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Highlights

- Influence of relative humidity on P-wave velocity in dry rock was studied.
- When the relative humidity increased, P-wave velocity decreased.
- The changes in velocity are caused by the capillary condensation of water vapor.
- Clays in rock have remarkable influence on the changes in velocity.
- The crack condition in dry rock is affected by the change of the relative humidity.

P-wave propagation in dry rocks under controlled temperature and humidity

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Abstract

An understanding of the distribution of cracks in rock, which partially control P-wave velocity, is important for understanding fracturing in rock. In this study, we measured P-wave velocities in the Berea, Shirahama, and Kushiro sandstones and the Oshima granite in air with controlled temperature and relative humidity, and investigated how they change under different humidity conditions. P-wave velocity was measured in air at a constant temperature and a relative humidity of either 50% or 90%. It was found that when the relative humidity increased from 50% to 90%, P-wave velocity decreased and the water content increased in all rock samples. In contrast, when we decreased the relative humidity to 50%, P-wave velocity increased and the water content decreased. The observed changes in velocity are considered to have been caused by changes in the amount of available water in pores or cracks with tiny apertures by the capillary condensation. If the amount of the condensed water increases, the compressive stress around the tiny pores and cracks decreases. This decrease of the internal compressive stress affected the decrease of P-wave velocity in rock. It is recognized that the changes of P-wave velocity under different relative humidity were larger for rocks in which more clay minerals were included. The rock crack condition is found to be affected by the change of the relative humidity, which affects the stability of a rock mass.

Keywords: P-wave velocity, Rock, Temperature, Humidity, Capillary condensation, Clay

1. Introduction

Pre-existing cracks are ubiquitous at a wide range of scales in crustal rocks. In the upper crust, the presence of cracks has remarkable effects on the physical, transport, strength and fracturing properties of rock. Therefore, investigations of the distribution of cracks in rock can be important.

The existence of cracks makes rock more compliant [1], and also makes them more permeable if the cracks are linked [2, 3]. In the case of granite, the preferred orientation of pre-existing cracks produces anisotropies in strength [4, 5] and fracture toughness [6]. In particular, it has been shown that fracture toughness is lowest when fracturing occurs in the direction parallel to the rift plane in which most pre-existing cracks are distributed [6].

Humidity is known to affect strength and fracturing in rock. For example, Fujii et al. [7] reported that the strength of sandstone in Kushiro Coal Mine in Japan (Kushiro sandstone) decreases as water content rises. According to Fujii et al., rock fall is common in a mining gallery in Kushiro Coal Mine during summer when the relative humidity is high. Also, Nara et al. [8, 9] reported from subcritical crack growth measurements that the crack velocity at a given stress intensity factor increases when the relative humidity increases in air. Nasser et al. [10] reported that the fracture toughness of granite decreases as the density of cracks increases. Nara et al. [11] showed that the fracture toughness of rock in air decreases when the relative humidity increases. Kataoka et al. [12] reported that the fracture toughness of rock decreases as water vapor pressure increases. These reports indicate that mechanical properties such as strength and resistance to fracturing in rock are dependent on the relative humidity of water vapor pressure in the surrounding environment. In addition, the conditions of pre-existing cracks and pores in rocks may change; i.e., some pre-existing cracks and pores may open

while others close when the relative humidity in the surrounding environment changes. Therefore, it is important to investigate the opening and closing of cracks and pores under different relative humidities.

In that regard, the effects of relative humidity on crack opening and closing in rock have not been sufficiently investigated. In general, P-wave velocity in rock depends on the density of the crack [13-16] and the porosity [17]. An effective method for investigating the influence of the relative humidity on rock cracks is, therefore, the measurement of P-wave velocity under different relative humidity conditions. Temperature and relative humidity can be controlled precisely in a laboratory. Thus, measurements of wave velocity in a laboratory under controlled temperature and relative humidity conditions can be made effectively.

In this study, we measured P-wave velocities in samples of the Berea, Shirahama, and Kushiro sandstones and Oshima granite in air under a controlled temperature and relative humidity. In particular, we investigated changes in velocity under various humidity conditions to assess whether the opening or closing of crack and pores happens in the rock in response to changes in the relative humidity of the surrounding environment. Simultaneously, we measured the water content of the rock. Note that temporal changes in the P-wave velocity and water content were investigated at the same time under controlled humidity conditions.

2. Rock samples

In this study, we used samples of Berea sandstone (Ohio, USA), Shirahama sandstone (Wakayama Prefecture, Japan), Kushiro sandstone (Hokkaido Prefecture, Japan), and Oshima granite (Ehime Prefecture, Japan). Photomicrographs of these rock samples

taken under crossed nicols and ultraviolet light are shown in Figure 1. For sandstone samples, it is recognized that the distribution of circular pores is significant. In contrast, in the case of Oshima granite, the distribution of microcracks is significant and few pores can be observed. The aperture of most microcracks is less than 1 μm .

Pore size distribution in the Berea, Shirahama and Kushiro sandstones was measured by mercury porosimetry, as shown in Figure 2. In this figure, it is clear that the Berea sandstone has many pores $> 10 \mu\text{m}$ in diameter. Conversely, the Shirahama and Kushiro sandstones mainly have pores $< 1 \mu\text{m}$ in diameter. The average values of pore diameter for these sandstones calculated from the pore size distributions are shown in Table 1.

Gas permeability of these rock samples was measured by gas permeameter (TEMCO, MP-401) (Table 2). For the Oshima granite, the measurements were conducted normal to the rift plane. Gas permeability in the Berea sandstone is greater than those in the Shirahama and Kushiro sandstones, and the Oshima granite. The values of the porosity measured using the suggested ISRM water saturation method are also shown in Table 2. The porosity of the Berea sandstone is the highest of the four rock samples.

We prepared two cylindrical specimens (30 mm in diameter and 60 mm in length) from each rock sample. One was used to measure P-wave velocity, and the other was used to measure water content. Before the measurements were made, the cylindrical specimens were dried in an oven at 105°C for more than 24 hours, then weighed. In Table 3, the length, diameter and weight of the dry rock specimens used to measure water content are summarized.

3. Methods

3.1 Measuring P-wave velocity

To measure P-wave velocity, an ultrasonic transmission method was used. We glued piezoelectric sensors with a 1 MHz resonant frequency directly onto the surfaces of the cylindrical specimen with epoxy glue to measure the velocity in the axial direction. Note that the sensors attached to the rock specimen were covered by a silicone sealant for waterproofing.

Then specimens were placed in a chamber where the temperature and relative humidity could be controlled, and we measured P-wave velocity and water content.

3.2 Experimental conditions

In this study, we kept the temperature constant and only changed the relative humidity in the chamber during the wave velocity measurements. The relative humidity was set initially at 50% and maintained at that level for several days. We then increased the relative humidity to 90% and maintained that level for several more days. Finally, we decreased the humidity to the initial value (50%) where it remained constant for the rest of the experiment. We conducted this procedure at 20°C, 50°C and 80°C.

4. Results

To confirm that the measurement system and sensors work well in high humidity conditions, we measured P-wave velocity in stainless steel, the physical properties of which are not affected by humidity. We used a stainless steel cube (40 mm on each side) for this measurement. Temporal changes of relative humidity and P-wave velocity for the stainless steel sample are shown in Figure 3. The P-wave velocity in stainless steel did not change when the relative humidity changed. The change of the relative humidity is considered to have had no influence on the sensors, and the measurement system in

this study works well.

Figure 4 shows waveforms for the Berea, Shirahama, and Kushiro sandstones, and Oshima granite; the first arrivals of P-wave energy are indicated by arrows. Note that the first P-wave arrivals for the sandstone samples are obviously dependent on relative humidity. It is clear that the P-wave velocity in dry sandstone becomes lower when the relative humidity is higher. In contrast, this tendency is much weaker for granite. Note also that the amplitude for the first peak of the waveform decreases when the humidity is higher.

Temporal changes of P-wave velocity and water content in the Berea sandstone at 20°C, 50°C and 80°C are shown in Figure 5. Water content was recognized to increase and P-wave velocity to decrease rapidly when we increased the relative humidity in the chamber from 50% to 90%. When we then decreased the relative humidity to 50% again, the water content decreased and P-wave velocity increased.

Figures 6 and 7 show the temporal changes of P-wave velocity and water content for the Shirahama and Kushiro sandstones, respectively. In these sandstones, the changes in P-wave velocity and water content show similar tendencies to those of the Berea sandstone. However, the changes of both P-wave velocity and water content in the Shirahama and Kushiro sandstones are shown to be more gradual than those for the Berea sandstone when the relative humidity changed.

Figure 8 shows the temporal changes of P-wave velocity and water content in the Oshima granite. P-wave velocity in the Oshima granite was measured in three orthogonal directions, i.e., in the directions normal to the so-called rift, grain, and hardway planes [4, 5, 13, 14]. The changes in P-wave velocity and water content show similar tendencies to those observed for sandstones, even though the changes were

smaller. In addition, changes in both P-wave velocity and water content for the granite were more gradual than those for the sandstones when the relative humidity changed.

In Table 4, averages of P-wave velocities for each temperature and humidity condition are summarized, along with the differences in the P-wave velocity between each humidity condition. The difference in P-wave velocity between different temperatures was observed to be small. In contrast, when the relative humidity was different, the difference in the velocity was obvious. In particular, the differences in P-wave velocity for the Shirahama and Kushiro sandstone were remarkable. On the other hand, the difference for Oshima granite was smaller than sandstones. In the case of P-wave propagation normal to rift plane in Oshima granite, the change of P-wave velocity was more remarkable than other 2 directions (normal to grain and hardway planes).

5. Discussion

P-wave velocity in rocks is generally known to decrease with increasing the crack density. Therefore, to explain changes in P-wave velocity under different relative humidities, it is necessary to consider changes in the condition of cracks in a rock. In particular, it is essential to consider whether cracks open or close under different relative humidities.

Rocks generally include numerous pores and cracks with tiny apertures. If the aperture is very small, water vapor turns to liquid water by capillary condensation and cracks and pores with small apertures are therefore immersed in liquid water. Furthermore, if they are immersed in a liquid, suction occurs by liquid building, and compressive stress can apply there. This suction decreases as the radius of curvature of

the condensed liquid increases. Additionally, any increase in relative humidity will lead to an increase in the volume of the condensed water present. Using the Young–Laplace equation, which describes the capillary pressure difference sustained across an interface between two static fluids such as water and air, it is possible to approximate the compressive stress around cracks or pores [18]. The pressure is expressed as:

$$p = \frac{2\sigma}{R_1}, \quad (1)$$

where p is the pressure due to capillary condensation (i.e., compressive stress around the crack), σ is the surface tension of water (73×10^{-3} N/m), and R_1 is radius of curvature of the liquid surface. When the relative humidity of the surrounding environment increases, the volume of condensed water in tiny pores—and consequently the radius of curvature of the liquid surface—also increases. In this case, the suction therefore decreases. As a result, the contact condition of mineral grains in the sandstone and granite is changed and the P-wave velocity is altered following the change in the relative humidity.

From Table 4, it is recognized that the change of P-wave velocity in Oshima granite propagating normal to rift plane was larger than those normal to grain and hardway planes. In granite, most cracks distribute parallel to rift plane. Therefore, it is considered that the more closure of cracks and more increase of grain contacts due to capillary condensation of water vapor occurred for the cracks parallel to rift plane.

It is well-known that the wave velocities are related to the elastic moduli of materials. Precisely, Clark et al. [19] and Pimienta et al. [20] have investigated the change of elastic wave velocity in several sedimentary rocks under different humidity conditions as a function of moisture adsorption. Tittmann [21] and Tittmann et al. [22] have reported the influence of the moisture adsorption on the attenuation of elastic wave.

Murphy et al. [23] reported the reduction of elastic properties of sedimentary rocks considering the influence of moisture adsorption on grain contact, which was based on the model developed by Johnson et al. [24].

As shown in Section 4, the changes of P-wave velocities in the Shirahama and Kushiro sandstones were more remarkable than those in the Berea sandstone. The Shirahama and Kushiro sandstones are considered to include numerous cracks and pores with tiny apertures and capillary condensation occur in various positions. Therefore, changes in the internal compressive stress become significant and lead to a change in P-wave velocity as the surrounding relative humidity also changes.

In the case of granite, the range of P-wave velocities under various relative humidities was lower than those of the sandstones. This may be because of the difference in rigidity between granite and sandstones. Young's moduli for the Berea, Shirahama and Kushiro sandstones were determined to be 8.20, 6.23 and 9.12 MPa, respectively [9]. In contrast, Young's modulus for the Oshima granite was 60.9 MPa [25]. According to Walsh [26], compressibility increases as Young's modulus decreases. Therefore, less compressive deformation occurred in granite, resulting in smaller increases or decreases of the contact areas of cracks and correspondingly smaller changes in P-wave velocity.

According to the results of Pimienta et al. [20], the cement materials in rock could influence the change of the velocity under different humidity conditions. Nara et al. [9, 12] reported that the more cement materials, i.e., clay minerals were included in Shirahama sandstone and Kushiro sandstone than Berea sandstone. Table 4 shows that the percentages of the change (reduction) of wave velocities in Shirahama and Kushiro sandstones are larger than Berea sandstone when the relative humidity increased. It is suggested that the weakening of the elastic properties of clays (illite and smectite [9,

12]) in Shirahama and Kushiro sandstones influenced the reduction of P-wave velocity under the higher relative humidity condition. In addition, it is considered that the change of the wave velocity in Oshima granite was smaller because few clays are contained.

According to Guéguen and Kachanov [27], the aspect ratio of the cracks affects the elastic properties of rock when the rock is saturated. In addition, it is suggested that the crack opening due to condensation may influence only the aspect ratio of the cracks, and not the crack density. However, the measurements by Sano et al. [13] and Nara et al. [28] show that the increase of the grain contacts can occur and the cracks in rock (even in granite) close partly even if the effective confining pressure is less than 10MPa. In this case, the crack density in rock decrease which brings about the increase of wave velocity and elastic moduli.

The difference in time required for water content and P-wave velocity to stabilize after changing the relative humidity in the chamber for each rock sample can be observed. That time is obviously short for the Berea sandstone. Differences in pore size and gas permeability are considered to affect this result. Air, which includes water vapor, permeates smoothly into rocks with high gas permeability (e.g., the Berea sandstone), and then the water content and P-wave velocity change quickly.

From the results of this study, we conclude that P-wave velocity in rock will change as a result of changes in the relative humidity in the air. Increases in humidity are well known to lead to a significant acceleration of crack growth and a decrease in the long-term strength of rock [28]. As described in Section 1, in the Kushiro Coal Mine, rock falls often happen when humidity is high [7]. When a decrease in P-wave velocity in a rock mass is observed to coincide with an increase of humidity, failure from the surface of the rock mass may well be imminent. The results of this study offer

fundamental information concerning the weakening of a rock mass structure.

6. Conclusions

In this study, we measured P-wave velocities in three kinds of sandstones (Berea, Shirahama and Kushiro sandstones) and one granite (Oshima granite) in air with a controlled temperature and relative humidity. In particular, we investigated changes in P-wave velocity in dry rocks kept at a constant temperature while the relative humidity was changed. P-wave velocity was shown to change as humidity changed in the surrounding environment. If the relative humidity was increased, P-wave velocity decreased in all rock samples. P-wave velocity changes in the sandstone samples were more remarkable than those in the granite. The changes in P-wave velocity for the Shirahama and Kushiro sandstones were larger than those in the Berea sandstone, because the Shirahama and Kushiro sandstones included more clay minerals, cracks and pores with tiny apertures. We conclude that the condition of cracks and small-aperture pores in rock changes under as humidity varies, which in turn affects the mechanical stability of a rock mass.

Acknowledgement

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Figure captions

Figure 1. Photomicrographs of Berea sandstone ([a] and [b]), Shirahama sandstone ([c] and [d]), Kushiro sandstone ([e] and [f]), and Oshima granite ([g] and [h]). The height and length of the photomicrographs of Shirahama sandstone are 0.53 mm and 0.98 mm, respectively. The height and length of photomicrographs of other samples are 1.85 mm and 3.42 mm, respectively. (a), (c), (e), and (f) were taken under crossed nicols. (b), (d), (f), and (h) were taken under ultraviolet light.

Figure 2. Pore size distributions of Berea sandstone, Shirahama sandstone and Kushiro sandstone.

Figure 3. Temporal changes of P-wave velocity in stainless steel and relative humidity.

Figure 4. Waveforms obtained for rock samples. (a), (b), and (c): Berea sandstone at 20°C, 50°C, and 80°C, respectively, (d), (e), and (f): Shirahama sandstone at 20°C, 50°C, and 80°C, respectively, (g), (h), and (i): Kushiro sandstone at 20°C, 50°C, and 80°C, respectively, (j) and (k): Oshima granite normal to rift plane at 50°C and 80°C, respectively, (l) and (m): Oshima granite normal to grain plane at 50°C and 80°C, respectively, (n) and (o): Oshima granite normal to hardway plane at 50°C and 80°C, respectively.

Figure 5. Temporal changes of P-wave velocity and water content for Berea sandstone. (a): at 20°C. (b): at 50°C. (c): at 80°C.

Figure 6. Temporal changes of P-wave velocity and water content for Shirahama sandstone. (a): at 20°C. (b): at 50°C. (c): at 80°C.

Figure 7. Temporal changes of P-wave velocity and water content for Kushiro sandstone. (a): at 20°C. (b): at 50°C. (c): at 80°C.

Figure 8. Temporal changes of P-wave velocity and water content for Oshima granite. (a) and (b): normal to rift plane at 50°C and 80°C, respectively, (c) and (d): normal to grain plane at 50°C and 80°C, respectively, (e) and (f): normal to hardway plane at 50°C and 80°C, respectively.

Table captions

Table 1. Average values of pore diameter of Berea sandstone, Shirahama sandstone and Kushiro sandstone

Table 2. Gas permeability of Berea sandstone, Shirahama sandstone and Kushiro sandstone

Table 3. Size and dry weight of rock specimens

Table 4. Averages of P-wave velocities in each condition

Table 1. Average values of pore diameter of Berea sandstone, Shirahama sandstone and

Kushiro sandstone

Rock samples	Average values of pore diameter [μm]
Berea sandstone	22.0
Shirahama sandstone	0.84
Kushiro sandstone	1.15

Table 2. Gas permeability and porosity of Berea sandstone, Shirahama sandstone,

Kushiro sandstone and Oshima granite

Rock samples	Gas permeability [md]	Porosity [%]
Berea sandstone	509	20
Shirahama sandstone	39	13
Kushiro sandstone	27	11
Oshima granite	2 (normal to rift plane)	0.5

Table 3. Size and dry weight of rock specimens

Type of rock	Length [mm]	Diameter [mm]	Dry weight [g]
Berea sandstone	60.00	29.35	84.447
Shirahama sandstone	59.85	29.25	92.730
Kushiro sandstone	59.65	29.55	97.528

Table 4. Averages of P-wave velocities in each condition

Type of rock	Temperature	P-wave velocity [km/s]		
		50%	90%	Difference
Berea sandstone	20°C	2.27	2.08	0.19
	50°C	2.21	2.03	0.18
	80°C	2.18	2.02	0.16
Shirahama sandstone	20°C	2.48	2.11	0.37
	50°C	2.42	2.05	0.37
	80°C	2.33	2.01	0.32
Kushiro sandstone	20°C	2.90	2.61	0.29
	50°C	2.85	2.50	0.35
	80°C	2.77	2.37	0.40
Oshima granite normal to rift plane	50°C	4.41	4.34	0.07
	80°C	4.28	4.22	0.06
Oshima granite normal to grain plane	50°C	4.79	4.73	0.06
	80°C	4.72	4.67	0.05
Oshima granite normal to hardway plane	50°C	4.99	4.94	0.05
	80°C	4.89	4.85	0.04

Figure1a

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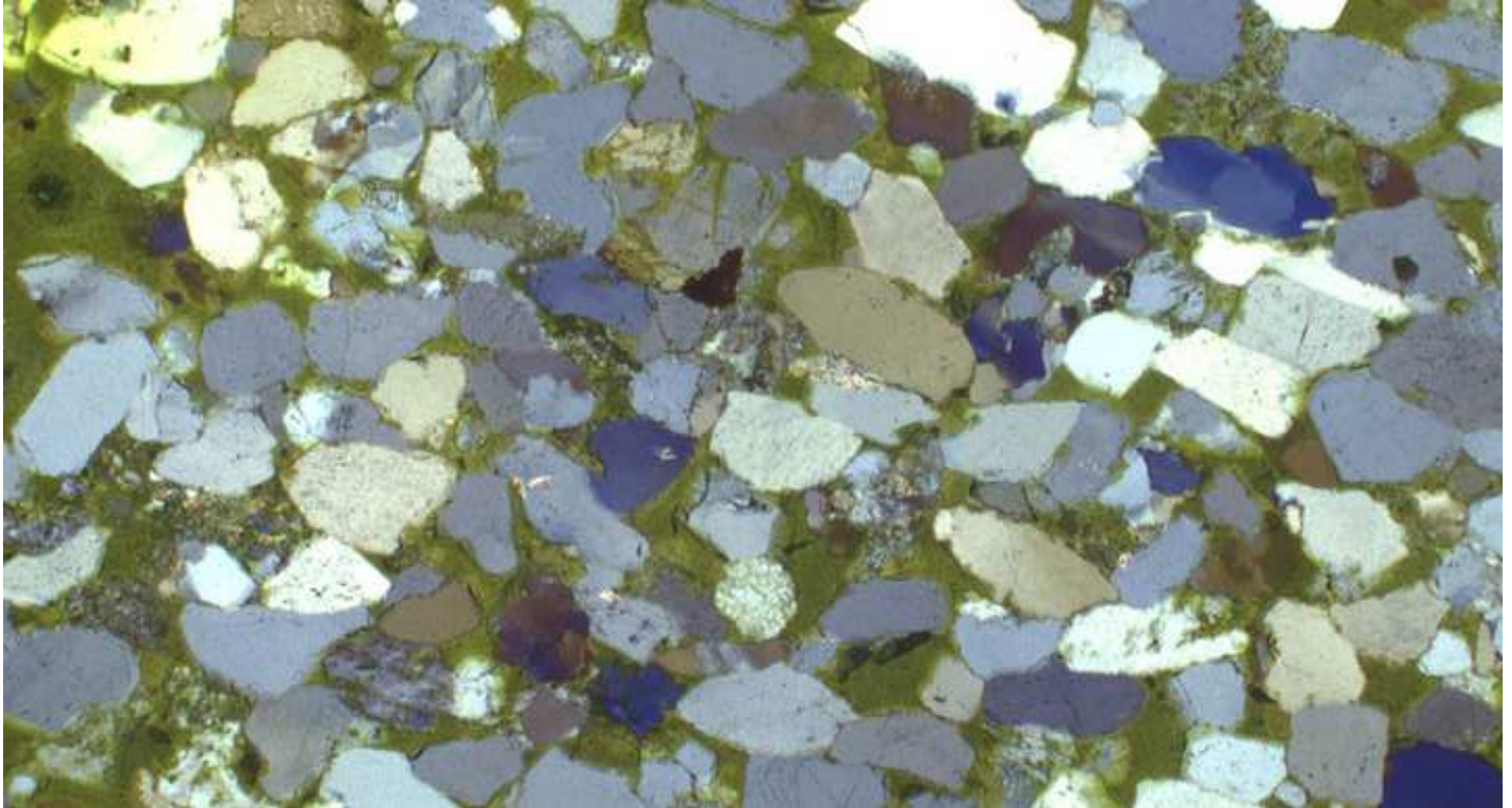


Figure1b
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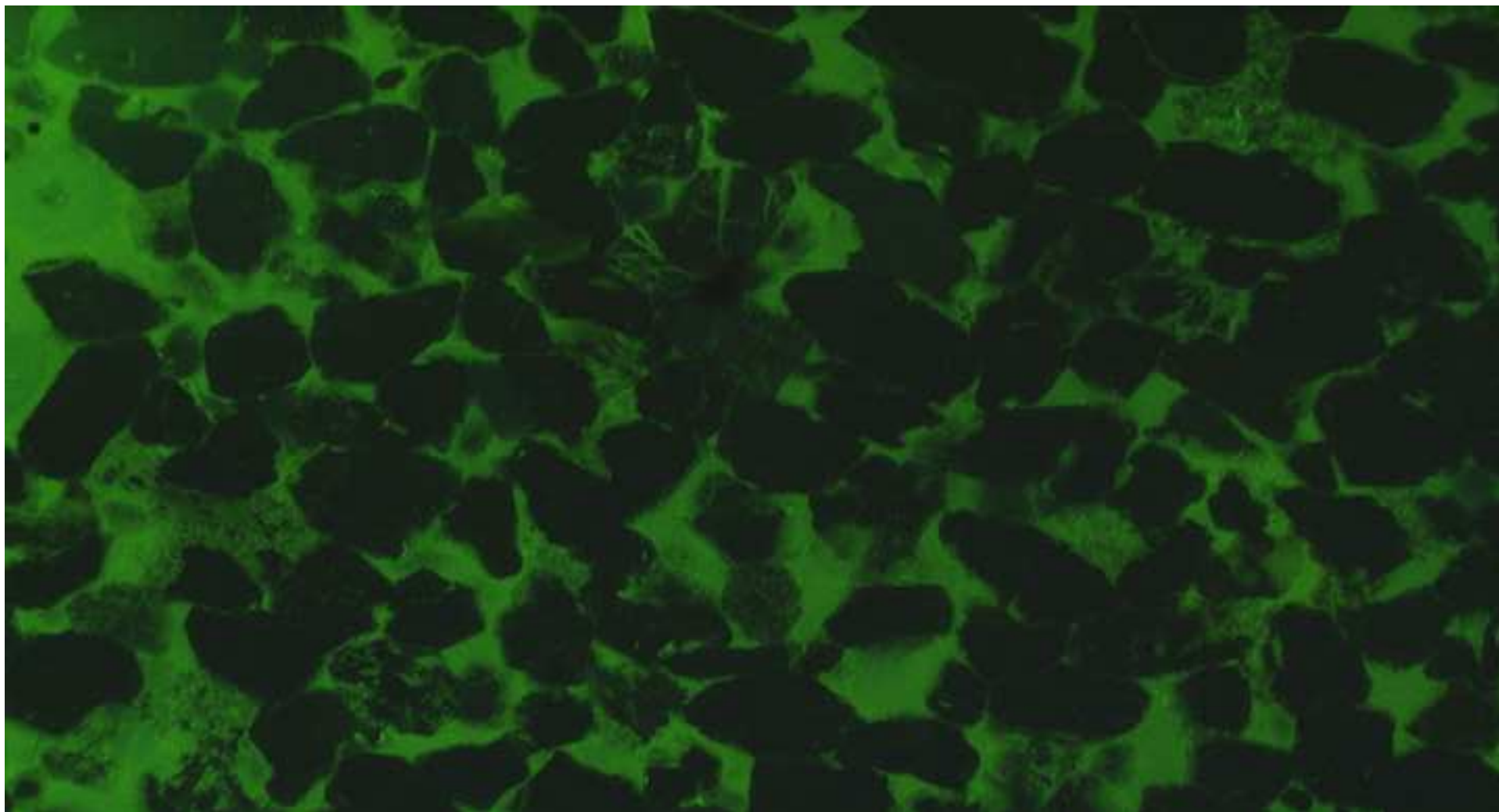


Figure1c

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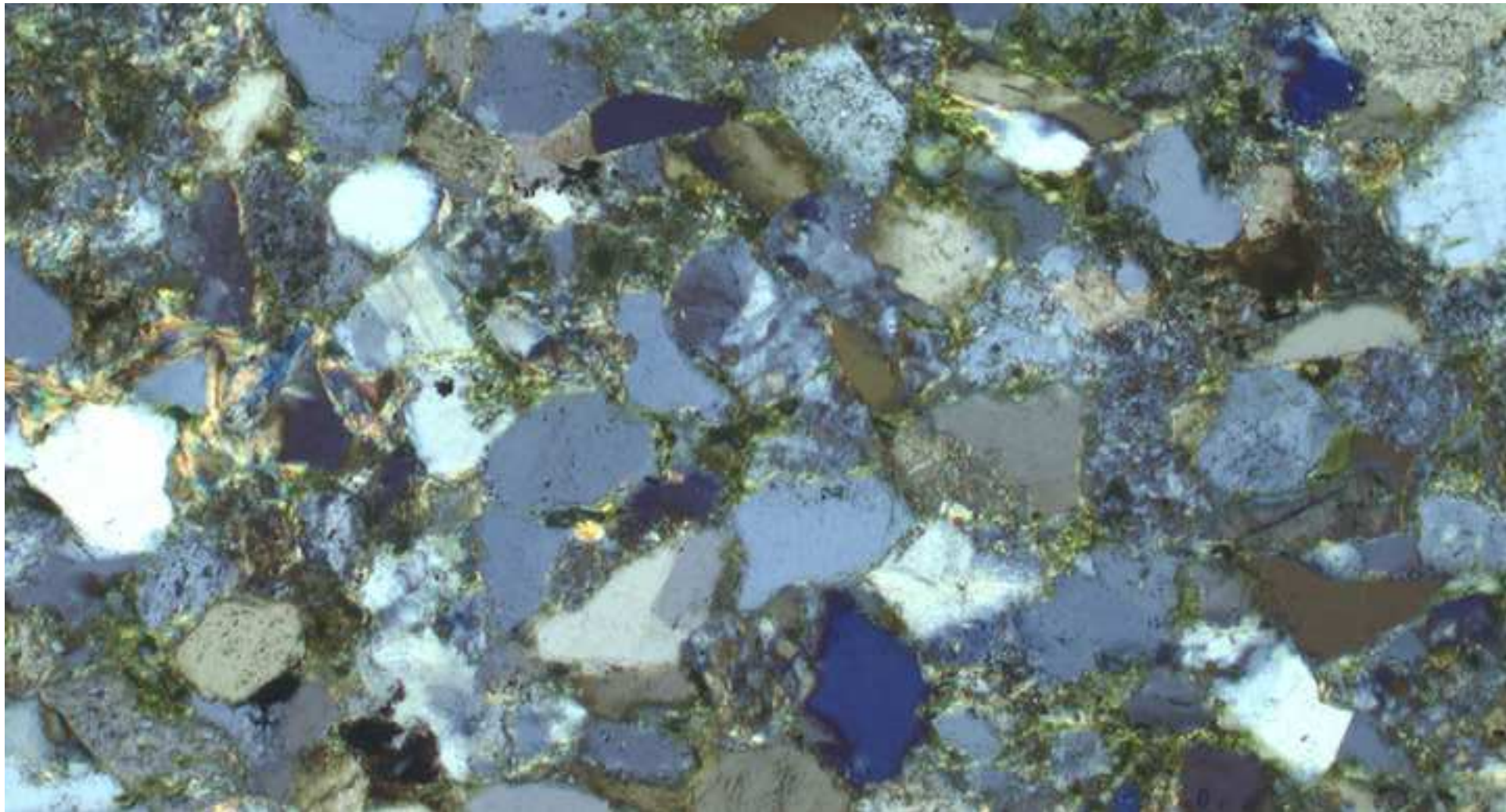


Figure1d

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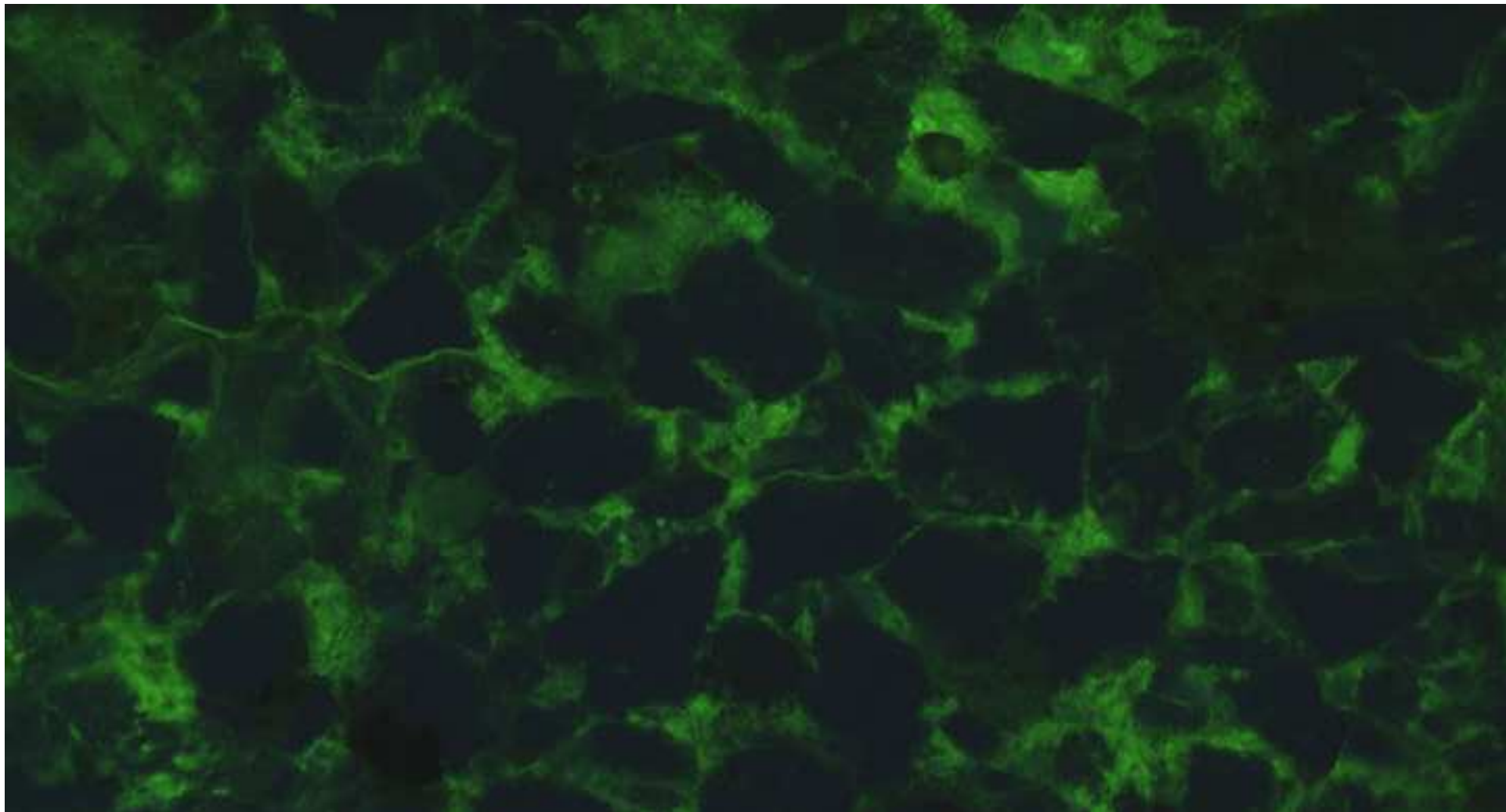


Figure1e
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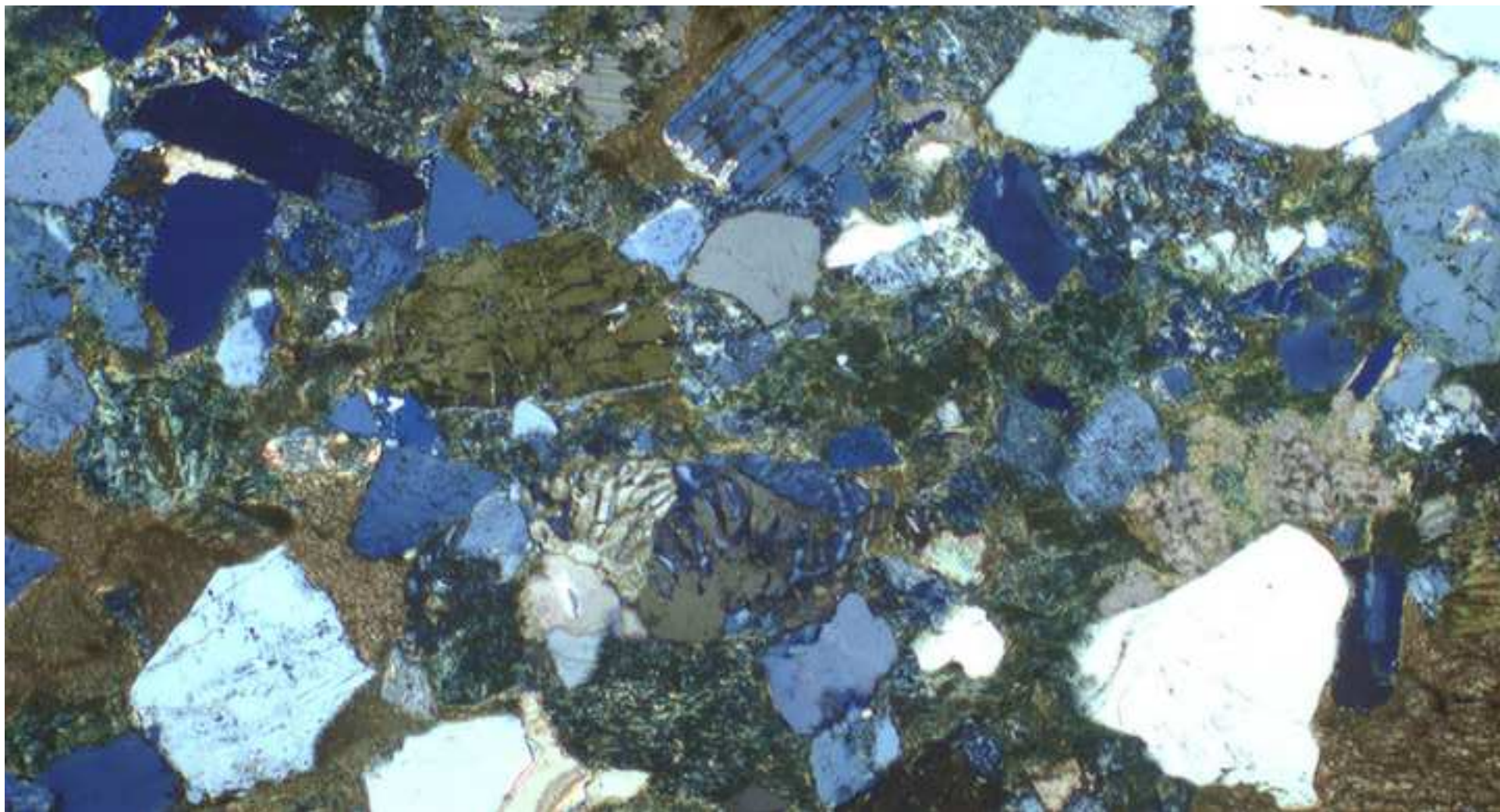


Figure1f

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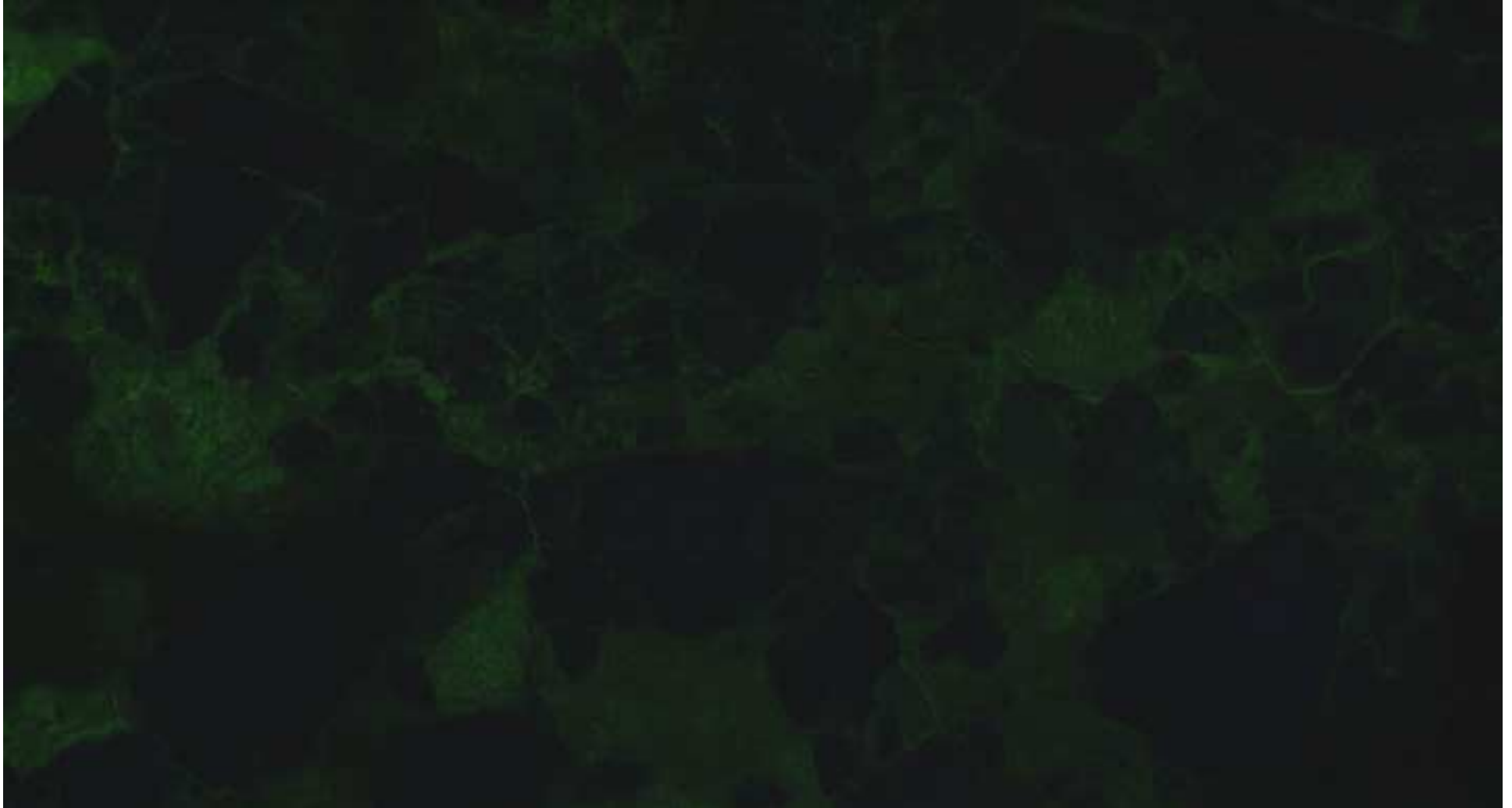


Figure1g

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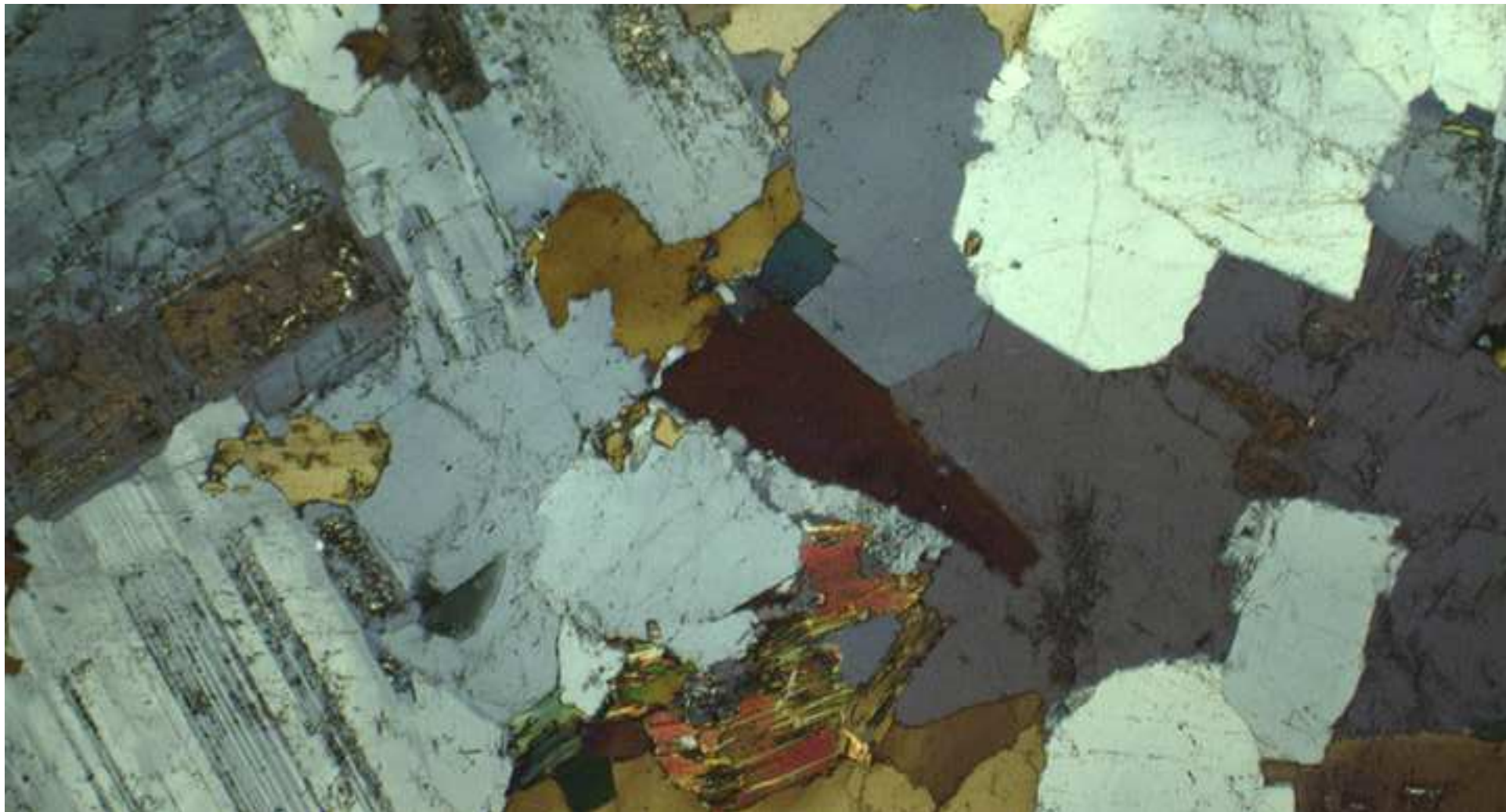


Figure1h

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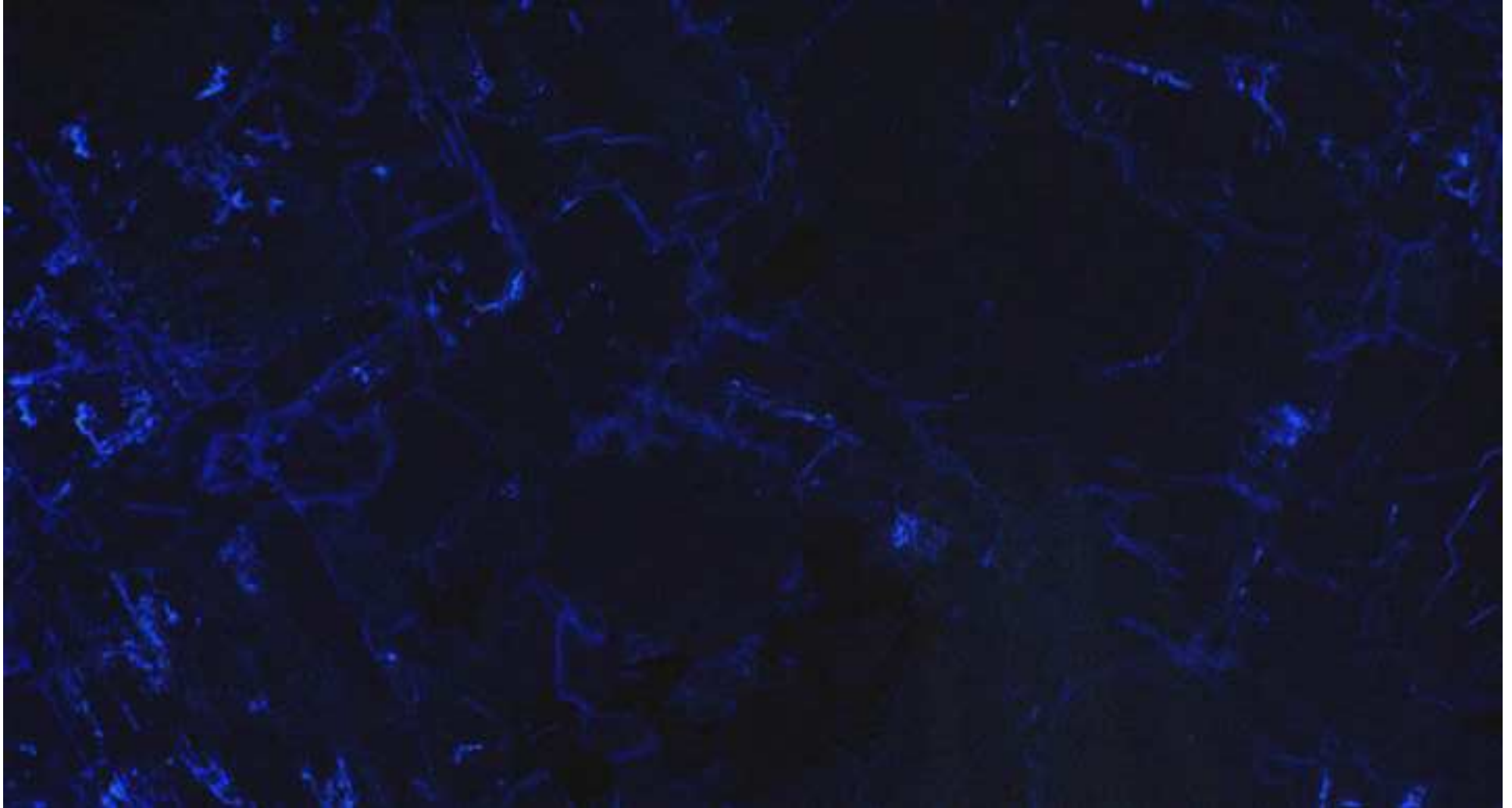


Figure2

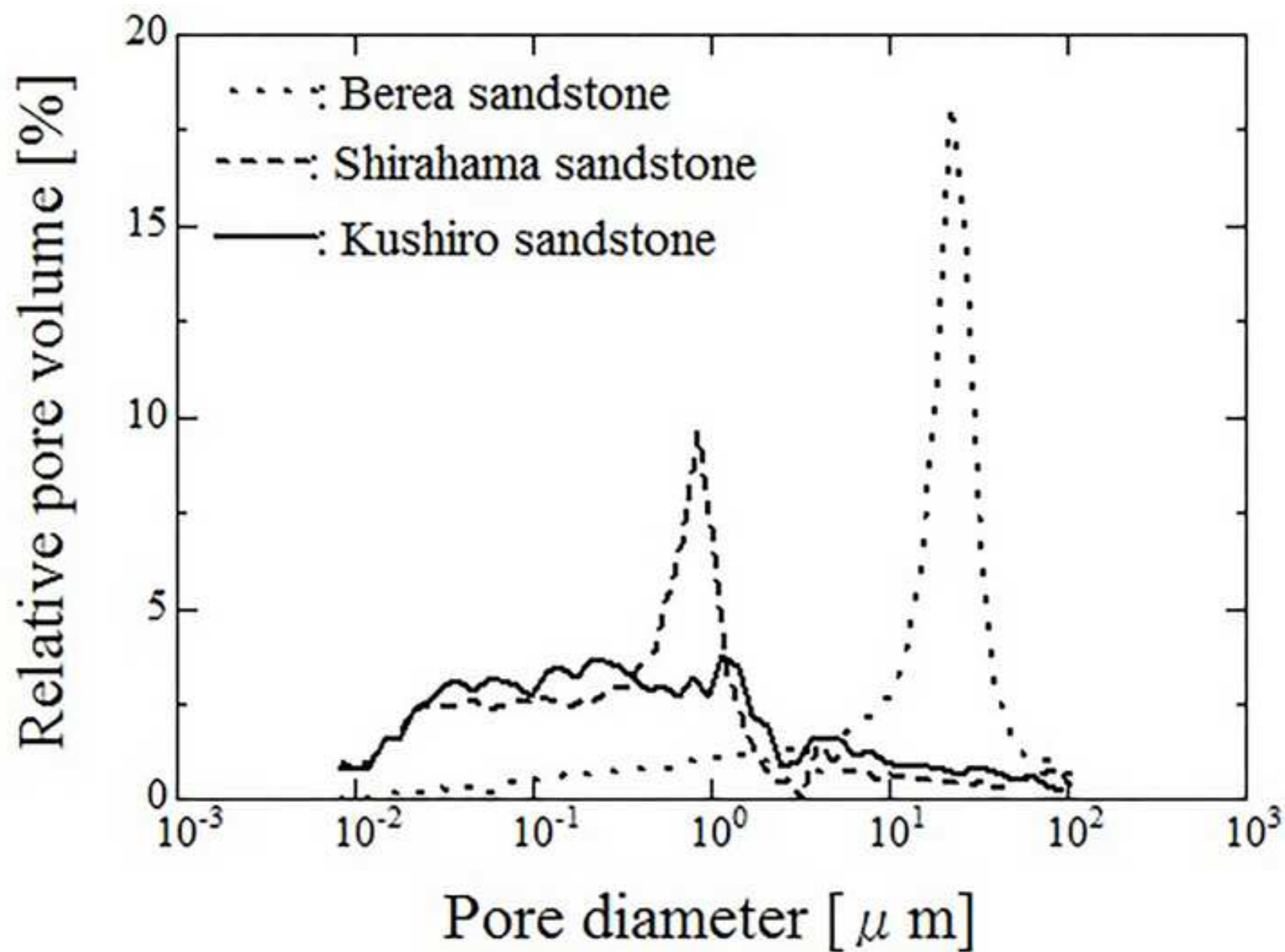
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Figure3

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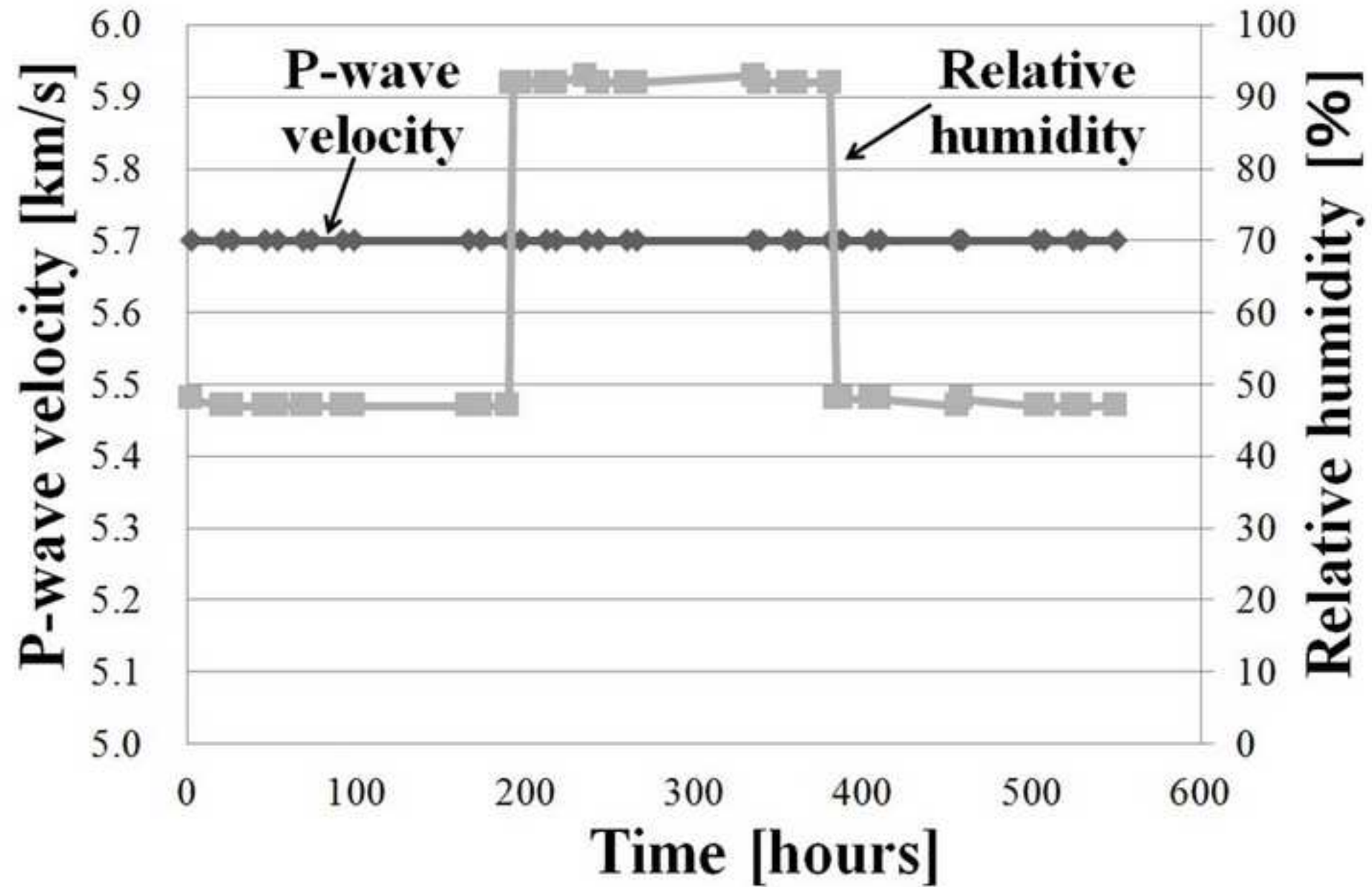


Figure4a

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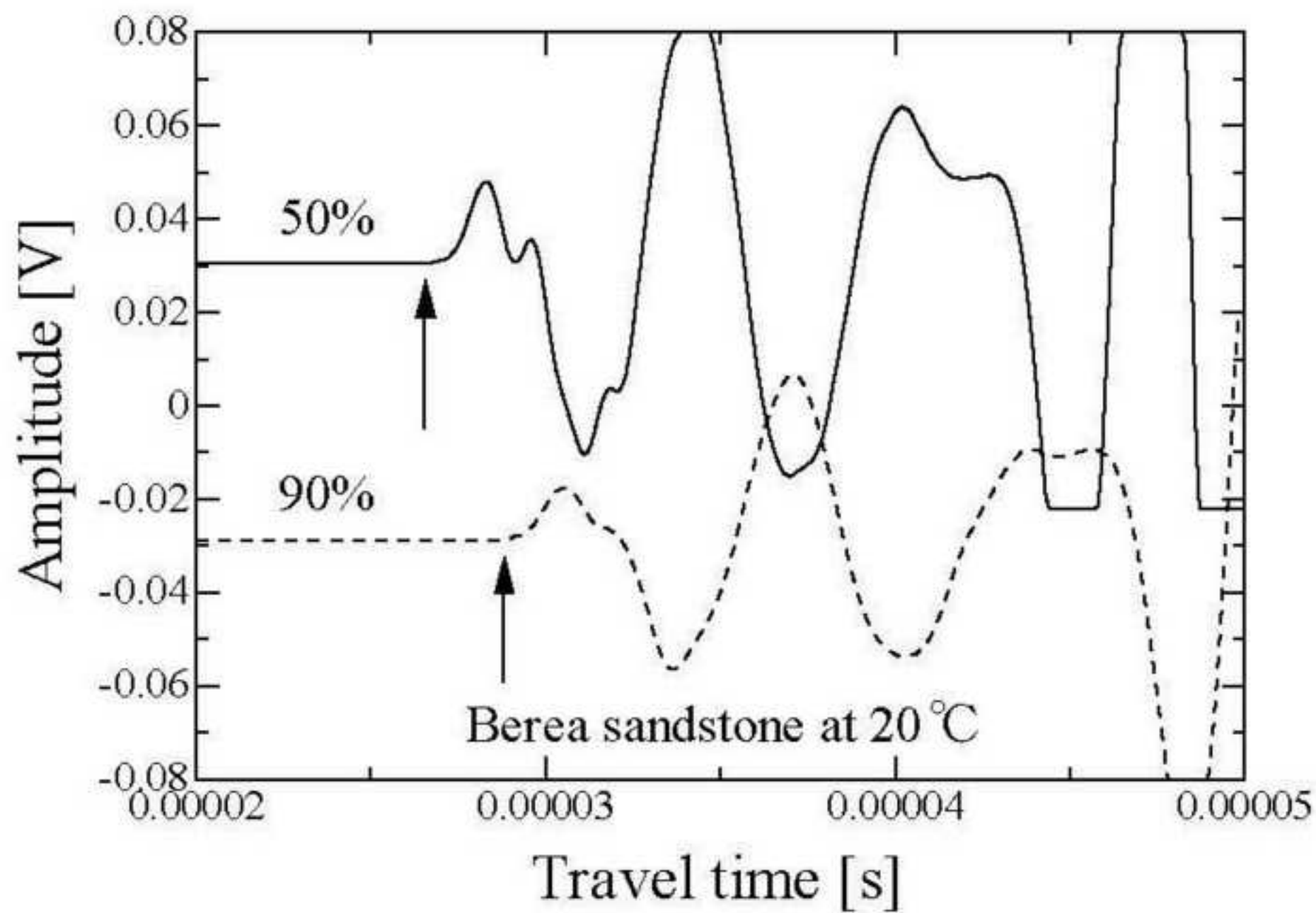


Figure4b

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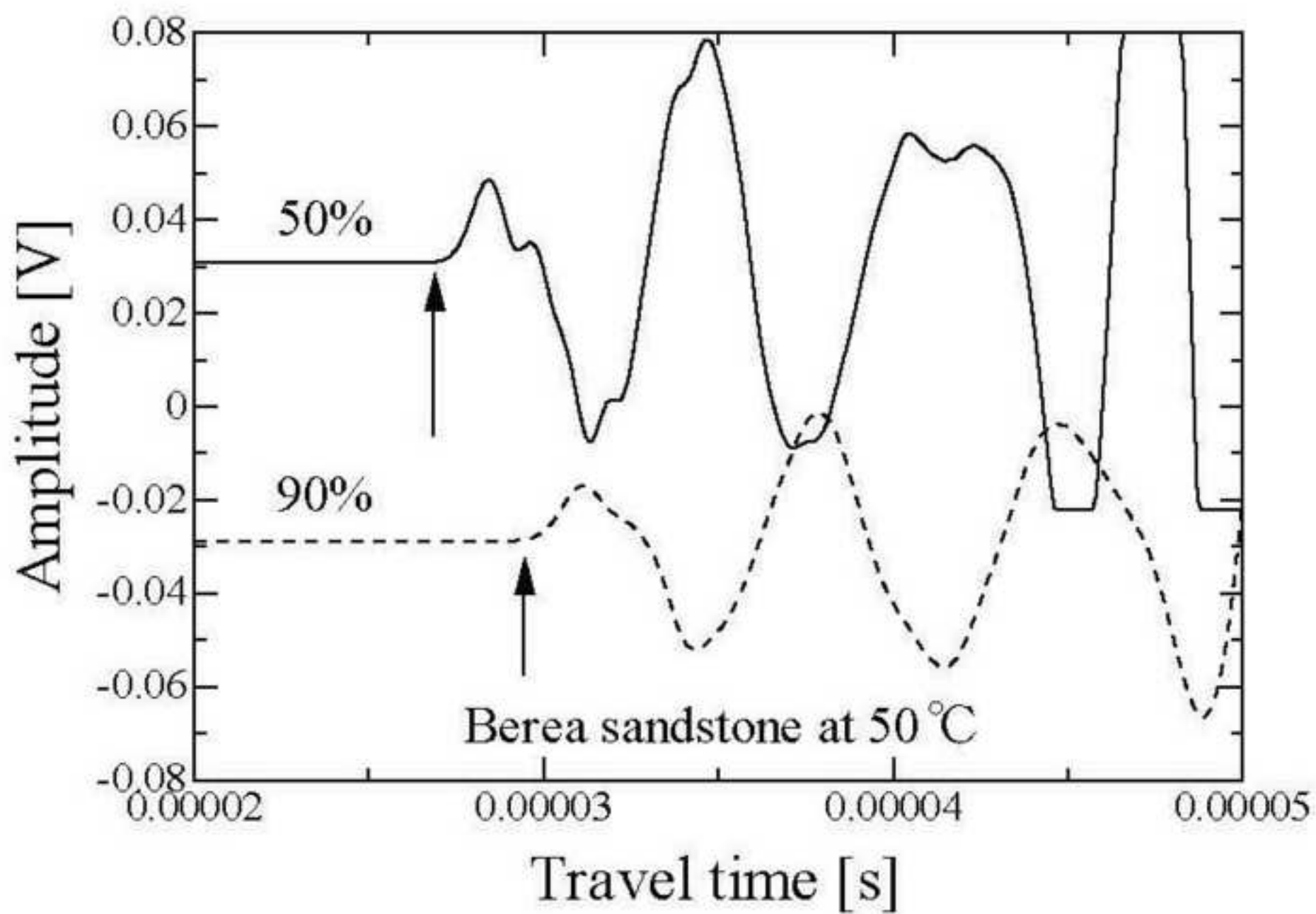


Figure4c

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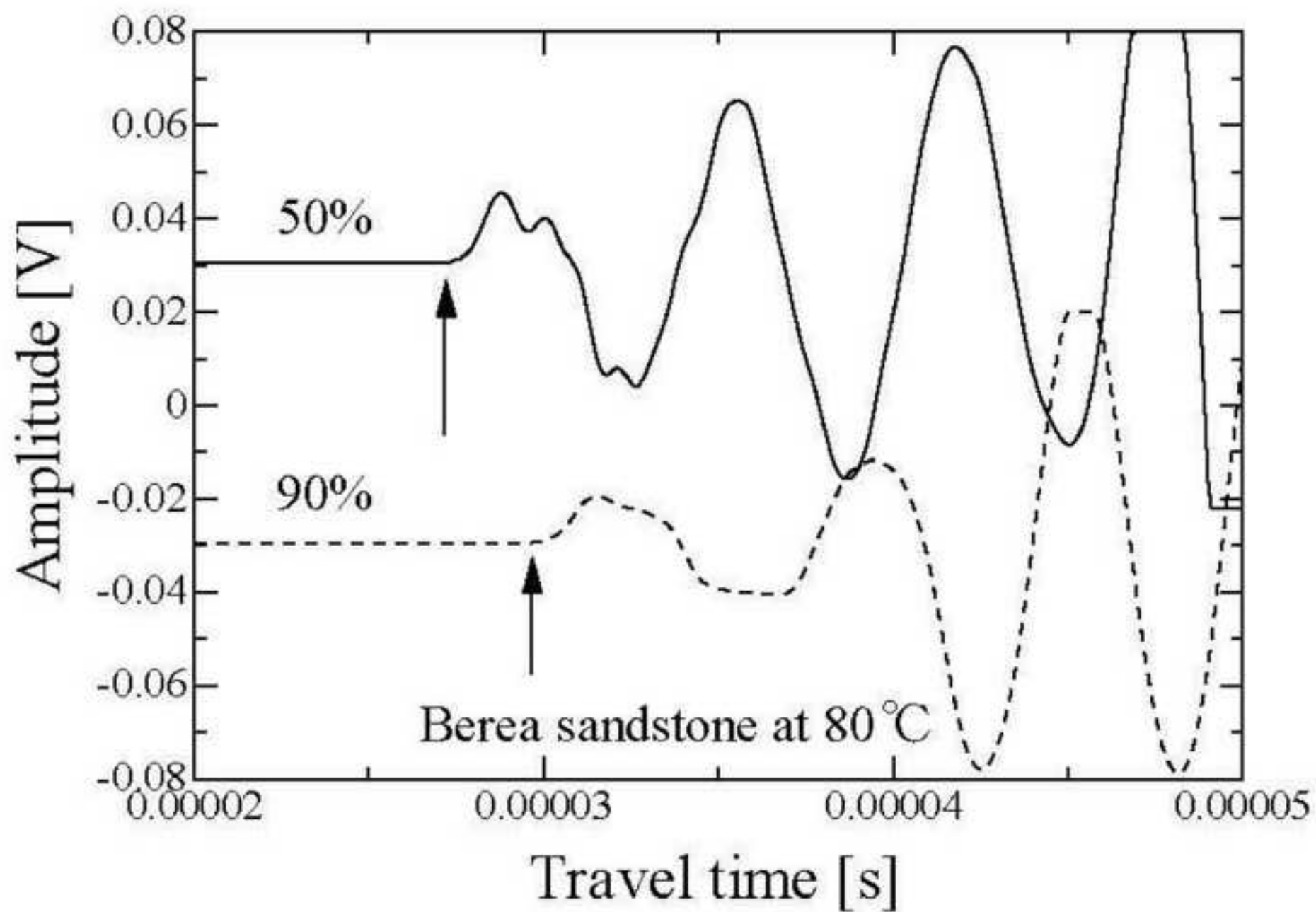


Figure4d

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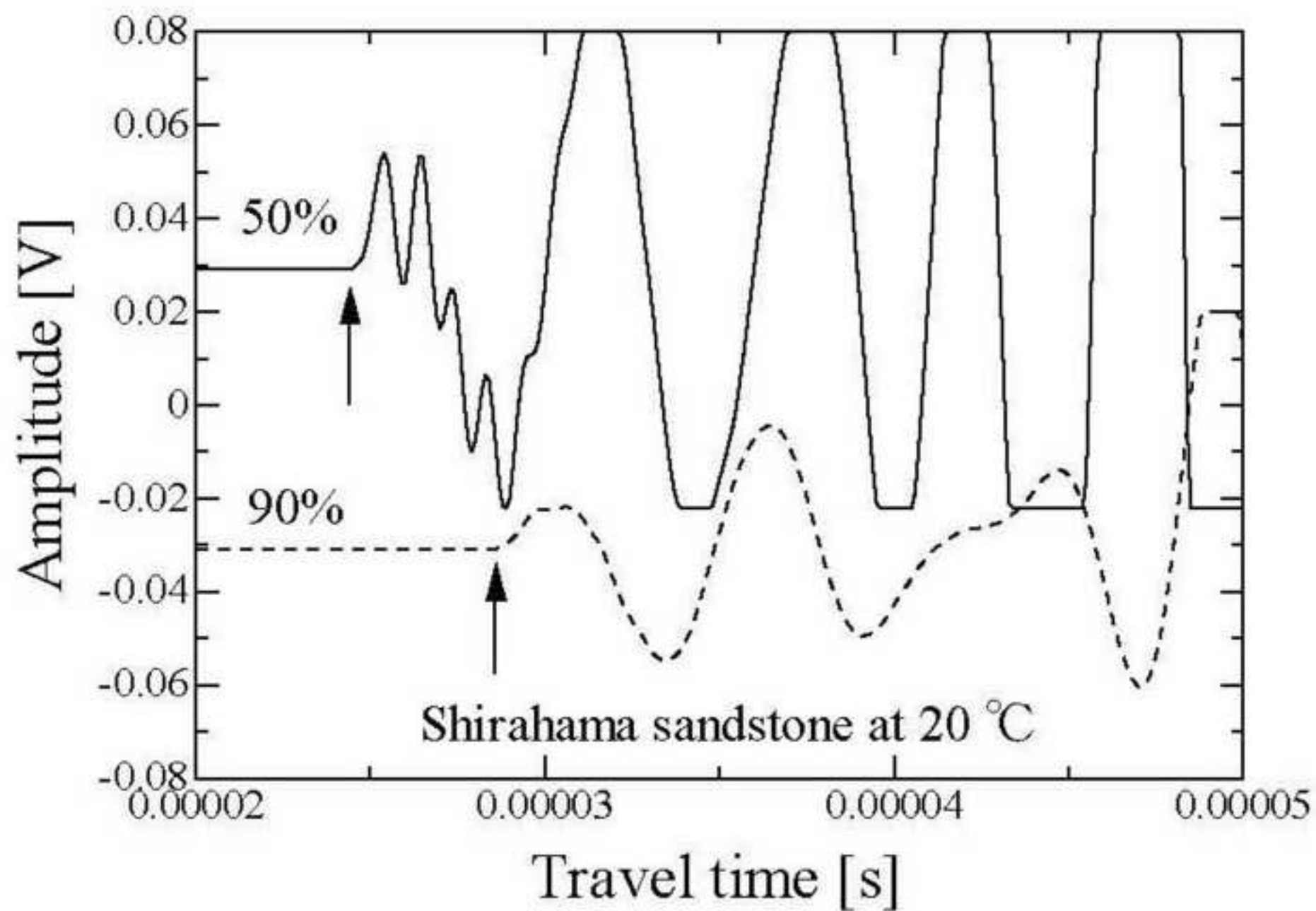


Figure4e

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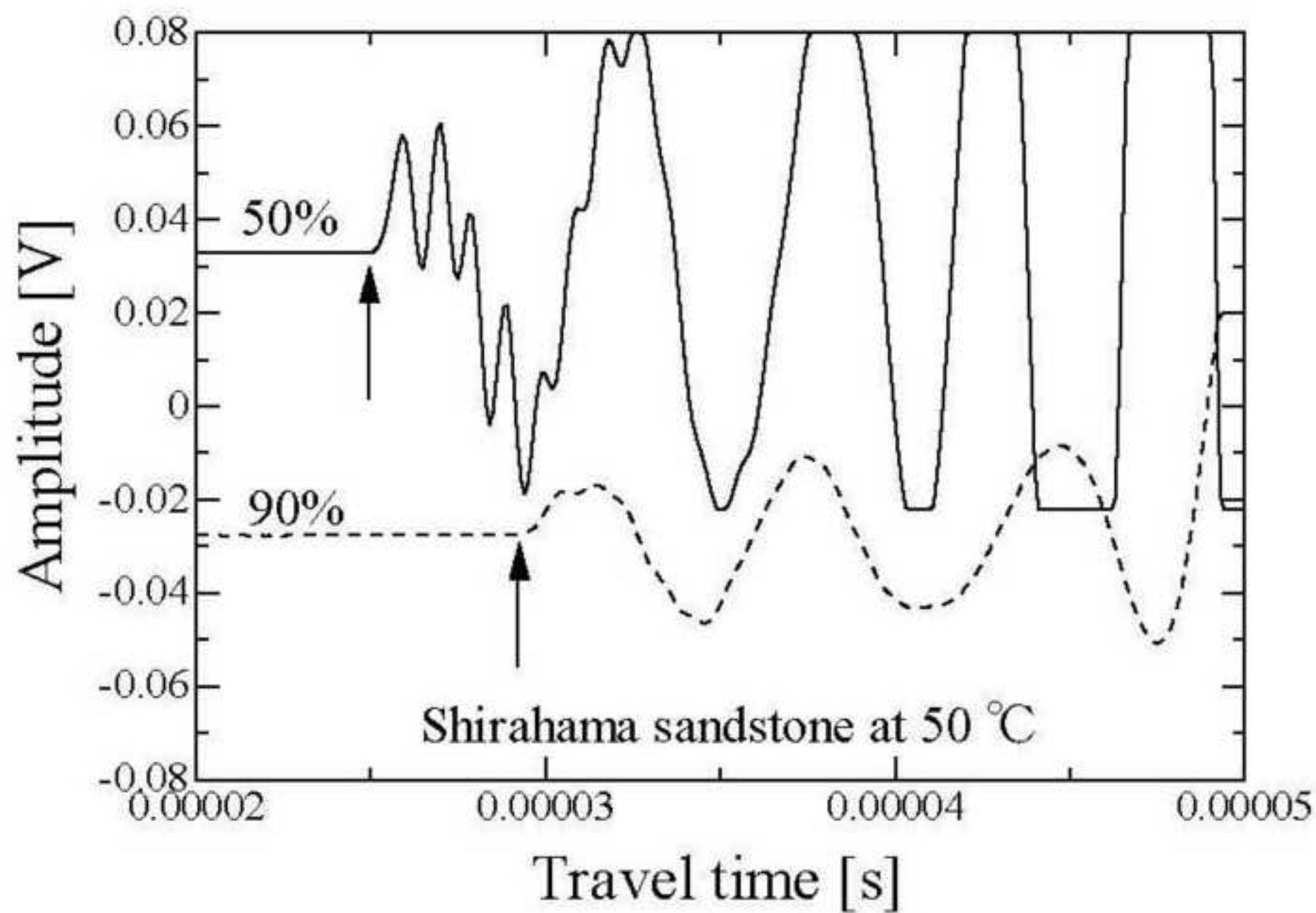


Figure4f

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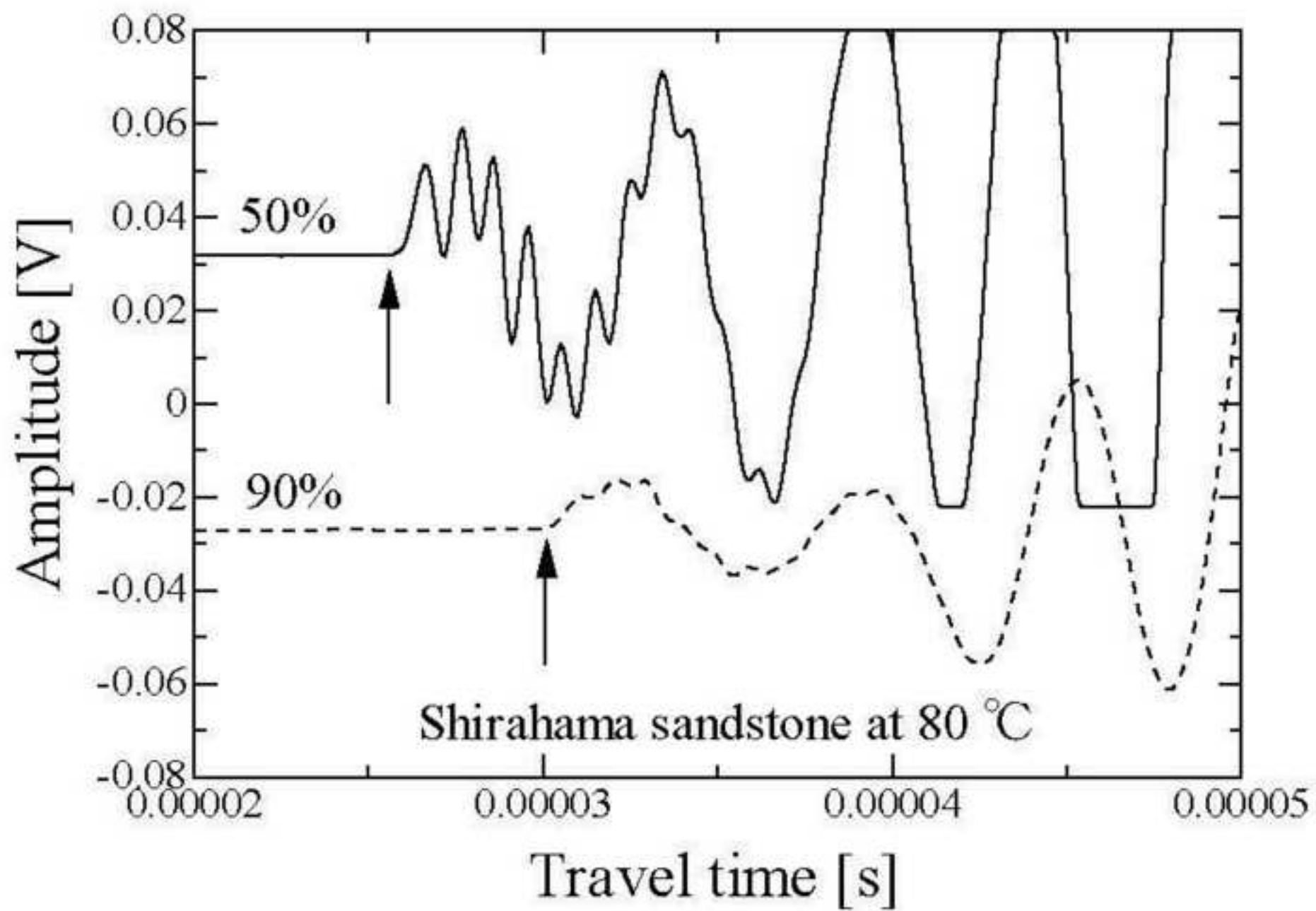


Figure4g

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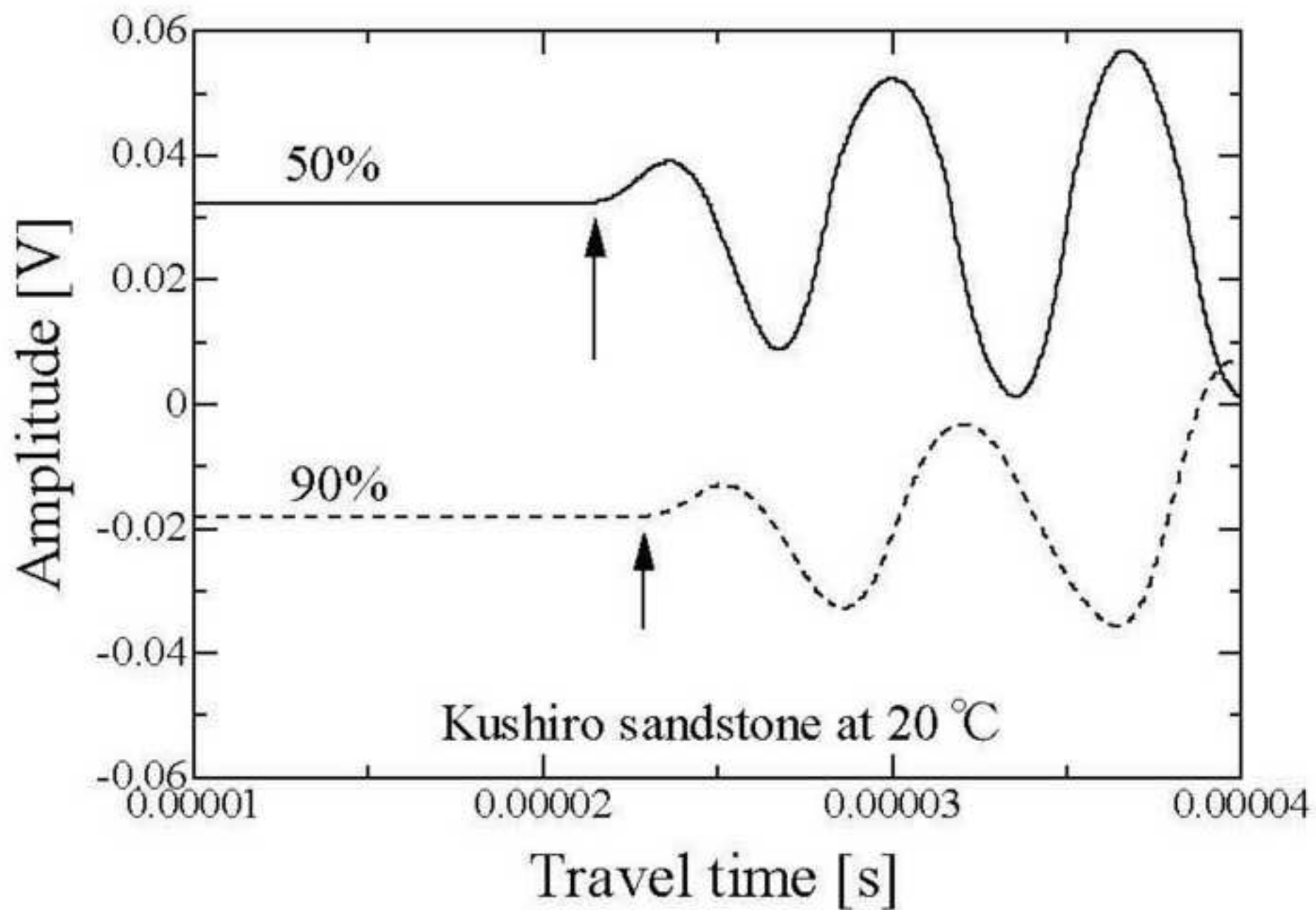


Figure4h

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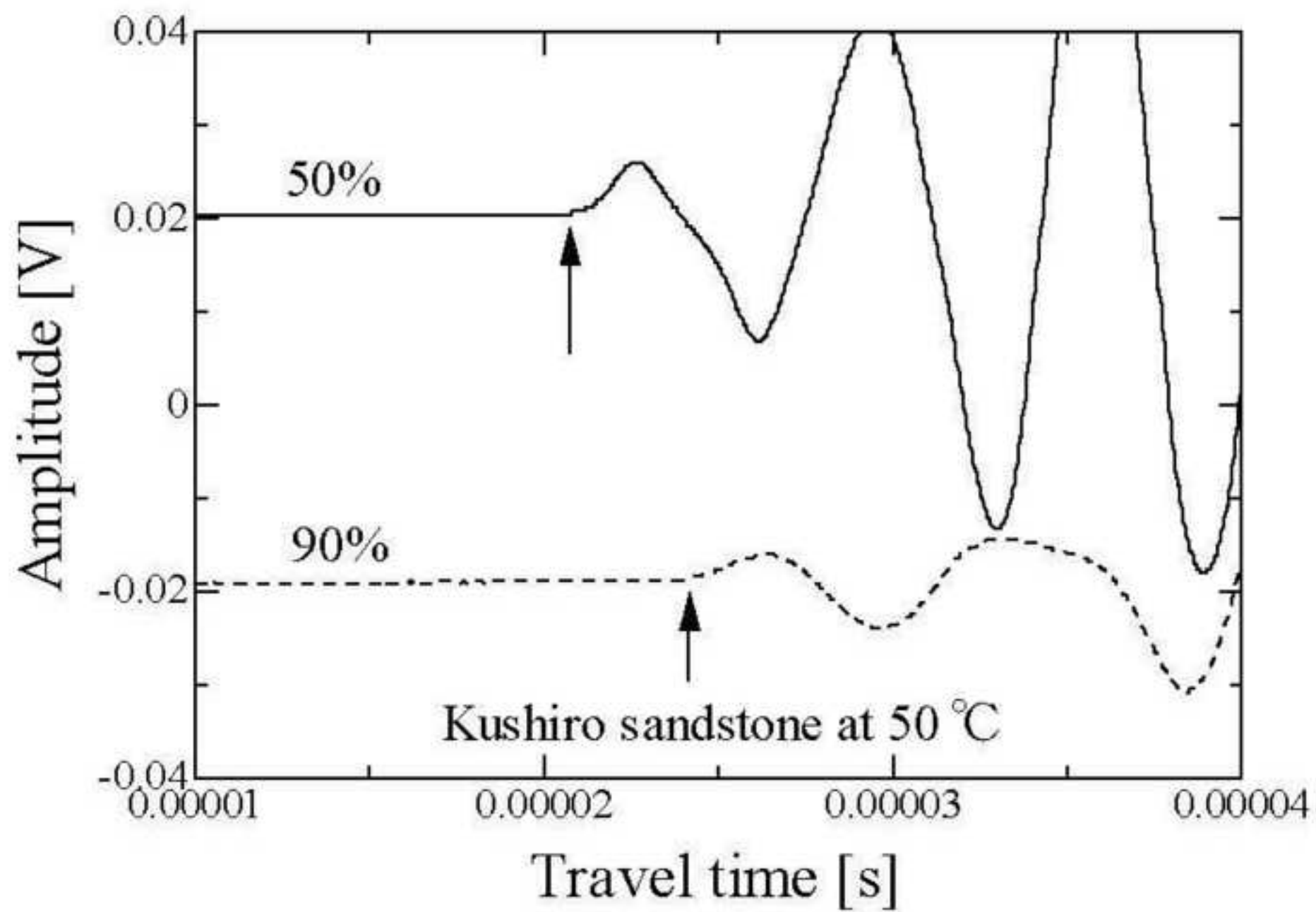


Figure4i
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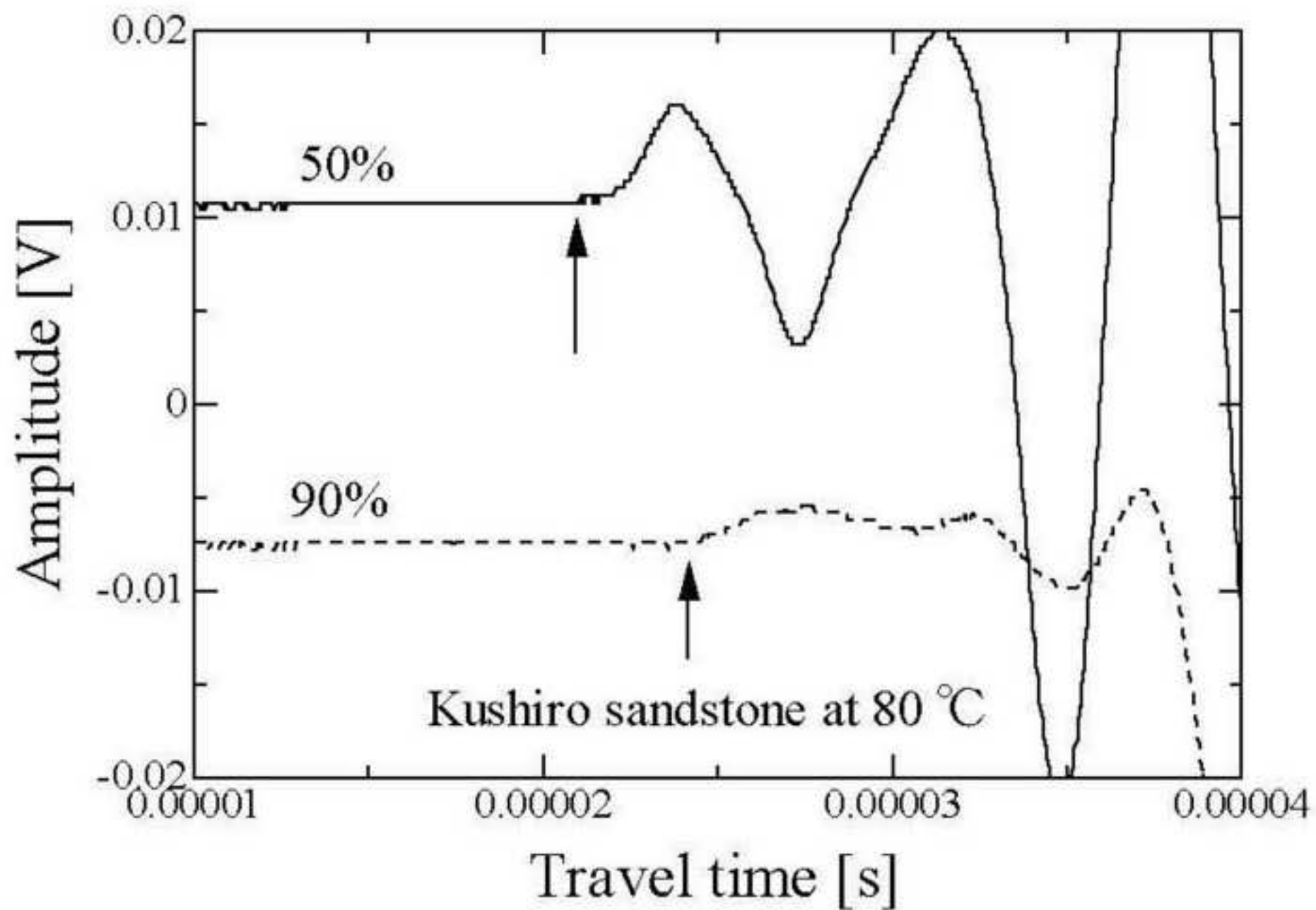


Figure4j

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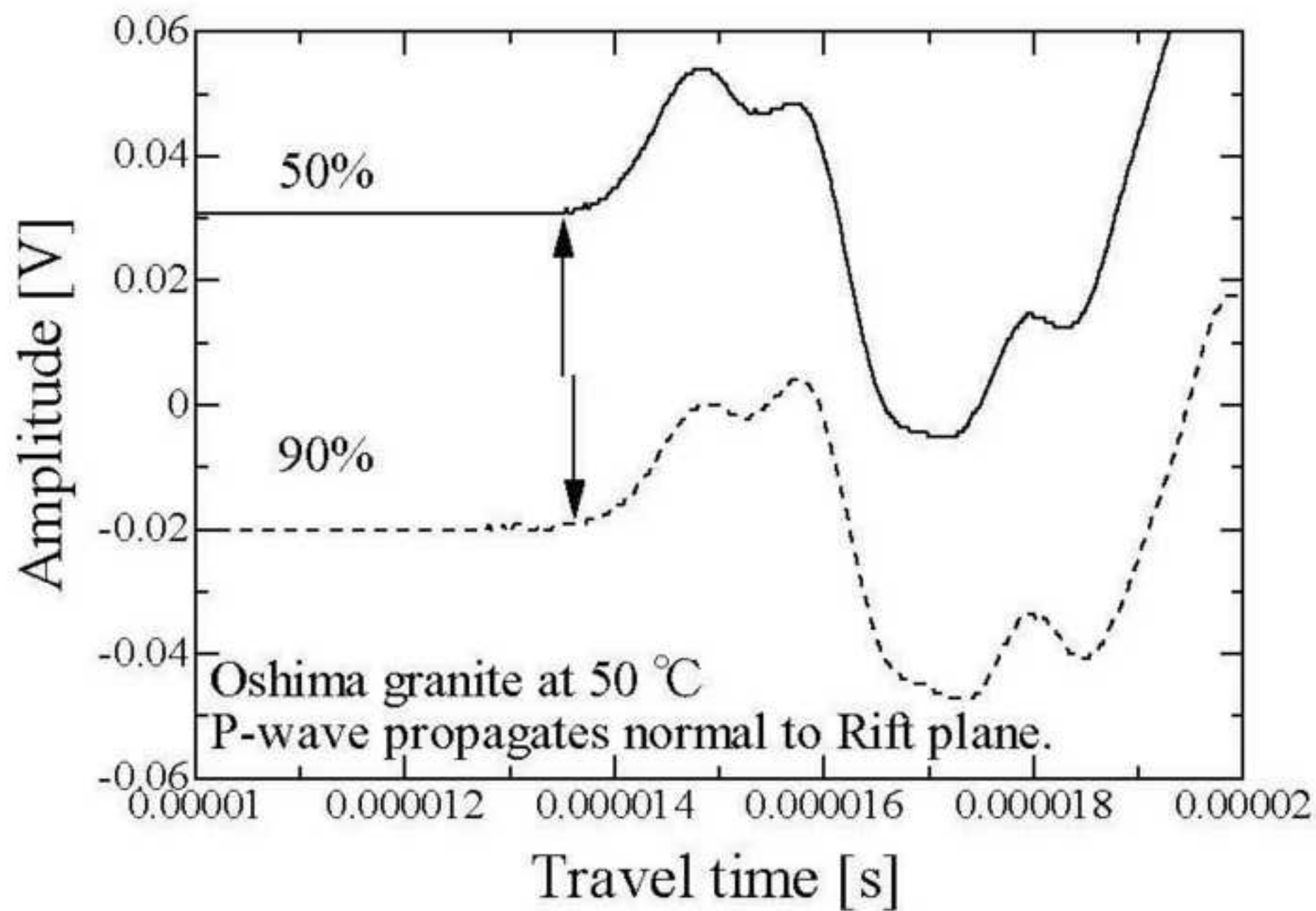


Figure4k

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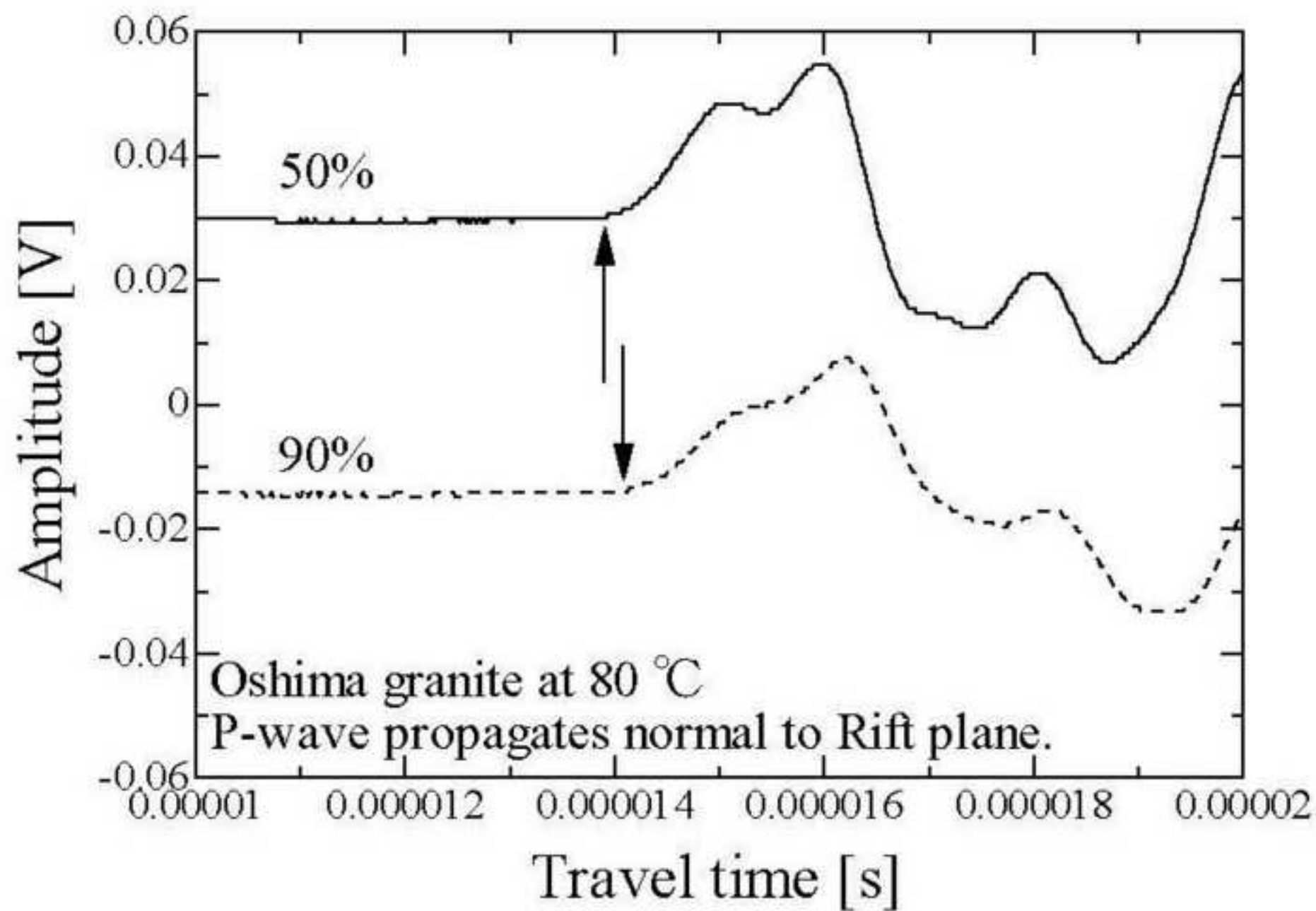


Figure41

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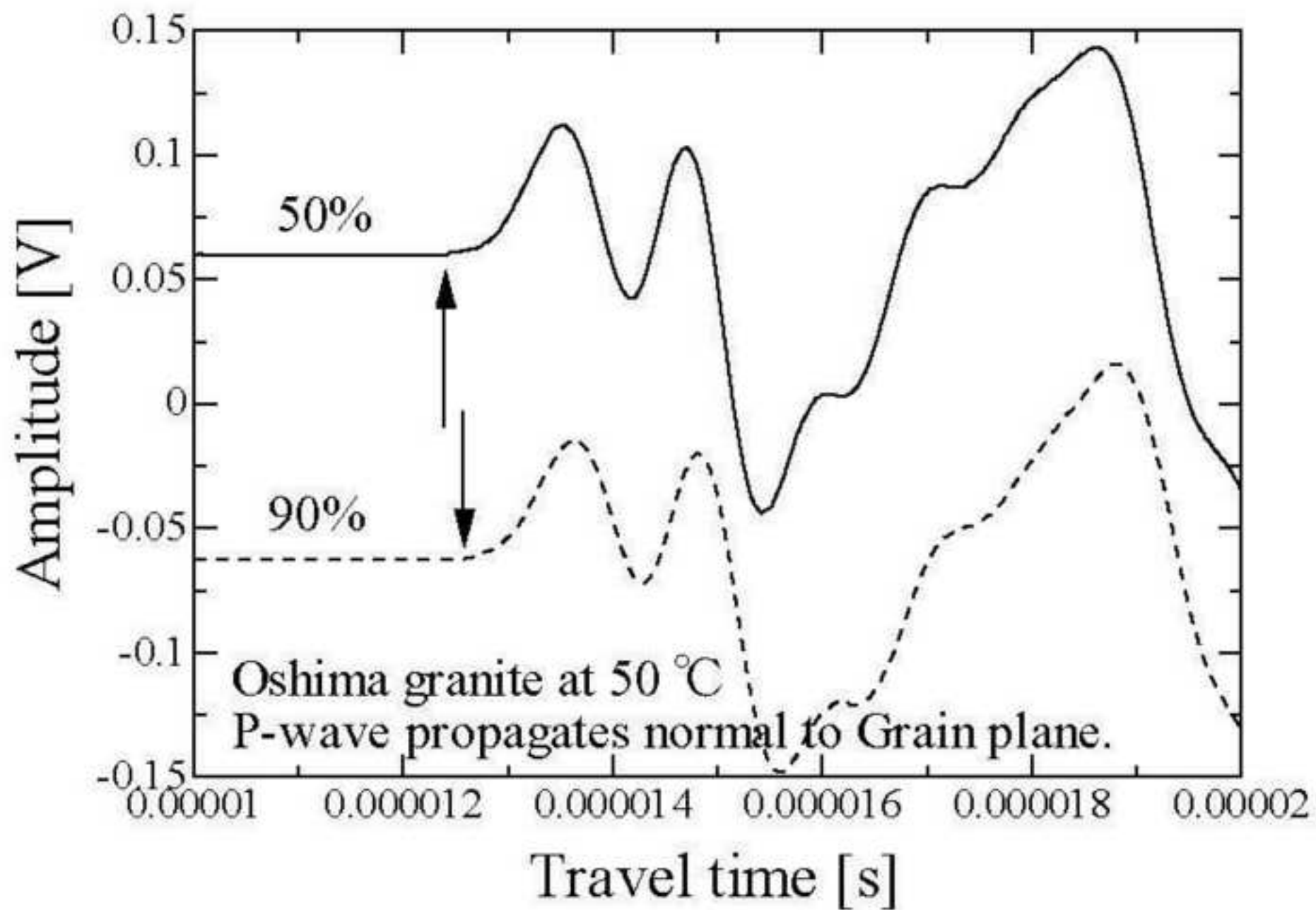


Figure4m

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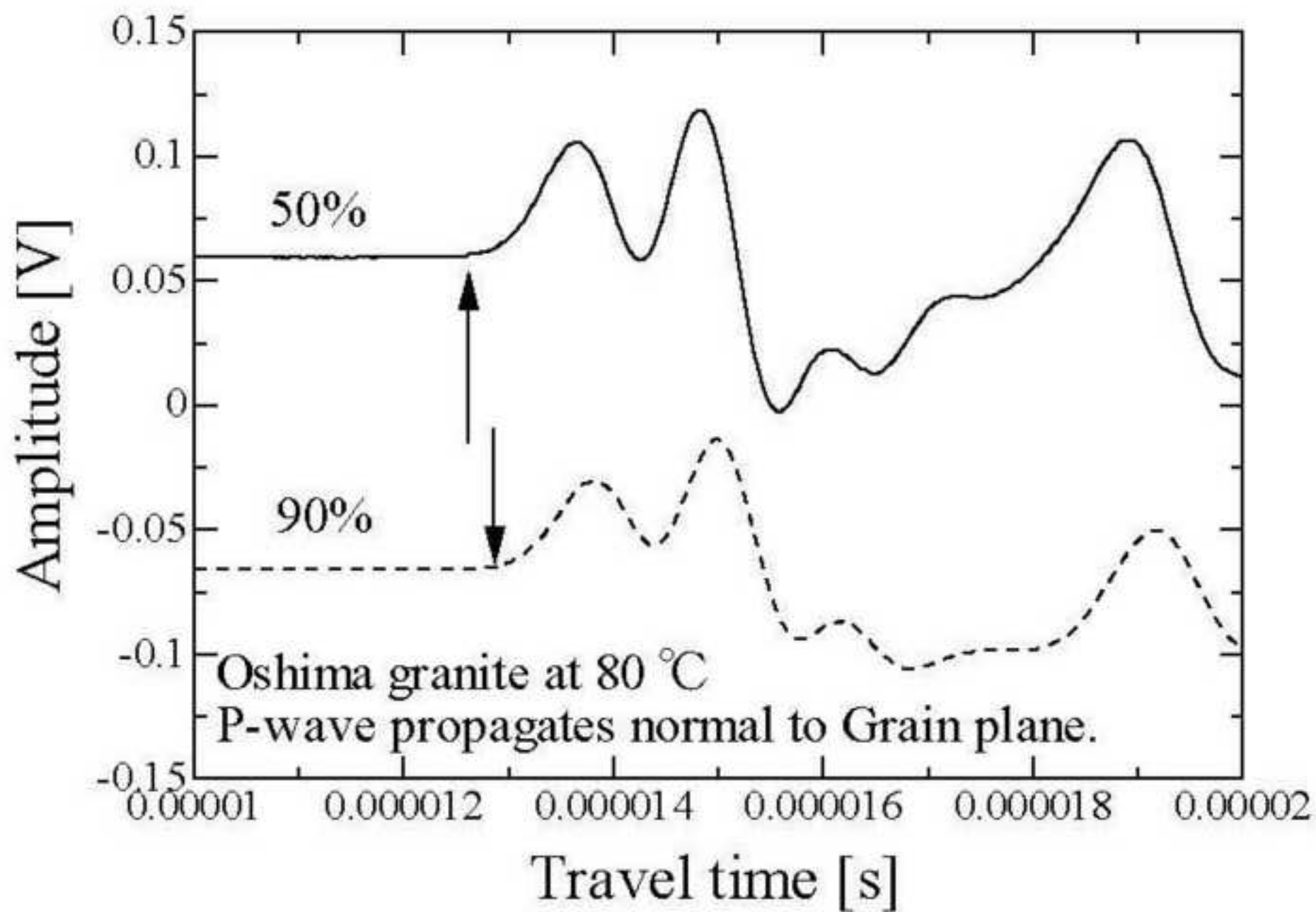


Figure4n

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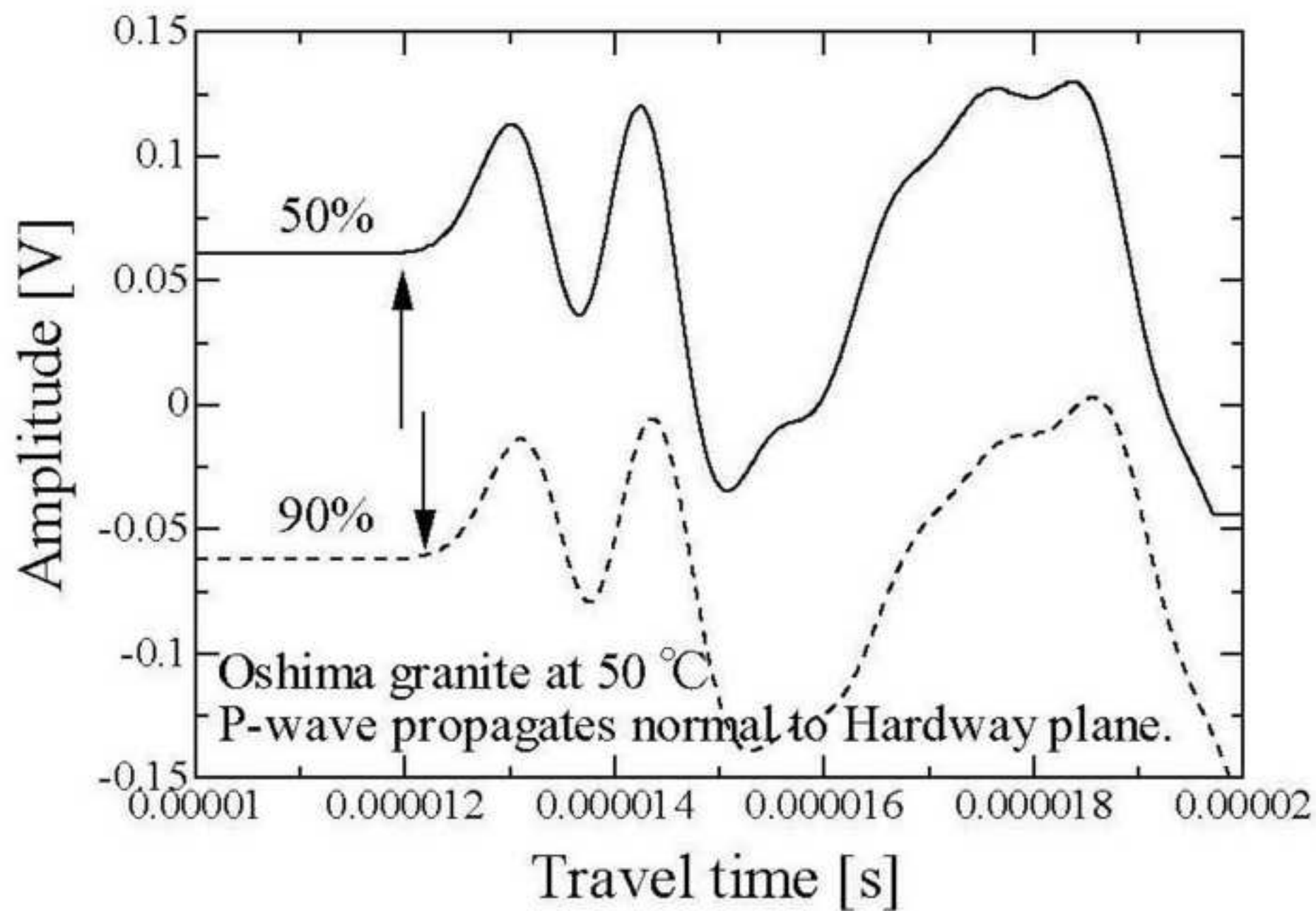


Figure40

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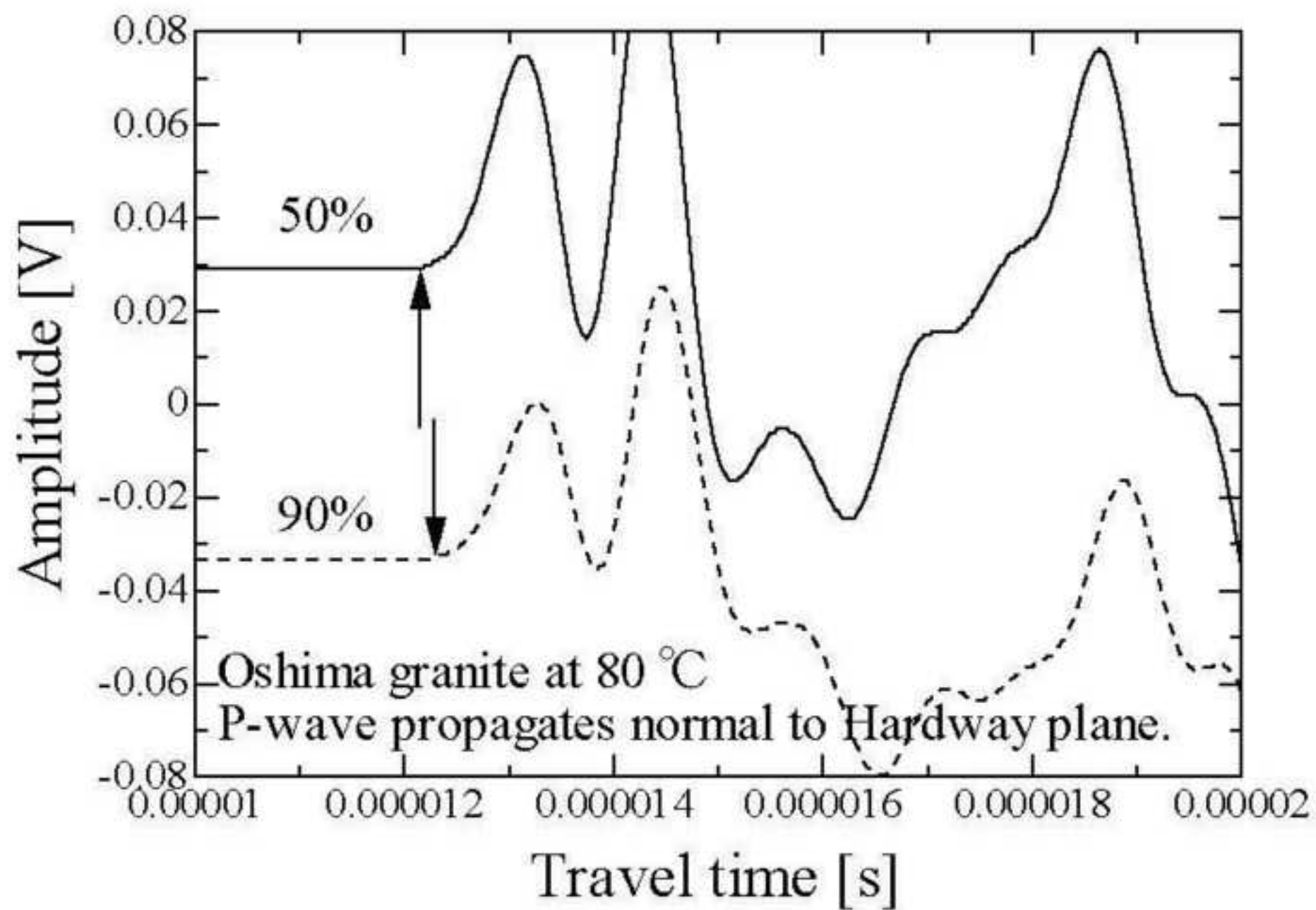


Figure5a

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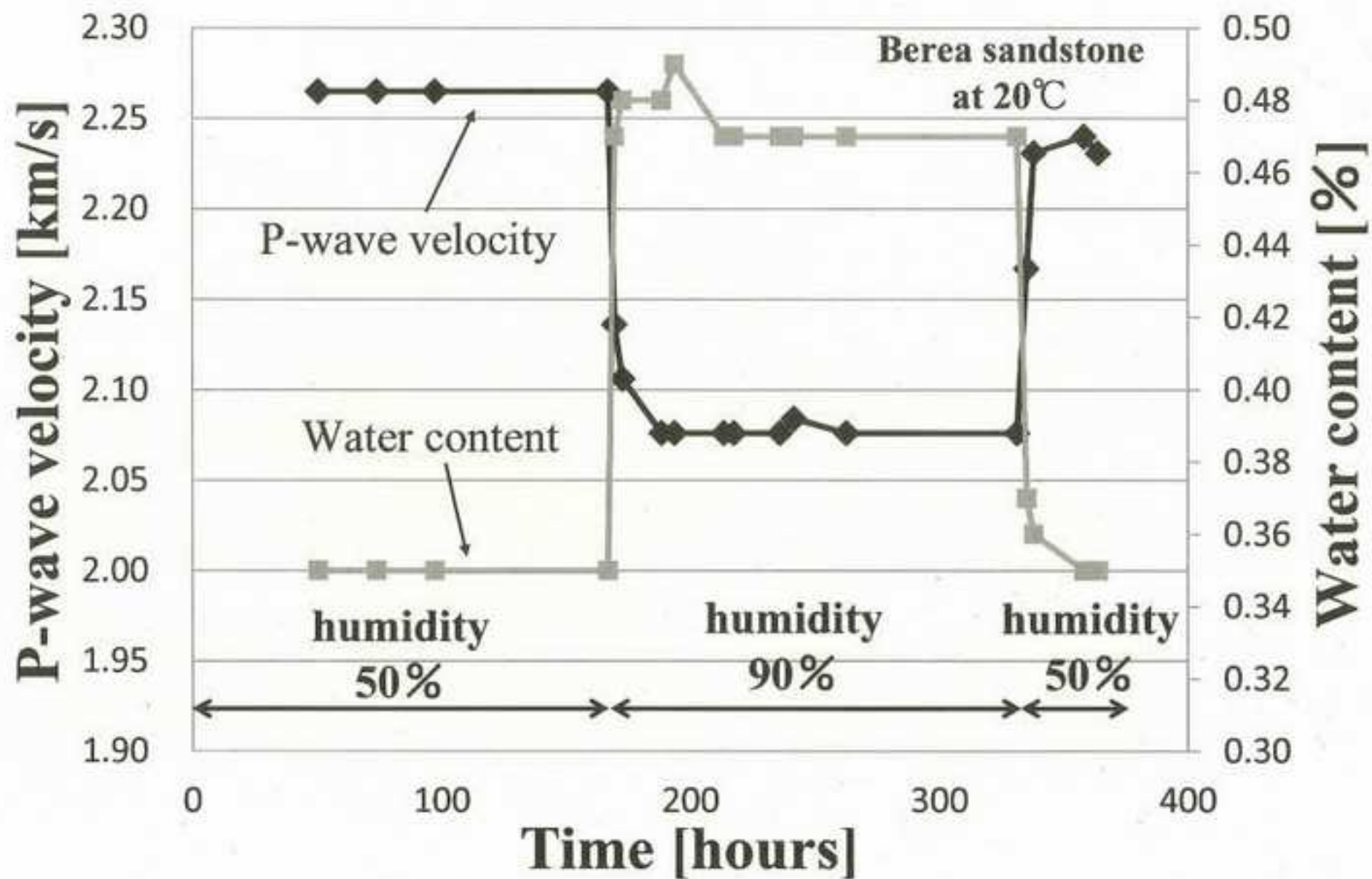


Figure5b

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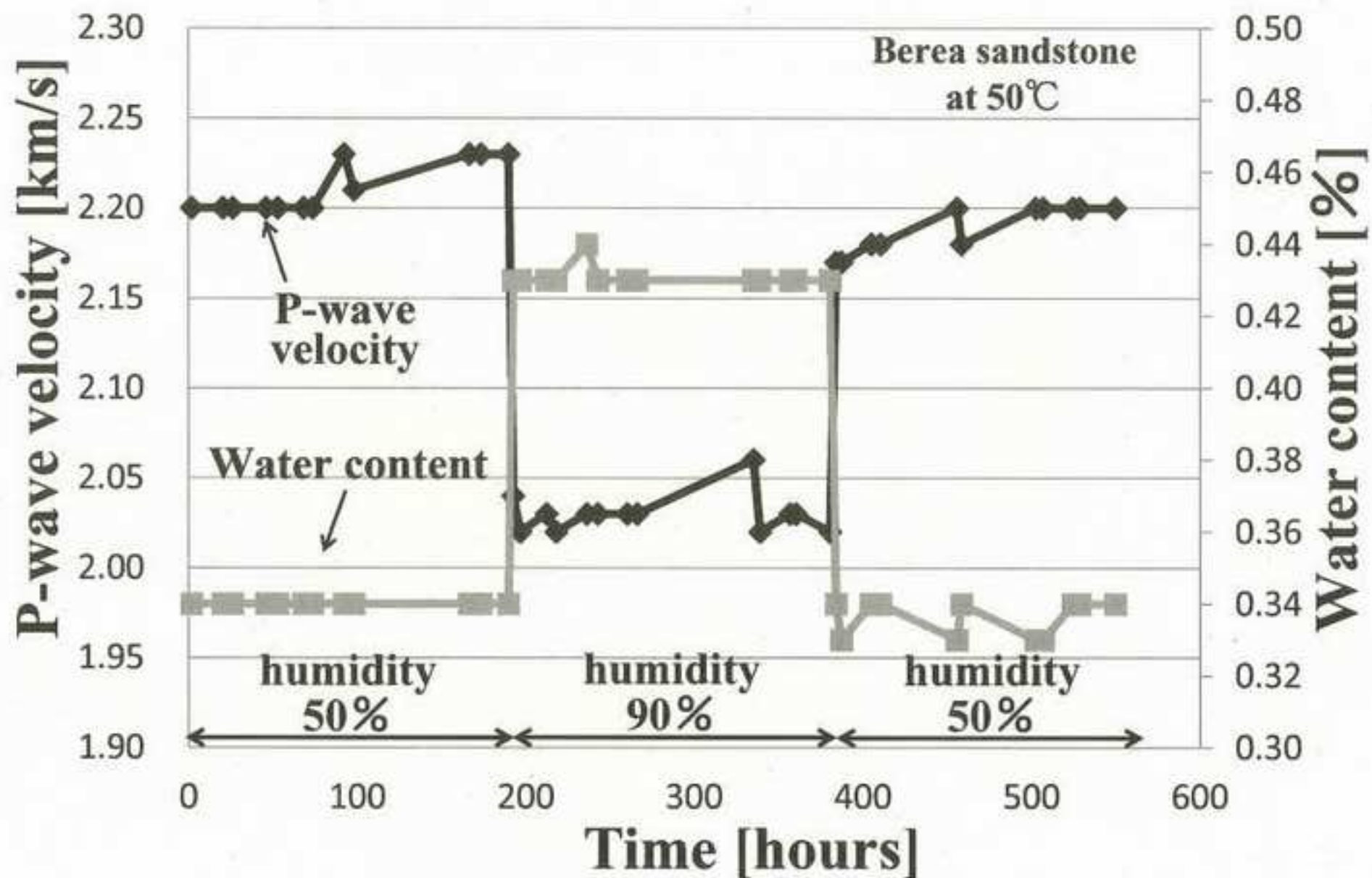


Figure5c
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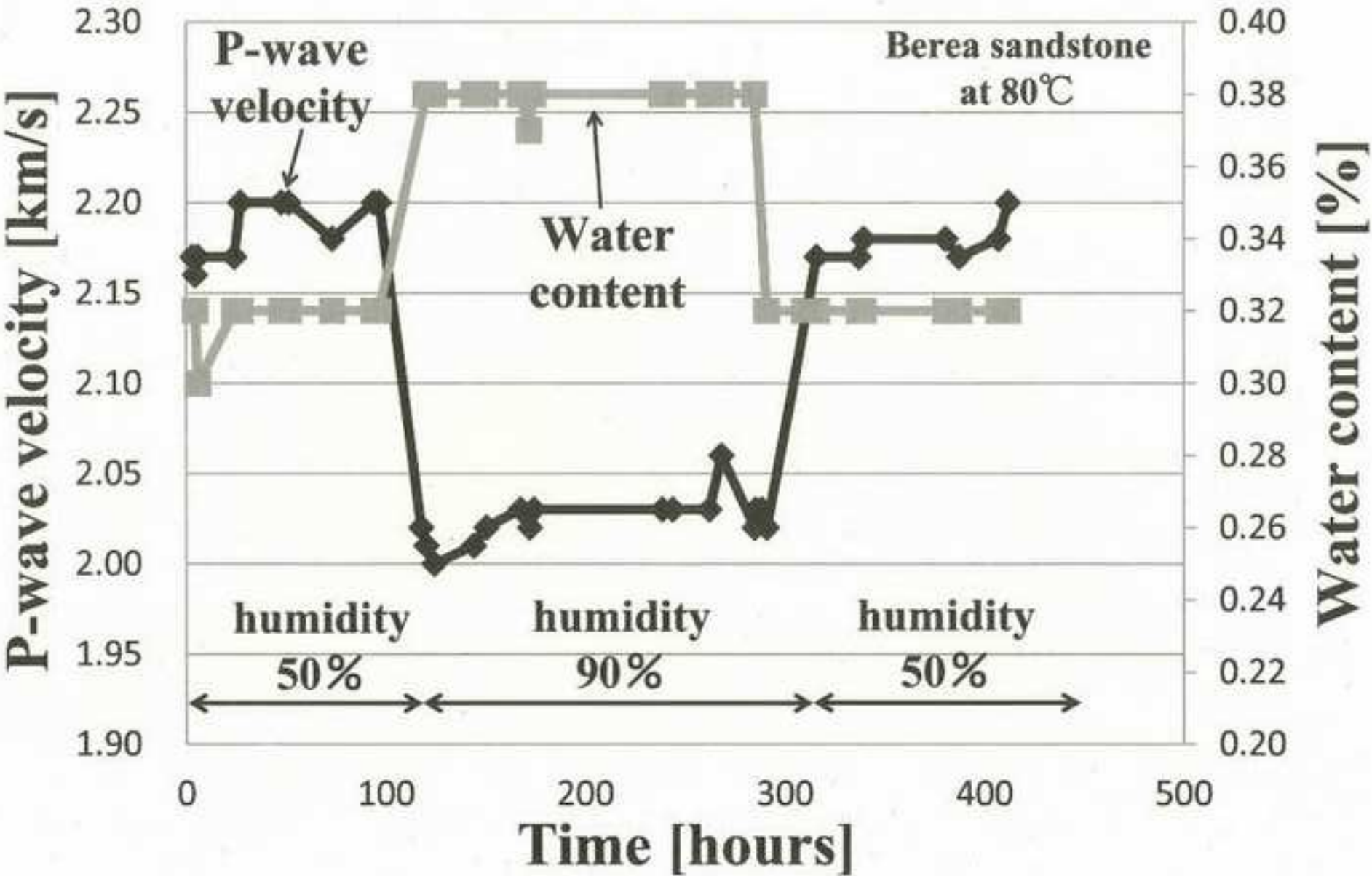


Figure6a

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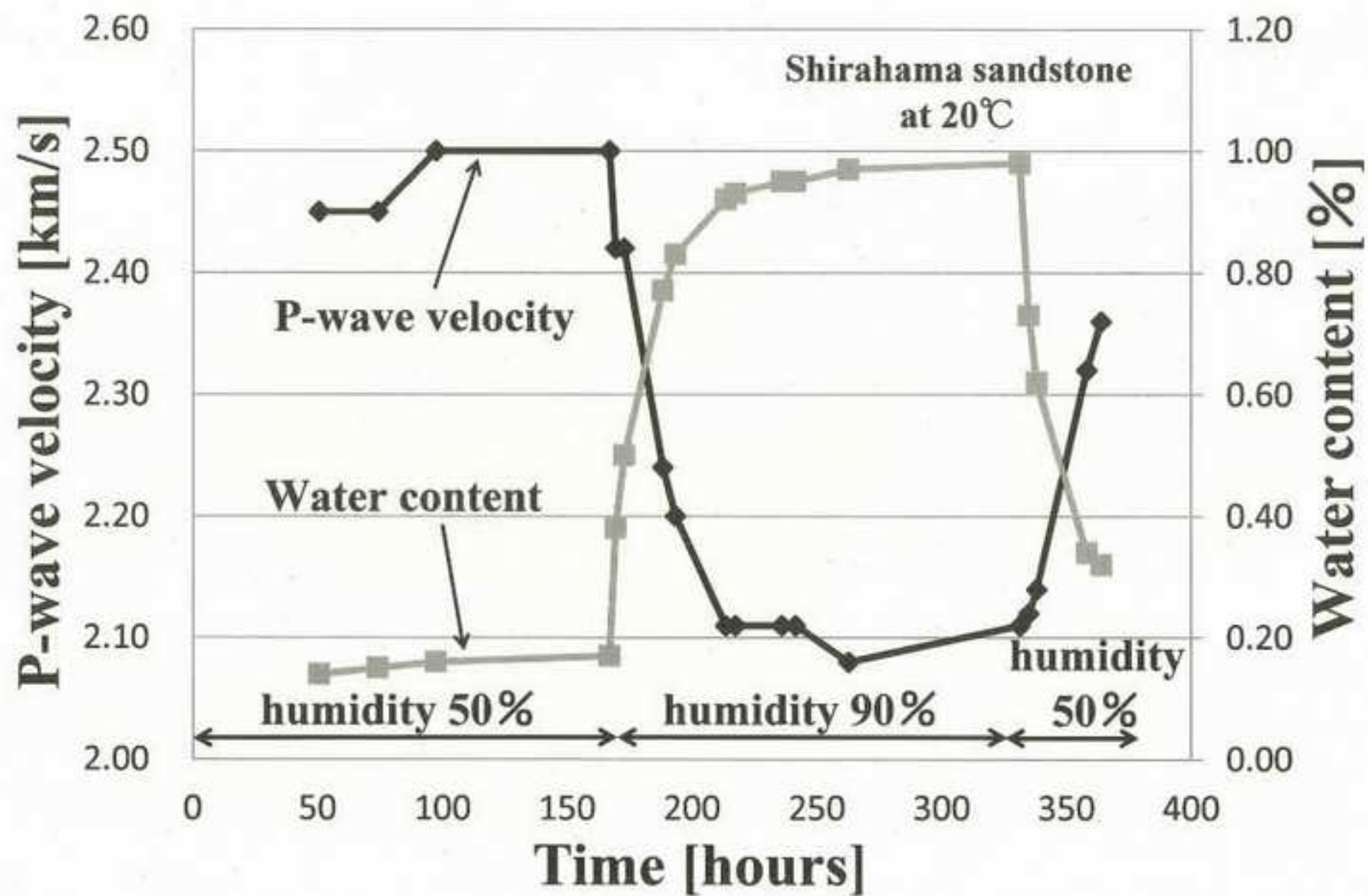


Figure6b
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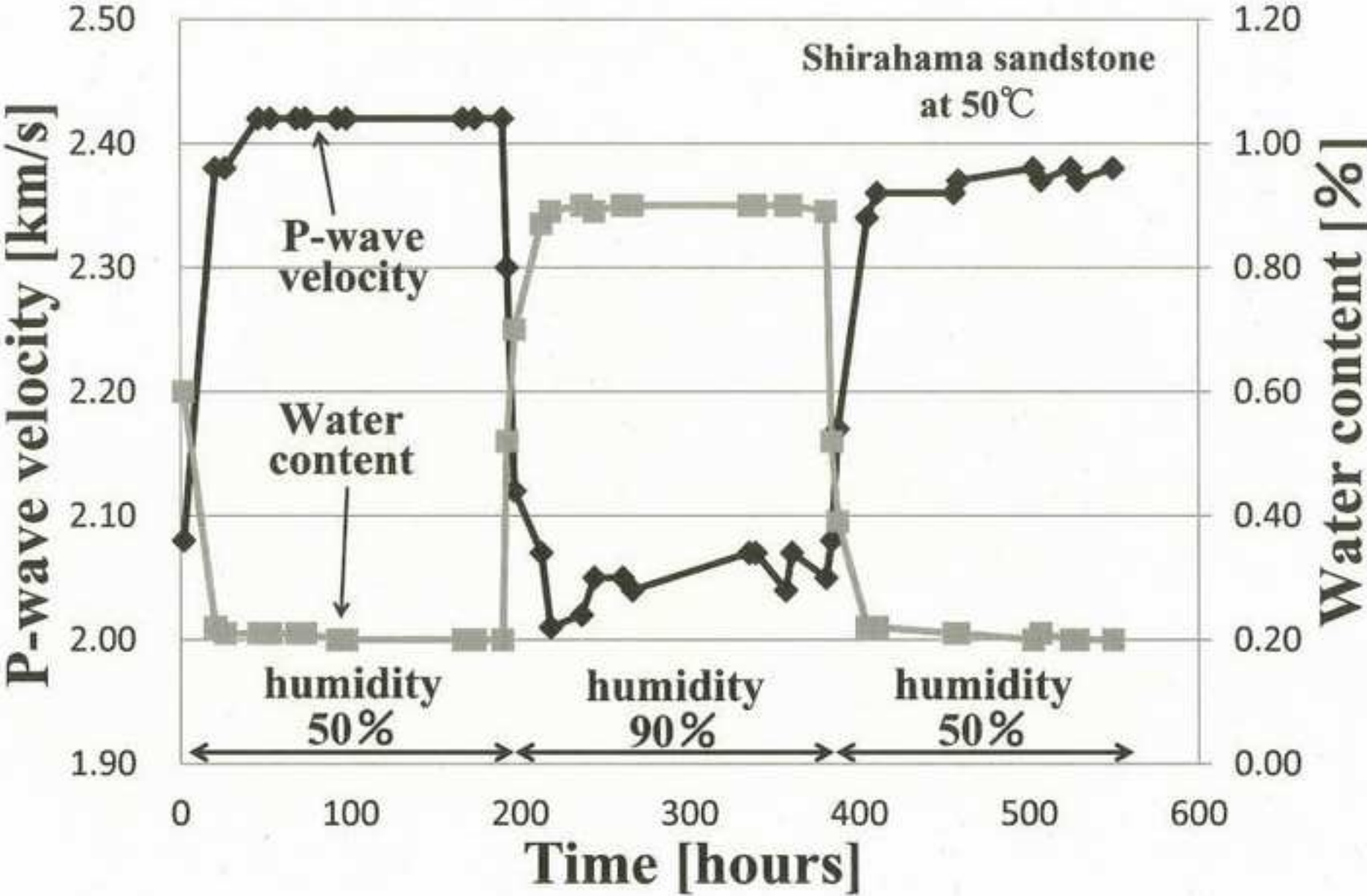


Figure6c
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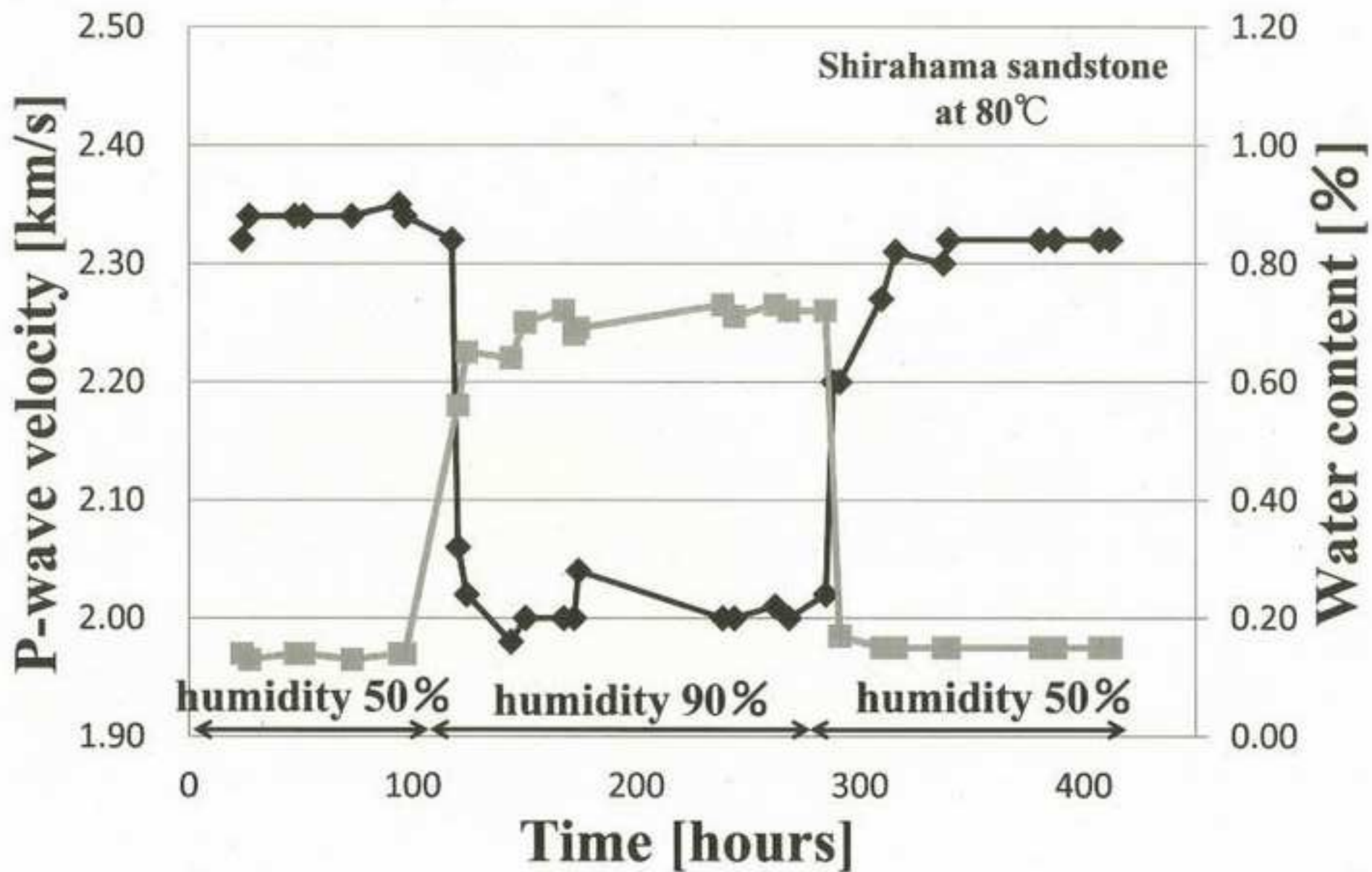


Figure7a
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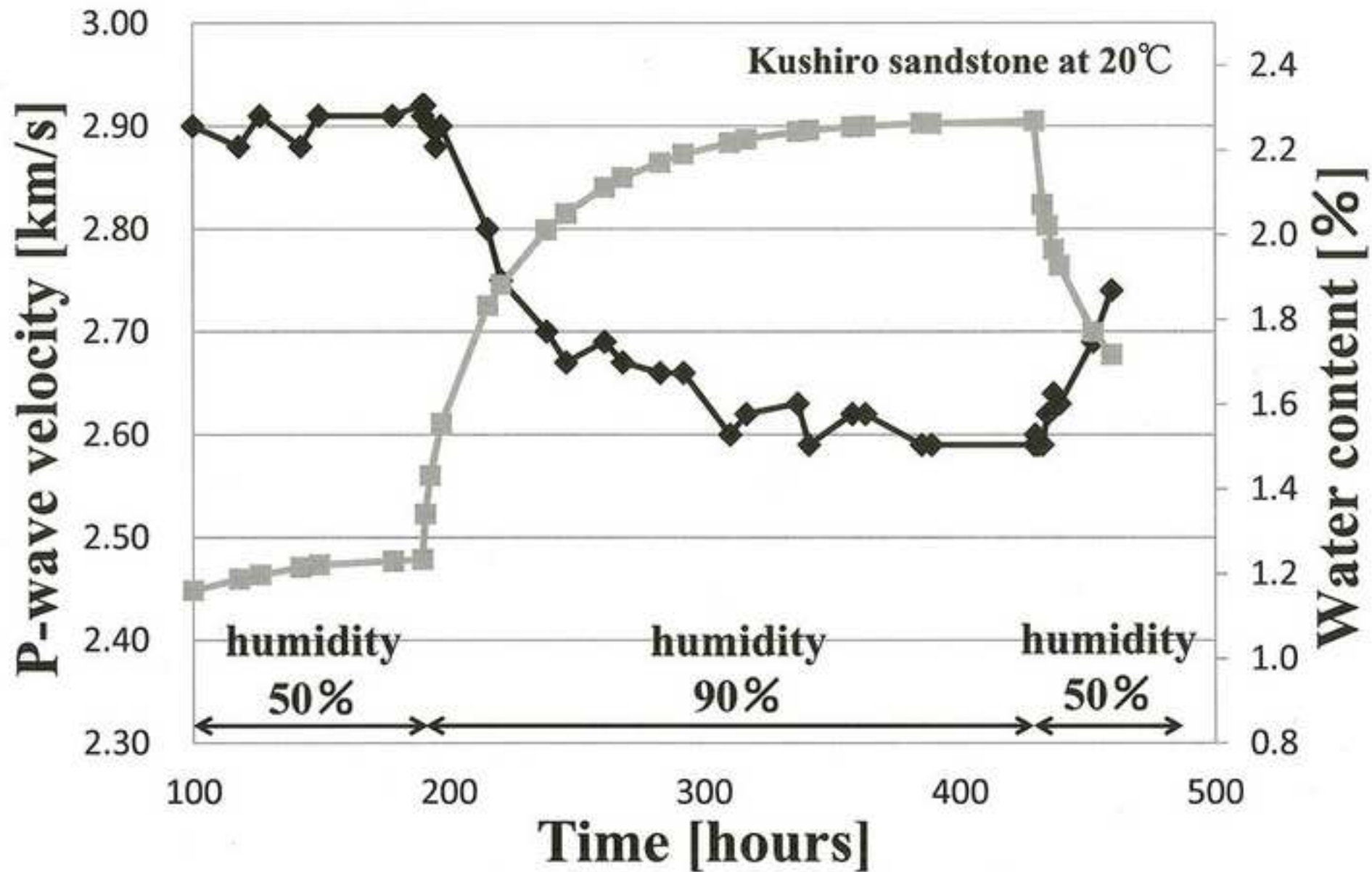


Figure7b
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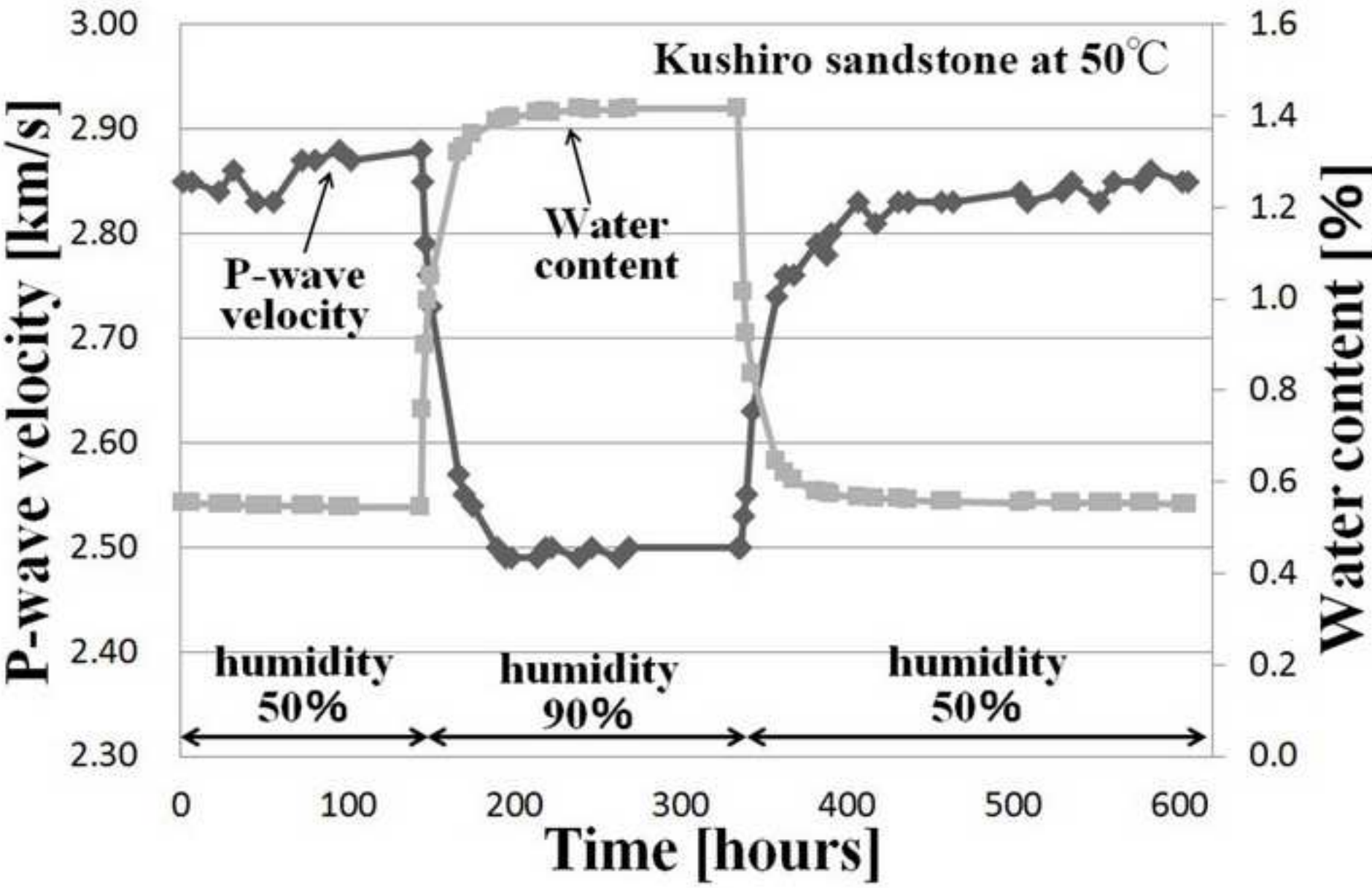


Figure7c
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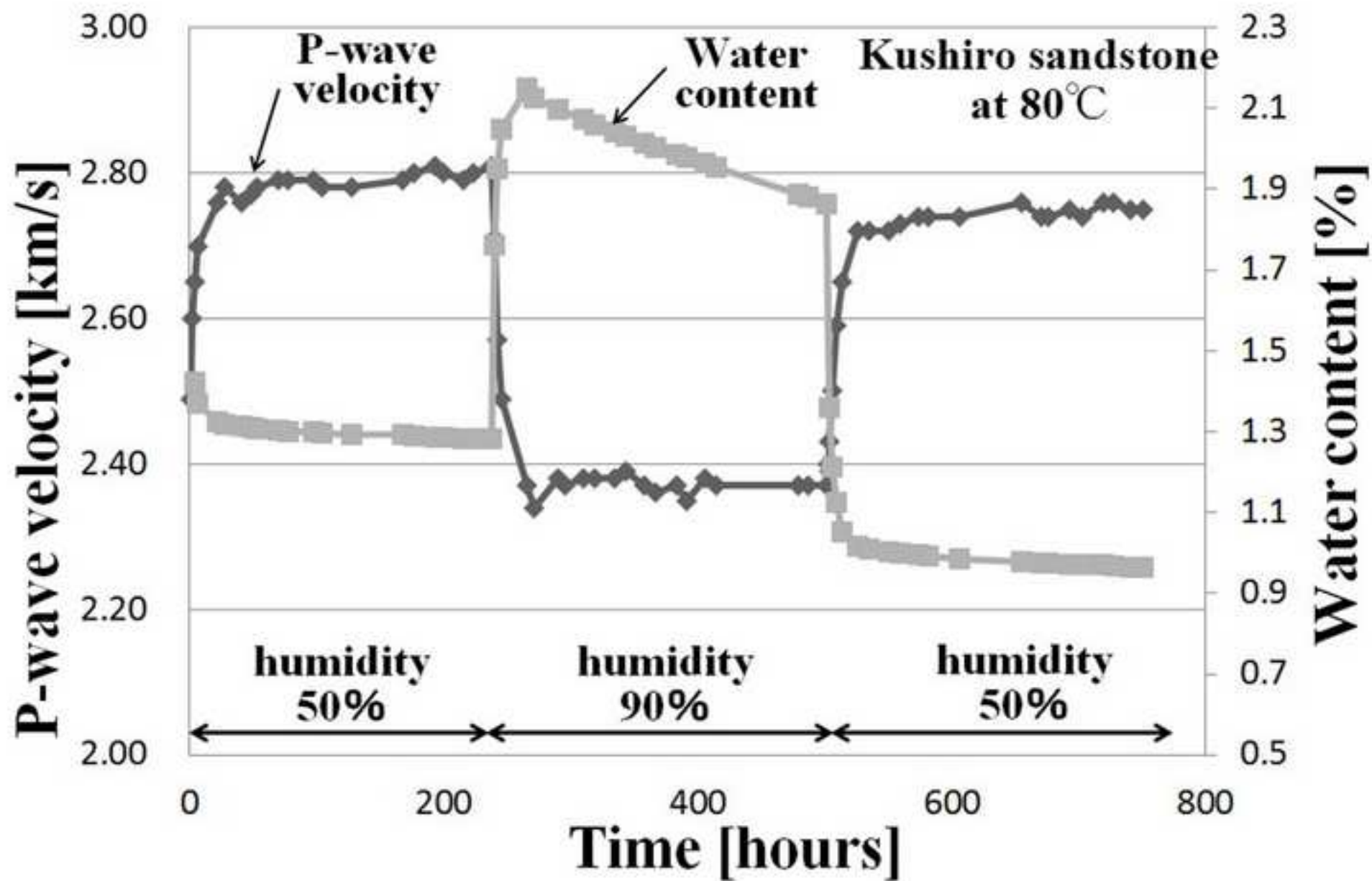


Figure8a

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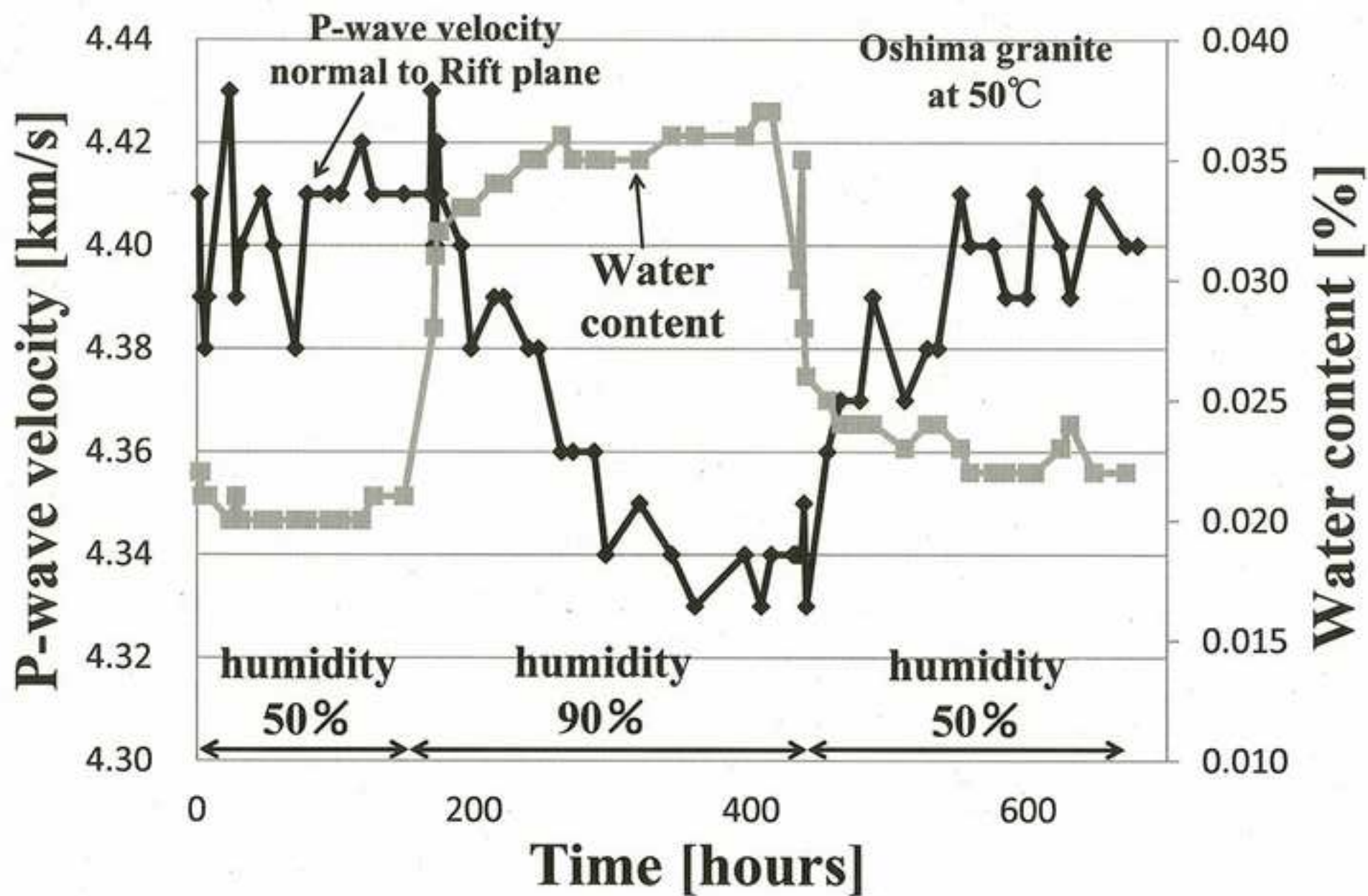


Figure8b

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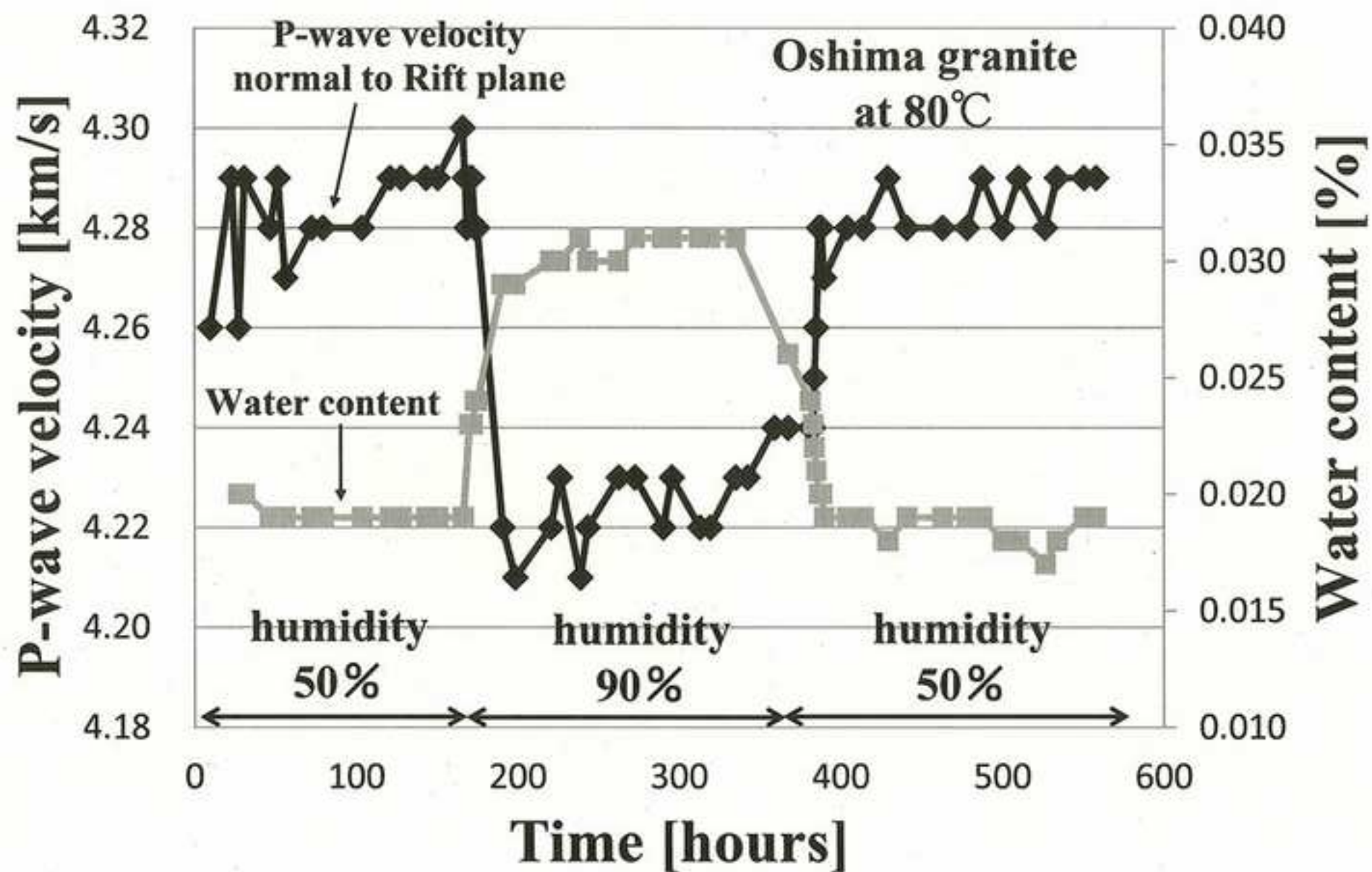


Figure8c
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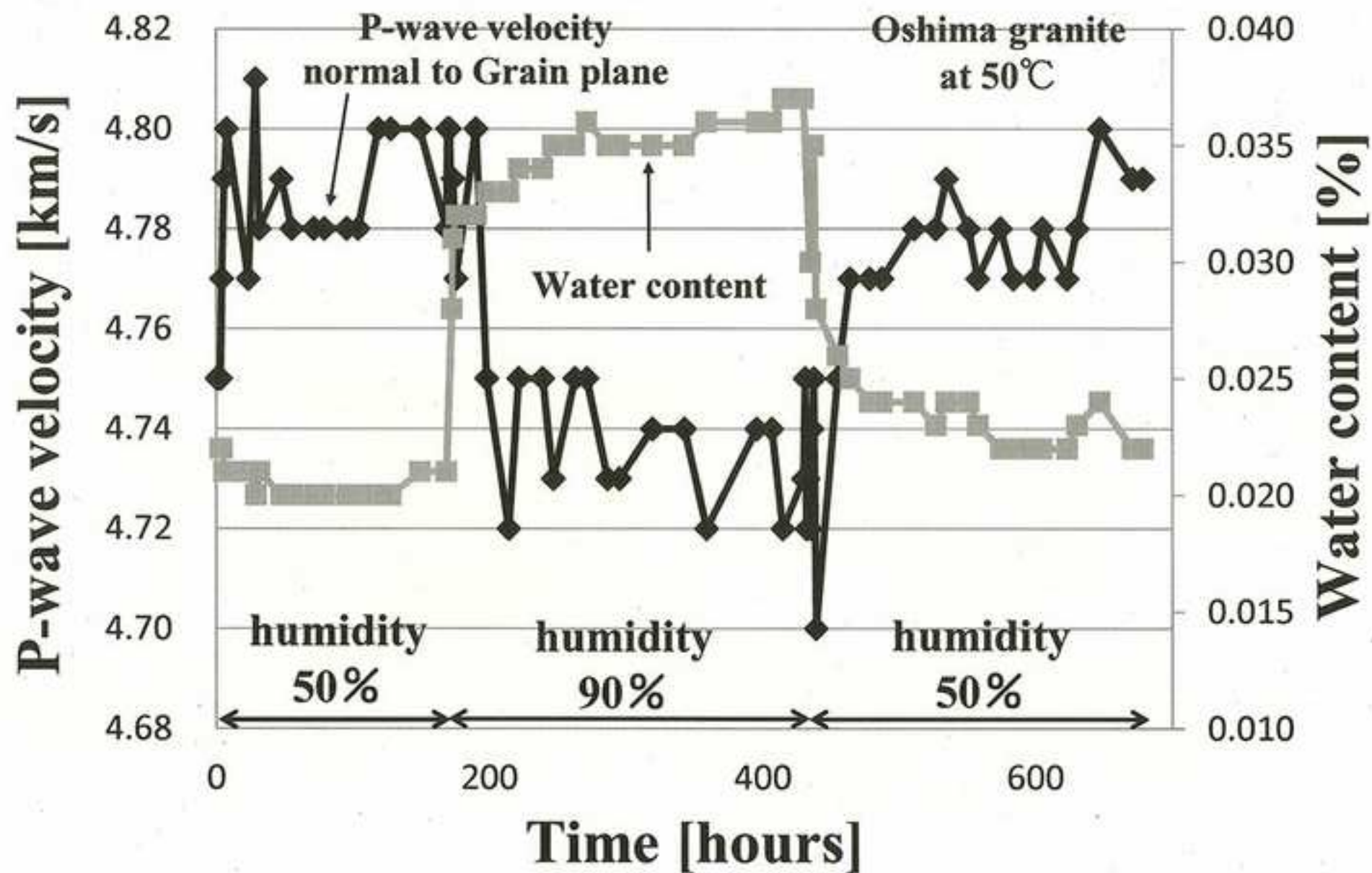


Figure8d

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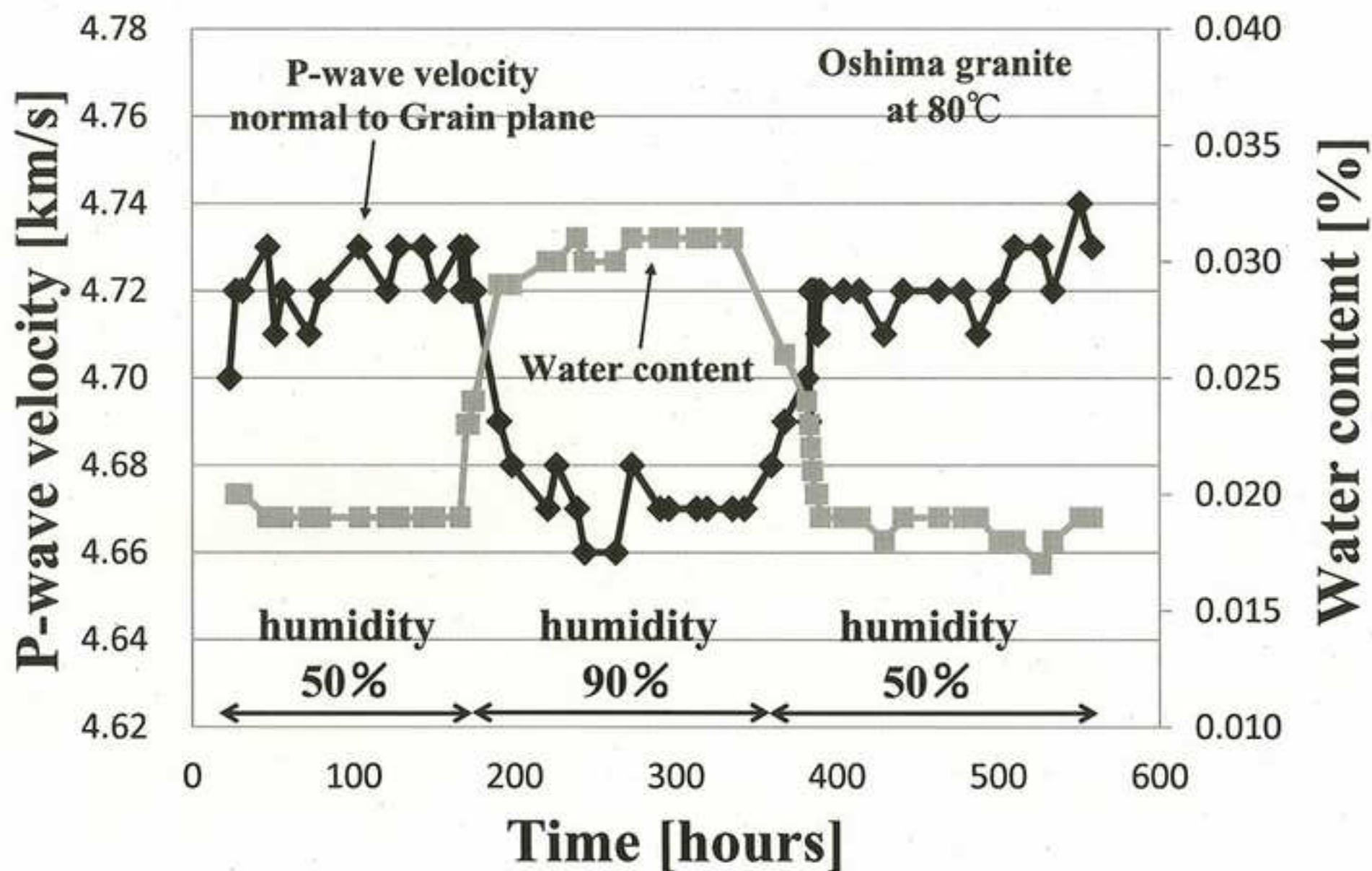


Figure8e
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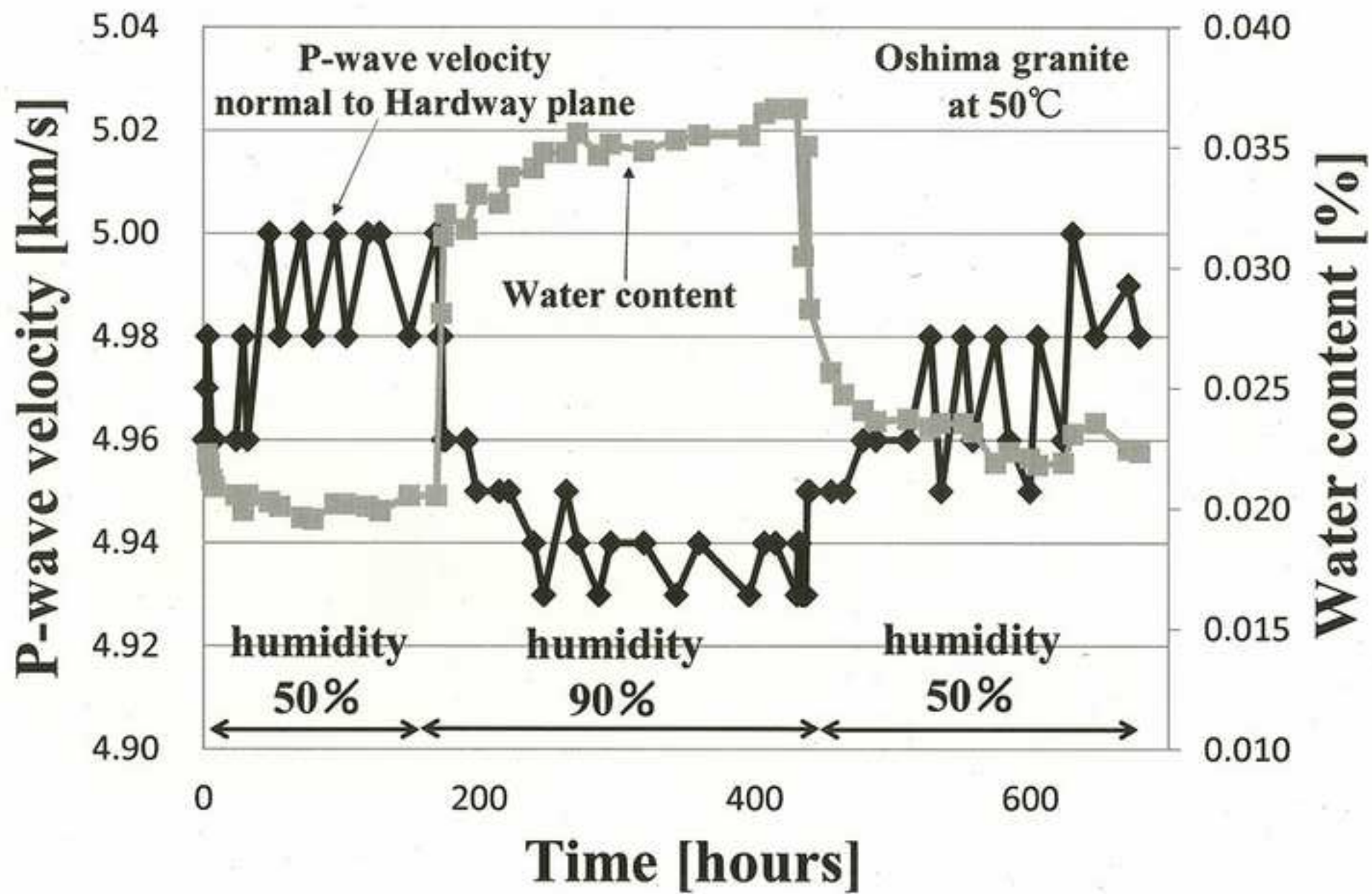


Figure8f
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