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BATHYMETRIC HIGHS AND THE DEVELOPMENT OF CONVERGENT PLATE BOUNDARIES

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Abstract. The distribution of great earthquakes along subduction boundaries shows a spatial correlation with the distribution of major bathymetric features of the underthrusting ocean floor. At locations where aseismic ridges, zones of seamounts or other bathymetric highs intersect active trenches, great earthquakes have occurred rarely if at all during recorded history. By contrast, nearly all segments of the margins opposite smooth, low-lying ocean floor have experienced at least one known large earthquake. In addition, locations where rises intersect trenches often show other evidence of modified subduction such as the absence or near absence of low-angle thrust-type focal mechanisms, gaps and irregularities in the line of active volcanoes and gaps in intermediate-depth hypocenters. One interpretation is that oceanic lithosphere varies significantly in average density and that aseismic ridges or other uplifted regions delineate relatively buoyant zones that resist subduction upon interaction with an active trench. Along some segments of convergent boundaries that are highly active as source regions of great earthquakes and tsunamis, there exists a profusion of ridges, scarps, deep-sea marine terraces or perched basins. Some evidence indicates that these morphologic features may be directly related to the occurrence of great shocks. Thus, the detailed bathymetry along the landward wall of trenches may constitute an invaluable guide to the long-term seismic and tsunamic regime.

Introduction

Along convergent boundaries wide variations are observed both in tectonic style and in the distribution of large shallow earthquakes. That is, along extensive segments of some island arcs great earthquakes were infrequent or absent during recorded history, and near many of these same segments Quaternary volcanism is largely absent.

Most of these areas of relative quiescence correspond spatially with locations where major bathymetric features of the underthrusting sea floor appear to be interacting with the convergent margin. Based, therefore, on a summary of evidence from most of the major subduction zones of the earth, we conclude that bathymetric highs within the sea floor are a major influence in the development of convergent plate boundaries.

Although the mechanism for this proposed interaction is not well understood, we prefer as a working hypothesis that aseismic ridges or other bathymetric highs may delineate zones of oceanic lithosphere that are buoyant relative to "typical" oceanic lithosphere. Such buoyant zones may resist subduction on interaction with an active trench. Under this hypothesis variations may exist in the average density or buoyancy of both slabs near the contact area. For example, an aseismic ridge might subduct partially to perhaps 100-150 km beneath an overthrusting continent whereas the same feature may subduct not at all on interaction with an oceanic island arc in the manner suggested by Vogt [1973] and Vogt et al. [1976]. While the evidence available to us does not fully establish the buoyancy hypothesis, this concept appears to explain at least some areas of severely modified subduction.

Modified Subduction

Western Pacific

The subduction zones along the western margin of the Pacific illustrate the variations in seismic-tectonic regimes that commonly occur where bathymetric features interact with active trenches. The distribution of great shocks, active volcanoes and major bathymetric features for the western Pacific are summarized in Figure 1.

From the figure wide contrasts are evident in both bathymetry and the rupture lengths of large earthquakes between the northern and southern parts of the plate boundary. Toward the north the ocean floor seaward of the trench is relatively low and smooth while the ocean floor east of the Mariana-Bonin zones is a region of nearly continuous seamounts, aseismic ridges and other bathymetric highs. Bathymetric charts with greater detail show an even more dramatic contrast than is indicated by the figure.

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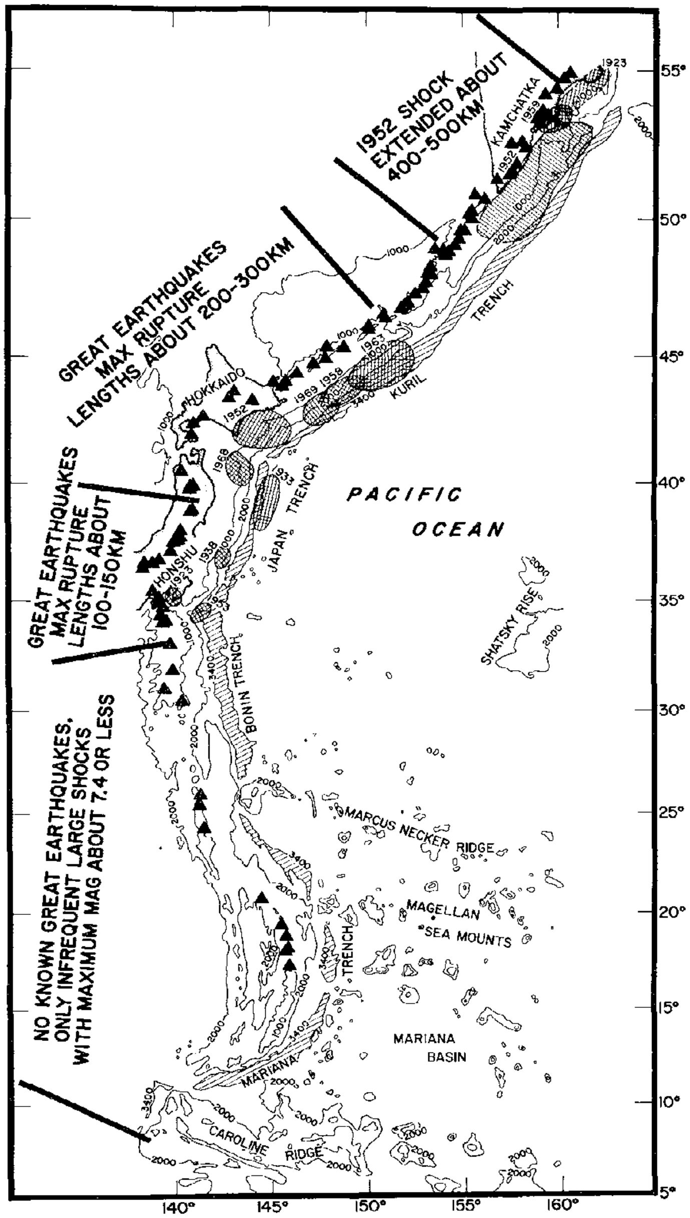

Figure 1. A comparison of bathymetry [Chase, 1970], rupture zones of large earthquakes (cross-hatching) and active volcanoes (solid triangles) along the western Pacific. Note the smooth ocean floor, large rupture zones and nearly continuous chain of volcanoes toward the north (Kamchatka-Kurile-Japan). Contrast these features with the irregular bathymetry, absence of great earthquakes and gaps and irregularities in the line of active volcanoes along the Bonin and Marianas arcs.

Near northern Japan-Kuriles-Kamchatka, opposite the low smooth sea floor, great shallow earthquakes are common, and many known shocks exceed 200 km in rupture length. Opposite the irregular sea floor toward the south earthquakes of such rupture lengths are unknown and even the shocks of magnitude about 7 are not frequent. (Richter [1958] lists one shock of magnitude 8.1 in 1902 but macroseismic evidence does not indicate that this event should be considered a great earthquake.)

Notice also from the figure the relatively continuous and linear chains of active volcanoes toward the north and contrast this with the gaps and offsets in volcanism in the south. This same pattern of gaps and offsets in active volcanism is observed near many other zones of interaction with ridges and seamounts.

Earthquakes, Tsunamis and Tectonics near the Japan Trench

Near the Japanese Islands, there exists a seismic-tsunamic record for about 1000 years or more which, while short geologically, is highly significant in that the record is equal to or greater than many recurrence intervals for great earthquakes. The record indicates distinctly different histories between adjacent regions of the Japan Trench i.e. regions which lie along the same plate margin. The area of northeastern Honshu, opposite the northern half of the trench, was subjected repeatedly to great earthquakes and destructive tsunamis. Toward the southern half of the trench, near a prominent zone of seamounts, the largest known shocks were only moderately large and destructive tsunamis originated rarely, if at all.

Figure 2 shows data for earthquakes, tsunamis and bathymetric features near the Japan Trench. The estimated rupture zones are characteristically larger north of about 38°N (Figure 2) and, while estimates are shown for only 50 years, the historic record clearly supports this interpretation [Musha, 1950; Utsu, written communication, 1975]. Tsunami source regions for about 70 years (Figure 2b) show a similar distribution which is also supported by extensive historic records [Iida et al., 1967; Hatori, written communication, 1975]. A prominent zone of seamounts appears to be interacting with the southern half of the trench while the sea floor tends to be smoother and low-lying opposite the northern half of the trench (Figure 2c). Thus, in this region where historic records extend back many recurrence intervals, there appears to be at least a spatial relationship between the morphology of the subducting sea floor and the distribution of great earthquakes and tsunamis.

Ryukyu Arc - Southwest Japan

For many hundreds of years, great shallow earthquakes have occurred regularly along the Nankai Trough near southwest Japan [Ando, 1975a, b]. Immediately southwest, however, along southern Kyushu and the central-northern

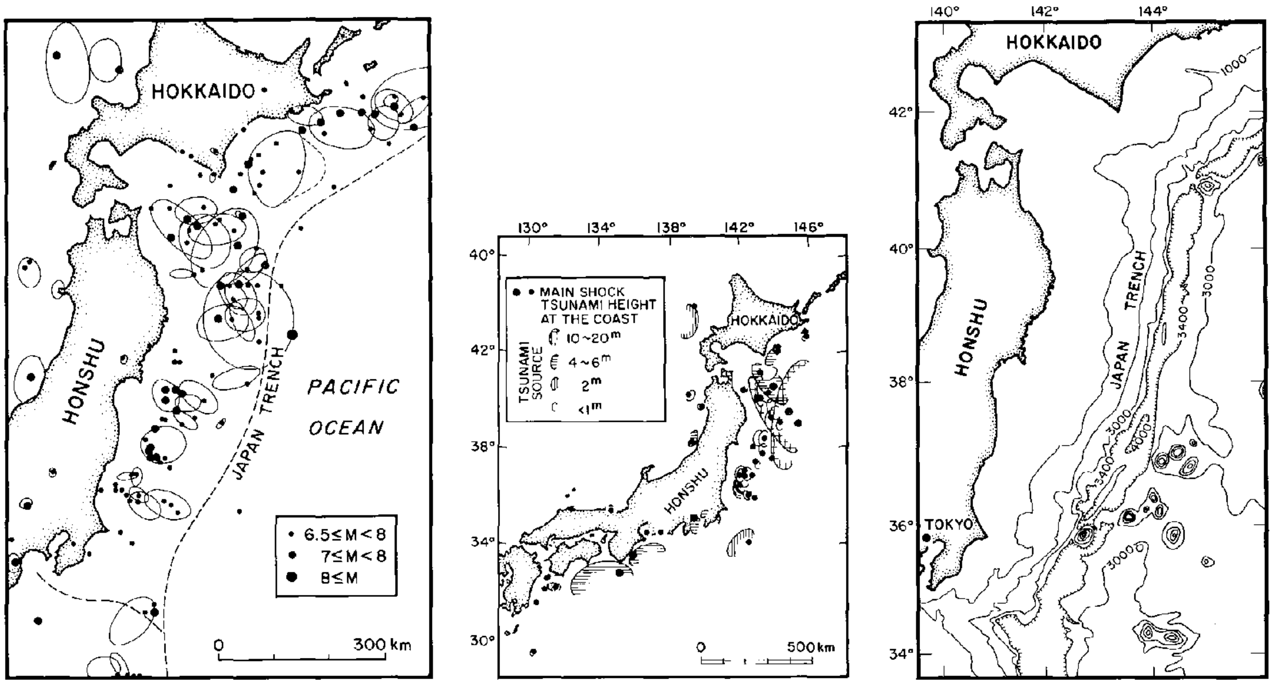

Figure 2. Seismicity and tectonics near the Japan Trench: 2a) Epicenters and focal regions of shallow earthquakes of magnitude 6.5 and larger from 1926 to 1973 after Utsu [1974]. Note the characteristically smaller focal regions near the southern half of the Japan Trench. 2b) Tsunami sources near Japan for 76 years (1893-1968) after Hatori [1969]. Distribution during past centuries was similar [Hatori, 1975]. Note large tsunami sources near northern half of Japan Trench. 2c) Bathymetry near Japan Trench after Chase et al. [1970]. Note zone of seamounts near southern half of trench and smooth ocean floor seaward of northern half of trench where great earthquakes and tsunamis have originated.

Ryukyu arc, great shallow earthquakes are unknown. Notice from Figure 3 that this striking change in the seismicity of great earthquakes occurs almost exactly where the Kyushu-Palau ridge intersects the plate margin near southeastern Kyushu. The change in seismicity is rather abrupt in space and consistent for 1000 years or more and suggests that the northeastern terminus of the Kyushu-Palau ridge is exerting a major influence on the tectonics of subduction near southern Kyushu.

The distribution of large earthquakes along the remainder of the Ryukyu arc also appears to be influenced by bathymetric features although the variations are less striking. Larger earthquakes, at least one (1771) of which was accompanied by a destructive sea wave and much loss of life, occurred near the southwestern end of the arc (Figure 3). By contrast the central portion of the plate boundary, from a point northeast of Okinawa to the intersection of the Kyushu-Palau ridge with the island of Kyushu, has experienced only occasional large earthquakes and these shocks provided no evidence of long rupture zones. Seaward of this central portion is a broad zone of irregular bathymetry with several aseismic ridges.

The active volcanoes along the island arc are, in this case, almost coterminous with the zone of irregular bathymetry on the sea floor seaward of the arc. This distribution is an exception to that found along most subduction zones and, perhaps, may be attributed to recent changes (1-2 my bp) in plate motion.

Other Subduction Zones

Most major subduction zones show the same distribution pattern as shown above: great earthquakes are infrequent or absent along those segments where significant bathymetric features appear to be interacting with the convergent margin [Kelleher and McCann, 1976]. By contrast most segments near regions of smooth, low-lying sea floor have experienced at least one large shallow earthquake.

The near absence of earthquake mechanisms indicating shallow-angle thrusting is another characteristic of convergent margins near major bathymetric highs. For example, Katsumata and Sykes [1969] found few such mechanisms along the Marianas-Bonin arcs whereas Stauder [1975], for a somewhat larger time interval, found numerous thrust-type mechanisms along the Hokkaido-Kuriles-Kamchatka zone (Figure 1).

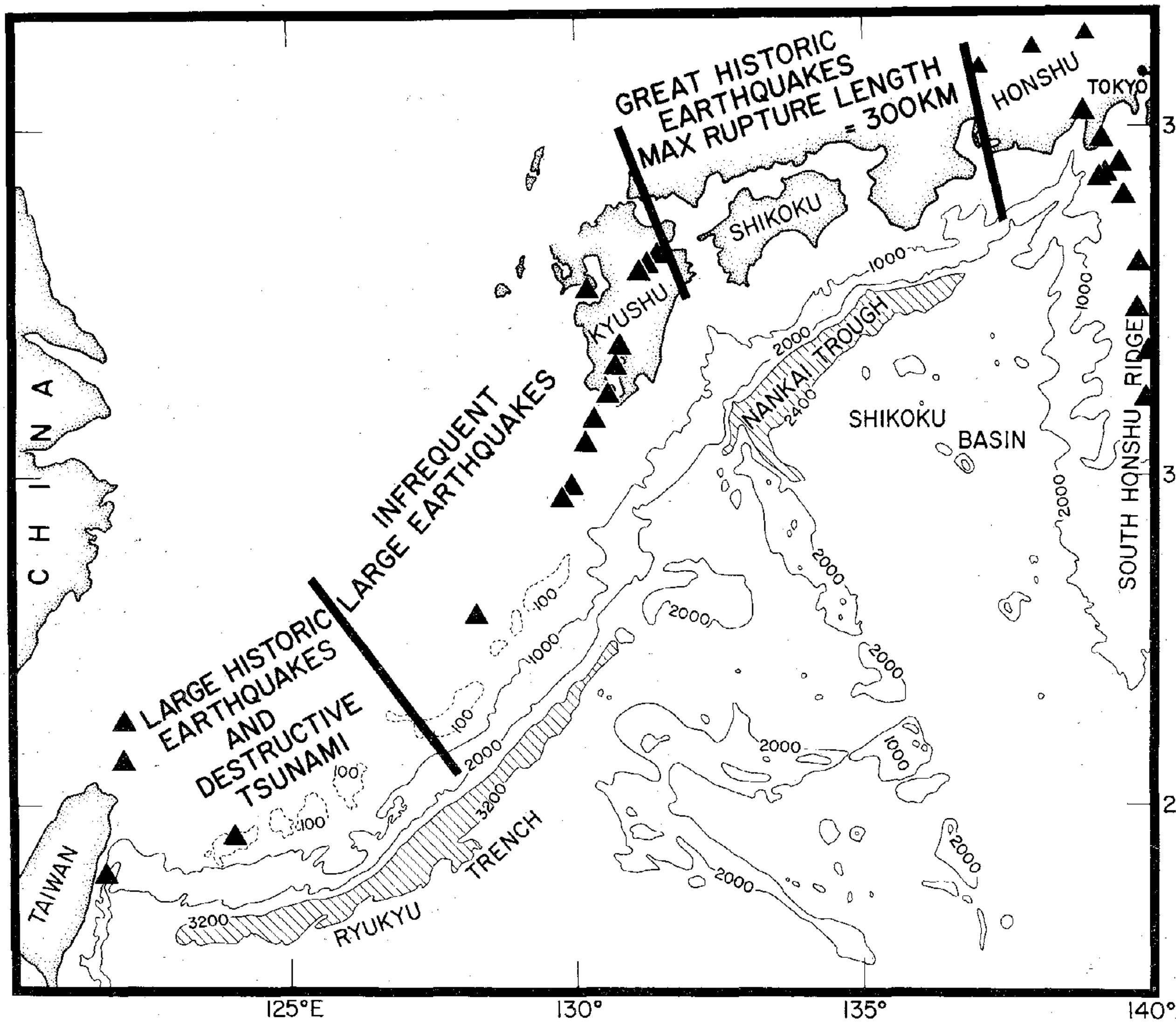

Figure 3. Bathymetry, large earthquake sources and active volcanoes along the Ryukyu arc-southwest Japan. Note the absence of great earthquakes near the zone of irregular bathymetry colliding at present with the central Ryukyus and part of Kyushu.

Crustal Roots and the Buoyancy Hypothesis

Nearly all aseismic ridges and other elevated features of the sea floor provide evidence of structural roots. Both the crustal velocities and depth to M discontinuity suggest a crustal structure intermediate between "oceanic" and "continental" regions of the crust. Because of the very small differences in density that are involved it is not possible to make a direct examination of the buoyancy hypothesis.

The data available at present, however, do not contradict the buoyancy hypothesis. In fact the typical dimensions observed for crustal roots appear to be consistent, based on current density estimates, with a tendency to resist subduction. Assuming an average difference of 0.7 gm/cc between oceanic crust and upper mantle, a 70 km thick lithosphere and no shearing of the ridge at the trench, then a difference in crustal thickness (i.e., increment caused by a crustal root) of 5 km or more would decrease average lithospheric density by about .05 gm/cc. This value, .05 gm/cc, is the approximate difference between subducting lithosphere and the surrounding asthenosphere by most estimates [Jacoby, 1970; Grow, 1973] and, thus, the buoyancy hypothesis is at least consistent with observations available at present.

Scarps, Ridges and Deep-Sea Terraces as Indicators of Seismic-Tsunamic Source Regions

Along some segments of subduction boundaries the morphology of the inner wall of the trench is distinguished by a highly developed series of ridges, scarps, deep-sea terraces or perched basins. Some of these same locations have an active seismic history including a record of one or more great shallow earthquakes accompanied by destructive sea waves. Thus, while the development of the inner wall may be dominated by the sediment supply, it is possible that large thrust earthquakes provide their own unique contribution to the evolving pattern of imbricate thrust faults described by Karig and Sharman [1975] and Seely et al. [1974].

The morphology of the inner wall, therefore, may yield important clues concerning the long-term seismic-tsunamic history of a particular section of the plate margin. Specifically, an extremely rough topography with numerous fresh scarps and ridges, and with well-developed deep-sea terraces or perched basins may indicate that the region is a prime source area for large earthquakes and tsunamis.

Although tsunamis are generated by earthquakes, the implications of a tsunami record differ slightly from those of a seismic record. That is, the generation of a seismic sea wave requires substantial deformation at the sediment-water interface. Thus, tsunamic source regions may be intimately related to the changes in trench morphology wrought by an earthquake, i.e., such source regions may be the submarine equivalent of zones of surface faulting on land. The following examples provide insight into the potential relationships among great thrust earthquakes, the accompanying sea wave and deformations of the sea floor.

1964 Alaskan Earthquake

During the 1964 Alaskan earthquake, rupture propagated about 800 km parallel to the trench axis, a largely underwater ridge or scarp formed which probably extended about 400 km (about 10-12 m vertical deformation), and a Pacific-wide sea wave was generated. The examination of these features by Plafker [1969] is indicated in Figure 4; the profiles in the lower figure indicate the mechanism of the ridge formation. The ridge or scarp can be taken as the axis of a broad zone of uplift and the formation mechanism is interpreted here as displacement on an upper branch of the pattern of imbricate thrusts.

Of interest to the present discussion are two considerations: 1) the mechanism of the ridge formation is clearly suitable as a first step in the formation of a deep-sea terrace or perched basin and 2) the length of the ridge is a significant fractional part of the total rupture length. Certainly deep-sea terraces or perched basins may evolve through mechanisms other than that suggested here. Nonetheless, the observed deformation for the 1964 earthquake would act as a sediment trap leading to basin or terrace development and if the same branch of the thrust fault system is activated repeatedly during recurring great earthquakes, then an even larger ridge or scarp would form.

The second consideration is obvious but nontrivial: larger ruptures would tend to be associated with longer ridges. That is, despite complications, a greater extent of surface breakage tends to accompany larger rupture zones [Tocher, 1958; Thatcher and Hanks, 1973]. Thus, if deep-sea terraces are related to large thrust earthquakes as suggested above, then it is quite likely that the larger thrust earthquakes are associated with larger basins or terraces.

Deep-Sea Terraces along the Japan Trench

Numerous deep-sea terraces have developed along the inner wall of the Japan Trench near eastern Honshu. The size and distribution of these terraces according to Iwabuchi [1968] are shown in Figure 5. The most striking feature

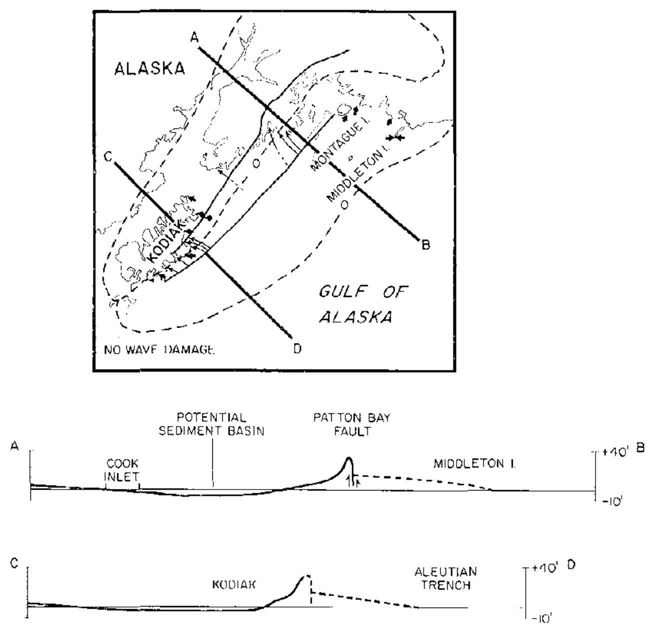

Figure 4. Land deformation and tsunami source region for the 1964 Alaskan earthquake after Plafker [1969]. In upper figure, zero isobase (dashed line) enclose axes of uplift and subsidence (solid lines). Direction (wide solid arrows) and estimated travel distance (narrow, larger arrows) of the sea wave are also indicated. Note that the ridge or scarp which formed during this shock (lower figure) is suitable as a first step in the formation of a deep-sea terrace.

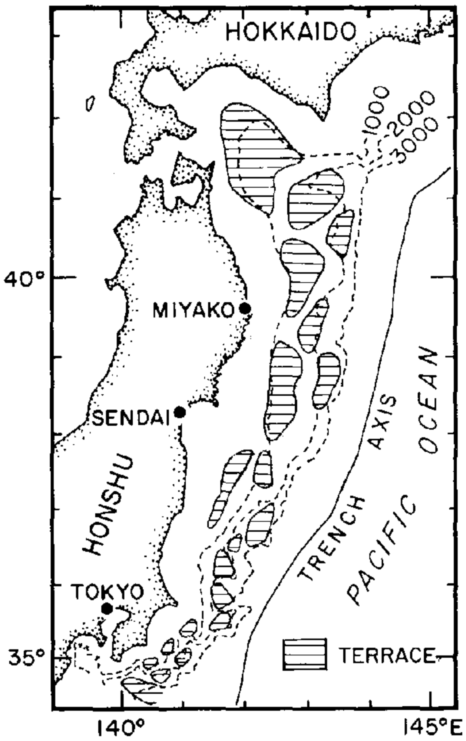

Figure 5. Deep-sea terraces near eastern Honshu after Iwabuchi [1968]. Note that characteristically larger terraces have formed near the northern part of the trench, the source for larger earthquakes and tsunamis (see Figure 2).

is the difference in size of terraces going from north to south. Most terraces north of about 38°N are significantly larger than those to the south.

Compare Figure 5 with the earthquake-tsunami distribution for the same region shown previously in Figure 2. The convergent margin near eastern Honshu presents a clear-cut example whereby larger seismic-tsunamic sources are at least spatially related to larger basins and terraces.

Other Examples of Possible Earthquake Morphology

The above discussion of the 1964 Alaskan earthquake and the margin near eastern Honshu are not isolated examples and numerous other instances can be cited where a profusion of ridges, scarps and terraces occur along margin segments that are active source regions for great earthquakes and tsunamis. The great Aleutian terraces [Marlow et al., 1973] occur near some of the largest known rupture zones [Sykes, 1971]. The source region of the tsunami generated by the 1946 Aleutian earthquake corresponds with the location of Unimak seamount. We suggest here that this "seamount" may be simply a striking indication of ridge formation. The great Mexican earthquake of 1932 (estimate of rupture zone in Kelleher et al. [1973]) appears to coincide with the large perched basin described by Ross and Shor [1965].

Along the Nankai Trough near southwest Japan a series of large deep-sea terraces (see Figure 19 of Yonekura, 1975) correspond almost exactly with the tectonic blocks which Ando [1975b] found to be associated with the recurring great earthquakes of southwest Japan. Recent detailed studies by A. Mogi and T. Sato of the Japanese Maritime Safety Agency (Mogi, 1976, unpublished data) show the inner wall of the Nankai Trough to be a succession of countless ridges and scarps which clearly diminish and possibly disappear near southern Kyushu. Notice from Figure 3 that great earthquakes and tsunamis are unknown near southern Kyushu where the Kyushu-Palau ridge interacts with the margin.

Summary and Conclusions

Major bathymetric features appear to exert a profound effect on the subduction process and may actually terminate the process either temporarily or permanently. Such features may delineate zones of lithosphere that are buoyant relative to typical oceanic lithosphere. Under this hypothesis of relative buoyancy the influence of bathymetric features on the subduction process is summarized in Figure 6.

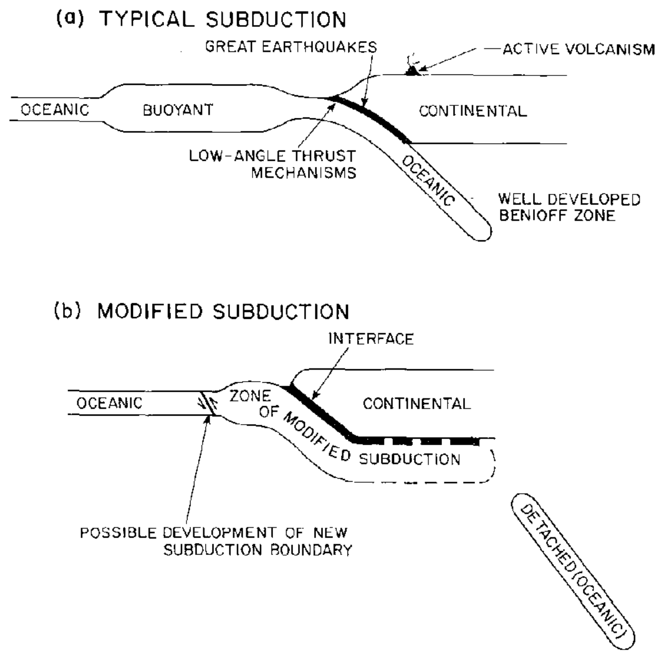

Figure 6. Speculative Summary of bathymetric features interacting with a subduction margin based on the buoyancy hypothesis. Note the inferred tendency toward quiescence upon interaction with buoyant zone i.e. large shallow shocks tend to be smaller (rupture length) and less frequent; volcanism may become inactive.

In Figure 6a the principal characteristics of typical subduction are indicated including active volcanism, great earthquakes, numerous low-angle, thrust-type mechanisms and a well-defined Benioff zone. Figure 6b suggests that the convergent margin is modified by interaction with a zone of buoyant lithosphere that resists subduction. A major effect is a tendency toward quiescence with large earthquakes becoming smaller and less frequent, and active volcanism diminishing or terminating. The leading, downdip slab of typical oceanic lithosphere may detach under these conditions and a new subduction boundary may eventually develop.

A rough topography along the inner wall including many scarps, ridges and terraces may indicate that the area is an active source region for great earthquakes and destructive tsunamis. Thus, the morphology of the inner wall may be a crucial guide to long-term seismic-tsunamic risk.

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