Chapter 1

Outline of Noto Peninsula and Toyama Bay: Tectonic and Geological Framework

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Abstract

Outline of the attractive archaeological site is overviewed from the geomorphological, geological and geophysical points of view. Categorized landforms of the Japanese Archipelago indicate that the Mawaki site is placed on a stable plateau facing the Japan Sea backarc basin. Large facies variety in volcaniclastic and marine sedimentary sequence around the site records long-term paleoenvironmental changes after the rifting event in the Miocene. Sharp contrasts in gravity and geomagnetic anomalies delineate deep-rooted structure related with cumulative crustal deformation under strong tectonic stress, which has concurrently enhanced recent activities on remarkable reverse fault zones. Three-dimensional perspective of the study area surrounded by such deformation front is presented utilizing new datasets of reflection seismic survey.

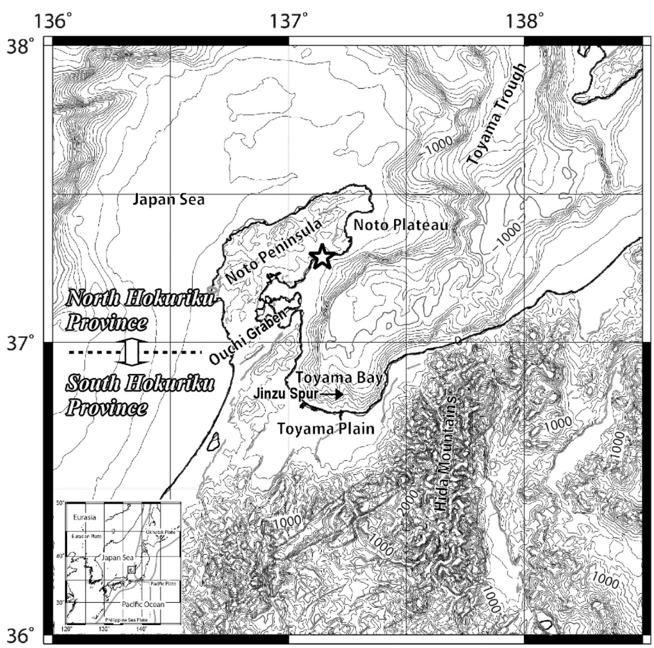

Figure 1.1 *Landforms of the Hokuriku Province. Star denotes the Mawaki archaeological site. Summit level contours are in 100 m interval. Inset shows plate tectonic configuration around southwest Japan.*

1.1 Landforms

The Mawaki archaeological site is located on the eastern coast of the Noto Peninsula in Hokuriku Province, central Japan (Figure 1.1). Regional characteristics from the viewpoints of earth science are summarized in this chapter, which should help readers to cultivate perspective view on the longstanding attractive ancient ruins.

Noto Peninsula looks like a forearm embracing the Toyama Bay, which is an 1,000-m deep basin fringed with 3,000-m mountains of the Japan Alps. Divided by NE-SW Ouchi Graben, the root of the peninsula constitutes a part of active geomorphic block that is referred to as South Hokuriku Province in this chapter, whereas its tip including the Mawaki site has a feature of peneplain and referred to as North Hokuriku Province.

Active landforms of the South Hokuriku Province are summarized based on concise description by Fujii (1988) as follows. The Hida Mountains act as eastern and southern border of the province and supply enormous amount of detritus to form grand alluvial fans in the Toyama Plain. Active uplift of the mountainous range reaches 5 mm/year. Active deformation is also reflected in tilted surface of river terraces, altitude and gradient of which are getting larger with age. In sharp contrast, the Toyama Bay (Figure 1.1) is actively subsiding during the Quaternary. Its shelf is quite narrow as a result of progradation of alluvial fans and vigorous coastal erosion. Beyond fault-related rugged slope, its basal area is divided by the Jinzu Spur into eastern and western portions and merged northeastward into mouth of the Toyama Trough.

North Hokuriku Province is interpreted as a low-relief continental fragment in the Japan Sea largely immune to tectonic movements throughout the Neogene and Quaternary, and the shelf that surrounds it is quite narrow. Around the Mawaki site, altitudes of marine terraces correlated with oxygen isotope stages 5e, 7, and 9 are about 40 m, 60 m to 70 m, and 100 m, respectively

(Koike and Machida, 2001), and the average uplift rate is 0.3 mm/year.

1.2 Geology

We first set focus on the North Hokuriku Province (Figure 1.2), and present a brief geologic summary. Most of its surface consists of altered early Miocene volcanic rocks (Anamizu and Yanagida Formations), which is underlain by sporadic exposures of the Mesozoic Funatsu Granites accompanied with metamorphic rocks and overlain by middle to late Miocene diatomaceous mudstone. The Mawaki site is surrounded by the Neogene volcaniclastic hills about 100 m high and is located on an alluvial plain between 4 m and 12 m above sea level.

Thick piles of volcaniclastic and marine sediments burying an enormous basin of the South Hokuriku Province are cut by numerous active faults (Figure 1.3). It is noted that the NE-SW trending faults constitute some bunches of neotectonic zones, of which characteristics will be discussed in the following 'Tectonics' section.

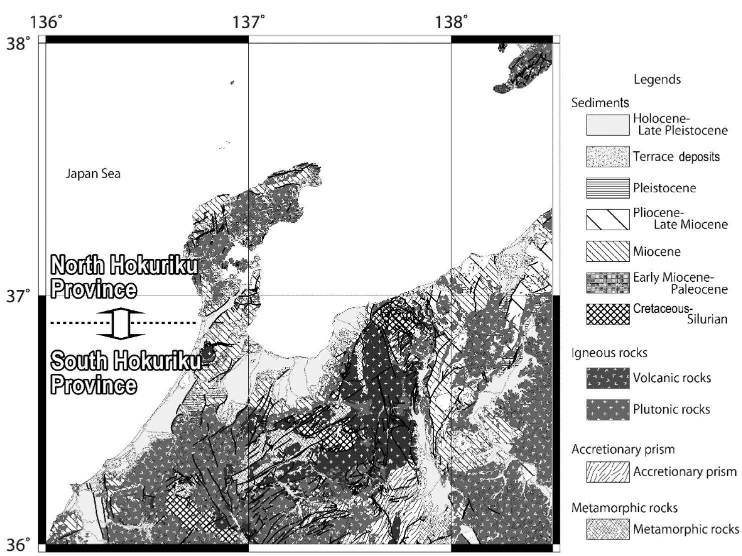

Figure 1.2 *Simplified geologic map of the Hokuriku Province in central Japan.*

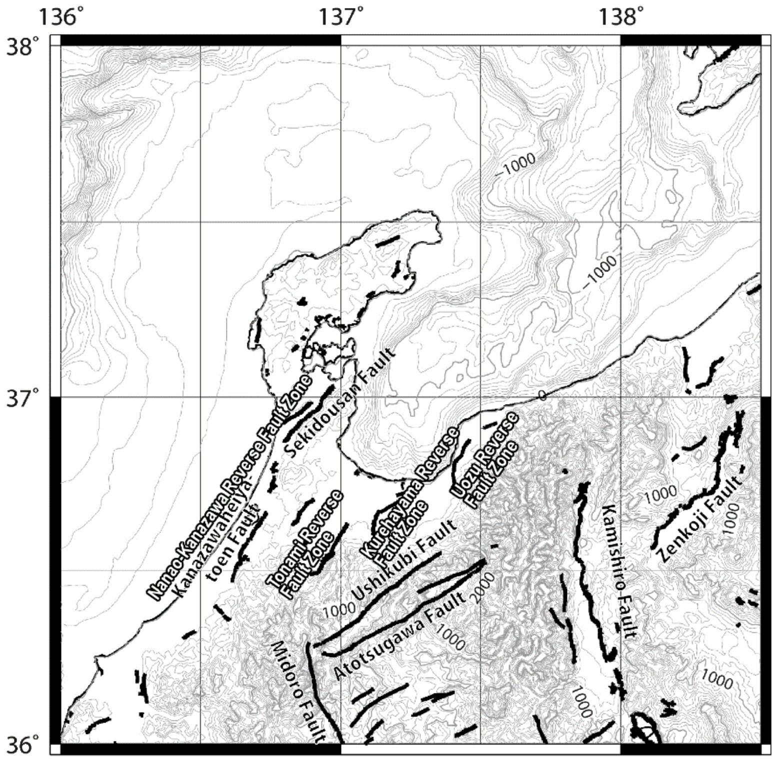

Figure 1.3 *Active faults around the Hokuriku Province.*

1.3 Geophysics

1.3.1 Gravity Anomaly

In Figure 1.4, we show gravity anomaly map assuming the Bouguer density of 2670 kg/m^3. The Bouguer gravity anomaly map shown in Figure 1.4 is the residual Bouguer gravity anomaly map of which the first trend surface estimated by the least square method was removed from the original Bouguer gravity anomaly.

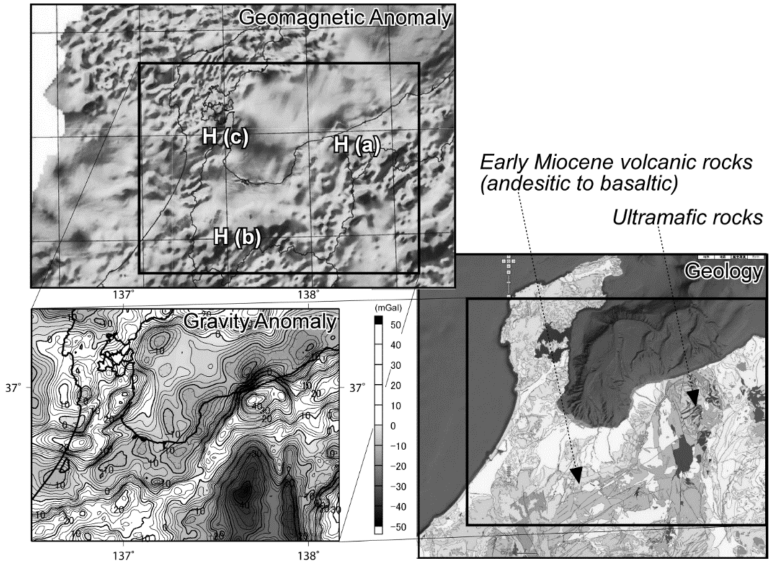

Figure 1.4 *Geomagnetic anomaly trend around the Hokuriku Province (Nakatsuka and Okuma, 2005) together with Bouguer gravity anomaly (Komazawa, 2004) and geologic (Geological Survey of Japan, 2012) maps. Annotation 'H' in geomagnetic anomaly map corresponds to area accompanied by remarkable high (positive) anomaly.*

Low gravity anomalies in the southeast region in the study area are corresponding to the northern part of mountain range in central Japan and might be caused by isostasy due to the loads of mountains because they have heights beyond 3,000 m. In addition, the north-south long and narrow low gravity anomaly is caused by Matsumoto Basin which is the tectonic basin with thick sedimentary layer (e.g., Okubo et al., 1990).

Toyama Basin and Toyama Bay are characterized by low gravity anomalies, which are caused by low density materials such as fan and Quaternary sediments. On the other hand, the Noto Peninsula including Mawaki and the eastern part of the Toyama Basin are characterized by high gravity anomalies. These high gravity anomalies are close to low gravity area and there are steep gradients between these gravity anomalies. The steep gradient in the eastern part of Toyama Basin is corresponding to the Kurobishi-Yama Fault (Tsujimura, 1926). The southern part of the steep gravity gradient in the western Toyama is corresponding to the Tonami-Heiya Seien Fault Zone including Isurugi Fault (e.g., Ikebe, 1949).

The northern part of the steep gradient in the western part of the basin was found by dense gravity survey (e.g., Sunami and Kono, 1988; Hagita et al., 1997). Although tectonic lines and fault topographies such as fault scarps have not been confirmed around this steep gradient zone, they have suggested that concealed faults (e.g., Himi Fault) would exist in this zone. Sutou et al. (2004) showed that epicentres of micro-earthquakes distributed in the steep zone, and that this steep gradient can be explained by basement deformation reaching 1 km. In their subsurface modelling, they considered the characteristics of the surface geology and explained the steep gravity gradient by deformation of basement without deformation of the Quaternary sediment near the surface.

1.3.2 Geomagnetic Anomaly

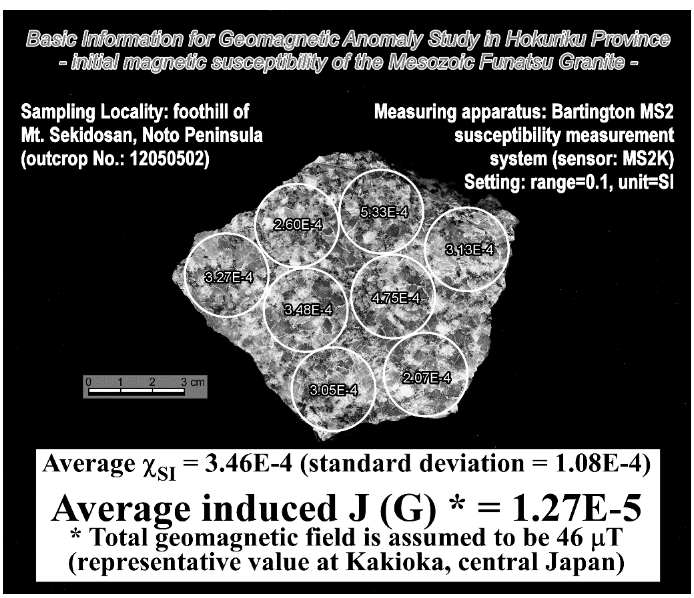

Figure 1.5 *Results of measurement of initial magnetic susceptibility of the Funatsu Granites exposed in the Noto Peninsula.*

Reflecting inhomogeneity in basement rocks, there are several conspicuous highs of geomagnetic anomaly around the study area (Figure 1.4). Geomagnetic anomalies on the eastern (H(a) in Figure 1.4) and southern (H(b)) margins of the South Hokuriku Province are accompanied with positive Bouguer gravity anomaly and probably originated from ultramafic complex in the Hida Marginal Belt and widely-exposed early Miocene volcanics.

Origin of another domal anomaly around the border of the North and South Hokuriku Provinces (H(c)) remains unsolved. To evaluate contribution of the sporadic Funatsu Granites as an anomaly source, we undertook a rock magnetic experiment. A hand-specimen was taken at the foothill of Mt. Sekidosan located on the positive anomaly, and its initial magnetic susceptibility was measured on a flat surface using a Bartington MS2 susceptibility meter equipped with a contact sensor (MS2K). Results summarized in Figure 1.5 clearly demonstrate that induced magnetization of the Funatsu Granites is too weak to generate the observed anomaly. As for the plutonic body, Hirooka et al. (1983) showed that natural remanent magnetization is also scored quite low and ruled out of candidates.

Alternative possible theory for the conspicuous positive anomaly is a hypothetical failed rift around the North Hokuriku Province. Itoh et al. (2006) submitted a paleogeographic reconstruction before the event of backarc opening of the Japan Sea. They assumed a failed rift around the area of the present analysis based on distribution of the early Miocene rift-margin type volcanism (Figure 1.6). We, then, propose that a bunch of syn-rifting volcanics are buried under the North Hokuriku Province, generating clustered geomagnetic anomalies in the area.

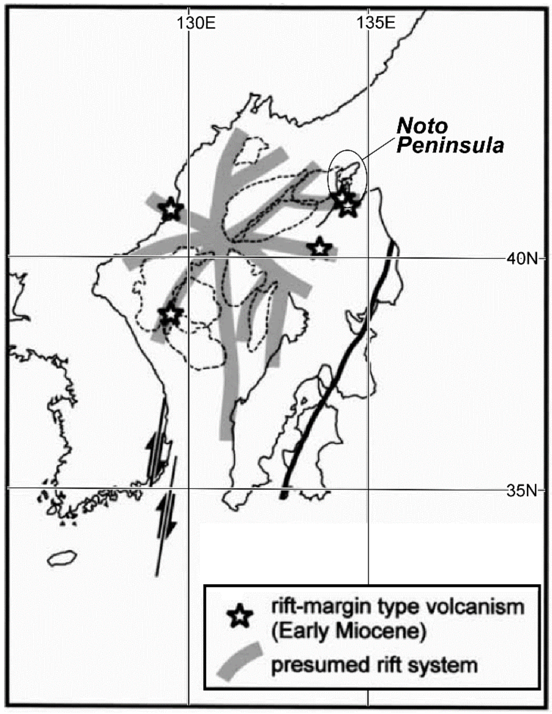

Figure 1.6 *Paleogeographic reconstruction of southwest Japan in an initial rifting stage of the Japan Sea after Itoh et al. (2006).*

1.3.3 Seismic Survey

In 1987, an offshore seismic survey (Nishitsugaru-Niigata-Oki) was conducted on the backarc shelf of northeast Japan using M/V KAIYO, by MITI (Ministry of International Trade and Industry). During the shooting of 4,010 km seismic lines, 96 channels of hydrophones (with an interval of 25 m) recorded the energy released from a 70 l (4,244 $in.^3$) tuned airgun array, shot at 25 m interval. Raw seismic data were stacked and then subjected to a post-stack processing sequence in order to enhance the resolution.

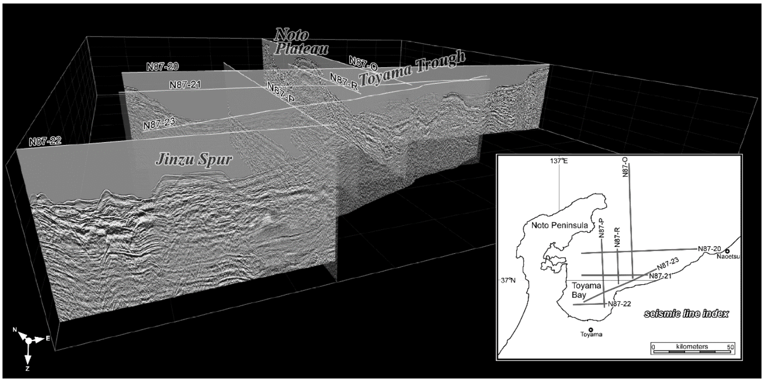

Figure 1.7 *A bird's-eye image of submarine topographic and structural architectures around the Toyama Bay based on reflection seismic profiles of the Nishitsugaru-Niigata-Oki offshore survey.*

Figure 1.7 presents a bird's-eye view of submarine topographic and structural architectures around the Toyama Bay based on the reflection seismic profiles. The Noto Plateau, Toyama Trough and Jinzu Spur are delineated as an undeformed basement high, a longstanding channel and a fault-bounded horst, respectively. Flat sedimentary top of the Jinzu Spur is partly tilted, implying active deformation.

Figure 1.8 shows depth-converted seismic profiles of the N-S line N87-O. It is noted that some discontinuous but strong reflectors are identified within acoustic basement of the Noto Plateau. It may be originated from syn-rifting intrusive bodies, which are responsible for conspicuous geomagnetic anomalies in the area (see Figure 1.4). Depth-converted profile of the E-W line N87-22 (Figure 1.9) is highly provocative. The Jinzu Spur is a horst bounded by normal faults. Separation of seismic horizons and lateral change in thickness of interpreted geologic units clearly demonstrate that the extensional feature has developed since the Pliocene. Controversial point is that the regional tectonic stress during the period was compressive as discussed in the next section. To understand the complex structural trend, numerical deformation modeling of upper crust may be effective.

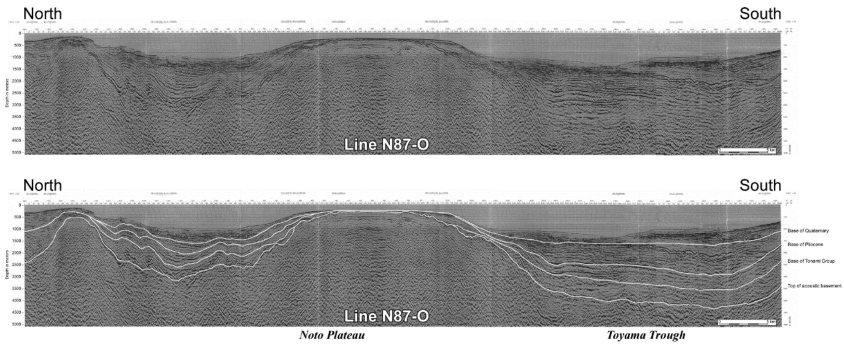

Figure 1.8 *Depth-converted seismic profiles (top, raw; bottom, interpreted) of the N-S line N87-O. See Figure 1.7 for line location.*

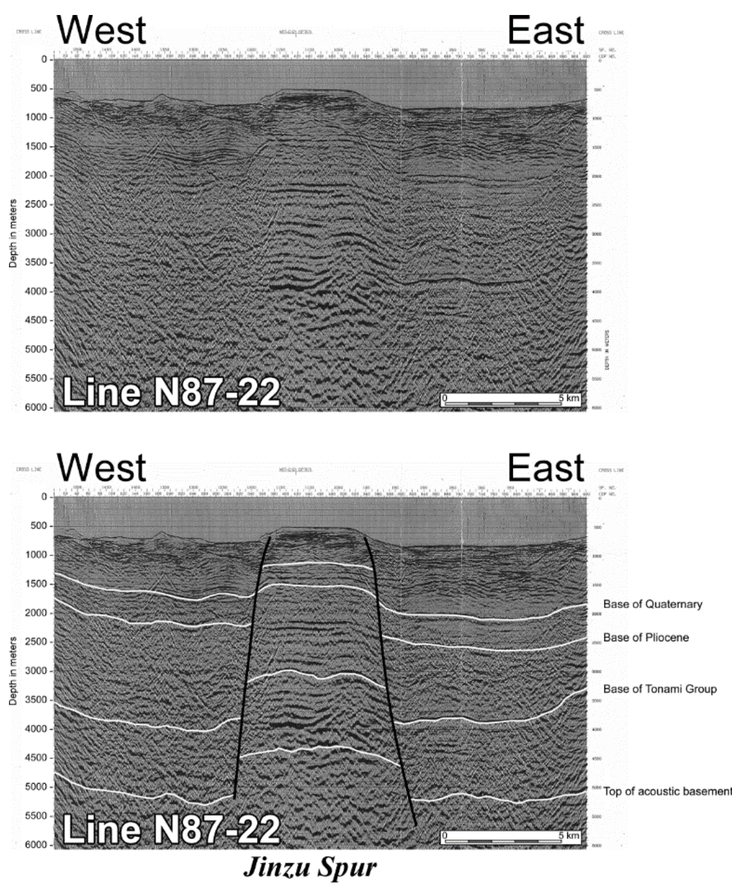

Figure 1.9 *Depth-converted seismic profiles (top, raw; bottom, interpreted) of the E-W line N87-22. See Figure 1.7 for line location.*

Figures 1.10, 1.11 and 1.12 are isopach maps around the Toyama Bay for the total sediment thickness, Miocene sediments and Plio- / Pleistocene sediments, respectively. Sedimentary layers are thickest around the deepest portion of the bay (Figure 1.10), a fact which is suggestive of deficit in the balance of subsidence / burial in spite of enormous clastic influx from the Japan Alps hinterland. Miocene isopach (Figure 1.11) indicates that northeastern part of the bay was under stagnant subsidence, whereas prominent depocenters developed in the southwestern portion. Although coeval sediments on adjacent land are rather thin, the confined depression may have relation with deep-rooted structure along the western coast of the bay delineated through gravity analysis. Sedimentation pattern in recent periods (Figure 1.12) represents shrinkage of basin as a result of rising compressive regime around the South Hokuriku Province.

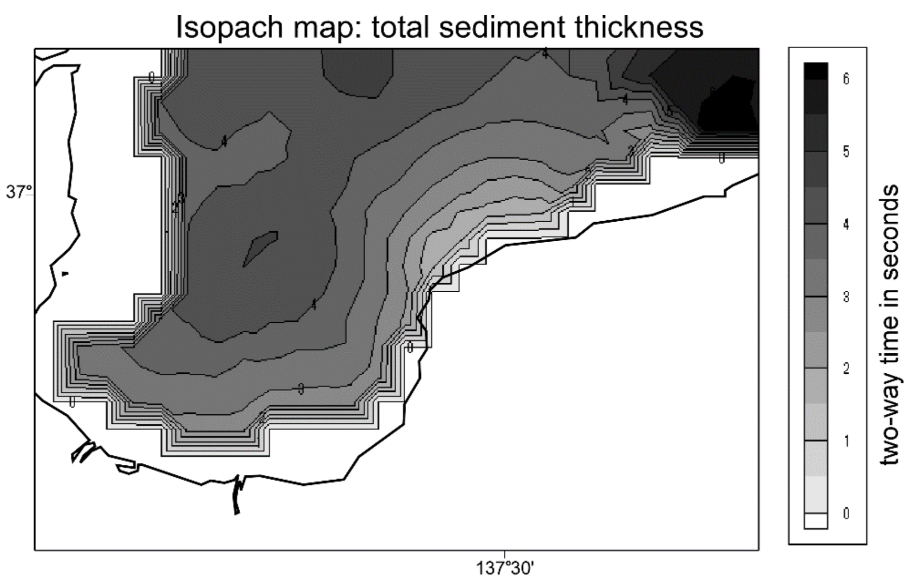

Figure 1.10 *Two-way time isopach map around the Toyama Bay: total sediment thickness.*

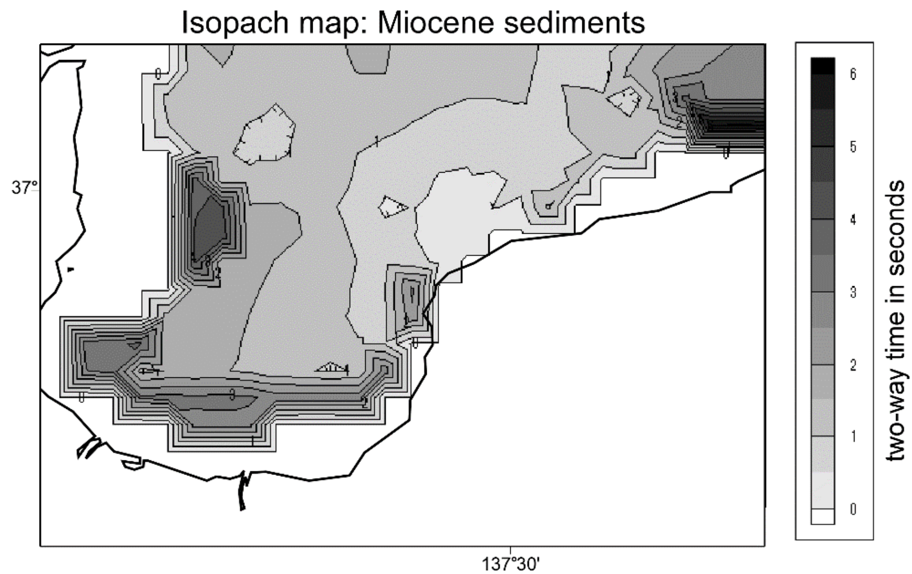

Figure 1.11 *Two-way time isopach map around the Toyama Bay: Miocene sediments.*

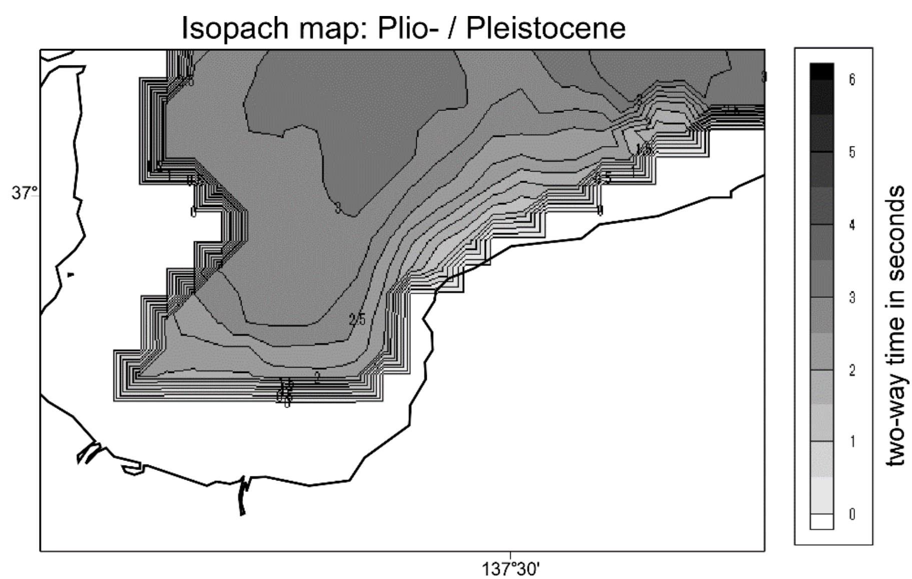

Figure 1.12 *Two-way time isopach map around the Toyama Bay: Plio- / Pleistocene sediments.*

1.4 Tectonics

1.4.1 Miocene Backarc Rifting

Most important tectonic event governing geomorphic and paleoenvironmental changes around the Hokuriku Province is the Miocene backarc rifting of the Japan Sea. Since 1980s, numerous researchers have studied the remarkable event by any possible means of analysis. Although fruits of marine geological surveys were summarized by Jolivet and Tamaki (1992) and Tada and Tamaki (1992), survey sites were chosen excluding basin center because frequent discharge of flammable gases cannot be controlled by using a non-riser drilling vessel. Hence we describe features of the event on firm ground data.

I Geological Evidence

Hayakawa and Takemura (1987) described an event sequence in the Yatsuo area, a prominent hilly area in central part of the South Hokuriku Province (Figure 1.2). They showed that the early to middle Miocene Yatsuo Group is a cycle of transgressive unit accompanied with intensive volcanism. Paleoenvironmental analysis revealed that the initial littoral to shelf settings had deepened into slope to basin floor settings simultaneously with accumulation of the marine sediments as thick as 1,500 m. It is inevitably postulated that the massive subsidence was linked to thinning of backarc crust and vigorous faulting along rift zones during the Japan Sea opening event, because the Yatsuo Group is one of the lowermost marine Cenozoic strata upon the backarc margin. Their investigation also showed that the Yatsuo Group was unconformably overlain by non-volcanic clastics of the Tonami Group, base of which constitutes a continuous seismic horizon in the Toyama Bay as mentioned above, suggesting a drastic change in basin configuration and stagnant subsidence since the late Miocene. Away from the backarc rift zones, Neogene strata in the North Hokuriku Province are much thinner than those in the southern domain.

II Paleomagnetic Analysis

Formation process of the western Japan Sea is characterized by fan-shaped backarc spreading as a result of rapid clockwise rotation of southwest Japan, which was elucidated through pioneering paleomagnetic studies by Otofuji and his colleagues. For example, Otofuji and Matsuda (1987) estimated amount of the early Miocene tectonic rotation and submitted the first-time reliable paleogeographic reconstruction before rifting. Their kinematic model, however, did not contain the Hokuriku Province reflecting incomplete dataset at that point in time.

Itoh (1988) presented paleomagnetic data sufficient to evaluate the Cenozoic tectonic episodes around the Hokuriku Province. He pointed out that the clockwise rotation angle of the study area is smaller than that of the main part of southwest Japan, presumably related to regional bending in an arc-arc collision event. Based on along-arc declination changes determined for the early Miocene rocks in Hokuriku, Itoh and Ito (1989) submitted a model of ductile deformation of the crust in a short period.

Magnetostratigraphy was first studied by Itoh and Hayakawa (1988) for the thick Neogene sequence in the Yatsuo area, and their numerical estimation of sedimentation rates lent support to the paleoenvironmental model after Hayakawa and Takemura (1987). These research results during two decades was summed up by Tamaki et al. (2006), who presented a complete paleomagnetic dataset of the Yatsuo Group and most reliable stratigraphic correlation.

1.4.2 Neotectonic Events

As suggested by Huzita (1980), southwest Japan in late Cenozoic has been suffering progressive E-W tectonic stress in general, which is often regarded as an effect of accelerated subduction of the Pacific Plate. Since recent events are directly linked to environmental and/or geographical circumstances of the

Mawaki site, we investigate neotectonic episodes specific for the Hokuriku Province in the following sections.

I Emergence of Compressive Regime Around Hokuriku

Itoh et al. (1997) presented the Neogene to Quaternary burial history on the backarc shelf of southwest Japan based on stratigraphic data obtained from deep exploration boreholes. Although their age determination was not precise enough to evaluate the Quaternary change in tectonic regimes, ubiquitous accelerated subsidence since 5 Ma has been confirmed in the backarc basin including the Hokuriku Province. Fujii et al. (1976) pointed out that contemporaneous uplift of hilly province was under way. Thus the recent landforms in Hokuriku may have developed under a compressive regime.

In reference to remarkable gradient in Bouguer anomaly around the Toyama Bay (Section 1.3.1), Ohkubo et al. (2000) stated that the Pliocene strata along the western coast is unconformably overlain by the Junicho Formation, which is assigned to the early Quaternary (Satoguchi and Nagahashi, 2012). Hayakawa and Takemura (1987) presumed a hiatus between the Pliocene and Pleistocene units in the Yatsuo area. Itoh (1985) found that the Pleistocene Yokoo Formation on the northeastern point of the South Hokuriku Province is settled on the middle Miocene units, with a 10 m.y.-long hiatus. The stratigraphic gap implies change of tectonic stress and basin configuration.

II Active Faults

Ikeda et al. (2002) recognized the Uozu, Kurehayama, Tonami and Nanao-Kanazawa in Figure 1.3 as major reverse fault zones in the Hokuriku Province, which are unexceptionally characterized by NE-SW trend. The Ouchi Graben, defined as boundary between the North and South Hokuriku Provinces, is a part of the Nanao-Kanazawa reverse fault zone. Research Group for Active Faults of Japan (1991) gave detailed description of constituent ruptures of those fault zones, and confirmed dominant vertical slips.

It seems, however, that the geomorphological approaches have not shown comprehensive view of the neotectonic deformation. For instance, quite steep gravity gradient and grand inclined terrace around the eastern part of the province are much larger tectonic features than the adjoining Uozu fault zone. Subsurface structure inferred from the Bouguer anomaly seems to accord with trend of prominent faults along the foothills of mountainous range as described by Tsujimura (1926). Based on paleomagnetic analysis, Itoh and Watanabe (1988) revealed that the sedimentary rocks on the northeastern point of the South Hokuriku Province have suffered significant rotation during the Quaternary under strong E-W compressive stress. Further interdisciplinary research should be organized for construction of realistic model of the tectonic zone.

1.4.3 Origin of Paradoxical Bouguer Anomaly Around the Jinzu Spur

As shown in seismic profiles (Figures 1.7 and 1.9), the Jinzu Spur is convex upward. In general, high gravity anomalies should be obtained over these structures, but here low gravity anomaly was observed over the spur.

There are two possible interpretations for the conspicuous gravity trend on the Jinzu Spur. As shown in Figure 1.9, geologic units constituting the horst are cut by small faults in the course of structural build-up. Such mechanical disturbance may result in decrease of effective density of the topographic high. Another option is to assume inherent density contrast of sedimentary layers between crest and foothills of the active structure. Figure 1.1 suggests that the western and eastern flanks of the spur are the pathway of voluminous clastics derived from large rivers, Jinzu and Joganji, respectively. Density of the fluvial units burying the channel probably tends to be higher than fine-grained levee sediments, reflecting prompt compaction. Thus the specific negative anomaly is attributed to difference in material property of shallow geologic units.

We adopt the latter assumption that the Quaternary sediments on both sides of the Jinzu Spur would have higher density than the spur, and estimated density contrast which would make meaningful low gravity anomaly over the upward convex structure by Talwani's method (Talwani et al., 1959). As a result, it was found that the density contrast of 50 kg/m^3 (0.05 g/cm^3) led to meaningful decrease of gravity anomaly (about 1.5 mGal) over the spur.

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