself is laterally continuous even in the less volcanic across-arc section of northeastern Japan [15]. The zone consists of hydrous and partially molten peridotite receiving water from the progressive dehydration reactions of the subducting hydrous slab, which might be continuous in the along-arc direction [16]. The most common primary magma from the upper mantle in the island arc region is basaltic magma [16] in which water contents of the hydrous mantle should be exclusively partitioned into the rising basaltic magma (Figure 4c). However, primary basaltic magma cannot rise from all over the low-velocity zone (Figure 5) because the dynamics of diapir are subject to the Rayleigh–Taylor-type instability processes, for example, [17,18]. Rising basaltic magma is then sporadically clustered with some spacing (Figure 5). An entity of the magmatic LFEs can thus be explained by the rising basaltic magma from the low-velocity zone (Figure 5). Therefore, the magmatic LFEs provide us a tool to observe basaltic magma conduits from the upper mantle to the lower and upper crust.

5.4. The Brittle–Plastic Transition Depicted by the LFE and HFE Boundary

As the rock deformation phase transitions from the brittle, semi-brittle, and plastic regions with increasing pressure and temperature [19], the temperature threshold of the brittle–plastic transition cannot be uniquely determined in general. However, it was proposed that the temperature of the brittle–plastic transition for silicic rocks under active tectonic regions can be practically restricted to the temperature range of 370–400 °C, as proposed by Fournier [20]. Immediately after Fournier's insight, the well WD-1a was drilled into a depth of 3729 m penetrating extremely young granodiorite and tonalite intrusion below 2860 m in the Kakkonda geothermal field in northeastern Japan in 1995 [21]. The bottom hole temperature exceeded 500 °C, and the temperature logging curve had an inflection point at a depth of 3100 m and a temperature of 380 °C [22]. This inflection point was ascribed to the bottom of the permeable hydrothermal convection and the brittle–plastic transition [7]. The observed temperature of 380 °C was consistent with the estimated temperature range of 370–400 °C, as proposed by Fournier [20]. The bottom of the seismogenic layer in several volcanic fields in northeastern Japan is also estimated to be 380 °C [23,24]. Consequently, the temperature threshold of 380 °C may be reasonable for the brittle–plastic transition on the silicic upper crust in northeastern Japan.

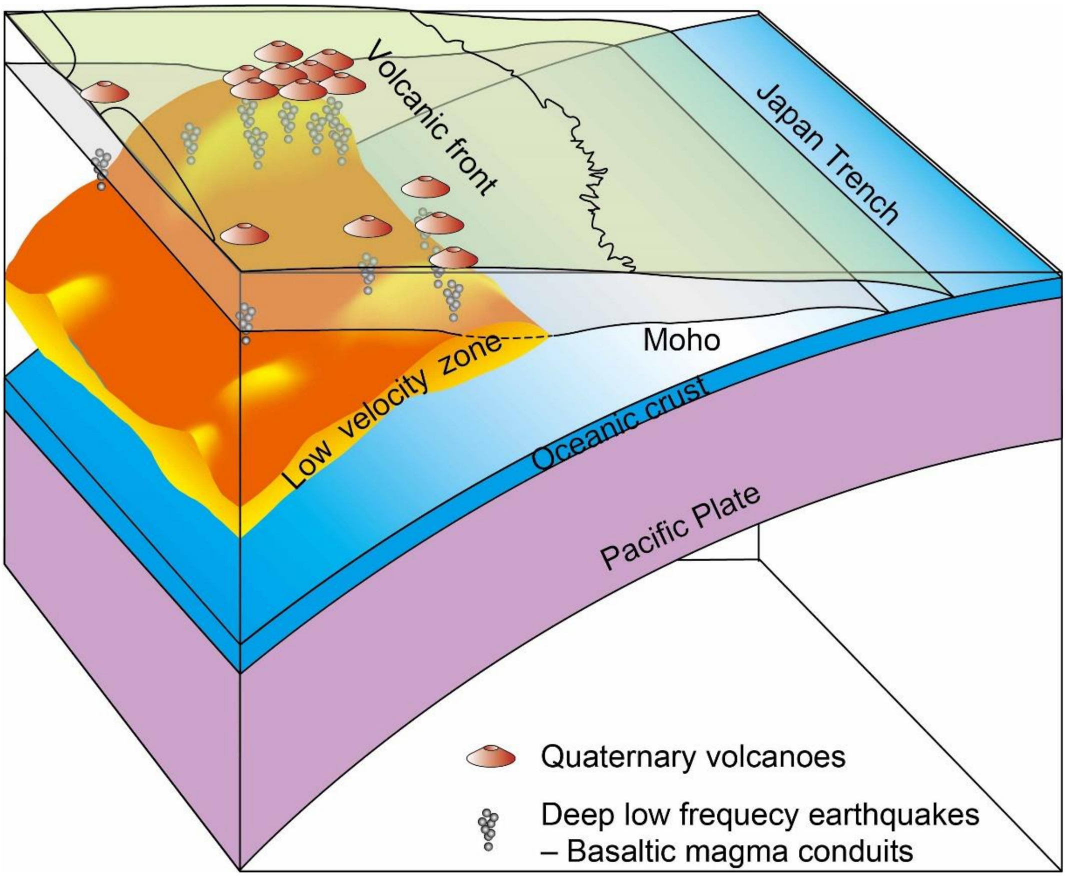

Figure 5. A conceptual model of the sporadic LFEs clusters as rising basaltic magma conduits from the continuous low-velocity zone in northeastern Japan. The low-velocity zone was roughly sketched from [15].

The brittle–plastic transition can then be easily determined by the boundary between the two types of earthquakes providing an intra-crustal isotherm at 380 °C. The aseismic gaps between the magmatic LFEs and their overhead HFEs reveal the brittle–plastic transition and the isotherm at 380 °C.

5.5. Possibility of Thermal Monitoring of the Lithosphere by the LFE and HFE Boundary

Based on the above discussion, the chronological depth variation of the LFE and HFE boundary represented by the assumed brittle–plastic transition curve can be used for the dynamic thermal monitoring of the lithosphere (Figure 3). For example, when the chronological depth variations of the assumed brittle–plastic transition in six volcanic fields are compared, the variations throughout the 17-year period are classified into three types (Figure 3). One is a slightly increasing type as seen in Mutsu Hiuchi Dake, which exhibits a cooling trend (Figure 3c). The second is an almost constant type, as observed in Hokkaido Komagatake and Takahara Yama, implying constant thermal trends (Figure 3a,e). The third is a slightly decreasing type as observed in Nakitsura Yama, Iwate San, and Fuji San, which suggests heating trends (Figure 3b,d,f). Steeply facing relationships between the LFEs and HFEs in Iwate San and Fuji San are also consistent with the heating trends as a result of the current active magmatism. Therefore, although more data for the year can be expected, these chronological depth variations of the LFE and HFE boundaries provide a possible tool for the thermal monitoring of the lithosphere. Three volcanic fields have historic eruption records. Magmatic eruptions occurred in Hokkaido Komagatake in 1640, 1694, 1856, 1929, and 1942, in Iwate San at 1686 and 1732, and in Fuji San in 1707 [25]. Unfortunately, the 17 years' observation period of the magmatic LFEs is too short to compare to these eruption records.

Chronological depth variations can also be observed in relationships with large-scale subduction zone earthquakes. When the two-year moving curves of LFEs are compared to the two large-scale subduction zone earthquakes, their shallower curves correspond well to the time of the occurrence of the 2003 Tokachi-Oki Earthquake in the northern four volcanic fields (Figure 3a–d). Although the variation range is less than the LFE curves, the assumed brittle–plastic transition curves also form slightly shallower peaks in the four volcanic fields at the time of the 2003 Tokachi-Oki Earthquake occurrence. In addition, the activation of some vertical LFE swarms was detected in Hokkaido Komagatake and Mutsu Hiuchi Dake at the time of occurrence of the 2003 Tokachi-Oki Earthquake (Figure 3a,c). Therefore, mutual relationships can be recognized between the depth variations of the isotherm and the large-scale subduction zone earthquake. The magnitude of the 2011 Tohoku-Oki Earthquake was extremely large for the effect to be observed in the short period, and the relationships to the depth variation were less obvious than those of the 2003 Tokachi-Oki Earthquake. However, the two-year moving curves of the LFEs show shallower peaks in a period two years before and after the 2011 Tohoku-Oki Earthquake in all six volcanic fields, although the variation range in Fuji San is relatively small (Figure 3). In addition, the HFEs were activated since the 2011 Tohoku-Oki Earthquake in Iwate San, Takahara Yama, and particularly in Fuji San. According to the above observations, it can be summarized that the LFE activation and crustal heating tend to occur before the occurrence of the large-scale subduction zone earthquakes (Figure 6). On the contrary, HFE activation and crustal cooling tend to occur from large-scale subduction zone earthquakes.

The 2011 Tohoku-Oki Earthquake provides numerous accounts of subduction zone earthquakes, where the tectonic stress was accumulated in the subduction zone for years by strong coupling on the so-called asperity until the mainshock (Figure 6a). Then, the thrust ruptured during the mainshock, as a large-scale subduction zone earthquake suddenly released the accumulated tectonic stress, resulting in the rebounding relaxation deformation (Figure 6b). For example, the maximum slip of thrust movement on the hypocenter of the 2011 Tohoku-Oki Earthquake was estimated to be 62 m [26]. This resulted in the dramatic stress relaxation of the continental crust from the accumulated tectonic stress.

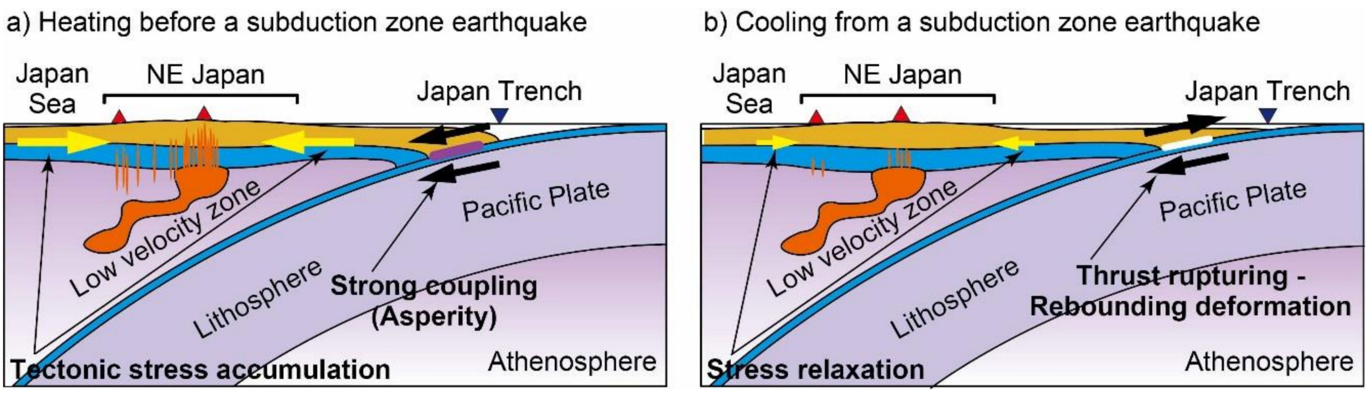

Figure 6. A conceptual model showing active basaltic magma rises before a large-scale subduction zone earthquake and inactive basaltic magma rises after the earthquake. (**a**) A heating process before a subduction zone earthquake: the accumulating tectonic stress by strong coupling on the asperity accelerates the rising of pumping basaltic magma. (**b**) A cooling process from a subduction zone earthquake: thrust rupture relaxation decelerates the rising of pumping basaltic magma.

According to this knowledge, thermal evolution induced by large-scale subduction zone earthquakes can be explained by the following general model (Figure 6).

Before the occurrence of the large-scale subduction zone earthquake, accumulated contractional tectonic stress accelerated the pumping effect of the partially molten basaltic magma in the low-velocity zone and activated basaltic magma rising in addition to replenishment from the upper mantle to the shallower crust. Consequently, the magmatic LFE activity and crustal heating prevailed in this stage (Figure 6a). From the mainshock of the large-scale subduction zone earthquake, the relaxation of the accumulated tectonic stress decelerated the pumping effect of the partially molten basaltic magma in the low-velocity zone and deactivated the rising and replenishment of basaltic magma from the upper mantle to the shallower crust. As a result, the brittle HFE activity and crustal cooling prevailed in this stage (Figure 6b). One might speculate that, before the large-scale subduction zone earthquake, contractional tectonic stress prevents magma from rising to the shallower crust. However, recent deep geothermal wells demonstrate that the shallower magmatic intrusions are more dominant in the contractional tectonic fields by the efficient buoyancy of magma in the high-density host rocks [27].

6. Conclusions

Some volcanoes have active deep conduits of basaltic magma replenishment from the low-velocity zone to their subvolcanic magma chambers, while others do not comprise replenishment conduits probably having been lost at a certain time of their lives. This critically important difference of volcanoes can be detected by signals from magmatic deep low-frequency earthquakes. Therefore, magmatic deep low-frequency earthquakes and their interactive overhead high-frequency earthquakes provide a tool to monitor the thermal evolution of the lithosphere and to explore sustainable geothermal resources with basaltic magma replenishment systems.

Based on the chronological monitoring, the following general model is considered. Before large-scale subduction zone earthquakes, contractional tectonic stress accelerates basaltic magma rising from the low-velocity zone, and consequently, the magmatic deep low-frequency earthquake activity and crustal heating prevail in the upper crust. From large-scale subduction zone earthquakes, relaxation of contractional tectonic stress decelerates basaltic magma rising from the low-velocity zone, and as a result, the ordinary high-frequency earthquake activity and crustal cooling prevail in the upper crust. In other words, large-scale subduction zone earthquakes are a stress releaser and a magmatism inhibitor.

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Data Availability Statement: As described in this article, the earthquake catalog of the Japan Meteorological Agency (JMA) is open to public.

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