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Radiocarbon dating of residual organic matter in travertine formed along the Yumoto Fault in Oga Peninsula, northeast Japan: Implications for long-term hot spring activity under the influence of earthquakes

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ABSTRACT

Radiocarbon dating was performed on trace amounts of organic matter included in travertines formed along the Yumoto fault in Oga Peninsula, NE Japan. The reliability of the dating method was confirmed by the consistency of ages obtained with the stratigraphy of the travertine mound and the ratio of carbon stable isotopes. The radiocarbon chronology of the travertines shows that (1) the hot springs at Oga have been active for approximately 29,000 years, with average depositional rates ranging from 0.24 to 1.75 mm/yr, and (2) the principal hot spring activity has migrated southward with time. Variations in the accumulation rates and the progressive migration of the main focus of the hot spring activity imply irregular spring behaviour. This behaviour has not been influenced by paleoclimate, but may have been controlled by the earthquakes that occur frequently in the region around Oga Peninsula.

1. Introduction

Calcium carbonate deposits precipitated in fluvial, lacustrine and terrestrial environments from thermal water are referred to as *travertines* (in this paper, we consistently use the name travertine, regardless of the lithofacies characteristics; Ford and Pedley, 1996; Pentecost, 2005; Pedley, 2009). Travertines are widespread all over the world, particularly in regions underlain by carbonate bedrock and in active geothermal areas, such as the classical Europe–Mediterranean region (e.g., Pentecost, 1995; Pedley, 2009) and Yellowstone National Park (e.g., Fouke et al., 2000; Chafetz and Guidry, 2003; Fouke, 2011). Travertine has been used as a natural archive for tracing hot spring activity (e.g., Crossey et al., 2006; Veysey et al., 2008).

Age control of travertine accumulation is important for the interpretation of the long-term history of hot springs (Pentecost, 2005). Radiocarbon dating based on the decay of ^{14}C is the most extensively used method for dating deposits up to several tens of thousands of years old (e.g., Reimer et al., 2009). Radiocarbon dating has been performed mostly in carbonate minerals consisting of travertine (e.g., Srdoč et al., 1980, 1983, 1986; Preece, 1991; Fontes et al., 1996; Zak et al., 2002). However, when using radiometric methods to date carbonate minerals in travertine, there are often issues of reliability, particularly regarding the migration of both radiometric parent and daughter species during diagenesis and hard-water effects due to dead radiocarbon derived from the bedrock (e.g., Fontes et al., 1996; Genty et al., 1999). However, when organic matter from terrestrial plants deposited with carbonate on the surface of the travertine mound is preserved, radiocarbon techniques may provide the most reliable ages for travertine (e.g., Pazdur et al., 1988; Winsborough et al., 1996; Caran et al., 2001; Rainey and Jones, 2010). The development of accelerator mass spectrometry (AMS) ^{14}C dating techniques has made it possible to obtain precise ages even for travertine with trace organic carbon contents (e.g., Wagner, 1998). However there are only several examples applying this method to date travertines.

It is well known that travertine development is affected by climate and tectonics. Many radiometric dates of travertine in European and Mediterranean regions have shown that travertine accumulation is associated with shallow water circulation, essentially under climate control (e.g., Henning et al., 1983; Horvatinčić et al., 2003; Pentecost, 2005; Faccenna et al., 2008; Zentmyer et al., 2008; Sun and Liu, 2010). However, only a few studies have considered the controlling factors

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of travertine formation associated with thermal water from an endogenic source and/or geothermal activity. If hot springs discharge in regions that are tectonically active, earthquakes and fault movements could control the hot spring activity (Brogi and Capezzuoli, 2009; Brogi et al., 2010). The travertines in Tivoli in Italy and western Anatolia in Turkey, which are deposited along active faults, have been studied with the aim of clarifying the relationship between hot spring activity and faulting (e.g., Hancock, et al., 1999; Piper et al., 2007; Uysal et al., 2007; Faccenna, et al., 2008). In Japan, an active tectonic region under intense E–W compression associated with the subduction of oceanic plates, several small travertine masses have been found in geothermal areas and along large-scale faults (e.g., Kitano, 1963; Kitano and Hood, 1965; Takashima and Kano, 2005; Takashima et al., 2008). In the Oga Peninsula, a backarc region of northeast Japan, hot springs that discharge along the Yumoto fault, which is presumed to be active, are associated with travertine formation (Fig. 1). This is an ideal area to study the long-term history of hot springs under a tectonically active regime.

To clarify the long-term activity of hot springs and the factors that control the accumulation of travertine under the influence of frequent earthquakes and faulting, we investigated the lithofacies of the travertines along the Yumoto fault and determined their absolute ages by the radiocarbon dating method. The possible role of earthquakes on hot spring activity was discussed based on chronological data and historical records. Special consideration was also given to the validity of radiocarbon dating for the residual organic matter in the travertine. This study demonstrates that the ages obtained by this method are reliable and widely applicable to travertines deposited in late Quaternary.

2. Geological setting

A series of Eocene to late Quaternary deposits have developed in Oga Peninsula, a backarc region of NE Japan (Huzioka, 1959; Shiraishi, 2000; Oguchi et al., 2008). The crust of NE Japan had undergone E–W extension associated with the spreading of the Japan Sea during the early to late Miocene. Since the Pliocene, the succession of NE Japan has been shortened under the intense E–W compression stress field (Sato and Amano, 1991) accompanied by N–S trending folds and reverse faults. The western part of Oga Peninsula, where mainly Paleogene volcanic rocks are exposed, is mountainous with steep topography. Late Pleistocene marine terraces have developed in both the central and the northwestern parts of the peninsula (Shiraishi, 2000; Shiraishi et al., 2008). These terraces are underlain by middle Miocene to Pleistocene marine sediments.

The Oga and Yumoto hot springs are located at the northwestern part of Oga Peninsula along the prominent lineament of the NNE–SSW-trending Yumoto fault, which lies on the northern part of the topographic boundary between the central terraces and the western mountains (Fig. 1). Based on the tilting of terraces and the distribution of strata across the Yumoto fault, it has been assumed that the west side of the fault has been progressively undergoing uplift

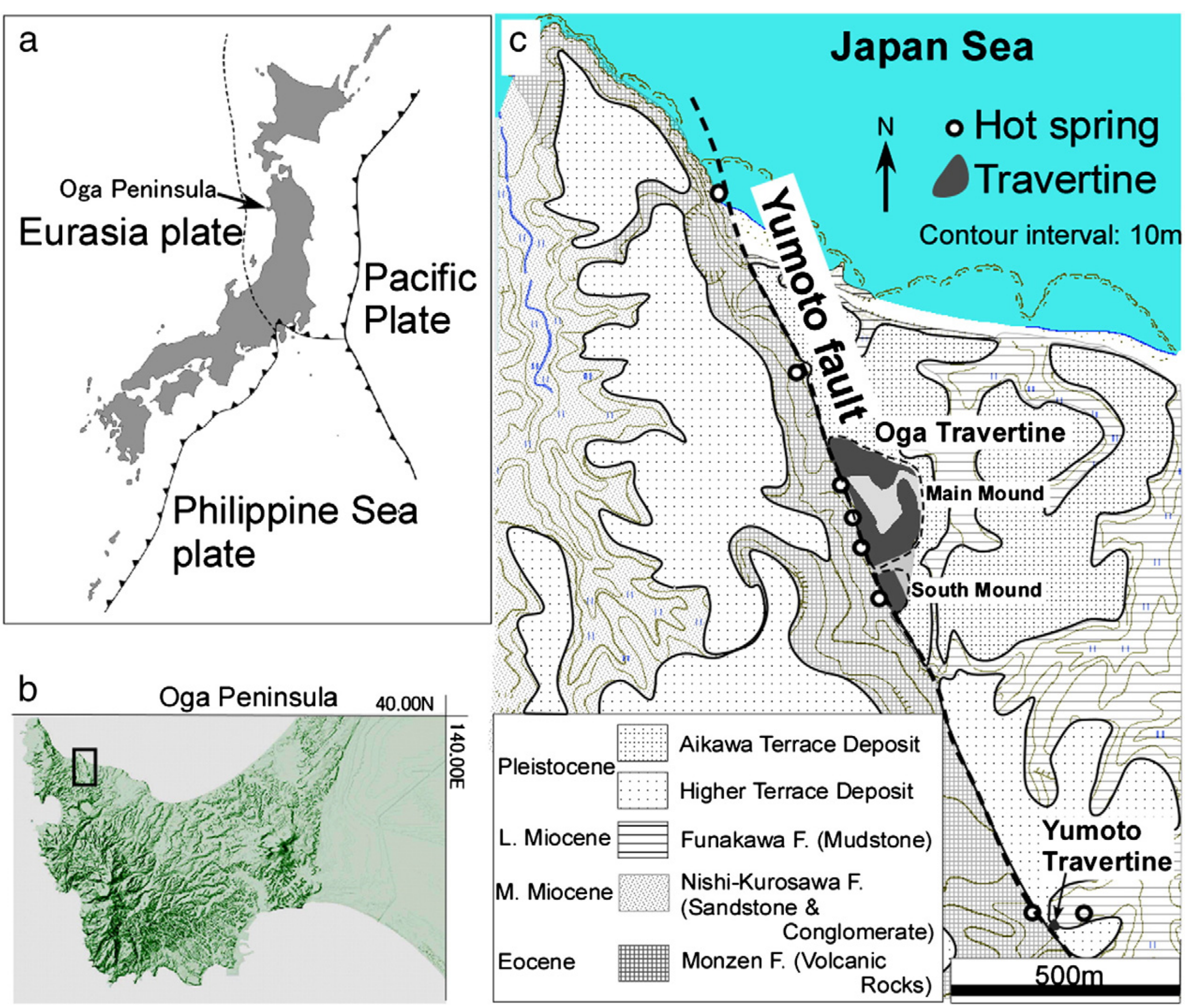


Fig. 1. a) Plate boundaries around Japan. b) Topographic map of Oga Peninsula. c) Geological map of the Oga and Yumoto hot springs area, Oga Peninsula. Yumoto fault, hot springs and travertines are shown in the map.

Fig. 2. Photograph of the Oga-main travertine mound (Outcrop 8 indicated in Fig. 3). The mound is approximately 8 m high.

(The research group for active faults, 1991). A distinct fault scarp has developed along the fault, with the west side approximately 20 m higher than the east side. The correlation of terraces across the Yumoto fault has not yet been confirmed. In the Yumoto–Oga hot springs, volcanic rocks of the late Eocene Monzen Formation on the west side and mudstones of late Miocene Funakawa Formation on the east side are juxtaposed along the Yumoto fault.

The travertine at Oga hot springs (The Oga travertine) was first reported by Chitani (1925). However, no detailed study of this travertine has been conducted during the past nine decades. The Oga travertine deposits lies at the foot of the fault scarp and on the Aikawa terrace, the lowest marine terrace developed in the NW part of Oga Peninsula, which is thought to have become emergent early during marine isotope stage 3 (MIS 3) at approximately 50,000 years ago (Shiraishi, 2000). The Oga travertine forms a terrace mound up to 8 m thick, 400 m in extent along the scarp, and 200 m in E–W width (Figs. 1c and 2). This large travertine mound consists of the main and the south mounds. The Oga travertine mound was quarried for metal smelting during the late 19th to early 20th centuries. Although approximately half of the travertine volume has been removed, including the boundary of the two mounds, many outcrops remain that are suitable for observation of the inner structure of the mound. In the Yumoto hot springs, 500 m south of the Oga hot springs along the Yumoto fault, another small travertine body that is several cubic meters in size has formed (the Yumoto travertine). At both the Yumoto and Oga hot springs, thermal waters are discharged from vents and wells along the scarp of the Yumoto fault. According to historical records (Akita Prefecture, 1881), the Yumoto hot springs have been used as a public bath since at least the early 17th century, while in the Oga hot springs, thermal water had not been discharged before mining operations had begun in the late 19th century. In the 1960s and 70s, several wells were bored in a search for a large amount of

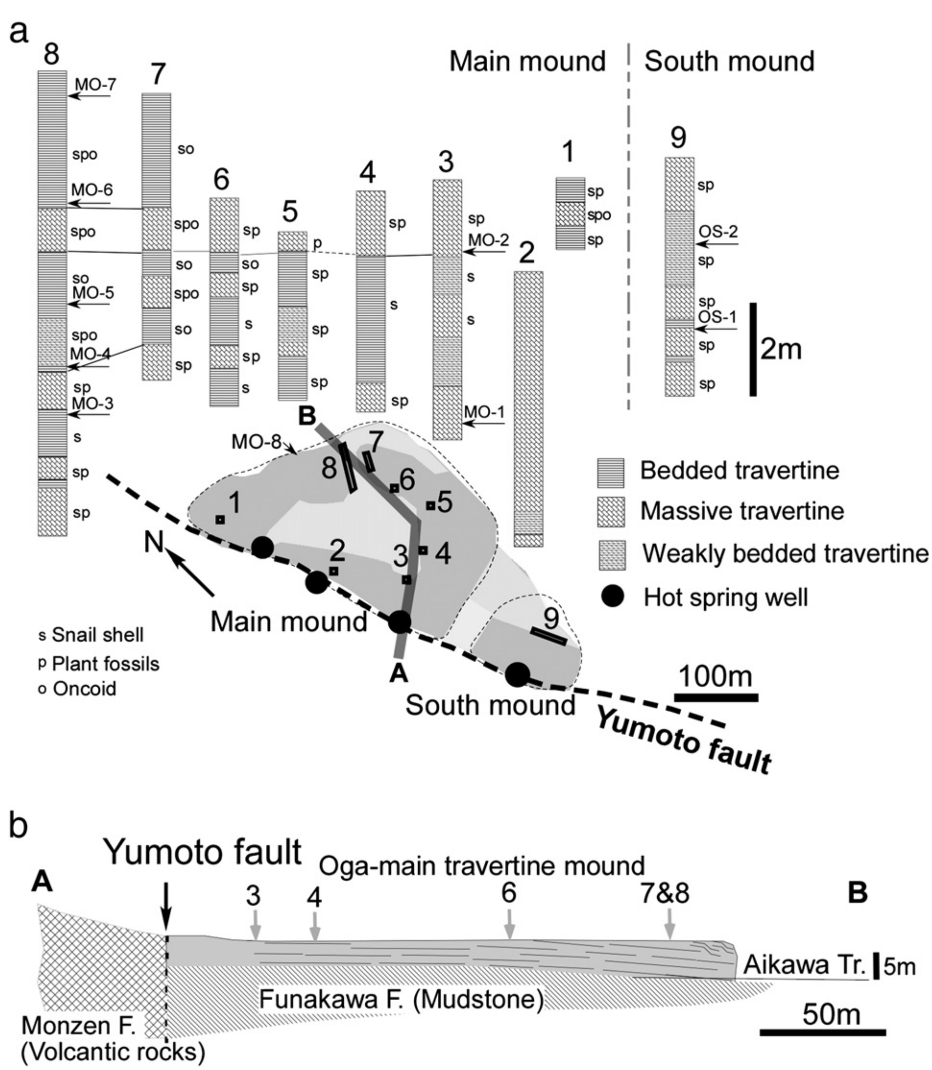


Fig. 3. a) Lithofacies of travertine mounds. The numbers indicated in the map correspond to the locations of outcrops where each column was made. b) Simplified cross-section of the Oga-main travertine mound.

thermal water in both areas. There are currently a few naturally flowing hot springs, and the thermal water is pumped from wells that are 10 to 50 m deep. Therefore, recent carbonate precipitations are only found inside pipes and along the effluent drains of the hot spring water.

The thermal water is of the near-neutral Na–Cl type, with a low Mg/Ca ratio (approximately 0.5) and a relatively high temperature ranging from 51 to 54 °C.

Recently, Furuhashi et al. (2008) studied the geochemical characteristics of the travertines as well as recent deposits and hot spring water from both the Oga and Yumoto hot springs. The ratios of carbon stable isotopes (δ^{13}C expressed relative to PDB) of modern deposits and travertines show similar values, ranging from −0.8 to 2.7‰. The ratios of oxygen stable isotopes (δ^{18}O expressed relative to SMOW) range from 17.1 and 18.4‰ for modern precipitation and from 19.8 to 22.3‰ for travertine. According to their interpretation, dissolved carbonate in the hot spring water originates from carbonate-rich shallow marine sediments of the middle Miocene Nishikurosawa Formation, which probably lie deep below the surface. The thermal waters of both the Yumoto and Oga hot springs are meteoric waters in origin and are preserved in marine sediments. The difference of δ^{18}O values between the past and modern deposits could be due to the amount of exchange between the carbonate rocks and thermal water being greater during former periods of travertine formation than today.

3. Methods

Mesoscopic facies observation and sample collection were carried out at all the accessible outcrops throughout the Oga travertine mound and Yumoto travertine (Fig. 3). The constituents of the travertines were determined using an X-ray diffractometer (Rigaku MultiFlex) with a Cu-Kα radiation at 40 kV and 30 mA and a scanning speed of 1°/mm. Analyses were carried out for bulk travertine samples and for samples of which the carbonate minerals had been removed by hydrochloric acid (HCl).

The organic carbon contents were measured for five samples from Oga -main mound and one from Oga-south mound (Table 1) by a CHN element analyser (Perkin-Elmer; 2004-2CHNS/O). Organic materials in the travertines were detected by elemental mapping using a scanning electron microscope with energy dispersive spectrometry (SEM-EDS) under low vacuum in the non-carbon coating mode.

The AMS radiocarbon dating method was applied to the residual organic matter included in the travertine samples. Eight samples were collected from the Oga-main travertine mound, two from the Oga-south mound, and one from the Yumoto travertine (Table 1, Fig. 3). Younger organic materials that became attached to the surface of the travertine samples after deposition were carefully removed. The samples were then treated with hydrochloric acid (<3 N) wash to remove carbonate minerals from organic matter (e.g., Winsborough et al., 1996). The radiocarbon age and δ^{13}C were measured at Beta Analytic Inc., Miami. The radiocarbon ages measured were converted to conventional radiocarbon ages (Stuiver and Polach, 1977) and then calibrated using the radiocarbon calibration program OxCal version 4.1.6 (Bronk Ramsay, 2009), which is available for the IntCal09 calibration curve (Reimer et al., 2009). The δ^{13}C values are reported relative to PDB.

Table 1
Organic carbon contents, δ^{13}C values of organic carbon and radiocarbon ages of travertines along Yumoto fault.

Sample	Organic carbon (permil)	δ^{13}C (permil)	^{14}C age (yrBP)	2σ cal BP range	Outcrop	Level (m)
OM-1	0.04	−23.6	22,940 ± 140	26,935–28,177	3	0
OM-2		−25.9	15,780 ± 70	18,716–19,305	3	3.2
OM-3	0.09	−25.6	21,160 ± 80	24,954–25,612	8	1.2
OM-4		−26.6	20,330 ± 80	23,923–24,498	8	2
OM-5	0.68	−25.6	16,450 ± 80	19,413–19,886	8	3.2
OM-6	0.31	−24.9	13,870 ± 60	16,772–17,154	8	5.2
OM-7	0.53	−25.9	11,400 ± 60	13,136–13,397	8	7.5
OM-8		−26.9	11,150 ± 60	12,796–13,211	Edge	0
OS-1		−25.3	9440 ± 60	10,512–11,069	9	1.8
OS-2	0.64	−26.5	5990 ± 40	6736–6942	9	3.5
YM-1		−24.2	4450 ± 40	4882–5289	Yumoto	

4. Results

4.1. Lithofacies of travertine

4.1.1. Composition of travertine

Plant fossils, such as stems of reeds, leaves, branches and trunks of trees, are present in layers throughout the Oga and Yumoto travertines (Fig. 3). The carbonaceous organic matter of plant fossils in the Oga travertine has decomposed and has almost entirely leached away. In the Yumoto travertine, however, organic matter from leaves and stems is still preserved. The travertines in both areas also contain abundant aquatic snail (Gastropoda) shells (Fig. 3). The ubiquity of these shells indicates the former existence of an environment in which shallow pools with flowing water were widespread across the surface of the travertine mound.

The results of the bulk sample analysis showed that all the travertine carbonates along the Yumoto fault are calcite, while those of recent deposits are all aragonite. The travertines are composed of mostly calcium carbonate (90.0–99.6 wt.%), with subordinate hydrated ferric iron minerals (predominantly goethite) and trace amounts of siliciclastic minerals and organic matter. The organic carbon contents range from 0.04 to 0.68‰ (Table 1). The organic materials in the travertine can be clearly distinguished from the carbonate minerals, as there is a domain with both a high concentration of carbon and an absence of calcium in the element maps (Fig. 4a,b and c). Under SEM (Fig. 4a), they are isolated among the carbonate matrix and show rounded shapes with no specific structure as tissues of plants, and the size mostly less than 50 μm.

4.1.2. Facies of Oga-main travertine mound

A common feature in the Oga-main travertine mound is bedding and laminae with a thickness ranging from one to tens of millimetres. In the columns in Fig. 3, the lithofacies of the travertine was classified into bedded, weakly bedded and massive on the basis of the degree of bedding and lamination development. The bedding is almost parallel to the topography of the terrace mound, which dips gently (<10°) towards the NE or is sub-horizontal (Fig. 3). At the edge of the mound (distal part), the travertine ends with cascades and steep cliff topographies, where stepwise bedding forms often develop. In the proximal part near the fault scarp, lithofacies of travertine typically develop with dense and poorly laminated fabric and scarce cavities and fossils (columns 2 and 3 in Figs. 3, 5a). The intermediate to distal part of the mound is characterised by bedded travertine, which is generally porous and crumbly and commonly contains plant and snail fossils (Fig. 5b and c). This lithofacies is similar to that of calcareous deposits developed under an ambient temperature condition (e.g., Ford and Pedley, 1996; Guo and Riding, 1998; Pentecost, 2005). The main components of the bedded travertine are predominantly aggregates of subspherical particles that are hundreds of micrometer in size and subordinately stacks of thin platy fragments that might be paper-thin rafts (Fig. 5d). The relative content of these main components and the contrast of pore volume define the bedding of the travertine. The bedded travertine is intercalated by several massive layers that are 30 to 150 cm thick (Fig. 5b and e) with abundant plant fossils and cavities of irregular size and shape, suggesting that a large amount of plant material may occasionally flow into the travertine mound. Hollow places among the horizontal beds in the distal part are filled with numerous oncoids (Fig. 5f), indicating the presence of a water pool environment. The oncoids grow

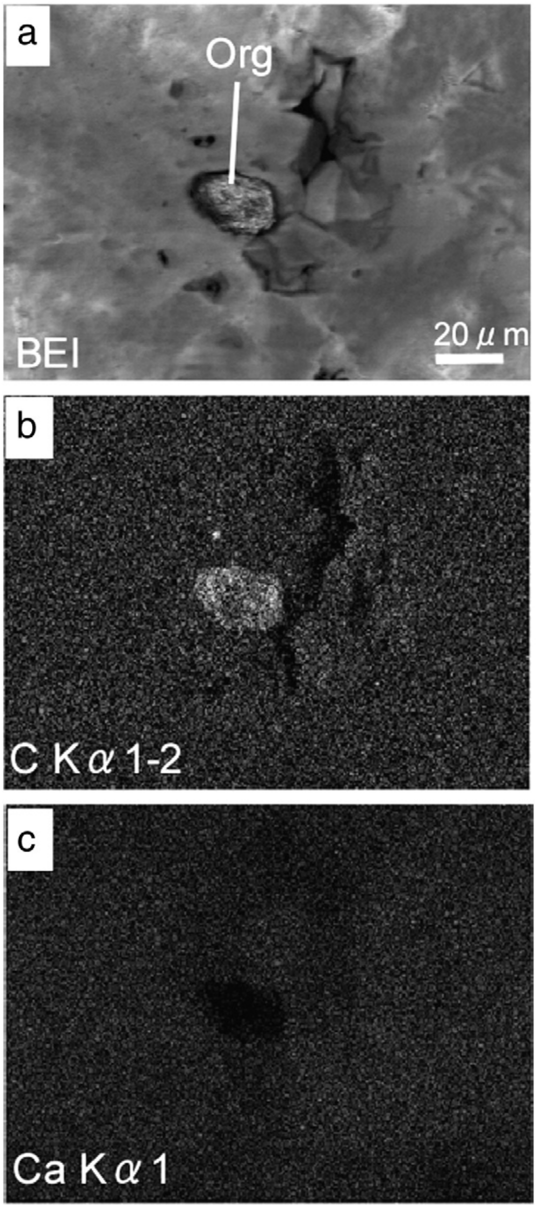


Fig. 4. Backscattered electron image a), and EDS elementary map showing the distribution of carbon b) and calcium c) of an area of travertine from outcrop 8 in the Oga-main mound. Residual organic matter among a carbonate matrix (Org in a)) is detected as a domain with both a relatively high concentration of carbon (white area in b)) and the absence of calcium (dark area in c)).

around nuclei. Each nucleus is a small clastic plant or snail shell fragment with a spherical or constricted ellipsoidal form and a diameter ranging from 5 to 30 mm. Recrystallisation of the travertine deposit prevails over the mound, although syn-depositional textures can be also recognised by mesoscopic observation. Recrystallised calcite grains are coarsely grown, particularly in the stratigraphically lower horizon. Well-defined erosional surfaces and layers containing abundant siliciclastic materials are not visible in the Oga travertine mound. Fracture-fill breccias and healed cracks are not found in the mound except in the proximal part near the fault scarp, where a weakly brecciated horizon is present.

4.1.3. Facies of Oga-south travertine mound

The Oga-south travertine mound probably formed in a different depositional environment from the main mound. Although bedding is also recognisable in the south travertine mound, the texture is relatively massive, particularly in the lower horizon (column 9 in Fig. 3). High concentrations of plant fossils are included in the travertine (Fig. 5g), but the organic carbon content is very low—approximately 0.64‰ (Table 1)—although the content is higher than those at other travertines along the Yumoto fault. The travertine also contains abundant ferric hydrates and siliciclastic components such as quartz, feldspar and clay minerals, which have a total content of up to 3.5 wt.%. These characteristics imply that the Oga-south travertine mound accumulated large amounts of plants and soils flown from the fault scarp and the terrace behind. A micritic texture is preserved in the travertine deposit, although recrystallised calcite spar is partially growing.

4.1.4. Facies of the Yumoto travertine

A small travertine mass developed in a low scarp along a short stream in the Yumoto hot springs, which is several tens of metres north of the recent hot spring well. The travertine shows a stromatolite texture mainly consisting of stacks of folded layers of gently to steeply dipping (Fig. 5h). Diagenesis has not yet occurred, so there is unconsolidated matter with a reddish brown colour between carbonate layers. These layers are mixtures of ferric hydrate and clay, which also contain tissues of plants.

4.2. Radiocarbon ages and $\delta^{13}C$ values

The radiocarbon ages of 11 travertine samples collected along the Yumoto fault range from 28,177 cal BP (calendar years BP; BP = 1950 AD) to 4882 cal BP and are consistently in stratigraphic order (Table 1, Fig. 6). The sample from the lowermost horizon collected in the Oga-main travertine mound (sample OM-1, at the base of column 2) yielded ages of 26,935–28,177 cal BP. Sample OM-2, collected from a horizon 3.2 m above OM-1, yielded dates of 18,716–19,305 cal BP. Samples OM-3, OM-4, OM-5 and OM-6 from outcrop 8, which are numbered in stratigraphic sequence from lower horizons upwards, yielded dates of 24,954–25,612, 23,923–24,498, 19,413–19,886 and 16,772–17,154 cal BP, respectively. Sample OM-7, from the summit of the Oga-main mound, and OM-8, from the foot of the cascade at the end of the mound, yielded dates of 13,136–13,397 and 12,796–13,211 cal BP, respectively. Samples OS-1 and OS-2 collected from horizons 1.8 m and 3.6 m above base in column 10 of the Oga-south mound yielded young ages of 10,512–11,069 and 6736–6943 cal BP, respectively. The Yumoto travertine (YM-1) has the youngest radiocarbon age of 4882–5289 cal BP.

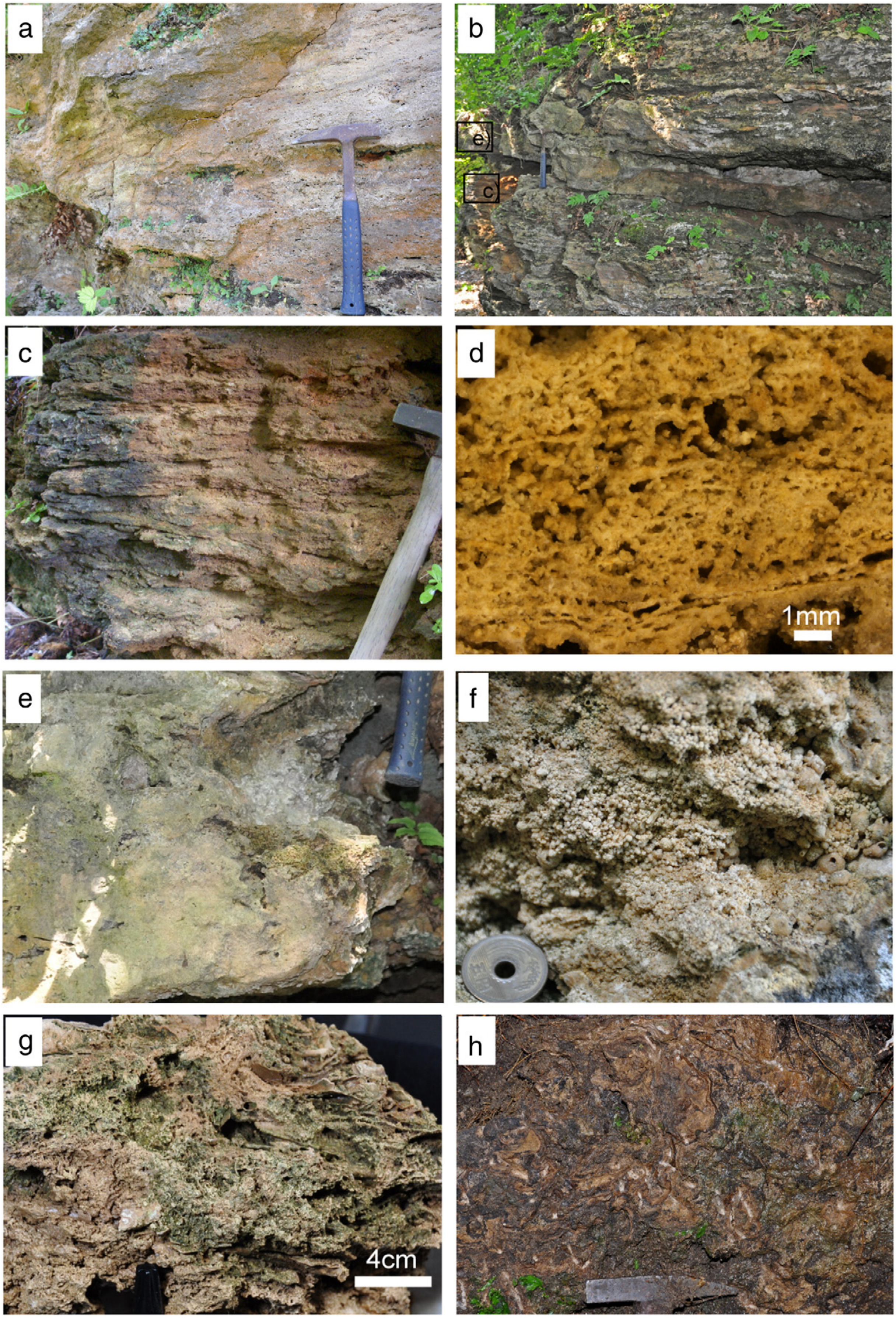
The $\delta^{13}C$ (PDB) values of the dated travertine samples are also shown in Table 1. The values are significantly negative, ranging from −23.6 to −26.9‰.

5. Discussion

5.1. Reliability of dating

The radiocarbon dating of the trace amounts of organic matter present in the travertine yielded late Pleistocene to Holocene ages ranging from approximately 28,200 to 4900 years ago. Pazdur et al. (1988), Winsborough et al. (1996) and Caran et al. (2001) discussed the validity of this method and noted that the organic matter should ideally be: 1) contemporary with calcite precipitation when incorporated in the travertine, 2) excluded from later contamination, 3) prevented from secondary fractionation, and 4) unaffected by carbon derived from non-contemporaneous environments (i.e., hard-water effects).

The dated organic matter in the travertine meets these criteria according to the following field observations and geochemical data: 1) The travertines studied contain abundant macro plant fossils derived from land vegetation, which were undoubtedly deposited on the travertine mound contemporaneously with the carbonate. 2) The ages obtained are consistent with their stratigraphic order. Besides, there is no evidence suggesting a long hiatus in sedimentation in the travertine mounds. Therefore, organisms were buried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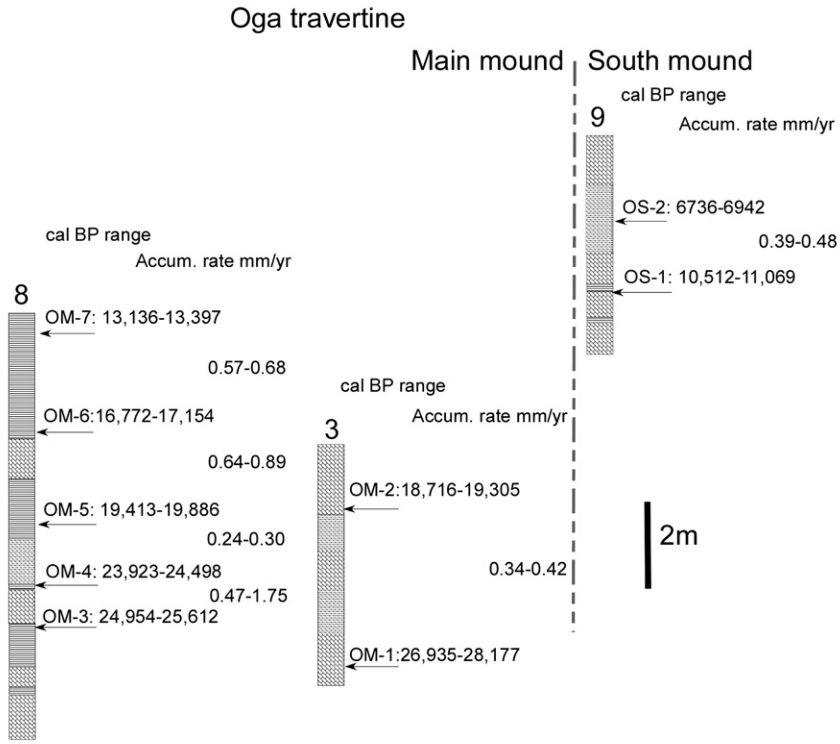

Fig. 6. Diagrams showing radiocarbon ages and inferred average accumulation rates of Oga travertines.

successively during aggradation of the travertine mound, which would have preserved residual organic matter from later contamination. 3) The travertines do not contain minerals that form preferentially under reduced conditions, in which the fractionation of carbon by anaerobic microbial processes could have occurred. 4) Finally, all of the dated samples have very low δ^{13}C values of $<-23.0‰$ (Table 1), which implies that the carbon mainly has a C3 plant origin and is likely to have been little affected by carbon derived from the host carbonate rocks of the Nishikurosawa Formation, which produce δ^{13}C values of -6.7 to 1.6‰ (Furuhashi et al., 2008). These facts show that radiocarbon dating for residual organic matter can be valid even for travertine that contains only trace amounts.

5.2. Reconstruction of hot spring activity along the Yumoto fault

Figure 6 shows that the average accumulation rates between the dated horizons in the Oga travertine mounds range from 0.24 to 1.75 mm/yr. These accumulation rates are far lower than those of thermogen travertines and are comparable to those precipitated at ambient water temperature (e.g., Kitano, 1963; Chafetz and Guidry, 2003; Kano et al., 2003; Pentecost, 2005; Arenas et al., 2010; Gradziński, 2010; Vázquez-Urbez et al., 2010). Accumulation rates vary with the position and lithofacies in the travertine mound. In the Oga-main travertine mound, the mean deposition rate of the massive travertine layers is estimated to be 0.47 to 1.75 mm/yr from the ages and thickness between OM-3 and 4. On the other hand, the deposition rate of the bedded travertine is only 0.24 to 0.68 mm/yr.

The horizon with the oldest radiocarbon age in this study (corresponding to the base level of column 2) is at least several tens of centimetres higher than the basal horizon of the Oga travertine mound. Therefore, the beginning of the accumulation of the travertine can be estimated between 28,000 and 30,000 years ago, assuming accumulation rates ranging from 0.41 to 0.34 mm/yr. In the Oga-south travertine mound (column 9), the dated horizons are 1.8 m higher than the basal level and 1.5 m lower than the summit. Therefore, using the accumulation rate for the south travertine (0.39–0.48 mm/yr), it can be estimated that its accumulation began between 14,000 and 16,000 years ago and terminated at an age between 2900 to 3800 years ago. In the Yumoto area, hot spring discharge has continued without the development of a large travertine mound since the age between 4900 and 5300 years ago.

In summary, since 29,000 years ago, hot spring activity has continued along the Yumoto fault, and the focus of hot spring activity has migrated progressively towards the southern area along the fault. Clear evidence of a hiatus in deposition, such as an erosional surface or intercalation of loess deposits, has not been found in the interior of travertine mounds. This result suggests that the hot springs have flowed more or less continuously without any long breaks in discharge.

5.3. Factors controlling hot spring activity

The formation of travertine is sensitive to the climate and the environment and can therefore be used as a tool for reconstruction of paleoclimate (e.g., Henning et al., 1983; Sweeting et al., 1991; Frank et al., 2000; Soligo et al., 2002; Martin-Algarra et al., 2003; Pentecost, 2005; Sun and Liu, 2010). In Europe and Mediterranean regions, radiometric ages have shown that interglacial periods from 125,000 to 115,000 years ago and from 9000 to 4000 years ago were the optimum for travertine formation, while during glacial periods, particularly from 40,000 to 20,000 years ago, little travertine was

Fig. 5. a) Lithofacies of the proximal part (Outcrop 3) of the Oga-main mound. b) Outcrop of bedded travertine intercalated by a massive layer in the intermediate part of (Outcrop 8) the Oga-main mound. c) Close-up of a bedded travertine (area c) in b)). d) Crumbly and porous fabric of the intermediate to distal parts of the Oga-main mound, which consists of spherical particles that are randomly connected and fragments of thin plates. e) Close-up of a massive travertine layer (area e) in b)). f) Oncoids concentrated in the distal part of the Oga-main travertine mound g) Lithofacies of the Oga-south travertine mound, which is rich in fossils of snails and plants. h) Lithofacies of the Yumoto travertine.

forming. A humid climate and high-stands of sea level during interglacial periods would raise the water table and enhance fluid circulation near the surface, enabling travertine deposition. Japan did not have any ice sheet cover during the last glacial period, but the climate on the Japan Sea side of NE Japan has been interpreted as being cooler and drier than today (e.g., Tsukada, 1983). In the Oga region, however, accumulation of travertine continued from 29,000 to 3400 years ago along the Yumoto fault. Assuming 40 °C/km as the geothermal gradient for Oga Peninsula (e.g., Tanaka et al., 1999) and a minimal heat loss during the ascent of thermal water, the depth of the reservoir of the Oga and Yumoto hot springs at 55 °C is estimated to be 1000 m. Therefore, it can be concluded that thermal water of the Oga hot springs may have upwelled from deep underground and been little influenced by the fluctuation of the water table level caused by climate change.

The Oga Peninsula region has been tectonically active throughout the Quaternary under an intense E–W compressive stress field. Seismic activity associated with reverse faulting occurs frequently in this region (e.g., Sato and Amano, 1991; Okamura et al., 1995). Previous reports on hot springs and travertines have pointed out a close relationship between tectonic activity and travertine deposition (e.g., Muir Wood, 1994; Hancock, et al., 1999; Piper et al., 2007; Uysal et al., 2007). The possible effects of faulting and earthquake activity on travertine deposition are summarised as follows. 1) Due to intense fracturing by repeated faulting, the zone of the active fault acts as a conduit for the circulation and discharge of thermal water. 2) Because a vent of thermal water that has been opened by fracturing in a seismic event would be sealed by carbonate precipitation in a short time, travertine deposition is likely to be rather episodic. 3) Large seismic events could induce a change of volumetric strain around the active fault, which would affect subsurface hydrodynamics. Therefore, the hot spring activity and travertine accumulation along Yumoto fault may also have been influenced by faulting and seismic events.

Information of past fault activity can often be obtained by analysing extensional fissures (Hancock et al., 1999; Piper et al., 2007; Uysal et al., 2007) and brittle deformation structures (e.g., Faccenna et al., 2008; Brogi et al., 2010) that developed in travertine mounds. The dating of fissure ridge travertine may also provide some important information for establishing recurrence intervals of faulting (Hancock et al., 1999; Piper et al., 2007; Uysal et al., 2007). The onset of the Oga travertine deposition could have been due to movement along the Yumoto fault because large-scale fracturing of the crust is necessary for the discharge of large volumes of thermal water. Unfortunately, extensional fissures and deformation structures such as offsets of mounds, intense fractures and breccias caused by later fault movements have not been found in the interior of the travertine along the Yumoto fault.

The Yumoto fault has formed along interface between late Eocene volcanic rocks and late Miocene to Pleistocene mudstones in the Yumoto–Oga hot springs area. A large difference in the mechanical properties between the two lithologies likely induces fractures at the interface during earthquakes even associated with another fault activity. Breakage of the carbonate seal along the fault plane could open new conduits for thermal water, resulting in a temporary break in discharge under the reduced pressure. Therefore, hot spring flow and travertine formation along the Yumoto fault could have been controlled by local earthquake activity as well as activity of the fault itself.

Two processes might affect the hot spring activity after a temporary stoppage in flow. In one case, the main activity would shift to a new conduit. Shifts in activity to the south along the Yumoto fault occurred at least twice — at approximately 15,000 to 13,000 and 5000 to 3400 years ago.

In the other case, a previously inactive vent would have been reactivated when new fractures became sealed by the precipitation of carbonate minerals. Some evidences supporting this scenario can be found in local historic literatures that record hot spring activity associated with earthquakes since the middle of the 18th century (Table 2; Akita prefecture, 1881; Usami, 2003). According to the records, large earthquake movements seem to have frequently caused the Yumoto hot springs to stop flowing, with the temporary migration of discharge to other sites (Table 2). Large earthquakes that might have caused strong ground motion in the Oga Peninsula have occurred at least 13 times during the last 300 years (Fig. 7). The date of each event recorded in the local literature (Table 2) either coincides or nearly coincides with those of earthquakes that had been confirmed historically (Fig. 7). Both the 1810 Bunka–Oga and 1939 Showa–Oga earthquakes, which had epicentres probably located in the Oga Peninsula (Fig. 7), resulting in major destruction in this area. Many reports and papers (written in Japanese and listed by Usami, 2003) provide reliable records for the periods of flow stoppage and recovery of the Yumoto hot springs that are linked to earthquakes. In the Bunka–Oga earthquake, thermal water in the Yumoto hot springs stopped for a period with new discharge along the fault on the seashore that continued for several years after the earthquakes. Immediately after the Showa–Oga earthquake, thermal water spouted from many places around the Oga travertine mound for several months, while a gushing flow from the Yumoto hot springs intensified for several days then gradually decreased and ultimately stopped approximately three months later. In this way, frequent seismic events have led to short-term fluctuations in the hot spring activity along the Yumoto fault with inactive intervals of several to several tens of years during periods of flow of several tens to one hundred years.

5.4. Carbonate mineral phases of past and modern deposits

In the Oga and Yumoto hot springs, carbonate minerals consisting of travertine mounds are all calcite, whereas aragonite is presently precipitated from hot spring water. Metastable aragonite deposition preferentially occurs under high temperature and high Mg/Ca ratio conditions (Pentecost, 2005). The lower limit temperature for aragonite precipitation at a low Mg/Ca ratio is approximately 40 °C, a temperature under which only calcite will be deposited. The Oga and Yumoto hot springs discharge thermal water with temperature ranging from 51 to 55 °C and a low Mg/Ca ratio (approximately 0.5; Table 1) at which aragonite tends to be deposited.

Table 2
Hot spring activity in relation to recorded earthquake since the middle 18th century.

Event	Date (year/month/day)	Hot spring activity
(1)[a]	1736–1740	Discharge in Yumoto hot springs temporarily stopped for 15 years.
(2)[a]	1767/3/8	Discharge from two of three vents in Yumoto area then recovered several tens of years later.
(3)[a]	1780/7/19	Discharge in Yumoto hot springs temporarily Stopped for 7 years.
(4)[a,b]	1810/11/25	Discharge in Yumoto area stopped for several years. New discharge occurred on the seashore.
(5)[a]	1830–1843	Discharge stopped in Yumoto area, while the discharge on the seashore increased. Then, Yumoto hot springs recovered three years later.
(6)[b]	1939/5/1	Gushing from Yumoto hot springs temporarily intensified for several days and then gradually decreased for three months before stopping. Large volume of thermal water discharged from many around Oga travertine mound for several months
(7)[b]	1983/5/26	Distinct changes were not detected. Water became turbid in a few wells.

[a] Akita prefecture (1881).
[b] Usami (2003).

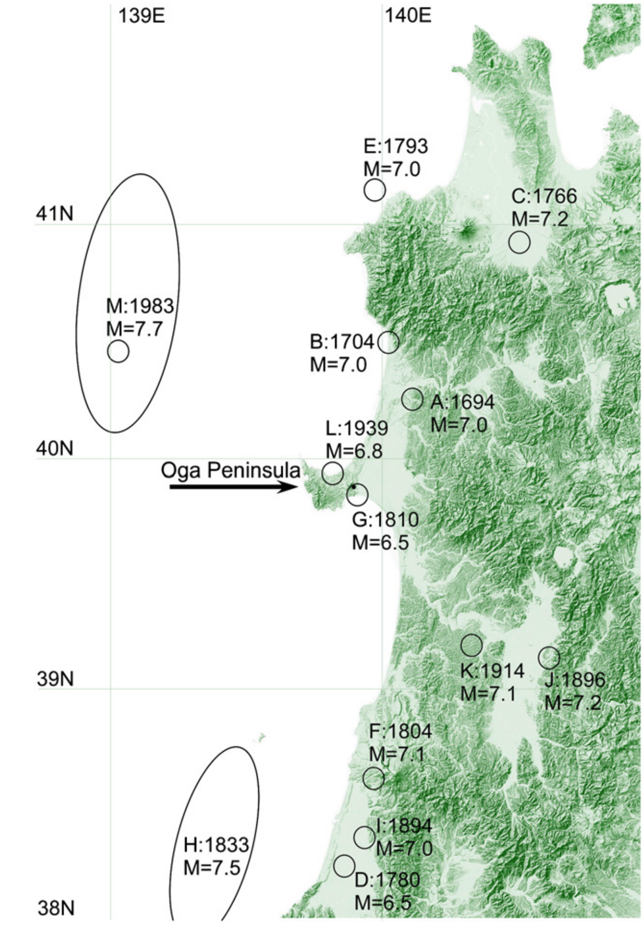

Fig. 7. Dates, epicentres and magnitudes of large earthquakes that possibly produced strong ground motion in the Oga Peninsula for the last 300 years. A: Noshiro, B: Iwadate, C: Tsugaru, D: Sakata, E: Ajigasawa, F: Kisakata, G: Bunka–Oga, H: Shonai-oki, I: Shonai, J: Rikuu, K: Akita-Senboku, L: Showa–Oga, M: Nihonkai-chubu.

Furuhashi et al. (2008) reported that the $\delta^{18}O$ values of the Oga travertines are approximately 3.5‰ lower than those of modern calcareous deposits. They primarily discussed the effect of water–rock interactions to explain the differences in $\delta^{18}O$ values with the assumption of a steady water temperature in the hot springs until recently. In this case, aragonite may have been precipitated from thermal water during the accumulation of travertine mounds and may have completely transformed to calcite, a stable polymorph under the ambient condition, after deposition.

However, it is also possible to interpret the differences in $\delta^{18}O$ values as being mainly due to a change in the precipitation temperature of carbonate. In this case, a difference of 3.5‰ in $\delta^{18}O$ values is equivalent to that in temperature up to 20 °C, and therefore, the past water temperatures of the hot springs may have been much lower than recent values. This hypothesis can consistently account for the very low accumulation rates of Oga travertines and the characteristics of lithofacies in the intermediate to distal parts of the main mound, which are typical of precipitation at ambient water temperature, as well as the non-appearance of aragonite from the travertine mounds despite the present aragonite deposition. An increase in the temperature of the thermal water could be explained by changes in the depth and pathways of the thermal water source along the Yumoto fault under the influence of earthquakes. However, further detailed investigation of the travertine texture is required to clarify the reason for the difference in mineral phases in past and present deposits.

6. Conclusions

To reconstruct long-term hot spring activity under the influence of seismicity in a tectonically active region, ^{14}C radiometric dating was performed on travertines along the Yumoto fault in the Oga Peninsula, NE Japan. The ages obtained from the radiocarbon dating of residual organic matter are consistent with the stratigraphy in the travertine mounds. The $\delta^{13}C$ values imply that the organic carbon is dominantly of C3 plant origin and has been little affected by subsequent changes. These results have confirmed the validity of the radiocarbon ages of the residual organic matter preserved in the travertine. This method is very useful particularly when the reliability of radiometric methods dating carbonate minerals is threatened by the migration of radiometric species after deposition and/or hard-water effects.

Radiocarbon dating showed that the hot springs have been active since approximately 29,000 years ago, with average depositional rates ranging from 0.24 to 1.75 mm/yr, and it expresses a tendency for the focus of hot spring activity to migrate southwards with time. Variations in accumulation rates and the progressive migration of the main hot spring activity imply unsteady hot spring activity that has been controlled by local seismic events. This study shows that earthquakes and faulting could be a prime controlling factor for long-term hot spring activity and travertine deposition as well as climatic and environmental conditions.

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