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Geomorphic Evidence of Paleoeartquakes during Holocene on Principal Thrust Fault Zones in the Tohoku District, Northeast Japan

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Abstract In the present study, seven areas of Tohoku district (Yokote, Kitakami, Shonai, Yamagata, Nagai-Yonezawa, Sendai, and Fukushima) having features of surface faulting and rupturing are examined to determine the timing and amount of displacement of the most recent surface faulting per event, recurrence interval between events, and the vertical slip rate during Holocene.

Holocene terraces that contribute towards the topographic reference of faulting are classified into three levels, which can correlate throughout the area of study. Across the faults, each Holocene terrace differentiated by age has different heights of scarp produced as a result of fault displacement. This indicates that they have experienced different number of surface faulting events during the Holocene time. The results from trenching surveys conducted in previous studies were found to be consistent with the age of the recent events deduced from geomorphic evidence. This helps in improving the time localization of such events.

The displacements of the most recent events recorded on the Holocene surface range from 1.5 to 3.5 m, implying that each of these zones can be divided into several behavioral segments. The calculated recurrence intervals during the past 10,000 years for each fault are based on assumed values with inferred time spans for each event, that were found to range from 1,500 years to over 10,000 years based on geomorphic evidence of paleoeartquakes and fault parameters. From the formative age of the most recent faulted terrace and the oldest surface wherein faulting was absent, it can be concluded that the most recent events took place within the last 3,000 years in all the areas investigated. The vertical slip rate of each fault in the Holocene time is similar in range to that due to the deformed late Pleistocene terraces, suggesting that the current rates of tectonic deformation in this region have been continuing since the late Pleistocene time.

Key words: Active fault, Holocene, Fault scarp, Recent event, Amount of displacement, Recurrence interval, Tohoku District

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1. Introduction

Northeastern Japan is one of the most typical island arc-trench systems. Principal thrust faults extending in a direction parallel to the arc delineate the topographic boundary between the mountains and basins in Tohoku district, which fall in the *Moderately compressed class* of principal subduction zones along the pacific rim (Jarrard, 1986). The results from the comprehensive study of active faults are obtained from the work done at The Research Group for Active Faults of Japan (1980; 1991), which puts an order of 0.1 mm/yr for the average slip rate for the principal faults in the district. Later works by Ikeda et al. (2002) and Nakata and Imaizumi (2002) described the precise location and approximate amount of surface deformation of these active faults. Especially in urban areas, active fault maps describing their length and distribution in detail are made available in the district for the purpose of disaster prevention, land infrastructure planning and civil engineering (Imaizumi et al., 1996; 2000; 2001; 2002; 2004; Sawa et al., 2000a; 2001; Miyauchi et al., 2001; 2002; 2004 Yagi et al., 2001; 2002). Deep fault geometry also plays an important role in the understanding of the relationship between underground seismogenic and surface faults in order to clarify the regional characteristics (Imaizumi and Sato, 2005). A comprehensive analysis of the deep geometry of such active fault systems require fundamental information in the form of surface faults, because their morphology provides a basis for the understanding of the behavior of underground seismogenic faults.

Recently, lots of new data have been made available on active faults in the district of Tohoku. These help in the estimation of the degree of fault activity. They also indicate that most of these faults belonging to each of the major fault zones have been active during the late Pleistocene and thus have a high probability for future reactivation. In order to gain insight into the ages of prehistoric faulting events, excavation or trenching survey across a fault is generally considered to be the most efficient method. All these recent events, however, are not completely understood by this method alone. This is because the information gained by trench excavation is from a single site whereas the interpretation is along a fault.

From the known expansion data on recent faulting in Tohoku district, several faulting events during the Holocene were envisaged based on the average slip rate and amount of displacement derived from the late Pleistocene terraces. As a matter of fact, some events due to Holocene faulting have already been observed in several areas of the district. Comparatively little information has come out of investigations on active faults based on timing of the most recent event, recurrence interval, amount of displacement by a single event, and the average slip rate. A main reason is that very few detailed studies have been performed on surface ruptures.

Recent fault activity can be seen as the displacement of landforms and can be
clearly differentiated as compared to those from earlier times. To identify the recent fault activity, morphologic study along a fault trace is needed as well as the trenching survey (Togo, 2000). If the history of activation during the Holocene time is obtained, we can then estimate their future activity and also compare the ongoing tectonic deformation with different time scales seen in this district. This study, therefore, primarily targets evidence of such prehistoric faulting activity based on the classification of Holocene terraces as topographic references. This is because the fault scarps associated with several recent events are generally preserved across these landforms, and they can be correlated throughout the area under investigation.

Detailed geomorphic mapping shows several Holocene terraces being distributed in Yokote basin, Kitakami lowland, Shonai plain, Yamagata basin, Nagai-Yonezawa basin, Sendai plain, and Fukushima basin, whose margins are bounded by principal thrust faults from adjacent mountains or hilly regions. Repeated Holocene movement on these faults has left scarps on each Holocene surface. The author focuses on the morphology of the scarps and geomorphic configuration of faulted terraces in order to interpret the history of Holocene faulting on several principal thrust faults. Time of occurrence and vertical displacement of the most recent event, recurrence intervals and average slip rate in the Holocene time provide critical insights into the long-term prediction of inland earthquakes and the rates of current tectonic and seismic activity in the district.

2. Methods

Scarps having different heights observed on each Holocene terrace by age across the faults show that they have undergone different number of surface faulting events during the Holocene time. The size and morphology of the scarp on the most recent of faulted terrace were found to be consistent to that from a single-event-displacement. The observed increase in amplitude of the vertical ground surface offsets from the recent terraces to the older ones during the Holocene indicates that these larger measured surface offsets are a result of the cumulative vertical displacement during the Holocene time. Generally, the morphology of the scarp is controlled by its local orientation with respect to the regional orientation of the fault, and by the thickness and mechanical properties of the surface sediments. The amount of displacement per single event differs specifically from the center of the fault towards the end and is similar to that of a decreasing ratio of fault slip towards the end. The author discusses cumulative results from events, which are preserved as small scarps on surfaces within the same site where the local differences in the vertical displacement are negligible. Further support for recent fault activity can be found from evidences obtained from this study using data from several sites along a fault and across
different scarp heights on the Pleistocene terraces and at different ages.

In this work, terraces are classified broadly into groups (H, M, L) in descending order by considering the geomorphological evidences based on the interpretation of aerial photographs with different scales and from field surveys. Along with previously reported data, it is reasonable to assume that the H terraces formed before the last interglacial era, M terraces between the last interglacial to last glacial era, and the L terraces during the last glacial to the post glacial era. Each terrace group is locally differentiated into several sub groups such as L1 to L3 terrace. In the L terrace group, L3 terrace stands for the Holocene terrace and is further subdivided into three levels such as L3-1, L3-2, and L3-3 terrace based on the gradient distinction and difference in elevation from a current riverbed. Formative ages of the Holocene terrace in each area under investigation have already been obtained by radiocarbon dating in previous studies.

3. Regional settings

Due to shorting since Pliocene, thrust faults, whose activity have continued since the late Pliocene (Sato and Amano, 1991), are formed on the back arc of the Tohoku District (Sato, 1994). The hanging walls have been grown as mountainous regions, while Quaternary sedimentary basins have been formed on the footwalls. Two major uplifted zones, called the Ou Backbone Range along the Quaternary volcanic front and Dewa Hills in the back-arc region, bounded by several thrust faults have developed in the Tohoku district (Fig. 1). Kitakami lowland is developed between the Kitakami Mountain Ranges (Non-volcanic outer arc) and Ou Backbone Range. Yokote, Yamagata, Nagai, and Yonezawa basins constitute the inter-mountain basins between the Ou Backbone Range and Dewa Hills. The Shonai plain facing on the Japan Sea is one of the sedimentary basins on the west of the hills. Sendai plain and Fukushima basin are developed along the eastern foot of the Backbone Range. Several active faults developed along the margin of each basin and plain in this district and are playing a major role in the development of landforms in scales comparable to mountains and basins (Yoshikawa et al., 1973; Kaizuka, 1998, etc.). Imaizumi (1999) pointed out that mountains whose margins are delineated of active faults are generally higher than those having no active fault or having small activity for this region. Watanabe (1989a) has suggested that active faults and volcanoes are symptoms of tectonically active regions. Tajikara and Ikeda (2005) show that the pattern of vertical deformation, which has been taking place since Pliocene time, is in accordance with the current topography. They also suggest that the formation of a clear topographical boundary between a range and a basin can be mainly attributed to a slip on the active faults in this district.
At the west side of the Backbone Range in this area, an active fault zone dipping towards east delineates the eastern margin of the Yokote basin. At the opposite side, the fault zone of the Kitakami lowland was formed as a westward dipping normal fault during early Miocene, which later reactivated as a reverse fault during the late Tertiary era (Sato et al., 2002a). Deep seismic reflection profiling allows the interpretation of crustal structures and fault geometry across the Ou Backbone Range. This shows the development of two fault zones along both sides that converges near the bottom of seismogenic layer. Fault reactivation is also recognized in the Sendai plain (Sato et al., 2002b) and probably at Yonezawa basin also (Ikeda et al., 2002), based on comparisons with the thickness of Tertiary sediments between the hanging wall and the footwall. In contrast, the eastern marginal fault zone of the Yokote basin is
younger and reverse faulting took place since 2.4 Ma (Sato et al., 1997).

Similarly, at both sides of Dewa Hills, which is other uplifted area on the east, bounded by the active faults developed in Shonai plain and Yamagata basin. The eastern Shonai thrust and fold zone is composed of three major reverse faults running parallel to each other, in which the front has progressively migrated basin-ward with time, indicating that their total activity has increased since early Pleistocene (Komatsubara, 1997). On the other hand, fault zones in the east side of the Hills show different distributions of surface tracing along the strike, thus influencing the history of basin forming. Western marginal fault zone of the Yamagata basin formed as a relatively flat basin floor composed of widely spread alluvial plains (Suzuki, 1988).

At the south side of the Yamagata basin, the Nagai and Yonezawa basin, defined as one of inter-mountain basins, developed parallel to the arc with N-S trending. Western margin of the Nagai basin is bounded by reverse faults dipping westward with relatively large angle, and is probably originated from the Tanakura tectonic line truncating the late Cretaceous granitic rock (Miyauchi et al., 2004).

In the southern part of study area, a fault zone was found to extend 60 km long the NE to SW trending and delineate the eastern fringe of the Backbone range. The fault zone deformed the terraces along the western marginal area of the Fukushima basin (Fujiwara, 1958; Otsuki et al., 1977; Watanabe, 1985). The Fukushima basin is subdivided into northern and southern halves, in terms of morphotectonic features and their tectonic evolutions (Watanabe, 1985).

Though almost all the faults in the district have been active during the Holocene with a high probability for future reactivation, there are no historical records of faulting events except for the surface rupture attributed to the 1896 Rikuu earthquake in the Yokote basin.

4. Geomorphic evidence of paleoearthquakes during the Holocene time

4.1 Marginal fault zone at the western Yokote basin

At the eastern edge of the Yokote basin close to the foot of the Ou Backbone Range, several active faults extending to about 56 km in length constitute a fault zone trending north to south (Fig. 2). It is relatively easy to recognize that rupture traces that are most recent exist on the Holocene terraces in the northern part of the fault zone. This is because those earthquake faults were associated with the latest seismic event called the Rikuu Earthquake (M. 7.2), that took place on 31\textsuperscript{st} August 1896 and have been preserved well in the form of fault landforms. From this point of view, the northern part of the eastern marginal faults are one of the most distinguished active reverse faults in Japan, as compared to those that have no historical record on faulting. During the last earthquake, the movement of the southern part of the fault zone has
Fig. 2 Map showing classification of terraces and distribution of active faults in the northern part of the Yokote basin based on aerial photographic interpretation and field observations. The contour interval is 10 m. The solid line shows the fault where the surface trace is discernible; dashed where inferred; and dotted where concealed. The U and D denote upthrown and downthrown sides of the active faults, respectively. This pattern of description about active faults applies to the other corresponding figures. Details of the Holocene fault scarp geomorphology are shown in Fig. 3, 5, 7, and 8. See Fig. 1 for corresponding locations.
not been reported (Matsuda et al., 1980). This study mainly focuses on the northern part of the fault zone composed of the Shiraiwa fault, Ota fault and Senya fault which were active during the late Holocene time.

Nakata (1976) has shown the degree of faulting since the late Pleistocene and estimated the vertical slip rate to be 0.5 to 0.8 mm/yr. Matsuda et al. (1980) has illustrated a Holocene faulting event before the Rikuu earthquake from geomorphic evidences. Hirano (1984) has estimated the age of the penultimate event to be between 2,700 and 4,400 yr B.P.. Many later works on the fault has shown that the pre-1986 earthquake occurred at about 3,500 yr B.P. and the possibility of recurrence has an interval of about 3,000 to 4,000 years (Research Group for the Senya Fault, 1986; Imaizumi et al., 1989, Matsuta et al., 2001; etc).

Holocene terraces are classified into three levels such as L3-1 to L3-3 terraces in descending order. L3-1 terrace is dated to be 5,730±150 y.B.P. (Hirano, 1984), and at 5,800 to 6,000 y.B.P. (Uchida, 2004MS), the L3-2 at 3,500 to 5,000 y.B.P. (Research Group for the Senya Fault, 1986), and the L3-3, 2,580±80 y.B.P. (Hirano, 1984), and at 880 to 1,100 y.B.P. (Uchida, 2004MS). As indicated by these values, the formative ages of L3-1, L3-2 and L3-3 terraces can be estimated to be at 6,000, 3,500, and 1,500 years ago, respectively.

**Northern part of the fault zone**

The Shiraiwa fault extends to about 9 km in length from the Tama River to the Sainai River (Fig. 1). The recent activity of the fault is recorded as displacement of the late Pleistocene terraces with the amount of offset increasing with age. Fault scarps associated with the Rikuu earthquake are clearly identified as having 1.5 to 2.0 m in vertical component and are preserved on the youngest surface.

In the vicinity of the Shiraiwa-Nenbutsuden, the fault truncates several different levels of fluvial terraces along the Saito River (Fig. 3). Relative heights of the scarp on these decrease from Pleistocene to Holocene terraces, except for those on the modern alluvial plain. In the hanging wall of the fault, the Pleistocene terraces are warped down and westward. These facts indicate that the Shiraiwa fault has repeated its activity since the Pleistocene time. Two Holocene terraces having different elevation from the present riverbed have developed along the Saito River crossing the fault trace. L3-2 terrace is displaced 3.8 m vertically, as depicted in profile b-b' (Fig. 4). On the other hand, the vertical offset of the L3-3 terrace is 1.7 m (Profile a-a' in Fig. 4), which is caused by the latest event in 1896. The amount of vertical displacement as preserved on the L3-2 terrace is clearly larger than that on L3-3, indicating that the frequency of faulting events were twice as much after the formation of the L3-2 terrace.

In the Southern part of the Shiraiwa fault, three levels of Holocene terraces are
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![Diagram showing geomorphological map]

**Fig. 3** Detailed geomorphological map showing distribution of terraces and the Shiraiwa fault in the vicinity of Shiraiwa-nenbutsuden. Contour interval is 5 m. See Fig. 2 for the corresponding location.

distributed in a similar manner along the Kurisawa River (Fig. 5). Each Holocene terrace crosses the surface trace of the fault and is apparently cut by the same. The amounts of displacements as preserved on them are 4.8 m, 3.1 m and 1.3 m respectively (Topographic profiles shown in Fig. 6), suggesting a progressive vertical displacement and at least three faulting events during the Holocene time.

The surface trace produced by the most recent event can readily be recognized in the central part of the fault zone (the Ota fault) generated during the 1896 earthquake, which is located 2 km eastward from the other faults (Fig. 7). It extends 3 km in
length to the adjacent area of mountain, and cuts the L3-2 and L3-3 terraces having vertical extends of 1.5 to 2 m and 3 m, respectively. Miyauchi et al. (1997) have reported fault features that appear at several locations along the fault scarps indicating a vertical slip of 1.5 m associated with the most recent event and also the occurrence of another event before 6,500 y.B.P..

The Senya fault extends 12 km in length from the Kawaguchi River to Maruko River constituting the southern part of the 1896 rupture. Progressively larger vertical offsets of the successively older surfaces reflect repeated earthquakes in the late Pleistocene time. According to Ikeda (1983), these movements have shifted basinward to the present active fault in western foothills of Mahiru Range where recent surface rupture occurred within the basin rather than at the front of the range. At Ichijogi area, vertical offset on the surface accompanied by the last event was found to be 3.5 m (Matuda et al., 1980), which represents the maximum vertical displacement in the fault zone. At the mouth of small valleys, fault traces are often curved upward in the

Fig. 4  Topographic profiles showing the deformation and amount of vertical displacement on terraces along both banks of the Saito River across the fault. Locations of the profiles are shown in Fig. 3.
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Fig. 5 Detailed geomorphological map showing distribution of terraces and the Shiraiwa fault in the vicinity of Kurisawa. Contour interval is 5 m. See Fig. 2 for the corresponding location.

Direction of the valley (Matsuda et al., 1980; Imaizumi et al., 1989 and 2006). Research Group for the Senya Fault (1986) and Imaizumi et al. (1989) have excavated trenches and also carried out a borehole survey across the fault to investigate paleoearthquake and the recurrence time of the fault. Their studies have shown two events, a penultimate and the most recent, in the surface sediments.

Along the Maruko River flowing westward from the Senya Hills, it appears that
three levels of Holocene terraces have developed and displaced by the fault (Fig. 8). At least three events are derived from differential fault scarps preserved on the Holocene terraces. The offsets of each Holocene terrace are 5.5 m, 3.8 m and 2.0 m vertically (Profile g-g' to i-i' in Fig. 9), suggesting them as evidences for the offsets of three paleoearthquakes as preserved on the L3-1 terrace. The penultimate and the most recent events are on the L3-2 terrace, and only the 1896 rupture is on the L3-3 terrace.

**Southern part of the fault zone**

In the southern part of the fault zone, Pleistocene terraces dated to 38 ka B.P. are displaced 4.8 to 11.5 m vertically by the fault (Akita Prefectural Government, 1998; 1999). A terrace that was assumed to be formed between 6,000 to 10,000 years ago was displaced 2.2 m vertically (Akita Prefectural Government, 1999). However, no direct evidence of late Holocene surface rupture corresponding to the L3-2 and L3-3 terrace can be found along the fault trace. A possible interpretation of these results can be such that the surface offsets irrespective of the movement of the fault in the southern part of the fault zone during the late Holocene time.
Fig. 7  Detailed geomorphological map showing distribution of terraces and the Ota fault. Contour intervals are 2.5 m at the northern bank of the Sainai River and 5 m at the southern bank. See Fig. 2 for the corresponding location.
Holocene faulting of the Yokote basin

Geomorphic facts indicate that the surface ruptures associated with the penultimate and the recent 1896 events have emerged as well preserved scraps on the late
Holocene terraces in the northern part of the fault zone. Moreover, it is also evident that three faulting events have occurred after the formation of the L3-1 terrace dated 6,000 years ago which is based on the progressive vertical displacement, and yield a vertical slip rate of 0.92 mm/yr during the Holocene time. On the other hand, in the southern part, the average slip rate during the Holocene was estimated to be at 0.22–0.37 mm/yr. Similarly, vertical slip rate since the late Pleistocene for the northern part is 0.72 mm/yr as inferred from the amount of displacement of the L1 terrace (dated to be 25,000 years ago; Akita Prefectural Government, 1999) having a vertical deformation of 18 m.

In the southern part, the Pleistocene terrace dated at 38 ka B.P. was found to be displaced vertically with an extent of 4.8 to 11.5 m, indicating that the vertical slip rate in the last 38,000 years is 0.13–0.30 mm/yr.

Considering the amount of vertical offset preserved on each of the Holocene as well as Pleistocene terraces, the degree of activity during the Holocene time in the
northern part of the fault zone was found to be relatively higher than that in the southern part in the Yokote basin.

4.2 Western marginal fault zone of the Kitakami lowland

In the western marginal region of Kitakami lowland, a fault zone consisting of many active reverse faults delineate the boundary between the Ou Backbone range and the lowland. It extends in length to about 62 km trending from north to south (Fig. 10). Watanabe (1989b) has reported that the Kitakami lowland can be subdivided into three subregions such as the northern, central, and southern parts from the viewpoint of geological structure and basin development. Pleistocene terraces, being effective references for the confirming of displacements, are well developed and their ages can be determined by stratigraphy of the quaternary tephras (Watanabe, 1991). Fujiwara (1959), Miyagi (1975), and Nakata (1976) have described the distribution of faults with progressive amounts of displacement during the late Pleistocene. Awata (1988) has shown that the two events, one between 4,000 and 7,800 years ago and the other before 7,800 years ago were deducted from trenching survey in the northern part of the fault zone in the Shiwa area (Fig. 10). To the west of Hanamaki area, several faults run parallel to each other. Watanabe et al. (1994) have reported that two events could be inferred from the trenching survey; in which the recent event occurred less than 6,000 years ago and the previous one less than 20,000 years ago. Iwate Prefectural Government (1998) has shown an event, which happened 4,500 years ago across the same fault region investigated by Watanabe et al. (1994). Miyauchi et al. (2002) have described a new surface trace associated with the recent rupture located toward the basin from the fault trace excavated in previous works. Later work by Goto et al. (2003), who have investigated eastern fault towards the basin have pointed out that the most recent event in the northern fault zone occurred during the past 3,300 years. On the other hand, at the southern part of the fault zone, Holocene faulting events have not been evident except for an early Holocene event derived from deformed terraces dated to be at 7,270±50 y.B.P. (Iwate Prefectural Government, 1998).

Holocene surfaces are classified into three levels such as L3-1 to L3-3 terraces in descending order. Except for the L3-1 terrace in the southern part dated to be at about 7,000 years ago, age of the Holocene terraces has not been obtained yet. The author assumes that L3-2 and L3-3 terraces were formed 3,000 and 1,500 years ago, respectively, considering the fact that their morphological features correspond to those of the dated terraces from other areas. L3-2 and L3-3 terraces in this region were lower than other terraces developed along the river having less than 2 to 5 m above the current stream level at the crossing of these faults.

For comparison with the long-term slip rate, displacements of late Pleistocene terraces are also shown. L1 terraces are subdivided into L1H and L1L terrace which
Fig. 10 Map showing topography and distribution of active faults along the western margin of the Kitakami lowland. Relationship between terraces and faults are shown in Fig. 11 and 14. See Fig. 1 for the corresponding location.
are dated to be at about 25ka and 20ka, respectively (Iwate Prefectural Government, 1998). However, formative age of L2 terrace is assumed to be at 12-15ka.

**Northern part of the Kitakami lowland**

From the Shiwa to Hanamaki area, several terraces differentiated by age are found to be distributed across and deformed by four faults named Uwandaira faults (Research Group for Active Faults, 1991, see Fig. 10) which run nearly parallel to each other and are found to be an arcuate surface trace of faults eastward, as shown in Fig. 11. Figure 12 shows that F2 and F4 are the main faults that cause uplifting of the mountain range. Along F2, M and L1 terraces are deformed, but there is no evidence of surface rupture on the Holocene terraces. On the other hand, L3-1 and L3-2 terraces cross the surface trace of F4 and are apparently cut by the same. This fact suggests little or no movement in F2 at least during the Holocene.

In the vicinity of Urushitachi (Fig. 12), L3-2 terrace is deformed and vertically offset 0.8 to 1.2 m (Profile k-k' and l-l' in Fig. 13). On the L3-1 terrace, a scarplet with 3.0 m vertical deformation is recognized (Profile j-j' in Fig. 13). F4 surface trace extends southward to the Tomizawa area where the vertical offset on the L3-1 terrace is 3.3 m (Profile m-m' in Fig. 13). On the left bank of the Mimitori River, L3-2 terrace cross the F4 surface trace and the modern alluvial plain along the Kuzumaru River, however, are not faulted or separated, suggesting a fault scarp that is completely buried or eroded by recent fluvial materials after the formation of L3-2. Consequently, the small scarp identified on the L3-2 terrace is the displacement associated with the most recent event of surface rupture.

**Southern part of the Kitakami lowland**

In the southern part of the Kitakami lowland, the fault trace extending North to South with relatively straight lines delineate the western fringe of the lowland (see Fig. 10). L1 terraces are well distributed widely along each River and are cut by these faults. In the region between the Geto and Isawa River, dissected H terraces dated to be over 200 ka B.P. (Watanabe, 1989a ; b ; 1990 ; 1991) have particularly been recognized (Fig. 14(a)). Many surface traces of faults displacing the H terraces with short and straight lines are observed, but other younger terraces show no evidence of having been faulted along the surface traces except for the eastern one. Watanabe (1989a) has described that in the southern part, it seems likely that the late quaternary faulting is not so active as compared to the northern part.

Faulted Holocene terraces are observed at two sites in a dissecting valley of H terraces. In the Yokoshida area, between the Sabukawa and Shirirae River, the fault produces eastward facing scarps across the Pleistocene terraces with vertical deforma-
Fig. 11 Map showing distribution of terraces and active faults in the northern part of the Kitakami lowland based on aerial photographic interpretation and field observations. Contour intervals are 5 m in the lowland and 10 m in the mountainous area, respectively. Details of the geomorphology of the Holocene fault scarp are shown in Fig. 12. See Fig. 10 for the corresponding location.
Fig. 12 Detailed geomorphological map showing the distribution of active faults in the northern part of the Kitakami lowland. Contour intervals are 5 m in the lowland and 10m in the mountainous area, respectively. Locations of the sites surveyed by previous works are also annotated. See Fig. 11 for the corresponding location. Topographic profiles of Holocene terraces are shown in Fig. 13.
Fig. 13  Topographic profiles showing the deformation and amount of vertical displacement on Holocene terraces across the fault in the northern part of the Kitakami lowland. The corresponding locations of the profiles are shown in Fig. 12.

...tions ranging from 70 m on the H terrace and 40 m on the M2 terrace, respectively (Fig. 14(b)). At the northern part of the Yokoshida in Fig. 14(b), a small fault scarp is recognized on the L3-1 terrace having a vertical separation of 2.5 m (Profile o-o' in Fig.
Fig. 14  (a) Map showing distribution of terraces and active faults in the southern part of the Kitakami lowland based on aerial photographic interpretation and field observations. Contour intervals are 5m in the lowland and 10m in the mountainous area, respectively. (b), (c) Details of the relationship between Holocene terraces and faults in the vicinity of Yokoshida and Kawame. Amounts of vertical offset on Pleistocene terraces in the Yokoshida area are labeled on (b). Topographic profiles on Holocene terraces are illustrated in Fig. 15. See Fig. 10 for the corresponding location.
Fig. 15. Topographic profiles showing the deformation and amount of vertical displacement on Holocene terraces across the fault in the southern part of the Kitakami lowland. The corresponding locations of the profiles are shown in Fig. 14(b) and (c).

Similarly at the Kawame area, the eastern fault that is distributed on the H terraces deforms the L3-1 terrace developed along the small river in the dissecting valley (Fig. 14(c)). Vertical offset on the L3-1 terrace is 2.5 m (Profile p-p' in Fig. 15). However, there is no deformation on the L3-2 terrace or on other younger ones.

Holocene faulting of the Kitakami lowland

On the Uwandaira faults constituting the northern part of the fault zone, several Holocene events have been pointed out by the trenching surveys as mentioned before. Scarp s of height 0.8 to 1.2 m preserved on L3-2 terrace indicate that the surface rupture associated with the most recent event has emerged during the late Holocene time. If the formative ages of the L3-2 and L3-3 terraces are assumed to be Holocene as dated in other areas, then the most recent faulting event may have occurred between 1,500 to 3,000 years ago. These geomorphic facts are also compatible with the previous work done by Goto et al. (2003). Moreover, it is evident that the vertical displacement of L3-1 terrace is approximately three times that of L3-2, indicating that there were three events that took place after the formation of the L3-1 terrace by considering their progressive vertical displacement.

On the other hand, in the southern part, the youngest terrace displaced by Holocene faulting is the L3-1 terrace, indicating that no surface rupture has occurred in the late Holocene after the formation of the L3-2 terrace. Considering the vertical
displacements of 2.5 and 3.3 m preserved on the L3-1 terrace are produced by a single faulting event, 2 to 4 events can be assumed after the formation of the L1 terrace in the southern part. On the average the vertical slip rate during the Holocene is estimated to be at 0.43–0.47 mm/yr in the northern part, and 0.36–0.47 mm/yr in the southern part.

The amount of deformation on the Pleistocene terrace indicates the multiple faulting events and related earthquake ruptures to be visible as well. At the Ureshita-uchi area in the northern part, vertical offsets of L1-H and L1-L terraces are 10–12 m and 7–8 m, respectively. Along the Minitori River, the scarp on the L1-H represents a vertical slip of 10 m during the last 25,000 years. Similarly, the L1-H terrace is displaced 6 to 10 m vertically at several sites in the southern part. Accordingly, the vertical slip rates since the late Pleistocene are estimated to be at 0.35–0.48 mm/yr in the northern part, and at 0.24–0.40 mm/yr in the southern part of the fault zone.

4.3 Marginal fault zone in the eastern Shonai plain

In the western part of the Dewa hills, several active thrust and fold systems trends mainly north to south (Komatsubara, 1997; 1998). A principal active fault zone extending to about 40 km in length and belonging to the thrust and fold systems delineates the eastern fringe of the Shonai plain (Fig. 16). This zone comprises of two major faults. Holocene activity on the northern part of the fault zone named Kannonji fault has been studied in detail previously. The most recent event occurred therein later than 2,500 y.B.P. and other events probably between 4,300 and 4,500 y.B.P., and around 6,000 to 6,300 y.B.P., respectively (Suzuki et al., 1989; 1994). Similarly, the Matsuyama fault, which constitutes the southern part of the fault zone, has been reported to have undergone Holocene activity by previous studies (Ota, 1998; Sawa et al., 2000b; etc.), however, no precise investigation has been performed at the fault along 8 km on the southern side of the Mogami River. This paper, therefore, describes the slip rate and Holocene fault activity in the southern part of the fault zone from results obtained by borehole surveys reported in a paper in Japanese (Mizumoto et al., 2005), previously.

Southern part of the Shonai plain

The young terrace surfaces, probably formed in and around MIS2 in this region are classified into L1 and L2 terrace. L3 terrace represents a Holocene terrace as illustrated in Figure 17. The L3 terrace can be subdivided into three, specifically L3-1, L3-2, and L3-3 terraces respectively. Evidence for recent surface faulting events have been obtained through the study of several sites along the fault and across different vertical displacements of fault scarps on the terrace surfaces having different ages. A small scarp having a vertical displacement of 1-1.5 m is recognized on the
Fig. 16 Map showing distribution of active faults along the eastern margin of Shonai plain. Locations of active faults are taken from Nakata and Imazumi (2002) and Ikeda et al. (2002).
Fig. 17 Map showing classification of terraces and distribution of active faults in the southern part of the Shonai plain (Mizumoto et al., 2005). Contour intervals are 5m in the plain and 10m in the mountainous area, respectively. Location of borehole survey is shown in Fig. 14. See Fig. 16 for the corresponding location.
L3-2 terrace indicating the displacement associated with the most recent event. Borehole survey was carried out on the L3-3 terrace where a fault scarp was absent. Twenty-nine boreholes were dug about 400 m long across the flexure scarp zone on an alluvial fan terrace (Fig. 18). The Borehole data were collected at 20 m intervals in the main area of interest with 5 to 10 m in depth.

The gathered strata were divided into I-III layers based on their facies (Fig. 19). Layers I and II mainly composed of sandy gravel and silt of about 4 m in thickness from the top going downward. The layer I sediments constitute the L3-3 terrace, and layer II the L3-2 terrace. Layer III mainly consisted of peaty clay. A conspicuous peat layer which has been probably deposited at about 5,500 to 6,000 yrs.B.P.
Holocene fault activity in the Shonai plain

At the northern part of the fault zone in the Shonai plain, recurrence intervals in the Holocene has been estimated to be less than 2,000 years, and the amount of surface displacement associated with the latest event was found to be about 1 m (Suzuki et al., 1989). Vertical offset of the stratum with an extent of 3.3 m dated to be at 5,300 to 6,300 years ago indicates an average slip rate of 0.52–0.62 mm/yr during the Holocene time (Suzuki et al., 1994).

Similarly, in the southern part of the fault zone, vertical displacements corresponding to L3-1 terrace dated to be at 6,500 years ago (Ota et al., 2000) and L3-2 which was about 3,000 years ago (Komatsubara, 1997) are found to be 4–5 m (Sawa et al., 2000b) and 1.5 m (Sawa et al., 1996) respectively. This yields an average slip rate of 0.62 to

(Yamagata Prefectural Government, 2000) was observed in the upper part of this III layer. Deformation of the peat layer indicates that a vertical offset of this layer can be estimated to be 3.7 m (Fig. 20, A). In addition, layer II was also found to be deformed (1.2 m) which could be caused by a single recent faulting event (Fig. 20, B). The amount of this displacement shows almost a similar value of the surface fault scarp as seen on the L3-2 terrace. It is also evident that vertical displacement of layer III is approximately three times as that of layer II. The geomorphic evidence and also the geologic cross sections across the fault indicate that three faulting events may have occurred since the last 5,500 to 6,000 years based on the progressive vertical displacement. Accordingly, the vertical offset and the possible age thus determined suggest a vertical slip rate of about 0.62–0.67 mm/yr of the fault (Mizumoto et al., 2005).
Geomorphic Evidence of Paleoearthquakes during Holocene on Principal Thrust Fault Zones in the Tohoku District, Northeast Japan

When the peaty layer of borehole core 2 corresponds to the upper part of the layer III, which probably may have deposited at about 5,500-6,000 yrs B.P., the amount of vertical displacement can be estimated to be 3.7 m... (A).

The offset and probable age show vertical slip rate of the fault during the Holocene to be 0.92 to 0.67 mm/yr.

Fig. 20 Amounts of vertical displacement in the Holocene resulting from subsurface geological profile modified from Mizumoto et al. (2005).

0.77 mm/yr, based on the vertical separation in the southern part of the fault zone during the Holocene time. Ota (1998) has also pointed out a Holocene faulting event that occurred between 7,000 to 8,000 years ago by trenching survey. Although the recurrence of faulting based on landforms on the southern segment has not been established due to the lack of topographic references, a displacement of 1.5 m on the L3-2 terrace is considered to be a vertical offset per faulting event, leading to at least three events after the formation of the L3-1 terrace. Similarly, faulted surface deposits derived from the borehole survey carried out in the southern part also show progressive displacement characteristic of Holocene faulting. Because of the similarity on Holocene fault activity, the two faults, which constitute the southern part of the fault zone and extending to both sides of the Mogami River, are considered to be a series of active faults and newly named to be the Matsuyama-Karikawa fault having a length of about 18 km (Mizumoto et al., 2005).

Displacements of late Pleistocene terrace at several sites also permit a consideration of recent faulting and the estimation of the slip rate. Late Pleistocene terraces corresponding to the L1 terrace formed at about 18,000-20,000 years ago are displaced 7.5-12 m vertically along the fault in the northern side of the Mogami River (Sawa et al., 2000b). Similarly, along the southern extent of the borehole site, scarp heights of 14 m are observed on the late Pleistocene terrace which probably formed at 20,000 years ago. Consequently, the vertical slip rate in the past 20,000 years is estimated to be at 0.38-0.70 mm/yr in the southern part. Average slip rates in the northern part of the fault zone cannot be estimated because of insufficient data of late Pleistocene terrace referred to as topographic references.
4.4 Marginal fault zone of the western Yamagata basin

In the west side of the Yamagata basin, a fault zone trending north to south extends to about 45 km in length in the adjacent area east of the Dewa Hills (Fig. 21, see also Fig. 1). In the northern part, the fault zone displacing the Pleistocene terraces consists of several overlapping faults (Fig. 21). Suzuki (1988) has described the characteristics of active tectonic features in order to clarify the history of basin formation. Imaizumi et al. (1999) have pointed out that an eastward fault amongst the overlapping faults is considered to be a major fault at present, suggesting that the other faults may have disconnected and consequently developed as smaller faults on the upper side of the major fault. On the contrary, at the southern side of the Sagae River, surface traces mapped with relatively straight fault lines delineate the western fringe of the basin.

The trenching survey carried out in the northern part shows that twice the number of events took place during the Holocene time between 4,000 to 5,000 years ago and 7,000 to 8,000 years ago respectively. However, in the southern part of the fault zone only a single faulting event occurred about 4,000 years ago that has been reported (Yamagata Prefectural Government, 1999; 2000). Toda et al. (2006) have found more than four events in the past 10,000 years at the northern part and only one at the trench site in the southern fault zone. Taking into account the amount of displacement and average slip rate of the faults as derived from late Pleistocene terraces by the previous studies, several faulting events are expected to be preserved on Holocene terrace surfaces, in particular, on the southern part of the fault zone.

Holocene terraces are classified into three levels—L3-1 to L3-3 terrace in descending order. In the southern part, Yamagata Prefectural Government (2000) has reported the age of several Holocene sediments by trenching wall and borehole surveys, indicating the age of L3-1 and L3-2 terraces to be about 6,000 and 2,500 years ago. Age of the L3-3 terrace has not been obtained yet. The author make the assumption that the L3-3 terrace was formed 1,500 years ago by considering the fact that L3-3 terrace in this area is the lowest terrace developed along the river and has a vertical extent of less than 2 to 3 m above present stream level at the crossing of the faults.

Northern part of the Yamagata basin

Surface fault traces are recognized from Oishida to the northern side of the Sagae River. At several sites, small fault scarps are interpreted as being the result of a recent event. In the vicinity of Yokoyama, Holocene terraces are deformed with a progressive vertical displacement (Fig. 22). The L3-1 is an alluvial fan surface developed from the western hilly area. On the other hand, L3-2 is a previous flood plain along the Mogami River. L3-1 and L3-2 terraces are vertically displaced to an extent about 4 m and 2 m, respectively. However no surface deformation of the fault
Fig. 21  Map showing topography and distribution of active faults along the western margin of the Yamagata basin based on aerial photographic interpretation and field observations. Contour intervals are 5 m in the basin floor and 10 m in the mountainous area, respectively. Relationship between terraces and faults are shown in Fig. 22 and 23. See Fig. 1 for the corresponding location.
is identified on the L3-3 terrace and modern alluvial plain, indicating that it is possible to define the displacement of L3-2 terrace as being attributed to the most recent event. Two different vertical extents of the fault scarps on each Holocene terrace allow for the recognition of at least two surface faulting events during the past 6,000 years in this area.
Southern part of the Yamagata basin

Figure 23 shows the fault zone consisting of two overlapping principal faults in the southern side of the Sagae River (Yagi et al., 2001). Between the Yanagisawa and Kanezawa area, the Holocene terrace can be classified into three levels as before that are obviously distributed lower than the late Pleistocene terraces (Fig. 24). Along the Ishikozawa River, the L3-1 terrace is formed in flexure scarp facing the lowland and having a vertical deformation of 3.5 m. At the opposite bank of the river, the observed displacements on the L3-2 and L3-3 terraces are almost similar in amount as vertical offset (1.0 to 1.5 m).

In the southern area of the Yananobe, two levels of late Pleistocene terraces (L1, L2) are seen to be well developed and onto the margin of mountainous area (Fig. 23). Holocene terraces are developed eastward along dissected valley of small rivers. There are three overlapping faults extending North to South, which truncates several different levels of fluvial terraces. The traces of the most recent rupture, however, exist only along the fault that lay towards the basin. This fact implies that the fault movement has shifted towards the basin with time during the late Pleistocene. It is true that reverse faults commonly migrate towards the basin with time, this also shows that it is possible for this migration to occur geologically in such a short time.

At the southern part of the fault zone, two faults, which show geomorphic evidence of recent activity are recognized as a N-S trending, and run parallel to each other (Fig. 25). Figure 26 shows the vertical offset of 2.0 m on the L3-1 terrace across the western fault, but no deformation is recognized on the L3-2 and L3-3 terraces across it. On the contrary, along the eastern side, towards the basin, L3-2 and L3-3 terraces are deformed vertically with an extent of 1.5 to 1.8 m. These similar amounts of displacement shown by both terraces (L3-2 and L3-3) are attributed to a recent faulting event. Because the surface trace bifurcates into two traces with small scarps, total amount of vertical separation across the two faults remains roughly the same at 3.8 m after the formation of the L3-1 terrace.

Accordingly, geomorphic evidences along the faults indicate that the surface ruptures have occurred twice after the formation of the L3-1 terrace. Furthermore, the most recent event may have occurred after the formative age of the L3-3 terrace in the southern part of the fault zone.

Holocene fault activity of the Yamagata basin

In order to describe the Holocene fault activity based on the morphological features, three levels of Holocene terraces are used which, are referred to as topographic references. At the northern part of the fault zone, two events are preserved on the L3-1 terrace, and one on the L3-2 terrace. Similarly, the cumulative result of these two faulting events can be recognized on the L3-1 terrace, and the one on the L3-
Fig. 23 Map showing classification of terraces and distribution of active faults in the southern part of the Yamagata basin. Contour intervals are 5 m in the basin floor and 10 m in the mountainous area, respectively. Selected Holocene offsets in detail are highlighted in Fig. 24, 25 and Fig. 26, respectively. See Fig. 21 for the corresponding location.
2 and L3-3 terraces seem to have developed across the faults in the southern part. Scarps formed by a single faulting event with vertical extents of 1.5 to 2.0 m are preserved on the L3-2 terrace in the north part, and on L3-3 terrace in the south part, suggesting that the most recent event of this fault zone may have occurred at a
Fig. 25 Geomorphological map showing the distribution of active fault in the vicinity of Murakizawa, in the southern part of the Yamagata basin. Contour interval is 2.5 m. Geomorphological details of the Holocene fault scarp are shown in Fig. 26. See Fig. 23 for corresponding location.
different time than that of the northern part. As indicated by the values which are derived from topographic profiles measured perpendicular to the trace of the scarp, average slip rate during the Holocene is 0.67 mm/yr in the northern part, and 0.58-0.63 mm/yr in the southern part of the fault zone.

The vertical slip rates derived from Pleistocene terraces are also shown and described below. In the northern part, the total amount of vertical displacement for overlapping fault is 13-15 m corresponding to a probable age of 20 ka for the L1 terrace. Similarly, along the southern part of the fault zone, scarp heights of 15 m are observed on the late Pleistocene terrace, which may have formed 25,000 years ago.
Consequently, the vertical slip rates in the past 20,000–2,5000 years were estimated to be at 0.52–0.60 mm/yr for the northern part, and 0.60 mm/yr for the southern part, respectively. These rates are found to be comparable with that of Holocene.

4.5 Marginal fault zone of the western Nagai and Yonezawa basin

At the western boundary region of the Nagai and Yonezawa basins, reverse faults dipping westward and extending to about 22 km long in Nagai and 20 km in Yonezawa and trending north to south (Fig. 27) can be recognized. An average slip rate of 0.3 to 0.5 mm/yr in the Nagai basin is derived from the Pleistocene terraces deformed by the faults with a progressive amount of displacement (Yagi, 1999; Miyauchi et al., 2004). However, comparatively little information is available on recent faulting events in the Yonezawa basin.

The last seismic event of the faults in the Nagai basin took place about 2,000 years ago and the probability of recurrence lies in the interval between 3,000 and 7,000 years (Miyauchi et al., 2004). Similarly, faulting events during the Holocene have occurred about 6,600 years ago in the Yonezawa basin (Yamagata Prefectural Government, 2002). This study, therefore, illustrates the fundamental information regarding the Holocene fault morphology in both basins by geomorphic investigations.

Holocene terraces are classified into three levels, i.e., L3-1 to L3-3 terrace in the descending order. Yamagata Prefectural Government (2002) has reported the age of the L3-1 terrace to be 6,000 years ago in the Nagai basin and 8,000 years ago in the Yonezawa basin. The L3-2 terrace developed along the Nogawa River is dated to be at 3,120±70 y.B.P (Yagi, 1999) and also 2,235±70 y.B.P (Miyauchi et al., 2004). However, no result has been reported on the age of L3-3 terraces so far. Considering the fact that these L3-3 terraces are the lowest ones developed along the river at present, it is reasonable to assume that they were formed at about 1,500 years ago.

**Nagai basin**

In the northern part of the basin, scarp heights of about 1.5 m associated with the latest faulting event are visible on the Holocene terrace surfaces distributed in the adjacent areas of the mountains (Separation noted in Fig. 27). The surface faulting and rupture observed on the L3-2 terrace are relatively fresh and definitely of late Holocene time. At the northern side of the Nogawa River, in the Teraizumi area, a scarp height of about 1.5 m can be recognized on the late Holocene surface in the small valley (Location is shown in Fig. 27). Yamagata Prefectural Government (2002) has carried out a borehole survey across this fault scarp and concluded that alluvial fan sediments aged between 2,300 to 3,300 cal.y.B.P. were deformed 1.4 m vertically.

In the southern bank of the Nogawa River, fault scarps that are 2.5 m in height have been preserved on the L3-2 terrace (Yagi, 1999; Miyauchi et al., 2004, Location
Fig. 27 Map showing topography and distribution of active faults in the Nagai and Yonezawa basin based on aerial photographic interpretation and field observations. Numerical annotations show amounts of vertical offset on terraces at each location. Details of the relationship between Holocene terraces and the faults are highlighted in Fig. 28, 29, 30, and 31, respectively. See Fig. 1 for the corresponding location.
is also annotated in Fig. 27). Along its southern boundary, the trace is seem to fork near the Hagyu River (Fig. 28(a)). The L3-1 and L3-2 terraces are intersected by the eastern fault trace having vertical component of 1.2 and 1.3 m, respectively (Profile q-q' and r-r' in Fig. 28(b)). However, no deformation of the Holocene terrace across the western fault trace could be recognized. Vertical displacements preserved on the two Holocene terraces are similar, suggesting that there is no progressive vertical displacement between them. Accordingly, after the formation of the L3-1 terrace, only a single faulting event has occurred in this area. This is supported by the fact that scarps having vertical dimensions of 1.5 to 2.0 m are recognized on the L3-1 terrace dated to be about 6 ka ago and developed between the Hagyu and Nogawa rivers (Yamagata Prefectural Government, 2002, see the numerical annotation in Fig. 27).

At the southern part of the basin, the fault crosses several terraces developed along the Okitama-shira River (Fig. 29(a)). Pleistocene terraces are warped downward and eastward to a relatively strait fault trace trending North to South. Holocene surface rupture has been recognized on the L3-2 terrace with a vertical deformation of 1.5 m (Profile s-s' in Fig. 29(b)).

Yonezawa basin

In the Yonezawa basin, a small fault scrap could be identified that has formed on the Holocene terraces in the mid to southern part of the basin, even though recent surface rupture is not relatively conspicuous as in the case of Nagai basin. Holocene terraces are abundant on the northern and southern banks of the Kuro River (Fig. 30(a)). On the northern bank, L3-2 terraces are faulted with a vertical component of 1.1 m (Profile t-t' in Fig. 30(b)). On the opposite side a scarp of 0.7 m having a vertical displacement is visible on the L3-2 terrace (Profile u-u' in Fig. 30(b)). Contrary to this, there is no displacement on the L3-3 terraces. On the basis of the geomorphic evidence of surface faulting, the L3-2 terrace is considered to be the youngest of all the faulted terraces in the basin.

In the vicinity of the Fukiyashiki, the L3-1 terrace was found to be dated at about 8 ka ago (Yamagata Prefectural Government, 2002) and was developed in the southern bank of the Omono River (Fig. 31(a)). The amount of vertical displacement observed on the L3-1 terrace is 2.4 m (Profile v-v' in Fig. 31(b)). However, scarps are not preserved on the L3-3 terrace and the lower modern alluvial plain. Scarp heights of the L3-1 terrace are clearly too large to be due to a single event preserved on the L3-2 terrace as mentioned before and in the site near the Kuro River. Thus suggesting a probability that they are the cumulative result of at least two events on the L3-1. But based on the above values it is not clear as to the growth increments of the higher fault scarps between separate sites along the same fault.
Fig. 28 (a) Detailed geomorphological map showing the distribution of the active fault in the vicinity of Hagyu, southern part of the Nagai basin. Contour interval is 5 m. See Fig. 27 for the corresponding location of the figure. (b) Topographical profiles and vertical offsets on Holocene terraces across the fault and along the Hagyu River.
Fig. 29 (a) Detailed geomorphological map showing distribution of active fault in the vicinity of Tubaki, southern part of the Nagai basin. Contour interval is 5 m. See Fig. 27 for the corresponding location (b) Topographical profile and vertical offset of the youngest faulted terrace across the fault and along the northern bank of the Okitama-Shira River.
Fig. 30  (a) Detailed geomorphological map showing distribution of active fault along both banks of the Kuro River, central part of the Yonezawa basin. Contour interval is 5 m. See Fig. 27 for the corresponding location. (b) Topographical profiles and vertical offsets on Holocene terraces across the fault and along the Kuro River.
Fig. 31  (a) Detailed geomorphological map showing distribution of the active fault in the vicinity of Fukiyashiki, southern part of the Yonezawa basin. Contour interval is 1 m. See Fig. 27 for the corresponding location. (b) Topographical profile and vertical offset of the faulted Holocene terrace across the fault and along the south bank of the Omono River.
Holocene fault activity in the Nagai and Yonezawa basin

On both basins, the faults were still active during the Holocene time. Additionally, the progressive amounts of displacement on the Holocene terraces suggest that at least two faulting events occurred during the last 10,000 years in the Yonezawa basin. Displacements on the L3-1 and L3-2 terraces in the Nagai basin reveal that the last event occurred after the formation of the L3-2 terrace, but remained inactive within the last 2,500 to 6,000 years. The youngest faulted terrace is the L3-2 terrace in both basins, implying that the most recent surface rupture may have occurred at the same time.

Although average slip rates and interval of the recurrence in activity during the last 10,000 years in the Nagai basin could not be estimated because of insufficient data on Holocene faulting, displacement of late Pleistocene terrace in several areas permits an interpretation of recent faulting. At the northern side of the Nogawa River, (Teraizumi area), a late Pleistocene terrace (L2 terrace) dated to be at 17,857±92 y.B.P (Yamagata Prefectural Government, 2002) was found to be displaced with a vertical component of 7 m (Fig. 27). By comparing with the vertical component of the surface offset on the L2 terrace and L3-2 terrace for a single event gives 3 to 4 faulting events roughly after the formation of the L2 terrace. Similarly, in the area between the Hagyu and Nogawa Rivers, vertical displacement corresponding to the L2 terrace is found to be about 7 m (Miyauchi et al., 2004). This scarp on the L2 terrace is undoubtedly the product of repeated faulting events. These scarps that are preserved on the Holocene terraces nearby the L2 terrace may slip 2.0 to 2.5 m per faulting event, and 3 to 4 events may have occurred in the past 15,000 to 18,000 years. The southern part of the Nagai basin also faulted 6 to 7 m vertically in comparison to the L2 terrace. If a displacement of 1.5 m on the L3-2 terrace nearby the L2 terrace is characteristic of a vertical slip per event for this part of the fault, then the displacement of L2 indicates that 4 to 5 events could have occurred within the past 15,000 to 18,000 years. These scarp data indicates that the average slip rate can be estimated to be 0.34 to 0.39 mm/yr, suggesting possible repetition times for faulting to be 3,500 to 6,000 years for the western marginal fault in the Nagai basin.

In the Yonezawa basin, as mentioned before, vertical component of surface offset on the L3-1 terrace along the Omono river implies a cumulative result from two events. This can be obtained from the fact that the size and morphology of the scarp on the youngest faulted terrace (L3-2 terrace) are consistent with that from a single-event displacement. As indicated by these values, average slip rate of the Holocene is 0.23 to 0.29 mm/yr. Yamagata Prefectural Government (2002) has described that the peaty layer dated to be about 24,000 years ago is deformed 7 m vertically. This was obtained by borehole survey in the south bank of the Omono river, indicating a slip rate of 0.29 mm/yr during the late Pleistocene. This rate is comparable to that of the
Holocene. Additionally, a scarp height of 3.5 m preserved on the corresponding L2 terrace is clearly too large for the L3-1 terrace (See the numerical annotation in Fig. 31(a)), representing scarps formed by several faulting events.

4.6 Active fault in the Sendai plain

Figure 32 and 33 shows that there are two principal faults trending NE to SW namely, the Nagamachi-Rifu fault 26 km in length (Nakata et al., 1976) and the Nigatake fault (Takahashi et al., 2005), which run parallel to each other across the central part of the Sendai plain (Imaizumi et al., 1996). In the hanging wall of the Nagamachi-Rifu fault, a conspicuous reverse fault named Dainenji-yama fault exists, dipping eastward and trending in the same direction as the two faults. Nakata et al. (1976) have described the deformation of the Pleistocene terraces across the Nagamachi-Rifu fault and the Dainenji-yama fault, concluding that the vertical slip rates are more than 0.5 mm/yr for the former and 0.1 mm/yr for the latter, respectively. Sato et al. (2002b) have suggested that the Nagamachi-Rifu fault has reactivated from normal faulting in Miocene to reverse faulting since Pliocene.

The Nigatake fault was considered to be a blind thrust based on the data of seismic reflection profiles. However, it revealed that the fault deforms the ground surfaces as a flexure from southern bank of the Nanakita River to the northern side of the Hirose River (Ikeda et al., 2002; Sato et al., 2002b). The area between the Nagamachi-Rifu and Nigatake faults is 10 to 20 m above the present sea level. Takahashi and Imaizumi (2005) have reported that the area identified as having a gentle slope of uplifted surface to the Nigatake fault is not a modern alluvial surface but continuation of terrace surfaces from the upthrown side of the Nagamachi-Rifu fault based on geological cross sections of borehole data.

Several terraces have developed along each river flowing eastward and deformed by the faults in this area. Nakata and Imaizumi (2002) have shown that the vertical offset of the Uwamachi terrace which has formed possibly around 50-60 ka and the Nakamachi terrace Iat 26 ka (Nakata et al., 1976) are 15 m and 10 m across the Nagamachi-Rifu fault (See the numerical annotation shown in Fig. 33). Figure 33 also illustrates a zone of about 200 to 300 m in width at the hanging wall of the Nigatake fault which tilts towards the scarp.

The last seismic event of the Nagamachi-Rifu fault probably occurred within the last 2,200 years based on the borehole survey across the fault (Hirano et al., 2003; Awata et al., 2003). Miyagi Prefectural Government (1999) has suggested that two possible faulting events had occurred during the Holocene based on the liquefaction features observed in borehole cores from the nearby fault. In the northern area, the upper limit of the alluvial basal gravel bed which is slightly older than 7,880 y.B.P is offset 4-5 m vertically by the fault, assuming at least two faulting events during the
Fig. 32  Map showing topography and the distribution of active faults in the Sendai plain based on aerial photographic interpretation and field observations. Details of the relationship between terraces and the faults are shown in Fig. 33. See Fig. 1 for the corresponding location.
Fig. 33 Map showing classification of terraces and distribution of active faults in the northern part of the Sendai plain. The faults are labeled as follows: Nigatake fault (NTF), Nagamachi–Rifu fault (NRF), and Dainenji–yama Fault (DYF). Contour intervals are 1 m in the plain and 2 m in the hilly area, respectively. Amounts of vertical offset on terraces are annotated from Nakata et al. (1976) and Nakata and Imaizumi (2002). Topographic profiles and geological columnar section are shown in Fig. 34. See Fig. 32 for the corresponding location.

Holocene and with a recurrence interval of 3,100 to 3,400 years or longer (Awata, 2004).

Holocene fault activity in the Sendai plain
In the southern bank of the Nanakita River, a previous flood plain has uplifted and
emerged from the activity of the Nagamachi-Rifu fault. Taking into consideration the geomorphic settings and the age of this surface (dated to be at 2,200 y.B.P., Awata et al., 2003), this work correlates the surface with the L3-2 terrace from other studies. The vertical offset of the L3-2 terrace is 1.4 m as derived from a topographic profile measured perpendicular to the trace of the scarp (Fig. 34). This fact indicates that the most recent surface rupture on the Nagamachi-Rifu fault occurred after the formation of the L3-2 terrace. However, other Holocene terraces referred to as topographic references were not recognized. It is difficult to indicate the cumulative result of several events based on the Holocene terrace deformation along the fault. In that respect, this paper follows the result from previous works carried out on Holocene

Fig. 34 Topographic profiles and geological columnar section in the Iwakiri area show the deformation and amount of vertical displacements on Holocene deposits across the fault in the north part of Sendai plain, modified from Hirano et al. (2003). The corresponding locations are shown in Fig. 33.
fault activity as mentioned before. Average rate of vertical slip during the Holocene time were obtained under the assumption that slip rates during the late Pleistocene are referenced with respect to that during the Holocene time.

4.7 Active fault zone of the Fukushima basin

In the western margin of the Fukushima basin, several faults delineate the boundary between the mountain and basin area (Fig. 35 and also see Fig. 1). These fault traces were found to prolong successively northward towards the Shiroishi area constituting a fault zone extending to about 60 km in length. Surface traces of the same have already been carried out by previous works (Fujiwara, 1958; Shinya, 1984; Watanabe, 1985; Research Group for Active Faults of Japan, 1991; Imaizumi et al., 2000; Sawa et al., 2000; Watanabe et al., 2000; Ikeda et al., 2002; Nakata and Imaizumi, 2002; etc.). Based on the discontinuity and orientation of the fault trace, at least three major segments can be roughly differentiated in this fault zone as follows (also shown in Fig. 35). From the northern part of the Shiroishi area extending in the N-S direction to the Fukushima basin called Murata, Shiroishi and Kosugo faults respectively. In the northern part of the Fukushima basin, the fault zone is made up of the Fujita Higashi and Kori faults trending NE to SW, respectively. Similarly, the southern part comprises of the Daiyama and Tsuchiyu faults trending mainly in the N-S direction.

In the Shiroishi area, Shinya (1984) described a deformed Holocene terrace with a vertical displacement of 4.5 m (see the numerical annotation in Fig. 35). Based on the trenching survey on the terrace, there are two faulting events recognized in the past 7,000 years (Miyagi Prefectural Government, 2001). Later work by Watanabe et al. (2003) have reported that the most recent event occurred between 2,200 and 2,400 y.B.P. In the northern part of the Fukushima basin, surface sediments dated to be 1,800 years ago found in the small valley crossing the fault trace were not faulted (Fukushima Prefectural Government, 1997). Other information about Holocene faulting activity in this part are not available yet. In the southern part, the most recent event has occurred between 1,900 and 2000 y.B.P., besides, other Holocene events are also found to have occurred between 5,600 and 6,300 y.B.P., 8,500 and 9,000 y.B.P., respectively (Watanabe et al., 2003).

Holocene surfaces are classified into three levels such as L3-1 to L3-3 terrace in descending order as mentioned before. The formative age of the L3-1 terrace along the Shiroishi River is dated to be at about 7 ka ago (Miyagi Prefectural Government, 2001). In the southern part, those corresponding to the L3-1 terraces are dated to be at 5,980±60 y.B.P., 6,400±80 y.B.P. (Fukushima Prefectural Government, 1997; 1998). At the southern part of the basin, age of a Holocene terrace corresponding to L3-2 is dated to be at 2,400±120 y.B.P. (Shinya, 1984). These data obtained by previous
Fig. 35 Map showing topography and distribution of active faults in and around the Fukushima basin based on aerial photographic interpretation and field observations. Relationship between terraces and faults are shown in Fig. 36 and 37. See Fig. 1 for the corresponding location.
works enable us to assume the formative age of the L3-1 to be 7,000 years ago in the Shiroishi area, 6,000 years ago in the northern part of the basin, and that of the L3-2 terrace to be 2,500 years ago in the southern part, respectively. Though the age of the L3-3 terrace has not been obtained yet, the author assume that the L3-3 terrace is formed 1,500 years ago by considering the facts that morphological features of the L3-3 terrace correlate with those dated L3-3 terraces from other areas. The L3-3 terrace in this area is the lowest one developed along the present river less than 2 to 3 m above the present level at the fault crossing. Other Holocene terraces that provide no direct information on the formative age were assumed to be at 6,000 years ago from that of the L3-1 and 3,000 years ago in case of L3-2 terrace from previously reported data on dating of the Holocene terraces in other areas.

**Shiroishi Area**

From the northern area of the Fukushima basin, surface ruptures associated with the Holocene faulting event are mapped from the right bank of the Matsukawa River to the Kosugo area. Scarp heights of about 1.5 m are recognized continuously on the L3-2 terrace, whereas no evidence of surface deformation is identified on the L3-3 terrace and the active flood plain. At the northern part of the Shiroishi area, there is an en echelon step of the trace at intervals of 2 km. Cumulative result from the Holocene faulting events in the northern part is observed in the vicinity of Kamiyashiki (Fig. 36). The L3-1 terrace was found to have deformed about 4.0 m vertically. On the other hand, fault scarp heights of 2.0 m have been preserved on the L3-2 terrace. At the left bank of the Kosute River, L3-2 terrace was also found to have deformed with a vertical component of 2.0 m. In this area, vertical component of the offset on the L3-2 terrace can be regarded as the surface rupture associated with a single event, indicating that scarps on the L3-1 terrace are formed by at least twice the faulting events. Along the southerly prolongation of the Shimoyashiki area, several Pleistocene terraces are found to be deformed by the N-S trending faults.

**Northern part of the Fukushima basin**

The Fukushima basin can be subdivided into a northern half and a southern half based on the distinct differences in geomorphic settings, fault pattern, and the subsurface structures of the basins (Watanabe, 1985). The fault zone trending NE to SW delineate the adjacent area east of mountains in the northern part of the basin (Fig. 37). Pleistocene terraces are found to be displaced along the fault trace with antithetic reverse fault on the hanging wall. Faulted Holocene terrace, attributed to a recent activity are developed in the vicinity of Handa (Fig. 38). Vertical component of the surface offset on the L3-1 terrace is 2.9 and 3.6 m, respectively (Profile w-w' and x-x' in Fig. 39). L3-2 terraces are also faulted vertically with 1.5 to 2.0 m (see the numeri-
Southern part of the Fukushima basin

Surface trace of the fault with relatively straight fault lines delineates the western fringe of the southern part of the basin (Fig. 39). Watanabe (1985) has suggested that in comparison with that of the northern part, the marginal faults in the southern part are considered to be a high angle secondary fault developing in the hanging wall above
The master fault based on a fault model.

Holocene surface ruptures are observed in several areas. Progressive displacement during the Holocene derived from surface deformation is observed in the vicinity of the Ubado area (Fig. 40). There are two rivers flowing eastward and forming several terraces along them. Near the Sukawa River, the L3-2 terrace is cut by the fault with a vertical component of 1.5 m. Correspondingly, a small scarp on the L3-2 terrace along the Shiratsu River shows a vertical slip of 1.5 m, and was likely to be formed during a single ground-rupturing event. A scarp having a vertical component
of 2.5 m on the L3-1 terrace is a significant amount of displacement as compared to that on the L3-2 terrace. This fact indicates that at least two faulting events could have occurred after the formation of the L3-1 terrace in the southern part of the fault zone. The timing of the latest and penultimate faulting events observed on the surface coincide with the result of the previous work by Watanabe et al. (2003).

**Holocene faulting activity of the Fukushima basin**

All over the fault zone, morphology of the scarps clearly confirms that each of the faults was still active during the Holocene time. Additionally, the progressive amounts of displacement on the Holocene terraces suggest that at least two faulting events have occurred during past 10,000 years. Displacements that have appeared on the L3-2 terrace in selected areas have revealed that the last movement has occurred after the formation of the L3-2 terrace and before the L3-3 terrace. Average slip rates and recurrence intervals based on geomorphic investigations in the Holocene are
0.57 mm/yr in the Shiroishi area, 0.48 to 0.60 mm/yr in the northern part of the basin, and 0.42 mm/yr in the southern part of the basin, respectively.

Besides the data for amount of displacement on Pleistocene terraces, a comparable rate of vertical slip with the Holocene was also obtained. At the Shiroishi area, the L1 terrace (probably formed 25,000 years ago) and the L2 terrace (formed at about 12,000-15,000 years ago) are found to have displaced 15 m and 7 m vertically. In the northern part of the Fukushima basin, vertical offsets of 14.5 m along the fault are recognized on the L1 terrace dated to be at 25 ka ago in Ubugawasa (Shinya, 1984), and 5.5 m on the L2 terrace (probably formed 12,000-15,000 years ago) at Handa, respectively. In the southern part, L1 terraces are developed correspondingly along the rivers and displaced 15 m vertically. As indicated by these values, the average vertical slip rates are estimated to be at 0.47-0.60 mm/yr in Shiroishi, 0.37-0.58 mm/yr in the northern part of the basin, and 0.60 mm/yr in the southern part of the basin, respectively.
5. Results and discussion

5.1 Amount of vertical displacement and timing of the most recent faulting event

Holocene terraces that contribute towards topographic reference of faulting are subdivided into three levels in the study area. Although the interpretation of the age is sketchy, the L3-1 terrace is expected to have formed in the early to mid Holocene and is generally dated to be at 6,000 to 7,000 years ago in the area under investigation.
Similarly, the L3-2 terrace may have formed 2,500 to 3,500 years ago, and the L3-3 around 1,500 years ago, respectively (Fig. 41).

Data from fault scarp of Holocene terraces in several areas allows for the interpretation of Holocene faulting. A Holocene faulting event is required by the age of the faulted terrace as well as their evidence in trenches. Assuming that a fault intersected the L3-2 terrace and did not do so for the L3-3 terrace, the most recent event of the fault could be between the time after the formation of the L3-2 terrace and before the L3-3 terrace. In this case, the timing of the faulting event ranges from the formative age of a L3-2 to that of a L3-3 terrace. Results of trenching survey from previous works are consistent with the timing of the most recent events in each area as derived from geomorphic evidence, which supports improved temporal resolution. The faulted L3-2 terraces are found to be distributed in almost all areas (Fig. 41), indicating that the most recent event associated with surface rupture along the faults occurred in the past 3,000 years (Fig. 42(b) and also see Fig. 41).

Maximum vertical displacement from the most recent event were found to cause 1.0 to 3.5 m high scarps (Fig. 42 (a) and also see Fig. 41). In the Shonai, northern part of the Kitakami, and the Yonezawa areas, the scarp is relatively smaller compared to other areas. The most likely cause is that the low-angle thrust faults probably reach to the surface in those areas (Watanabe et al., 1994; Suzuki et al., 1989; Yamagata Prefectural Government, 2002). The important consideration here is that the vertical displacements from a single event preserved on the Holocene surfaces are considerably less than that predicted for the entire length of a fault zone. This fact implies each fault zones can be divided into several behavioral segments (McCalpin, 1996).

5.2 Recurrence intervals between surface faulting events of paleoearthquakes during the Holocene time

As evident in the Holocene terrace deformation and from the results of trenching by previous works, the duration of time intervals of surface faulting events accompanied by paleoearthquakes can be roughly estimated (Fig. 42(c) and also see Fig. 41). When the ages of two or more events are obtained, the difference between the events indicates the minimum recurrence interval. The age of each faulting events that has occurred during prehistorical time has a margin of error associated with it, because of lack of accurate age determination by the present paleo-seismic investigations. Recurrence intervals, therefore, are described with maximum and minimum values within the age range of the two events. Similarly, even though the number of events is locally ambiguous, it is possible to assume the presence of Holocene faulting event based on the evidence from scarp heights associated with each event, the cumulative displacement, and average recurrence intervals.

In the northern part of the fault zone in Yokote basin, a recurrence interval is
Fig. 41 Space-time diagram showing the distribution of Holocene terraces and the ages of the faulting events. The inferred time span for each event is shown by the shaded boxes, with the preferred age range shown by the darker shade in each box. The table below summarizes the data for vertical displacements and timing of the most recent event, recurrence intervals, and average slip rate in vertical component during the Holocene time on each fault constituting the principal fault zone in the study area, respectively. The average slip rate of each fault during the Holocene is similar in range to that obtained for the deformed late Pleistocene terraces.
found to be consistent with the 3,400 year interval between the 1896 event and the age of the penultimate event determined by stratigraphic evidences from excavations (Research Group for the Senya fault, 1986). Considering the cumulative displacement on faulted Holocene terrace formed probably 6,000 years ago, the event before the penultimate one is thought to have occurred within the past 3,500 to 6,000 years. Taking into consideration the 3,400-year interval of surface faulting event, the event before the penultimate one may have been occurred close to 6,000 years ago. The
time of intervals between the penultimate and the event before implies a different recurrence intervals of faulting. Accordingly, these intervals for the events cause repetition of faulting dated to be at 2,500 to 3,400 years for the northern part of the fault zone. Besides, another event during the early Holocene is assumed to be between 8,500 to 9,500 years ago on the basis of recurrence intervals and the cumulative result of several events preserved on the late Pleistocene terraces.

In contrast, only one Holocene event has been recognized in the southern part of the Yokote basin. Absence of deformation of the L3-2 terrace surface and the younger one indicate that repetition of the faulting event is more than 3,500 years. Based on comparisons of the scarp height of a Pleistocene terrace dated to be 38,000 years ago and a probable Holocene terrace (Akita Prefectural Government, 1999), about 2 to 5 events may have occurred during last 38,000 years, which suggests possible repetition times for faulting with extent of 7,300 to 17,400 years in the southern part. In the northern part of the fault zone in the Kitakami lowland, the recurrence intervals were derived from geomorphic evidence as deformed terraces and from results of trenching survey. The L3-2 terrace formed probably 3,000 years ago intersected by a single faulting event. On the other hand, The L3-3 terrace probably formed 1,500 years ago was found to be stationary. This fact indicates that more than 1,500 years have passed since the last event, implying the minimum time of recurrence interval. The penultimate event occurred about 4,500 years ago (Iwate Prefectural Government, 1998) and indicates a maximum time of recurrence of 3,000 years which is considerable. Meanwhile in the southern part, scarps heights of 2.5 m and 3.3 m on the L3-1 terraces are considered to be produced from single faulting event. Scarps representing vertical slips of 6 to 10 m preserved on the L1 H terrace are the product of multiple faulting events. Considering this, about 2 to 4 faulting events might have occurred during the last 25,000 years on the L3-1 terrace as evident from displacements which are characteristic of the vertical slip per event for this part of the fault zone. Consequently, recurrence intervals of 6,000 to 13,000 years can be obtained for the southern part of the fault zone in the Kitakami lowland.

In the northern part of the Shonai plain, ages of Holocene faulting events have already been reported by Suzuki et al. (1989; 1994). Recurrence intervals in the northern part are estimated at 1,500-2,000 years following the results of Suzuki et al. (1989; 1994). In the southern part, three faulting events can be assumed since the last 5,500 to 6,000 years based on the assumption that the most recent faulted scarp or sediment is characteristic of the vertical slip per event for this part of the fault zone. Using the same method, recurrence intervals for this part are estimated to be 1,500-2,000 years. Another event during the early Holocene is assumed, based on the range of calculated recurrence intervals and scarps on late Pleistocene terraces formed by multiple faulting events, in both parts of the fault zone.
In the northern part of the Yamagata basin, result of stratigraphic evidence from excavations (Yamagata Prefectural Government, 1998; 1999) and geomorphic indications of Holocene faulting activity provide an interval of 2,000 to 3,500 years for the surface faulting event. In contrast, most recent surface rupture from faulting in the southern part is observed on the L3-3 terrace and probably formed around 1,500 years ago. In addition, no information about historical records on earthquake faulting has ever been reported on this part, implying that there was no surface rupture since the last 1,000 years. The scarp data, therefore, indicate that the last event with surface offset in the southern part may have occurred between 1,000 and 1,500 years ago. Age of the penultimate event can be determined as 3,900 to 4,400 years ago (Yamagata Prefectural Government, 1998; 1999) and that of the most recent event indicate recurrence intervals of 2,400 to 3,400 years for surface faulting in this part. The value of recurrence intervals, scarps on the late Pleistocene terraces, and amount of vertical offset per a single event imply another faulting event during the early Holocene time in this part.

In the Nagai basin, as explained before, possible recurrence intervals of surface faulting are found to be 3,500 to 6,000 years as derived from scarp heights on the late Pleistocene terraces. Besides, another event is assumed between 6,000 to 8,500 years ago obtained from recurrence intervals and the scarp height of late Pleistocene terraces. In the Yonezawa basin, the L3-3 terrace surface probably formed 1,500 years ago and the younger was found to be stationary. This fact indicates that more than 1,500 years have passed since the timing of the most recent event. This value also indicates the minimum time of recurrence interval. Taking into consideration that the scarp of L3-1 terrace may have formed by the cumulative result of two events, recurrence intervals are estimated to be at 3,250 to 6,500 years.

The Nagamachi-Rifu fault has moved in the past 2,200 years (Hirano, 2003; Awata, 2003). Besides, there was no surface rupture in the last 1,000 years on the basis of absence information about historical earthquake faulting in this area, implying that the most recent event may have occurred between 1,000 to 2,200 years. Besides, the penultimate event that were assumed to be after 7,900 years ago result from the offset of the upper limit of the alluvial basal gravel bed (Awata, 2004). This study, therefore, assumes recurrence intervals of 3,100 to 6,900 years in the fault, with reference to the results from previous works.

In the northern part of the marginal fault zone of the western Fukushima basin, minimum time for recurrence intervals can be estimated to be at 2,300 years obtained by two faulting events occurred between 2,400 and 7,000 years ago. By using this minimum value, the age of the penultimate event can be assumed to be between 4,700 to 7,000 years ago. Accordingly, recurrence intervals for this part is considered to be 2,300 to 4,600 years. Moreover, another event may have occurred between 6,000 to
11,600 years ago as seen from these recurrence intervals and scarps formed by multiple faulting events on the late Pleistocene terraces, in this part of the fault zone. Similarly, in central part of the fault zone, recurrence intervals are calculated to be 2,100 to 4,800 years as in the previous method. This fact also suggests that a penultimate event may have been occurred between 3,900 and 6,000 years ago, and the event before that between 6,000 to 11,600 years ago. In the southern part of the fault zone, information about recurrence intervals follow the result by Watanabe et al. (2003) to be 3,000 to 4,000 years.

Minimum recurrence intervals are shown for the fault zone of the Shonai plain, and for the northern part of the Kitakami lowland compared to those from all the faults in this area. The western marginal fault zones of Nagai and Yonezawa basin are considered as having slightly longer recurrence intervals during the Holocene as compared to the fault zones in the inter mountain basin. The southern parts of the fault zone in the Kitakami and Yokote basin both have relatively larger recurrence intervals indicating that on both sides of the Ou Backbone Range, duration of time intervals of surface rupture seem to be symmetric along the fault strike. Each part of the fault zone in the Fukushima basin indicates a similar duration of time intervals for surface faulting event.

5.3 Rate of vertical slip based on the surface offset during the Holocene time

The average slip rate in vertical component of each fault during Holocene time is similar in range to that obtained for the deformed late Pleistocene terraces. Although much less accurate, apparent similarities in vertical slip rates for different time scales at a given site leave open the possibility that vertical slip rates in the Holocene have been generally consistent over the last 10,000 to 30,000 years for each fault in this area (Fig. 41). In the northern part of the Yokote basin, the vertical slip rate during the Holocene has been conspicuously higher, because the amount of displacement in this fault includes the historical 1986 earthquake with a Holocene of limited time span (Fig. 42(d) and also see Fig. 41).

Marginal faults of Shonai plain and Yamagata basin show relatively higher value for slip rate. In contrast, the fault zones of Nagai and Yonezawa basins and the southern part of the fault zone in the Yokote basin and the Kitakami lowland shows a lower slip rate resulting from relatively longer recurrence intervals and scarp data as mentioned before. Viewed broadly, regional average values of the rate imply a tendency of slightly larger rate in the western side of study area.

6. Conclusion

The morphology of the scarps and geomorphic configuration of faulted deposits
allow for the interpretation of the history of Holocene faulting on several principal fault zones in the Tohoku district. Repeated Holocene movement on the faults has left different heights of scarp on young terraces. This paper classifies the Holocene terraces into three levels in order to identify each faulting event. Although interpretation of the age is sketchy, several events during the Holocene are implied, given the size of the scarps. Holocene movement is also strongly supported by data obtained from trench excavation from many previous reports. The forms of surface faulting and rupture described in this area are compatible with these trenching data. Besides, other Holocene faulting events that have not been known are evident on the morphology of the scarps or presumed on the basis of recurrence intervals and scarp heights produced by several faulting events on the late Pleistocene terraces.

It has been proposed that all the principal faults on each major fault zone have moved by characteristic earthquakes, in which each fault rupture repeatedly, and displays approximately the same amount of displacement during each successive event. Displacements per single event of the faults show a vertical displacement of 1.5 to 2.0 m (at most 3.5 m). Across the faults this amount has no direct relation to the hypothetical amounts of offsets estimated from the entire length of a fault zone. This fact implies that major fault zones in this area are composed of several behavioral segments moving with respect to each other.

The most recent events of almost all the faults have occurred in the past 3,000 years and the possibility of recurrence lies in the interval between 2,000 and 4,000 years as a whole except for the southern part of the fault zones in the Kitakami lowland and Yokote basin. The vertical slip rates of each fault zone during the Holocene show comparable values during the past 20,000 years, suggesting that rates of ongoing tectonic deformation in this district have been continuing since the late Pleistocene.

Trenching survey and dating of surface deposits will provide further evidence for each event. More detailed work is necessary to resolve this issue. It appears that consideration of spatio-temporal relationships of activity on each fault is more suitable for a detailed characterization of active tectonics in this area and the details of the same will be reported in a future paper.

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