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Chapter 2

Cenozoic Fault Zone Activity and Geologic Evolution of the Offshore Regions of Fukushima and Miyagi Prefectures, Northeastern Japan, Based on Petroleum Exploration Data

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Additional information is available at the end of the chapter

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Abstract

Three major fault zones were identified in the offshore regions of Fukushima and Miyagi prefectures, northeastern Japan, from petroleum exploration seismic and well data acquired by the Ministry of Economy, Trade and Industry (METI) and its predecessor: the Kesennuma tectonic line (KTL), the Ishinomaki tectonic line (ITL), and the Joban tectonic line (JTL). The stratigraphic relationships indicate that these tectonic lines were activated during the Middle Miocene, and that their activity was likely closely connected with the opening of the Japan Sea and the drifting of the northeast Japan arc to its current position. Parts of these tectonic lines were reactivated during the Late Pliocene and Quaternary in the Sendai Bay area.

Keywords: northeast Japan arc, tectonic lines, strike-slip fault, Fukushima, Miyagi

1. Introduction

The East Asian Japanese Islands are located on the convergent margin of the western Pacific Ocean. These islands are tectonically characterized by backarcs (e.g., the Japan Sea, Okinawa Trough, and Okhotsk Basin), island arcs (e.g., the Kuril, northeast Japan, Izu-Bonin, southwest Japan, and Ryukyu arcs), and trenches (e.g., the Japan, Izu-Ogasawara, Kuril, and Ryukyu trenches, and the Sagami and Nankai troughs). The various tectonic settings of the Japanese islands were determined by onshore geological research, as well as offshore oceanic geological surveys and oceanic geophysical measurements. The tectonic transformation around the Japanese islands is therefore thought to have occurred as follows:

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(i) clockwise rotation of the southwest Japan arc (e.g., [1]),

(ii) deformation of the northeast Japan arc by NNW-SSE-trending strike-slip faults (e.g., [2–5]),

(iii) ocean floor spreading in the northern Japan Sea (e.g., [6–8]),

(iv) extension of the continental crust in the southern Japan Sea (e.g., [7, 9, 10]),

(v) inversion tectonics at the plate boundary on the eastern margin of the northern Japan Sea (e.g., [11]), and

(vi) rotation of the Philippine Sea Plate (e.g., [12, 13]).

Geotectonic research has predominantly focused on tectonic structure, deep crust processes, and the interaction and internal structure of oceanic and overriding plates. In contrast, scientific drilling and seismic surveys are generally not planned and designed to observe the thick Cretaceous and Cenozoic sediments on the overriding plate of arc-trench systems. Consequently, causes of the formation and deformation processes of the Japanese offshore basins are rarely discussed. Counter to the general research trend, the Japanese government has been acquiring geological and geophysical data for petroleum exploration for many years. The Ministry of International Trade and Industry (MITI) and its successor the Ministry of Economy, Trade and Industry (METI) have been conducting *MITI/METI Exploratory Survey for Petroleum Resources* programs through several iterations of a *Five-Year Plan for Domestic Oil and Natural Gas Resources*. The database covers the sedimentary basins occupying the shelf around the Japanese islands and primarily consists of data collected from more than 30 offshore exploratory wells, two-dimensional (2D) seismic surveys from an area >100,000 km, and three-dimensional (3D) seismic surveys over approximately 50,000 km^2. This database facilitates discussion of the formation/deformation of the sedimentary basins, because the surveys were originally designed to investigate thick Cretaceous and Cenozoic sediments for petroleum exploration [14]. This study focuses on the sedimentary basins in the eastern offshore regions of Fukushima and Miyagi prefectures, northeastern Japan and uses seismic structural interpretation to investigate the sedimentary and deformation patterns of the basins. These sedimentary and deformation patterns are compared with the already known tectonic framework of the northeast Japan arc and the arc-trench system. The results of this study will contribute to the on-going discussions of the active structures and/or long-term tectonic movement of northeastern Japan and may help elucidate the mechanisms of large earthquakes and disasters. The study results will also provide background knowledge for assessing global environmental variation.

2. Database

Data sets of the MITI/METI seismic survey results and geological information from three MITI exploratory wells were used to assess the tectonic framework of the forearc basins of the northeast Japan arc. The study area encompasses approximately 36,000 km^2 of the shelf adjacent to the Fukushima and Miyagi prefectures, Japan.

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2.1. MITI/METI seismic surveys

The Reconnaissance Geophysical Survey "Minami Sanriku-Kashima Oki" (MITI Seismic-MSK) was conducted by MITI in 1986 using the survey vessel *Kaiyomaru*. A survey of approximately 2500 km of 2D seismic lines was performed in the area from Miyagi to the Fukushima Pacific coast using a 15–20 km grid [15].

The Reconnaissance Geophysical Survey "Abukuma Ridge Nanbu 3D" (METI 3D Seismic-ARN) was conducted by METI in 2009 using the 3D geophysical survey vessel *Shigen*.

The line locations for the 2D seismic survey and area covered by the 3D seismic survey are shown in **Figure 1**, with detailed specifications for those seismic surveys provided in **Table 1**.

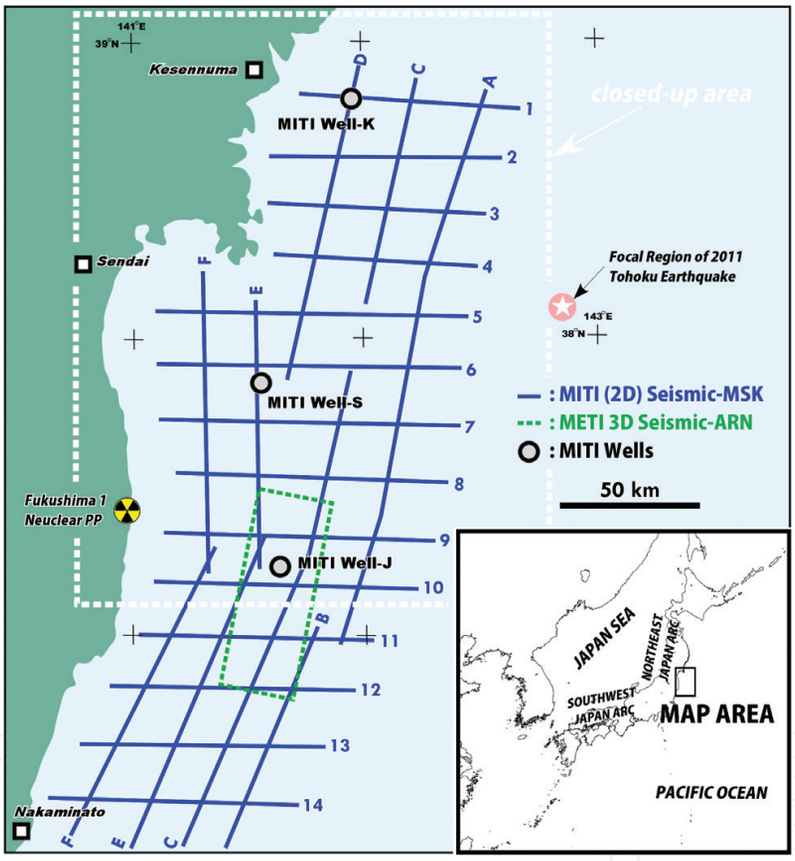


Figure 1. Index map showing the seismic lines, area, and wellsite locations. The blue lines are line location of MITI Reconnaissance Geophysical Survey "Minami Sanriku-Kashima Oki" (MITI Seismic-MSK). The numbers and alphabets indicate line name. The green dashed open box indicates the area of METI Reconnaissance Geophysical Survey "Abukuma Ridge Nanbu 3D" (METI 3D Seismic-ARN). The open circles are the location of MITI Kesennuma-oki well (MITI Well-K), MITI Soma-oki well (MITI Well-S), and MITI Joban-oki well (MITI Well-J).

2.2. MITI exploratory wells

The exploratory well "MITI Kesennuma Oki" (MITI Well-K) was drilled by MITI in 1985, approximately 30 km ESE from Kesennuma City in Miyagi prefecture, Japan. A Cretaceous

granitic rock body was observed at a depth of 1843 m below mean sea level (MSL), and drilling was stopped at a depth of 2027 m MSL [16].

The exploratory well "MITI Joban Oki" (MITI Well-J) was drilled by MITI in 1990 approximately 60 km ENE from Onahama City in Fukushima prefecture, Japan. Cretaceous sediments overlain by Quaternary and Neogene strata were observed at a depth of 1345 m MSL, and drilling was continued for approximately 3000 m through the Cretaceous succession to a total depth of 3170 m MSL [17].

The exploratory well "MITI Soma Oki" (MITI Well-S) was drilled by MITI in 1991 approximately 50 km east of Soma City in Fukushima Prefecture, Japan. A Paleogene unit overlain by Quaternary and Neogene successions was observed at a depth of 1625 m MSL, and Cretaceous clastics were observed at a depth of 2450 m MSL, with a total well depth of 3500 m MSL [18].

The locations of these three MITI exploratory wells are shown in **Figure 1**, and the stratigraphic details are listed in **Table 2**.

	MITI Seismic-MSK	**METI 3D Seismic-ARN**
	Two-dimensional (2D)	**Three-dimensional (3D)**
Formal survey name	MITI Reconnaissance	METI Reconnaissance
	Geophysical Survey	Geophysical Survey
	"Minami Sanriku-Kashima Oki"	"Abukuma Ridge Nanbu 3D"
Year acquired	1986	2009
Vessel	Kaiyo Maru	Shigen
Data volume	2500.50 km	1950 km^2 (full fold)
Energy source (size)	Airgun (3223 cu.in.)	Airgun (3090 cu.in. × 2)
Streamer	2400 m	4800 m × 10
Group number	96	—
Fold	48	—
CMP bin size	—	inline: 12.5 m, xline: 25 m
Sample interval	4 ms	4 ms
Record length	5000 ms	8000 ms
Line number or area shape	EW: 14	EW: 25 km
	NS: 6	NS: 80 km

Table 1. Specifications of the MITI seismic surveys.

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		MITI Well-K	MITI Well-S	MITI Well-J
Specification	Formal well name	MITI Kesennuma-oki	MITI Soma-oki	MITI Joban-oki
	Owner	Ministry of International Trade and Industry		
	Operator	Teikoku oil	Japex	Teikoku oil
	Spud in date	1984.12.04.	1990.06.21.	1991.07.13.
	Rig released date	1985.02.13.	1990.09.25.	1991.10.17.
	Water depth	240 m	137.2 m	268 m
	Total depth	2027 m	3500 m	3170 m
	Vertical/deviated	Vertical	Vertical	Vertical
	Well head location	38°48′27″ N	37°51′07″ N	37°14′28″ N
		141°58′01″ E	141°34′45″ E	141°38′30″ E
Stratigraphy	Base Quaternary	—	—	402 m
	Base Pliocene	—	525 m	588 m
	Base Upper Miocene	—	582 m	—
	Base Middle Miocene	—	825 m	625 m
	Base Lower Miocene	508 m (base Tertiary)	1562 m	1345 m
	Base Paleogene	—	2450 m	—
	Base Upper Cretaceous	1843 m	(3500 m TD)	(3170 m TD)
	TD horizon	Lower Cretaceous (granitic rock)	Upper Cretaceous	Upper Cretaceous (Turonian)

Table 2. Specifications and stratigraphy of the MITI wells. All depth from mean sea level (MSL).

3. Methods

This study was performed as follows:

(i) Stratigraphic horizons and stratigraphic units were recognized on the seismic profiles from MITI Seismic-MSK based on a general seismic interpretation method (**Table 3**).

(ii) The approximate stratigraphic position of each horizon was designated based on the stratigraphic information from MITI Well-K, Well-S, and Well-J [16–18].

(iii) Notable evidence of deformation was observed and interpreted as tectonic lineations based on planar continuity.

(iv) A discontinuity (an unconformity and its correlative conformity) was recognized in the northwestern part of the study area based on a seismic sequence interpretation method [19, 20].

(v) The relationship between these structural and stratigraphic features and the known characteristics of the adjacent onshore region was assessed.

Seismic unit	Horizon name of unit top	Geological system
A	-	Quaternary
B	Horizon 1	Pliocene
C	Horizon 2	Upper Miocene
D	Horizon 3	Middle Miocene
E	Horizon 4	Lower Miocene
F	Horizon 5	Paleogene
G	Horizon 6	Cretaceous
H	Horizon 7	Paleozoic/Mesozoic/Cretaceous Granite

Table 3. Stratigraphic position of the seismic units and their bounding horizons detected on MITI seismic MSK by using the seismic stratigraphic method.

4. Stratigraphic control of seismic units

Unit H, recognized below 1843 m in measured depth (MD) of MITI Well-K, is granite [16]. An radiometric age determination on the cored granite indicates an Early Cretaceous age, and the rock body is inferred to be correlative to intrusive granites in the South Kitakami Belt consisting of Mesozoic and Paleozoic strata [21].

Unit G is recognized below 2450 mMD of MITI Well-S [18], the interval from 508 to 1843 mMD at MITI Well-K [16], and in the interval from 1345 mMD to the total depth of 3170 mMD at MITI Well-J [17]. Cretaceous calcareous nannofossils, planktic foraminifer fossils, and radioralian fossils have been reported from the intervals.

Unit F, found in the interval from 1562 to 2450 mMD at MITI Well-S, is correlative to Paleogene based on pollen biostratigraphic analysis. Its coaly lithofacies suggest that Unit F is equivalent to the coal-bearing Paleogene strata outcropping at the adjoining onshore area [18, 22].

From Unit E, recognized in the interval from 625 to 1345 mMD at MITI Well-J and the interval from 82 to 1562 mMD at MITI Well-S, Early Miocene diatom fossils and calcareous nannofossils and radioralian fossils have been reported [17, 18, 22].

Unit D is confirmed in the interval from 582 to 825 mMD and the interval from 588 to 625 mMD at MITI Well-S and Well-J, respectively. The Middle Miocene diatom fossils have been reported from those successions [17, 18].

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Unit C, found in the interval from 525 to 582 mMD at MITI Well-S, includes Late Miocene radioralian fossils [18].

Unit B is correlative to Pliocene based on calcareous nannofossil biostratigraphic analysis [17].

Unit A is correlative to Quaternary based on the calcareous nannofossil and diatom biostratigraphic analyses [17, 18].

5. Results

The positions of faults and their direction of extension were estimated using seismic interpretations of the heteromorphic and structural gaps of the traced horizons. Although several smaller fault zones were identified, three relatively large fault zones were designated as tectonic lines.

5.1. The Kesennuma tectonic line

This tectonic line is located in the northern part of the study area and is typically recognized at position 1 on Line 1 (p1-1) of MITI Seismic-MSK (**Figure 2**).

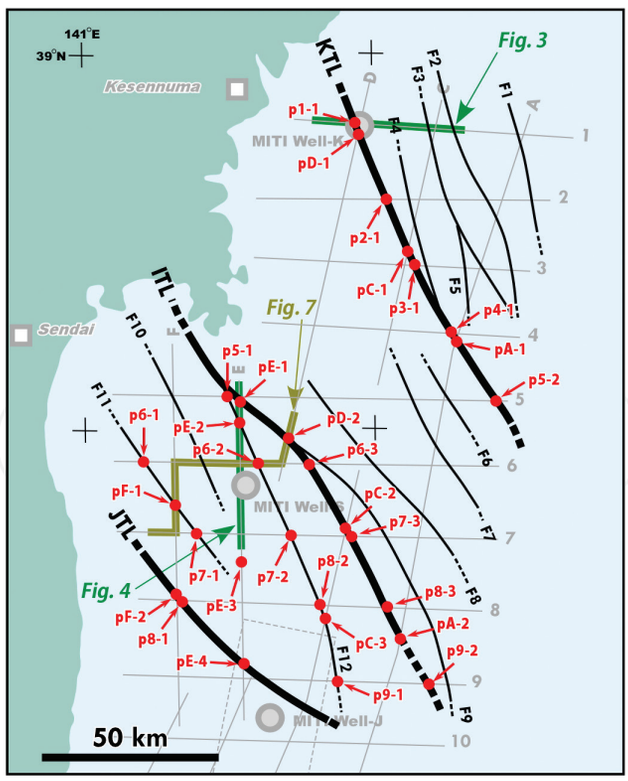


Figure 2. Map showing the positions of faults and deformed strata observed on the seismic sections (red solid circles), and traced lines of the tectonic lines (heavy black lines) and other fault zones (thinner black lines). In addition, the locations of seismic section in **Figures 3**, **4**, and **7** are shown (colored heavy lines).

Horizon 7, the upper limit of Unit H (Cretaceous granite), is recognized in MITI Well-K at a depth of 1843 m MSL (corresponding to two-way travel time = 1.43 s). An apparent west-dipping normal fault and its derived faults are located west of the MITI Well-K location on the Line 1 section (**Figure 3**). A rock unit with a two-way travel time upper limit of 1.5–2.0 s is recognized west of the fault zone, and is characterized by irregularly shaped, low frequency reflectors. The seismic facies characteristics of this unit resemble those of Unit H east of the fault zone. Furthermore, this unit decreases in depth toward a western shoreline and changes into a seismically transparent facies. Paleozoic and Mesozoic strata and granitic rocks of the southern Kitakami Belt are exposed at the surface in the region of extension. Therefore, the upper limit of this rock unit is correlative with Horizon 7, which is the top of Unit H. These spatial relationships were also observed at position pD-1 and indicate an apparent south-dipping normal fault. Therefore, the fault zone consists of a southwest-dipping normal fault with a NNW-SSE trend. The author tentatively designates this fault zone the Kesennuma tectonic line (KTL).

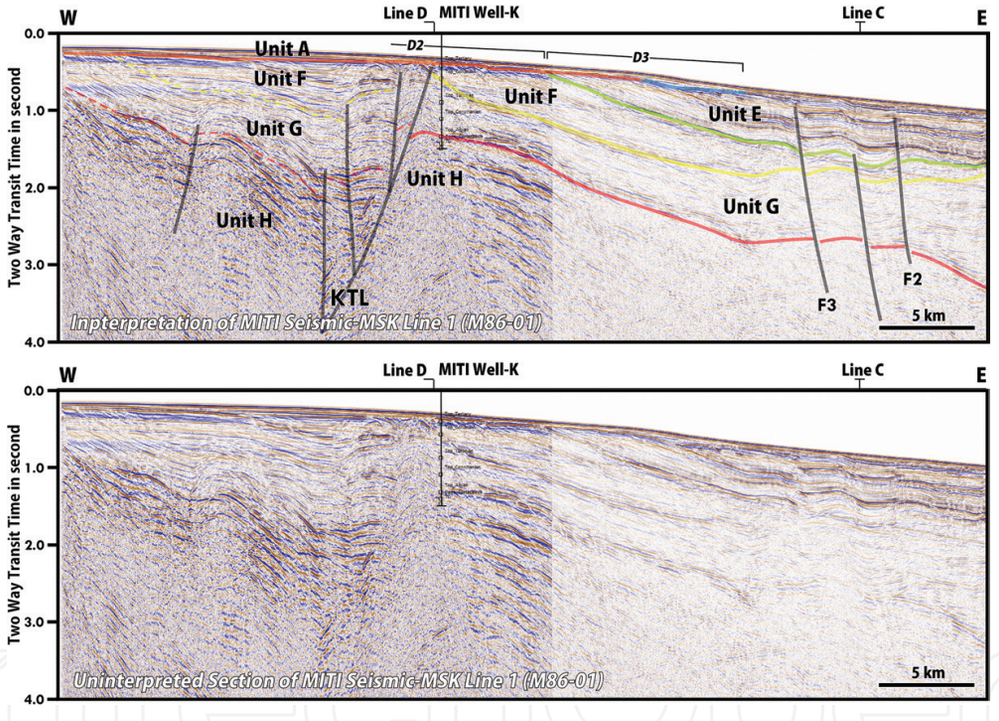


Figure 3. Uninterpreted section of MITI Seismic-MSK Line 1 (below), and its structural and stratigraphic interpretation (above).

The KTL, bounding the eastern edge of the wedge-shaped sedimentary body above Horizon 7 on Line 1, is traceable to positions p2-1, p3-1, and pC-1 with similar fault characteristics. It can also tentatively be traced to positions p4-1, pA-1, and p5-2 because some evidence of deformation is recognized, although the fault characteristics are not an exact match.

Despite a lack of direct stratigraphic control, based on a comprehensive regional seismic stratigraphic interpretation the wedge-shaped sedimentary body may consist largely of Cretaceous, Paleogene, and Lower to Middle Miocene sediments. The Upper Miocene and

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older strata are deformed by the KTL; however, the deformation does not extend into the overlying Units B (Pliocene) and A (Quaternary).

5.2. Ishinomaki tectonic line

This fault zone is located in the middle and southern parts of the study area. An apparent south-dipping normal fault is recognized at position pE-1 on the north-south Line E (**Figure 2**). In addition, an apparent west-dipping normal fault is observed at position p5-1 crossing the east-west Line 5 (**Figure 4**). These are judged to be different appearances of a single southwest-dipping and NW-SE trending normal fault zone. The author tentatively designates this fault zone the Ishinomaki tectonic line (ITL).

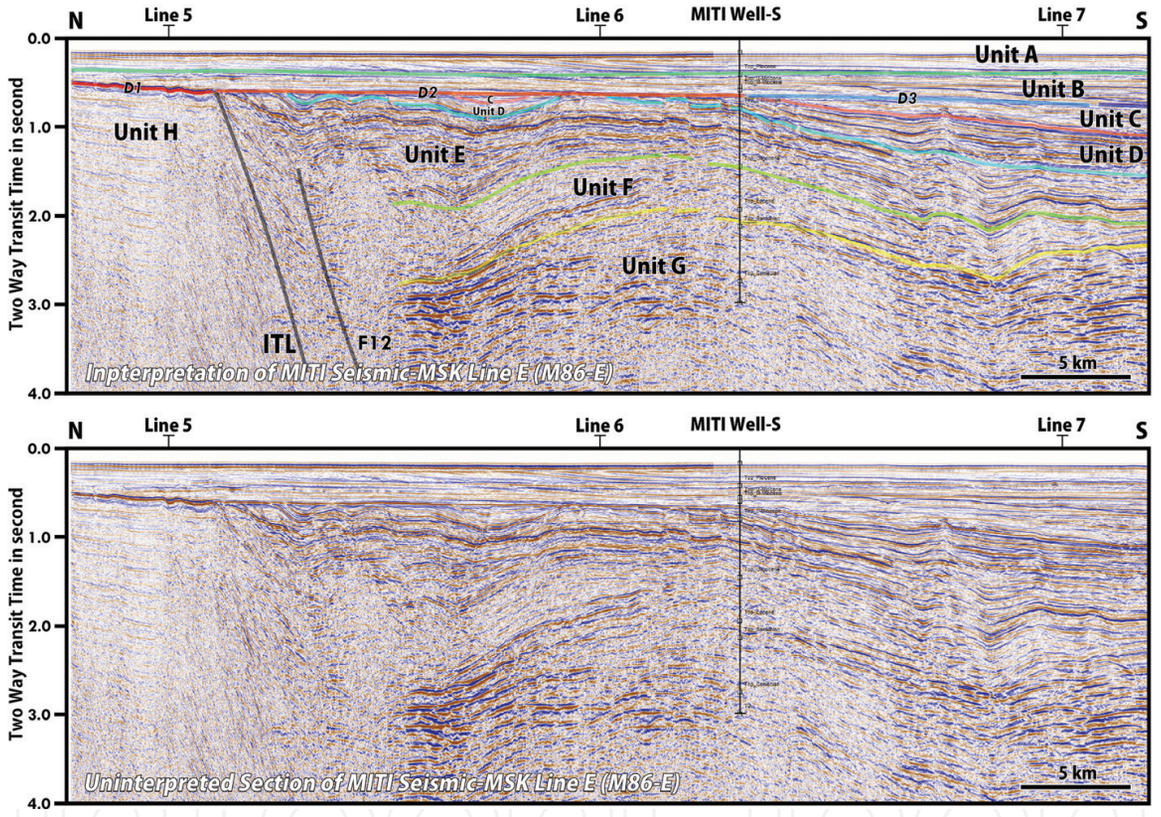


Figure 4. Uninterpreted section of MITI Seismic-MSK Line E (below), and its structural and stratigraphic interpretation (above).

The footwall block of the ITL primarily consists of a seismically transparent layer, estimated to be the seaward extension of the southern Kitakami Belt, composed of Unit H (Paleozoic and Mesozoic strata, and granitic rocks). Horizon 7, the upper limit of Unit H, increases in depth east of position p5-1, and is overlain by the wedge-shaped sedimentary body seen on Lines 1–4. Based on stratigraphic data from MITI Well-S, the hanging wall block of the ITL is interpreted to consist of Units B to G (Paleogene and Neogene, and likely also Cretaceous). The northwestern extension of the ITL is not found at the north end of Line F, although the units making up the hanging wall block are recognized. The southeastern extension of the ITL can be traced to

positions pD-2, p6-3, pC-2, p7-3, and p8-3. It is characterized by deformed strata, although the vertical fault displacement is not clearly detected because it passes through the wedge-shaped sedimentary body consisting of Cretaceous and Cenozoic strata seen near MITI Well-K, and then extends southward. F12, a branched fault zone of the ITL, is also identified on the southwest side, avnd is observed at positions pE-2, p6-2, p7-3, p8-2, pC-3, and p9-1. The deformation caused by the ITL does not generally extend into the overlying Units B (Pliocene) and A (Quaternary); however, the northwest portion of the ITL slightly displaces the Pliocene and Quaternary units.

5.3. Joban tectonic line

This fault zone is located in the southwestern part of the study area. An apparent north-dipping normal fault is recognized at position pF-2 on the north-south trending Line F (**Figure 2**). A flexural structure of Unit E (Lower Miocene), differentiated from the overburden, is found at position p8-1. Based on the spatial relationships, this fault zone is an apparent northeast-dipping normal fault, with a left-lateral strike-slip sense. The southeastern extension of this fault zone is found at position pE-4. The author tentatively designates this fault zone the Joban tectonic line (JTL).

F11 is another fault zone similar to the JTL, and is recognized at positions p6-1, p7-1, and pF-1. Unit C (Upper Miocene) and older strata are deformed by the JTL; however, the deformation does not extend into the overlying Units B (Pliocene) and A (Quaternary). A set of the JTL and F11 faces the ITL across the graben that occupies Sendai Bay, and shows a NW to SE extensional trend.

5.4. Other faults

Fault F4, derived from the KTL, is found on the northeast side of the KTL. Faults F1, F2, F3, and F5 are recognized northeast of the KTL and F4, and are characterized by a direction and dip similar to the KTL and F4. Faults F6, F7, F8, and F9 are found in the area between the ITL and the KTL/F11. F6 and F7 are northeast-dipping normal faults. In contrast, F8 and F9 are southwest-dipping similar to the ITL. F10 is found within the graben between the ITL and the JTL/F11. All of these fault zones and the three tectonic lines show a NW-SE to NNW-SSE extensional trend.

5.5. Discontinuity

As a distinctive feature of basin development, a discontinuity is recognized in the seismic sections in the northwestern and western near-coast part of the study area. The strata above the discontinuity are Units B (Pliocene) and A (Quaternary). This discontinuity is subdivided into three zones based on the ages of the underlying strata and seismic sequence configurations (**Figure 5**).

The zone where eroded Unit H (Paleozoic, Mesozoic, and granitic rocks) unconformably underlies Unit B (Pliocene) is designated D1 (**Figure 6**). D1 is discernible at the western ends of Lines 2, 3, 4, 6, and 7 by an irregular or rough surface and its undersurface truncation, which is a type of reflection termination (Vail [19]). The eroded top surfaces of horsts are unconformably overlain by Unit B (Pliocene) at the western end of Lines 5 and 6 and the northern end of Line F (**Figure 7**).

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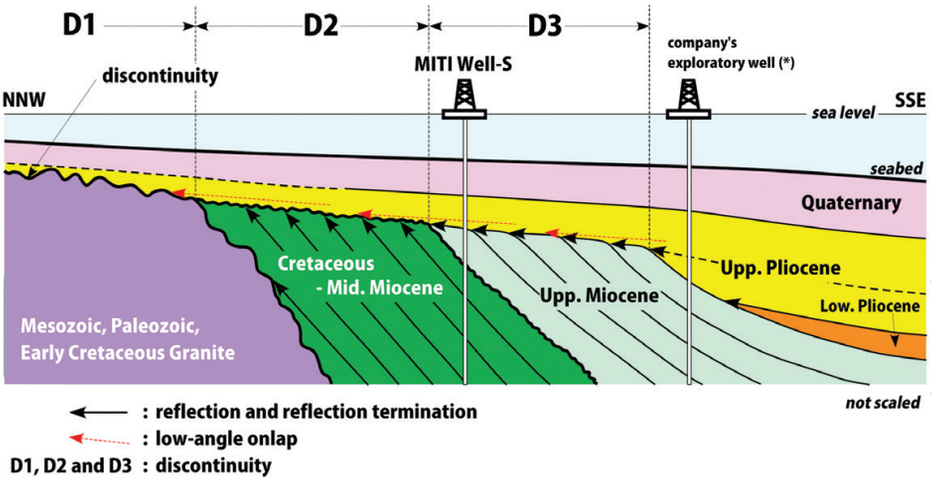


Figure 5. Schematic dip sectional image of the discontinuity and its subdivision showing stratigraphic relationship between its undersurface and overlying strata.

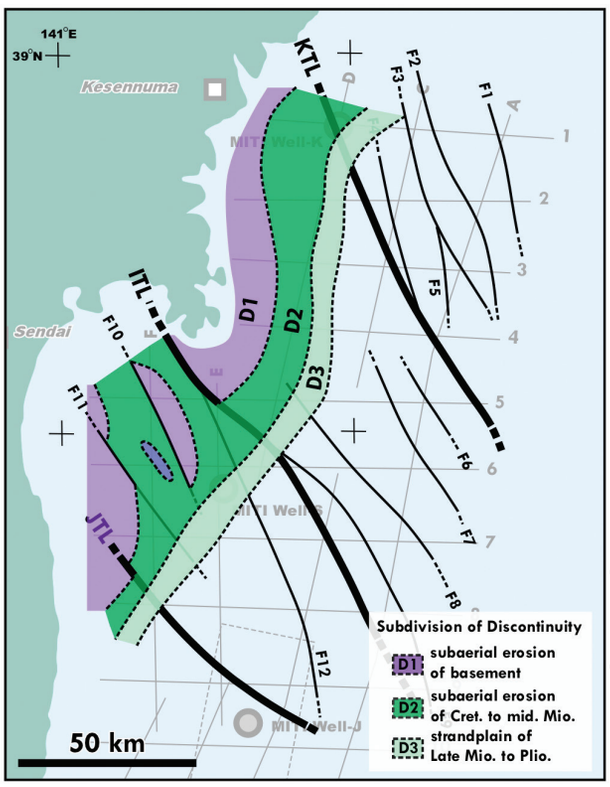


Figure 6. Map showing the distribution of discontinuity and its subdivisional zones.

The zone where eroded units G (Cretaceous) and F (Paleogene) underlie Unit B (Pliocene) is designated D2. D2 is found in the areas east and southeast of D1, and can be detected by low angle onlaps on a relatively smooth surface, its undersurface truncation, and east- or southeast-dipping reflections.

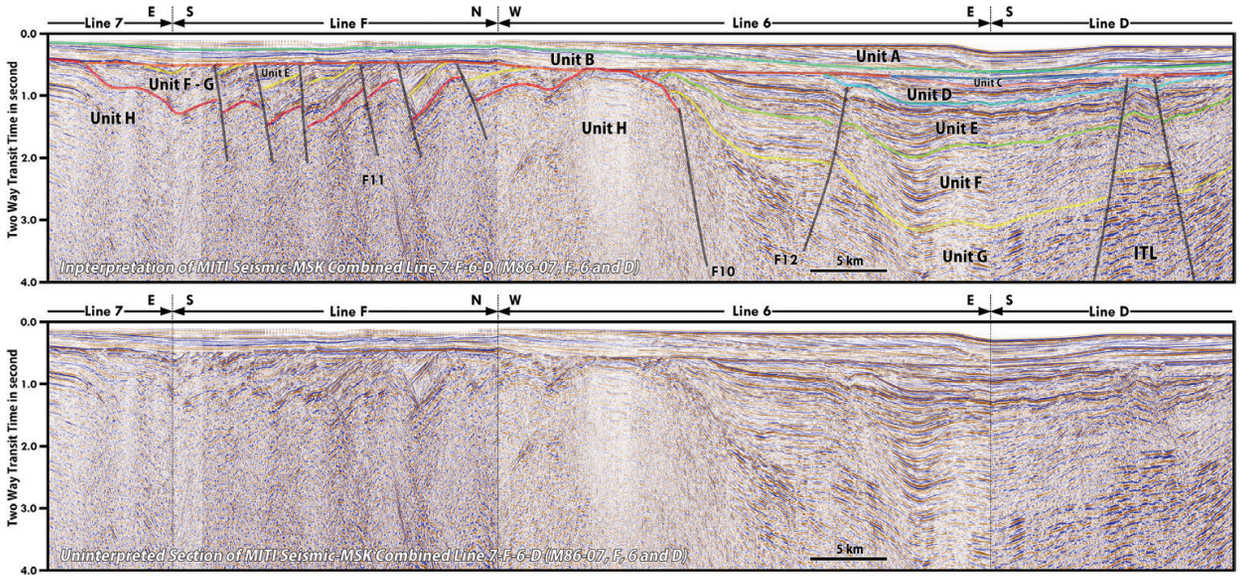


Figure 7. Uninterpreted composite Section of MITI Seismic-MSK Lines 7, F, 6, and D (below), and its structural and stratigraphic interpretation (above).

The zone where the top surface of the prograding Unit C (Upper Miocene) is overlain by Unit B (Pliocene) is designated D3. There is no seismic stratigraphic evidence of erosion in D3, and undersurface toplap of east- or southeast-dipping reflections are observed.

6. Discussion

6.1. Strike of the tectonic lines

The KTL, ITL, JTL and other fault zones are observed in the 2D MITI Seismic-MSK data acquired using an approximately 15–20 km grid. This means that the existence of a fault or deformed strata cannot be confirmed within the grid boxes lacking seismic lines. This is common for regional 2D seismic data sets, and does not mean that they are not useful for the interpretation of fault strike. With sufficiently high intensity, length, and a relatively stable extension direction, a tectonic line identified on a single seismic line may extend to any position on three other seismic lines surrounding the grid box. Thus, the observed deformation points are located on the lines extending NW-SE to NNW-SSE. This interpretation of the strike direction of the tectonic lines is supported by marine geological surveys and an active fault survey as described below.

Marine geological maps covering the northwestern part of the study area were compiled using a high resolution and high density shallow 2D seismic data set acquired by the Geological Survey of Japan. A shallow part of the northwestern portion of the ITL is indicated on the map off "Kinkazan" as the Ishinomaki Bay Fault, which extends NNW-SSE [23]. A shallow, northwestern portion of KTL is shown on the map off "Kamaishi", which also extends NNW-SSE [24].

Tohoku Electric Power Co., Inc. conducted the active fault survey around the northern part of Sendai Bay using high resolution and high density shallow 2D seismic data set. The results

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of the survey are documented in handouts from a meeting held by the Nuclear Regulation Authority of Japan on April 16, 2014 [25]. The handout suggests that a NNW-SSE trending fault system identified by the survey may correspond to the Ishinomaki Bay Fault.

6.2. Sense of the tectonic lines

The tectonic lines are estimated to have a relatively straight extensional trend. However, the sense of displacement is not as constant. For example, a tectonic line that appears as a normal fault with relatively large vertical displacement in one area can be identified in other area as local deformation of strata without vertical displacement. Generally, a fault with a vertical component of displacement is relatively recognizable on a 2D seismic profile compared with strike-slip or wrench faults lacking vertical displacement, because seismic surveys use vertical elastic waves and measure their reflections.

The following model is proposed to further the discussion (**Figure 8 (1)**):

(i) there is a syncline located west of a north-south trending anticline,

(ii) a northwest-southeast trending sinistral strike-slip fault cuts both the syncline and anticline diagonally,

(iii) the fault plane dips southwest,

(iv) the displacement of the strike-slip fault is half of the wavelength of the syncline-anticline cycle, and

(v) some east-west 2D seismic lines are available in this area.

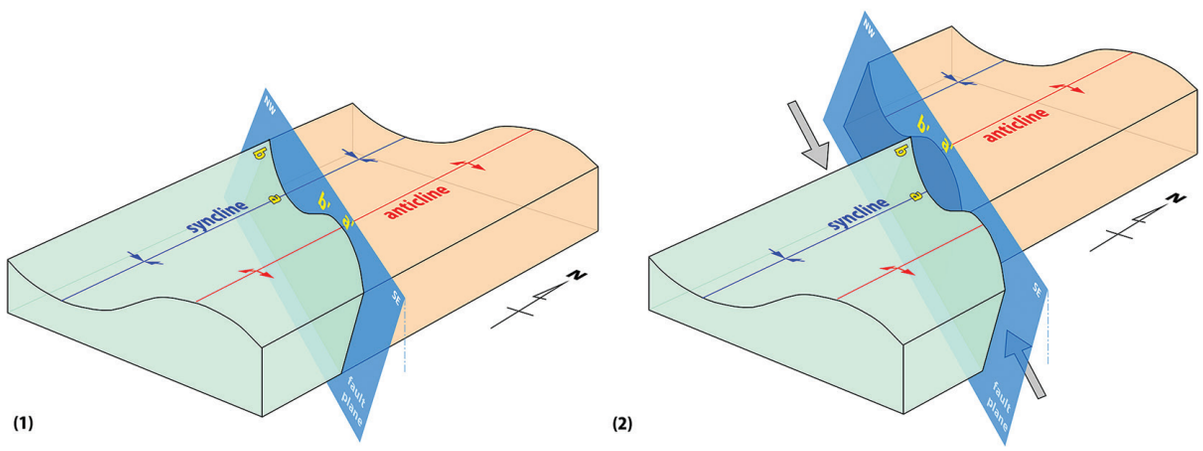


Figure 8. Conceptual model illustrating a north-south trending syncline and anticline set cut by a diagonal southwest dipping sinistral strike-slip fault.

Within this model, because the southwest block of the fault slips toward the southeast, the axis of the syncline (a) may adjoin the axis of the anticline (a′) on the northeast block (**Figure 8 (2)**). The fault will appear as a west-dipping normal fault with significant vertical displacement on the east-west seismic line at this position (**Figure 9**).

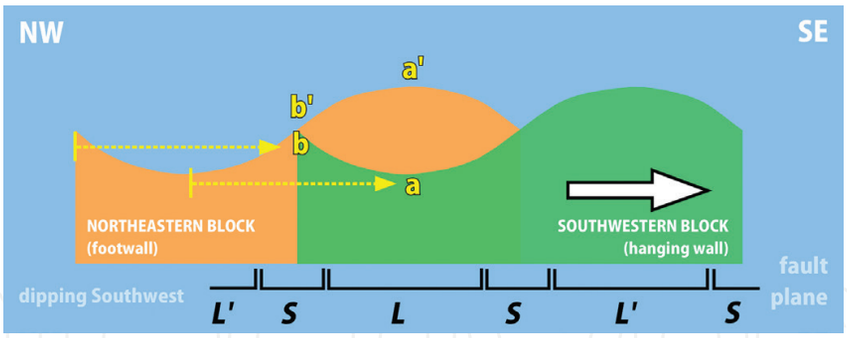


Figure 9. The fault plane view of the conceptual model in **Figure 8** showing the positional relationship between the northeastern block and southwestern block after sinistral strike-slip. [L] and [L'] represent the area with apparent significant vertical displacement, and [S] represents the area with less vertical displacement. Furthermore, [L] will appear apparent southwest-dipping normal fault and [L'] will be reverse fault.

In contrast, with the same fault activity, the western flank of the syncline (b) on the southwest block may be adjacent to the western flank of the anticline (b') on the northeast block. The less vertically displaced deformation will be observed in the seismic section at this position.

This model suggests that the strike-slip sense causes tectonic lines to appear as an apparently normal fault, with vertical displacement in one area and as deformed strata lacking vertical displacement in other areas. Flower-like faulting and local folding without significant vertical displacement are frequently observed on the lines of the MITI Seismic-MSK survey. With this evidence, it is conceivable that the tectonic lines in the study area may have a strike-slip sense. If it is possible to acquire enough data, based on the above-mentioned model the horizontal displacement and direction of movement should be discussed in detail. However, the 2D MITI Seismic-MSK survey, with its rough grid data, is not worthy of further sophisticated discussion.

In contrast, 3D seismic data can be used for such discussions if the conditions are suitable. For example, the so-called "Abukuma Ridge" [26], lying subsurface along the edge of the continental shelf in the study area, is cut by the southeastern extension of the JTL. Based on METI 3D Seismic-ARN data this deformation is caused by a sinistral strike-slip fault [27].

6.3. Formation age of the discontinuity

D2, part of the discontinuity, is characterized by an eroded flat surface of Cretaceous to Middle Miocene strata overlain by Pliocene units with a low angle onlap. Based on a micro-biostratigraphic study using a company's exploratory well samples, this surface at position pE-3 is covered by Upper Pliocene sediments and lacks the Lower Pliocene units [28]. This suggests that the low angle onlap above D2 must be a coastal onlap at the base of the Upper Pliocene, indicating a landward shift of the coastline (transgression) in the Late Pliocene.

The landward portion of the discontinuity, D1, is characterized by an eroded undulating surface of Paleozoic to Mesozoic sediments or granitic rocks overlain by Upper Pliocene sediments. This surface is interpreted as a drowned coast caused by further transgression in the Late Pliocene. This interpretation is supported by the landward connection of D1 to the recent Sanriku coast ria.

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The basinward portion of the discontinuity, D3, is characterized by toplap or asymptotic truncation of Upper Miocene strata overlain by low angle onlap of Upper Pliocene sediments. This surface is relatively flat, and in some areas, lowers stepwise basinward. This suggests that D3 was formed as a Late Miocene strand plain. In the eastern and southeastern basinward directions, D3 is correlative with Horizon 2 at the top of Upper Miocene. Farther southeast, the Lower Pliocene conformably overlies the Upper Miocene [29]. Therefore, the relative sea level fall that formed the discontinuity, which consists of D1, the D2 erosional surface, and the D3 strand plain is estimated to have occurred during the Middle Pliocene.

Upper Miocene strata with a vertical thickness of 57 m were detected in the interval between depths 525 and 582 m MSL below D2 at MITI Well-S, and are unconformably underlain by Middle Miocene units [18]. Based on the stratigraphic data from the well drilled near position pE-3 this interval corresponds to the lower portion of the Upper Miocene [22, 28]. The unconformity between the Middle Miocene and the lower part of the Upper Miocene is also truncated by the erosion that occurred on the D2 surface. This stratigraphic relationship indicates that the erosion began after the deposition of the lower part of the Upper Miocene strata. Therefore, the discontinuity is interpreted to have formed between the early Late Miocene and Late Pliocene.

6.4. Active age of the tectonic lines

The discontinuity is not folded or faulted by the KTL or the JTL/F11. In addition, the ITL does not deform the discontinuity and its overlying sediments except in the Sendai Bay area. The strata above the discontinuity are generally flat and stable despite the existence of tectonic lines like the KTL, JTL, and ITL, as well as the undulating topography of the discontinuity itself. This likely indicates that the most active period of the tectonic lines had ended before the formation of the discontinuity, terminating before the Late Miocene. Furthermore, based on the interpretation of the METI Seismic ARN data, the Lower Miocene strata are cut at the Abkukuma Ridge by the southeast portion of the JTL [27]. Therefore, it is inferred that the tectonic lines were most active at least during the early Middle Miocene.

Those tectonic lines resemble generally Tanakura Tectonic Line (TTL), Hatakawa Tectonic Line (HTL), or Futaba Fault (FF) in sense [3, 4], which are the most important tectonic elements of the southern part of northeastern Japan. The activity of TTL had been active until the Middle Miocene; however, the activity is devided into several stages after the Middle Cretaceous. TTL is considered to connect the east margin of the Japan Sea Transform (JET) bounding the eastern limit of spreading area of the northern Japan Sea [4]. The Middle Miocene is the age of final stage for the opening of Japan Basin and Yamato Basin [6, 7]. The characteristics and sense of KTL, ITL, and JTL should be considered from a wider viewpoint of large scale tectonic framework around the northeastern Japan and northern Japan Sea.

6.5. Subsurface graben in Sendai Bay

The ITL is a fault with an apparent southwest dip in the Sendai Bay area. In contrast, the JTL/F11 is an apparent northeast-dipping fault. Therefore, the area bounded in the northeast by

the ITL and in the southwest by the JTL/F11 is a graben that extends NNW, landward to the Kitakami Lowland that is characterized by a graben-like topographic feature [30]. Based on the active age of the boundary-limiting tectonic lines, this graben is inferred to have formed prior to the Middle Miocene.

The ITL does not generally deform the discontinuity and its overburden in the study area; however, it does displace shallow sediments within the Sendai Bay area. This deformation is possibly due to an active structure, because the deformed overburden consists of Upper Pliocene and Quaternary sediments. The footwall of the ITL in the deformed area is interpreted to consist of rigid rocks within the Southern Kitakami Belt, such as Mesozoic sediments, Paleozoic sediments, or granitic rocks. This suggests that the Sendai Bay portion of the ITL is reactivated, or that the relatively unrigid Cretaceous to Middle Miocene hanging wall strata are differentially compacted.

The MITI Seismic-MSK data show an upward swelling of the hanging wall block along the tectonic line that seems to indicate the occurrence of inversion tectonics during the Pliocene or Pleistocene. Although no displacement seems to reach the ocean bottom, because the Pliocene and Pleistocene deposits are thin their internal seismic facies and reflection termination patterns are not easily observed or recognized. The existence of several multiples beneath the ocean bottom further complicates the proper observation of seismic characters in this series of seismic data.

The Ishinomaki Bay Fault (the northwestern shallow portion of the ITL) is a reverse fault that cuts the discontinuity and reaches the overlying uAK supersequence that is roughly correlative with the Upper Pliocene; however, no evidence for the deformation of the Pleistocene AK2r subsequence has been noted [23]. Based on the interpretation of the Tohoku Electric Power survey results, some active faults displace not only the discontinuity and its overlying Pliocene strata, but also influence the lower part of the Pleistocene sediments.

Based on the evidence presented, the deformation of the discontinuity and its overlying sediments is inferred to reflect inversion tectonics, with a reactivation of the ITL.

7. Conclusion

The tectonic deformation history of the offshore regions of the Fukushima and Miyagi prefectures, Japan, was studied using MITI Seismic-MSK, METI 3D Seismic-ARN, and MITI well data. Three major tectonic lines and several medium-scale fault zones were recognized in the study area.

Despite the limitations of the large grids of the 2D seismic configuration, based on a general interpretation method the strike direction of the tectonic lines is inferred to be NNW-SSE to NW-SE.

The sense of the tectonic lines is not constant for each line. This can occur in the case of oblique cuts of anticlinal-synclinal trends by a strike-slip fault. In this case a sinistral strike-slip fault displaces the axis of the Abukuma Ridge, as determined from the METI 3D Seismic-ARN data.

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Based on this investigation, the most active period of the tectonic lines is estimated to be after the Early Miocene, during which time Abukuma Ridge was formed. The activity ceased prior to the formation of the discontinuity that eroded the strata deformed by the activity of the tectonic lines. The discontinuity is interpreted to have formed between the early Late Miocene to Late Pliocene. Therefore, the tectonic lines must have been active during the early Middle Miocene at least. Based on the stratigraphic interpretation of MITI Seismic-MSK sections, an angular unconformity between the Lower Miocene succession and its overlying Middle Miocene is recognized in the part of this study area. The sedimentary basin including this study area has a two-story layered configuration bounded by the top Lower Miocene unconformity. The second story is obviously the succession in the forearc basin of the island arc after drifted to its current position. The lower story, in contrast, may represent succession within a basin of a continental margin arc in front of the Eurasian Continent. Not only the top Lower Miocene unconformity but also the tectonic lines detected in this study must have close relationship with such major tectonic deformation process of East Asia.

The tectonic lines bounding the subsurface graben in the Sendai Bay Area affected the deformation of the discontinuity and its overlying strata. The deformation must therefore be related to Quaternary inversion tectonics with a reactivation of the ITL. This graben is inferred to extend landward to the Kitakami Lowland.

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