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Subduction and accretion in the Japan Trench

Forearc area
Thrust
Subduction
Japan Trench

Zone avant-arc
Chevauchement
Subduction
Fosse du Japon

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ABSTRACT

Some fundamental geomorphologic elements are distinguished in the forearc area. They are the volcanic chain, the basement high, the subduction complex and the trench. A sedimentary basin may occur behind or at the front of the basement high. These geomorphologic features are variable both by the mode of development and their location. The morphology and structure of the NE Japan margin reflect the cumulative effects of subduction since late Oligocence. The Upper Cretaceous basement is overlain by a few kilometers thick Late Cenozoic sediments on the Japan Trench forearc (Tohoku forearc).

Structural features in the forearc such as the trend of the basin, faults, trench axis and the horst and grabens of the outer trench slope reflect a block structure whose individual elements are of limited width. The forearc is dominantly controlled by horizontal compressional stress due to the horizontal movement toward and subduction under the arc. However, local horizontal tensional force is suggested by surficial features of the forearc. The subduction complex is primarily governed by thrusts which cut the underthrusted oceanic basement beneath the complex, which suggests that there may be no way to consume the subduction complex to deeper parts of the subduction zone under the continental plate.

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RÉSUMÉ

Subduction et accrétion dans la fosse du Japon

Dans la zone avant-arc, on distingue quelques éléments géomorphologiques fondamentaux : la chaîne volcanique, le bombement de la croûte, le complexe de subduction et la fosse. Un bassin sédimentaire peut se développer à l'arrière où à l'avant du bombement de la croûte. Ces caractères morphologiques varient d'après leur mode de développement et leur situation. La morphologie et la structure de la marge NE du Japon reflète l'ensemble des effets de la subduction depuis l'Oligocène supérieur. La croûte Crétacée est surmontée par quelques kilomètres de sédiments du Cénozoïque supérieur dans le bassin avant-arc du Japon (Tohoku).

Les caractères structuraux dans la zone avant-arc comme l'orientation du bassin, les failles, l'axe de la fosse et les horsts et grabens de la pente externe de la fosse reflètent une structure en blocs de petite dimension. La zone avant-arc est contrôlée principalement par les contraintes horizontales de compression dues aux mouvements horizontaux et la subduction sous l'arc. Cependant, des forces locales de tension horizontales sont suggérées par les structures superficielles de la zone avant-arc. Le complexe de subduction est surtout gouverné par des chevauchements qui recoupent la croûte océanique enfouie sous le complexe, ce qui rend difficile l'existence d'un processus de destruction du complexe de subduction dans les parties les plus profondes de la zone de subduction sous la plaque continentale.

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INTRODUCTION

Many geomorphological and geological models for island arc system have been proposed since the late 1960's. Earlier discussions on arc systems were based on land geology (Matsuda, Uyeda, 1970 ; Dewey, Bird, 1970 ; Sugimura, Uyeda, 1973) in which a Pacific type orogenesis or Cordilleran type orogenesis was postulated in contrast to the collision type orogenesis. Many results of continuous seismic reflection surveys in various forearcs of the circum-Pacific belt have been presented since the middle 1960's. The forearc tectonics are governed by the subduction of the oceanic plate under the continental crust. New models for modern forearcs have been presented as a result of more recent surveys, especially by multichannel seismic reflection profiling and drilling by the Deep Sea Drilling Project (DSDP). Forearc basins underlain by basement consisting of material scraped off the underthrust plate associated with a high bordering the basin and the subduction complex have been postulated (Dickinson, 1973 ; Karig, Sharmann III, 1975 ; Karig, 1977 ; Seely, 1979 ; Dickinson, Seely, 1979). Forearc basins underlain by a basement consisting of continental crust or crustal remnants have also been postulated (Honza *et al.*, 1977 ; Kulm, Schweller, 1977 ; Von Huene *et al.*, 1978 ; Husson *et al.*, 1978).

Many offshore data have been accumulated by the Geological Survey of Japan in the NW Pacific Rim, especially around Japan (Fig. 1). The purpose of this paper is to present such data pertaining especilly to the tectonics of the Tohoku forearc and the Japan Trench, and to discuss the Japanese situation in comparison to the tectonics of the Sunda forearc (Karig et al., 1979), the Mid-America forearc (Seely, 1979 ; Moore *et al.*, 1979 ; Aubouin *et al.*, 1979), The Peru-Chile forearc (Kulm, Schweller, 1977) and Aleutian forearc (Von Huene, 1979).

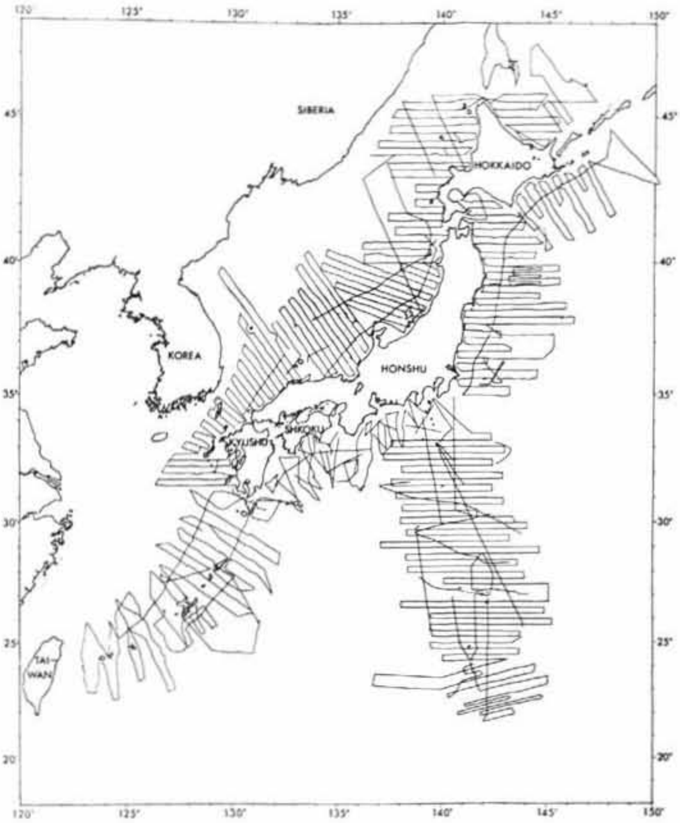

Figure 1

Geophysical survey lines 1975 to 1979 by Geological Survey of Japan in the NW Pacific Rim.

MODELS FOR FOREARC TECTONICS

Here, the term forearc is applied to the area between the active volcanic chain and the outer edge of the oceanic trench associated with that arc (Seely, 1979). Some characteristic features are observed in the forearc area. A basement high between the volcanic chain and the trench consists of mountains onshore or a submarine structural high overlain by modern slope sediments (Fig. 2). There may be a prominent terrace or trough comprising the continental shelf or parts of the slope. The slope commonly has a knick point or break that is referred to as trench slope break or ridge. The term of the inner trench slope is used here for the deeper part of the slope from the break to the trench on which benches may occur. The terms of outer trench slope for the oceanward slope of the trench and trench swell, instead of outer arch or outer rise, for the outer morphologic bridge oceanward of the trench are used here.

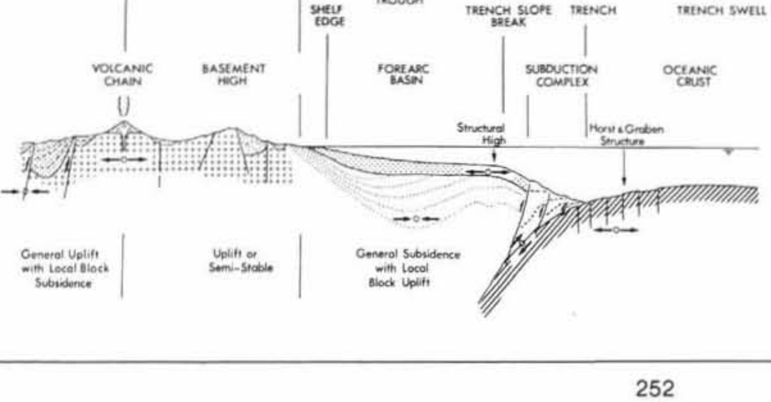

Figure 2

Shallow structural model and stress condition of the forearc illustrating the Japan Trench area (Tohoku forearc) and terminology used in this paper. Deeper stress is cited from the focal mechanism solution (Yoshii, 1979). Open triangle : volcanic chain ; dotted : modern basins ; plus and dotted layers : basement.

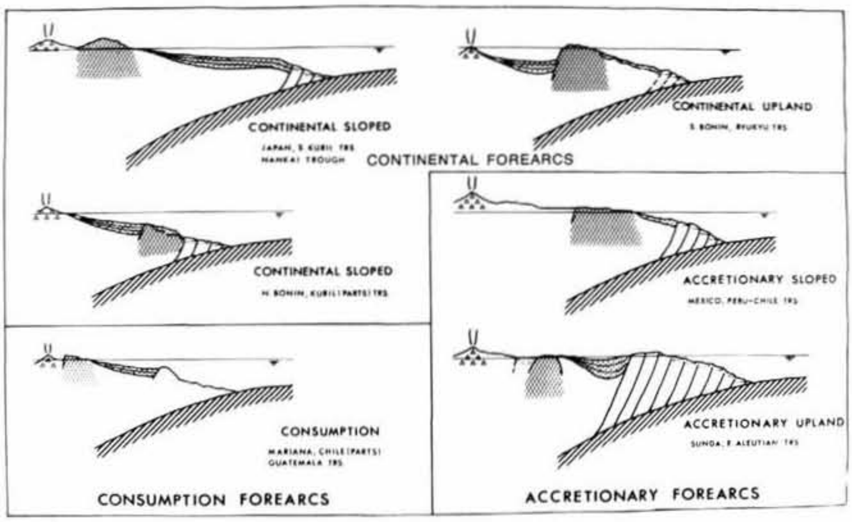

Figure 3

Models of modern forearcs. Fundamental framework of the forearc is similar in all cases, except in model of consumption, only variable in some of geomorphologic positions. Open triangle : volcanic chain ; dotted : forearc basin ; meshed : basement high.

There may be three types of forearcs, the first that consists of a slope underlain by a continental crust and others consisting of a part of the slope underlain by an accretionary prism. Forearcs of the former type can be categorized as consumption. The latters are one dominantly underlain by a continental crust categorizing these as continental forearcs and the other dominantly underlain by an accretionary prism categorizing these as accretionary forearcs in which the subduction complex extends upward to the trench slope break (Fig. 3). Common features which are associated with all of the forearcs are the active volcanic chain, the basement high and the trench, even there may be discontinuities in some of the features in them. At present, there are some uncertainties concerning the existence of consumption or tectonic erosion at the base of some forearcs which has been postulated on the basis of DSDP drilling results in the Mariana forearc (Hussong *et al.*, 1978) and the geomorphology in parts of the Peru-Chile forearc (Kulm, Schweller, 1977). A more or less sediment filled basin may occur between the volcanic chain and the basement high or between the basement high and the subduction complex. The position of the basement high is variable. There may be a mountain range onshore such as in the Tohoku Arc, Seinan Japan Arc and Peru-Chile Arc, or a mid-slope high (trench slope break or outer ridge) such as in parts of the Bonin Arc, in parts of the Mariana Arc and parts of the Kuril Arc, or an islands chain such as in the Ryukyu Arc and in parts of the Bonin and Mariana Arcs.

TECTONICS OF THE TOHOKU ARC

The Tohoku Arc System has been active since the late Oligocene when subduction of the Pacific plate started after complete consumption of the Kula plate. This was accompanied by vigorous volcanic activity and rapid sedimentation in the backarc basin and by subsidence on the forearc side (Honza *et al.*, 1977 ; Honza, 1979). Before the onset of activities on the Tohoku Arc, some tectonic activity had occurred in the NW mainland of Japan during the Late Paleozoic and during the Middle Mesozoic (Fig. 4). This is documented by the volcanic activity in each period and paired metamorphic belts of the Hida-Sangun couple (Late Paleozoic) and the Ryoke-Sanbagawa couple (Middle Mesozoic). However, some of the metamorphic ages are presently under discussion because of conflicting evidence from geological observation and absolute age determinations (Tanaka, 1977).

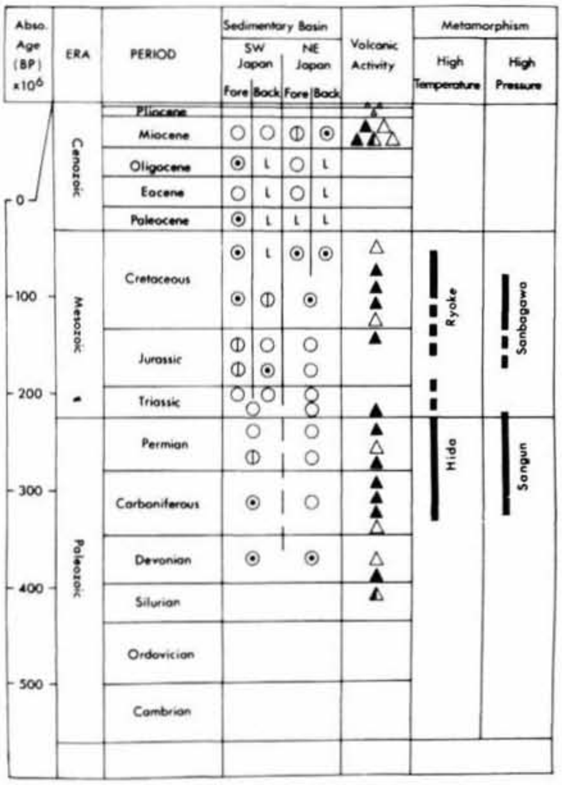

Figure 4

Generalized geological history of SW Japan, compiled from Matsumoto (1967) and Tanaka (1977). Two periods of arc activity are inferred from volcanic activity and metamorphism during Late Paleozoic and Middle Mesozoic. The scale for the period between 0-100 my BP has been enlarged twofold. Sedimentary basin is indicated by circle with a dot (very large), circle with a line (large), open circle (moderate) and by L (no or thin deposition). Black triangles : mafic volcanism ; open triangles : acidic volcanism.

The Tohoku forearc may be characterized as a kind of continental sloped in Figure 3. It has a sedimentary basin with a fill a few kilometers thick between the basement high and subduction complex. The Upper Cretaceous to Paleogene basement is overlain by Late Cenozoic sediments covering the entire continental slope in the area (Honza, 1977 ; Honza *et al.*, 1978 ; Von Huene *et al.*, 1978). The Upper Cretaceous sequences are tilted westward and overlain by Paleogene sediments that are developed along the inner side of the slope. The boundary between the forearc basin and the subduction complex is presumably a thrust on the upper to middle part of the inner trench slope. Sediments in the forearc basin are gently folded to form smaller basins and highs. The trench slope break commonly represents an uplifted area behind which a small younger basin occures (Fig. 5).

BLOCK STRUCTURE IN THE FOREARC BASIN

The fold axes of The Late Cenozoic sediments in the forearc basin are approximately parallel to the trench axis. Each fold can be followed over a distance up to 100 km. Dominant uplifts occur along the coast and second order uplifts along the trench slope break. Predominant subsidence is seen along the central to inner part of the slope. This structural trend suggests a relative uplift on the landward side and subsidence on the seaward side with minor uplift on the trench slope break (Fig. 6 *a*).

Several attempts have been made to delineate the block structure of the forearc region from the distribution of aftershocks in the circum-Pacific belt (Mogi, 1969 ; Nagumo, 1970). This applies particularly to the structural blocks in the northern part of the Tohoku forearc. By analogy, structural units for the southern area have been depicted from structural trends alone (Honza *et al.*, 1977). Figure 6 *b* illustrates a compilation of suggested blocks on the structural trends for the area.

Most of the shelves on the forearc side of the Tohoku Arc were formed by a wave-cut terrace during the latest Pleistocene glaciation (Honza *et al.*, 1977). It is possible to infer that the amount of crustal deformation since the maximum sea-level lowering controls the depth of the wave-cut terrace at the shelf edge. It shows a sinuous curve with a wave length of one degree (approximately 110 km). This distance corresponds approximately to the north-south length of the structural blocks in the forearc basin. The boundaries of these structural blocks of the forearc coincide with the plunging ends of anticlines. Therefore, the boundary of a block at the shelf edge is likely to lie at the deepest point of the curve in Figure 7.

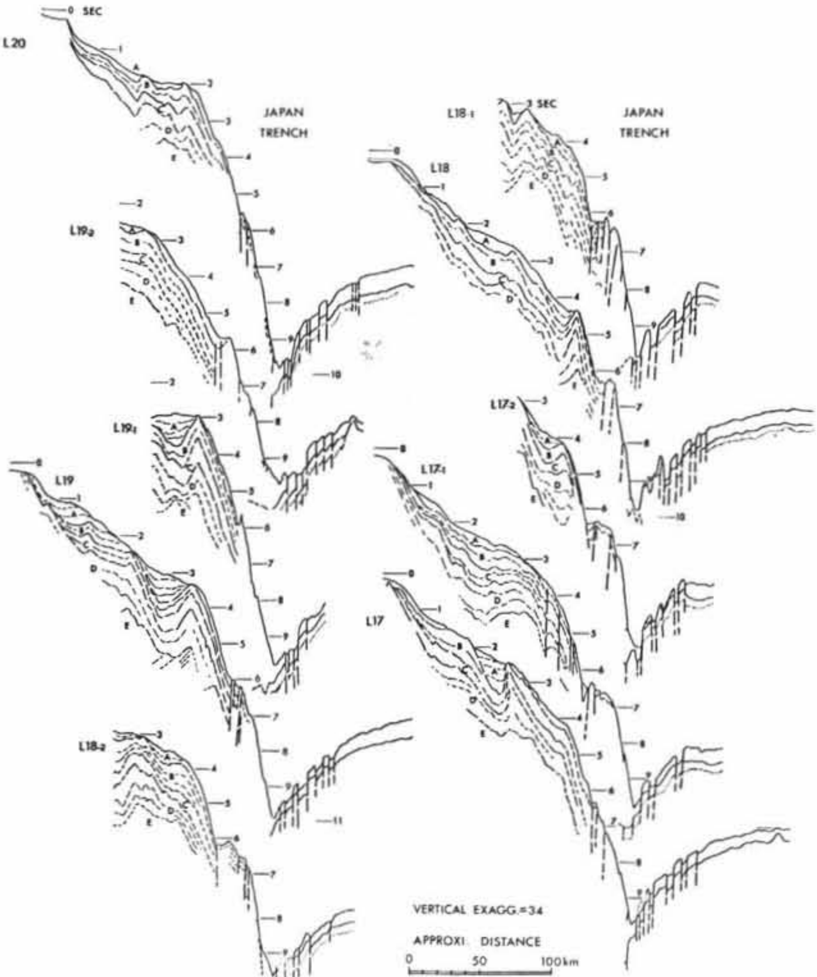

Figure 5

Reflection profiles in the detailed surveyed area (ship tracks shown on Fig. 8). Units A-E are Quaternary, Pliocene, upper Miocene, Middle-lower Miocene to late Oligocene and basement, respectively. The geological ages correspond to those given on the geological map of this area (Honza et al., *1978).*

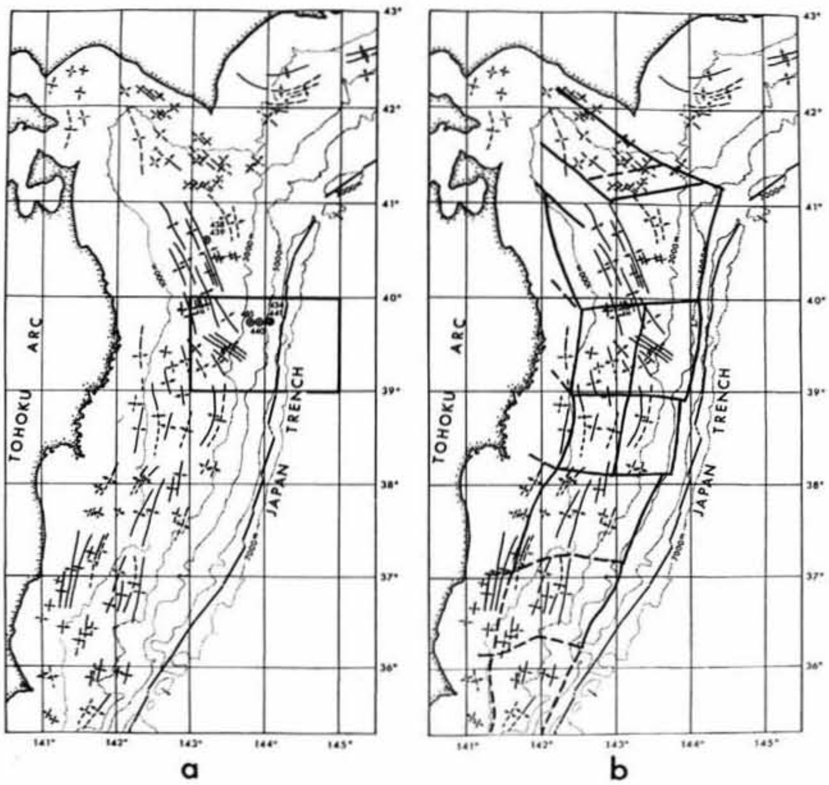

Figure 6

a : Structural trends in the forearc basin of the Tohoku Arc, compiled from the geological map of the area (Honza et al., *1978). The rectangle surrounded by a thick line is the detailed survey area illustrated in Figure 8. Thick lines along the Japan Trench show the axis of the trench.*
b : Block structures in the Tohoku forearc. Northern blocks (north of 38°N) are delineated by the distribution of aftershocks (Nagumo, 1970), southern blocks are delineated by structural trends alone (Honza et al., *1977).*

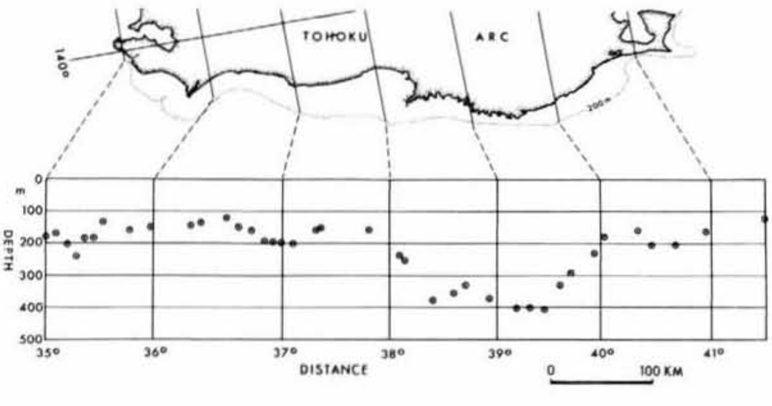

Figure 7

Depth of the wave-cut base on the shelf edge along the Tohoku forearc. The depth shows a sinuous curve whose minima seems to correlate with the plunging ends of anticlines in the forearc basin.

SURFICIAL STRUCTURES IN THE TRENCH AREA

A detailed survey over a portion of the Japan Trench and slope revealed interesting surficial structureal trends (Fig. 8). The dominant morphologic trends are approximately parallel to the trench axis, however, in each area minor trends deviate slightly from the main trend. The trench axis forms a straight line over limited distances, but abruptly changes its direction from one block to the next. The outer part of the continental slope and the inner trench slope in the northern block deepen gradually toward the trench, while slope of the southern block are characterized by relatively steep walls and a terrace. The faults bordering the terrace which occurs at a depth of 5,000 m to 5,400 m have an irregular strike.

The horst and graben structure of the outer trench slope has an oblique orientation with respect to the trench axis and extends 5 to 15 nautical miles long (Honza *et al.*, 1978 ; Honza, 1980).

STRESS DISTRIBUTION IN THE FOREARC

Dominant surficial stress over the island arc may be horizontal compressional stress which are exerted by the movement of the oceanic plate toward the arc and by subduction under the arc. However, local tensional force is revealed by the detailed survey of the forearc area. One of the surficial expressions of extensional structure is the horst and graben structure of the outer trench slope which may be due to the bending on the convex side of the oceanic plate. The faults are at right angle to the magnetic lineations (Uyeda *et al.*, 1967 ; Larson, Chase, 1972). This suggests that there may be initial weakness in the oceanic plate in the

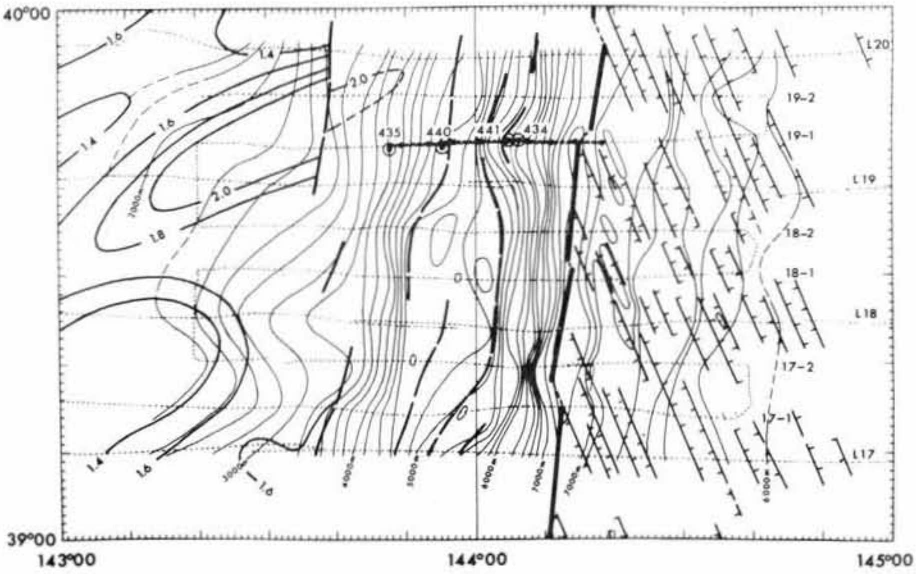

Figure 8

Detailed survey area in the Japan Trench and slope area. Thin dashed lines : ship tracks. Thin lines : corrected bathymetry. Thick lines with numbers on the upper slope are isochronal contours of the Late Cenozoic sediments in seconds. The thick dashed line is the track line of the multichannel seismic profile with nearby DSDP sites (dotted circles with numbers). Thick lines on the lower slope show faults. Heavy straight lines in the trench area show the trench axis. Thin strait lines with bars in the outer trench slope : faults associated with the horst and graben structure.

direction perpendicular to the spreading center. A group of normal faults is observed along the highs of forearc basin (Fig. 9). The group of faults may be a result of the uplift of basement which is associated with deformation of the overlying younger sediments. This has also been confirmed by drilling results of the DSDP Japan Trench Transect during Leg 57 (Von Huene *et al.*, 1978). Another region of horizontal tensional stress may occur along the volcanic chain where a gravity low and paired normal faults are observed. The stress field in the backarc area adjacent to the volcanic chain is changing from horizontal tensional to horizontal compressional field which is suggested by the tillted block movement associated with faults. General uplift is dominant in this area since the Pliocene accompanied by the local block subsidence.

General subsidence with local block uplift is dominant in the forearc basin. A relative uplift is commonly observed in the trench slope break. There may be an uplift or semistable area on the basement high (Fig. 2).

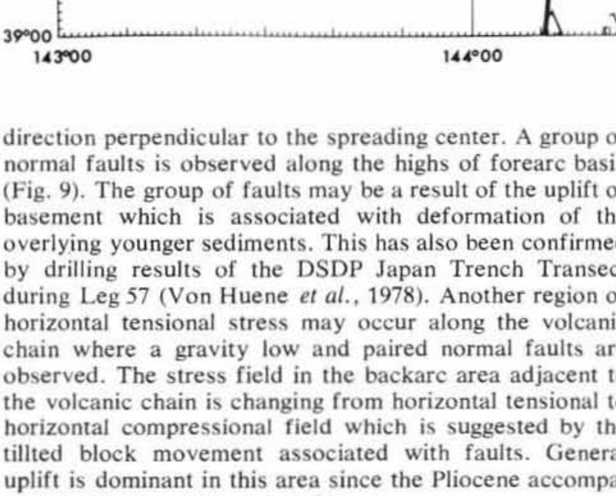

Figure 9

Seismic time section slong the DSDP sites 438, 438A, B and 439. Normal faults are dominant in the area.

SUBDUCTION COMPLEX IN THE JAPAN TRENCH

The Late Cenozoic and underlying Upper Cretaceous sediments show an abrupt change in the lower part of the inner trench slope. The stratified Late Cenozoic sediments and an unconformity between the underlying Upper Cretaceous sequence on the continental slope cannot be observed in the lower part of the inner trench slope (Fig. 10). Vague discontinous horizontal reflectors are observed among the dominant reflectors dipping landward. These reflectors may suggest sheared faults which caused deformation of the horizontal layers. The oceanic basement which can be traced from the outer trench slope under the trench to the subduction complex is cut by several large thrusts (Fig. 11). There is uncertainty in the area between the continental basement and the subduction complex where no thrust is recognizable in the profile. However, the layers are deformed along the contact zone between the continental basement and the subduction complex. This may suggest some structural deformation caused during subduction of the Pacific plate.

The thrusts which occur in both the subduction complex and the underthrusted oceanic basement may suggest that there is no displacement along the bottom of accretionary prism. It is inferred from the fact that the presumable melange which consists of the accretionary prism is fixed upon the oceanic basement on the inner trench slope and there may be no consumption of the presumable melange under the arc in this area.

DISCUSSION AND CONCLUSIONS

Morphologic variations in forearcs may be the products of a different initial location of the basement blocks with respect of the distance to the trench at the onset of the subduction. From the common distrubution of a basement high, it is inferred that arc systems may occur where some kind of continental or semi-continental material is distributed, even a few possible locations are suggested for the basement. More detailed surveys are required to confirm the geomorphology of the fundamental elements and the surficial

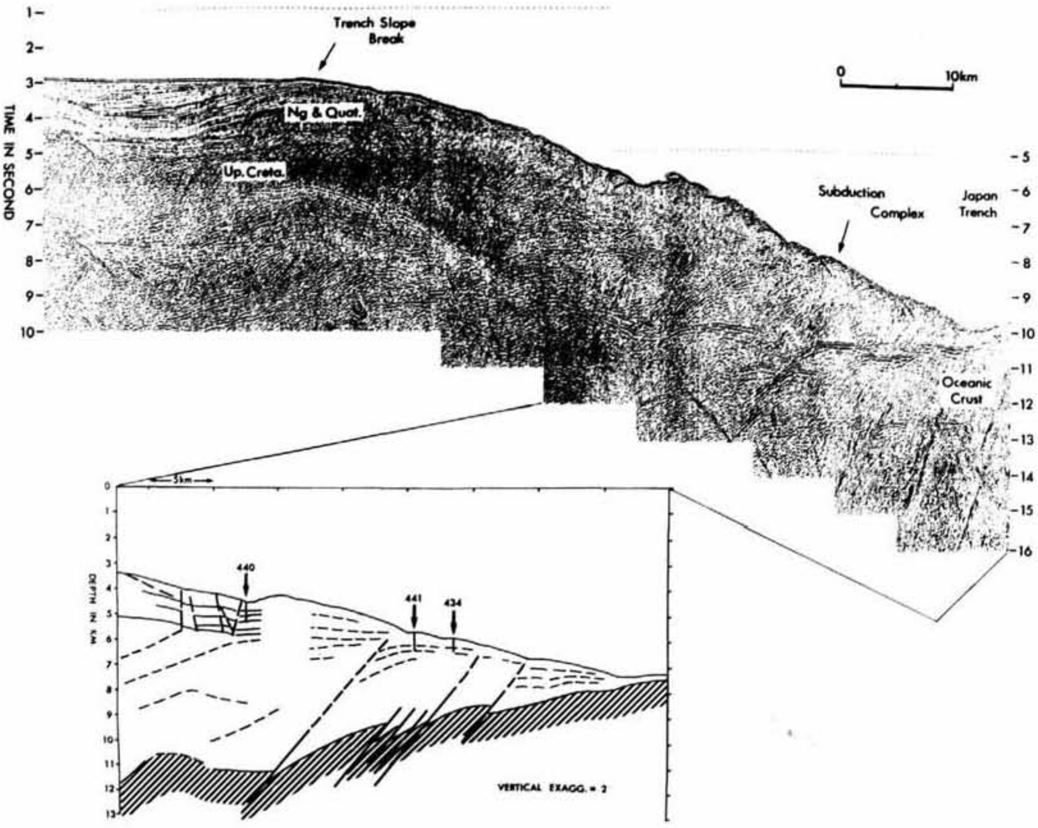

Figure 10

Seismic time section along the DSDP sites of Legs 56 and 57 (Nasu et al., *1980) and a schematic depth section of the inner trench slope area in which velocities from refraction measurements (Ludwig* et al., *1966 ; Murauchi* et al., *1977) have been added for the deeper horizons to convert in time section (ship track is shown on Fig. 8).*

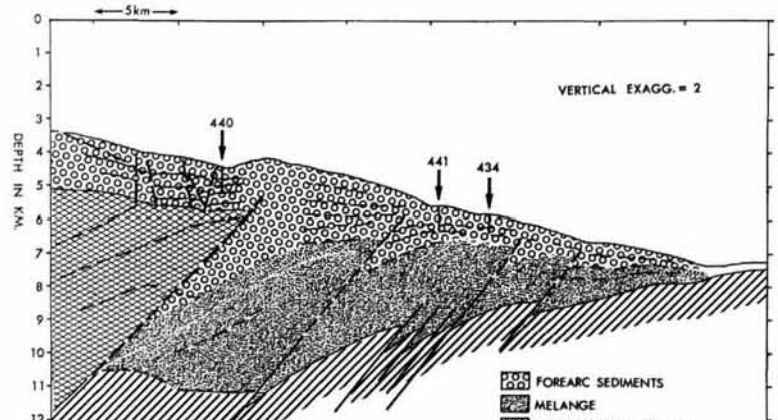

Figure 11

Diagrammatic structural interpretation of the profile in Figure 10.

structures prevailed in the forearc area in other areas. The horsts and grabens which trend obliquely to the Japan Trench axis also extend to the Kuril Trench where the trench axis is approximately parallel to the magnetic lineations of the oceanic plate. However, structural trend of the horsts and grabens is not depicted in the Kuril Trench. The horsts and grabens trending parallel to the magnetic lineations are reported in the Guatemala Trench (Aubouin *et al.*, 1979). It may suggest two trends of the horsts and grabens, one perpendicular and the other parallel to the magnetic lineations.

From the interpretation of the subduction complex in the Japan Trench, it is inferred that there may be no consumption of the subduction complex to deeper parts of the subduction zone beneath the continental crust. It has also been suggested in the seaward accretion model (Seely, 1979) and the extension of some underthrust along the inner part of the upper oceanic basement from the thrusts which cut both the accretionary prism and the upper most slices of the oceanic basement (Von Huene, 1979). Total downdip length of the subducted oceanic plate in the Japan Trench is suggested to be approximately 900 km or more during the Late Cenozoic. The displacements of the thrusts in the subduction complex is not enough to cover the entire length of the subduction of the oceanic plate during the Late Cenozoic.

An unconformity between Late Cenozoic sediments and underlying Upper Cretaceous sequences on the outer parts of the continental slope and the upper part of the inner trench slope may suggest an uplifted high or broad shelf having prevailed in the outer slope area during the Early Cenozoic. A lack of the terrigenous sediments or the continental crust in the modern outer slope area may imply that the consumption or tectonic erosion might have occurred at the onset of the subduction or the continental crust which had formed a slope during the Early Cenozoic might be underlying as a wedge beneath the modern outer wedge of the continental material.

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