Tectonics in the Mariana Arc : results of recent studies, including DSDP Leg 60

DSDP
Tectonics
Mariana Arc

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Arc des Mariannes

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ABSTRACT

The results of recently completed geological and geophysical studies of the tectonically active portions of the Mariana Island arc system are described. Leg 60 of the Deep Sea Drilling Project, and the drill site selection cruises that preceeded Leg 60, provided the bulk of these new data.

The Mariana forearc region consists of remnants of the Palau-Kyushu Ridge (rifted in the Oligocene) and the West Mariana Ridge (rifted in the late Miocene-early Pliocene), partially covered by modern arc sediments and volcanoes. The forearc is disrupted by apparent normal faults and vertical tectonic movement that ultimately produces net subsidence, with the degree of faulting and subsidence increasing closer to the trench. No compressional features are observed, even close to the locus of plate convergence in the trench. No evidence for accretion of Pacific ocean plate material onto the Mariana forearc was found. Instead, the proximity of old arc rocks to the trench and the apparent overall subsidence of the Mariana forearc suggest that it is being tectonically eroded by the subduction of the Pacific lithospheric plate.

Volcanism in the Mariana arc system seems to be continuous since Eocene, although periods of possible increased or decreased levels of volcanic activity can be interpreted from the drilling results.

The hydrothermally active Mariana Trough has been opening for at least the past 5 MY at a half rate of 1.5-2.0 cm/yr, and is now spreading roughly east-west with a recognizable spreading center/transform fault geometry from an axial graben near 18 °N latitude.

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RÉSUMÉ

Tectonique de l'arc des Mariannes : résultats de travaux récents, notamment du Leg 60 du DSDP.

Les résultats d'études géologiques et géophysiques récemment menées sur les parties tectoniquement actives du système de l'arc insulaire des Mariannes sont décrits. Le Leg 60 du Projet de Forages Profonds et les croisières préparatoires à la sélection des sites de forage qui ont précédé ce Leg, ont procuré l'ensemble de ces données nouvelles.

La région du *forearc* des Mariannes se compose des vestiges de la ride de Palau-Kyushu (séparée par rifting à l'Oligocène) et de la ride Ouest-Mariannes (séparée au Miocène terminal-Pliocène inférieur), partiellement couverts par des sédiments de l'arc récent et des volcans.

Le *forearc* est affecté par des failles normales et par des mouvements tectoniques verticaux qui entraînent enfin une nette subsidence ; l'intensité du faillage normal et la subsidence augmentent en allant vers la fosse. On n'observe aucune figure de compression, même au plus près du point de convergence des plaques dans la fosse. On n'a pas trouvé de signes d'accrétion du matériel de la plaque pacifique contre le *forearc* des Mariannes. Par contre, la proximité des séries de l'arc ancien avec la fosse et l'apparente subsidence générale du *forearc* des Mariannes suggèrent qu'il est soumis à une érosion tectonique due à la subduction de la plaque lithosphérique pacifique.

Le volcanisme dans le système de l'arc des Mariannes semble être continu depuis l'Éocène, bien qu'il soit possible de distinguer, d'après les données de forages, des périodes où le niveau d'activité volcanique a augmenté ou, au contraire, diminué.

Le bassin des Mariannes, avec son hydrothermalisme actif, s'est ouvert depuis au moins 5 millions d'années au demi-taux de 1,5-2 cm par an ; il s'ouvre actuellement approximativement selon une direction Est-Ouest, avec une géométrie reconnaissable comme un système zone d'accrétion/faille transformante, à partir d'un graben axial situé à environ 18° de latitude Nord.

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INTRODUCTION

The Mariana Arc system comprises several major north-south tectonic features which are forming as a result of the convergence of the Pacific and the Philippine lithospheric plates. From east to west, the most conspicuous of these active features are (Fig. 1) the Mariana Trough. Perhaps equally important, but less well-defined, tectonic features are the west edge of the Pacific plate, which has been drastically bent and broken prior to and after subduction, and the Mariana forearc between the trench and the axis of present arc volcanism. The forearc is also an area of intense faulting and crustal disruption and may have been the focus of recent volcanism.

Figure 1
Location map of trench and major ridges and basins of the Mariana Island arc system. Boxed area is region described in this paper.

For over a decade the Mariana Arc system has been the subject of considerable geologic and geophysical study because it is a relatively uncomplicated example of a particular tectonic component — the convergence zone between two purely oceanic plates. Karig (1971) presented a model for the geologic evolution of the region that has been the framework for subsequent studies. He suggested that the active volcanic areas that form above subduction zones sometimes split longitudinally. New seafloor crust is then generated in the extensional basins formed by this rifting. As these backarc basins enlarge, the inactive, remnant parts of the original arc move away from the still-active volcanic arc above the subduction zone. In the Mariana system, this sequence of events has occurred twice. First, an original Eocene island arc split and left a remnant arc (the Palau-Kyushu Ridge) behind an extensional backarc basin (the Parece Vela Basin). Then, late in the Miocene, the active volcanic arc rifted a second time and another backarc basin (the Mariana Trough) was formed, separating the remnant West Mariana Ridge and the presently active Mariana Island arc. This latest rifting is still in progress.

Because of its conceptual simplicity, and because of the many questions it raises about magma genesis, island arc structure, and the stresses and mechanisms involved in arc formation and rifting, Karig's model produced increased interest in the Mariana region. Both the SEATAR project (an internationally sponsored program of geologic and geophysical transects funded in the United States by the International Decade of Ocean Exploration) and the International Phase of Ocean Drilling (IPOD) of the Deep Sea Drilling Project (DSDP) planned studies of the Mariana Arc system along east-west transects at approximately 18 °N latitude. Several geology and geophysics cruises from the Hawaii Institute of Geophysics, Scripps Institute of Oceanography, and Lamont-Doherty Geological Observatory, as well as four months of deep-ocean scientific drilling (Legs 59 and 60) have been concentrated along this latitude during the past five years.

This paper is a progress report on the results of the tectonic aspects of these recent studies. We will restrict the discussion to the active eastern part of the transect (boxed area in Fig. 1). The authors were co-chief scientists on IPOD Leg 60, which sampled the Mariana Trench, forearc, and backarc basin, so we will emphasize particularly the results of this drilling.

SCIENTIFIC OBJECTIVES

The scientific objectives of the conventional research cruises were generally the same as those of the IPOD drilling. In fact, many of the cruises were drill site selection surveys.

The Pacific plate east of the Mariana Trench was studied to determine its age and crustal structure and was drilled to provide a section of sediment and upper crustal rocks that could be used as a reference of the material being delivered to the trench.

Studies of the Mariana arc and forearc, from the trench axis to the volcanic islands, were primarily directed toward determining the volcanic and tectonic history of the region. Although the general morphology of the arc-side trench wall was known, it was not known what portion, if any, of the forearc is composed of island arc volcanic rocks and what is Pacific sediments and rocks that have been scraped off the subducting plate and uplifted and accreted into the overriding Mariana forearc.

In the backarc basin, data were collected to help define the spreading, subsidence, and sedimentation history of the Mariana Trough. It was hoped that in addition to determining the age and rate of rifting, the geometry of the spreading could be defined to decide if these basins were opening from a stable spreading-ridge/transform fault system analogous to mid-ocean basin spreading centers. Are these small backarc basins similar to the basins that exist during the initial rifting stages of major ocean basins ?

Pacific plate

The Pacific plate just east of the Mariana Trench is shown as part of the Mesozoic quiet zone in Pacific-wide magnetic anomaly compilations such as that by Hilde *et al.* (1977). An apparent magnetic anomaly stripe was, however, found by Hussong (in press) during IPOD drill site surveys. Although the anomalies have not been identified, their orientation suggests that they may be the same Mesozoic sequence identified by Hilde *et al.* (1976) as the Japanese sequence.

Crustal structure in the area was determined by LaTraille and Hussong (1980) ; who found that the total thickness (6.8 km beneath 5.5 km of water) was similar to the average thickness of younger oceanic crust, but that the deeper layers 2 and 3 were thin. Layer 2A was, however, unusually thick, perhaps because of mid-plate volcanism (the area is part of the Magellan Seamount province) or the occurrence of very thick chert layers.

The bathymetry and generalized crustal structure of the tectonically active part of the Mariana arc system are shown in Figure 2, along with IPOD Leg 60 drill sites. This figure is a revised version of a similar block diagram published by Hussong, Uyeda *et al.* (1978).

During IPOD Leg 60, two holes were drilled at one location (site 452) on the Pacific plate (Table, Fig. 3) about 75 km east of the Mariana trench axis. Impenetrable cherts of probable Campanian age prevented further drilling after less than 50 m of Neogene sediment was cored. As the first reports of Leg 60 (Hussong *et al.*, 1978) pointed out, this site was one of 16 in the far western Pacific with a Cretaceous-Neogene disconformity. Because there is Neogene, and virtually no Paleogene, sediment on the deep sea floor in the western Pacific, if any sediments of these ages were found on the island arc side of the Mariana Trench, it is likely that they were not derived from the subducting oceanic plate.

Mariana Trench

A typical single-channel airgun seismic reflection profile across the Mariana Trench and forearc is shown as Figure 4 A. From east to west, note the development of horst and graben topography on the surface of the Pacific lithospheric plate as it bends prior to subduction. Note also the absence of any turbidite fill in the trench axis. No sediment ponds were found anywhere in the trench axis between 17°15'N and 18°15'N latitude, and almost no sediments were located anywhere on the inner (island arc) wall of the trench. The first clearly defined sediments were not observed until west of the trench slope break, at a depth in Figure 4 A of about 5.4 sec. (4,100 m). To the north and to the south of this figure, far more bathymetric relief was

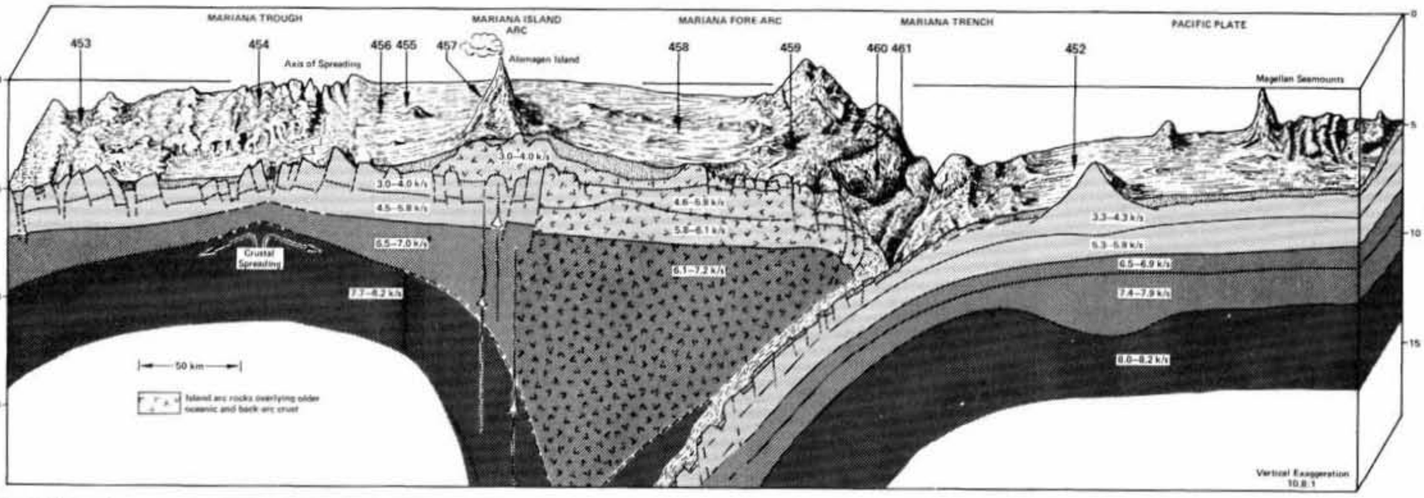

Figure 2

Physiographic diagram and generalized crustal structure of the tectonically active portion of the Mariana Island arc system, from Hussong (in press). Locations of DSDP Leg 60 drill sites 452 through 461 are indicated.

Table

DSDP Leg 60 drilling results

Hole	Environment	Latitude (N)	Longitude (E)	Water depth (m)	Total penetration (m)	Penetration into igneous basement (m)	Age of deepest sediments
452	old ocean basin	17°40.2′	148°38.7′	5858	28.0	—	Pleistocene
452A	old ocean basin	17°40.2′	148°38.8′	5863	46.5	—	Campanian
453	back-arc basin	17°54.4′	143°41.0′	4693	605.0	149.5	Earliest Pliocene
454	back-arc basin	18°00.8′	144°31.9′	3819	38.5	—	Late Pleistocene
454A	back-arc basin	18°00.8′	144°31.9′	3819	171.5	22.5*	Early Pleistocene
455	back-arc basin	17°51.3′	145°21.5′	3468	104.0	—	Early Pleistocene
456	bac-arc basin	17°54.7′	145°10.8′	3591	169.0	55.0	Early Pleistocene
456A	back-arc basin	17°54.7′	145°10.9′	3591	159.0	41.0	Early Pleistocene
457	active volcanic arc	17°50.0′	145°49.0′	2637	61.0	—	Late Pleistocene
458	fore-arc	17°51.8′	146°56.1′	3450	465.5	209.0	Early Oligocene
459	fore-arc	17°51.8′	147°18.1′	4130	3.5	—	Recent
459A	fore-arc	17°51.8′	147°18.1′	4120	67.0	—	—
459B	fore-arc	17°51.8′	147°18.1′	4115	691.5	132.5	Pre-late Eocene
460	inner trench wall	17°40.1′	147°35.9′	6451	85.0	—	Eocene
460A	inner trench wall	17°40.0′	147°35.2′	6443	99.5	—	Quaternary, reworked Eocene
461	inner trench wall	17°46.1′	147°41.2′	7029	20.5	—	Quaternary, reworked Eocene
461A	inner trench wall	17°46.0′	147°41.3′	7034	15.5	—	Quaternary, reworked Eocene

*interbedded basalt and sediments encountered from 67 to 149 m below the sea floor.

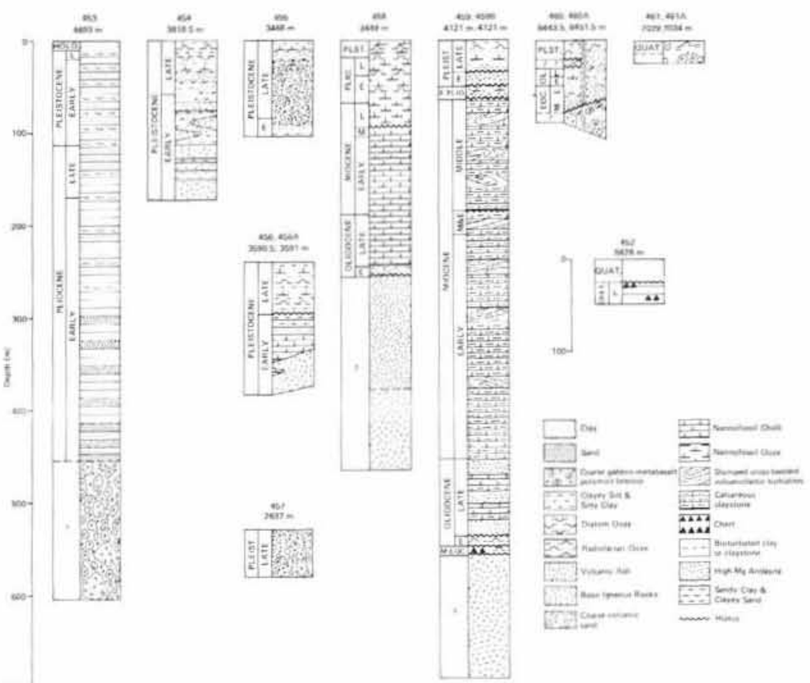

Figure 3
Lithologic columns for sites drilled on DSDP Leg 60.

observed on the forearc near the trench slope break. Note, for instance, the forearc seamount in Figure 2, which rises about 2,500 m above the surrounding sea floor. The origin of this feature, which has the general conical shape of a volcano, is unknown.

Two IPOD sites with two holes at each site, were drilled on the inner wall of the trench. At site 460, an 85-m-deep cored section revealed Pleistocene oozes overlying Eocene and Oligocene sediments. The calcareous nature of these Paleogene sediments suggests that they had subsided to their present depth of over 6 km after deposition above the carbonate compensation depth. A second hole at this site, hole 460 A, retrieved reworked and mixed sediments containing microfossils of all ages from Quaternary through Eocene.

Site 461, at a water depth of over 7 km, is the deepest site ever drilled in the ocean. Unfortunately, the penetration at the two holes attempted was very disappointing. Recovered

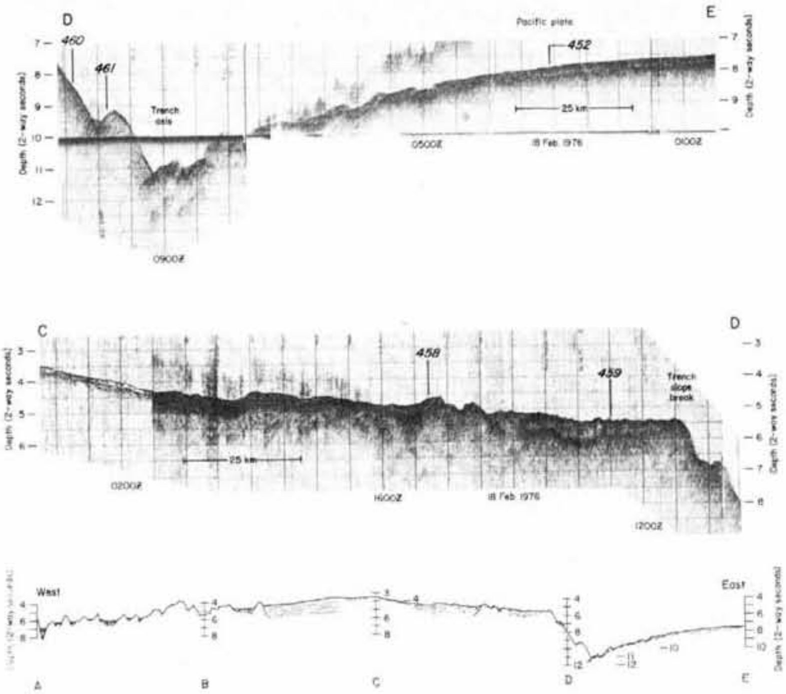

Figure 4 A

Single-channel reflection seismic profile across the Mariana trench and fore-arc region acquired by the Hawaii Institute of Geophysics during a drill site selection cruise (KK 760103 Leg 2). DSDP Leg 60 drill sites 452 and 458-461 are not on this profile, but are indicated at positions projected on to the profile. Note, on profile D-E, the development of tensional upper crustal faulting as the Pacific lithospheric plate is bent prior to subduction. On profile C-D the fore-arc is disrupted by small high-angle (presumably normal) faults that increase close to the trench.

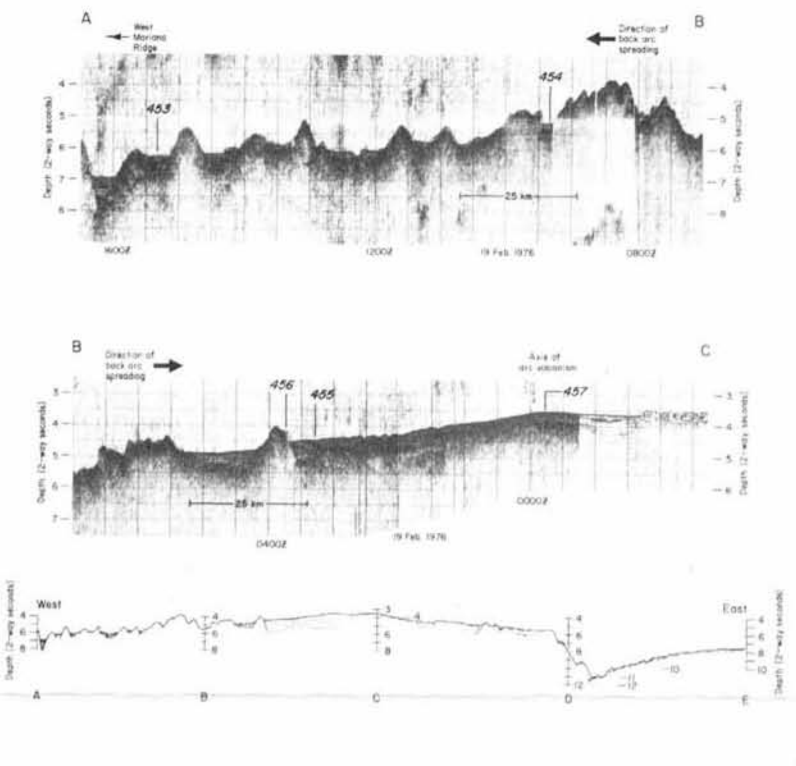

Figure 4 B

Continuation of seismic reflection profile shown in Figure 4 A. The axis of back arc spreading is approximately at point B.

were apparent olistostrome deposits, consisting of redeposited and mixed Cenozoic and Mesozoic sediments, as well as cobbles of igneous and metamorphic rocks. The Mesozoic fossils were apparently redeposited from nearby outcrops and include Late Cretaceous radiolarians in holes 460 A and 461, and Upper Jurassic calpionellids in hole 460 (Azema, Blanchet, in press).

At both sites 460 and 461, a polymict assortment of basalt, metabasalt, bronzite-andesite, and gabbro cobbles and fragments were cored. All of these rocks seemed to be debris mixed in with sediments and do not necessarily represent basement material. Chemically, all the rocks that were analyzed have island-arc, as opposed to ocean crust, affinities (Wood *et al.*, in press).

In addition to the chemical characteristics of the rocks, the age distribution and character of the fossils and the common calcareous sediments recovered from sites 460 and 461 suggest that all the material recovered from the inner wall of the trench came from the island arc. No evidence was found for accretion of ocean plate sediments to the overriding plate.

Mariana Arc and Forearc

Geophysical surveys on the Mariana forearc revealed thick sediments, commonly over a kilometer thick, overlying basement with velocities of 3.0-5.8 km/sec. (LaTraille, Hussong, 1980). This basement probably consists of arc volcanic rocks and intrusive igneous rocks. LaTraille and Hussong (1980) interpreted a layer with velocities of 6.1-6.5 km/sec. at sub-bottom depths of 4 to 5 km, that they suggest is the original backarc basin of oceanic crust upon which the arc volcanic rocks erupted. Occasional short-wavelength, high-amplitude gravity anomalies, such as identified but not interpreted by Sager (1980), may be caused by volcanic rocks that have been buried or partially buried by the forearc sediments.

The structure of the steep inner wall of the trench is poorly defined by seismic profiles. West of the trench slope break, however, where the seafloor is flatter, surface and subsurface structures are clearly delineated. Surprisingly, the forearc seafloor is dominated by extensive high-angle, normal faults as close as 30 km to the locus of plate convergence in the trench axis. These faults can be seen on the forearc in Figure 4 A, but are more readily seen in migrated multi-channel seismic reflection data (Fig. 5). Mrozowski and Hayes (1980) found the faults generally to parallel the strike of the arc, to have offsets ranging from 10 m to 200-300 m, and to extend in many places through the sediments and into the basement.

Two sites (458 and 459) were drilled on the forearc, and a third site (457) was drilled on the volcanic axis of the arc (Fig. 2). Site 457, on the slope of Alamagan Island, was of little value in that it was not possible to penetrate the recent coarse pyroclastic sand that blankets the region.

Drilling at both site 458, on a local 40-mgal gravity high that Hussong and Fryer (in press) suggest may be a buried volcanic pile, and site 459, just west of the trench slope break (Fig. 4 A), produced thick sediments and substantial sections of igneous basement (Table ; Fig. 3). On the basis of these cores, the IPOD Leg 60 scientists developed a sedimentary history for the forearc (Hussong *et al.*, 1978 and in press) that we will summarize. The basal sediments at both forearc sites are coarse, highly altered volcaniclastic

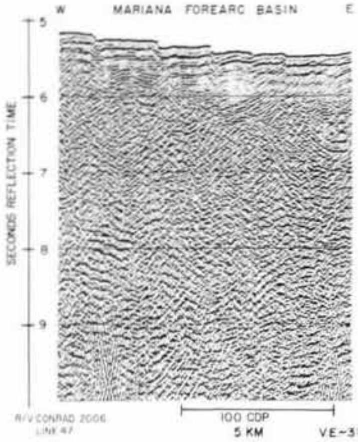

Figure 5

Enlargement of a portion of a multi-channel seismic reflection profile acquired by Lamont-Doherty Geological Observatory. The profile is on the fore-arc near DSDP site 459 (between 1130 Z and 1200 Z on profile CD, Fig. 4 A). The profile has been stacked and migrated to show the normal faults which are down-dropped on the east, toward the Mariana trench. Profile from Mrozowski and Hayes (1980).

debris deposited on island-arc-related volcanic basement in the early Oligocene at site 458, and the Eocene at site 459. From these beginnings to the middle Miocene, nannofossil chalks were being formed at site 458, whereas thick turbidites accumulated at site 459. The apparently undisturbed calcareous and vitric mud was being deposited during the same period at site 460, after which this trench wall site subsided to its present depth. The sedimentary sequences in both sites 458 and 459 have several hiatuses that are generally independent of each other except the prominent hiatus from late Miocene to Pliocene. The forearc sites then show an increase in biogenic sedimentation in the Pleistocene that, by recent time, had become primarily siliceous ooze.

As suggested in the Leg 60 Initial Reports Volume (Shipboard Party, in press), the sedimentary history of the forearc sites is strongly influenced by tectonic events. The Oligocene-Miocene chalks at site 458 appear to have been deposited near the equator. There are no turbidites at site 458, and the dominant chalk deposits in that hole suggest that the site was on a local bathymetric high, or uplifted part of the forearc. In contrast, thick turbidites at site 459 indicate that this part of the forearc was subject to subsidence relative to its surroundings (or uplift of the surrounding area), particularly during early Oligocene and Miocene times. At both sites, local sediment reworking and redeposition occurred at all times, even during the relatively quiescent chalk deposition at site 458. This reworking may be an effect of the dominant faulting observed in the seismic reflection profiles in the area.

The deeper, more consolidated, sediments at site 459 (and to lesser extent at site 458) were fractured and faulted. The dominant small-scale normal faulting observed in the cores supports the conclusion from the surface geophysical observations that the forearc is under tension.

Thin ash layers, and abundant volcanic glass, occur throughout the forearc sediment sections, although they are less apparent in the Oligocene ; their presence suggests nearby volcanic activity.

The upper 130 m of igneous basement at site 458 consists of bronzite- and clinopyroxene-bearing, nearly plagioclase-free lavas which resemble high-magnesian andesites found associated with boninites, an unusual and rare rock type found in some island arcs (Meijer *et al.*, in press). Chemically, these rocks are reported by Wood *et al.* (in press) to have Ni (60-100 ppm), Cr (170-300 ppm), and MgO (6.1-9.2 %), but low TiO_2 (0.28-.51%) and Zr (29-51 ppm), even though the SiO_2 in the rocks is high (52-54 %). Deeper in hole 458 these distinctive andesites are interbedded with two-pyroxene basalts which Wood *et al.* (in press) show are chemically similar to the tholeiitic basalts which dominate the site 459 basement and are typically found in island arcs.

The nearly 130 m of igneous basement cored at site 459 consists of vesicular, clinopyroxene-plagioclase, tholeiitic basalts in pillow lavas, flows, and possible sills. These basalts are high in SiO_2 (51.1-58.6 %), are quartz-normative, and have low TiO_2 (0.7-1.2 %), Ni (11-57 ppm), and Zr (36-73 ppm) as measured by Wood *et al.* (in press). The rocks also show a range of iron enrichment (Fe_2O_3 at 9.8-13.6 %) indicating that they are highly fractionated at typical values for island arc tholeiites.

The igneous rocks at sites 458 and 459 are highly fractured and altered to smectite-phillipsite assemblages. Natland and Mahoney (in press) found secondary palygorskite and celadonite in site 459 basalts which they suggest formed during an early oxidative stage of hydrothermal alteration.

Heat flow was measured by Uyeda and Horai (in press) in the holes at both sites 458 and 459, and in both it was below 1 HFU.

Bleil (in press) measured remnant magnetism in the igneous basement of the forearc sites. He found nine separate magnetic units with distinct inclinations in hole 458 — five in the high-magnesian andesites and four in the arc-tholeiitic basalts. Although some of these different units may be caused by displacement due to faulting, many correspond to chemical units in the rocks and are probably representative of secular variation in the earth's field, suggesting a lengthy history of igneous emplacement. The measurements at site 459 showed the igneous rocks to have extremely high magnetic intensities (consistent with their high iron enrichment) with shallow inclinations of both normal and reversed polarity.

Takigama and Ozima (in press) attempted to age-date igneous rocks from sites 458 and 459 using the ^{40}Ar-^{39}Ar method. A sample from site 459 yielded neither a plateau age nor an isochron because of alteration and air contamination. A sample from the high-magnesian andesites near the top of the igneous section in hole 458 yielded an isochron age of 33.6 MY, and a sample from the basalts deeper in the hole yielded an age of ca. 20 MY. Almost certainly the basalt age, and probably both the age dates at site 458, represent the time since secondary mineralization in these highly altered rocks, not the time of their emplacement.

Mariana Trough

Early studies of the Mariana Trough suggested that this backarc basin was actively spreading, on the basis of bathymetric trends and sediment distribution (Karig, 1971), the presence of fresh tholeiitic basalts (Hart *et al.*, 1972), and heat flow trends (Anderson, 1975). There were, however, no shallow earthquakes in the basin that were large enough to be detected by the world-wide seismic network, and attempts to correlate magnetic anomalies in the basin were unsuccessful. Thus, although it was agreed that the basin was opening, there was little evidence or agreement on the time or geometry of the spreading.

The results of field work related to IPOD drill site selection in 1976 and 1977 added considerably to understanding the tectonics of the Mariana Trough. With more complete bathymetric data available, Fryer and Hussong (in press) suggested that the spreading was symmetric and, at 18°N latitude, is centered at an axial graben (Fig. 4 B) trending about 330°T that is similar to the graben at other slow centers of spreading (e.g., the Mid-Atlantic Ridge). Beyond, extensional backarc basin crust is broken by normal faults into approximately north-south trending ridges that are rotated with their steep sides facing the apparent spreading center (Fig. 4 B). An east-trending bathymetric deep that cuts across the roughly north-trending ridges in the trough had been noticed by Karig (1971) and Bibee *et al.* (1980), but could be more clearly defined by Fryer and Hussong (in press) as an irregularly trending fracture zone that separates two distinct spreading centers (Fig. 6).

Bibee *et al.* (1980) tentatively correlated five magnetic profiles within 150 km of the center of the trough and suggested that the seafloor was spreading at a half-rate of 1.5 cm/yr. They were not able to correlate these same profiles at greater distances from the spreading axis. Hussong and Fryer (1980), using a larger data set, correlated east-west profiles north of 17°30′ N latitude and suggested that near 18°N the basin was opening at a half-rate of 1,65 cm/yr.

A SEATAR-sponsored deployment of ocean bottom seismometers around the 17°30′N fracture zone recorded numerous small (magnitude less than 3,5) earthquakes with an epicenter pattern (Hussong, Sinton, 1979) consistent with the ridge-transform spreading geometry shown in Figure 6.

Crustal structure in the Mariana Trough has been measured by Bibee *et al.* (1980), La Traille and Hussong (1980) and Ambos (1980). All these studies, using different data sets, suggest that the backarc basin has a crustal thickness of about 5-6 km, an unusually thick layer 2 A, and upper mantle with a low (generally less than 8 km/sec.) upper mantle seismic velocity. The seismic velocity structure of the Mariana Trough crust is, therefore, similar to that of the slow-spreading Mid-Atlantic Ridge.

Sager (1980) interpreted a free-air gravity profile across the trough and, using the crustal structure model of LaTraille and Hussong (in press) determined that the density of the crust and upper mantle in this backarc basin had to be lower than those observed in young lithosphere beneath deep ocean basins.

IPOD drilling in the Mariana Trough was very successful. Three sites were chosen to test the rate and geometry of spreading in the basin : one hole (site 453) in the supposedly oldest part of the trough on the western side ; a hole (site 454) as close as possible (some sediments are required for drilling) to the spreading center ; and a hole (site 456) through the Mariana volcanic arc sediment on the east side of the trough at an intermediate distance from the spreading axis. If spreading in the trough were symmetric, the basement at site 456 would be of intermediate age compared to the basement at the western sites. Site 455, was the original choice for an eastern trough site, but was moved to a nearby small bathymetric high (site 456) because coarse sandy turbidites at this site produced difficult drilling conditions.

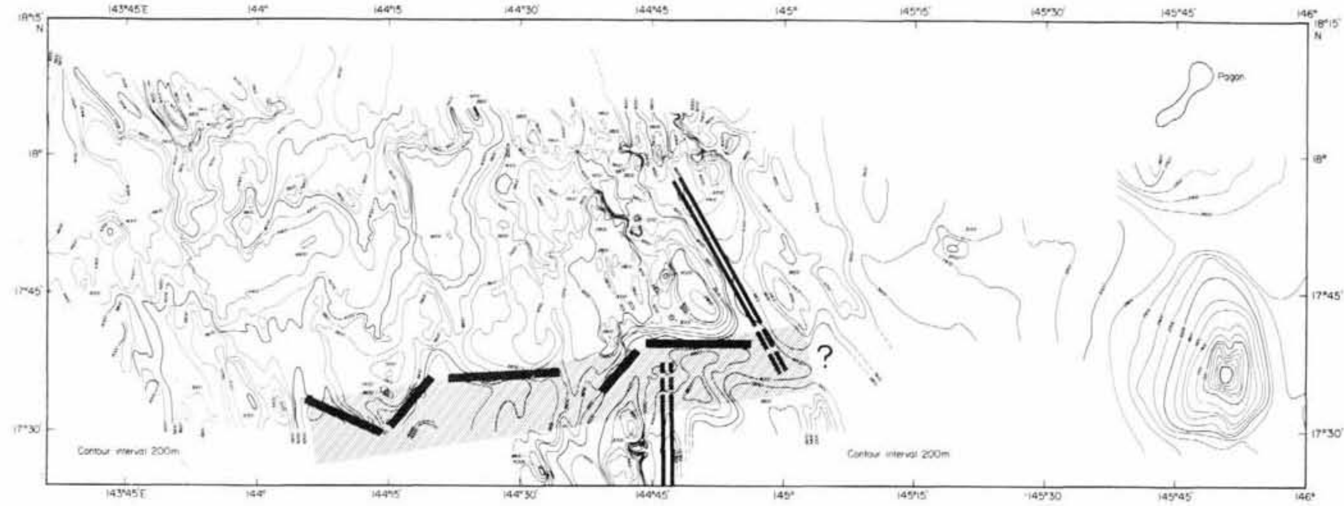

Figure 6

Sea floor spreading geometry in the Mariana Trough (from Fryer, Hussong, in press), based on bathymetry, sediment distribution, seismicity and magnetic anomalies. The axis of spreading trends 330°T in the northern part of the study area and from a north-south rift south of 17°35'N. The fracture zone between the spreading segments has an irregular trend that appears to represent the trace of a repeatedly re-orienting transform fault. The transform fault is sometimes perpendicular to the northern spreading segment, and other times is perpendicular to the southern spreading segment.

Sites 453, 454, and 456 all yielded turbidite sequences of volcaniclastic sediments that contain considerable hemipelagic and biogenic components. At all the sites, a mid-Pleistocene transition consists of siliceous oozes overlying, with low $CaCo_3$ content indicating deposition at a depth near the level of carbonate compensation.

The spreading history of the Mariana Trough that had been deduced during site surveys was also substantiated. Core from the westernmost hole (453) have a decreasing volcaniclastic component, reflecting the site's increasing distance from the volcanic arc as the trough opened. The increase in rates of sedimentation and volcaniclastic components during the period from about 0,3-0,9 MY suggests and increase in volcanic activity during that period. The paleontologic ages of the basal sediments (over 4,7-5,0 MY at site 453, 0,9-1,6 MY at site 454, and 1,6-1,8 MY at site 456) are also consistent with the model of symmetric spreading at a half-rate of less than 2 cm/yr.

One inconsistency that arose during the drilling, and that has not been resolved, has been described by Bleil (in press) on the basis of his measurement of paleomagnetic inclinations in the sediments. He found that the deeper sediments at sites 453 and 454 on the west side of the trough have low inclinations, suggesting strong latitudinal motion to the north during the past 5 MY. However, site 456 and the arc sites seem, by similar measurements, to have had little northward motion during the same time. On this evidence, Bleil (in press) suggests that the Mariana Trough near 18°N has opened in a northwest-southeast direction. This direction of opening appears to be inconsistent with other data and interpretations.

The igneous basement rocks at sites 454 and 456 are vesicular, sparsely phyric plagioclase and olivine-plagioclase pillow basalts and flows. At site 454 the igneous rocks are fresh and are interbedded with sediment layers. Two distinct chemical types, one typical of depleted mid-ocean ridge or marginal basin tholeiites and one with geochemical components similar to island-arc basalts, were recovered at site 454 (Wood *et al.*, in press). This may imply simultaneous supply of two fundamental magma types to this site in the center of the Mariana Trough. Heat flow at site 454 was measured at only 0,06 HFU (Uyeda, Horai, in press). This low value, in addition to other drilling characteristics, led Uyeda and Horai to conclude that sea water at site 454 was flowing down the hole and into the highly fractured, apparently highly permeable, basement rocks.

The basalts at site 456 were hydrothermally altered to chlorite-calcite-quartz-pyrite assemblages. The basal sediments were also highly altered and contained wairakite that Natland and Hekinian (in press) identified and used to suggest that temperature of alteration could have been as high as 200°C. Two holes, only 200 m apart, were drilled at site 456 and yielded heat flow values of 1.1 and 2.7 HFU (Uyeda, Horai, in press). This variability of heat flow, verified by later surface heat flow measurements which yielded local values ranging from 0 to 50 HFU (Hobart *et al.*, 1979), implies that the hydrothermal activity is still in progress. The extent of hydrothermal alteration diminishes quickly upward in the sediments and downward in the igneous rocks.

Site 453, which was planned to sample old Mariana Trough crustal rocks, yielded quite unexpected results. A sequence was cored including 86 m of a complex coarse gabbro/metabasalt polymict breccia overlying 62 m of metavolcanic breccias, over another 18 m of gabbroic breccia containing a 1.5-m interval of sheared serpentinized noritic gabbro. The basalts and most of the gabbros are metamorphosed to greenschist facies assemblages, and much of the sequence has also undergone hydrothermal alteration, causing retrograde metamorphism to a lower greenchist facies. An unspectacular downhole heat flow measurement of 2,7 HFU was obtained by Uyeda and Horai (in press), but subsequent surface measurements reported by Hobart *et al.* (1979) were high and variable and may indicate that hydrothermal circulation is still active in the area.

The metabasalts and gabbros at site 453 are chemically similar to those recovered from site 451, on the West Mariana Ridge, and sites 460 and 461, on the inner (island arc) wall of the Mariana Trench (Wood *et al.*, in press).

The apparent high degree of metamorphism and the chemical affinities of these rocks suggest that the igneous basement at site 453 is composed of island arc rocks that were emplaced at their present location during the early rifting of the Mariana Trough. Seismic reflection profiles over site 453 show reflectors below those depths penetrated by the drill, so there is uncertainty as to whether the arc-derived breccias are representative of all the crust beneath site 453, or whether backarc basin basalts lie at greater depths.

CONCLUSIONS

The results of Leg 60 drilling and geophysical studies provide considerable new tectonic information on the Mariana Arc-Trench system. No evidence was found to support a model of forearc accretion by emplacement of oceanic plate and trench axis sediments. No ocean basin sediments or rocks were recovered by drilling on the island arc side of the trench, although the deepest parts of the trench wall were not sampled. Igneous basement in the forearc is island-arc related and probably extends beyond the trench slope break to crop out on the trench wall. The age of the basal sediments in the forearc holes increases toward the trench axis, as does the degree of fracturing of these deep sediments. Vertical movement and tensional structures dominate the forearc area, from the large-scale block faulting in seismic reflection profiles, to the small normal faults in the core samples. The vertical movements seem to result in a net subsidence of the forearc that increases toward the trench, as implied from the presence of calcareous sediment well below carbonate compensation depth, the distribution of turbidites and the increasing intensity of tectonic deformation toward the trench.

Volcanic activity on the arc seems to have been fairly continuous, although periods of decreased (e.g., Late Oligocene) or increased (0,3-0,9 MY) activity are suggested by a chronology of volcanogenic components in the cores.

The Mariana Trough at 18°N is spreading at a half-rate of 1.5-2.0 cm/yr from a discontinuous axial graben, with a ridge-transform configuration that mimics mid-ocean spreading centers. The west edge of the Mariana Trough, although bathymetrically part of the backarc basin, may be floored by old island-arc rocks that subsided during early rifting, rather than that by younger backarc basin crust. Hydrothermal activity is extensive in the backarc basin.

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