Paper:

The Catastrophic Tombi Landslide and Accompanying Landslide Dams Induced by the 1858 Hietsu Earthquake

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In the Joganji River basin, huge volume of sediment has been carried downstream and has formed the alluvial fan. The sediment runoff (erosion) volume is assumed to be 1.2 $\times$ 10^{11} m^3, accounting by the hypsometric curve of the Joganji River, which indicates the amount corresponding to rise in the mountains of the upstream, 1 mm/year at average, since the start of the quaternary period. The fast-flowing Joganji River originating on the Tateyama Volcano slope was, until the end of the Edo Period (1607-1867), relatively stable as indicated by boat services operating from the river mouth to the fan apex.
The Hietsu earthquake on April 9, 1858, caused numerous sediment disasters along the Atotsugawa fault system, some of the sediment movements built up landslide dams. Especially the catastrophic Tombi Landslide (Tombi-Kuzure) in the Tateyama Caldera, the upstream of the Joganji River, was the largest in the earthquake. The volume of the Tombi Landslide is estimated 103-127 million m^3, one of the largest movements in the world calculated the volume difference of the configuration and the landform before the landslide based on wide-ranging historical data. The landslide dam broke twice – on April 23, 14 days after the quake and June 7, 59 days after it –, generating a large-scale outburst flood and sediment deposition on the Joganji River's alluvial fan.
Considering the carbon (^{14}C) dating for the years 220-320 of pieces of wood sample at some deposits along the upstream of the Joganji River, it suggests that major sediment movement may have occurred in the Hietsu earthquake. But the years 720-940 suggest that major sediment movement may have occurred previously.
Topographicaly, such a huge landslide is part of the mountain range erosion and disintegration process, making it important to be able to predict potential sediment movement's scale and form accurately enough to minimize disaster and to better understand the overall landslide occurrence topographical changes.

Keywords: Hietsu Earthquake, Atotsugawa Fault, Tombi Landslide, landslide dam, outburst flood

1. Introduction

Large-scale sediment movement damming a river channel builds up water upstream that may, in turn, lead to extensive local flooding. Overflow from such a landslide dam may also breach the dam, causing further flooding downstream. This paper intends to study the landslide in the Jintu and Joganji Rivers, at the central Japan, caused by the Hietsu earthquake (Richter scale magnitude 7.3-7.6) on April 9, 1858, and especially the conditions of the catastrophic landslide named Tombi-Kuzure (Tombi collapse) in the Joganji River, figured out through comparisons with extant documents and maps and details the history of its geomorphic development based on intervening research results.

The Hietsu earthquake caused numerous sediment disasters along the Atotsugawa fault system, mainly in the Odori and Miya Rivers near the quake epicenter and the Joganji River, the distribution and damages of which are surveyed by extant documents, maps and the stone monuments.

On the other hand, the fast-flowing Joganji River originating on the Tateyama Volcano slope, that was damaged the most wreck of field and villages, was relatively stable as indicated by boat services operating from the river mouth to the fan apex until the end of the Edo Period (1607-1867), before the earthquake. The Hietsu earthquake, however, touched off the catastrophic "Tombi-Kuzure," the large landslide on the Yukawa River's left bank at the head of the Joganji River forming a landslide dam (Machida, 1962, Ouchi and Mizuyama, 1989). The landslide dam broke twice – on April 23, 14 days after the quake and June 7, 59 days after it –, generating a large-scale outburst flood and sediment deposition on the Joganji River' alluvial fan. These debris flows completely transform the Joganji River into the one of most devastated rivers in Japan and have generated serious sediment runoff that remains an ongoing problem despite numerous sabo facilities in the century since.

Topographically, the Tombi-Kuzure landslide is a part of the mountain range erosion, then the authors try to estimate the undermined volume of the upstream of the

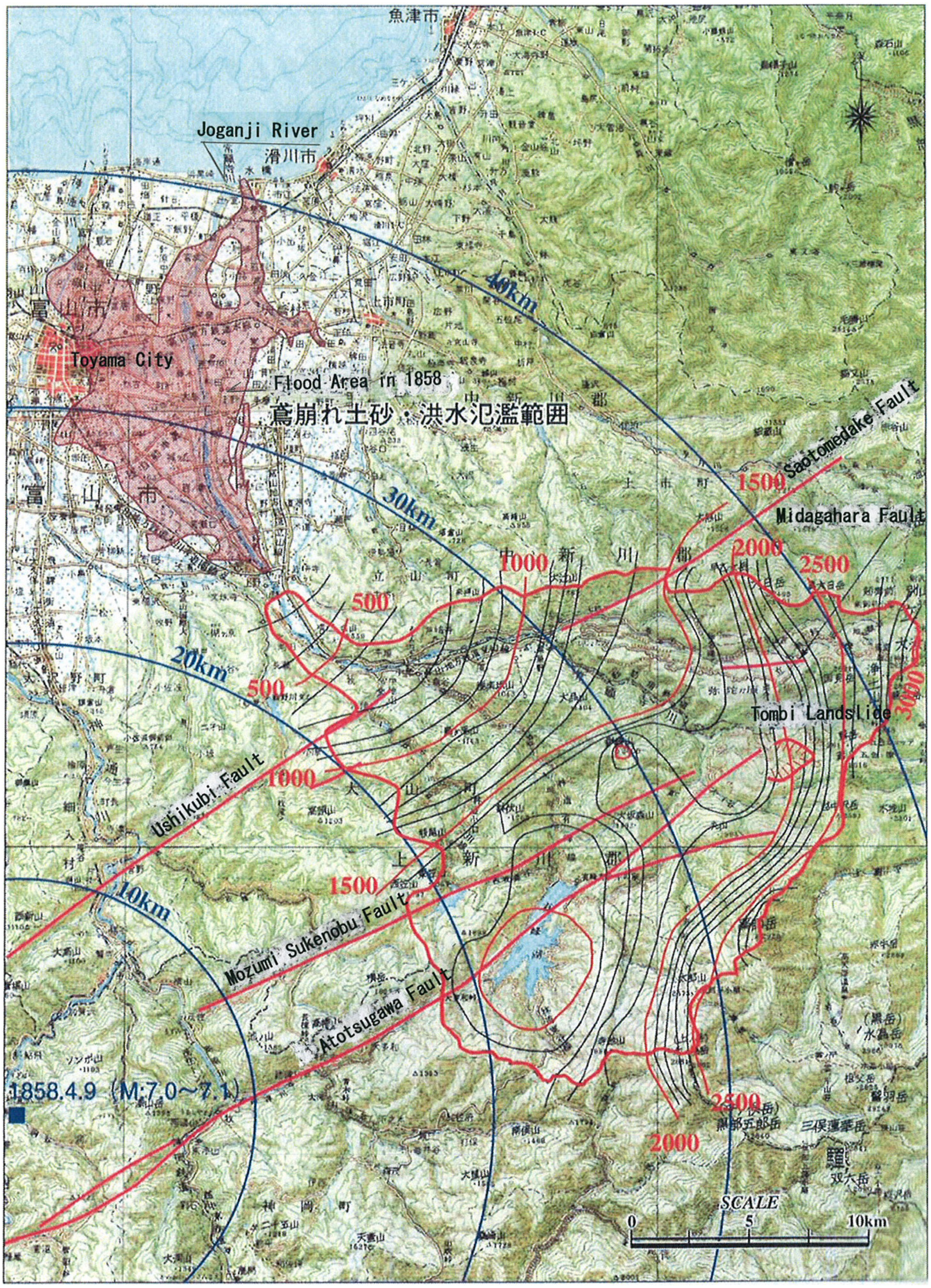


Fig. 1. Catchment area of the Joganji River (summit level restored with 4-km valley fill method) (Tabata et al., 2000).

Joganji River drawing the hypsometric curve in order to consider the weight of a large scale of landslide such as the Tombi-Kuzure landslide in the process of disintegration.

Disasters caused by a landslide due to an earthquake and breach of the landslide dam which induced by the landslide frequently occurred in the world. The large-scale landslide in not an everyday incident but may be inevitable in Japan with plenty of an earthquake, so grasping accurately a real collapse, a landslide dam due to it and burst of the dam, particularly a catastrophic one such as the Tombi-Kuzure landslide exposing the problems, is necessary to mitigate the casualties (Tabata et al., 2000, 2003, Inoue, 2009). The authors dug extant documents; surveys stone monuments built at the damaged sites, checked the traces of the configuration, as the result, dotted the landslide due to the Hietsu earthquake on the map and studied the formation of the landslide dam.

The authors estimated the volume of collapsed sediment of the Tombi-Kuzure to presume the pre-figure of the Tombi Mountain imaged on the extant documents and maps. And, testing of the carbon (^{14}C) dating of wood

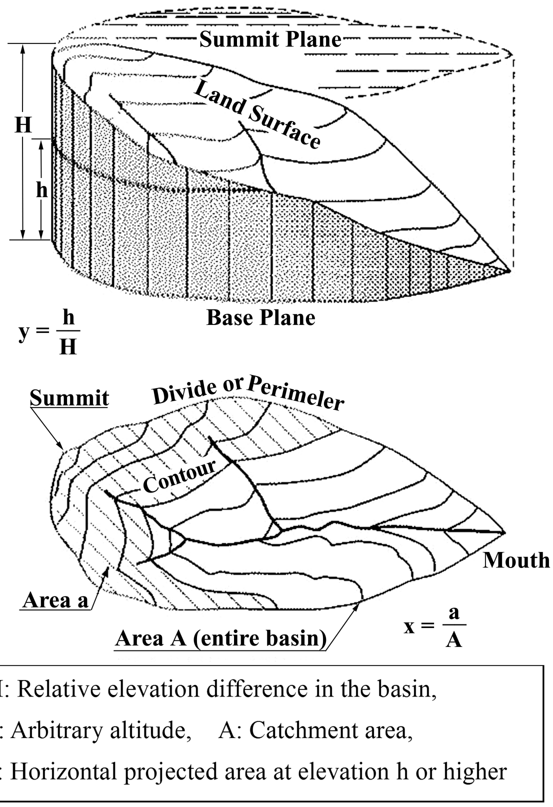


Fig. 2. Illustration for the Hypsometric Curve (Strahler, 1952).

pieces was conducted to distinguish the terrace deposits, which were located the carbon (^{14}C) dating in the upstream of the Joganji River, originated from the Tombi landslide in 1858 from that of in other years.

2. Joganji River Basin Sediment Erosion (Runoff) Volume

The fast-flowing Joganji River is 56 km long, has a catchment of 356 km^2, and features a relative elevation difference of 2992 m along the eastern Toyama Plain in Japan's main island of Honshu. Until just 162 years ago, the relatively stable river enabled boat services from the river's mouth to its fan apex as shown in **Fig. 1**.

One indicator of erosion along the entire basin is the hypsometric curve produced by Strahler (1952), indicating the area ratio of the altitudinal distribution within the basin with the ratio of arbitrary altitude "h" to altitude difference of the entire basin "H" (h/H) along the vertical axis and the ratio of the area at elevation h or higher "a" to the entire area "A" (a/A) along the horizontal axis in **Fig. 2**. Assuming the original (initial) geomorphic surface to be a horizontal projection plane tangent to the summit, areas above are eroded and those below are remainders.

Hypsometric integral α is the area enclosed by this curve and these axes – the volume of the mountain referencing the original geomorphic surface α in **Fig. 3** shows – the curve for the area upstream from the alluvial fan and $\alpha = 0.424$ (Tabata et al., 2000).

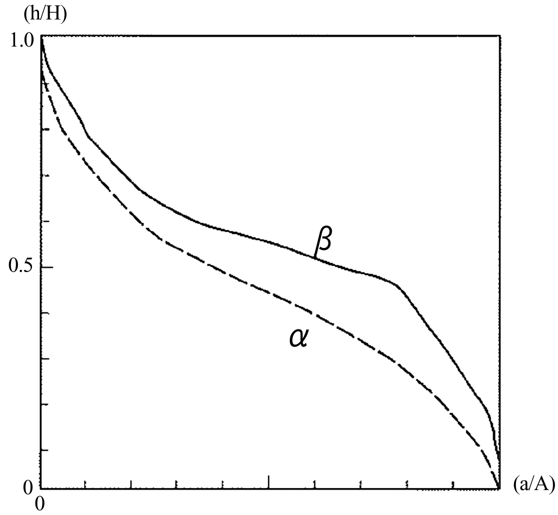


Fig. 3. Hypsometric Curve of the Joganji River (Tabata et al., 2000).

Although the Japanese archipelago is subject to violent crustal movement and volcanic activity, this is not to assume a summit plane as the original geomorphic surface. For hills, plateaus, or slopes at the foot of volcanoes with the original geomorphic surfaces identified, it is more realistic to consider a summit plane drawn with a reasonable valley fill width as the original geomorphic surface. The summit level is a geomorphic surface assumed to be tangent to the summit or mountain for restoring the original topology by filling the valleys that carves the mountains as shown in **Fig. 1** restoring the summit level by a 4-km valley fill and the hypsometric curve for the summit using $\beta = 0.542$.

The Joganji River catchment to fan apex $A = 347$ km^2 and relative elevation difference $H = 2830$ m (peak elevation 2992 m, fan apex elevation 162 m) and total erosion volume V_1 is determined by

$$\begin{aligned} V_1 &= AH(\beta - \alpha) \\ &= 3.46 \times 10^8 \times 2830 \times (0{,}542 - 0.424) \\ &= 1.16 \times 10^{11} \text{ m}^3 \end{aligned}$$

Even taking into account subsequent Tateyama Volcano activity and the generation and wide deposition of volcanic products such as modest-scale tephra, the sediment runoff (erosion) volume is assumed to be 1.2×10^{11} m^3.

The Joganji River' alluvial fan covers 66 km^2 with a gravel layer assumed to average 50 m thick based on geological data identifying the base – accumulated sediment of $V_{21} = 3.3 \times 10^9$ m^3. If the fan is viewed as part of a cone and measured based on a topographic map, radius r from the fan apex whose elevation contour is 11 km, the angle at which the alluvial fan spreads = 80 degrees and the altitude is 142 m, i.e., $V_{22} = 4.0 \times 10^9$ m^3. This makes total accumulated sediment between 3.3 and 4.0×10^9 m^3.

Of total sediment erosion V_1, sediment remaining in the fan from when the Tateyama Volcano was formed several hundred thousand years ago to the present V_2 accounts for a few percent, meaning that most of the original sediment

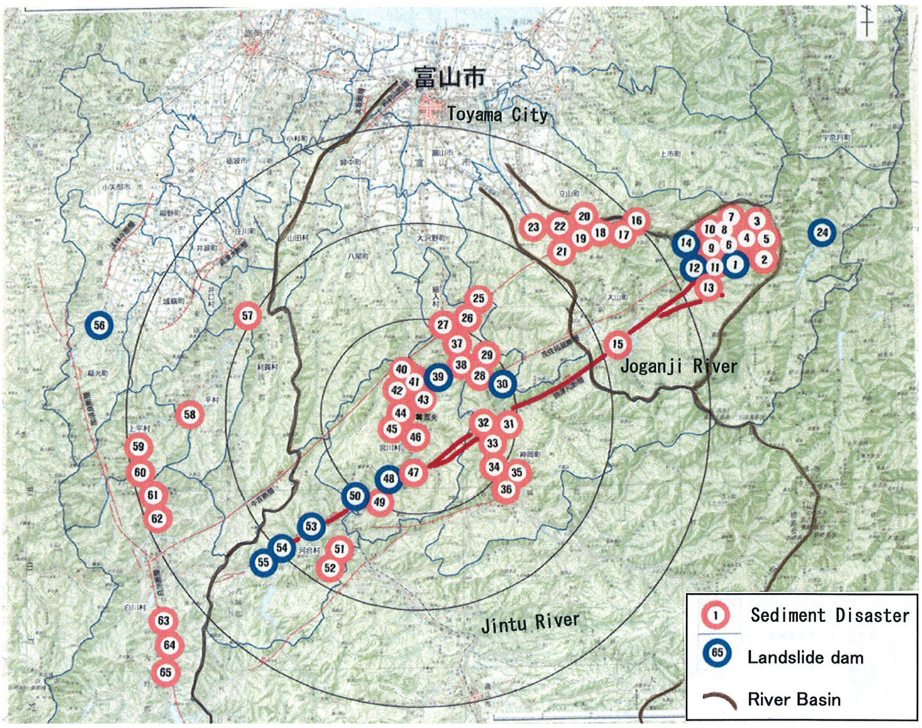


Fig. 4. Distribution of sediment disasters and landslide dams caused by the 1858 Hietsu Earthquake (Tateyama Sabo Works Office, 2002, Tabata et al., 2002).

flowed into Toyama Bay. In the geomorphic development context, such a fan is a temporary coarse-grained field, making V_2 as a few percent of V_1 reasonable. The Joganji enters Toyama Bay forming little alluvial lowland downstream.

According to the Research Group for Quaternary Crustal Movement (1969), the Toyama Plain has subsided 250 m since the Quaternary period started and Japan's central mountains have risen by 1500 m, averaging 1 mm/year relative to the plains during these 1.8 million years. Total Joganji River erosion (runoff) is represented by sediment volume V_1 (1.2×10^{11} m^3), indicating that, that an amount corresponding to the rise in the mountains since the start of the Quaternary period has eroded and been carried downstream.

3. Atotsugawa Fault System and Hietsu Earthquake

As shown in **Fig. 4**, the Hietsu Earthquake occurred on April 9, 1858, had a magnitude of 7.3 to 7.6 on the Richter scale and caused many sediment failures in the Atotsugawa fault system. Usami (1996) originally set the magnitude at 7.0 to 7.1 but a recent study by the Central Disaster Management Council ("On lessons learned from past disasters, 2009") determined it to have been 7.3 to 7.6.

The epicenter near Tsunokawa left particularly serious damage near the Odori and Miya Rivers at the Atotsugawa fault system, e.g., partially or totally destroying 77 of 98 houses in the Tsunokawa district – giving the earthquake the local name Tsunkawa Earthquake. A large number of major sediment movements and landslide dams built up in the Jintu River basin all subsequently broke.

4. Jintu River Basin Sediment Disasters

Immediately after the Hietsu Earthquake, water in the Jintu River began receding to where the "stream" could be crossed on foot. Some 20 hours later, at midnight, the river suddenly rose substantially and floodwater surges hit the lower Jintu River. The chains anchoring the robust "pontoon" bridge – the largest of its kind in Japan at the time – were broken and the bridge was washed away in the muddy water. The Toyama Han (fief) domain West Road and in the Kaga Han domain East Road along the Jintu River were both buried beneath landslide sediment, interrupting traffic between Hida (Gifu Prefecture) and Ecchu (Toyama Prefecture). Of the six outburst floods between April 22 and the end of July, that at the end of July appears to have been most serious.

4.1. Maruyama Nagatora Landslide (No.48 in Fig. 4)

A landslide at Maruyama Nagatora totally destroyed four and partially destroyed two other of seven local houses, killing 26 of 51 residents instantly (Miyagawa Village Compilation Committee,1981). As shown in **Fig. 5**, landslide sediment blocked the Miya River, a Jintu River branch, forming a landslide dam, behind which water built up and flooded areas to as far as Yomegafuchi 4 km upstream.

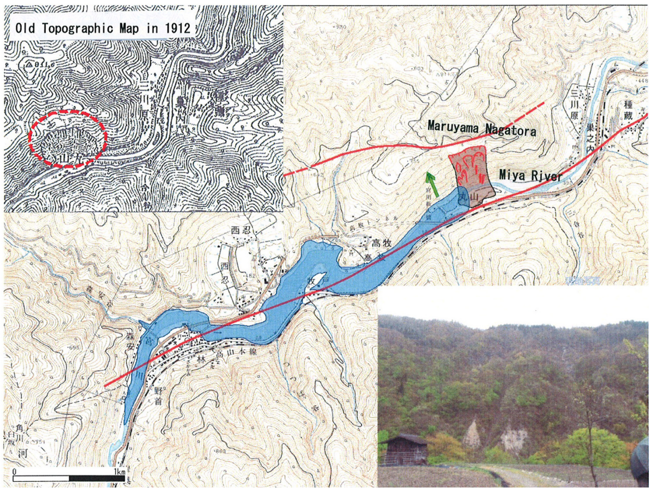


Fig. 5. Disaster map of landslide dam in Maruyama Nagatora (Inoue, 2009).

The landslide zone is estimated to have been 350 m long and 550 m wide, the landslide sediment volume 3.6 million m^3, the landslide dam 20 m high, ponding area 700,000 m^2, and ponding water 4.7 million m^3. An old topographic map surveyed in 1912 indicates post landslide topography. Landslide sediment buried houses on the opposite bank, together with 26 people, including 14 members of the Seikuro Morishita household. This landslide dam filled up and broke at noon two days later on April 11 – 57 hours after forming – indicating that average inflow to the dam was 23 m^3/s. Thanks to the fairly large amount of sediment damming the channel, breakage was gradual and no major damage was caused along the lower reaches of the Jintu River.

The post landslide topography became a designated Hida City historic site as the remains of the Ansei Earthquake landslide, and a monument commemorating disaster victims was erected at the site in October 1954 as shown in **Fig. 6**.

4.2. Motoda Aramachi Landslide (No.54 in Fig. 4)

Motoda Aramachi, a settlement on the right bank of the Odori River, is opposite a settlement called Tateishi. The steep slope behind Tateishi is called Mukaiyama. The Hietsu Earthquake triggered part of Mukaiyama, called Yanagidaira, into a major landslide, burying four houses in Tateishi and five in Aramachi, killing 53 people (Records of Kawai Village Compilation Committee, 1990). Landslide sediment dammed the Odori River, forming a landslide dam. Based on an interview with an elderly local resident, we determined that ponding water reached Tsukigase. The landslide site is estimated to have been 420 m long and 250 m wide, with a landslide sediment volume of 940,000 m^3, a landslide dam 30 m high, ponding area 340,000 m^2, and ponding water 3.4 million m^3. Thirteen hours postquake, at 16:00 on April 26, the dam broke, causing major flooding downstream. Tateishi was abandoned but Aramachi was rebuilt, and a

Fig. 6. Memorial stone monument in Maruyama.

Fig. 7. Memorial stone monument in Motoda Aramachi.

stone monument erected on the site of the former Motoda Elementary School as shown in **Fig. 7**.

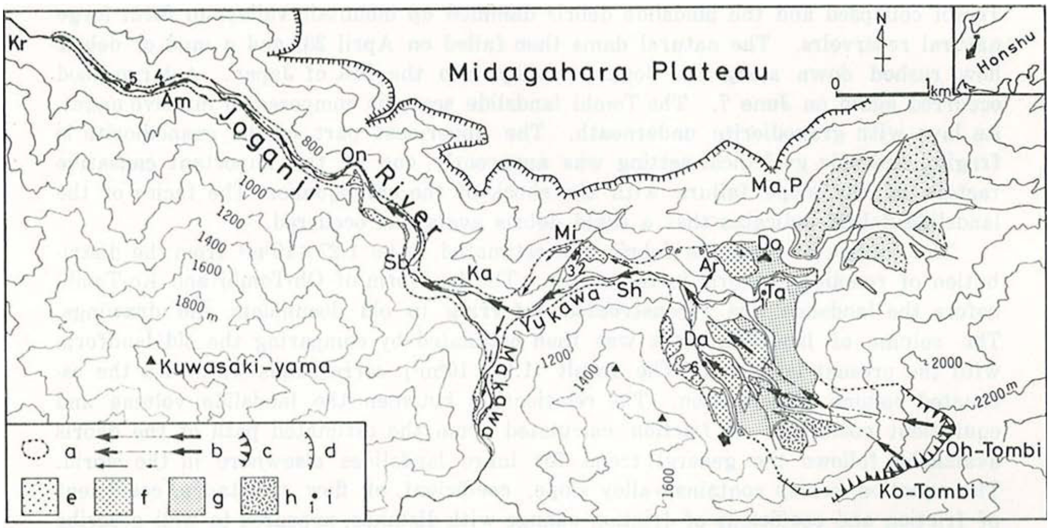
5. Tombi Landslide and Landslide Dam Outburst Flood

The Hietsu Earthquake caused several landslides along the Joganji River east of the Atotsugawa fault system, shown in **Fig. 2**, together with sediment disaster condition. The Tombi landslide in the Tateyama Caldera was the largest and its two subsequent landslide dam collapses caused enormous damage alomg the lower Joganji River.

5.1. Tombi Landslide Described in Old Documents

The Tombi landslide generated a debris avalanche that accumulated along the Joganji River from Yukawa in the Tateyama caldera. Ominous rumbling continued for some time and clouds of black smoke are said to have been clearly visible from the castle town of Toyama, as shown in many pictures.

Figure 8 charts sediment disaster conditions in 1858 along the upper Joganji River, based on field surveys, aerial photographs, historical materials, old maps rearrangement, etc. (Ouchi and Mizuyama, 1989). Near the confluence of the Yukawa and Makawa Rivers flowing from the Tateyama Caldera, sediment over the 150-m col accumulated, damming the Yukawa and Makawa Rivers and forming a large landslide dam. As shown in **Fig. 2**, landslides occurred many places besides to the Tombi landslide in the Joganji River valley, forming different-sized landslide dams. The Yukawa River landslide dam remains currently form the Dashiwara and Dojo Ponds.



a: Estimated extent of the Tombi debris avalanche. **b**: Estimated path of the Tombi debris avalanche. **Arrows** indicate the movemrnt of debris, **Large arrows with dash-dotted lines** indicate the estimated majar courses of the debris avalanche, which are approximated by the combination of straight lines and circular arcs. **The dash-one-dotted line** indicates the estimated major path of debris from Ko-Tombi to Karatani along the Yukawa-Joganji valley, and this is assumed to be the path of the Tombi landslide debris. **The dash-two-dotted line** shows the debris movement from Oh-Tombi.
c: Tombi landslide scarp. **d**: Others cliffs. **e**: Matsuo-daira and equivalent surfaces, **f**: Geomorphic surfaces formed by the Tombi landslide debris, including older depositional land surfaces which it covered. **g**: Geomorphic surfaces formed by Tombi landslide debris with apparent modification by later debris flows or flood flows. **h**: Bedrock hills or humps with relatively thin layers of landslide debris. **i:** Sampling points for C14 dating.
Da: Dashiwara, **Ta**: Tateyama Hot Springs, **Do**: Dojo pond, **Mi**: Mizutani, **Ka**: Kamba-daira **Sb**: Sabtani, **On**: Onigajo narrow, **Am**: Amadori, **Kr**: Karatani, **Ma.P**: Matsuo Path, **Ar**: Arimine Nino-tani

Fig. 8. Geomorphic surface distribution and estimated Tombi landslide debris path (Ouchi and Mizuyama, 1989).

The Oyama Historical Folk-Memorial Museum Map of Tateyama Hot Springs shows a ridge from Ko- ("small") Tombi to the bottom of Oh- ("large") Tombi behind the Tateyama Hot Springs (then known as the Dashihara hot springs) proceeding the Tombi landslide, judging from their names, the two were a large and small steep peaks the summit. Landslide and rockfalls of different scales originating from precipitous slopes must have caused damage many times before the Tombi landslide occurred.

A local administrator astonished by the extraordinary Joganji River behavior immediately tried an on-the-spot investigation, but the river had turned into a muddy sea and road along the river had been impassable at several places by landslides. Given the heavy snow, negotiating the road along the Joganji River was no longer possible. At Iwakura Temple, 12 strong men were chosen to detour along the opposite bank and climb 2089.7 m Mt. Kuwasaki to survey the caldera from the summit. This extremely precipitous route caused five to drop out on the way, but the remaining seven reach Mt. Kuwasaki summit. The disastrous conditions inside the Tateyama Caldera reported to Iwakuraji were promptly conveyed to the Kaga- Han clan. **Fig. 9** shows current Tateyama Caldera topography based on photographs from when we climbed Mt. Kuwasaki.

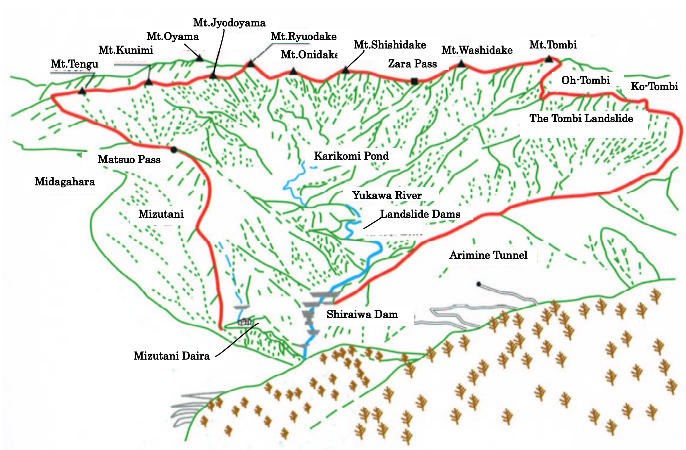


Fig. 9. Tateyama Caldera from Mt. Kuwasaki summit (Tabata et al., 2002).

At Ashikura Temple, eight men went around the hill behind the settlement to get to the river upstream from the Shomyo Waterfall, crossing the stream and reaching one end of the Midagahara Plateau, then climbed to the Matsuo Pass and confirmed from the north the disastrous conditions inside the Tateyama Caldera that were then immediately reported to the Kaga- Han clan.

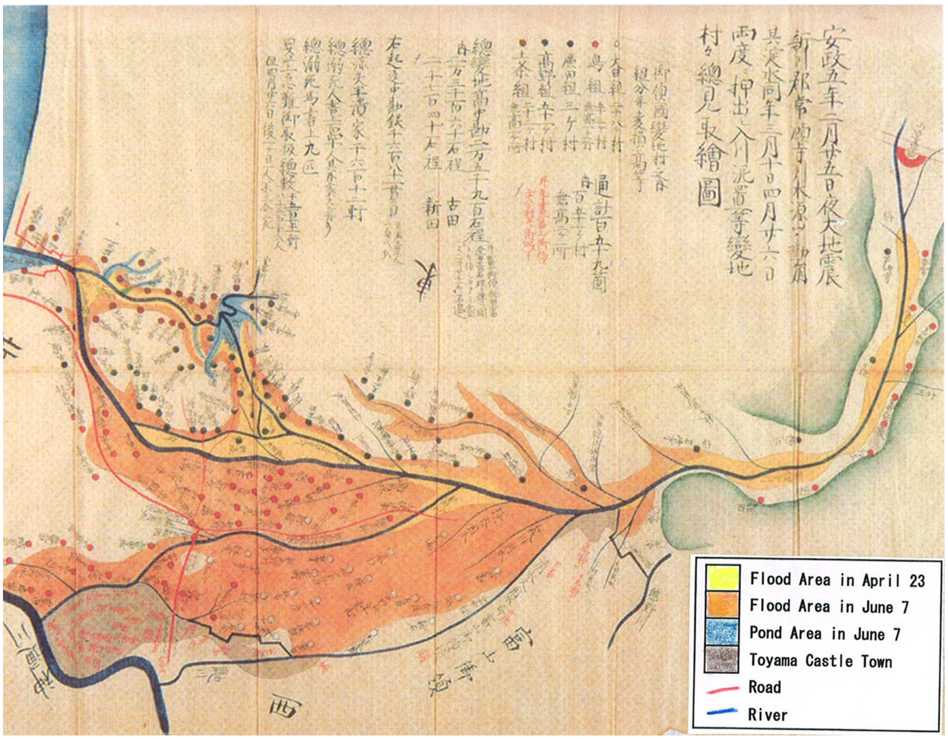


Fig. 10. Old disaster map showing 1858 sediment destruction at the Joganji River Fan (Namerikawa City Museum).

Fig. 11. Memorial stone monument in Nenpoji temple.

The landslide dam triggered by the Tombi landslide broke twice – on April 23, 2 weeks after the Hietsu earthquake and on June 7, 59 days thereafter – tremendously damaging the Joganji River Fan downstream. **Fig. 10** shows outburst flood conditions, from an old disaster map showing the 1858 sediment disaster at the Joganji River fan owned by the Namerikawa City Museum. **Fig. 1** indicates the extent of flooding following the dam failures flooding almost the entire Joganji River Fan.

Buddhist residents of Iwakura Temple related that "Ko-Tombi and Oh-Tombi behind Dashiwara Hot Springs significantly collapsed under the landslide mass, and the hot spring resort apparently disappeared from the landscape" (Toyama Local History Society, 1976). As seen from around the Matsuo Pass, the Tombi landslide did not cause a large mountain to disappear, and previous topography differed little from that at present the report states that "20 to 30 percent from the top of Oh-Tombi and over half of Ko-Tombi collapsed."

Immediately after the landslide dam's first failure, the Tateyama Hot Springs were buried completely under debris tens of meters deep and 30 to 40 people, including construction laborers working at the spa, were killed instantly. **Fig. 11** shows the monument to them later built at Nenpoji Temple in Hongu, Oyamamachi, in Toyama City.

Matsuodani and Mizutani on the north bank of the Yukawa River, opposite the Tateyama Hot Springs, and steep mountains such as Onigajo and Kumadaore near the confluence of the Yukawa and Makawa Rivers also collapsed, and the Yukawa and Makawa Rivers were backed up and many landslide dams filled with muddy water. The mountains rumbled ominously and thick smoke bellowed from the area around the Karikomi Pond as shown in **Fig. 9**. The Magoike Pond (Mago Karikomi Pond) east of the Kamikomi Pond was originally been a coldwater body but the earthquake caused boiling water to suddenly spout at a few locations.

These reports were also conveyed to the Toyama- Han clan, and citizens were in an uproar about the possibility of a huge mass of muddy water rushing down the mountain and turning the Toyama Plain into a sea of mud, subsequently evacuating their household belongings and families to high ground to the west near the Kureha Hills. The entire Toyama Castle town was thrown into a panic when Toyama- Han chief Toshiyasu Maeda, also left.

Table 1. Results of C14 dating of wood pieces obtained from landslide debris.

No.	Sampling Location	Sampling point	Elevation(m)	Measurement No.	C14 date (yBP)
1	near the site of Tateyama Hot Springs Inn	10-15m below the terrace surface	1310	TH-1226	940±90
2	Mizutani	10-15m below the terrace surface	1090	TH-1224	730±90
3	Mizutani	30-40m below the terrace surface	1070	TH-1225	880±90
4	Amadori	1-2m above the present river bed	620	TH-1223	320±100
5	Amadori-Karatani	near the present river bed	570	TH-1222	720±90
6	Dashidaira	near the valley bottom	1304	TH-1238	220±100

(Ouchi & Mizuyama, 1989)

5.2. Tombi Landslide Sediment Movement

Based on the field surveys, the Tombi landslide sediment consists of fractured rock blocks, indicating that debris avalanches occurred similar to those in the Ontake (Denjo) landslide of Mt. Ontake, due to the 1984 Western Nagano Prefecture Earthquake, which had magnitude of 6.9 on the Richter scale. The geomorphic surface deposited by the debris avalanche can be traced intermittently 12 km downstream from Dashiwara through Mizutani-daira, the confluence of the Yukawa and Makawa Rivers, and Kamba-daira to Onigajo, as shown in **Fig. 8**. The deposit forming the Mizutani Terrace is 100 m thick. Machida (1962) thought that material between the Mizutani-daira riverbed and the geomorphic surface consisted entirely of Tombi landslide sediment, but the boring survey by Tateyama Mountain Area Sabo Office showed the presence of basement rock 50 m from the Mizutani-daira riverbed.

Seen from the bottom up, the debris landslide deposit at the bottom gives way to a debris flow deposit containing much wood, followed by a muddy deposit, with the top 10 to 20 m consisting of a flood flow deposit with a slight sorting of gravel. Similar trends continue downstream, suggesting that the flow started as a debris avalanche, turned into a debris flow, and moved in several surges. The debris avalanche deposit apparently stopped at a narrow section near Onigajo.

The top deposit is considered debris and outburst flood deposit accompanying the two Tombi landslide dam failures. **Table 1** shows carbon (^{14}C) dating of pieces of wood sampled in 1984 and 1985 field surveys (Inoue et al., 1986, Ouchi and Mizuyama, 1989). Data significantly varying indicate an age of a few hundred years and we decided that the wood in question was included at sediment movements in 1858. Dating for 720 to 940 years, however, show that the deposit may have been due to major sediment movement before the 1858 Tombi landslide. This dating results from testing conducted over 25 years ago, and pieces of wood still found here and there on Joganji River valley terrace cliffs suggest the usefulness of taking and dating fresh samples using in the latest high-accuracy dating.

Field surveys show that the precipice near Oh-Tombi is brownish yellow due to deterioration by sulfurization but ground around Ko-Tombi is fresh andesite. Landslide masses between Dashiwara-daira and the right bank of the Yukawa River are mostly from Oh-Tombi, while those from Ko-Tombi are frequently found from the Dashiwara Valley exit to downstream from Mizutani. Andesite rock masses at the Dashiwara Valley exit presumably from Ko-Tombi lie a top landslide masses from Oh-Tombi. Oh-Tombi and Ko-Tombi apparently collapsed around the ridges extending northwest from their summits in the Hietsu earthquake and the Ko-Tombi landslide appears to have been slightly later judging from the deposition sequence, with debris falling down to Dashiwara-daira. Given these observations, Tombi landslide sediment flowed as shown by arrows in **Fig. 8**. Oh-Tombi landslide spread across Dashiwara-daira to completely bury the Tateyama Hot Springs and Yukawa Valley. Judging from the elevation of the plateau downstream from the Dojo Pond, part of sediment ran into the Kumadaore slope on west of Dashiwara and was deflected up the right Yukawa Valley bank before flowing back in the opposite direction. Oh-Tombi landslide masses are found on basement granodiorite fairly high up the Arimine Sannotani Valley landslide slope downstream from the plateau topography downstream from the Dojo Pond. Ko-Tombi landslide masses arrived later, moved almost straight, and buried the area around Mizutani to form Mizutani-daira (terrace). They then encountered the right Yukawa Valley bank slope and turned toward the Makawa River, crossing the small ridge between the Yukawa and Makawa Rivers to reach the terrace plain on the left bank 1.5 km upstream along the Makawa River. Products lost most of their kinetic energy crossing the small ridge, became mixed with subsequent flow, and traveled 12 km down the Joganji River valley, almost completely aggrading the river valley up to Onigajo and forming two landslide dams in the upper reaches of the Yukawa and Makawa Rivers.

5.3. Estimated Tombi Landslide Value

5.3.1. Restored Pre- and Post-landslide Topography

Based on maps and field survey results, topographies before and after the Tombi landslide were estimated to create bird's eye views in **Fig. 12** (Ouchi & Mizuyama, 1989). These were then used to aid in reading topography information as mesh data to output a contour map of pre-landslide topography, which was compared to the current

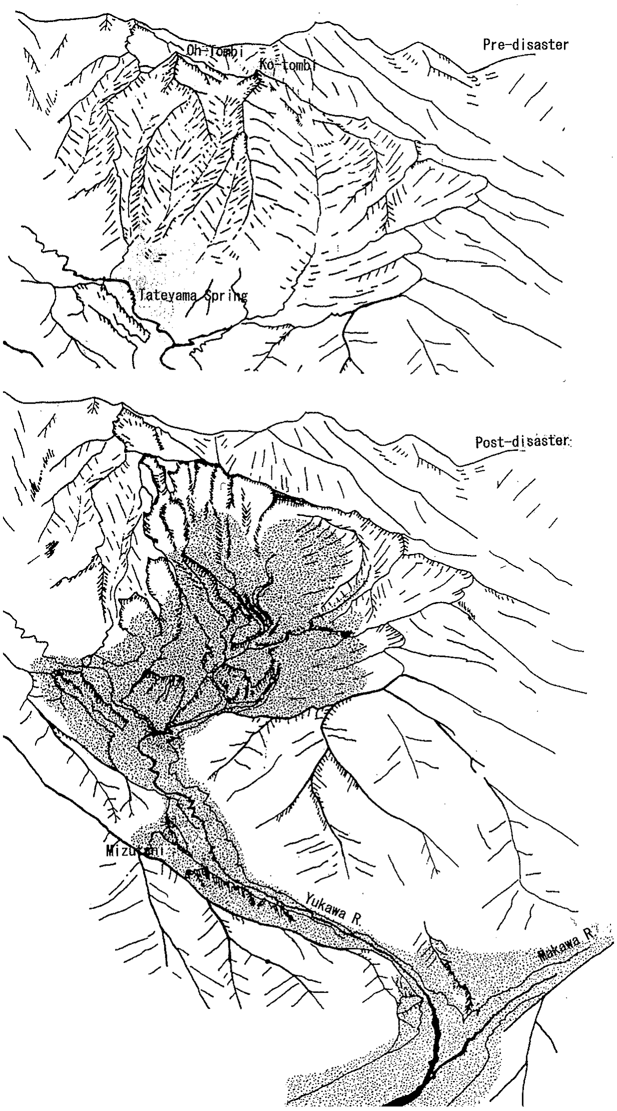


Fig. 12. Bird's eye views of the Tombi landslide. (Pre- and Post- disaster).

topographic map to determine the extent of geomorphic change, yielding a maximum 240 m failure depth. Using this to estimate the landslide sediment volume, yielding 48 million m^3 from the Oh-Tombi district and 66 million m^3 from the Ko-Tombi district for a total of 114 million m^3.

5.3.2. Estimated Accumulated Sediment Volume

Machida (1962) estimated total landslide sediment volume from the Tombi landslide assuming that sediment accumulation was 270 million m^3 in District A from the landslide to the Shiraiwa Dam, 100 million m^3 in District B from Shiraiwa to the Joganji River valley, and 36 million m^3 in District C from the fan apex to the river mouth, and estimated total sediment volume at 410 million m^3. Machida (1986) modified an earlier opinion, stating that the above values summed the three sediment movements at the Tombi failure and two landslide dam failures following by the Hietsu Earthquake and that sediment from the middle to the Joganji River downstream of Onigajo resulted from secondary movements at the landslide dam failures, concluding that Tombi landslide sediment totaled 270 million m^3 for District A from the collapse site to the Shiraiwa Dam.

Assuming that such a landslide sediment volume as 270 to 410 million m^3 premised that the mountain above Dashiwara was significantly large, mostly collapsed at once, and disappeared. Estimated landslide sediment volume up to now was based on deposit observation, but accurately identifying deposits from the Tombi landslide is extremely difficult, as is distinguishing these deposits from deposits generated at the two landslide dam failures. Much of the deposits deposit from the Tombi landslide deposits, ran off into the mid and lower reaches of the Joganji River due to the two dam failures and existed in the Joganji River valley now only interspersed. For the 1984 Ontake landslide, likewise, most sediment flowed downstream, although flow marks exist fairly high in the river valley (Tajimi Work Office, 2002, 2004). Most trees in the debris avalanche area now were leveled by the flow, leaving clear flow marks in its wake. In the 28 years since the avalanche, vegetation has recovered and made flow marks gradually less distinct, in turn linking the highest flow and deposit accumulation marks in different location between the left and right banks and yielding an excessive estimate of accumulated sediment volume.

In and around the west side of the Dashiwara Pond, andesite breccia from the Tombi landslide accumulated and Tombi landslide sediment is assumed to have built up, but on the opposite bank of the Yukawa, along with the distribution of landslide sediment and the Mizutani depositional terrace, a pyroclastic flow deposit covered basement rock of the hill on the downstream side of Dojo Pond, suggesting that Tombi landslide sediment is rather thin (Ouchi and Mizuyama, 1989) based on the estimate of Machida (1962). The block-shaped hill, believed to be a Tombi landslide deposit upstream of Dashiwara, turned out to be basement rock. Basement rock outcrops are also visible on the valley floor and walls of Dashiwara and the Tombi landslide deposit covers basement rock only very thinly, leading us to conclude that most of the deposit flowed downstream. The block-shaped hill has an area of 250,000 m^2 and, assuming a deposit 2 to 4 m thick, the deposition volume is 500,000 to 1 million m^3. Old pyroclastic flow deposits on the hill downstream of the Dojo Pond on the right bank of the Yukawa River lead us to conclude that this deposit is also thinner than predicted by the Machida (1962) theory. Accumulated Dashiwara sediment volume (1.6 million m^2 in area) was 48 million m^3, assuming an average accumulation layer 30 m thick. The sediment volume damming the Yukawa Valley is estimated to have been 5 million m^3, so total accumulated sediment for District A from the collapse site to the Shiraiwa Dam is estimated at 54 million m^3.

While Machida (1962) attributed all of the Mizutani Terrace to Tombi landslide sediment, basement granodiorite is exposed 30 m from the current riverbed. A Tateyama

Table 2. Acumulated seiment volume of the Tombi landslide.

	Machida(1962)		Ouchi & Mizuyama(1989)	
	Area	Volume Million m^3	Area	Volume Million m^3
A	Landslide Site to Shiraiwa Dam	270	Block-shaped hill	0.5-1.0
			Dashiwara aria	48
			Yukawa Valley	5
			Sub Total	**54**
B	Shiraiwa to Jpganji R. Valley	100	(1) Mizutani-daira aria	6
			(2) Kamba-daira aria	2
			(3) Makawa River aria	11
			(4) Confluence of Yu. & Ma. River to Onigajo	30
			(5) Onigajo to Karatani	15
			(6) Karatani to Yokoe	9
			Sub Total	**73**
			Sub Total (except (5)&(6))	**49**
C	Joganji fan apex to Joganji R. mouth	36		
	Total	**270-406**		**103-127**

Mountain Area Sabo Office boring survey showed basement rock up to 50 m from the Mizutani-daira riverbed, indicating that the Tombi landslide around Mizutani-daira is 100 m thick. Conversely, the terrace on the left bank of the Makawa River 1.5 km upstream from the Yukawa and Makawa River confluence is formed from Tombi landslide collapse products traveling up the Makawa River, and making Tombi landslide sediment volume along the Makawa River greater than that given by Machida (1962). In District B from Shiraiwa to the Joganji River valley, we estimate deposition of (1) 6 million m^3 near Mizutani-daira, (2) 2 million m^3 near Kamba-daira, (3) 11 million m^3 along the Makawa River assuming a layer 50 m thick, (4) 30 million m^3 from the Makawa and Yukawa confluence to Onigajo assuming a layer 50 m thick, (5) 15 million m^3 from Onigajo to Karatani assuming a layer 20 m thick, and (6) 9 million m^3 from Karatani to Yokoe assuming a layer 20 m thick.

Landslide sediment of 73 million m^3 thus accumulated throughout District B.

Based on these estimates, total accumulated sediment volume from the Tombi landslide is estimated at 127 million m^3, consisting of aggregates Districts A and B (Inoue et al., 1986, Mizuyama et al., 1987, Ouchi and Mizuyama, 1989). Because estimates (5) and (6) downstream from Onigajo are considered runoff or sediment deposited after the landslide dam failure, 24 million m^3 is subtracted from this aggregate, leaving 103 million m^3.

Tombi landslide sediment volume is in any case somewhere between 103 and 127 million m^3, for a total of $1/4$ of 410 million m^3, the current generally – accepted volume – a landslide on a scale exceeding 100 million m^3 is still extremely large even from a global perspective. As shown in **Table 1**, carbon dating includes values for 720 to 940 years, means that a large landslide of several tens of millions m^3 may have occurred in those days. Ascertaining the facts, however, will require further detailed investigation of terrace deposits along the Joganji River in the future.

Many deposit terraces such as Matsuo-daira occur deeper in the Tateyama Caldera (Nozaki, et al., 2009), with roughly 200 million m^3 of unstable deposits remaining.

5.4. Historical Landslide Dam Formation and Failure and Outburst Flood Generation

Based on wide-ranging historical data, we sought to explain how landslide dams formed and broke and how outburst floods occurred.

The Ecchu Tateyama Henjiroku, owned by Toyama Prefectural library, states that "in the area upstream from the Makawa River, rock collapsed from both mountains...," suggesting that upstream slope landslide sediment constitutes part of the landslide dam formed on the Makawa River as shown in **Fig. 8**. Tombi landslide deposits also exists along the edge of the terrace plain at 1,000 m, and we estimate the landslide dam to have been 150 m high, the ponding area 750,000 m^2 (catchment area: 79 km^2), and the ponding water 37.5 million m^3, based on a $1/25000$ topographic map and aerial photos.

The Tateyama Disaster Damage Report, owned by Kanazawa Municipal library, states that "Matsuo Mizutani Mountain collapsed in places, making the course of the Yukawa River unidentifiable." The Ashikura Niemon Report relates, "Water flowing smoothly under fallen rocks and no water pools are found, meaning no worry of flooding exists, and a muddy pool 180 m square is observed near a Tateyama hot springs bathhouse."

The Ansei 5 Ecchu Tateyama Henjiroku, owned by Toyama Prefectural library, describes "a large pond 900 $\times$ 550 m and seven other ponds have formed," suggesting that water flowing from of the Yukawa River included a large volume of melt-water flowing mostly beneath the deposit and little water ponding on the surface. From this, we estimate the Yukawa River landslide dam had a ponding altitude of 1350 m, the dam was 20 m high, the ponding area was 640,000 m^2 (catchment area: 10 km^2), and ponding water had a volume of 4.1 million m^3.

At the time of the Hietsu Earthquake on April 9, the upper Joganji River reaches were covered with thick snow and little surface water existed. With the advent of spring and rising temperatures, melt flow water increased, becoming caught behind the landslide dam. Given the catchment area and the dam crest elevation and profile, we determined that the Makawa River landslide dam broke 14 days later on April 23 and that on the Yukawa River 59 days later on June 7.

At the first landslide dam failure, much snow still remaining in the Tateyama Caldera, triggered a snow flood. Another earthquake with a magnitude of 5.7 on the Richter scale and an epicenter near Omachi City in Nagano Prefecture striking that same day may have triggered the slope failure, breaking the landslide dam. Contemporary descriptions including the Sakai Family Archives stated that "Dokodo Mountain fell into the landslide dam lake." Ecchu Tateyama Henjiroku states that "70 percent of the water was driven out when a place called Dokoiwa fell." We thus determined that a landslide dam failure near Dokodo on the Makawa River triggered the first flood when it overflowed due to landslide sediment and melting snow inflow.

The Ansei Earthquake Oh-Tombi and Ko-Tombi Landslide Dam Collapse Map from the Sugiki Archives shows rows of Tateyama Hot Springs houses submerged by huge landslide dam failures on the Yukawa River 45 days after the earthquake on May 24. The Tateyama Oh-Tombi Landslide Map of the Toyama Prefectural Library shows landslide dam lakes remaining at Tombi landslide deposits even after the second landslide dam failed 59 days later on June 7. Large landslide deposits thus remained near Dashiwara despite the two dam failures, together with some ponds.

The Ecchu Tateyama Henjiroku from the Maeda Archives of the Toyama Prefectural Library, describes the first outburst flood, on the Makawa River, producing a past-like flow with a low water content, suggesting that snowmelt had progressed little and that the flow engulfed the sediment and driftwood aggrading the Joganji River valley and causing it to rush downstream in a single burst. In the second outburst flood on the Yukawa River, a large snow flood including the Makawa and Shomyo Rivers apparently added to Tombi landslide sediment, causing a mixed flow current with high water content.

Records including the Chisui Kembunroku relate the following about the middle reaches between Senjugahara and Okada:

- The Kannon Temple survived in Senjugahara but 70 to 80 percent of the Japanese cedar trees planted there were pushed over and submerged by the sediment.
- Torii standing 5.4 m tall at both ends of the Fuji Bridge of Omi – a wisteria suspension bridge between Omi and Chigaki Villages – were buried, and the main bridge is unaccounted for.
- Chigaki Village rice fields were buried under stones and mud that flowed out.
- Areas up to the Kameiwa of Makimura were filled with large stones.
- The river course from Tateyama Hot Springs to Okada Village was filled with large stones, mud, and driftwood.

As shown in **Fig. 10**, outburst flood deposits due to the second landslide dam failure were massive, flooding across and accumulated over the entire the Joganji River fan. Sediment accumulating on the alluvial fan consisted of boulder-mixed sediment called "Tombi Doro (mud)," reported to have been very hard and raising problem when attempts were made to restore arable land at the time, "Tombi mud" is now no longer to be found.

Outburst flood deposits when the first landslide dam burst were paste-like flows containing Tombi mud and a high sediment concentration, causing them to accumulate along the Joganji River. The flow from the second dam burst traveled over accumulated sediment from the first burst and flooded places across the entire fan, slowing near the fan downstream to where many districts escaped flooding due to slight elevations such as main roads on the sand dunes.

Kaga- Han clan records state that debris and flood flows from the first outburst flood damaged 66 towns and villages, mainly on the east side of the Joganji River, drowning five persons, sweeping away or destroying over 250 houses and 78 storehouses and barns, and rendering agricultural land with a recognized yield of over 5,236 koku (about 150 kg) barren. The second outburst flood hit 74 towns and villages, again mainly on the east side of the Joganji River, drowning 135, adversely affecting the lives of 7,350, sweeping away or destroying over 1,360 houses and 808 storehouses and barns, and rendering agricultural land yielding over 20,560 koku barren. Records of the second dam failure also show that 18 towns and villages were adversely affected and agricultural land with a yield of over 7,360 koku was rendered barren in the Toyama-Han fief east of the Itachi River.

6. Conclusions

The fast-flowing Joganji River originating at the Tateyama Volcano was relatively stable until the end of the Edo Period, as shown by boat services operating from the river mouth to the alluvial fan apex. The Hietsu Earthquake on April 9, 1858, changed all this, however, causing the large-scale Tombi Landslide damming the head of the Joganji River. The resulting landslide dam burst on two occasions, generating large outburst floods and damaging the fan downstream, making the Joganji River one of Japan's most devastated rivers. Mid and upper-reach sabo dam projects in the century since have not solved the problem of persistent sediment runoff.

Topographically, such a landslide is part of the mountain range erosion and disintegration process, making it important to be able to predict potential sediment movements scale and form accuratedly enough to minimize disaster and to better understand the overall landslide occurrence and subsequent topographical changes.

Having presented topographic research results on the major sediment movement in 1858 based on extant documents and maps, we plan to further study landslide dam failure based on results to the present using techniques such as landslide dam failure simulation.

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