The Basic Concept and Appearance of Tunnel Kilns: Ethnoarchaeology and Sue-Ware Kilns from the Point of View of Experimental Archaeology

Masaaki Kidachi

Translation from Japanese into English: Robert Sträter

Abstract: The author describes the principle of the kiln drawing flames from the basic design of the kiln, the inclination angle of the floor, the relationship between the volume of the firing section and the opening area of the firing and smoke outlet, and the temperature of the room. Furthermore, the points to be noted when excavating a kiln are described separately for the firing port, the combustion and firing sections, and the ceiling of the firing section. In addition, from the results of experiments on Sue-ware anagama kilns, the color tone and temperature difference, stress on the kiln itself, refractoriness of the soil and fuel consumption are explained.

Keywords: Structure of kiln, tunnel kilns, flame ignition, inclination angle, temperature difference, color tone, stress of Sue-ware kilns

3.1. Firing principle of tunnel kilns: about “pulling the flame”

Climbing kilns are made and built on slopes. However, depending on the construction of the kiln type, the choosing of a site changes significantly. Construction and site conditions of a kiln are in a symbiotic relationship.

3.1.1. The ignition and extinguishing of embers (oki)

When modern potters fire with tunnel kilns or multi-chambered climbing kilns (Renbō-shiki Noborigama, Fig. 3.1), they pay attention to the intensity of the flame. They may notice a stagnation of temperature during the firing, perhaps because the fire does not burn well even though plenty of fuel has been added. Potters describe this state as “pulling the flame.” To ensure the correct temperature, different measures must be applied. For instance, by mixing and piling up the accumulated charcoal in the firebox and supplying oxygen to the smoldering charcoal, the firing is accelerated. Other measures include shifting the thrown-in burning material, exchanging large pieces of firewood with fast-burning scantlings, or closing and opening the flue.

If the fuel burns well, the firewood ignites, and after heat emission, it turns to embers. The embers cover the entire floor of the firebox and keep the interior of the kiln warm. Nevertheless, if too many embers accumulate, adding the next batch of firewood makes the space smaller, which causes a hard burning of the firewood so that the embers are scratched out from the firebox. Regarding the color of the embers, some potters differentiate between “bad embers” (extinguished embers) and “good embers.” “Bad embers” are dark and never burn out well. “Good embers” are bright, burn down smoothly, become ash, and the speed at which the next firewood is replaced by new embers is fast. We can say that the renewal of firewood and embers is the decisive factor for the temperature rise in the kiln. On the other hand, if the embers, which kept the kiln warm, are scratched out, the temperature of the interior of the kiln will fall suddenly. This does not mean that it returns to zero, because the entire kiln has already accumulated heat, but it wastes time and fuel.

According to modern potters, the ignition of embers can be good or bad. The reason is not only the kiln’s construction; some other causes like changes in the environment or the kiln firing may be assumed. Not all causes can be made clear, but first, the basic concept of kiln firing should be explained.

3.1.2. The principle of the flame’s ignition

If the supply of oxygen and carbon dioxide is optimal, even when the space is closed, the burning will be accelerated. A tunnel kiln was dug like a tunnel in a slope, and air flows one way from the stokehole to the flue hole. This flow becomes proportionally faster if there is a significant difference in height between the stokehole and the flue hole. If the stokehole’s outlet area and the flue hole are large, it becomes proportionally faster.

Inclination angle of the floor and basic design of kilns.

Takuma Yogo points out the importance of the ratio of the
difference in height between the stokehole and the flue hole, and their horizontal distance (Yogo 2010: 102). The decisive point of the kiln’s construction is not the floor’s inclination angle, but the difference in the height of the stokehole and the flue hole, and the horizontal distance is interrelated.

If this is the case, then the supposed angle, which is a connected line between the floor of the stokehole and the back side of the flue, influences the power of the flame. Let it be called the “S-F angle” provisionally (Fig. 3.2). Because there are some cases where the flue remains, it is possible to compare and examine the flame’s ignition by the difference between the elevation near the stokehole and the elevation of the flue, and their horizontal distance (Kidachi 2019: 34–35).

Today’s potters increase the flame’s ignition through the height of the chimney, but the products are in the kiln, and because of this, they make the floor of the firebox as horizontal as possible, and so it is necessary to increase the S-F angle via the chimney. There are no verifications of chimneys through Sue-ware (Japanese stoneware) kiln excavations. The slope of Sue-ware tunnel kiln floors are steeper than today’s tunnel kilns. There is a big difference in height between the stokehole and the flue hole of the kiln. The kiln itself is considered to have played the role of the chimney.

**Capacity of the firebox and aperture size of the stokehole and flue hole.** The essential factor determining the surface area of the firebox’s aperture and the flue is the capacity of the firebox (Furutani 1994: 38–39). Because a tunnel kiln is a room where the firebox and firing chamber are located next to each other, distinguishing the boundary is not easy. Nevertheless, by detailed observation of the burning state of the walls and floor and the charcoal and ashes from excavations, it is possible to confirm the combustion’s extent. However, when more than half the ceiling has collapsed, it is challenging to figure out an exact calculation of the firebox’s volume. Besides, it is arduous to explain the surface area of the apertures of the firebox and the flue through excavations. In particular, it is complicated to determine the opening area at the time of firing because the firing mouth is repeatedly created and destroyed each time it is operated. It may be possible to estimate the size of the opening from the area of the burned part.

As above, due to the S-F angle of a tunnel kiln, the flame’s ignition is strong. Furthermore, depending on the increase and decrease of the firebox’s surface area and flue hole’s aperture, the degree of this strength can be controlled. Modern tunnel kilns use this concept, and all is planned according to the clay, the form of the product, the amount of available fuel, and feeding time. The balance is determined by various factors such as the firebox’s size, the fuel’s opening surface area, or the chimney’s length. However, because of weather and atmospheric pressure, conditions are rarely, if ever, identical. When the balance between natural conditions and kiln firing crumbles, a stagnation of temperature rise can be assumed.
3.1.3. Temperature differences in the kiln

The flame in the firebox stretches out widely, but it cannot heat the whole firing chamber, which is several meters long. There are high temperatures in parts, which face the firebox (in front of the fire). However, the temperature falls rapidly in parts near the flue. Because the fire rises to the ceiling, the floor’s temperature is low, and that of the ceiling area becomes high.

We can say that the tunnel kiln has a structure whose primary purpose is to raise the kiln’s temperature rather than homogenize the temperature. The temperature difference inside the kiln cannot be avoided in the upper construction. Nevertheless, by taking enough time for the roasting step and continuing the heating, the temperature difference can be reduced. Once the temperature is raised, the temperature difference cannot be reduced (Furutani 1994: 129).

3.1.4. A flame that requires heat

If there is a temperature difference in the kiln, the flame flows to the warm part, avoiding the cool part. Once the flame’s flow has started, it cannot be easily changed. To heat the inside of the kiln without any temperature difference, consideration must be given to the fuel input location and the air passages.

If the difference in height between the entrance and exit is large, the flame’s pulling will be intense. If a chimney is constructed during firing, the S-F angle increases noticeably. However, the cooled chimney does not show the expected effect. If the chimney is installed from the beginning, because the kiln firing warms the chimney at the same time, the original effect is maintained (Furutani 1994: 39).

A temperature difference inside the kiln is unavoidable in the upper construction of a tunnel kiln, but by a moderate rise in the temperature of the whole kiln, the difference in temperature can be reduced. That is why the beginning of kiln firing is particularly important. At first, a small fire is lighted outside the stokehole, and when the outer wall heats up, the flame will get progressively closer to the inside of the stokehole. If the warmed firewood burns directly inside the firebox, the high temperature inside the kiln rises immediately, and stonewares may be damaged. If the firing part of the kiln takes time, it can be heated later, but if the entrance is not heated at first, it will not be sufficient. Furthermore, if the stokehole’s outer wall is not heated at first, it will be difficult to warm the kiln’s back. If the first roasting is incomplete, the required temperature will not be reached. Modern potters say that it is essential to slowly warm the temperature in order from the entrance to the flue hole by roasting for a long time, to eliminate temperature irregularities inside the kiln and unevenness of the flame (Furutani 1994: 126–29).

3.1.5. Eructation of the kiln

In modern kilns, flames may spout out from the firebox. Some potters call this phenomenon “eructation,” which is a bad sign for the flame’s pulling. This phenomenon is produced because the flame’s flow, which should face towards the flue, does not grow favorably. When the rising of temperature is not going well, or when the firewood is thrown in too fast, the phenomenon will be excited. In modern tunnel kilns, there are numerous cases in which soot sticks to the firebox’s surroundings. It is not a “burp,” but happens because the flame often leaks to the outside of the stokehole.

3.2. Evidence of kiln sites

3.2.1. Stovehole

The stokehole is the entrance of the kiln, where the firewood is added during the firing stage. In ethnological examples, the stokehole is built after the kiln is filled, and at the moment of taking everything out, it will be destroyed. Therefore, it is difficult to confirm a stokehole at the site unless the conditions are excellent. The detected “stokehole” is likely to be only a trace of a broken stokehole (Kidachi 2010: 126–27).

The beginning of kiln firing from the ethnological perspective. In ethnological examples of Japan, it was necessary to remove humidity from products and the kiln, so at the beginning of kiln firing, a large amount of firewood was thrown in to let the humidity volatilize gradually. Today’s potters call firing by kiln “kiln burning.” It is a fact that the kiln is burnt to bake the products but, if the kiln is not burnt, products cannot be burnt. In order to fire a product, the temperature of the whole kiln should
be raised, and the radiant heat should be used to fire the product. The temperature is increased from the outside to the inside of the firebox, and then to the firing section.

**The unique entrance of the kiln: the entrance of the chevron shape.** At the kiln site in Hyogo prefecture, the kiln entrances are in the shape of a chevron, which is often burnt red. No similar fireboxes can be seen in other ethnological cases. Some assumptions about the firing of an empty vessel at the beginning at the kiln’s construction were made, whether the surroundings of the kiln’s entrance were widely burnt or the roasting opened a large aperture, and the stokehole narrowed successively. It is supposed that the stokehole narrowed. Generally, it is believed that the stokehole did not change from the beginning to the end of firing. However, the possibility should be considered that the shape of the “stokehole” and the firing section’s position have changed. By this token, the chevron-shaped entrance could not entirely be a unique case.

**The process of detecting a stokehole.** It is necessary to comprehensively investigate the preservation of the remains which are recognized as a stokehole at the excavation site, from detailed observation and the distribution of the collapsed kiln wall and black coal layers. As one indicator for identifying the stokehole, there is a method that verifies the distribution area of the charcoal layer. However, it is necessary to note the next point. During firing, a large amount of embers may be scraped out to extinguish the fire if necessary, as they may have accumulated as charcoal. Moreover, immediately after emptying the kiln, a large amount of charcoal produced by reduction cooling of the kiln-fired burning material should be left, but the product cannot be taken out without removing the charcoal. It is assumed that large charcoal pieces were reused as fuel. Hence, a loss of information is possible after the charcoal was scratched out because it is left spread out on the floor. The charcoal would have been trampled into fine fragments and dust by the kiln removal work.

An even more effective indication for determining the location of the stokehole is the distribution area of the red burned soil, which was detected in the charcoal’s lower layer. It is presumed that the area of red burned soil developed when the flame spread into the kiln after the beginning of firing and roasting outside the firebox. If we verify the movement’s extent, we can probably conclude the place of the first firing. Nevertheless, if the firebox is destroyed at the time of the kiln’s discharge, these fragments will accumulate as red burned soil. It is necessary to distinguish between red burned soil burned *in situ* and red burned soil of secondary deposition.

Furthermore, it is possible that the ceiling construction of the firebox area collapsed and accumulated on the floor – that the collapsed ceiling of the firebox part slipped down the sloped floor. There are many examples in which collapsed kiln wall fragments have tumbled down and accumulated because the firebox parts are almost flat. For that reason, although we have excavated around the firebox area, it is difficult to identify which part is the collapsed kiln wall fragment, and observing the ceiling wall fragment’s burning state will ensure accuracy. In the firebox area, the temperature increases even more, and there are many confirmed cases with glaze. It is expected that the temperature becomes gradually lower at the kiln’s back than in the firebox part. Through conditional comparisons, we can reconstruct the original location.

**The ceiling of the firebox area’s entrance.** The sunken kiln was a dug-out ceiling; however, entire parts of those are not dug out, and most of the stokehole is constructed on the ground. The carved ceiling is that of the firing chamber. The sunken kiln type’s firebox at the Karimata site in Ogōri in Fukuoka prefecture has a constructed ceiling. At the time of excavation, the whole ceiling was collapsed, but by detailed observation of the side walls, a provisional ceiling construction has been confirmed (Mochizuki 2010: 41–42). The ceiling construction of the firebox section may be closely related to the shape of the stokehole. In this way, based on the stokehole, it is assumed that the firebox part would collapse on to other parts and be destroyed at the moment of the kiln’s discharging. Hence, it is difficult for it to remain. Nevertheless, there are examples that confirm those collapsed remains directly above the floor. Sometimes there are traces left on side walls as changes in the burn color. At excavation sites, detailed observation and documentation are necessary.

The precise observation of detectable remains like side walls and the floor allow us to set a certain standard. However, if the verification of the collapsed ceiling fragment’s preservation state moves forward, it will help in understanding the remains of the firebox’s provisional ceiling and the stokehole.

**The situation of the stokehole’s front area.** At sunken kilns, the soil is thrown outside the stokehole to construct a flat surface in front of it. On the other hand, temporary storage for production use should be considered. In the case of a sunken kiln, a large amount of dug-out soil is discharged, but at the beginning of digging, it is assumed that a vertical precipice was scraped out. Perhaps a horizontal hole was dug into the near-vertical wall. Independent from the scratching out of the wall, some flat areas are formed. In the case of a steep slope, the discharged soil slips down the slope and forms no flat surface. If there were no steep slopes, the discharged soil would form a flat surface. The flat surface would have been made lower than the kiln so as to improve efficiency and keep out rainwater. It is necessary to pay attention to the topographical modifications nearby and around the time of the kiln’s construction.

In case of a semi-sunken kiln, the amount of dug-out soil is small, and the discharged soil would be used to form a ceiling. Thus, it is assumed that the amount of discharged soil was scarce. It is possible to dig down the
kiln’s surroundings and float its body, but the topography’s modification in front of the firebox area is not apparent.

Besides, many semi-sunken kilns at the Ushikubi kiln site in Fukuoka prefecture were constructed on steep slopes, and the front parts were carved out. An embankment cannot be confirmed. In this case, dug-out soil as well as the failed products and the charcoal were thrown away below the slope. There are many cases in which such sloped topography is used in the sunken kilns, but even in the case of semi-sunken kilns, there are some confirmed and selected examples.

3.2.2. The firebox and firing chamber

In the case of a tunnel kiln, the firebox and the firing chamber follow one after another, and it is often difficult to differentiate between them. In the case of a tile kiln, there are prepared steps (Ōkawa 1985: 30), and examples can be confirmed in which the firebox and firing chamber are divided. However, in the case of a Sue-ware kiln, it cannot be divided in general. When some of the fuel is left as charcoal or ash, it is assumed that its distribution area reflects the firebox’s size, but attention should be paid to the fact that the distribution extent of charcoal and ash changes with each firing. It is possible that the range of the firebox section moved with each firing, just as the stokehole might have moved during firing. In that way, the size of the stokeholes identified in the excavations would then be the overlap of the burning areas experienced in multiple kiln firings.

The firebox’s ceiling. The ceiling of the firebox part is where, in general, the temperature becomes higher inside the kiln. Air enters the stokehole, the flame of the firebox part rises diagonally to the firing chamber’s ceiling, and the part which is in the combustion zone but quite near the firing chamber becomes hottest. Hence, this part of the ceiling inside the kiln was the easiest to damage, and it may have had to be repaired after each firing.

When temperatures become high, as in ash-glazed stoneware kilns, the ceiling cannot withstand the temperature, so columns, called pillars, are erected to prevent it from collapsing. It was thought that they were installed to divide the flame evenly. However, to achieve that, it would be enough to arrange the position of large products during the kiln firing. According to a thermal simulation conducted by the Japan Atomic Energy Agency, “Technical Exchange Meeting on Echizenyaki Stonewares,” the ceiling temperature of that portion is the highest when there is no pillar. Conversely, when a pillar is set up, the pillar takes away the heat of the kiln (Technical Exchange Meeting on Echizen Ware 1998; Kidachi 2010: 122). It cannot be said that it played no role in “dividing the flame,” but it cannot be thought that it had no role except to support the ceiling.

In conventional excavation research, sufficient attention has not been paid to the restoration condition of the burning stability of the firebox’s ceiling. If a collapsed ceiling remained on the floor, these fragments would become a crucial factor in knowing how to repair and burn. Usually, we try to verify repair traces of tunnel kilns by cutting open the side walls and the floor, but in this part of the kiln’s inside the temperature is low, and it is a part that does not need so many repairs. The part that is indispensable for knowing the firing temperature is the fragments, and observation of these is essential. This is a principle that is not only limited to tunnel kilns.

3.2.3. The flue hole and the accompanying facilities in the kiln’s and chimney’s surroundings

The flue hole and the chimney. For controlling the flame’s ignition in modern kiln firing, the flue hole is opened and closed during the firing. It is possible that such work was also performed on Sue-ware kilns, but because a cooling reduction was conducted at Sue-ware kilns, it was necessary to seal the flue hole and stokehole completely airtight after the kiln firing was finished. If there is a flat surface in the flue hole’s surroundings, it is assumed that an opening and closing were used. Because it is impossible to look through the stokehole to the end of the kiln during a firing test, the firing situation is often observed at the flue hole during firing. Since the firing mouth is narrowed down, the closer to the final stage, the worse the kiln’s visibility from the firing mouth. By observing both the flue hole and the stokehole, the firing situation of the kiln’s inside can be estimated.

In the case of a Sue-ware kiln, in order to avoid the accumulation of water at the flue hole, which runs on the surface, there is sometimes a drainage ditch that encloses the flue hole. It is assumed that the flat surface around the flue hole was not just a work surface, but also functioned as just such a water barrier. There is a sunken kiln with a groove in the smoke exhaust part, which is part of the Sue-ware kiln. It is presumed that the flame’s flow blown out can be estimated by the firing state and the construction of the fuel to accelerate or suppress the smoke emission. The idea that different works like accelerating or suppressing the smoke can be conducted around the flue hole is fascinating. For this reason, detailed observation at excavation research sites is necessary (Mochizuki 2010: 60–61).

That the height difference between flue hole and stokehole is important for the flame’s ignition has already been mentioned above. However, due to the ditch, which is fixed at the flue hole, the height difference between stokehole and flue hole would be smaller than the height difference of the original ground surface and would have suppressed the flame’s lighting.

Because a kiln with a ditch has a hollowed-out form, the difference in height must be enormous. Besides, the temperature on the floor is reduced, and the fuel consumption increases. Various measures are required, such as narrowing the opening area of the flue hole and the
stokehole to prevent fuel consumption and heat loss due to smoke exhaust. It also depends on the location’s condition, like terrain, but it is assumed that the main reason for installing the ditch at the flue zone is the idea of reducing the efficiency degree, even though it is a sunken kiln type.

The accompanying features of the kiln’s surroundings. In the case of a semi-sunken kiln, many cases can confirm extensive changes in the environment of the kiln. Remarkably, a continuous pit was laid around the ditch to allow rainwater to escape the surroundings while protecting the exposed kiln ceiling. This not only let the rainwater flow off, but also became a stairway or a passage for applying the flue hole, and it is possible that it was used during the repair of the exposed ceiling. If a crack forms in the ceiling zone, air can leak out from it. As reduction cooling would lead to oxidation, modern Daruma kilns were cooled after firing by adding muddy water to the entire kiln, filling in the cracks. Similar work was necessary. Furthermore, there are also cases where the slopes around the kiln have been modified like terraced fields to provide flat surfaces. This area may have been used as a fireplace or a simple workshop. Ethnoarchaeological studies of people who lived in the mountains are indispensable in clarifying the supply lines of the potters at that time, such as the passage to the kiln and the locations of the mountain paths. Ethnological examples of modern charcoal kilns should be consulted (Fujiwara 2020).

Near the kiln, the workshop or the pit for clay mining can be detected, and there are also good examples for reconstructing the supply ways. However, from a multitude of Sue-ware kilns in western Japan, there are many cases in which only the kilns can be detected in the mountainous regions, and in contrast, it is highly possible that the workshops were built in the plain’s settlements. In the east of Japan, both kilns and workshops were generally built in mountainous regions. It is becoming clear that there were significant regional differences, but it is assumed that these differences indicate whether the Sue-ware production system was relatively independent of the local community. Even if the kilns are similar, the facilities around them may differ depending on the difference in the social systems that supported them.

3.3. Firing experiment with Sue-ware tunnel kilns

3.3.1. An experiment with temperature difference and color tone

The atmosphere that determines the color of Sue ware: experiment with cooling and firing. Because the soil’s components decide the color of the finished product, the firing and the cooling, the color tone of stonewares is diverse. Experiments have revealed that Sue ware has a blue-gray color and is cool and reduced (Sasaki & Yogo 2004, Yogo 2010).

Therefore, I would like to introduce the experiment with the firing and construction of a Sue kiln conducted by the Kiln Research Society (Kidachi 2010). By observing the fired products from the experiment, it was found that many of the pieces placed in contact with the firebox were bluish-grey and firmly baked, and the natural glaze was melted. The black color of the stonewares which were arranged near kiln’s back wall had faded, and although ash fall is confirmed, it does not melt. Ash falls down on the whole firing zone, but there is only a small part in front of the fire that melts. It can be said that the firing temperature was high enough to melt the ash only in the limited part in front of the fire. Ashes move from the front of the fire to the kiln’s back and gradually change their appearance due to the temperature difference, thus: “melting (vitrification) → solidifying and adhering (welding) → mere powder ash.” Depending on the kiln firing, the atmosphere inside the kiln changes precipitously. During the stage of removing the moisture from the kiln by roasting and gradually raising the kiln’s temperature, an oxidizing atmosphere is maintained in the kiln. After reaching a specific temperature, we finally enter the “offensive fire” stage.

The firewood will suddenly remove the temperature of the firebox zone if put in the high-temperature firebox part. The firewood, which absorbs the kiln’s heat, will begin to burn rapidly. At first, it produces a situation of oxygen deficiency, then dark black smoke rises, and the kiln’s inside part turns into an airtight atmosphere. Due to the oxygen deficiency, the goods in front of the fire will be directly covered with dark black smoke, i.e. the warm air of a reduced atmosphere. By throwing in the next load of firewood without changing the state of reduction, this state can be kept, but the kiln’s inside temperature will not rise. If the reduced state declines, it turns into an oxidative atmosphere, black smoke turns into flames, and high temperatures result. The burning of firewood is accelerated, and depending on the oxidative flame, the temperature of the inner kiln rises. After a while, the view into the flame-filled kiln widens and the products glowing from the heat become visible in white. The oxidative atmosphere stage is the moment of the highest firing temperature. If this moment is passed by, the kiln’s inner temperature will begin to fall. Burned firewood turns into embers because a large amount of heat will no longer be generated. These embers take on the role of the firebox’s heat insulation, but they do not raise the temperature of the firing chamber. This is because the embers do not generate long-stretching flames.

Just before the temperature inside the kiln begins to drop gradually, one adds new firewood. In this way, through a change in reduction and oxidation, the temperature rises, and offensive firing is conducted by balancing the timing when firewood is thrown into the kiln and the amount, the oxidative atmosphere; in the other way, the reduction atmosphere can be prolonged.

When the desired temperature is finally reached, a large amount of firewood is thrown in, and the kiln is sealed entirely airtight. The firewood tries to burn in the high
temperature, but since the air inlet and outlet are completely closed, this deprives the kiln of oxygen. From the kiln wall to the products, it burns by consuming all of the oxygen, but it cannot burn out and turns into charcoal. A high temperature produces a strongly reduced atmosphere, and while maintaining this atmosphere, it successively cools down the kiln, so that the Sue ware shows its reduction color. It is not only the product but also the inner walls of the kilns, the ceiling, the floor, and all turn to that reduction color.

After the kiln is closed, the walls shrink, causing fissures. Therefore, to avoid air leaks, mud and muddy water are put on the whole kiln to cover the crevices. Directly after occlusion, the kiln’s inside spits out a large amount of smoke caused by the burned firewood, and because the pressure becomes higher, smoke is emitted from the kiln walls, the stokehole and the flue hole. The work of putting mud and muddy water on parts where smoke is rising and covering crevices must be done repeatedly. If the work eases off and the pressure is low, oxygen enters the inner kiln through the crevices, and it turns to an oxidative atmosphere so that the color tone becomes red. This post-occlusion treatment is thus essential for producing a blue-gray tone.

The formation of the ash pile. In the experiment, reduction cooling could not be performed successfully. Due to the foundation, there is a limit in the kiln’s fire resistance, and at the moment of the kiln’s closing, a large amount of firewood could not be thrown in. Hence, at the moment of the kiln’s cleaning, a large quantity of the added firewood burned out to ash in the firebox, and there was very little charcoal left. Despite the firing experiment having been performed for ten years, this did not form a disposal area of ashes and burnt-out charcoals (hatabara) like at the Sue kiln excavated around the haibara prefecture. Through observation of the firing stage, it was possible to fire the reduced color sueki. Through observation of the firing stage, it turned out that only the part exposed to the intense flame was discolored. After the added firewood starts to burn, a large amount of black smoke is spat out, but its temperature is still low. It gradually oxidizes and turns into flames, but during this transitional stage, the goods may turn into a reductive state. Once it was fired at high temperature, even if an oxidative state was reached at a lower temperature, it would not return to the oxidized color. Nevertheless, it is difficult to obtain a perfect reductive color. Furthermore, in order to observe the product’s burning state, a photograph was taken during the firing process. When around 1000° is surpassed, and the oxidation progresses, the flame inside the kiln turns transparent, and a white glimmer can be easily seen on the products. At that moment, the hot part of the product shines brightly on the protruding parts, and the slightly dented parts become darker. When it was left as it was and the temperature inside the kiln began to drop, the protruding parts on the contrary changed to a dark color tone and the slightly dented parts began to shine white. Because cold air enters from the stokehole, the protruding parts would directly hit the cold air. Since the cold air cannot directly hit the hollow portion, it seems that the heat was still stored, and the temperature seemed to rise relatively. After that and because firewood was thrown in, it became impossible to observe the kiln inside. The air directly hits the protruding parts in front of the fire, slightly reducing the high temperature, then the cold air has a slightly oxidizing effect. It is assumed that the differences in temperature and atmosphere strongly influence the product’s firing condition and also its color tone.

It is presumed that the color tone of Sue ware is determined by reducing the cooling stage’s atmosphere and the influence of the reducing flame. In addition, many of the early examples of Sue ware have a sepiya-colored cross-section and are fired firmly. It is the coloring by high-temperature firing in an oxidative atmosphere that turns the cross-section sepiya-colored. It is assumed that the product was fired at a high temperature while maintaining the oxidation state, and the reduction cooling was performed after the temperature decreased in the final stage. Since the reduction cooling temperature is low, it is assumed that the reducing atmosphere was not able to break into the cross-section that had been fired at high temperature. In many cases, only the surface is reduced and cooled, with a dark bluish color. Therefore, in the early stage of the kiln introduction, it is possible that the offensive firing maintained an oxidizing atmosphere, and that the reducing atmosphere used in the experimental kiln did not occur.

Baking of products and the kiln-filling position – the actual state of temperature difference. When fired in an experimental kiln with a total length of about 7 m (no refractory bricks used), the kiln’s chimney’s temperature was about 200° lower than that of the firebox. Even in the Sue-ware experimental kiln (made of refractory brick) at the Ogōri City Archaeological Center in Fukuoka prefecture, a temperature difference of about 200° was confirmed even though it was a small kiln of about 4 m. In these experiments, the temperature near the ceiling
was measured using a 50 cm thermocouple, but similar temperature differences were confirmed in the experiments measured with a 1 m long thermocouple. This is the case not only in front of and behind the fire of the firing chamber; it has also been confirmed that similar large temperature differences in the kiln’s inside near the ceiling and the floor occur (Technology Exchange Meeting of Echizen Stoneware 1998). It was also confirmed that in the case of large goods, the hot wind of the high temperature near the ceiling hits the products’ rims and blows into the inside of the product. Because the hot wind’s temperature near the floor is lower than near the ceiling, a huge temperature difference between the product’s inside and outside occurs. Inside large ancient Sue-ware pots, even though firing near the rim is well done, there are many cases where the bottom’s outer surface is poorly fired and is whitish gray and soft. Observations of the inside and outside surfaces of large goods are rarely done, but it would be important to understand the form and height of the ceiling of course, depending on the kiln-filling position and the shapes of the rim and body portion of a massive product, both when hot air is easily blown and when hot air is not blown.

Since it is a fact that a temperature difference occurs inside a kiln, it is necessary to reduce the difference a bit by devising a firing method, such as prolonging the firing time or performing “intermittent firing.” The temperature difference between the areas in front of and behind the fire will spread widely if the firewood is rushed. The floor surface is where it is particularly difficult to store heat. The flame inevitably rises, and the temperature near the ceiling rises.

After the firing experiment was continued for over ten years, the kiln was fired continuously for three days and nights. It was changed to “stop the fire” that interrupts the kiln at night. The advancing age of the participants made it difficult to work continuously for an extended time, but as a result of this experiment, it seems that the entire kiln will accumulate heat due to the leftover embers, and the temperature difference will decrease, and the flame of the kiln will crawl on the floor. Although the number of days of firing increases and the loss of firewood fuel is unavoidable to a certain extent due to stopping the burning, it is an effective means of reducing the temperature difference. However, it is not possible to confirm by excavation research whether this procedure was conducted.

The form and temperature difference of the kiln’s rear. In the firing experiment kiln, it is assumed that the firing of the products, which are packed in the rear area, was relatively weak, and the firing temperature was low. The construction of kilns in which only the rear of the kiln is sharply narrowed, and the slope is strengthened, is due to the fact that the heat was concentrated to make the kiln’s temperature uniform. Nevertheless, the positioning of goods in the kiln’s rear area on a steep slope is difficult.

If a temperature difference of about 200° between the part in front of the fire in the firing chamber and behind the fire at the kiln’s rear area is supposed, and the temperature in the rear zone was raised (or it was attempted to raise it) to 1150°, then the firing temperature of the foremost part of the firing chamber must have risen to 1350°. In that case, the temperature in the ceiling’s vicinity should have become higher than in the vicinity of the floor on which the products were placed. This high temperature requires a considerable amount of fuel, and the ceiling can collapse. Furthermore, from the experiences of the firing experiments, it is assumed that the temperature rising to 1350° would exceed the limits of the kiln’s fire resistance and stamina, and a temperature rising to this extent was problematic. It is assumed that the kiln was fired while maintaining the temperature balance between the kiln firing section and the kiln rear.

In modern kiln-packing, products that are to be fired at a high temperature are placed in the front of the firing section. The medieval (Kamakura and Muromachi period in Japan; 1199–1573) stoneware kilns were constructed in the same way, and even in the early modern (Azuchi-Momoyama and Edo period in Japan; 1573–1868) multi-chambered climbing kilns, the temperature difference inside the room was unavoidable, so the products and glaze were changed depending on the kiln filling position and height (Kinkodō Kamesuke 1830). It is assumed that even at the Sue-ware kilns, vessels for liquid storage like jars, bowls and narrow-necked jars, which are sorts that must not leak due to firing failures or cracks, were placed in front of the fire and tableware that does not need high firing temperatures was placed near the kiln’s rear.

3.3.2. The stress of Sue-ware kilns

Stress concerning the temperature difference. Due to the location conditions of the kiln’s construction, geological features like terrain and water become essential. When the bedrock is stable, a sunken kiln cannot be built, and if it is too fragile, there is the danger of cave-ins. Fire resistance is also important. Notably, the ceiling part of the firing chamber is where the temperature rises the most, and if it cannot endure the high temperature, the ceiling collapses. If the ceiling temperature is more than 200° higher than the floor surface, and someone wants to bake the product at 1150°, the combustion ceiling will be as hot as 1350°. Not much base soil can withstand such high temperatures.

Contraction stress concerning the sintering. Clay is said to shrink by 10 per cent when dried and by 10 per cent more when sintered at 1100° or higher. If the ground is good, the ratio will decrease, but the shrinkage due to drying and firing will be 10 per cent. If the wall surfaces of the kiln have the same clay, a 5 m long tunnel kiln will shrink about 50 cm and a 10 m long kiln about 1 m. Since it touches the ground, a gap is created between it and the ground, and it does not shrink so much due to cracking, but the kiln itself also receives immense shrinkage stress due to firing. Products are not fired several times, but kilns are heated over and over again. Therefore, the already-fired material is added and kneaded into clay to suppress
the shrinkage as much as possible to build the kiln wall’s surfaces.

**Fuel consumption and the soil’s fire resistance.** Even in modern brick kilns, old bricks that have already been baked are preferred. In the case of new materials such as firebricks, the fire resistance is high, but since a large amount of heat is required to burn the bricks, older firebricks that have been baked are most effective (Furutani 1994: 49). Even modern potters reuse materials from old multi-chambered climbing kilns instead of firebricks to economize fuel. The fire resistance of modern firebricks is high, and a large amount of fuel is necessary to heat them, but traditional clay bricks are already baked, so they warm up quickly and save on fuel (Furutani 1981: 105). If such information is applied to the Sue kiln, it is not always necessary to select a ground with extremely high fire resistance. Although it is necessary to have a degree of fire resistance and stability that can prevent a ceiling collapse, if the degree of fire resistance is too high, fuel consumption will increase. It is better to choose the right ground. There is also the opinion that kilns made of soil of the same clay quality as potter’s clay are suitable (Ōgami 1981: 26).

In the Sue-ware tunnel kiln, it was common to mix chopped straw with a length of 3 to 5 cm into the ceiling frame. A similar mixture of clay and susa (straw) is used for the clay walls of modern Japanese architecture. In modern earth walls, it is sometimes explained that the susa fibers play the role of connecting clay. However, in Sue kilns, the effect is only temporary because the plant fibers are burned out by the fire. As a result of measuring the shrinkage rate of clay mixed with straw, it can be confirmed that the clay that the shrinkage by about 20 per cent depending on drying and firing is reduced by 10 per cent (Kidachi 2010: 113). Because there are few experimental cases, it is necessary to confirm the effect with a large amount of soil.

3.4. The whole life of a kiln: the reuse of a “tunnel kiln”

3.4.1. The diversion of kiln walls

There are examples of kiln sites where the floor of the kiln has been planed. Moriuchi Shuzo thought that the burnt floor might have been planed off to be used as a material for the kiln walls. (Moriuchi 2002). General excavations focus on the construction and operation of kilns but have not fully considered the post-abolition phase. The remaining evidence is not only from the construction to the abolition, but also contains all from the abolition to the present, so the life history of a kiln should be investigated and considered an important point. According to Tsunejiro Ito, who has traditional skills in charcoal-making and slash-and-burn cultivation, charcoal-making craftsmen excavated the old Sue-ware kiln site, collected the kiln walls, and crushed and mixed them into the new charcoal-made kiln wall soil. The sand-like “fired powder” from the kiln wall had already been burned and contracted. If this were included, the kiln would become solid, and the shrinkage rate of the kiln walls would be minimized. For charcoal-making craftsmen, Sue-ware kiln sites become valuable sources of knowledge (Kidachi 2012: 26–27).

Such conversion was probably not only limited to present-day charcoal kilns. From cases where the floor of Sue-ware kiln sites was scratched off, it is supposed that collapsed ceilings and side walls were brought out from where they belonged. It is necessary to check not only the floor leveling but also the preservation of the kiln wall pieces buried in the soil. Although it is challenging to specify when the material was taken out, it should be considered whether it was immediately after the kiln was abolished or after some time had passed.

3.4.2. Analysis to exclude mixed objects

The more detailed the examination, the more the possibility that the ceiling has been taken away for reuse, as described above, becomes clear, but it is limited to the sunken kiln type. Most of the ceiling frame constructions left little room for investigation because the ceiling collapsed quickly. Excavation location information is no longer sufficient for analysis in the kiln. It is possible that some of the artefacts on the floor are newer than when the kiln was in operation, and detailed observation of the stratigraphic deposits and accompanying artefacts is essential. However, there have been few attempts to reconstruct various activities from the kilns’ buried condition. There are even cases where the soil layer pattern in the kiln is not available, and even if it were, there are many cases where no consideration has been given to its meaning. Even when the excavated material from the floor is reported, it is necessary to think about various situations that may have arisen after the abolition of the kiln.

Even if it was confirmed that there was no prospective mixing, and in the case that the old stoneware fragments were used as a fired pillar at the time of the final kiln firing, the concept of reliable floor material would collapse. It is important to note that kiln artifacts may have been relocated, whether they are in the ash pile or inside the kiln. The “mixed products” themselves are evidence of reuse of the kiln, which is also historically accurate. A detailed examination should consider the time of reuse and the method of the investigation itself. The life history of the kiln cannot be analyzed only through the perception that it was disturbed.

3.4.3. The kiln’s life history

In traditional Japanese archeology, the reliable extraction of artifacts at the beginning of the operation without prospective mixing was an essential viewpoint for investigation. However, the actual condition cannot be approached unless the life of the kiln is investigated. Why was a kiln built there? Who and where did they get the
bases for placing the pottery in the kiln? Where was the clay collected, and where was the workshop? How can the flow lines related to kiln firing be restored? What was the nature of the surrounding environment before, during and after the kiln operation? After the kiln was shut down, was it left alone, or was it reused? In the future, it will be necessary not only to discard artifacts of different ages from the kiln as mixed products but also to ask why they were mixed.

We have turned away from that analysis and focused only on the time the kiln was operating. From now on, we need to look a little further. It is possible that the state that we had assumed for the appearance of the kiln at the time of operation was the result of reuse after its abolition. If we do not pay attention to the kiln’s whole life, including the time after abolition, we cannot reconstruct the appearance at the time of operation.

The tunnel kiln is a simple construction, but various types of knowledge and information are used in making it. The excavated Sue kilns on the Japanese archipelago are numerous (Kiln Research Society 2010). To investigate the actual situation in detail, it is necessary to carry out firing experiments and detailed observation of the remains while keeping in mind the basic principles of the kiln described above. If we do not have the technology to fire a kiln, we cannot clarify the meaning of the kiln structure. We have been forced to experience it by repeating firing experiments (Kidachi et al. 2010). This is only an interim report on the research, but we hope it will help to observe the remains of the kilns and consider their function.

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Abstract: Archaeological research on kiln sites involves a wide range of additional disciplines in order to answer questions that archaeologists pose on their material and findings. Since kiln research typically poses questions on material used and processed, on the construction of kilns and firing technology which can only be solved with methods from natural science and engineering, kiln research is interdisciplinary in the first place. This essay summarizes the experiences of a decade of decidedly interdisciplinary research at the Nakadake Sanroku Kiln Site Center and other projects, tries to categorize the various patterns of collaboration and emphasizes the importance of an “agile” approach, which turned out to improve the results significantly as compared to traditional interdisciplinary research patterns.

Keywords: Agile Research, Interdisciplinarity, Archaeometry, Natural Sciences, Engineering, Research Process, Communication

4.1. Kiln research and interdisciplinarity

Archaeology benefits greatly from methods, theories and tools borrowed from other disciplines. Our sources are material remains of human life uncovered from the soil. Our method is excavating and documenting with words, drawings, photography, structured data and 3D data. The technology for excavating and documenting is getting increasingly sophisticated in the course of technological evolution in other disciplines, and recent developments are breathtaking. But excavation and documentation alone does not create a sensible narrative for understanding the past, the society, or whatever we are looking for to understand. Archaeologists need knowledge, ideas, methods, and tools from other sciences in order to make sense of their sources.

Kiln research is one of those fields of archaeological studies that are particularly dependent on interdisciplinary work. The construction and material of a kiln, the firing process and the firing material have to be understood from the point of view of an engineer as well as a potterer, excavated materials have to be handed over to mineralogists and other specialists in material sciences in order to understand the heat stress on the material and draw conclusion about temperatures and firing duration. Geologists can help finding sources of raw materials and, together with mineralogists, can offer hypotheses about the processing of the raw materials into an intermediate product that is then fired in the kiln. Of course, experiments under strict scientific observation and in cooperation with potters and other practitioners – whose expertise from another non-scholarly angle is highly valued – can help solving this problem from an additional angle. This is in contrast to a more archaeocentric and discipline oriented understanding, an understanding that is more focussed on problems, and which adds methods from various disciplines and even non-scientific knowledge to a project when needed. Thus, the constellation of disciplines involved in a problem may change in the course of the ongoing research due to new insights. However, the archaeologist stays in the center since research on kiln sites as such almost always starts with the finds and findings – the typical matter of archaeological study.

The interdisciplinary aspect in kiln research is not limited to questions of materials and technology: The social and political organisation of the craftsmen, accessibility of material and distribution of products as well as their role in the historical development of the region are another important aspect. In these cases kiln research is more leaning towards the humanities and collaboration with historians, sociologists, economists – to mention only the most obvious relations. This book introduces studies that deal with parts of all of these aspects in different regions and times, but this essay shall concentrate on cooperation regarding the technological and material aspects rather than on cooperation with researchers from other disciplines in the humanities. Cooperations between archaeologists and researchers from the natural sciences or engineering departments can pose problems on a research project because of the different “cultures” or traditions in these departments as compared to the humanities.