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Research Article

Electrical Resistivity Structure and Helium Isotopes around Naruko Volcano, Northeastern Japan and Its Implication for the Distribution of Crustal Magma

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The two-dimensional electrical resistivity structure beneath Naruko volcano was determined using magnetotelluric soundings. The resulting model shows that a prominent conductor exists through the middle crust to the uppermost mantle beneath the volcano. The location of the conductor agrees closely with a seismic low-velocity zone. Low-frequency microearthquakes occur near the conductor around the Moho depth. The cutoff depth of crustal earthquakes is coincident with the upper boundary of the conductor, implying that the conductor has a temperature appreciably higher than 400°C. Furthermore, new helium isotope data from hot springs around the volcano were obtained. The spatial distribution of the observed $^{3}He/^{4}He$ ratios reveals the extent of mantle-derived materials beneath Naruko volcano. Consequently, it is apparent that the conductor determined beneath the volcano reflects the presence of high-temperature mantle-derived materials such as magmas and/or related fluids derived from active magmatism in the northeastern Japan subduction zone.

1. Introduction

Naruko volcano is an active volcano situated in the volcanic front of the northeastern Japan Arc (Figure 1), where the Pacific Plate is subducting along the Japan Trench beneath the North American Plate. A number of seismological studies have investigated the structure of the crust and mantle beneath northeastern Japan, including Naruko volcano. These include studies investigating seismic velocity structure (e.g., [1, 2]), attenuation structure (e.g., [3]), distribution of S-wave reflectors (e.g., [4]), and low-frequency microearthquakes (e.g., [5, 6]). These studies generally confirm the existence of partial melts and related aqueous fluids in the crust and upper mantle that are imaged as seismic low-velocity and high-attenuation zones with distinct S-wave reflectors and are associated with low-frequency microearthquakes.

Magnetotelluric (MT) soundings can image the electrical resistivity structure of the crust. The resistivity is mainly controlled by the presence and connectivity of fluids in pore spaces and the content of conductive minerals such as graphite, rather than due to the resistivity of the rock itself (e.g., [11]). The inclusion of even a small amount of connected melt or fluids beneath a volcano can greatly decrease the bulk resistivity of the rock mass. Although recent MT studies have investigated the two-dimensional (2D) electrical resistivity structure in several locations in northeastern Japan (e.g., [12–14]), the crustal magma distribution related to seismological regimes beneath Naruko volcano has not been clearly imaged yet.

Helium isotopes can be useful geochemical indicators of mantle-derived materials within the crust, owing to the distinct difference in isotopic compositions between the crust ($^{3}He/^{4}He$ ratio of $\sim 10^{-8}$) and the upper mantle ($^{3}He/^{4}He$

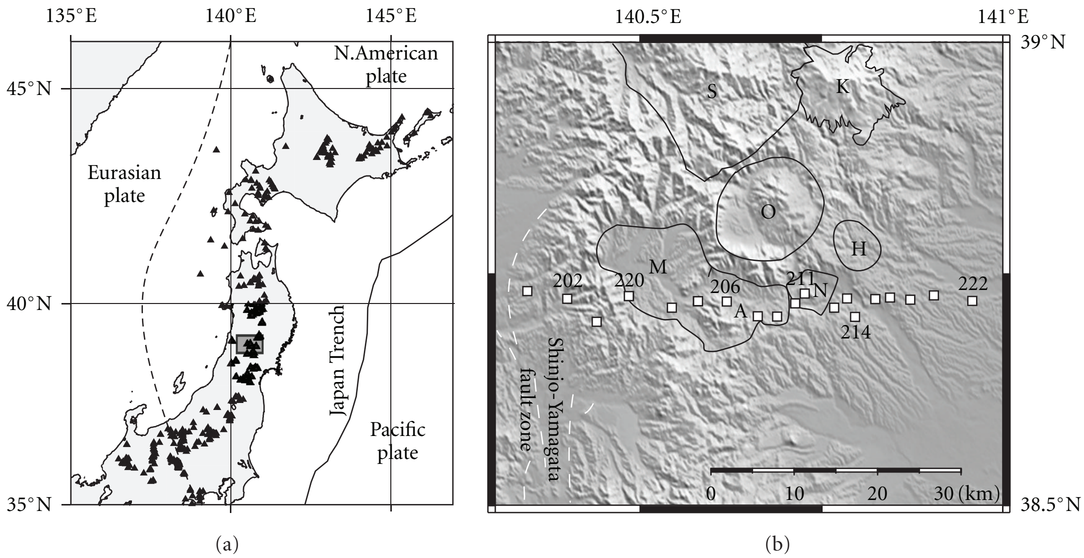

Figure 1: (a) Distribution of plate boundaries in northeastern Japan. The rectangle denotes the study area shown as Figure 1(b). Solid triangles show the Quaternary volcanoes [7]. (b) Distribution of volcanoes (solid lines) and active faults (broken lines) in the study area. The MT sites (open squares) are also shown. A: Akakura Caldera Volcano (Pliocene to 1 Ma), H: Hanayama Caldera volcano (Miocene), K: Kurikoma Volcano (0.5 Ma to present), M: Mukaimachi Caldera Volcano (Pliocene to 0.6 Ma), N: Naruko Caldera Volcano (0.05 Ma to present), O: Onikobe Caldera Volcano (0.5 to 0.2 Ma), S: Sanzugawa Caldera Volcano (Late Miocene to Pliocene) [8–10].

ratio of $\sim 10^{-5}$) (e.g., [15]). The helium isotope ratios of volcanic gases and hydrothermal fluids in volcanic regions are usually similar to those of mantle-derived helium, because mantle melting is the most likely mechanism responsible for the transfer of ^{3}He from the mantle into the crust where the volatiles would be released directly from a magma body to the Earth's surface water (e.g., [16]).

In this study, we tried to determine the detailed 2D electrical resistivity structure using MT soundings and obtain the geographic distribution of $^3\text{He}/^4\text{He}$ ratios around Naruko volcano and examined the relationship to other geophysical regimes. The present results shed light on the spatial relationship between the geophysical anomaly and helium isotope variations around the volcanic region.

2. Magnetotelluric Soundings

2.1. Observations and Data. Many calderas and composite volcanoes of Quaternary age exist in the study area (Figure 1(b)). The basement rocks beneath the volcanoes mainly consist of Early to Middle Miocene volcanic or sedimentary rocks and Cretaceous granite [17]. Naruko volcano is a poorly defined caldera approximately 7 km in diameter [8]. The caldera contains a cluster of four dacitic lava domes of Holocene age surrounding the 400 m wide lake-filled Katanuma crater.

An almost E-W oriented MT survey line consisting of 19 stations was run across Naruko volcano (Figure 1(b)). The data were collected from 2003 October 9 to November 17 using five-component (three magnetic and two telluric components) wide-band MT instruments (Phoenix MTU-5 system). The data were acquired in the frequency range between 0.00055 and 320 Hz. Owing to the significant magnetic storm and absence of leakage current from nearby DC railways, quality of impedances for this survey was excellent. Because cultural noise near each site could severely affect the measurements, the time series analysis focused on the nocturnal data. We also had simultaneous measurements from a remote reference site in Marumori city, which is approximately 100 km from the study area. All of the instruments were synchronized using a Global Positioning System. Using remote reference technique [18], we were able to reduce the unfavorable cultural noise in and around the study area.

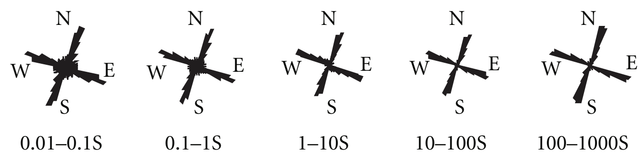

Figure 2: Rose diagrams of impedance strikes estimated by tensor decompositions [19]. Note that the $\pi/2$ ambiguities are also included in each diagram.

We estimated electrical strike directions from individual impedance data by tensor decompositions [19], where distortion parameters were set as site dependent and period dependent. The distribution of strike estimates for period-dependent decompositions is shown in Figure 2. Note that $\pi/2$ uncertainty is taken into account. We note that the two-dimensionality is well supported for both N60°W and N30°E direction over the whole profile and for most periods. The strike direction of N30°E is generally consistent with the strike of active faults on the surface and the seismic low-velocity zone in the crust and upper mantle, which is caused

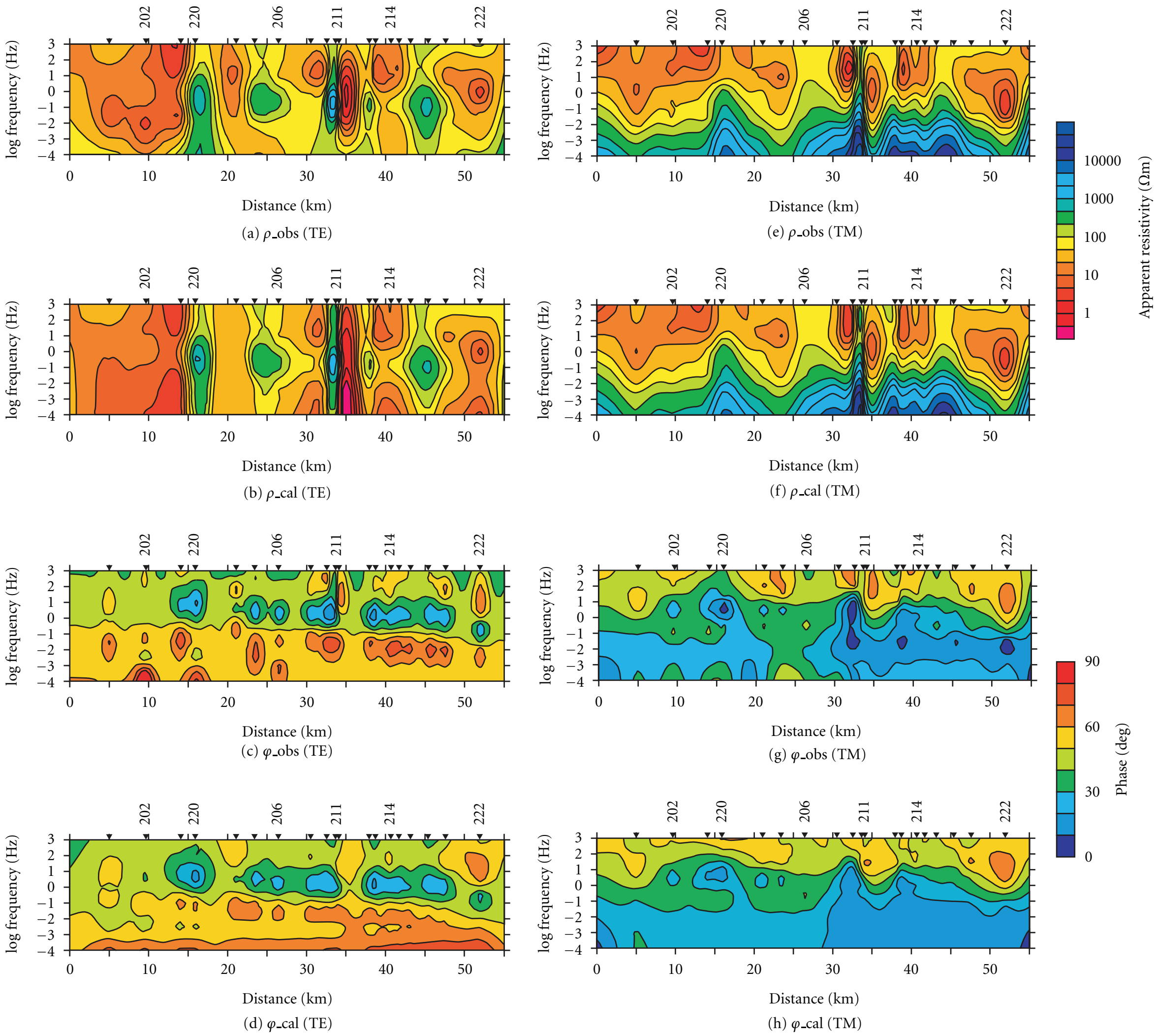

Figure 3: Pseudo-sections for the observed and calculated apparent resistivity and phases for the TE (a)–(d) and TM (e)–(h) modes; ((a) and (e)) observed apparent resistivity, ((b) and (f)) calculated apparent resistivity, ((c) and (g)) observed phase, and ((d) and (h)) calculated phase.

by a zone of partial melting (e.g., [1, 2]) in northeastern Japan. Considering these feature, we took N30°E as a regional strike direction for the 2D modeling.

2.2. Modeling and Results. For a two-dimensional structure, the impedance strikes can be described in terms of distinct modes corresponding to the electric field parallel (TE mode) and perpendicular (TM mode) to the strike (N30°E direction). The apparent resistivity and phase data from both TE and TM modes were inverted simultaneously using the inversion code of Ogawa and Uchida [20] that includes the static shift as a model parameter during the inversion. Data misfit, model roughness, and static shift norms were simultaneously minimized using Akaike's Bayesian Information Criterion (ABIC). The initial model assumed a uniform earth with resistivity of 100 Ωm. An assumed error floor in apparent resistivity of 10% was used together with the equivalent error floor for the phase data. After 20 iterations, the rms of data misfit converged to 2.04.

Figure 3 shows the comparisons between observed and calculated apparent resistivity and phase of TE and TM modes. Here the MT sites are projected perpendicular to the two-dimensional strike. Figure 3 shows a clear difference in the two modes. At around 100 s period, TE mode shows high phase (sensing conductors at depth), whereas TM mode shows low phase (sensing resistors at depth). This anisotropic response must be explained by two-dimensional modeling. The calculations were consistent with the observations for the most part.

Figure 4 shows the 2D resistivity model determined by the inversion. The inverted 2D resistivity model shows there is a resistive crust having resistivities of more than 1,000 Ωm below the near-surface conductive layer with depths of several hundred meters. In this study area, the basement rocks mainly consist of Early to Middle Miocene volcanic or sedimentary rocks and Cretaceous granite [17]. The compact and dry crustal rocks are characterized by high electrical resistivity up to 10,000 Ωm (e.g., [21]). Thus the resistive part

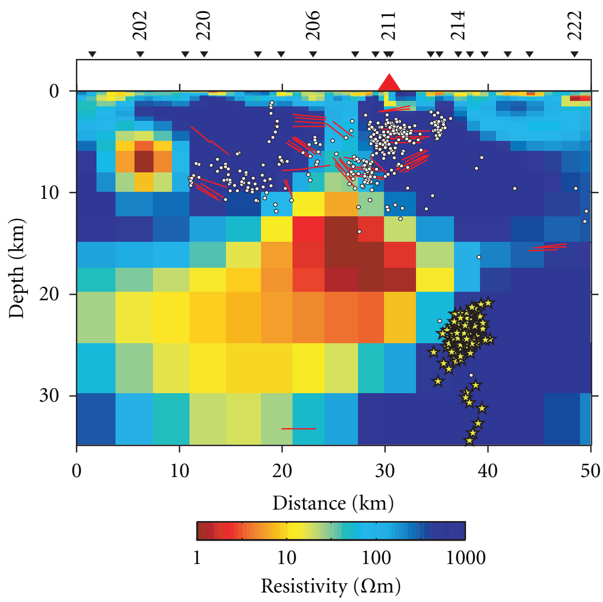

FIGURE 4: A two-dimensional resistivity model along the MT profile. The model was obtained by 2D inversion using an assumed strike direction of N30°E. Shallow micro-earthquakes and low-frequency micro-earthquakes within a 7.5 km width from the profiles are shown as white circles and yellow stars, respectively. Red lines indicate S-wave reflectors [4]. The black reverse triangles and the red triangle on the top of the figure denote the MT sites and volcanic center of Naruko volcano, respectively.

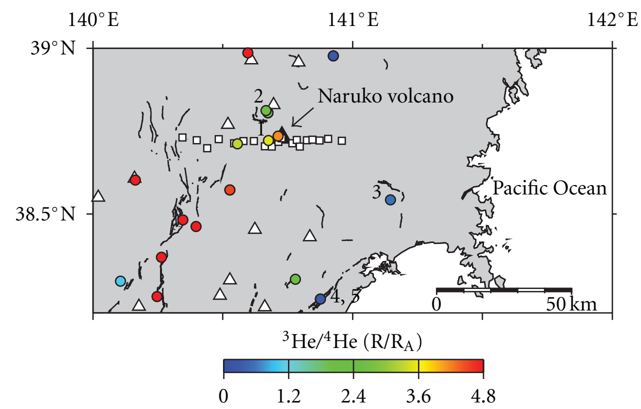

FIGURE 5: Geographic distribution of $^3He/^4He$ ratio of gases from hot springs. Numbers indicate sample number shown in Table 1. Black triangle, white triangle and bold lines indicate Naruko volcano, Quaternary volcanoes [7], and active faults [26], respectively. Data reported by Sano et al. [27], Sano and Wakita [28], Takaoka and Mizutani [29], Takaoka and Imada [30], Kita et al. [31], and Horiguchi and Matsuda [32] are also shown in this figure.

may reflect the upper and middle crust probably composed of less permeable metasedimentary and granitic rocks.

In contrast to the resistive crust, an anomalous conductive body of less than 100 Ωm is clearly visible beneath Naruko volcano (below sites 202 to 214). The conductor widens with depth and extends from the middle crust down to the base of the crust and perhaps into the upper mantle. Although metallic ore bodies can produce very high conductivities, they do not generally have spatial dimensions as large as that observed around Naruko volcano. Therefore, the conductor may be ascribed to the existence of interconnected fluids, either partial melts and/or high-temperature aqueous fluids. The bulk resistivity of a fluid-bearing rock depends on the conductivity of the fluid, its geometry and the amount of fluid. Laboratory measurements have shown that basaltic to granitic melts have resistivities in the range of 0.1–0.25 Ωm [22]. Aqueous fluids can be less resistive than molten materials, and samples from geothermal fields and fluid inclusions shows resistivities lower than 0.01 Ωm [23].

3. Helium Isotopes of Hot Springs

In order to obtain geochemical evidence indicating the presence of melt intrusions, we collected 5 samples from 4 hot springs around Naruko volcano. Gas samples were collected in glass sample containers with vacuum cocks at both ends. The gas was introduced into the container by water displacement using an inverted funnel and an injection syringe. Details of sample collection methods are given by Nagao et al. [24]. Where there was no visible bubbles, water samples were collected to measure the isotopic ratios of dissolved gases in water. The dissolved gases were quantitatively expelled from the solution by ultrasonic agitation and collected in a glass bottle. Major components of the gas samples were determined with gas chromatography method. The isotopic ratios of He and Ne were determined using the VG5400 system at the Laboratory for Earthquake Chemistry, University of Tokyo. Mass spectrometry details, including purification procedures, can be found in Aka et al. [25].

The $^3He/^4He$ ratios of the samples shown in Table 1, range from 0.29 to 3.47 R_A (R_A denotes the atmospheric $^3He/^4He$ ratio of 1.4×10^{-6}). Generally, the CO_2 rich samples have higher $^3He/^4He$ ratios than the N_2 rich ones. The geographical distribution of $^3He/^4He$ ratios around Naruko volcano is shown in Figure 5. There appears to be a sharp decrease in $^3He/^4He$ ratios laterally away from the volcano. Gas samples collected at the hot spring approximately 50 km away from the volcano, which are located on the forearc side of the volcanic front of Northeast Japan, have significantly lower $^3He/^4He$ ratios than the atmospheric value. In contrast, the maximum $^3He/^4He$ ratio has been obtained from the hot spring nearest to Naruko volcano [28], which is similar to the mean value of 5.4 ± 1.9 R_A for arc-related volcanism worldwide [16].

4. Discussion and Conclusions

Generally, the cut-off depth of crustal micro-earthquakes is thought to be in good agreement with the 400°C isotherm [33–35] and becomes shallower locally beneath active volcanoes (e.g., [6]). The hypocenters of shallow micro-earthquakes and low-frequency micro-earthquakes which

Table 1: Chemical and isotopic compositions of hot spring gases sampled observed in this study. The analytical error for $^4He/^{20}Ne$ is ~15% of the values given. Abbreviation: ND: not determined.

No.	1	2	3	4	5
Site Name	Nakayamadaira	Onikobe	Wakuya	Sendai-Atago	Sendai-Atago
Latitude	38.723	38.813	38.541	38.245	38.245
Longitude	140.677	140.667	141.149	140.879	140.879
Phase	Gas	Gas	Dissolved	Gas	Dissolved
$^3He/^4He$ ($\times 10^{-6}$) [$\pm 1\sigma$]	4.86 ± 0.17	3.62 ± 0.10	0.78 ± 0.03	0.46 ± 0.01	0.41 ± 0.01
$^3He/^4He$ (R/R_A)	3.47	2.59	0.56	0.33	0.29
$^4He/^{20}Ne$	6.3	1.3	2.6	591	410
CO_2 (%)	88	76.1	ND	6.1	ND
N_2 (%)	2	12	ND	92	ND
CH_4 (%)	0.23	0.048	ND	0.83	ND
O_2 (%)	0.02	0.11	ND	0.76	ND
He (%)	0.0001	0.0001	ND	0.042	ND
Ar (%)	0.058	0.22	ND	0.16	ND
$\delta^{18}O$ (‰)	−9.3	−10.4	−9.1	−6.7	−6.5
δD (‰)	−65	−68	−59	−36	−35
Temp. (°C)	99.4	99.3	21.6	16.7	18.6
pH	9.0	8.8	9.0	8.8	8.7

occurred in the period from 1994 to 2007 [36] are also shown in Figure 4. Although most crustal earthquakes are confined to the relatively resistive zone, the depth of hypocenters becomes shallower toward the west side of the volcanic center. In addition, the cut-off depth clearly coincides with the upper boundary of the conductive body in the crust, implying that the temperature of the conductor is higher than 400°C. The region of thinning of the brittle seismogenic layer is concordant with the distribution of high-temperature materials ascending from the upper mantle [37]. Tanaka et al. [38] indicated that the regions with anomalously high heat flow (>200 mW/m^2) generally are consistent with volcanic and geothermal areas. Near Naruko volcano, the heat flows are estimated to be about 200 mW/m^2, which are much higher than those of surrounding regions. Therefore, the conductor observed beneath the Naruko volcano could be attributed to melt and/or high-temperature fluid that correlate with active magmatism in the subduction zone.

Several seismic reflectors were detected in the upper crust at depths of 0–10 km by characteristic SxS phase identified beneath Naruko volcano [4] (Figure 4). Low-frequency micro-earthquakes, which are believed to be caused by sudden movements of melt and/or fluids in the crust [5, 6], are seen to occur adjacent to the conductor beneath the volcano (Figure 4). The seismological evidence indicating the S-wave reflectors and low-frequency micro-earthquakes is well supported for the presence of magmas and related to high-temperature fluids beneath Naruko volcano.

Seismic velocity structure of the crust and mantle is powerful geophysical tool for delineation of magma plumbing systems. Nakajima and Hasegawa [2] revealed three-dimensional P- (Vp) and S-wave velocity (Vs) and Vp/Vs ratio structures in and around the Naruko volcano by local travel time tomography. The determined structures indicate a narrow conduit in the upper crust with low Vp and low Vs indicative of H_2O-rich fluid pathways and an underlying broad region in the lower crust with low Vp, low Vs, and high Vp/Vs ratio, suggestive of a zone of partial melt. Our results show that the location of the conductor is closely consistent with the low Vp, low Vs, and/or high Vp/Vs ratio zone beneath Naruko volcano. A similar correlation between resistivity structure and seismological signatures was obtained beneath the Iide Mountains where the backarc nonvolcanic region of northeastern Japan, and latent magma storage have been detected in the crust [39].

High ^3He gases emanation and heat flux observed in volcanic and geothermal regions is recognized to be derived from the crustal magma storage [40, 41]. It is now well established that Japanese volcanic gases and hydrothermal fluids contain a considerable proportion of mantle-derived helium (e.g., [24]). The maximum $^3He/^4He$ ratio has been obtained from the hot spring nearest to Naruko volcano [28], which is similar to the mean value of $5.4 \pm 1.9\,R_A$ for arc-related volcanism worldwide [16] (Figure 5). The spatial variation in $^3He/^4He$ ratios reveals that the extent of the mantle-derived materials supplying primordial helium exists beneath the volcano where an anomalously conductive body was detected in the crust and the uppermost mantle. In contrast, the hot springs with rather low $^3He/^4He$ ratios are distributed outside of Naruko volcano (Figure 5). The trend is similar to the trend observed around active volcanoes and their surrounding regions [42]. Thus, it is apparent that the mantle helium supplied from magma and related fluids has been diluted by atmospheric and/or crustal components with lower $^3He/^4He$ ratios away from the volcanic center. Consequently, the location of the conductive body correlates with high-temperature hot springs with high $^3He/^4He$ ratio, thinning of the brittle seismogenic layer and anomalies of low seismic velocity in the crust and upper mantle. We conclude that the conductor reflects the presence of melts and related fluids in the crust, owing to active magmatism in the subduction zone.

Recent MT studies have revealed that shallow micro-earthquakes tend to occur in resistive zones or at the boundary between resistive and conductive zones in several regions (e.g., [43–46]). They suggested that the seismicity in the resistive upper crust overlying the midcrustal conductor is triggered by fluid migration into less permeable crust. Accordingly, the idea supports the presence of H_2O-rich fluids derived from the partial melting zone in the upper part of the conductor beneath Naruko volcano. Moreover it also means that the distribution of the fluids and the geothermal regime are not horizontally uniform, but localized. This heterogeneity seems to affect the occurrence of micro-earthquakes. Our results suppose that the crustal seismogenic zone is mainly controlled by the geothermal regime and fluid distribution in this volcanic area taking the findings of seismic and geothermal investigations into account.

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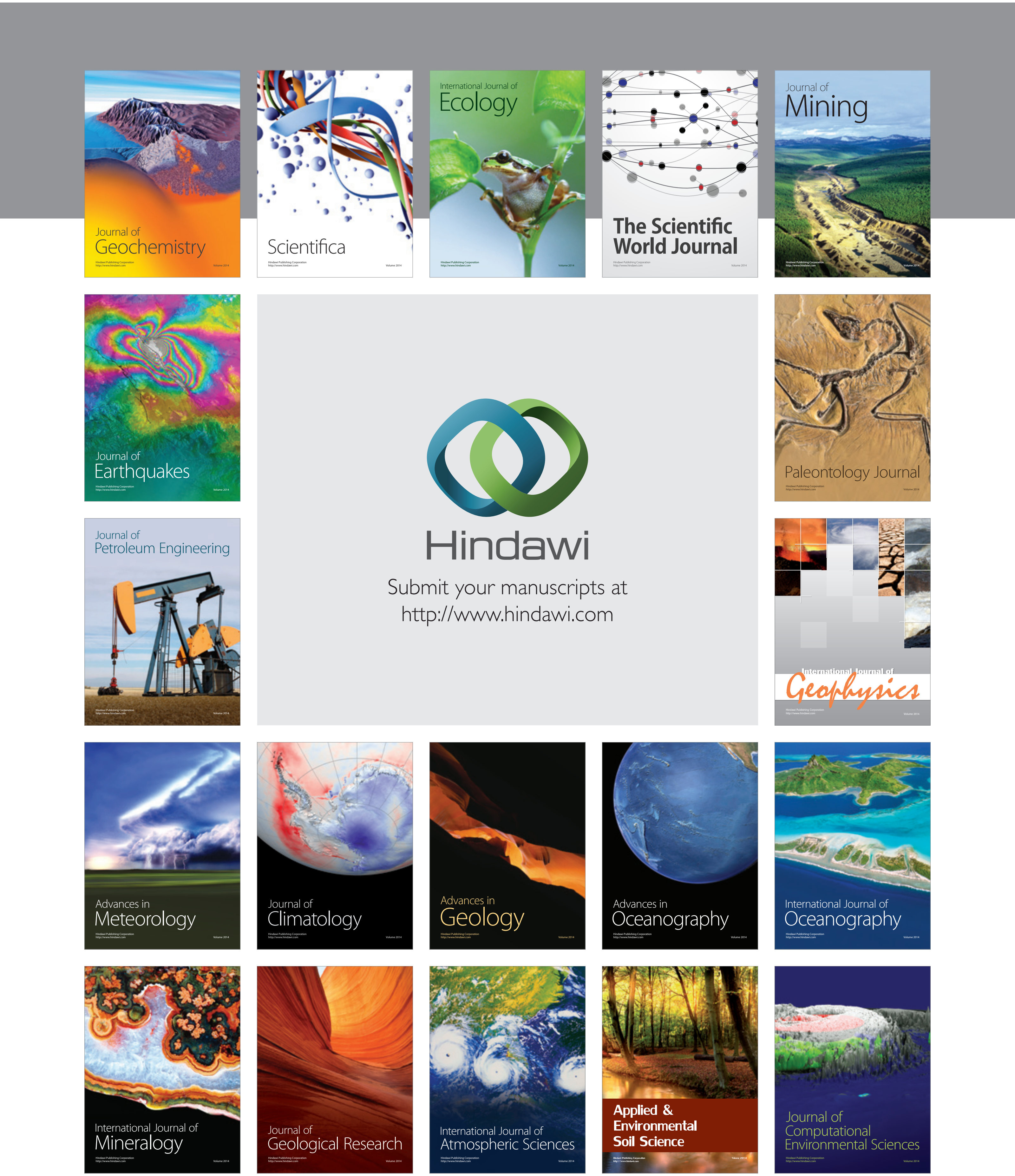
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