Subsidence of the Japan Trench forearc region of Northern Honshu

Japan Trench
Northern Honshu
Subduction
Subduction erosion
Thermally induced subsidence

Fosse du Japon
Honshu septentrional
Subduction
Érosion liée à la subduction
Subsidence thermique

M. G. Langseth [a], R. Von Huene [b], N. Nasu [c], H. Okada [d].
[a] Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964, USA.
[b] US Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, USA.
[c] Ocean Research Institute, University of Tokyo, 1-15-1 Minamidai, Nakano, Tokyo 164, Japan.
[d] Faculty of Science, Geoscience Institute, Shizuoka University, Shizuoka 422, Japan.

ABSTRACT

DSDP drilling results showed that at site 439 the Sanriku Shelf of Northeastern Honshu has subsided nearly 3,000 m during the Neogene. Integrating these results with seismic-reflection data indicates widespread subsidence that is locally as great as 6,000 m. We propose that this subsidence resulted from the initiation of subduction of Mesozoic lithosphere at the Sanriku Margin beginning 25-30 m.y.b.p. Temporal cooling of the mantle below the forearc area caused contraction and subsidence ; a simple model is presented to estimate the rate.

Oceanol. Acta, 1981. Proceedings 26th International Geological Congress, Geology of continental margins symposium, Paris, July 7-17, 1980, 173-179.

RÉSUMÉ

Affaissement du préarc de la fosse japonaise dans le nord-est de Honshu.

Les campagnes de forage du DSDP sur le site 439 ont démontré que le plateau de Sanriku, au nord-est de Honshu, s'est affaissé de près de 3000 m pendant le Néogène. L'intégration de ces résultats avec les données obtenues par réflexion sismique met en évidence un vaste affaissement, d'une envergure de 6000 m, à cet endroit. Nous proposons d'expliquer cet affaissement par la subduction de la lithosphère mésozoïque sur la marge du Sanriku, ayant commencé il y a 20-25 millions d'années. Le refroidissement, au cours du temps, du manteau sous le préarc produit une contraction et l'affaissement. Un modèle simple est présenté pour l'évaluation de la vitesse.

Oceanol. Acta, 1981. Actes 26e Congrès International de Géologie, colloque Géologie des marges continentales, Paris, 7-17 juil. 1980, 173-179.

INTRODUCTION

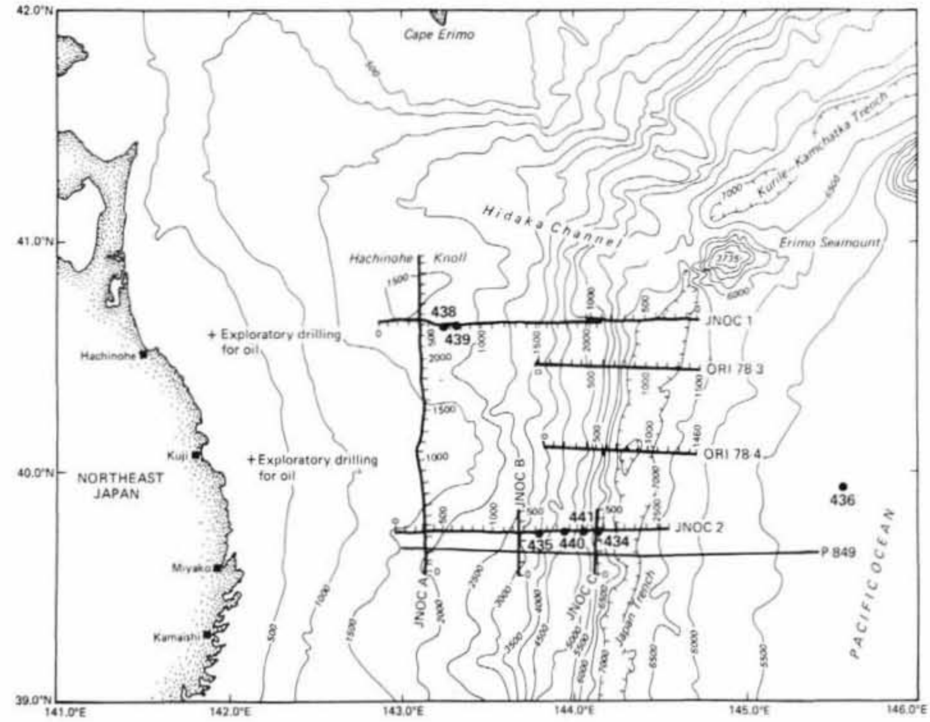
Deep-sea drilling on IPOD Legs 56 and 57 was aimed at increasing our understanding of the structure and evolution of the convergent margin off northeastern Honshu. The effort resulted in a line of drill sites located on multichannel seismic-reflection lines that crossed the Japan Trench at about 40°N latitude (Fig. 1 *a*).

The major physiographic elements of this margin are well shown by the single multichannel seismic profile that crosses the sites (Fig. 1 *b*). The Japan Trench at this point has maximum depths of 7,300-7,500 m. The outer wall of the trench has a gentle slope that rises to form a broad outer rise that is underlain by Early Cretaceous Pacific oceanic crust (Larson, Hilde, 1975). The seafloor is covered by a blanket of pelagic and hemipelagic sediments about 600 m thick. A linear set of horst and graben that intersect the axis of the Japan Trench at an acute angle are prominent on the outer wall (Ludwig *et al.*, 1966 ; Honza, 1978).

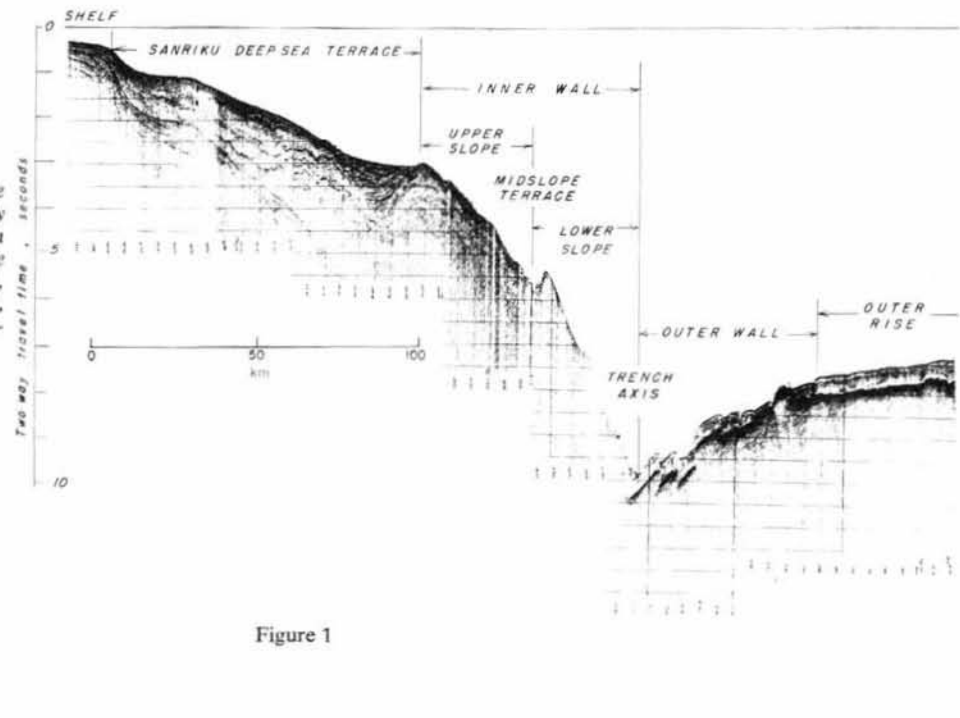
The shoreline of northeastern Honshu is about 200 km west of the trench, and the active volcanic arc is 100 km farther west. Between the shore and the trench is a broad terrace that dips gently seaward. At its distal end the depth is 2,500 m. This feature, called the Sanriku Deep Sea Terrace, has been shown by seismic-refraction observations to be underlain by a "continental type" velocity structure to depths of 20-25 km (Murauchi, Ludwig, 1980).

The landward wall of the Japan Trench is divided into two distinct parts on the basis of the morphology of the seafloor : a smooth, gently dipping upper slope, and a hummocky, more steeply dipping lower slope. The upper

Lamont Doherty Geological Observatory Contribution N° 3139.



a. Bathymetry of the Sanriku Margin showing the locations of several lines of multichannel seismic profiling. The locations of Legs 56 and 57 drill sites are also shown.



b. A single-channel seismic profile across the Japan Trench that is nearly coincident with the Line JNOC-2 in Figure 1a but extends from near shore to the vicinity of Site 436. This profile, made by the Ocean Research Institute, clearly illustrates the main physiographic features of the Sanriku Margin.

Figure 1

and lower slopes are separated by a narrow midslope terrace at water depths of 4,000 to 4,200 m. In most places the midslope terrace is underlain by a narrow basin filled with ponded sediments.

GEOPHYSICAL SURVEYS

Prior to drilling on the Japan Transect, a comprehensive program of geophysical and geologic surveying was carried out on the margin. The magnetic and gravity data and bathymetry and subbottom reflectors were mapped over the submerged area shown in Figure 1 along closely spaced lines, perpendicular to the contours (Honza, 1980). Several long lines of 24-channel seismic-reflection profiles were made across the Sanriku Deep Sea Terrace and trench by the Japan Exploration Co. (JAPEX), under contract to the Technology Research Center of the Japan National Oil Corporation, and two additional profiles were made later for the Ocean Research Institute (ORI-78-3 and 4, Nasu *et al.*, 1979 and 1980). A line made by the Shell Petroleum Company (P-849) was available to the scientists participating in the drilling program. The locations of these lines are in Figure 1 *a*.

The multichannel profiles provide the clearest representation of the structure of the margin ; tracings of time sections of lines 1 and 2 are shown in Figure 2. Reproductions of the processed multichannel seismic records can be found in the DSDP Initial Reports volume I of Leg 56 and 57 (Nasu *et al.*, 1980). A feature of particular interest to the subsidence history of the Deep-Sea Terrace is a prominent, angular unconformity that can be traced over most of the outer Deep Sea Terrace at a depth of 1 to 1.5 km below the seafloor. At site 439, this unconformity marks the boundary between flat-lying Neogene sediments and underlying Cretaceous deposits that are dipping landward. The tracings in Figure 2 show that some of the horizons in the Neogene section lap onto the unconformity. Von Huene *et al.* (1980) have interpreted this stratigraphy as indicating that the Cretaceous deposits were exposed above sea level during the Paleogene and subsequently subsided, allowing encroachment of the sea on the structural high. More direct evidence that the Cretaceous deposits were eroded subaerially comes from a study of the drill cores from site 439 where the unconformity was penetrated.

The acoustic reflector corresponding to the erosional unconformity can be traced well seaward of the trench slope break beneath the upper slope. In the vicinity of the midslope terrace, this reflector becomes less discernible, probably as a result of the numerous, closely spaced, normal faults that displace strata under the upper slope. Nonetheless, the unconformity can be traced with considerable confidence to the landward margin of the midslope terrace. At that point, the reflector is more than 6,000 m below sea level. Below the lower slope lies a mass of Neogene sediments that are being actively deformed by the forces associated with convergence of the Pacific and Asian plates. The midslope terrace, therefore, represents a fundamental tectonic boundary. The Cretaceous and older sediments that lie beneath the unconformity on the Sanriku Deep Sea Terrace are truncated at this boundary.

DRILLING RESULTS ON THE DEEP-SEA TERRACE

The westernmost DSDP sites on the Japan Transect (sites 438 and 439) are about 90 km west of the trench axis and landward of the trench-slope break (Fig. 1 *a*). This places them on a structural high, the Hachinohe Knoll, where the reflector corresponding to the erosional unconformity is within reach of the *Glomar Challenger's* drilling capability. Site 435 was drilled on the upper slope of the landward wall of the trench. The site has a water depth of 3,400 m and penetrated 250 m subbottom. The deepest samples obtained at site 435 are lower Pliocene.

Drilling at site 439 penetrated 1,157.5 m subbottom, and comparison of drill cores with the multichannel seismic profiles indicates that drilling penetrated the erosional unconformity. The deepest cores contained Cretaceous marine sediments. Overlying the Cretaceous deposits is a boulder conglomerate containing fresh, angular blocks of intermediate volcanic rocks. The size, angularity, and freshness of the blocks suggest that the source of these rocks was close to the site. Samples from the conglomerate that were dated radiometrically (Yanagisawa *et al.*, 1980) had crystallization ages of 22 to 24 m.y.b.p. The absence of marine fossils in the conglomerate suggests that it was deposited in a nonmarine environment.

A thick homogeneous sequence of Oligocene sandstone with well preserved pelecypods and gastropods overlies the

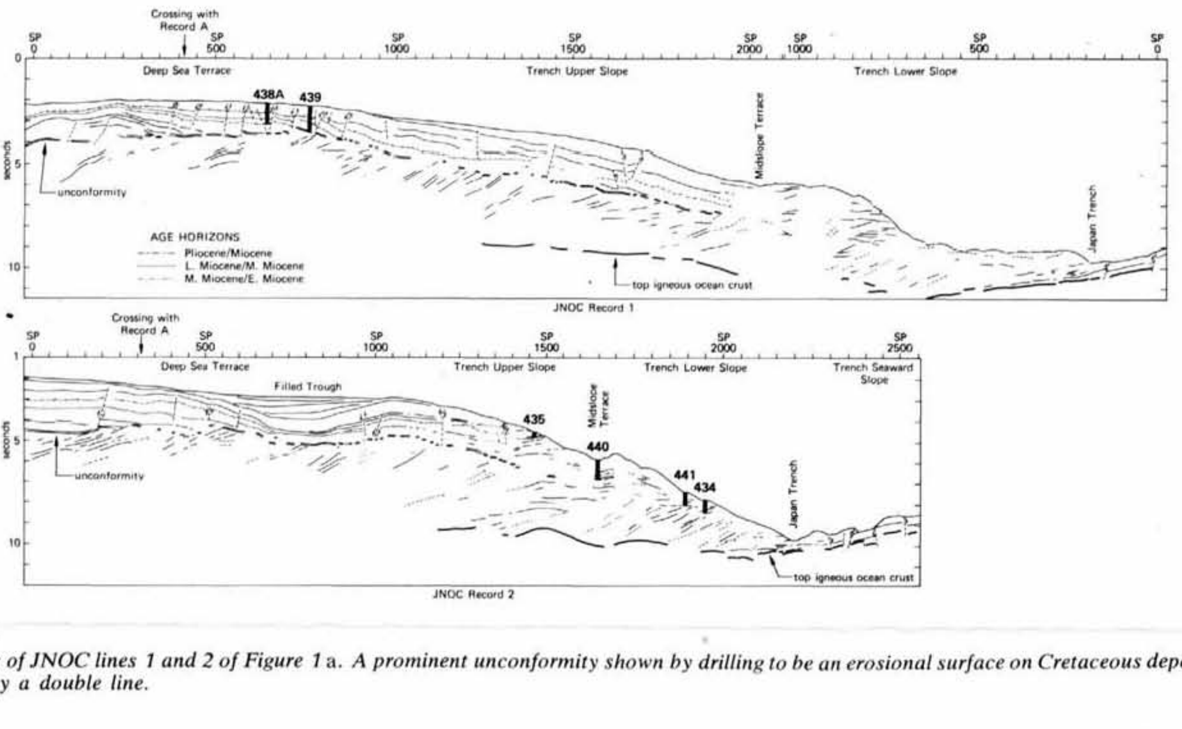


Figure 2

Tracings of JNOC lines 1 and 2 of Figure 1 a. *A prominent unconformity shown by drilling to be an erosional surface on Cretaceous deposits is shown by a double line.*

conglomerate. These strata were deposited in a shallow, high-energy marine environment. The Oligocene sediments are in turn overlain by a 1,000-m-thick sequence of Neogene sediments which grade from lower Miocene lithic wacke and lithic arenite at the bottom to Holocene fine grained diatomaceous siliceous mud at the top.

With this valuable section and the multichannel seismic profiles, it was possible for scientists of Leg 57 to reconstruct the late Tertiary history of the Sanriku Deep-Sea Terrace (von Huene *et al.*, 1978). During the late Paleogene, the land near site 439 stood above sea level as a paleolandmass, named by Leg 57 scientists the "Oyashio Paleolandmass". The paleolandmass is thought to have extended more than 50 km east of the present midslope terrace at the end of the Oligocene. At 24 to 22 m.y.b.p., intermediate volcanic rocks were extruded near sites 438 and 439 ; and the Oyashio Paleolandmass began to subside. The Neogene biostratigraphy and lithostratigraphy record a progressively deeper marine environment and more distal sediments. Benthic foraminifera in cores from sites 438 and 435 indicate that subsidence stopped toward the end of the Pliocene ; during the Pleistocene, the deep marine terrace was uplifted about 500 m (Keller, 1980).

The subsidence history is controlled only at the end points : the time of submergence, 22-24 MY, and the present depth of the Cretaceous unconformity. Intermediate points are estimated from depth ranges of benthic foraminifer assemblages in the stratigraphic column. In Figure 3, we show the subsidence history of the erosional unconformity at site 438/439, as a range of depths versus age. The depths have been corrected for sediment loading, assuming isostasy. Despite the uncertainties, it is clear that the subsidence of the Sanriku Terrace has been rapid. The rate is nearly 50 % higher than the subsidence of a typical midoceanic ridge (dashed line, Fig. 3).

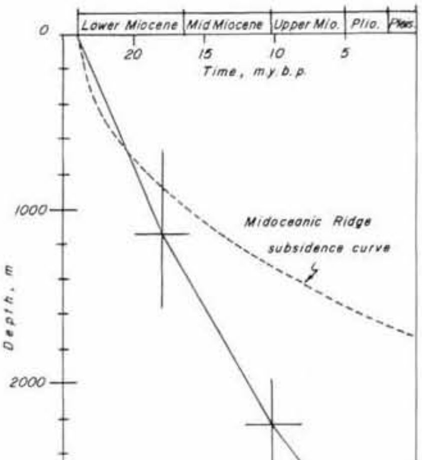


Figure 3

Subsidence curve of the Cretaceous unconformity at Site 438/439. The crosses at intermediate points are depth and age ranges indicated by benthic foraminifers.

CAUSE OF SUBSIDENCE OF THE DEEP MARINE TERRACE

It has been convincingly demonstrated that the subsidence of a midoceanic ridge results from thermal contraction of the lithosphere as it cools after formation at the ridge axis (Le Pichon, Langseth, 1969 ; Sclater, Francheteau, 1970). The cooling rate and, hence, the rate of subsidence are controlled by the thermal diffusivity of the lithosphere and initial temperature distribution. It seems reasonable to suggest that subsidence of the Sanriku Deep Sea Terrace is also due to cooling of the mantle below the forearc area of Japan. However, the subsidence rate, indicated in Figure 3, requires that the rate of mantle cooling must be greater than that provided by the conductive loss of heat at the surface. Faster cooling may be produced by mass transport of cold material into the mantle during subduction. This hypothesis leads us to suggest that the start of Neogene subsidence along the northeastern margin of Honshu marks the start of subduction in the vicinity of the present Japan Trench. Other factors that may contribute to the subsidence will be discussed in a subsequent section, but thermal cooling appears to be necessary for the amount of subsidence documented by the study of drill cores.

The start of subsidence in the forearc area of the present Japan Trench at the close of the Paleocene is coeval with other important geologic events in the Japan Island Arc. Primary among these is the start of active volcanism along the present magmatic arc to produce the pervasive Green Tuff. Evidence indicates that this volcanism, which is associated with subduction at the Japan Trench, began 25 m.y.b.p. (Cadet, Fujioka, 1980). During the Paleogene there is no geologic record of volcanic activity in Northern Honshu, and this absence may be taken as evidence that there was no active subduction during much of the Paleogene ; that is, no active subduction with the present geometry of the Japan Trench subduction regime. Second, evidence suggests that opening of the Sea of Japan began 25 to 30 m.y.b.p. For example, the heat flow through the floor of the Sea of Japan is well determined at about 95 mWm^{-2} (Yasui *et al.*, 1968 ; Watanabe *et al.*, 1977). This value is appropriate for lithosphere 25 to 30 m.y. old (e.g., Parsons, Sclater, 1977). The age deduced from the heat flow is supported by DSDP drilling in the Sea of Japan on Leg 31. The sedimentary accumulation rates at site 299 (Karig *et al.*, 1975), if extrapolated to the oceanic basement determined from seismic-reflection measurements, indicate an age of late Oligocene to early Miocene for the basal sediments. Thus, it appears that the motion that separated the Japanese Island Arc from the Asian Continental Massif occurred at about the same time that subsidence of the Oyashio Paleolandmass began.

COOLING DUE TO SUBSIDENCE

The initiation of subduction provides an efficient means to cool the mantle below the forearc area. As an example, we define a hypothetical model for the eastern Honshu margin. We assume that the thermal regime of the margin prior to the onset of subduction was appropriate for a stable 40-to 60 m.y.-old continental lithosphere, i.e., the surface heat-flow was about 70 mWm^{-2} (Polyak, Smirnov, 1968), then as the Pacific oceanic lithosphere began to underthrust the forearc area and penetrate the mantle, it carried with it low temperatures characteristic of 80-to 100-m.y.-old oceanic lithosphere. This "cold" lithosphere will displace the hot material in the mantle below the forearc area, causing a large decrease in mean temperature. This decrease, in turn, produces a net density increase of the upper mantle and commensurate subsidence of the forearc area.

An estimate of the amount of subsidence can be made by using any one of several numerical thermal models of subduction that have been developed over the past decade. We have chosen a model, recently developed by Hsui and Toksöz (1979), which is based on a kinematic model of subduction. This model simulates the start of subduction and includes effects of energy transfer by conduction, relative plate movements, and flow in the asthenosphere. In Figure 4 *a*, we show the thermal structure of a subduction zone based on a model that assumes a 100-km-thick lithosphere is being subducted at a rate of 10 cm/yr and is descending at an angle of 45°. Figure 4 compares the thermal structure for the static presubduction lithosphere with the structure after subduction has been underway for 20 m.y. After 20 m.y. of subduction, more than 2,000 km of lithosphere has been subducted. A large inversion in temperature has been produced by the intrusion of the oceanic lithosphere (Fig. 4 *b*). A profile of temperature difference between regimes before and after subduction down to 400 km is shown as a function of depth by the dashed line.

To estimate the change in elevation at this point, we consider a vertical column of mantle material, starting at sea level and extending to depth. We can calculate the change in length of that column, on the basis of its change in mean temperature, and the linear thermal expansion coefficient (3×10^{-5}°C^{-1} ; Skinner, 1969). Most of the temperature change occurs in the upper 200 km of the mantle. The models of Hsui and Toksöz (1979) predict a mean temperature change of about 370°C, which will produce a 1 % decrease in height in the column, or a 4-km shortening of a 400-km column. Further subsidence will result from loading by sediment and the water that floods the forearc once it subsides below sea level.

We use the Hsui and Toksöz numerical model simply to show that the amount of cooling caused by the start of subduction is of the right order of magnitude. The rough estimate of 4 km of subsidence is considerably greater than the observed 3 km of subsidence at site 439. However, the height of the column examined strongly affects the change in mean temperature that is calculated. We rather arbitrarily selected 400 km ; a different column height would produce a different change in temperature. In Figure 4 *a* the model predicts a significant upward counterflow of material in the asthenosphere below the slab. This flow is indicated by the upbowing of isotherms, and, as a result of this flow, higher temperature material is brought to shallower depths than before subduction started. The increase in temperature of the mantle below 400 km predicted by this model would partially compensate for contraction in the upper 400 km and yield a result more in agreement with the observed subsidence.

ELEVATION PROFILE OVER A SUBDUCTING SLAB

In the foregoing section, we assumed that changes in the surface elevation of a forearc reflect changes in mean temperature of the mantle, and we estimated the change in elevation at a single point 100 km from the trench axis over a subducting slab. The mean temperature of the mantle below the forearc varies greatly with distance from the axis, and therefore, these theoretical models predict an elevation profile over a trench as well. In Figure 5 *a* and *b*, we show theoretical topographic profiles across a trench-forearc complex before and after subduction. These profiles are calculated from the results of a computer model developed by DeLong *et al.* (1979). Their model uses a 5-km grid spacing and yields a detailed picture of the thermal regime in a subducting slab to a depth of 350 km. To compute the profile shown in Figure 5 *b*, we assumed that the mass of a 350-km vertical column of material below each point remains constant and that the crust below the forearc region is 25 km and has a density of 0.6 gm/cm^3 less than the mantle.

The resulting elevation profile suggests that two prominent features in forearc areas could result from changes in the thermal regime at depth. First, a downbowing of the forearc crust over the slab forms a "forearc basin" with a maximum depth of about 4 km, about 150 km from the trench. This is the point where the mean temperature of the upper 400 km decreases the most. Second, a "trench slope anticline" is produced near the edge of the forearc crust because the temperature change at depth due to subduction is less, on average, than at points farther from the trench. The temperature change is less because the oceanic lithosphere has not pentrated very deeply and, consequently, is replacing material with only slightly higher temperatures.

The rough estimates presented in the preceding discussion, based on published results of thermal models, suggest that surface elevation data and subsidence histories of forearc areas could be used to constrain many aspects of the

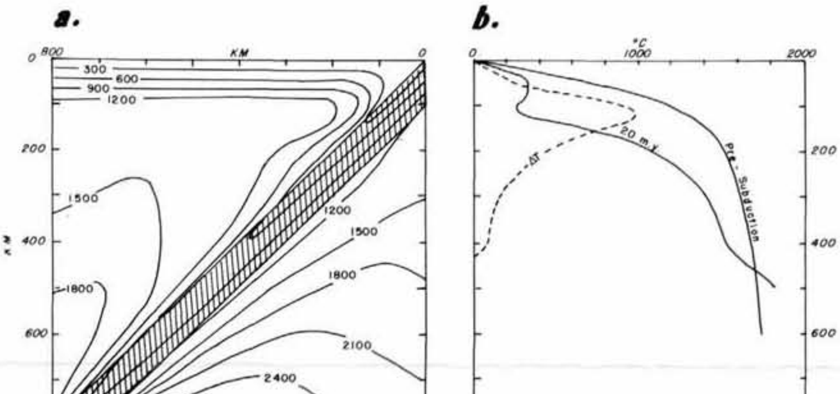


Figure 4

a. Isothermal structure below a subduction zone where subduction has been underway 20 MY (Hsui, Toksöz 1979).

b. Profiles of temperature before and after start of subduction beneath a point 100 km from the trench over the subducted slab. The dashed curve shows the difference in temperature.

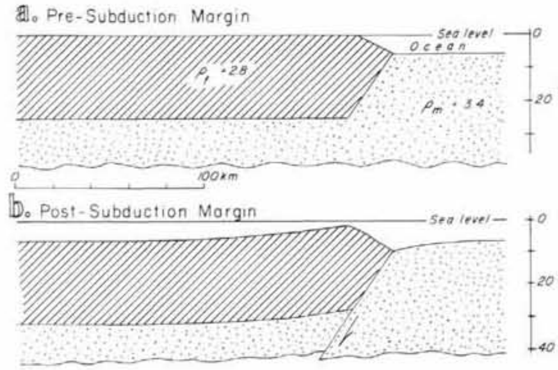


Figure 5
Elevation profiles before a *and after* b *subduction based on a thermal model developed by Delong* et al. *(1979).*

subduction process. To some extent, these relations have already been utilized by Delong and Fox to investigate changes in elevation and volcanic activity due to consumption of a ridge axis (Delong, Fox, 1977 ; Delong *et al.*, 1979). Thermal models, based on a kinematic description of the subduction process, also predict the variation of surface heat flow, free-air gravity, and geoidal heights, as well as the elevation of the earth's surface. To date, these constraints have not been used in concert to examine the validity of thermal models.

SUBSIDENCE DUE TO SUBDUCTION EROSION

Murauchi (1975) and Murauchi and Ludwig (1980) have proposed that subduction at the Japan Trench is eroding the forearc platform. In their model, erosion is occurring at the base of the overthrust wedge, where slabs of the platform crust are being sheared away and carried to depth. Interpretation of the multichannel seismic records and the stratigraphy at drill sites on the lower slope strongly supports active subduction erosion of the forearc crust (von Huene *et al.*, 1980). Tectonic erosion of the overthrust block has been inferred from geophysical and geologic data in other trenches (e.g. Rutland, 1971). Scholl *et al.* (1980) have recently compiled a bibliography on subduction erosion.

Subduction erosion leads to migration of the trench axis in the direction of underthrusting and, consequently, replacement of the forearc crust, which has continental densities, with oceanic crust and mantle. The process leads to the emplacement of a higher density material beneath the area of the forearc being eroded. Consequently, subsidence of the forearc will result from isostatic adjustments.

The subsidence rate is proportional to the rate of trench migration and can be roughly estimated if isostasy is assumed, even though trench areas are not in isostatic equilibrium. A simplified model for estimating the subsidence rate is shown in Figure 6. The trench axis, T, is assumed to migrate in the direction of underthrusting, at a rate v_T to a position T′, in a time interval Δt. The dip of the underthrusting lithosphere is θ, so that below point P the boundary between the forearc crust and the downgoing slab will move upward by an amount $v_T.\Delta t \tan\theta$. Assuming that each column, such as the one below point P, moves vertically to maintain the same mass to some compensation depth in the mantle, it can be shown that

$$\frac{\Delta e}{\Delta t} = v_T \tan\theta \left(\frac{\rho_m - \rho_f}{\rho_f - \rho_w}\right);$$

where $\Delta e/\Delta t$ is the rate for subsidence.

For the Japan Trench, reasonable values for the parameters lead to $\Delta e/\Delta t = 0.06\, v_T$. From this relation, it is clear that migration rates on the order of a few kilometers per million years or greater, would be required to produce significant subsidence rates. Migration rates of this order are compatible with the amount of forearc terrain that may have been eroded since the start of the Neogene (Murauchi, 1975 ; von Huene *et al.*, 1980). With this mechanism, subsidence occurs only beneath that part of the forearc crust that is in contact with the subducting slab ; region S in Figure 6. Although most of the evidence is indirect, strong arguments can be made that subduction erosion is occurring beneath the Japan Trench Forearc. If so, the shape of the inner wall is determined largely by the subduction-erosion mechanism. In particular, the downbowing of the Cretaceous forearc crust below the upper slope may be due to this process. That is, the leading edge of the forearc crust subsides, as the crust is progressively thinned by the stoping action of the underthrusting oceanic lithosphere, as suggested in Figure 6. As subduction erosion proceeds, the midslope terrace, the trench-slope-anticline, and the axis of the forearc basins will shift in the direction of underthrusting.

CONCLUSIONS

A study of drill cores from the forearc area east of Honshu reveals that the seafloor has rapidly subsided. This subsidence began at the close of the Paleogene and is contemporaneous with the start of volcanism to produce the Green Tuff Belts of northern Japan and with the opening of the Sea of Japan. The subsidence proceeded so rapidly that shelf sedimentation could not keep pace, resulting in the present deeply submerged Deep Sea Terrace and a trench slope formed of downbowed continental crust. We propose that this subsidence resulted primarily from the thermal effects associated with the start of subduction along, or near, the present loci of the Japan Trench, 25-30 m.y. ago.

Near the inner trench wall, other factors, such as subduction erosion of the forearc crust, may have contributed significantly to subsidence. The broader implication of this interpretation of the subsidence history of the Japan Trench margin is that subduction is not a steady-state process of the northeastern margin of Japan. There is no evidence of arc volcanism during the Paleogene and the margin appears to

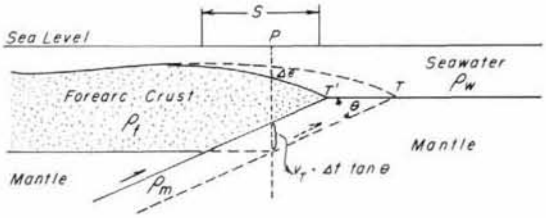


Figure 6
A simple isostatic model to illustrate how subduction erosion can cause subsidence in a forearc area. Point p *is fixed relative to the forearc. Crust below this point is thinned by subduction erosion as the trench migrates at a rate* v_T *from T to T′.*

have been a passive or possibly a transform margin. The tectonic evolution of areas of convergence is extremely hard to decipher because so much of the geologic record is destroyed by subduction. An investigation of vertical movement in forearc areas offers one means to establish a temporal framework for subduction events in the Tertiary.

Acknowledgements

This paper is based on only a fraction of the results of a huge effort on the part of the Deep Sea Drilling Project, the Japan Site Survey Committee, the Japanese National Oil Corporation, the Ocean Research Institute of the University of Tokyo, and many others to investigate the Sanriku Margin. We are deeply indebted to many persons who made this effort possible. In particular, we appreciate the help of Professor Yasufumi Ishiwada, Executive Director of the Japan Petroleum Development Corporation in obtaining the multichannel profiles. M. G. Langseth was supported by NSF grant OCE-79-19387. S. Delong, A. Watts and T. Engelder offered helpful criticisms of earlier versions of the manuscript.

REFERENCES

Cadet J. P., Fujioka K., 1980. Neogene volcanic ashes and explosive volcanism : Japan Trench transect, in : *Initial Reports of the Deep-Sea Drilling Project*, Leg 57, Vol. LVI-LVII, Part II, US Government Printing Office, Washington D.C., 1027-1041.

Delong S. E., Fox P. J., 1977. Geological consequences of ridge subduction, in : *Island arc, deep-sea trenches and back-arc basins*, edited by M. Talwani and W. C. Pitman III, Maurice Ewing Series, Vol. **1**, Am. Geophys. Union, 470 p., 221-228.

Delong S., Schwarz W. M., Anderson R. N., 1979. Thermal effects of ridge subduction, *Earth Planet. Sci. Lett.*, **44**, 239-246.

Honza E., 1978. Geological investigation of Japan and southern Kuril Trench and slope areas, GH 76-2 Cruise, April-June, 1976, *Geol. Surv. Jpn Cruise Rep.*, **7**, 1-127.

Honza E., 1980. Pre-site survey of the Japan Trench transect, in : *Initial Reports of the Deep Sea Drilling Project*, Vol. **LVI, LVII**, Part I, US Government Printing Office, Washington D.C., 449-458.

Hsui A. T., Toksöz M. N., 1979. The evolution of thermal structures beneath a subduction zone, *Tectonophysics*, **60**, 43-60.

Karig D. E., Ingle J. C. Jr *et al.*, 1975. Site 299, in : *Initial Reports of the Deep Sea Drilling Project, Vol. XXXI, Apra, Guam to Hakodate, Japan, June to August, 1973*, Nat. Sci. Found., Washington D.C., **10.**

Keller G., 1980. Benthic to foraminifers an paleobathymetry of the Japan Trench Area, in : *Initial Reports of the Deep Sea Drilling Project*, Leg 57, Vol. **LVI-LVII**, Part II, US Government Printing Office, Washington D.C., 835-865.

Larson R. L., Hilde T. W. C., 1975. A revised time scale of magnetic reversals for the Early Cretaceous and Late Jurassic, *J. Geophys. Res.*, **80**, 17, 2586-2594.

Le Pichon X., Langseth M. G. Jr, 1969. Heat flow from the mid-ocean ridges and seafloor spreading, *Tectonophysics*, **8**, 319-344.

Ludwig W. J., Ewing J. I., Ewing M., Murauchi S., Den N., Asano S., Hotta H., Hayakawa M., Asanuma T., Ichikawa K., Noguchi I., 1966. Sediments and structure of the Japan Trench, *J. Geophys. Res.*, **71**, 2121-2137.

Murauchi S., 1975. Crustal structure in the Philippine Sea, *Kaiyo-Kagaku* (Mar. Sci.), **7**, 537-542 (in Japanese).

Murauchi S., Ludwig Wm. J., 1980. Crustal structure of the Japan Trench : the effect of subduction of ocean crust, in : *Initial Reports of the Deep Sea Drilling Project*, Vol. **LVI-LVII**, Part I, US Government Printing Office, Washington D.C., 463-469.

Nasu N. et al., 1979. Multi-channel seismic reflection data across the Japan Trench, *IPOD-Jpn Basic Data Ser., No. 3*, Ocean Res. Inst., Univ. Tokyo, Japan.

Nasu N., von Huene R., Ishiwada Y., Langseth M., Bruns T., Honza E., 1980. Interpretations of multichannel seismic reflection data, Legs 56 and 57, Japan Trench transect, in : *Initial Reports of the Deep Sea Drilling Project*, Vol. **LVI-LVII**, Part 1, 489-504.

Parsons B., Sclater J. G., 1977. An analysis of variation of ocean floor bathymetry and heat flow with age, *J. Geophys. Res.*, **82**, 803-827.

Polyak B. G., Smirnov Ya. B., 1968. Relationship between terrestrial heat-flow and the tectonics of continents, *Geotectonics*, 205-213.

Rutland R. W. R., 1971. Andean orogeny and ocean floor spreading, *Nature*, **233**, 252-255.

Scholl D. W., von Huene R., Vallier T. L., Howell D. G., 1980. Sedimentary masses and concepts about tectonic processes at underthrust ocean margins, *Geology*, **8**, 564-568.

Sclater J. G., Francheteau J., 1970. The implications of terrestrial heat flow observations on current tectonic and geochemical models of the crust and upper mantle of the earth, *Geophys. J.R. Astron. Soc.*, **20**, 509-542.

Skinner B. J., 1966. Thermal expansion, in : *Handbook of physical constants*, Rev. edited by S. P. Clark Jr, **6**, 75-96.

Von Huene R., Langseth M., Nasu N., Okada H., 1980. Summary, Japan Trench transect, in : *Initial Reports of the Deep Sea Drilling Project*, Vol. **LVI-LVII**, Part I, US Government Printing Office, Washington D.C., 473-488.

Von Huene R., Nasu N. et al., 1978. Japan Trench transected, *Geotimes*, **23**, 16-21.

Watanabe T., Langseth M. G., Anderson R. N., 1977. Heat flow in back-arc basins of the Western Pacific, in : *Island arcs, deep sea trenches and back-arc basins*, edited by M. Talwani and W. C. Pitman III, Maurice Ewing Ser., Am. Geophys. Un., **1**, 137-161.