

Water percolating behavior indicated by the water chemistry within a decomposed granite slope, central Japan

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Abstract

Monitoring rainfall, discharge amount, and the chemistry of water from just beneath the groundwater table yielded a conceptual model of water percolation behavior within a decomposed granite slope in central Japan, providing a clue to evaluate a landslide hazard potential by rainstorms. When rainfall is strong enough, more than about 50 mm a day in this case, air pressure in the vadose zone probably increases temporarily because of the downward movement of a wetting front, pushing down the water of the capillary fringe. The capillary water has SiO₂ concentrations controlled by the precipitation of cristobalite. The water is rich in Ca, which is supplied from plagioclase with SiO₂. After the pushing down of the capillary water, rainwater with soil water in the unsaturated zone reaches the groundwater surface. The cation concentrations in the unsaturated soil water and the capillary water are affected by ion exchange.

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1. Introduction

Rainwater percolation within weathering profiles is very important in various scientific phenomena and engineering, such as weathering, geochemical erosion, hydrological budget within a catchment, pollutant migration, landslide generation, and so on, but has not yet been sufficiently clarified. This is partly because weathering profiles are specific to rock types and weathering conditions, and their characteristics and formative processes have been studied only recently and have not yet produced definitive results. Water filtration through vadose zone has been studied in the fields of soils science

and hydrology, and downward advancement of a wetting front (Bodman and Colman, 1943; Rubin and Steinhardt, 1964), its destabilization (Hill and Parlange, 1972; Raats, 1973; Philip, 1975; Hillel and Baker, 1988), and air entrapment beneath the wetting front are suggested (Bianchi and Haskell, 1966; Dixon and Linden, 1972; Kayane and Kaihotsu, 1988). The role of macropore for quick flow is reviewed by Beven and Germann (1982). However, direct response of the groundwater to rainfall event has not reported except for groundwater level (Bianchi and Haskell, 1966; Linden and Dixon, 1973; Kayane and Kaihotsu, 1988).

Granite, which is the rock type for this study, is commonly weathered as deep as tens of meters (Chigira, 2001), and has been prone to shallow landslides by rainstorms all over the world (Durgin, 1977; Calca-

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terra et al., 1996). Therefore, water filtration behavior within a weathering zone of granite is essential for the stability evaluation and prediction of rain-induced shallow landslide. However, very little is known on this issue. Weathering of granitic rocks has been studied from engineering geological view points (Moye, 1955; Ruxton and Berry, 1957; Dearman, 1974), geochemical or petrological view point (Wilson, 1966; Kimiya, 1981; Dong et al., 1998; Fritz, 1988; Murphy et al., 1998; White et al., 1998, 1999). However, few studies were made on the water filtration through weathered granite (Asano et al., 1996, 2003, 2004; Shimada et al., 1992, 1993). Recently, the Japanese Meteorological Agency developed a sophisticated alarming system against the hazard of landslide and debris flow by using a soil moisture index, which is based on the amount of soil moisture within three conceptual tanks connected in series (Okada et al., 2000). The tanks accumulate rainwater, which is calculated hourly on the basis of AMEDAS (Automated Meteorological Data Acquisition System) and radar data. The three tanks simulate the surface shallow layer, the intermediate layer, and the deeper layer, respectively, but they are merely conceptual. In order to predict the timing of landslides, we need to clarify the infiltration behavior of rainwater through weathering zones.

This study intends to clarify the downward percolating behavior of rainwater and soil water through the vadose zone to the groundwater table by investigation of the chemistry of the discharge through drill holes along the groundwater table within a decomposed granite slope.

2. Study site

The investigation site is located in the southern part of Shiga Prefecture, central Japan. This site is a hilly area with elevations from 450 to 650 m above sea level, and is underlain by Cretaceous Shigaraki granite (Collaborative Research Group for the Granites around Lake Biwa, 1982). The landform of the site has low relief with a relative height of less than 100 m from flat river bottoms. The granite is weathered as deep as more than 10 m, and almost all outcrops above the river bottoms consist of decomposed granite except for sporadically exposed core stones, while beneath stream bottoms less weathered and sound granite rock is expected. This area was hit by a heavy rainstorm in 1953 and devastating, widely distributed landslides were induced.

The study slope, which is at an elevation of about 450 m, was an artificial slope excavated presumably 8 m (detailed data are not available) from 1987 to 1988, 15

years before the start of the monitoring (Fig. 1). Four years after the excavation, low-angle drainage drill holes were excavated from the bottom of the cut slope; the drill holes are 20 m long, and set 5 m apart. We monitored discharging water from these drill holes (numbers #1 to #4). The cut slope is 27 m high with inclinations of 45° to 25°; the lower part is steeper than the upper. The deepest end of these drill holes was about 10 m below the slope surface in a vertical distance. PVC casings, 8.5 cm in outer diameter and with openings in the interval deeper than 4 m, were inserted into these holes. These drill holes have yielded water up to 1.6 L/min, and only the #3 hole sometimes dried up. We tried to extract water from different intervals from the #1 hole by separating the length of the hole with rubber packers and setting intakes along the axis of the drill hole, but after the packers had been set the discharge stopped, which indicates that the groundwater table is along the bottom of the drill hole and never reached the drill hole's axis. The groundwater table was also observed within a vertical drill hole in the middle of the slope (Fig. 1).

Only grasses grow on the lower part and coniferous trees planted just after the excavation have grown on the upper part of the study slope. The slope is underlain by decomposed granite, which can be seen in patches. The granite is coarse-grained and consists mainly of quartz, orthoclase, plagioclase, and biotite. The surface was loosened to a depth of 0.5 to 1 m, which was checked by portable cone penetration tests.

We measured temperature within the drill holes and obtained temperatures of 13.7 to 14.2 °C in the depth of the drill holes while the outside temperature was 18 °C. The temperatures deeper than 7 m were almost constant, with minimum values at 13, 12, and 16 m for #2, #3, and #4 holes, respectively. These findings indicate that at the temperature-minimum points, water presumably comes from deeper than 7 m.

Mean annual temperature at the site is 12.1 °C, the average in winter is 2 °C, the average in summer is 22.4 °C, and the mean annual precipitation is about 1500 mm (Hikone meteorological station of the Japan Meteorological Agency).

3. Methods

The monitoring interval was April 3 to December 1, 2003, during which the precipitation and discharge were measured and water was sampled from the drill holes at intervals from 1 to 7 days. The precipitation was monitored by using a tipping bucket rain gauge with a volume of 0.5 mm set on the middle of the slope.

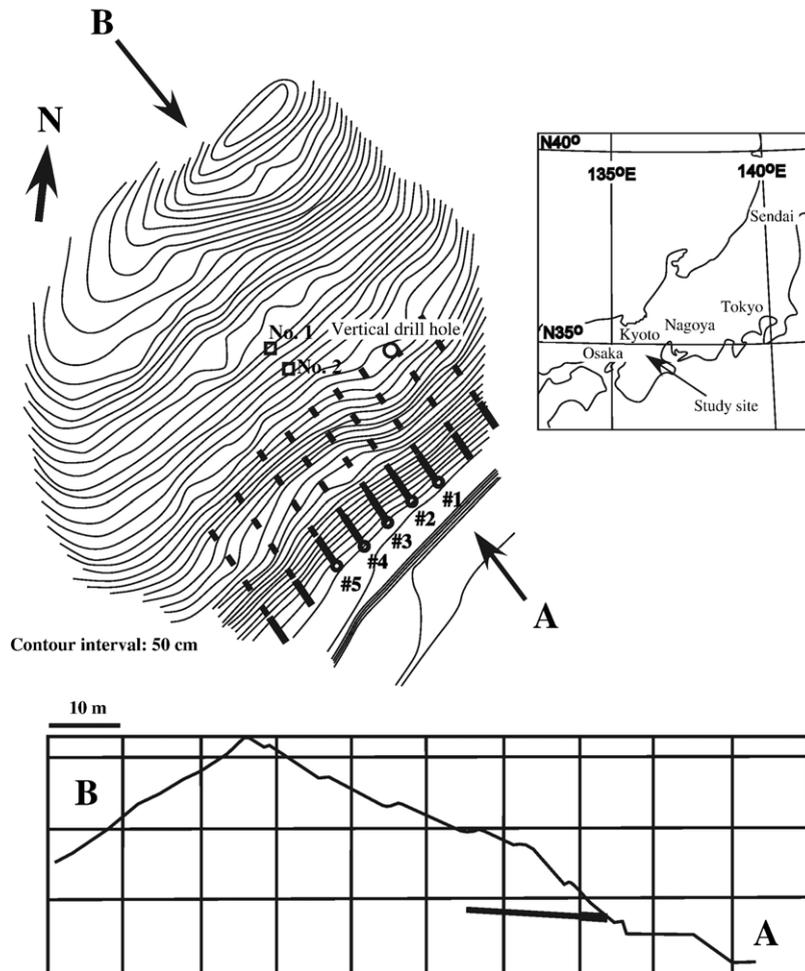


Fig. 1. Topographic map and a cross section of the monitored slope. Dashed lines indicate low-angle drill holes, in which #1 to #5 are numbered. A low-angle solid line in the cross section indicates a drill hole #1.

The rain gauge could not be used from August 30 to September 28, and during this interval, the precipitation data obtained at a Ministry of Land, Infrastructure, and Transportation station 1.4 km to the southeast of the study site were used. The drill holes for the monitoring were #2, 4, and 5. The discharge was measured manually at the time of water sampling. pH and electrical conductivity were measured at the site by using a glass electrode (IM-22P equipped with a glass electrode of GST-2729C made by DKK-TOA Corporation) and Twin Cond B-173 made by Horiba, Ltd. The accuracy of the pH meter was 0.1 and the accuracy of the conductivity meter was 4 $\mu\text{S}/\text{cm}$. Water samples were filtered through a membrane with 0.45 μm -pore size and were analyzed in the laboratory by using the molybdenum blue method for SiO_2 and ion chromatography for Na, K, Ca, Mg, Cl, and SO_4 . The colorimetric spectrometer and ion chromatography used were HIC-

6A and UV-2200A of Shimadzu Corporation, respectively. The detection limit of the ion chromatography was less than 10 ppb, and the experimental errors of the molybdenum blue method were less than 1%. Rainwater was also sampled and analyzed for these constituents: it was collected in a polypropylene bottle through a funnel with a ping-pong ball; the ball prevented the water from evaporation. Rainwater accumulated in a few to 7 days was sampled and analyzed 3 to 5 times per month from June to November.

4. Results and discussion

4.1. Discharge

The rainfall amount from April 1 to December 1 was 569 mm, with a maximum daily precipitation of 80.5 mm on August 14. The discharge amounts of

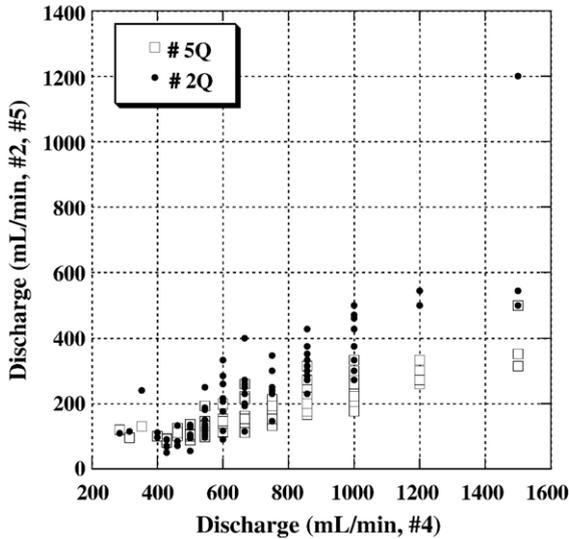


Fig. 2. Relationships among the discharge amounts from drill holes #2, #4, and #5. The discharges from #2 and #5 are positively related to the discharge from #4.

three drill holes were different probably because of the detailed hydrogeological structure near each drill hole, but they were positively related to each other (Fig. 2), indicating that the recharge response to rainfall events had a similar pattern among these three drill holes, but, in more detail, the timing of the discharge maximum after rainfall events varied from 1 to 7 days after rainfall events, as will be discussed later. The discharges from drill hole #4 were always the largest, and ranged 280–1500 mL/min; those from drill hole #2, from 50–1200 mL/min; and those from drill hole #5, 60–500 mL/min. The variation in discharge amount is influenced by antecedent rainfall, the effect of which is shown in Fig. 3 as diagrams of discharge versus antecedent rainfall over 10, 20, and 30 days. The correlation coefficient is largest at 20 days for #2 (0.82) and 30 days for #4 (0.55) and #5 (0.6) (Table 1), suggesting that rainfall effects on water discharge remain for tens of days. Fig. 3 also shows that as cumulative rainfall within the above time intervals approach zero, the discharges from #2 and #5 converge to zero while the discharge from #4 does not, which suggests that the relative amount of stationary lateral groundwater to the amount of recharge water from soil water is larger for #4 than for #2 or 5.

4.2. Chemistry

Averages and standard deviations of each element are shown in Table 2 for each drill hole and for accumulated rainwater.

Comparison of the chemistry of rainwater and that of discharge water showed that rainwater was richer than discharge water in potassium, indicating that potassium is adsorbed to weathered granite or consumed by biogenic activity during percolation. Chlorine was present in discharge at average concentrations of about the average plus one standard deviation of Cl in rainwater, and its standard deviations were much smaller than those in discharge water. This finding suggests that the Cl variations in discharge water reflect the variations in rainwater, which is smoothed during percolation. More sulfate was contained in discharge water than in rainwater, though the explanation for this has not been clarified yet. SiO₂ was not detected in rainwater.

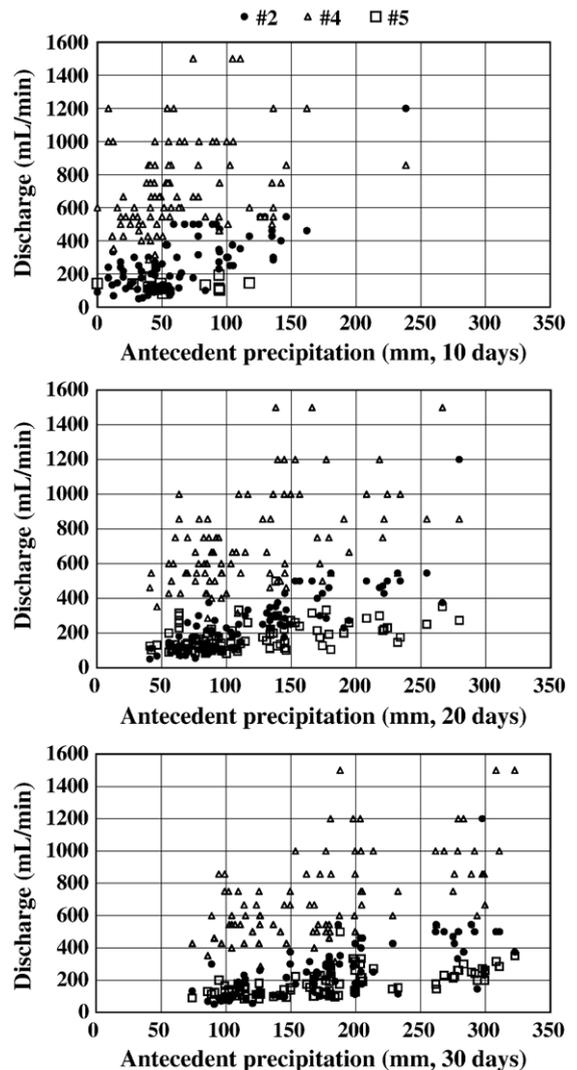


Fig. 3. Relationships between antecedent rainfall amounts and the discharge amounts from drill holes #2, #4, and #5. Antecedent periods are 10, 20, and 30 days from the top to the bottom, respectively.

Table 1
Correlation coefficients between the antecedent rainfalls and discharges

Drill hole	Interval (days)		
	10	20	30
#2	0.72	0.82	0.68
#4	0.27	0.46	0.55
#5	0.32	0.45	0.60

The interrelationships among the discharges for these respective elements are shown in Fig. 4. All components except Mg showed good positive relationships among the three drill holes, indicating that they behaved in a similar way in these drill holes. Electrical conductivities ranged from 35 to 90 $\mu\text{S}/\text{cm}$, and showed positive relationships among the three drill holes. PH values ranged from 6.2 to 7.4 and were lower in the water from drill hole #4 than in that from other drill holes.

4.2.1. SiO_2

Silica concentrations ranged from 0.33 to 0.52 mmol/L with fluctuations: gradual increases followed by abrupt decrease (Fig. 5). This fluctuation interval appears to have a lower limit, which approximately coincides with the solubility of cristobalite, 0.34 mmol/L, calculated from the equation of Fournier (1985). Dove (1995) reported solubilities of 0.23 mmol/L for cristobalite and 0.30 mmol/L for tridymite at 25°, but the solubilities of these facies are not well established. SiO_2 mainly comes from plagioclase of the decomposed granite, and Na and Ca are both released with it, but the total concentrations of Na and Ca are not related to the concentrations of SiO_2 (Fig. 6), which also indicates that some reactions occur after the dissolution of plagioclase.

Shimada et al. (1993) monitored silica concentration once a day in shallow groundwater at a weathered granite area near our study site for more than one year, and reported that the silica concentrations were

nearly constant at 0.3 to 0.33 mmol/L with temporary dilutions caused by heavy rainstorms. Although they did not provide an explanation for the constant values, it is strongly suggested that SiO_2 concentration is controlled by the solubility of cristobalite. However, the constant values of SiO_2 found by Shimada et al. (1992, 1993) were upper limits instead of lower limits, which was the case in our study. This is probably due to the fact that our study slope is an artificial cut slope, where reactive decomposed granite is exposed to filtrating water, whereas the study slope of Shimada et al. (1992, 1993) was a natural slope, where mineral surfaces have been exposed to filtrating water for long time. Plagioclase with a fresh reactive surface is dissolved to release SiO_2 into water, which is easily supersaturated with quartz, cristobalite, and often amorphous silica (Busenberg and Clemency, 1976), which suggests that once water is supersaturated with cristobalite, it approaches its equilibrium. On the other hand, plagioclase is expected to be dissolved more slowly under the condition of a natural slope; the water is not supersaturated with cristobalite. Chigira et al. (2002) studied the weathering profiles of rhyolitic vapor-phase crystallized ignimbrite and found that tridymite, the major constituent of the ignimbrite, is dissolved and cristobalite is formed at the weathering front. This finding supports the idea that SiO_2 concentrations in shallow groundwater in acidic igneous rocks are controlled by the solubility of cristobalite.

4.2.2. Ca, Na and Mg

Calcium concentrations ranged from 0.02 to 0.22 mmol/L, with the highest in #5 and the lowest in #2. Ca showed temporal changes, responding to rainfall events; these will be discussed later. Asano et al. (1996) analyzed the groundwater in granite slopes near our study site and reported Ca concentrations less than 0.03 mmol/L, which almost coincided with the through-

Table 2
Chemistry of discharge water from the drill holes and rainwater (mmol/L except for pH and EC ($\mu\text{S}/\text{cm}$))

		Na	K	Mg	Ca	Cl	SO_4	SiO_2	pH	EC ($\mu\text{S}/\text{cm}$)	Q (mL/min)
Hole 2	Ave	0.267	0.001	0.007	0.051	0.035	0.022	0.389	6.8	47.9	255
	Sdv	0.016	0.003	0.007	0.015	0.004	0.002	0.041	0.1	4.5	170
4	Ave	0.358	0.002	0.019	0.089	0.044	0.024	0.384	6.4	66.4	721
	Sdv	0.025	0.002	0.020	0.012	0.003	0.002	0.038	0.1	4.4	264
5	Ave	0.300	0.002	0.010	0.111	0.038	0.026	0.419	6.8	66.2	177
	Sdv	0.017	0.002	0.002	0.028	0.003	0.003	0.048	0.2	6.6	77
Rain	Ave	0.014	0.017	0.002	0.011	0.018	0.008	Nd	4.3	40.1	–
	Sdv	0.015	0.024	0.002	0.010	0.017	0.009	Nd	0.4	30.4	–

Monitoring interval: April 3 to December 1, 2003. We chose SiO_2 , Ca, Na, Mg, and EC for examining the water filtration behavior within the weathering profile: SiO_2 is not contained in rainwater, and Ca, Na, and Mg were contained in higher concentrations in the discharge water than in the rainwater. Ave: average; sdv: standard deviation.

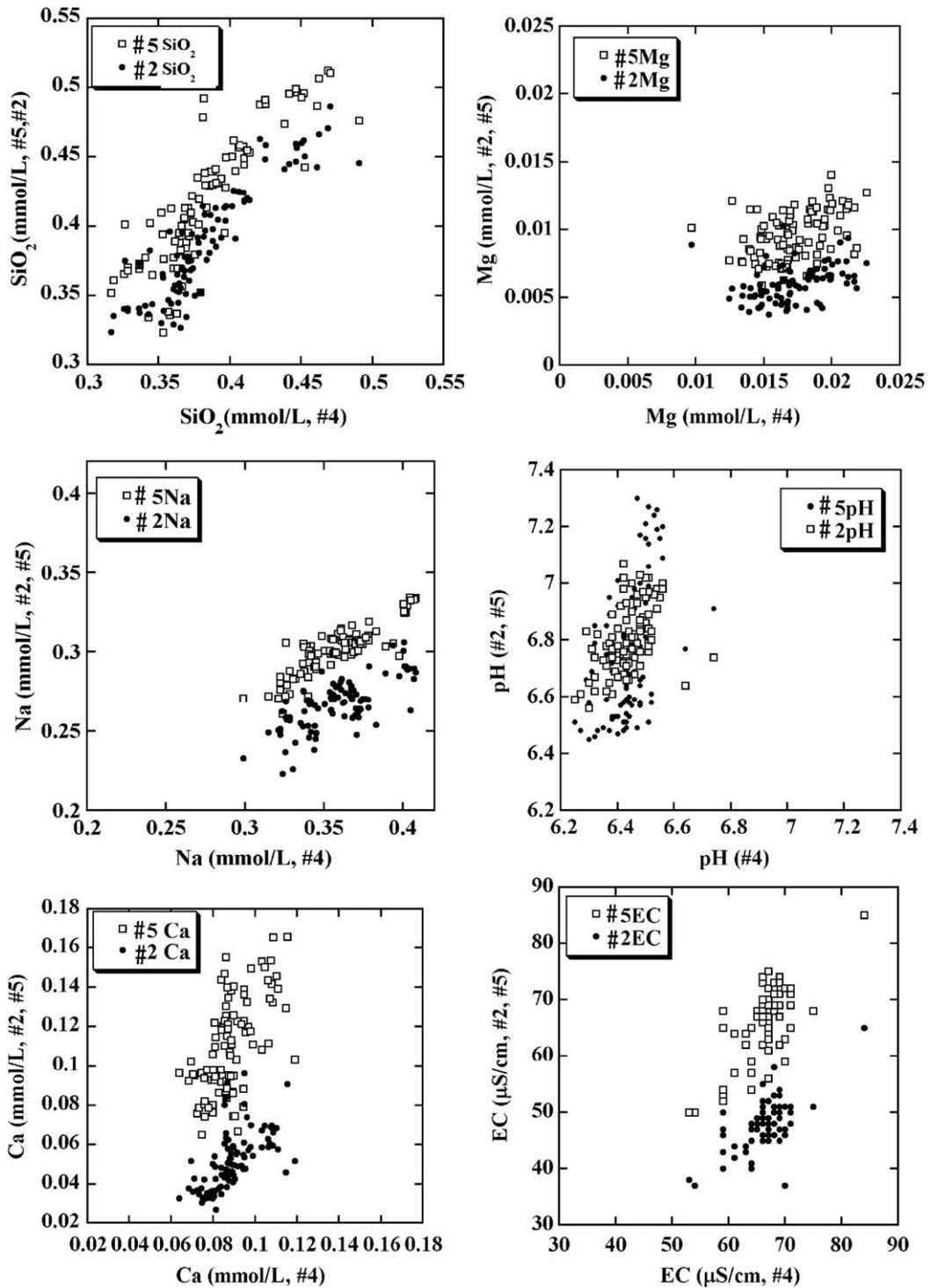


Fig. 4. Interrelationships among three discharges for SiO₂, Ca, Na, and Mg concentrations; electrical conductivity; and pH.

fall water in the forest, which was 0.005–0.03 mmol/L. In our study site, on the other hand, Ca in the rainfall averaged 0.01+0.01 mmol/L, and Ca in the discharge water averaged 0.086 mmol/L with a minimum of

0.02 mmol/L, indicating that a significant amount of Ca came from the decomposed granite. This may be due to the fact that the study slope was an artificial cut slope, exposing reactive decomposed granite. [Busenberg](#)

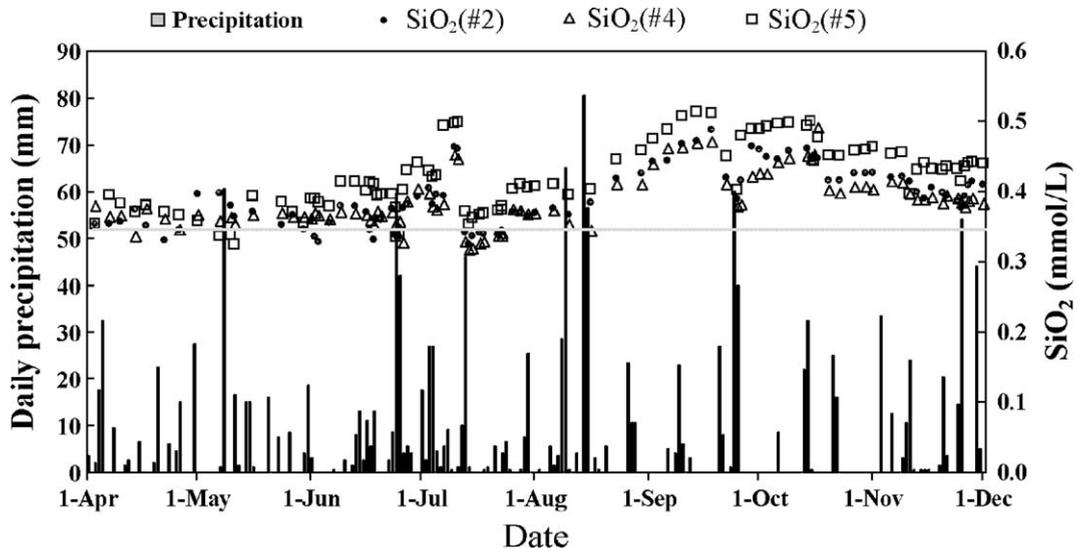


Fig. 5. Temporal changes in SiO_2 concentration. Cristobalite solubility is shown as a line of 0.34 mmol/L.

and Clemency (1976) showed that Ca concentration easily exceeds 0.4 mmol/L through batch dissolution experiments with plagioclase.

Sodium concentrations ranged from 0.15 to 0.45 mmol/L, with the maximum at #4 and the minimum at #2. The temporal changes of Na were not related to rainfall events. Paces (1972) obtained 0.1–0.4 mmol/L of Na from groundwater in a Bohemian granite area, and Asano et al. (1996, 2004) reported 0.1–0.4 mmol/L of Na in shallow groundwater in granite. The Na concentrations in our study site are consistent with these data. However, Ca concentrations were much higher in our study site than those reported for other natural slopes, which may be attributed to fact that the release rate of Ca from plagioclase is much higher than that of Na (Lasaga, 1998) and to the ion exchange reactions discussed later.

Magnesium concentrations ranged from 0.004–0.023 mmol/L, with the maximum at #4 and the minimum at #2. Asano et al. (1996, 2004) reported low Mg concentrations in the same order from groundwater in the granite area at the Tanakami Mountains near this site.

4.3. Ion exchange reactions suggested by the relations among cation concentrations

Cations Na, Ca, and Mg in the discharge water showed clear interrelationships, indicating that cation exchange reactions occurred during the filtration of soil water (Fig. 6). In the Na–Ca diagram, water from #4 is plotted along a line with an inclination of 2 : 1, and the water from #5 and #2 is plotted along a line with an almost constant Na concentration. In the Na–Mg dia-

gram, water from #4 is plotted along a line with an inclination of 2 : 1, and the water from #5 and #2 is plotted along a line with a constant Na concentration. Ion exchange equilibrium between monovalent cation and divalent cation produces a plot of these concentrations in water on a line with an inclination of 2 : 1 (Drever, 1997), so the above results indicate that ion exchange equilibrium is established for Na–Mg and Na–Ca for the water from #4 but not for the water from #5 and #2. The reason for this discrepancy is not clear, but it may be related to the fact that the rate of stationary lateral groundwater flow to the recharge water from soil water is larger for #4 than for #2 and #5, as mentioned earlier. Only downward filtration through a vadose zone might not be enough for the establishment of ion exchange equilibrium for Na–Ca or Na–Mg. In a diagram of Ca–Mg, the water from #4 and the water from #5 and #2 are plotted along different two lines, but these two lines have an inclination of 1 : 1. This indicates that ion exchange equilibrium is established for Ca–Mg for the water from all the drill holes.

4.4. The change in water chemistry and discharge amounts responding to rainfall events

During the monitoring interval, SiO_2 fluctuated; showing slow increase and abrupt decrease, and Ca also fluctuated but with apparently reverse patterns. The fluctuation patterns are shown for SiO_2 and Ca along with discharge amounts in Fig. 7. The timing of the abrupt decrease of SiO_2 coincided with the heavy rainfall events, though not all the heavy rainfall events

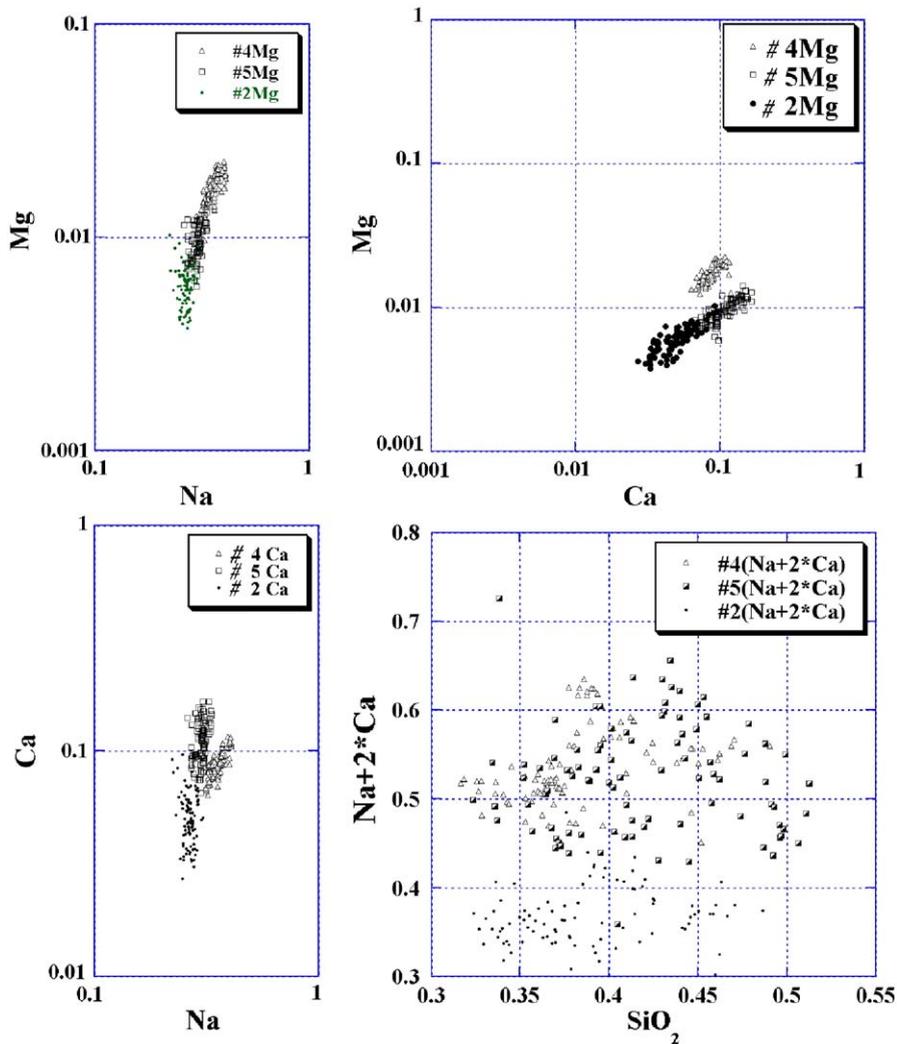


Fig. 6. Interrelationships among cations and SiO_2 .

were detected to be accompanied by an abrupt decrease of SiO_2 : for example, abrupt decrease occurred at the events of June 24–25 (101.5 mm), July 13 (46 mm), September 24 (60 mm), and October 13–14 (54.5 mm), as indicated by the arrows in Fig. 7. SiO_2 decrease occurred within 1 to 2 days after rainfall events, and discharge increased contemporaneously and reached the maximum after the minimum of SiO_2 concentrations had been reached. Ca concentrations also changed, though less remarkably than SiO_2 concentrations, in response to rainfall events. At the above rainfall events, Ca increased temporarily in the discharge from #2 and #5, whereas the change in the water from #4 was not significant. We could not recognize the correspondence of precipitation, SiO_2 change, and Ca change precisely except for the obvious ones as above. It is probably due to the fact that

rainwater filtrates and replaces the water in the vadose zone sequentially as is discussed below. So, when rainfall occurs one after another like August, the correspondence apparently disappears.

Water sampling intervals in our study were from 1 to 4 days, and not all data can be used to trace the detailed change in water chemistry according to the rainfall events; the most dense sampling before, during, and after rainfall events was made at a rainfall event in June, 51 mm from 8 pm on 23 to 8 am on 24, and 51.5 mm from 9 pm on 24 to 5 am on 25 (Table 3). Sampling dates before, during, and after this event were 9 am on 20, 9 am on 23, 9 am on 24, 3 pm on 24, 10 am on 25, 10 am on 26, and 10 am on 27 (Table 3). The results are shown in Fig. 8, in which hourly precipitation, discharge, SiO_2 concentration, Ca concentration, and electrical conductivity are shown. The concentrations are

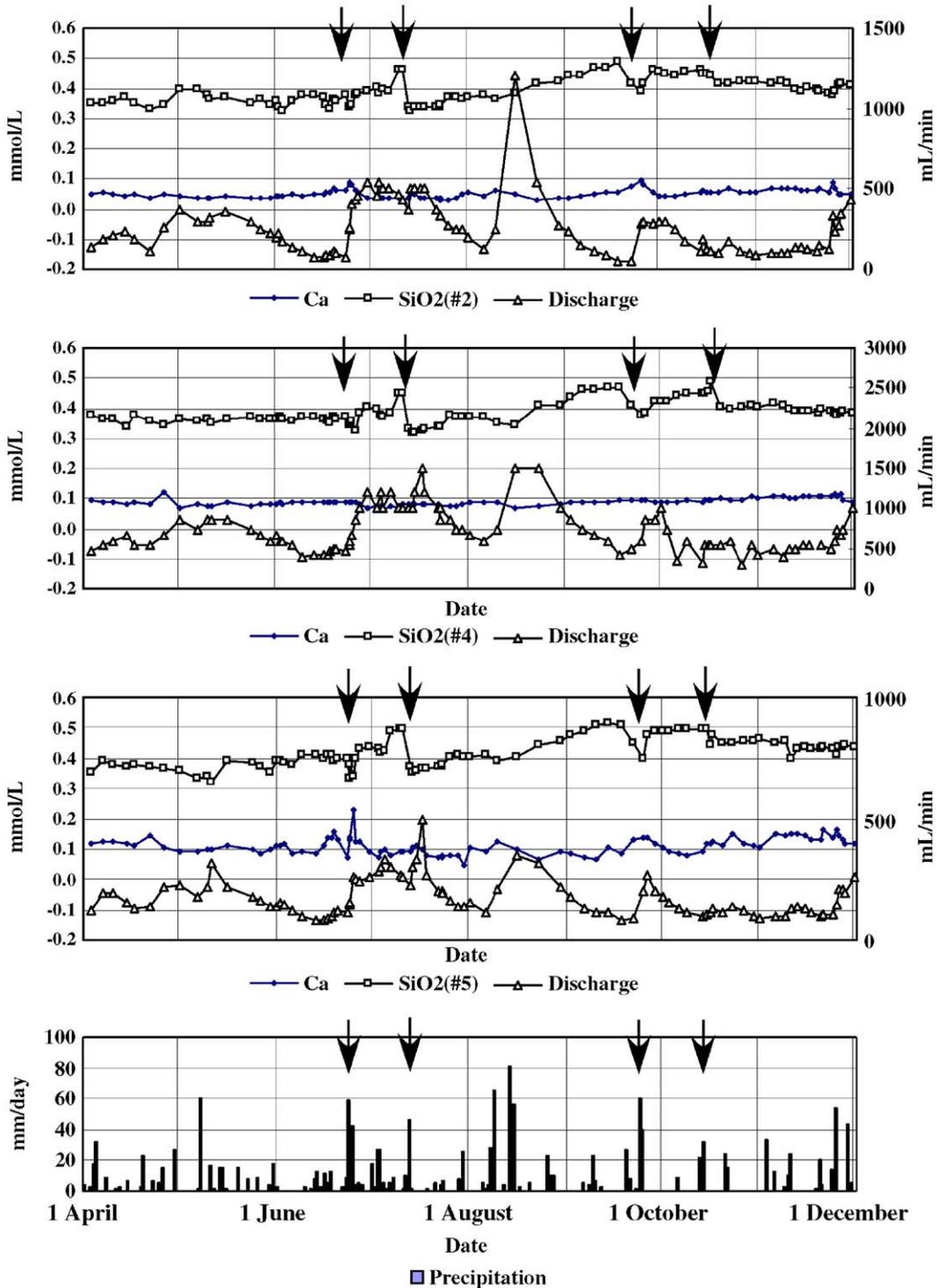


Fig. 7. Fluctuation patterns of SiO₂, Ca, and discharges. Arrows indicate abrupt decreases in SiO₂ concentration.

shown as the difference from the average of each composition (Table 2). The changes in these parameters were conspicuous in the discharges from #5 and #2 but less significant in #4. SiO₂ decreased by 0.04 to

0.06 mmol/L at the event and recovered to pre-event values on 27, 2 days after the event, for all the drill holes. Ca increased by 0.04 to 0.08 mmol/L at the event and recovered to the pre-event values on 27 for the

Table 3
Dense sampling time in June and July

20-Jun	23-Jun	24-Jun	25-Jun	26-Jun	27-Jun	30-Jun	3-Jul	4-Jul	5-Jul	7-Jul
9:00	9:00	9:00	15:00	10:00	10:00	10:00	9:00	9:00	9:00	11:00

The data are shown in Fig. 7.

water of #5 and #2, at which time no Ca change in the water from #4 was observed. Electrical conductivity apparently responded to the rainfall event, but the changes were almost within the range of accuracy. The increase in discharge from these three drill holes started at the time of the rainfall event and continued to June 30, much farther than the maximum or minimum of the chemical components and electrical conductivity.

The changes in SiO₂ and Ca concentrations, electrical conductivities, and discharges detected as outlined above were from intermittent sampling of a 6-h interval

at the minimum, so their time resolution was not sufficient for detailed analysis. However, continuous monitoring of the electrical conductivity and discharge performed for the same drill holes in 2004 indicates that the changes in these parameters very clearly correspond to rainfall events. The electrical conductivity meter used at this time was WM-22EP (accuracy <1 μS/cm; DKK-TOA Corporation). An example of the continuous monitoring is shown for #5 in Fig. 9. In the case shown in Fig. 9, the following changes occurred sequentially in response to a rainfall event of 47.5 mm

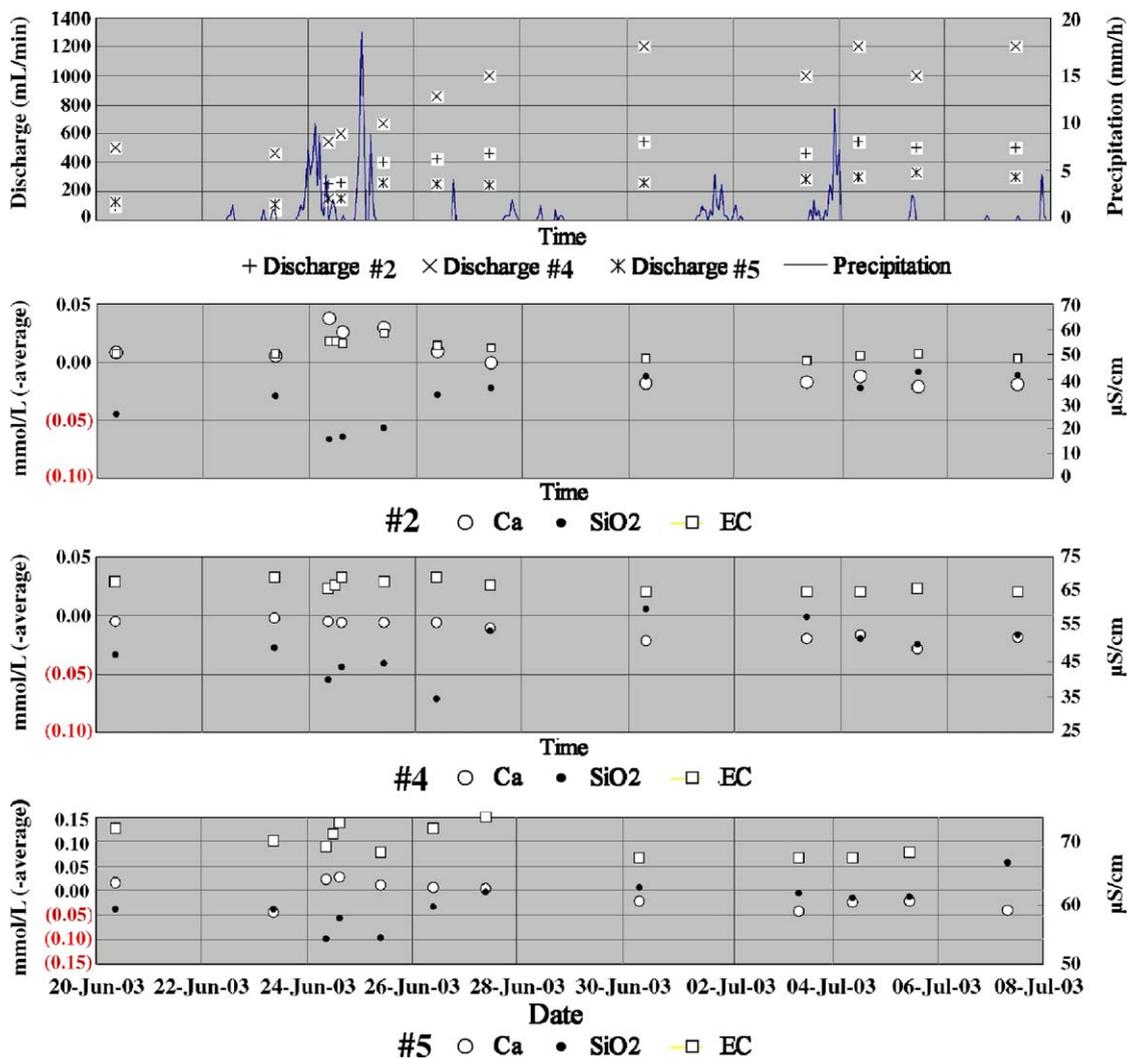


Fig. 8. The response of SiO₂, Ca, electrical conductivity, and discharge to a rainfall event.

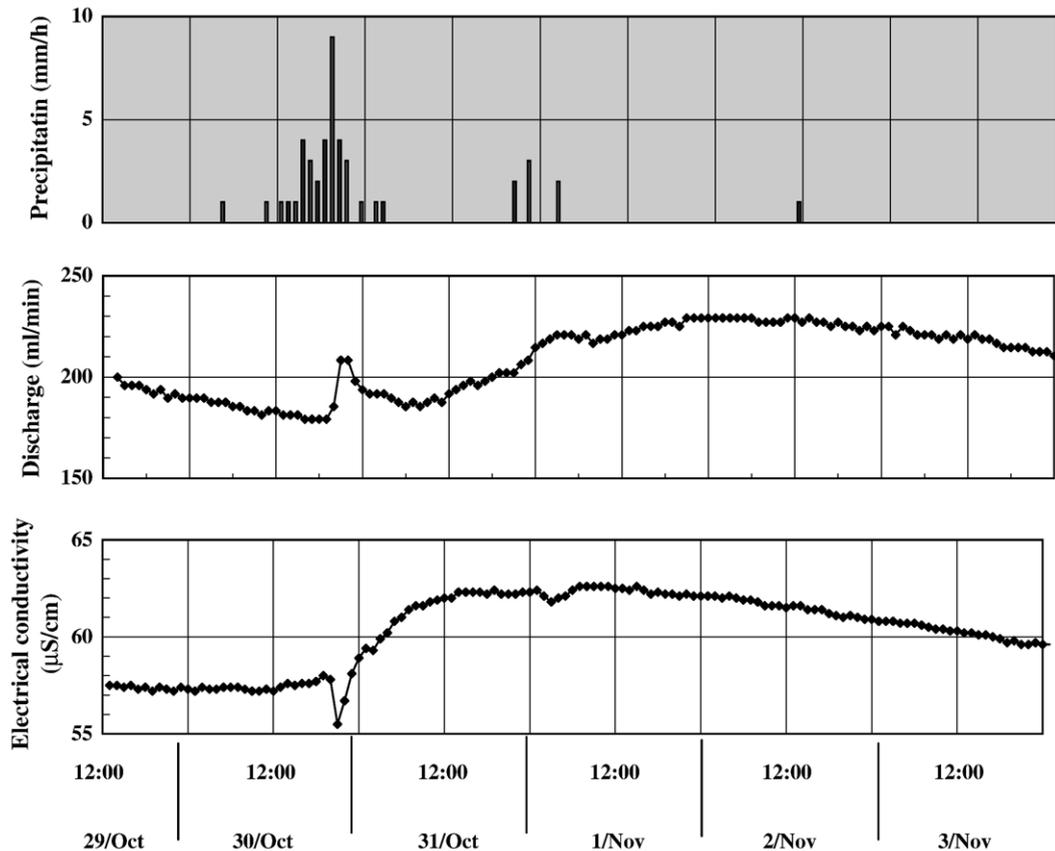


Fig. 9. Continuous monitoring results on discharge and electrical conductivity for the discharge from drill hole #5 in June, 2004.

precipitation. First, EC dropped and discharge increased temporarily within 1 h after the peak of rainfall, then EC gradually increased and reached its peak 20 h after the rainfall peak, and then decreased. In contrast, discharge increased further and reached its maximum 50 h after the rainfall peak. Similar response in EC and discharge was observed for almost all the rainfall events with cumulative amounts more than 30 mm. The water sampling for the chemical analysis in this study probably did not catch the first diluted water. However, the consecutive increase and decrease of EC were detected in accordance with the changes in SiO_2 and Ca concentrations. These findings strongly indicate that low- SiO_2 , high-Ca, and high-EC water is supplied to the groundwater at strong rainfall events.

4.5. Water percolation behavior within the vadose zone indicated by the response of water chemistry to rainfall events

The changes in water chemistry described above were detected from the water that emerges just beneath the groundwater table; hence they can be explained by

the water percolation behavior from the ground surface to the groundwater table through the vadose zone (Fig. 10). First, the spontaneous drop of EC and the increment in discharge amount at a rainfall event can be explained as quick inflow of rainwater to the groundwater table through fast paths like cracks (B in Fig. 10). This water disappears immediately after the end of a rainfall event. The next water, which has low SiO_2 and high Ca, cannot be explained by the mixture of concentrated soil water and diluted rainwater because Ca concentration is high at first. It must be concentrated soil water pushed down by the air pressure in the vadose zone, which is induced by the descending wetting front as was suggested by Bianchi and Haskell (1966) (C in Fig. 10). The air pressure propagation would not occur if fast paths like cracks were connected to the vadose zone beneath the wetting front, because the pressure would be vented (Dixon and Linden, 1972). Therefore, the fast flow mentioned above would be due to that cracks crossing the drill hole in its shallower part. Because the water we monitored was from just beneath the groundwater table, that water that is pushed down is from the capillary fringe above the

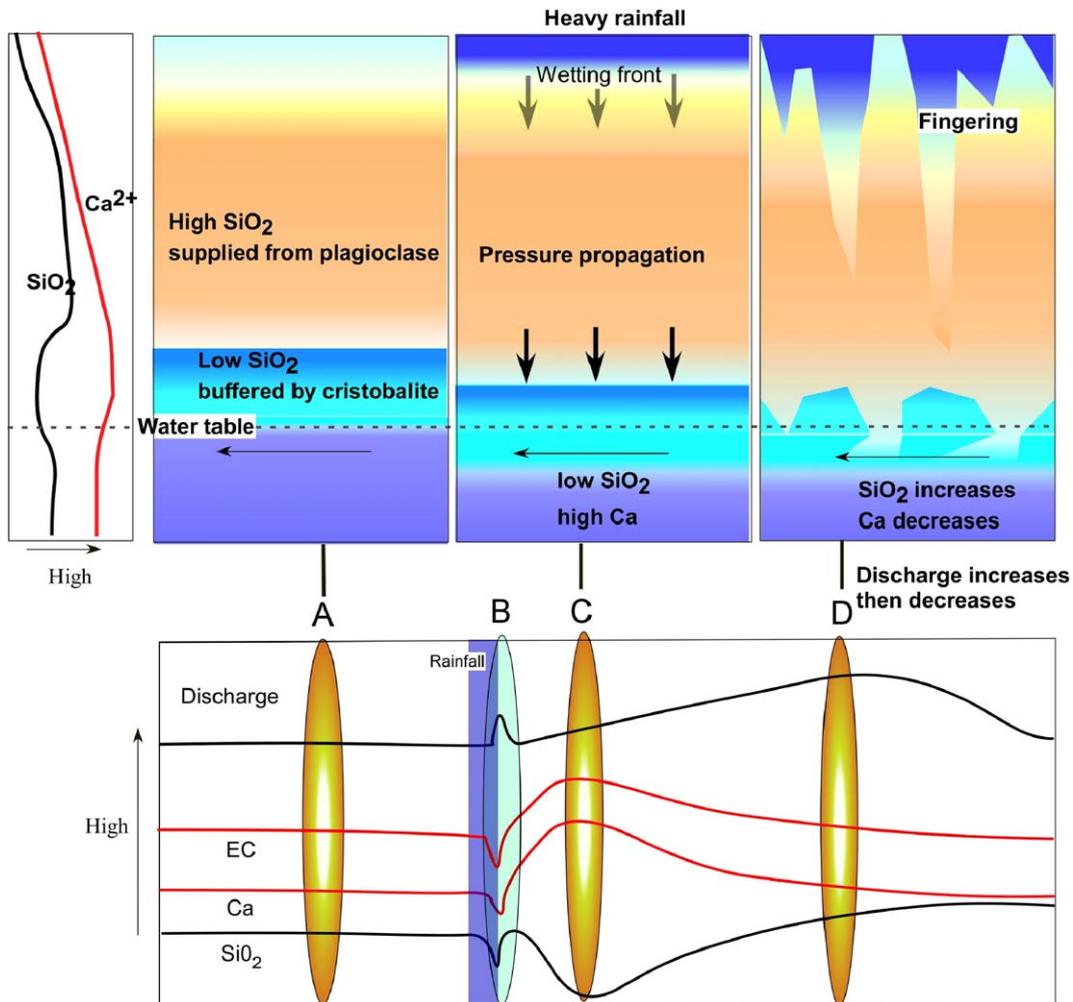


Fig. 10. Diagram explaining the changes of discharge, EC, and Ca and SiO_2 concentrations (lower) by the percolation of soil water and rainwater (upper). The upper left box schematically shows the average concentrations of SiO_2 and Ca in soil water.

groundwater table. The water from this capillary fringe has low SiO_2 concentrations close to equilibrium with cristobalite; thus, SiO_2 concentrations in the capillary fringe may be controlled by the precipitation of cristobalite. After this pushing down of the capillary fringe water, high SiO_2 , low Ca water, which seems to be soil water supplied with SiO_2 and Ca from plagioclase in the decomposed granite, follows. With time from rainfall events, rainwater itself goes down to the groundwater table, probably mixing with soil water and decreasing EC and increasing discharge (D in Fig. 10). Subsequently, discharge again decreases.

Yoshimura et al. (1992) monitored electrical conductivity in the discharge water from a cavern in limestone, and found that just after strong rainfalls, electrical conductivity increases before the discharge peak. They attributed the first concentrated discharge water

to the soil water in the vadose zone, which is pushed down by the infiltrated rainwater.

5. Conclusions

We monitored rainfall, discharge amount, and the chemistry of water from sub-horizontal drill holes just beneath the groundwater table within a decomposed granite slope for 10 months in central Japan. When rainfall was sufficiently strong, more than about 30 mm per day, characteristic water came out first, then more dilute but greater water flux came out, and then flux decreased again. The first characteristic water appears to be the capillary water pushed down by the air-pressure propagation induced by the downward movement of a wetting front. The SiO_2 concentration of this water was apparently controlled by the solubility of cristobalite and

was rich in Ca, which is supplied from plagioclase with SiO₂. After the pushing down of the capillary water, rainwater with soil water in the unsaturated zone reaches the groundwater table, which was indicated by further increase in the water flux and decrease in the electrical conductivity in the discharges from the drill holes. The cation concentrations in the unsaturated soil water and the capillary water are affected by ion exchange.

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