Climates That Cause Frost Shattering of Stone Objects

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SADATOSHI MIURA, TADATERU NISHIURA
Tokyo National Research Institute of Cultural Properties
MASAMI FUKUDA
Hokkaido University

ABSTRACT: The principles of protection from frost damage of stone relics kept in the open is discussed. Frost damage results mainly from heaving forces in the rock during freezing, the important factor being the rate of cycling and amplitude of fluctuation of temperature. After many freeze-thaw tests on tuff blocks, the principal material used for Japanese stone relics, the authors found that more than 10 cycles of −4 to +4°C/day causes rocks to break. The possible regions in Japan where this can occur are mapped from meteorological data. Treatments to protect stone materials in these regions are recommended.

[**KEY WORDS:** STONE, TUFF, DETERIORATION, TEMPERATURE, FROST SHATTERING, FREEZE-THAW TEST, JAPANESE CLIMATE]

1. INTRODUCTION

It is often said that Japan has a culture of paper and wood, whereas European countries have a culture of stone. Although this is largely correct there also exist many important ethnographic artifacts made from other materials. Among these are such important stone relics as *magaibutsu* (rock-cliff sculpture of Buddha), *doso-jin* (guardian deity), *komainu* (pairs of carved stone guardian dogs at the gate of Shinto shrines) and tumuli. These stone artifacts are in the open air and have long sustained damage from heat, cold or rain. Although some have been transferred to museums and are conserved in stable environmental conditions, many remain at their original sites. These will disintegrate rapidly unless soon adequately treated.

In Japan the study of the conservation of stone remains has progressed little, despite of their fragile characteristics. Indeed, a study is so difficult that it would not have been possible without recent progress in soil physics and resin production.

The authors have been conducting a study of the protection of stone remains from frost damage. General results have been reported [FUKUDA 1984; NISHIURA 1986], as has the mechanism of frost shattering of stone [FUKUDA 1983], and the effect of treatment with synthetic resins [NISHIURA, MIURA and FUKUDA 1984].

Fig. 1. *Magaibutsu* (rock-cliff Buddhas) of Usuki, Oita Prefecture.

Here we present the results of various laboratory and field experiments to evaluate the climate which causes frost shattering, [MIURA and FUKUDA 1985]. From the results we have prepared a tentative climatic map of areas in Japan where stone remains are susceptible to frost shattering.

2. FROST DAMAGE TO STONE

Physical, chemical and biological types of stone disintegration are recognized. Typical are: (1) frost shattering caused by the repetition of freezing-thawing of water contained within rocks; (2) flaking caused by recrystallization of salts dissolved in water when it vaporizes from the surface of rocks; and, (3) cracks or stains caused by roots or moss. A common misconception is that frost damage occurs only in cold regions. But our recent study indicates that it also occurs in such mild climates as those of central and southern Japan. Thus frost damage can be considered a major cause of the disintegration of stone remains in Japan.

Frost damage results principally from heaving forces in rocks during freezing [FUKUDA 1984]. Water migrates towards a freezing front through porous rocks, and accumulates at the front during freezing. The accumulated water forms icelenses in the frozen layer and causes rocks to break. This mechanism is analogous to frost heaving of soils.

The degree of heaving forces is controlled by three major factors: rock type, freezing conditions and water supplies. To assess the frost susceptibility of rocks, different types of rock specimens were measured for ultrasonic propagation velocity (V_p) and effective (open) porosity. According to Fukuda [1983], there is a distinct relationship between V_p and porosity (N). The formula is given experimentally as:

$$N = b \cdot exp(-a \cdot V_p)$$

where: $a = 0.64$ and $b = 83.69$ against the V_p of 400 kHz.

Weathering of rocks accompanies the increase and enlargement of pores in rocks. Thus rocks in a fresh state have low values of porosity whereas those in a well-weathered state have low values of V_p. According to an experiment using more than 30 different types of rocks from Hokkaido [FUKUDA 1984], rock specimens with a porosity of more than 20% and with a V_p of less than 2 km/sec were found to break easily after 10 cycles of freeze-thaw (−10 to +10°C 1 cycle/-day) (Fig. 2).

Fresh tuff, the rock most widely used for carvings in Japan, exhibits a porosity of nearly 40% and V_p of about 2 km/sec, whereas weathered tuff shows more than 40% and less than 1.5 km/sec. Thus stone objects made of frost-susceptible rocks require measures for preservation. Such measures should aim to prevent rocks from freezing (Fig. 3), to reduce the supply of water (Fig. 4) and to treat rocks with

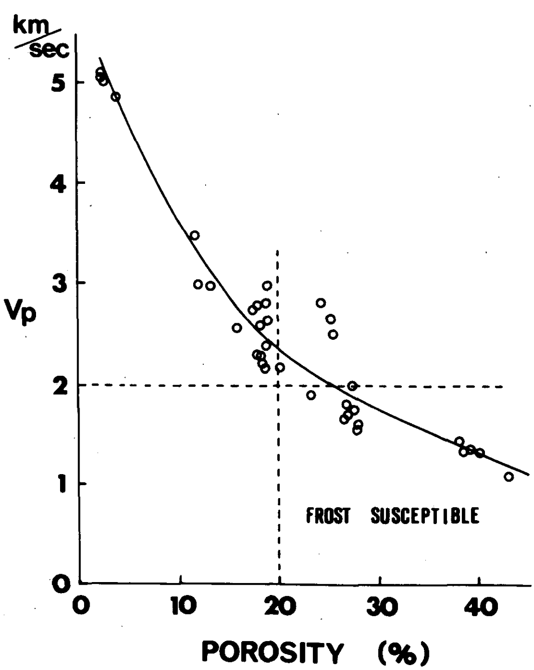

Fig. 2. The relationship between ultra-sonic propagation velocity (V_p) and porosity.

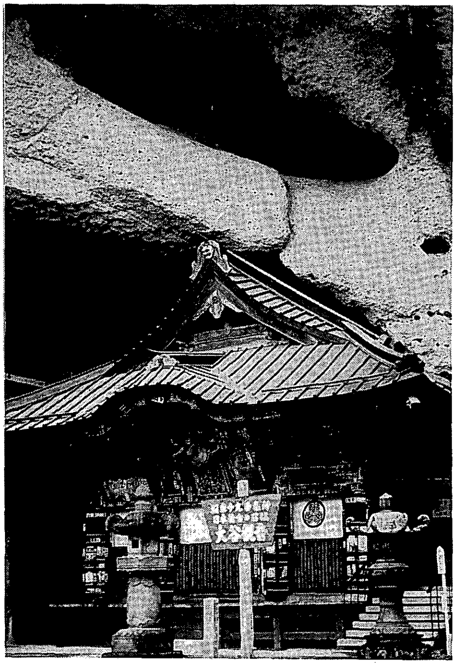

Fig. 3. Shelter for the rock-cliff Buddhas of Oya, Utsunomiya, Tochigi Prefecture, 10th–12th centuries.

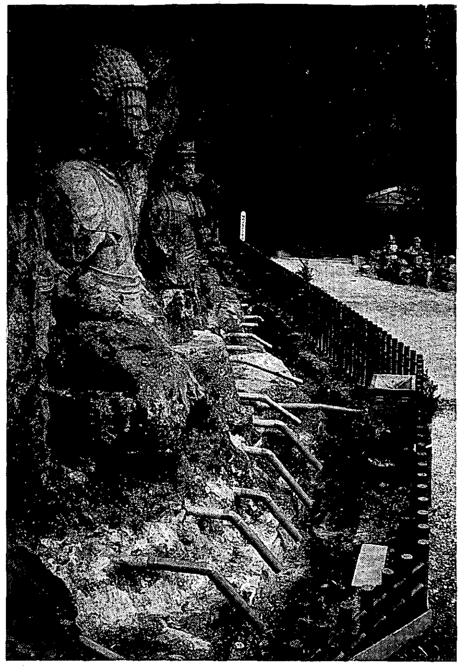

Fig. 4. Pipes and drains for the rock-cliff Buddhas of Usuki, Oita Prefecture.

synthetic resins. If all three factors are encompassed restoration work will be perfect, although very expensive.

3. RELATION BETWEEN TEMPERATURE CHANGE AND FROST SHATTERING OF ROCK

To evaluate the freeze-thaw condition, the amplitude of temperature changes above and below 0°C is of critical importance. In mid-winter water in bedrocks freezes to a certain depth. When the daytime surface temperature is above 0°C water in the surface zone of the rock melts. However, if the surface temperature is only 1/2 degrees above 0°C, the thawed part of the rock may be limited to the layer just close to the surface. Since rocks disintegrate by the thawing and the refreezing of water at certain depths, two experiments were conducted to determine the amplitude of temperature alternation above and below 0°C required to break stone objects.

The depth of freezing and thawing also depends on the length of a cycle of temperature alternation. If the cycle is long (*e.g.*, 1 cycle/year), thawing and freezing take place deep in rocks, with a small fluctuation of temperature around 0°C. As a result the rocks will be broken by frost shattering. In the experiments we examined the relation between frost shattering and daily temperature change (cycle/24 hours), because a daily change is more frequent (*i.e.,* more aggressive) than an annual change.

3.1 Dependence of Frost Shattering on Freezing Temperature

Specimens used were 5 cm cubes of tertiary tuff from Otaru (Hokkaido) with 50% porosity and 1.7 km/sec V_p. The specimens were placed in a plain vessel. A small quantity of water was poured into the vessel so that the specimens would be saturated with water during the experiment.

The experiment was accomplished with five series of freeze-thaw cycles. Each series included 10 cycles (1 cycle/day). The lowest temperature of the cycles was varied respectively according to the series: −2, −4, −6, −8 and −10°C, while the highest temperature was fixed at +10°C.

The specimens were broken into pieces after the freeze-thaw cycles. Dried residual weight (W_r) was measured using the largest piece. Then the residual weight ratio was calculated by W_r/W_d, where W_d indicates dried the weight of the specimen before the experiment. When the minimum temperature of the cycles was lower than −4°C, the breaking increased (Fig. 5).

3.2 Dependence of Frost Shattering on Thawing Temperature

Specimens used were 5 cm cubes of tertiary tuff from Oya (Tochigi Prefecture) with a porosity of 35–40% and a V_p of 2 km/sec. The specimens were set in a plain vessel in the same condition as in the previous experiment. The highest temperature of the freeze-thaw cycles was changed to +4, +6, and +10°C, while the lowest was fixed at −10°C. The freeze-thaw cycles were repeated 14 times. The specimens shattered when the maximum temperature of the cycles increased above 4°C.

From these results, it can be concluded that rocks (tertiary tuff) saturated with

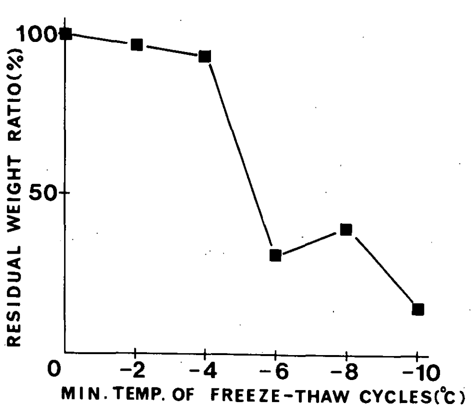

Fig. 5. Dependence of residual weight on freezing temperature.

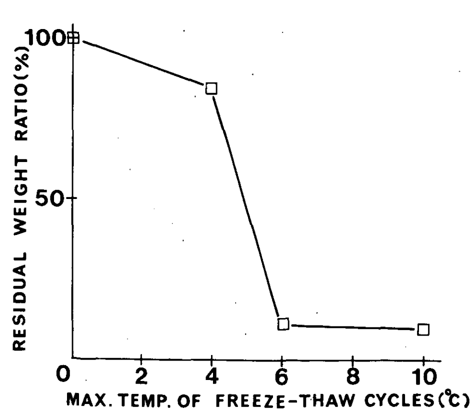

Fig. 6. Dependence of residual weight on thawing temperature.

water will be severely shattered when the temperature varies by more than +4 to −4°C in a day.

4. FREEZE-THAW CYCLES WITHIN A ROCK SPECIMEN

4.1 Calculation of Freeze-Thaw Cycles within a Bedrock Tuff

The depth of freeze-thaw alternations in rocks is estimated by the following calculations. Specimens of tuff were the same as in the first experiment described above. Thermal properties were measured in a laboratory using the thermal probe method (Table 1).

Table 1. Thermal diffusivity of tuff ($\times 10^{-3}$ cm^2/sec).

	Non-frozen (+10°C)	Frozen (−10°C)
Dry	1.3	1.6
Wet	3.0	3.8

Having obtained these thermal properties, the temperature profile of a bedrock tuff can be calculated using the following assumptions.

The surface temperature changes daily according to a sine curve expressed as:

$$Y_s = A_o \cdot sin\left\{\left(\frac{2\pi}{T}\right) \cdot t\right\}$$

Temperature (Y) at depth X is then given by the following equation,

$$Y = A_m + A_o \cdot exp\left(-X\sqrt{\frac{\pi}{kT}}\right) \cdot sin\left\{\left(\frac{2\pi}{T}\right) \cdot t\right\}$$

where: Y = temperature inside at depth X cm of a bedrock,
A_m = mean daily surface temperature,
A_0 = amplitude of surface temperature change,
X = depth (cm),
k = thermal diffusivity (cm^2/sec),
T = cycle (1 day = 86,400 sec),
t = elapsed time (sec).

If the bedrock tuff is wet the value of k is 3.0×10^{-3}, and the daily temperature alternations in various depths are calculated (Fig. 7). The rock effectively freezes and thaws daily at a depth of 10–20 cm from the surface, when the amplitude of the surface temperature is +5 to −5°C.

4.2 Experiment

An experiment was conducted to observe freeze-thaw cycles within a rock specimen under natural climatic conditions. A specimen of tertiary tuff was placed

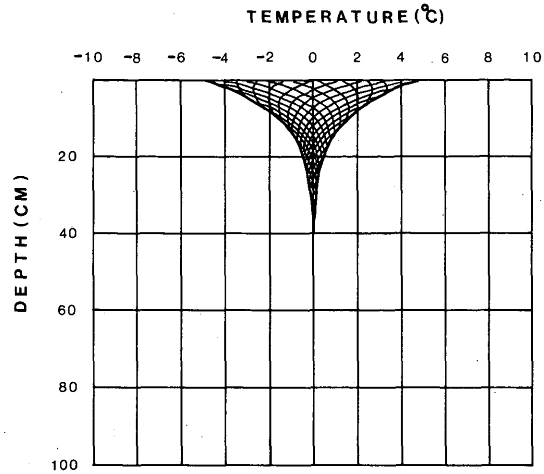

Fig. 7. Temperature fluctuation in bedrock of wet tuff (surface temperature range of +5 to −5°C).

at the south veranda (the second floor) of the Historical Institute of Saitama, from January 18 to March 27, 1984. The Institute is located at Ranzan, Saitama Prefecture, about 60 km northwest of central Tokyo. Compared with Tokyo this district is usually fine but cold in winter.

A temperature sensor (platinum resistance sensor) was inserted into the tuff specimen (30 × 30 × 15 cm) saturated with water in a vessel. The sensor was located 5 cm from the surface. Surface and air temperatures were measured by platinum resistance sensors. The sample temperatures were recorded by a data-logger (Field Memory, Hayasaka Co. Ltd.) at hourly intervals, transferred to a personal computer (NEC PC-9801), and calculated after the experiment.

Temperature alternations observed are shown in Fig. 8. The surface temperature fluctuated according to the air temperature, which varied about +5 to −5°C, whereas the inner temperature fluctuated around 0°C, with a delay of two hours or so. The slow descent of the inner temperature below 0°C implies a freezing of water contained by the specimen, because latent heat is released when water begins to freeze. If a rock is fine-grained and contains little water the release of latent heat will not be observed.

From this experiment it is concluded that the daily surface temperature of stone remains varies 1–2°C less than does the air temperature, when the surface is not exposed directly to the sun. When the diurnal range of air temperature is about +5 to −5°C, cycles of freezing-thawing caused by fluctuations around 0°C will occur some centimeters deep, if remains are saturated or nearly saturated with water. Frequent cycles of this type will certainly lead to eventual degradation.

5. EVALUATION OF POSSIBLE FROST DAMAGE IN JAPAN

From the above discussion it can be concluded that stone artifacts are suscepti-

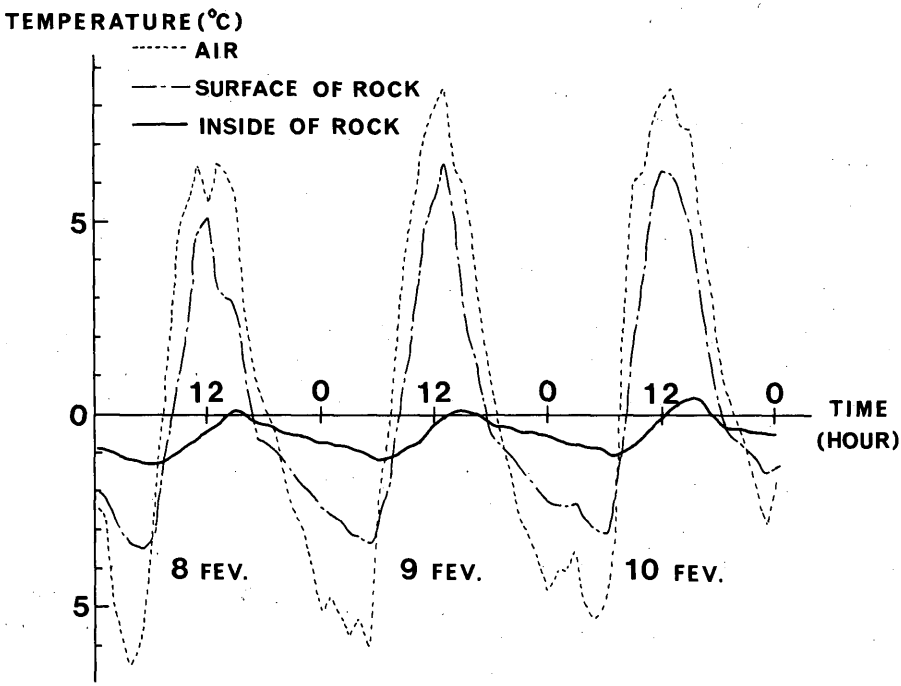

Fig. 8. Temperature changes of a rock specimen in the open-air.

ble to frost shattering when saturated with water and if the amplitude of diurnal temperature is greater than +4 to −4°C. To determine areas in Japan where frost damage is most likely to occur, and where countermeasures should be considered, winter season climatic data (air temperature and precipitation) from October, 1983 to May, 1984 were examined for 838 stations, using the AMeDAS* data of the Japan Meteorological Agency.

For temperature, the number of days with diurnal ranges greater than +4 to −4°C were counted at each locality. Then the localities with more than 10 days of such a range were mapped. (10 days was selected as the threshold value of the daily range because most non-treated tertiary tuff samples were destroyed after 10 cycles of +4 to −4°C/day.)

Localities with winter precipitation in excess of 200 mm were derived from the AMeDAS data and plotted on the same map. Precipitation, which may contribute to frost damage, was calculated as follows: when the monthly mean value of minimum temperature in a day is below 0°C, the precipitation during the month contributes to frost shattering, because a freeze-thaw cycle does not take place unless the temperature falls below 0°C, even if sufficient water is supplied. The sum of precipitation includes the precipitation of the month in which the mean max-

* AMeDAS = Automated Meteorological Data Aquisition System).

imum temperature is below 0°C. On such a day water within a rock is always frozen; thus a freeze-thaw cycle does not occur. But snow remains until the spring thaw season (as snow or ice) and causes freeze-thaw cycles in spring. In snowy and cold regions frequent cycles of freezing-thawing are observed mainly during the spring thaw (Fig. 9).

The areas which satisfy those temperature and precipitation conditions are shown in Fig. 10. Since in these areas two of the three conditions for frost shattering exist in winter, frequent cycles of freezing-thawing and a sufficient supply of water, stone remains should be conserved carefully to prevent frost damage. In the absence of conservation measures, in those areas some fragile stone remains will certainly be broken.

Fig. 10 demonstrates that possible areas for frost shattering occur mainly in cold and snowy regions (Hokkaido, Tohoku and Chubu). But they also occur in areas with a milder climate (Chugoku, Shikoku and Kyushu). It must be emphasized that Oita Prefecture, which has most of the important rock-cliff Buddhas in Japan, is included in the latter area. Kyushu is usually considered free from frost damage, because the climate is mild (annual mean temperature of Oita City=15.6°C). But Fig. 10 shows that the inland area of Kyushu has a more severe climate than hitherto imagined. Hakone, in the Kanto District, where there is a group of rock-cliff Buddhas designated as National Treasures, is also in the areas where frost damage could occur.

The solid line in Fig. 10 indicates areas where the monthly mean winter temperature is below 0°C. In these areas at least one cycle of freezing-thawing occurs in a year, if a rock is well moistened. Cycles of freezing-thawing will cause breaking of stone remains even in these areas. For example, the rock of Buddhas at Odaka (Fig. 11) freezes in winter (from late-January to early-February)(Fig. 12). During this time the outdoor mean temperature descends to −3 or −4°C and the

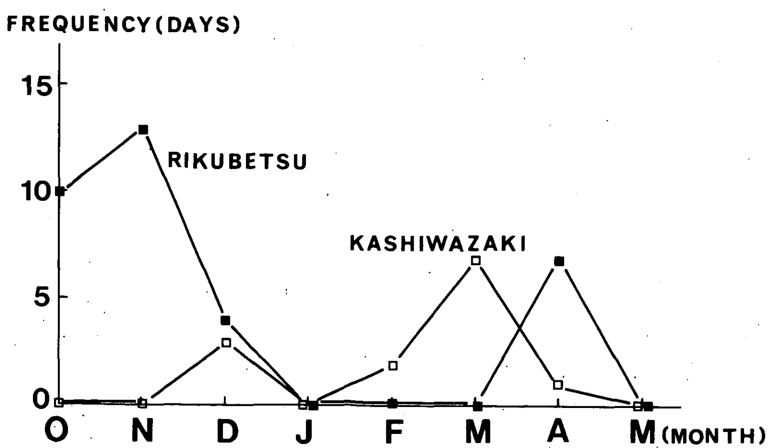

Fig. 9. Monthly frequency of freeze-thaw days with a fluctuation of more than +4 to −4°C (snowy and cold regions).

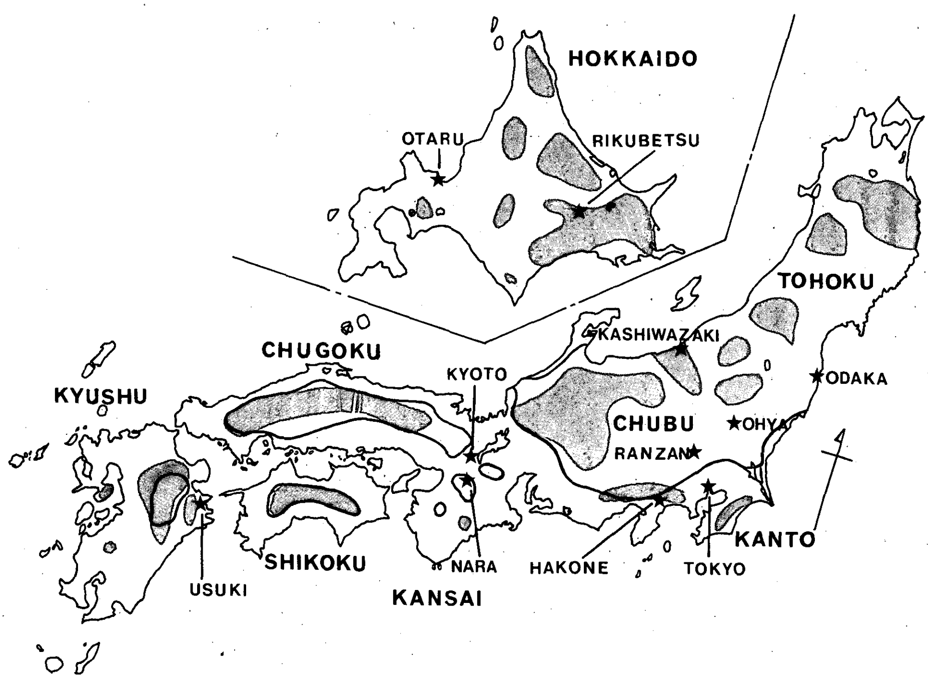

Fig. 10. Distribution of possible areas for frost shattering of stone artifacts. (This is a tentative map based on the AMeDAS data of 1983 Oct.–1984 May. More data might yield a different pattern.)

daily mean temperature inside also declines to -2 or $-3°C$, owing to insufficient heat insulation of the shelter covering the relics. Although this freezing-thawing cycle occurs only once a year, the sculptures have been damaged heavily and their eyes and noses have disappeared entirely, owing to the fragile nature of the rock from which they were carved.

6. CONCLUSION

Results of laboratory experiments on diurnal temperature change that causes frost shattering of rocks were examined. The phenomenon was also discussed theoretically. Then the critical amplitude of the fluctuation for tuff was evaluated at more than $+4$ to $-4°C$.

Winter climate was examined using temperature and precipitation data from 838 localities in Japan. The result were mapped in Fig. 10 and discussed. It was concluded that stone artifacts must be well protected from frost damage, especially in areas with large diurnal temperature ranges and abundant precipitation in winter. Even in other regions where the daily mean temperature is below 0°C for several weeks in winter, frost damage should be carefully protected against if sculptures have been carved from fragile rock material.

The following protective measures are recommended: reduction of water

Fig. 11. Rock-cliff Buddhas at Odaka, Fukushima Prefecture, 11th–13th centuries.

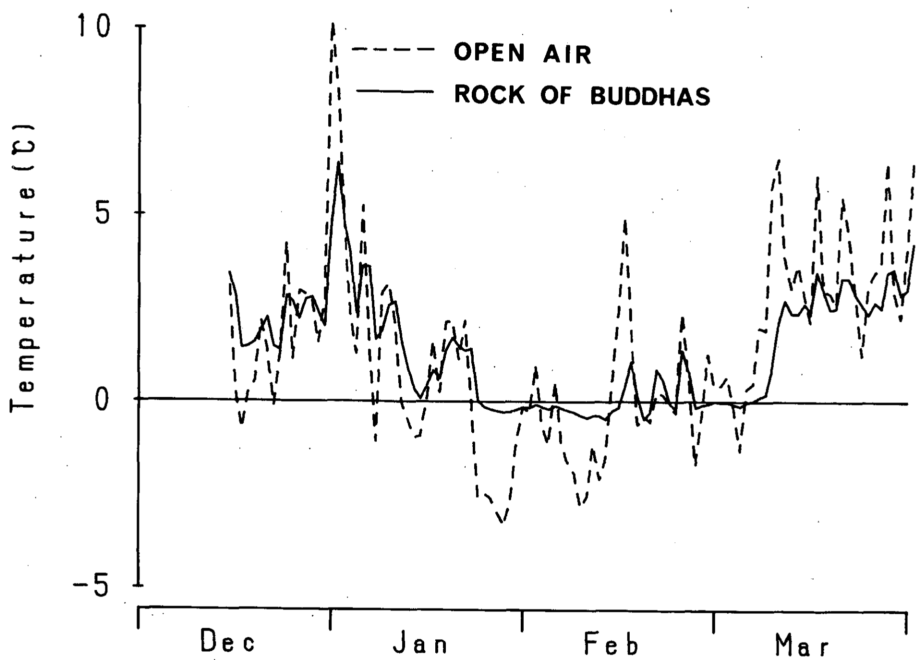

Fig. 12. Temperature fluctuation at Odaka.

supply, sheltering the artifacts and treating them with synthetic resins. These measures are explained in detail in Fukuda [1983, 1984], Nishiura, Fukuda and Miura [1984], and Nishiura [1986].

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