

Thematic Article

A bathymetric overview of the Mariana forearc

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Abstract Bathymetric data at a 200-m contour interval for the entire Mariana forearc, from south of 13°N to 25°N, permits the first comprehensive overview of this feature. The Mariana forearc represents a sediment-starved end-member. The forearc in its southern and central sections is divisible into a structurally complex eastern province and a less-deformed western province. Despite the absence of an accretionary complex the Mariana forearc has a well-defined outer-arc high; this probably results from a greater concentration of low-density serpentinized mantle lithosphere beneath the outer forearc relative to the inner forearc. This serpentinization gradient is coupled with differing deformational styles of thinner and more brittle lithosphere beneath the outer forearc compared to thicker and more ductile lithosphere beneath the inner forearc. The bathymetric data also support models calling for extension along-strike of the forearc, reflecting an increase in arc length accompanying the crescent-shaped opening of the Mariana Trough back-arc basin. Both northeast and northwest ridges and grabens can be identified, with the latter restricted to the southern part of the forearc and the former widely distributed in the central and northern forearc. Northeast-oriented extensional structures are supplanted northward by long, linear northwest-trending structures that are interpreted as left-lateral strike-slip faults. These variations in deformation along-strike of the forearc manifest a transition from nearly orthogonal convergence in the south to highly oblique convergence in the north.

Key words: bathymetry, forearc, Mariana arc.

INTRODUCTION

The forearc is the part of a convergent plate margin that lies between the trench and the magmatic front. Forearcs are important for a number of reasons. They overlie subducted lithosphere and sediments where these are first squeezed, and so represent sites where fluids and matter begin to be transferred from the subducting to the overlying plate. Forearcs are the best place to reconstruct arc history. The accretionary wedge, if present, records what was subducted, while sediments in forearc basins record the eruption and uplift history of the arc. Because it forms or is trapped when subduction

begins, studying forearc igneous basement can reveal how subduction began. A better understanding of forearcs is important for other reasons, such as mountain building and hydrocarbon exploration. Forearcs make up the vanguard when arcs collide, so reconstructing orogenic events depends on our ability to recognize deformed forearc igneous and sedimentary sequences. Most ophiolites represent forearc basement. Forearc basins are important sites of sediment and hydrocarbon accumulation and storage.

In spite of their importance, forearcs are difficult to study for two reasons. First, they are largely submerged. Second, many forearcs lie in regions of high sediment supply, so most of the forearc infrastructure is covered by sediments.

Accretionary prism development also reflects sediment supply, with large accretionary prisms found where sediment flux to the trench is high. Conversely, forearc basement is exposed where the sediment supply is low; Le Pichon *et al.* (1993) state that no active accretionary wedge exists where the average trench fill is less than 1 km. High-sediment-supply forearcs are characterized by thick sequences of relatively undeformed sediments derived from the arc and continent lying inboard and above deformed sediments that are scraped off the subducting plate, as well as shed from the arc and continent. Most forearc models are based on high-sediment-supply forearcs such as the Aleutians or Sumatra, which attract study because these lie closer to population centers and may contain oil. Forearcs from regions of low sediment flux, such as the Mariana forearc, are more poorly known. This is unfortunate, because 'naked forearcs' such as the Marianas provide opportunities for studying features of convergent margin processes that are difficult to examine in high-sediment-supply forearcs. In particular, naked forearcs provide unparalleled opportunities to examine the nature of forearc basement and the origin of the trench-slope break. The present paper focuses on the Mariana forearc as a superb example of a naked forearc by means of a bathymetric overview, based on US Navy sonar array sounding system (SASS) bathymetry.

METHODS

STUDY AREA

The location of the Mariana arc system and the bathymetric coverage presented here are shown in Fig. 1. The southernmost limit of the Mariana forearc for the purposes of this contribution lies at $\sim 13^\circ\text{N}$, which is the northernmost extent of major east-west-trending faults which truncate all forearc elements further south (Karig *et al.* 1978; Karig & Ranken 1983). The northernmost limit of the Mariana forearc lies at $\sim 24^\circ\text{N}$, where the active Mariana arc and the remnant arc of the West Mariana Ridge converge. The western limit of coverage is defined by the active volcanic arc; in some cases, coverage extends east of the trench axis because this allows us to see where seamounts are colliding with the forearc, and collision of seamount chains may be important controls of forearc structure.

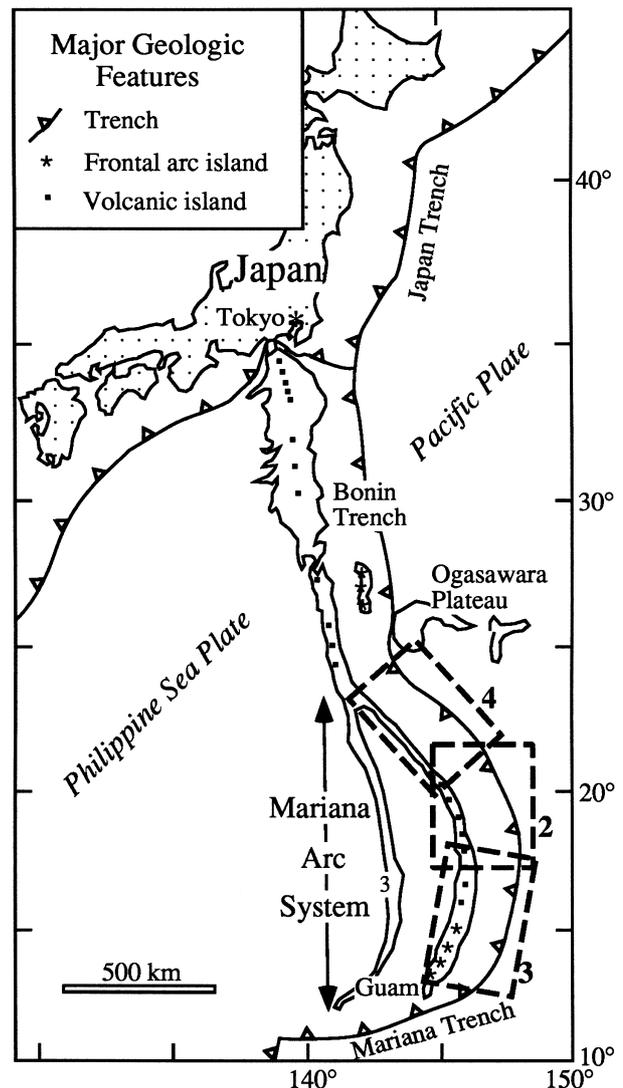


Fig. 1 Location of the Mariana arc system in the Western Pacific. Dashed boxes labeled 2, 3, and 4 approximate the position of maps shown in Figs 2–4.

The study area is large, and this dictates the size of features we discuss. The Mariana forearc is 200–220 km wide, and the present study focuses on an expanse that stretches ~ 1200 km from south to north. These dimensions are approximately those of Honshu, the largest of the Japanese islands. Another size comparison is with the state of California; the distance from San Diego to San Francisco is similar to that from Guam to the point of greatest curvature of the arc at 18°N . The reader should keep in mind the great extent of the study area, which means that many important but smaller features may be overlooked. For example, structural features observed in more detailed studies

(Karig & Ranken 1983; Mrozowski & Hayes 1980; Wessel *et al.* 1994) are mostly missed at the scale of our study. Our intent is to provide a broad overview of the Mariana forearc to serve as context for more detailed studies, and use the results of previous studies to guide our interpretations.

DATA COLLECTION AND PROCESSING

Data collection and processing for this project began in the late 1960s by the US Naval Oceanographic Office. LORAN-C and the Navy's transit satellite was used for horizontal control. The Sonar Array Sounding System (SASS) was used to collect depth information. The SASS, a multibeam sonar collector, employs a burst of acoustic energy that is transmitted from transponders on the ship's hull. Time delays between the highest and lowest transponders are pre-programmed with roll and pitch compensators, and a 'fan of sound' is sent out. An array of hydrophones allows the returned energy to be processed into range and angle data, which are further translated into raw depth and location. With the sound-velocity profile having been entered into the program, ray-bending corrections are made and applied. The output is then in corrected depths and lateral positions, and this is the sonar bottom. Further details are presented by Glenn (1970).

Bathymetric maps are components of a long-running study of the northwest Pacific region in general and the Izu-Bonin-Mariana (hereafter, IBM) arc system in particular (Bloomer *et al.* 1989; Fryer & Smoot 1985; Smoot 1983a,b, 1984, 1988, 1990, 1991, 1997; Stern *et al.* 1984, 1989; Taylor & Smoot 1984). The total-coverage bathymetry has been shown in a variety of formats, mostly in fathoms and in bits and pieces. This overview is a composite of all these previous studies. A computer program (GRASS 4.1) was used to show projections of the bathymetric data in a way that gives the appearance of being three dimensional (3-D).

BATHYMETRIC MAPS OF THE MARIANA FOREARC

The bathymetric maps are shown in Figs 2, 3, and 4. The forearc is depicted on three panels of approximately equal size and at the same scale. We can refer to the central Mariana forearc (Fig.2), the southern Mariana forearc (Fig.3),

and the northern Mariana forearc (Fig.4). We first discuss the central Mariana forearc because it is the best known of the three segments.

THE CENTRAL MARIANA FOREARC

The best known part of the central Mariana forearc lies between 18° and 19°N. The largest volcanoes in the Mariana arc (Pagan and Agri-gan) bound the forearc to the west. Two morphological provinces lie between the line of arc volcanoes and the trench, 200 km to the east (Fig.2). Smooth sea floor defines the western two-thirds of the forearc, which is inclined gently to the east and lies mostly at depths of 3–4 km below sea-level. This 'smooth' province reflects deposition of distal volcanoclastic turbidites, ash, and pelagic sediments. In contrast, the region between the smooth province and the trench has a rough, mountainous morphology. This 'rough' region is characterized by local relief of over 2 km. Rough and smooth morphological provinces are readily distinguished from perspective views in Figs 5, 6, and 7.

Rough and smooth forearc sectors correspond to two structural provinces: a western and an eastern structural province (Mrozowski & Hayes 1980). The western structural province (WSP) is typified by a thick sequence of well-stratified, relatively undeformed sediments above an eastward-shoaling basement reflector. Sediments of the WSP thicken to greater than 3 km in the flexural moat east of the active volcanic arc (Mrozowski & Hayes 1980). From Deep Sea Drilling Program (DSDP) sites 458 and 459 we infer that a relatively undeformed sedimentary sequence extending back at least into the late Eocene or early Oligocene is preserved in the forearc basin constructed on the WSP (Hussong & Uyeda 1981). A basaltic sill of late Miocene or younger age was penetrated at Ocean Drilling Program (ODP) site 781A (Marlow *et al.* 1992) and similar sills have been encountered in the Tonga forearc (Taylor *et al.* 1995), so forearc volcanic flows and intrusions comprise a minor component of the supracrustal succession in the WSP forearc basin. Although this broad basin is structurally much more simple than the eastern structural province (ESP), it is cut by numerous high-angle normal faults that parallel the arc and trench, with surface offsets that range from 10 to 250 m (Mrozowski & Hayes 1980). The DSDP drilling at sites 458 and 459 confirms that the deeper, more consolidated sediments are cut by

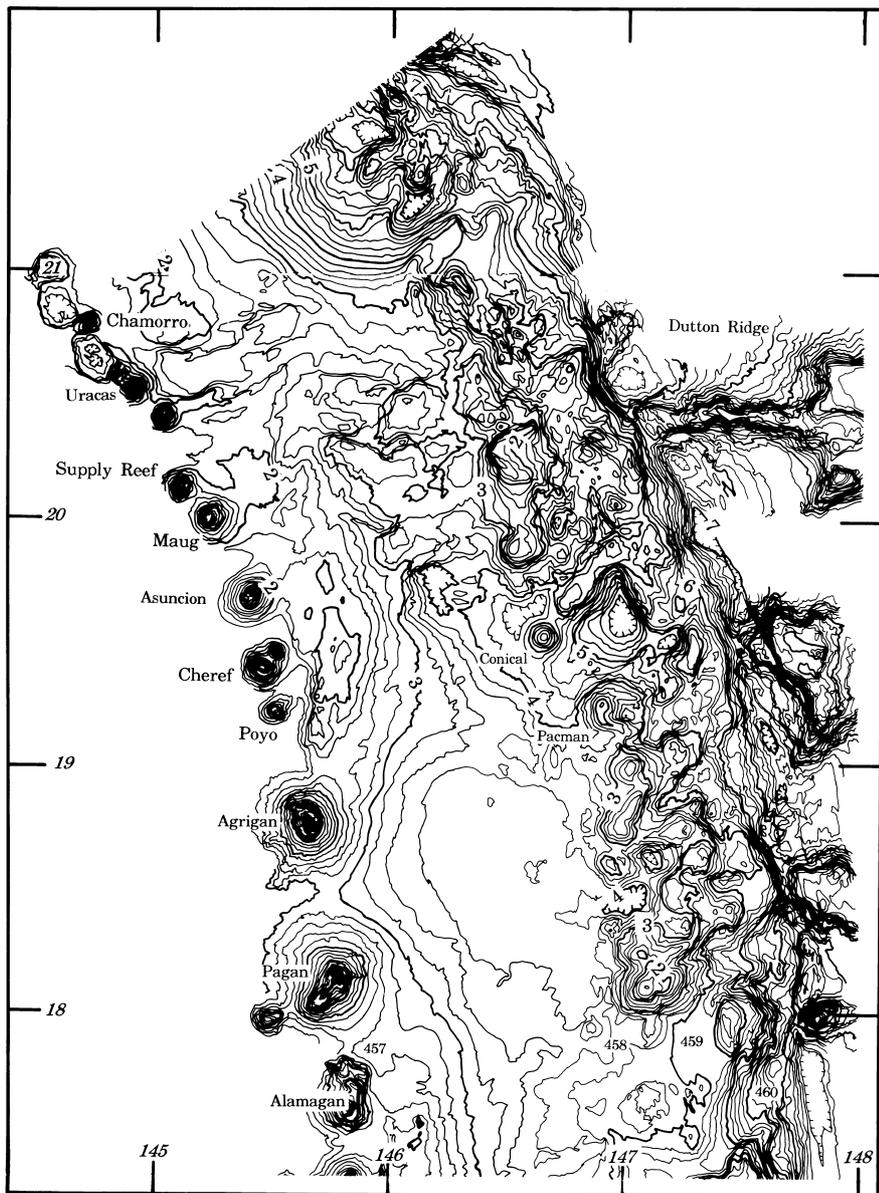


Fig. 2 Bathymetric map of the central Mariana forearc. Contour interval is 200 m, with heavy contours shown every 1000 m and labeled in km below sea-level. All of the islands, from Alamagan in the south to Uracas in the north, are active or dormant volcanoes, except for Maug, which is extinct. The Mariana Trench lies along or near the eastern limit of coverage, and can be traced through depths of 8 km in the south to 7 km in the north. Note that the locations of Conical and Pacman seamounts are shown, along with the approximate positions of DSDP sites 457, 458, 459, and 460.

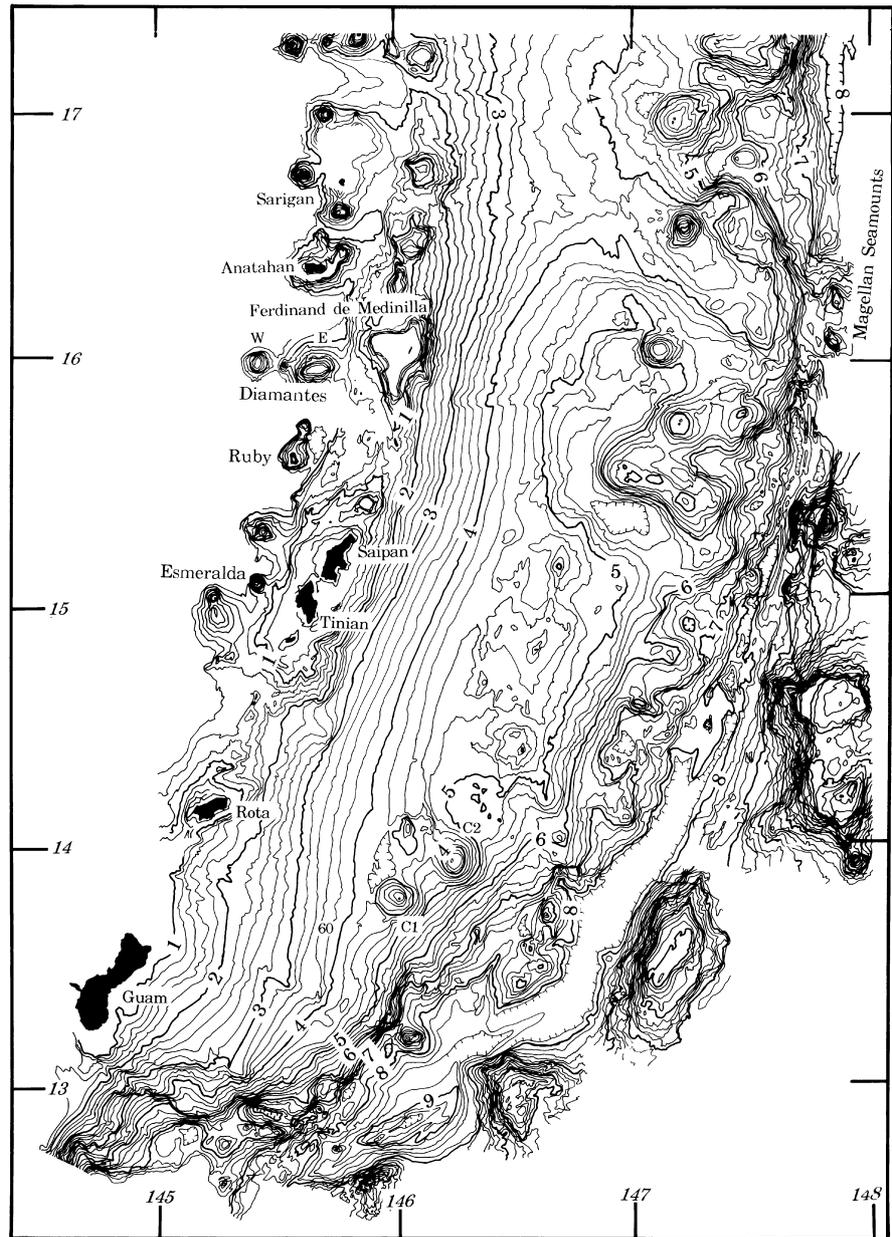
numerous normal faults, further indicating that the forearc is under tension (Hussong & Uyeda 1981). The WSP–ESP boundary is defined by the intersection of acoustic basement with the sea floor. The ESP is characterized by Mrozowski and Hayes (1980) as having a very high density of small and uncorrelatable normal faults.

In most of the central Mariana forearc, the sea floor of the WSP is deeper than the ESP. This indicates that the forearc basin has generally not reached sill depth, the point at which sedimentary flux from the forearc basin equals that into the trench. This may be one of the reasons that there is little evidence for submarine canyons, because it is argued that extensive submarine canyon formation begins after the forearc basin is

filled to the spill point of the outer-arc high (Klaus & Taylor 1991). The spill point is reached east of Pagan, and this may be responsible for the development of a short (~30-km-long) canyon leading into the trench northeast of site 459 (another apparent canyon trends northeast from near the ESP–WSP boundary at 18°30'N to the trench just north of 19°N). Because canyons initiate in the outer-arc high and grow by headward erosion (Taylor & Smoot 1984; Klaus & Taylor 1991), continuing tectonic instability in the ESP may prevent canyon formation.

Drilling this part of the Mariana forearc during DSDP Leg 60 demonstrated two important things. First, the forearc is underlain by an igneous basement of middle–late Eocene age. This

Fig. 3 Bathymetric map of the southern Mariana forearc. Contour interval is 200 m, with heavy contours shown every 1000 m and labeled every km below sea-level. The islands from Guam to Ferdinand de Medinilla manifest structural uplift along the frontal arc; active arc volcanism lies slightly to the west of the frontal arc. The Mariana Trench lies along or near the eastern limit of coverage, and can be traced through deeps of 9 km in the south to 8 km in the north. Note that the locations of Chamorro (C1) and Chamorro 2 (C2) forearc seamounts are shown, along with the approximate position of DSDP site 60.



result has been confirmed by studies of Eocene volcanic sequences on Saipan and Guam, dredging the inner wall of the Mariana Trench, and results from ODP Legs 125 and 126. Mariana forearc basement consists of depleted igneous rocks produced during and shortly after the beginning of subduction (Bloomer 1983; Bloomer & Hawkins 1983, 1987; Hickey & Frey 1982; Stern & Bloomer 1992). Scant evidence supports models calling for trapped oceanic crust to underlie the forearc; second, very little material has been transferred from the subducting Pacific plate to the Mariana forearc. Subsequent dredging studies have recovered what appear to be relatively

minor amounts of mid-ocean ridge basalt (MORB) and ocean island basalt (OIB) lavas associated with Cretaceous chert, which could be accreted material (Johnson *et al.* 1991), but may have been subcreted and then brought to the surface by entrainment in serpentine diapirs (Fryer *et al.* 1995). Dredging the inner trench wall more commonly recovers Tertiary igneous rocks with strong arc affinities. A controversy continues regarding how much of the forearc has been removed by tectonic erosion. Some of the forearc basement must have been downfaulted and subducted in order to expose the igneous basement (frontal erosion of von Huene & Scholl

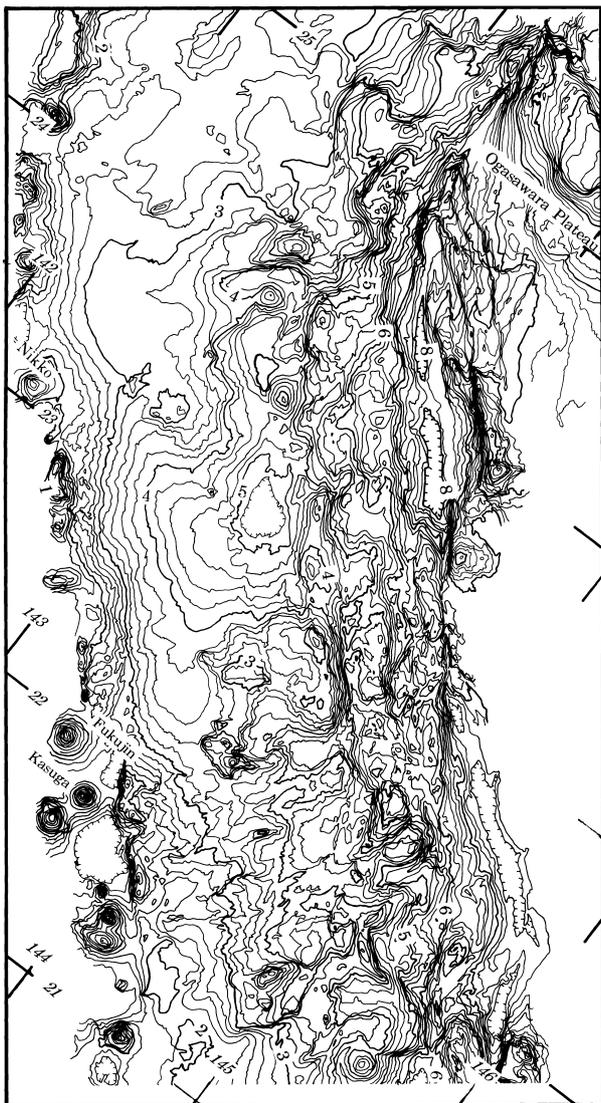


Fig. 4 Bathymetric map of the northern Mariana forearc. Contour interval is 200 m, with heavy contours shown every 1000 m and labeled as km below sea-level. The Mariana Trench lies along or near the eastern limit of coverage, and can be traced through deeps of >7 km in the south to 8 km in the north.

1991), but earlier estimates that 50–60 km or more must have been removed to expose arc basement (Bloomer 1983) are rendered unnecessary by the subduction initiation model of Stern and Bloomer (1992).

Given that the ESP and WSP are underlain by similar crustal materials, what is responsible for these very different morphologies? Clearly the WSP is much less deformed than the ESP, and the bathymetric data presented here allow us to identify three main structural trends and morphologies for the ESP. First, there are numerous conical features which are now understood to be where serpentinite diapirs breach the sea floor as

serpentinite mud volcanoes (Fryer *et al.* 1995). These serpentinite seamounts may be as large as 30 km or more in diameter. The relief developed by the serpentine seamounts largely defines the trench-slope break for this part of the Mariana arc system (Fryer & Pearce 1992). There is also a strong N30°W fault orientation that extends south from the northern Mariana forearc and intersects the trench near its point of maximum curvature $\sim 18^{\circ}30'N$. Nevertheless, this structural fabric is much less important in the central Mariana forearc than it is in the northern Mariana forearc. The N30°W fault system becomes increasingly important as Pacific–Mariana convergence increasingly parallels the strike of the trench, as is observed northward from $18^{\circ}N$ (Seno 1989). Finally, there is a well-defined N50°E structural trend that can be identified from $\sim 18^{\circ}N$ to $21^{\circ}10'N$. This is defined by ridges and intervening lows; intersection of the northwest and northeast structural fabrics may produce structures such as the 2-km-deep depression at $19^{\circ}30'N$, $146^{\circ}50'E$. The origin of the northeast-trending structure is probably related to forearc extension resulting from progressive increase in the radius of curvature of the Mariana arc, caused by differential opening of the Mariana Trough back-arc basin (Carlson & Melia 1984; Fryer & Pearce 1992). The differential opening of the Mariana Trough could also be related to ‘pinning’ of the arc in the north by the Michelson/Marcus-Necker Ridge and in the south by the Caroline Ridge (Hsui & Youngquist 1985; Smoot 1984). Karig *et al.* (1978) suggest an average extensional strain of 10% along the forearc associated with the opening of the Mariana Trough back-arc basin. The model of Hsui & Youngquist (1985) implies considerably greater (40–50% total) extension. Regardless of which model is closer to the truth, extension and deformation related to it are concentrated in the ESP relative to the WSP and in the central and southern segments relative to the northern forearc.

Serpentine mud volcanism is facilitated by extension such as appears to be occurring in the central Mariana forearc, and it is noteworthy that the greatest density of serpentine seamounts is located where the northeast-trending extensional structures are concentrated. This suggests that forearc extension is required to mobilize ascent of serpentine diapirs, an interpretation that is consistent with the absence of active serpentine mud volcanoes in forearcs that are not being stretched, such as the northern

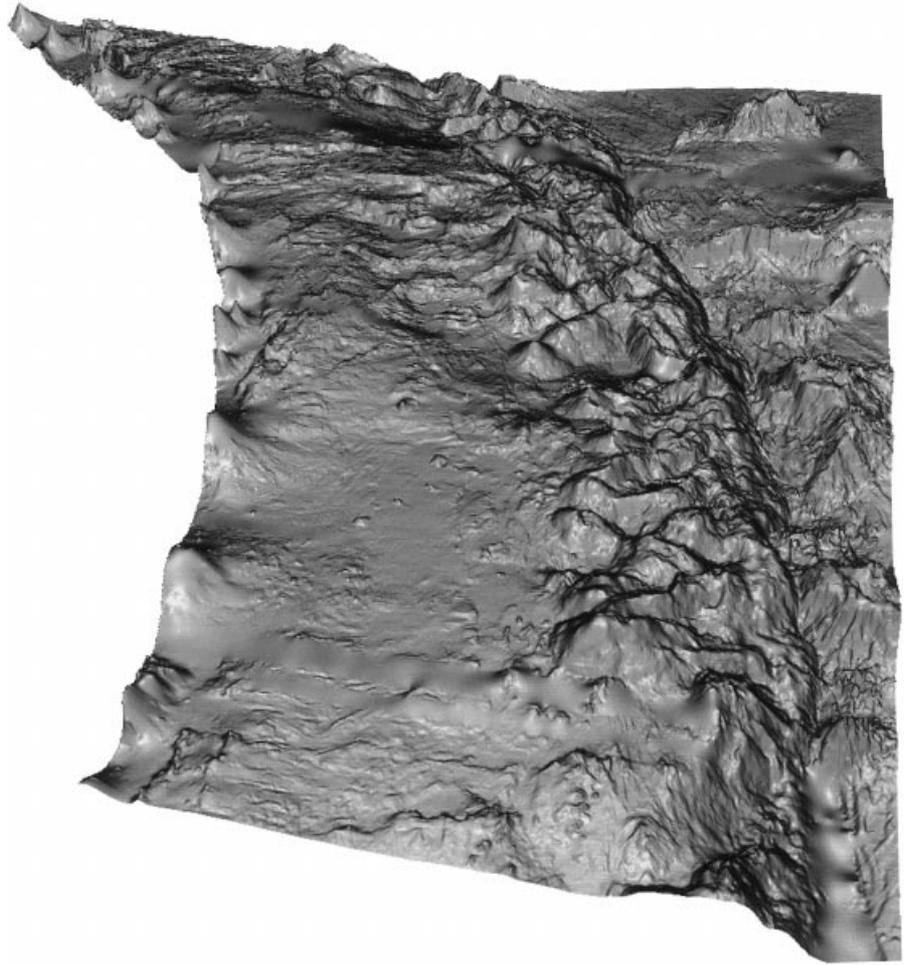


Fig. 5 Perspective view of the Central Mariana forearc, viewed from the south end of region covered by Fig. 2, looking towards the north. This perspective encompasses ~ 400 km of the forearc. Vertical exaggeration = $5\times$.

IBM or Tonga forearcs (Ishii *et al.* 1996). One interpretation of the sharp WSP–ESP boundary is that this is defined by the westward limit of minimum extension required to permit ascent of serpentine diapirs. Alternatively, the boundary may reflect deeper processes, such as the interaction between decreasing water flux with depth and increasing lithospheric thickness to the west. Lithosphere above the subduction zone and east of the boundary is < 50 km thick, whereas it is > 75 km thick west of the boundary. These two effects may combine so that mantle beneath the

ESP is largely serpentinized, whereas beneath the WSP serpentinization may be limited to that part of the mantle adjacent to the subducted slab. In this case, the uppermost mantle beneath the WSP may be relatively unfaulted so that diapiric ascent is precluded.

THE SOUTHERN MARIANA FOREARC

This segment of the arc is subducting the Pacific plate along a convergence vector that is perpendicular to the strike of the trench or nearly so

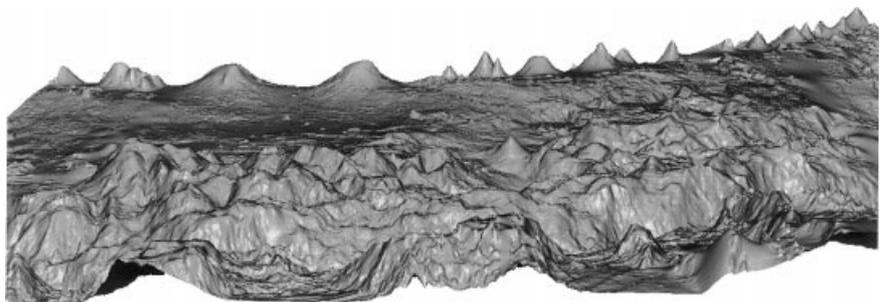


Fig. 6 Perspective view of the central Mariana forearc, viewed from the Pacific plate looking towards the west. The middle of the image is $\sim 19^{\circ}30'N$. This perspective encompasses ~ 400 km of the forearc. Vertical exaggeration = $5\times$.

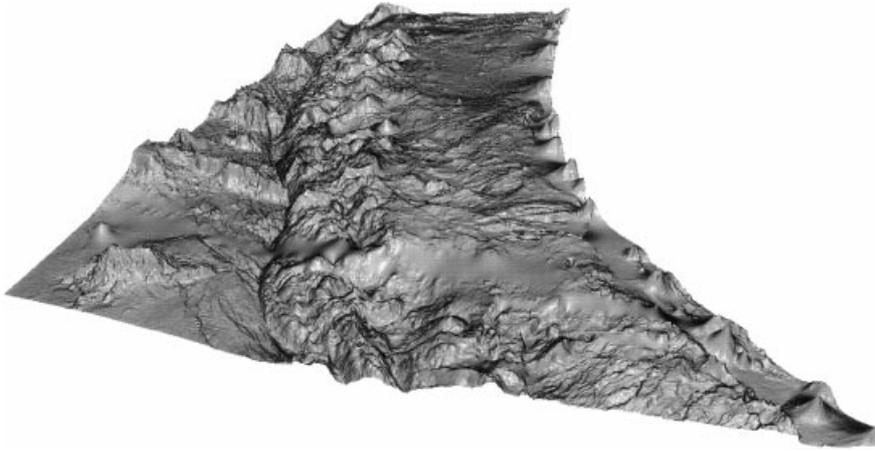


Fig. 7 Perspective view of the Central Mariana forearc, viewed from the north end of the region covered by Fig. 2, looking towards the south. This perspective encompasses ~ 400 km of the forearc. Vertical exaggeration = $5\times$.

(Seno 1989). The southern Mariana forearc is shown in Fig. 3. The most striking aspect of this segment is the well-developed structural ridge that lies just east of the active arc and extends for ~ 500 km north-northeast of Guam. This is the 'frontal arc' of Karig (1971) and includes the islands of Guam, Rota, Aguijin, Tinian, Saipan, and Ferdinand de Medinilla. The forearc is tilted northward so that its expression is subdued progressively to the north. A submerged equivalent of this structural ridge can be identified almost as far as 18° . The frontal arc south of Guam is reduced rapidly to the south by important east-west faults so that the frontal arc is not

expressed south of $12^\circ 30'N$. It is not clear why the frontal arc is so well developed in the southern Marianas, nor why the active arc is submerged where the frontal arc is emergent, while the frontal arc is missing where active arc volcanoes stand highest above sea-level. It is noteworthy, however, that the frontal arc is best developed in that sector of the arc where convergence is most nearly perpendicular to the trend of the trench. This suggests that convergence normal to the trend of the trench is required for development of the frontal arc.

The southern Mariana forearc provides good examples of the improvement in visualization

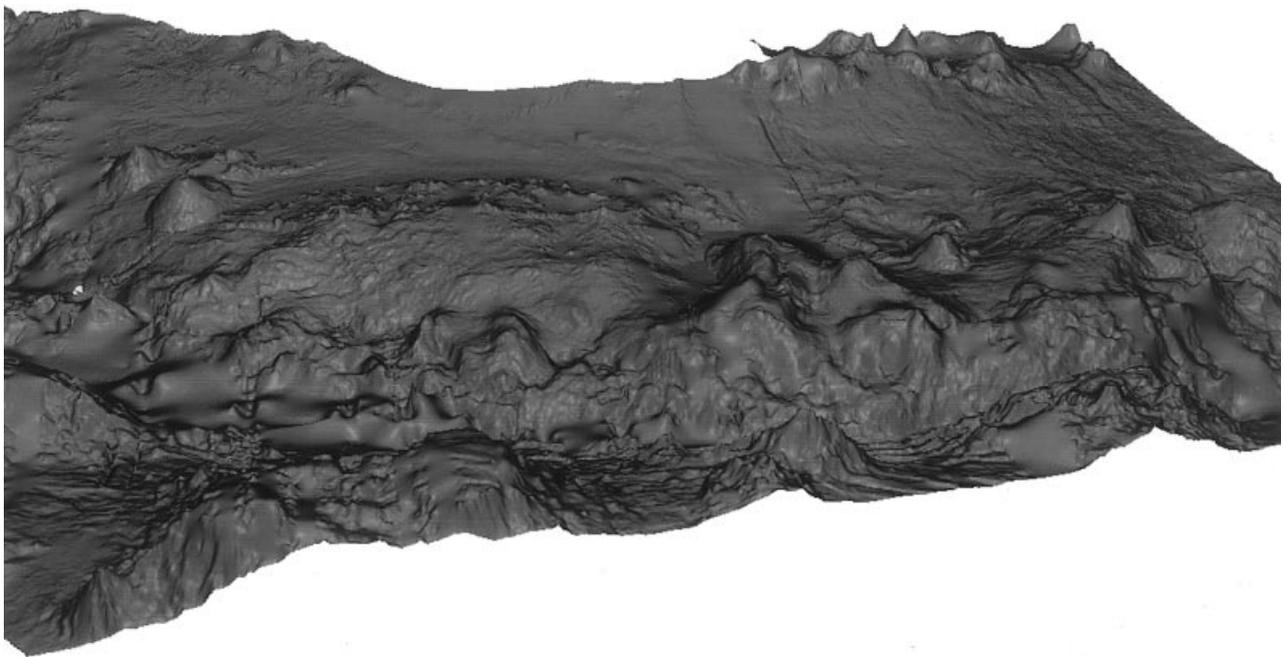


Fig. 8 Perspective view of the southern Mariana forearc, viewed from the Pacific plate looking towards the west. The southern limit of imaged region lies at $\sim 13^\circ 30'N$, and the northern limit extends almost up to the northern limit of the region covered by Fig. 3. This perspective encompasses ~ 400 km of the forearc. Vertical exaggeration = $5\times$.

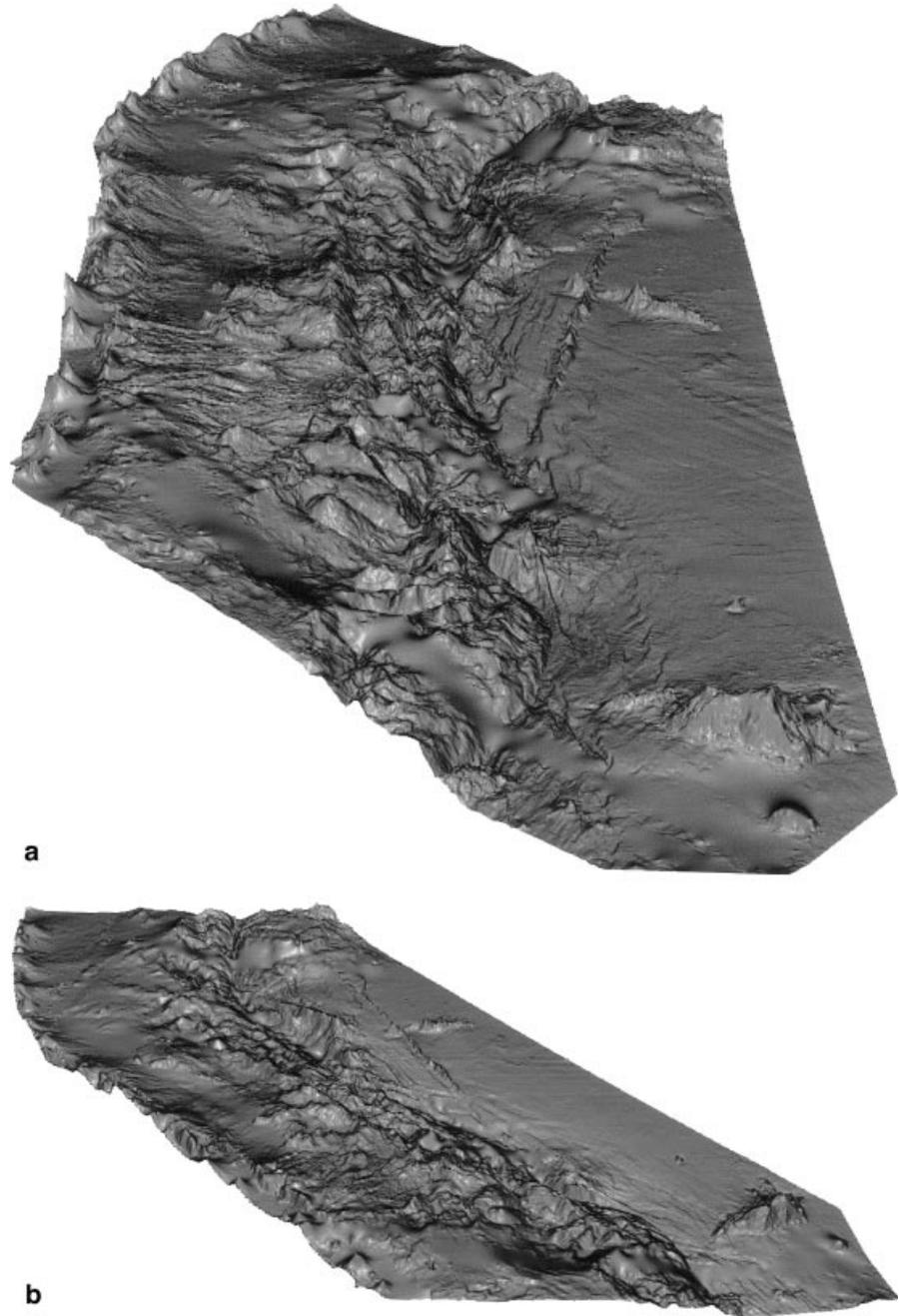


Fig. 9 Perspective views of the northern Mariana forearc. (a) Highly oblique view from the southeast, looking north-northwest; (b) less oblique view from the south, looking north. The area imaged is the same as that shown in Fig. 7. This perspective encompasses ~400 km of the forearc. Vertical exaggeration = 5x.

provided by swath-mapping over earlier reflection profiles. Compare Figs 6, 7, and 8 of Karig and Ranken (1983) with Figs 3 and 8 of the present report. Figure 6 of the older study (profile along $14^{\circ}30'N$) clearly traverses the broad ridge defining the trench slope break between $14^{\circ}10'$ and $15^{\circ}10'N$. The high that extends along 50 km of the lower slope traversed on the $13^{\circ}40'N$ profile in Fig. 7 of the older study is shown to be a complex faceted structural ridge. Two bathymetric highs shown on the east-northeast profile in Fig. 8 of the older study are

revealed to be serpentine seamounts Chamorro and Chamorro 2 (Fig. 3).

The boundary between the WSP and ESP of Mrozowski and Hayes (1980) can be extrapolated along a bathymetric and morphologic break into the southern Mariana forearc, although the relief of the WSP becomes increasingly subdued south of $15^{\circ}20'N$.

The WSP occupies a 70–80 km width of the forearc and lies immediately east of a relatively steep slope that defines the eastern margin of the frontal arc. The WSP in the southern Mariana

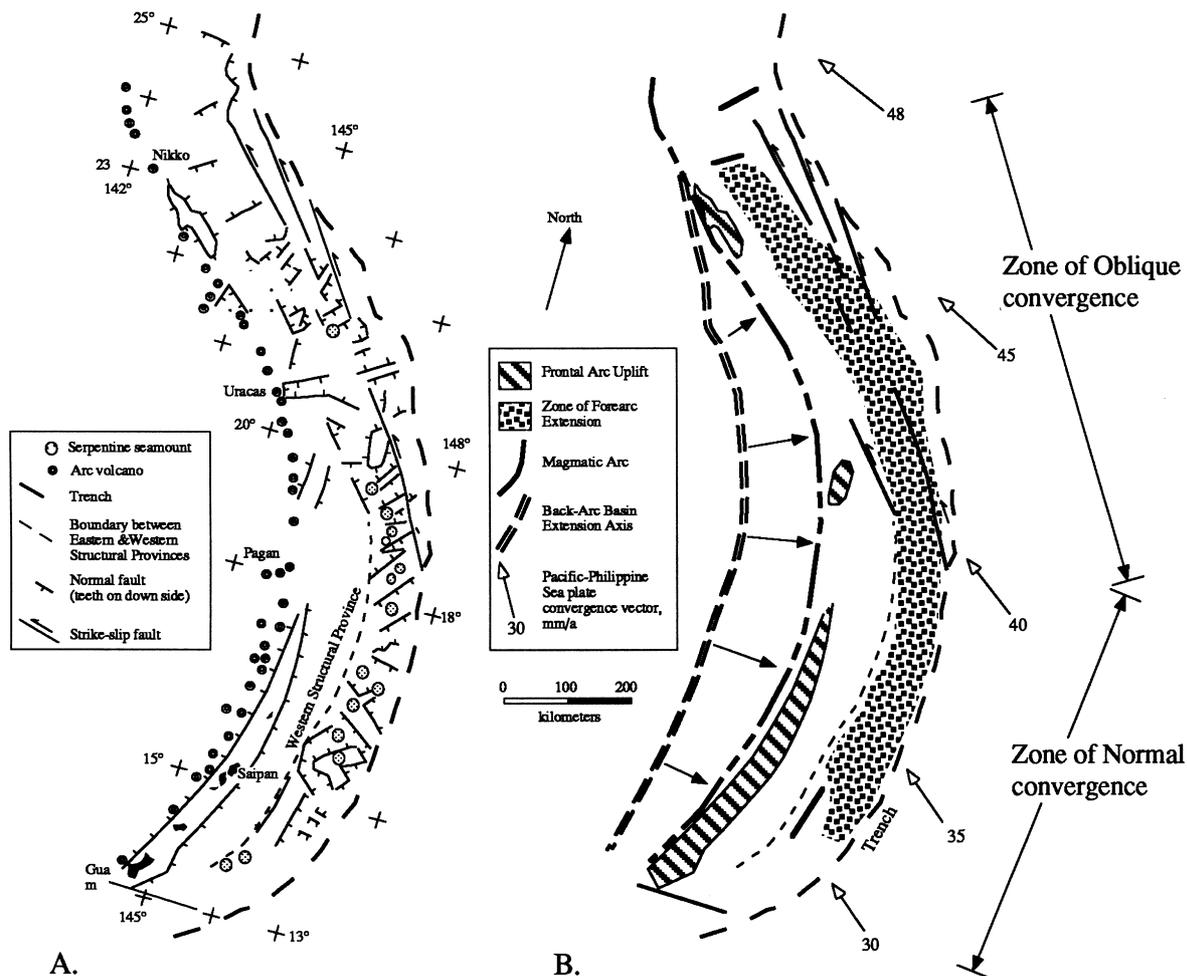


Fig. 10 Tectonic sketch maps of the Mariana forearc. (a) Generalized structures. The lightly stippled area near 22°N shows the location of the detailed study area of Wessel *et al.* (1994). (b) Generalized structural elements of frontal arc uplift, forearc extension zones, and regions of strike-slip faulting. These tectonic elements reflect the interaction of stresses associated with opening of the Mariana Trough back-arc basin and northwest-directed relative motion between the Pacific and Philippine Sea plates, as discussed in text.

forearc is defined by relatively smooth sea floor that deepens eastward from ~2–4 or 5 km water depth. This is succeeded to the east by rougher bathymetry defined by, from south to north: (i) serpentine mud volcanoes; (ii) a broad, trench-parallel ridge; and (iii) steep, short ridges striking at high angles to the trench. Serpentine mud volcanoes define the ESP from 13°40' to 14°25'N, and probably are sea floor expressions of serpentine diapirs like those from the central Mariana forearc. These are several tens of kilometers in diameter and 500–1500 m high. The two southern seamounts have steep trenchward slopes, and it is likely that debris flows from these seamounts are directed to the lower trench slope. The southernmost is called Chamorro Seamount (13°47'N, 146°03'E) by Fryer (1996 Fig. 10b) and has been investigated by dredging and Shinkai 6500 diving. This is a site of active

venting of fluids, with aragonite chimneys and rich biological communities (Fryer 1996). Recent serpentine mudflows containing clasts of ultramafic rocks up to 2–3 m in size were observed. Chamorro Seamount is clearly still tectonically active, issuing fluids and serpentine mud flows. The northern serpentine seamount (called Chamorro 2 Seamount by Fryer (1996)) is characterized by subdued summit relief and marks the south end of the previously mentioned broad ridge. This ridge rises as much as 600 m above the adjacent ESP sea floor and extends for ~40 km across the forearc before dropping precipitously into the lower trench slope. We speculate that this ridge marks a zone where buoyant serpentinite has not yet been organized into discrete diapirs.

We see no good evidence for erosional submarine canyons. A submarine canyon that was

identified by Karig (1971) between 16°N and 15°N appears to be tectonic in origin, almost certainly related to the L-shaped Lapulapu Ridge (centered on 15°30'N, 147°E). Lapulapu Ridge and its tectonic 'moat' may result from the collision of Magellan seamounts with the Mariana forearc (Smoot 1997), as a result of processes discussed by Fryer and Smoot (1985) and von Huene and Scholl (1991). Alternatively, this may mark the southernmost expression of normal faults, orientated at high angles to the trench, that characterize the ESP farther north. The 50-km-long southern limb of the Lapulapu Ridge trends ~N70°W, subparallel to a 90-km-long northwest-trending ridge that dominates the ESP at 16°20'N. The 80-km-long northern limb of the Lapulapu Ridge trends northeast, parallel to the dominant structural grain of the ESP. Several serpentine seamounts (P. Fryer pers. comm., 1997) are found on and northwest of the Lapulapu Ridge and on the unnamed, northwest-trending ridge; an unusually large serpentine seamount lies north of the northwest-trending ridge at 17°N.

Sedimentation rates in the WSP are very low, even in regions above the carbonate compensation depth (CCD), which lies at a depth of ~4.5 km (Seibold & Berger 1996). The DSDP site 60 was drilled in 3700 m of seawater, between Chamorro seamount and Guam. This encountered late middle Miocene marl at 50 m.b.s.f. and bottomed in early or middle Miocene ash at 350 m (Party 1971).

THE NORTHERN MARIANA FOREARC

This segment is conspicuously different from the other two segments in several ways. First, there is little evidence for serpentine seamounts. Relatively small candidates exist near 21°30'N, 23°20'N and 24°N, but the large seamounts common in the forearc farther south are missing. Second, it is difficult to extrapolate the ESP-WSP boundary into the northern segment. Instead, the entire width of the forearc is deformed. We can here describe in general terms an inner and outer forearc, but the sharp boundary between forearc provinces found to the south is missing (Fig. 9). As first noted by Fryer and Fryer (1987), deformation of the inner forearc is particularly clear in the region between 21°N and 22°15'N, where a northeast-trending grain is readily apparent. The detailed SeMARC II study of Wessel *et al.* (1994) of the inner forearc east of the Kasuga volcanoes

showed that this is a tectonic fabric. They identified the northeast-trending fabric of the inner forearc between 21°35'N and 22°10'N as a broad zone of normal faulting. Two general models were entertained by Wessel *et al.* (1994): radial tension due to increasing curvature of the arc and highly oblique plate convergence. The northeast-trending structural grain is difficult to identify north of 22°15'N, where the inner forearc is dominated by broader swells and sags. Deformation of the inner forearc is less apparent farther north, but is still much greater than that observed in the WSP of the central and southern segments.

The northeast-trending fabric of the inner forearc is truncated by the great northwest-trending faults that dominate the outer forearc. The northwest-trending system could manifest normal or strike-slip faults, or both. Although this forearc segment is characterized by a broad zone of shallow (<50 km) seismicity, scant focal mechanism data give conflicting results (Eguchi 1984), and new data will be required to answer this question. We note, however, that convergence between the Mariana forearc and Pacific plate is highly oblique along this segment, and strike-slip faulting is characteristic of convergent margins undergoing highly oblique convergence (Beck 1983; Ryan & Scholl 1989). At present it is impossible to quantify the extent to which convergence between the northern Mariana forearc is parallel to the trend of the arc, for three reasons. First, relative motion between the Philippine Sea and Pacific plates is poorly constrained. Second, sea floor spreading and rifting in the Mariana Trough forms a Mariana 'platelet' and the Euler pole between the Mariana platelet and the Philippine Sea plate is poorly constrained, or may be undefinable (Baker *et al.* 1996). Finally, the Mariana platelet appears to be undergoing considerable internal deformation, so that even if we knew Euler poles between the Philippine Sea and Pacific plates and between the Philippine Sea and any part of the Mariana 'platelet', this would still be insufficient to completely describe relative motion between the Pacific plate and Mariana forearc. Nevertheless, reasonable models such as that of Seno (1989) results in a relative convergence direction of 285° between the Pacific plate and the Philippine Sea plate at 24°N. This is not very different from the trench azimuth of 320°, so the general conclusion that the northern Mari-

ana forearc lies in a region of highly oblique plate convergence is inescapable. This is far more oblique than the 20° to 30° of oblique convergence suggested by Beck (1983) to be required to activate strike-slip faulting along convergent margins. We therefore conclude that the northwest-trending set of long, linear faults in the Mariana forearc reflect left-lateral strike-slip faults.

DISCUSSION

The bathymetric data reported here demonstrate that the Mariana forearc is a complex geological entity, but with systematic lateral variations both along- and across-strike. The scale of our overview allows us to isolate four important causes for this variability. The first contributing factor is transfer of material (mostly water) from the subducted Pacific plate. The second factor reflects the changing rheology of the westward-thickening mantle wedge. The third factor expresses along-strike extension of the forearc associated with opening of the Mariana Trough back-arc basin. The last factor is the oblique convergence of the Pacific plate. The first two factors are largely responsible for across-strike variations, whereas the fourth factor is important for along-strike variability. The third cause contributes to both along-strike and across-strike variability. The following discussion focuses on these processes.

Subduction engenders a complex transfer of matter across the plate interface associated with the Mariana forearc, with significant amounts of rock being removed from the hanging wall at the same time that large volumes of water are added to it. The inner wall of the Mariana Trench mostly exposes igneous basement of the forearc (Bloomer 1983; Bloomer & Hawkins 1987), and is a Type 2 (non-accretionary) trench according to the classification of von Huene and Scholl (1991). This indicates that not only is material not being 'bulldozed' off the down-going plate and added to the overriding plate by frontal accretion, matter has been removed from the forearc by frontal subduction erosion (Von Huene & Lallemand 1990). Additional material may be removed from the base of the Mariana forearc (Cloos & Shreve 1996). In contrast, water derived from the subducted plate is moving into and through the forearc (Kastner *et al.* 1991). The abundance of serpentine mud volcanoes and active fluid vent-

ing sites in the ESP suggests that transfer of water from the subducting plate to the base of the forearc is important for evolution of the Mariana forearc.

Dehydration of the subducted slab and sediments occurs by porosity reduction and mineral dehydration reactions (Kastner *et al.* 1991). We do not yet have good estimates of the water flux from the subducted plate but it is likely that the water yield generally decreases with increasing depth, and this will be reflected in changes seen in the forearc with increasing distance from the trench. This effect is magnified because with greater depth in the subduction zone (greater distance from the trench), less water is released from the slab and sediments and this acts on a greater thickness of overlying lithosphere. The result is that, whereas the lithospheric mantle adjacent to the trench is extensively (but not completely) serpentinized, the extent of serpentinization decreases rapidly away from the trench. Serpentinization results in a reduction of density to ~75–80% of the original peridotite (Coleman 1971), resulting in a volume increase of 25–33%. Completely serpentinized mantle is similar in density to basaltic or gabbroic oceanic crust and should rise through un-serpentinized mantle. Portions of the forearc that are underlain by highly serpentinized peridotite will therefore be elevated relative to those portions underlain by un-serpentinized peridotite. In the southern and central Mariana forearc the outer-arc high (OAH) is well-defined in spite of the fact that there is no accretionary prism. The Mariana OAH is composed of serpentine mud volcanoes and autochthonous basement fault blocks. The OAH of other arc systems may reflect a transition from accretionary prism to forearc 'buttress' (Dickinson 1995), but gradients in serpentinization across the forearc may be more important in controlling forearc architecture than heretofore acknowledged. Thus, much of the difference between the rugged ESP and smooth WSP may be ascribed the more extensively serpentinized mantle beneath the former relative to that beneath the latter.

A second cause of geological complexity across the Mariana forearc reflects rheological variations of the forearc wedge, and how this interacts with subducted seamounts. Along non-accreting convergent margins like the Marianas, the subduction of seamounts fractures the inner trench wall (von Huene & Scholl 1991). Subducted seamounts continue to focus stress for a consider-

able distance into the subduction zone (Cloos 1992). The restriction of serpentine mud volcanoes to the outer half of the Mariana forearc was suggested by Fryer *et al.* (1985) to mirror the way the mantle wedge responded to these stresses. They argued that the upper 30 km of the forearc wedge behaves in a brittle way, but at greater depths it behaves in a ductile way. Subduction of seamounts fractures the mantle wedge only where this is thinner than 30 km, and these fractures allow channelized fluid flow and ascent paths for serpentinized mantle. At greater depths the mantle wedge deforms without fracturing, and ascent channels are not created. Fryer *et al.* (1985) noted that the forearc lithosphere was 30 km thick \sim 100 km west of the trench, and this corresponds approximately to the ESP–WSP boundary.

The third cause of geological complexity in the Mariana forearc is arc-parallel extension caused by the ‘bowing-out’ of the arc associated with the crescent-shaped opening of the Mariana Trough. We commented on this earlier, but it is worth emphasizing that the very portions of the forearc that are subjected to the greatest arc-parallel extensional stresses lie closest to the trench (except in the Northern Mariana forearc, where oblique convergence apparently translates into dominant strike–slip faulting), where the forearc is most weakened by serpentinization and fracturing due to subducted seamounts. This portion of the forearc also overlies mantle lithosphere that is most likely to undergo brittle deformation, and thus rupture during extension.

Increasing radius of curvature of the Mariana forearc induces arc-parallel extension, manifested as radial, high-angle, normal–slip faults with horst-and-graben structures that are best developed near the trench. Arc-parallel extension can be approximated with a set of finite strain ellipsoids, with their major semi-principal axes everywhere parallel to the strike of the arc. The orientation of conjugate sets of maximum shear strain which accompany extension varies from north-northwest and east–west in the northern Mariana forearc to northwest and northeast in the south. Oblique convergence of the Pacific plate favors a northwest-directed compressional semi-principal axis of the regional stress ellipsoid. The implication of this stress–strain configuration is: (i) predominance of northwest-trending faults in the southern Mariana forearc; (ii) predominance of northeast-trending faults in the central part of the forearc; and (iii) develop-

ment of regionally significant north-northwest-trending sinistral strike–slip faults in the northern Mariana forearc.

A summary of Mariana forearc tectonic elements is presented in Fig. 10(a), where it can be seen that northwest-trending extensional structures in the ESP are restricted to the region between 15° and 17°N. Northeast-trending extensional structures in the ESP become common north of 17°N, and are much more important overall for controlling the ESP structural fabric than the northwest-trending set. This may be related to the increasing importance of northwest-trending left-lateral faults in the northern part of the forearc, because strain associated with northwest-trending sinistral faults favors development of northeast-trending extensional structures. Figure 10(b) presents a further simplification of forearc structures, with a broad zone of forearc extension shown extending from \sim 15°N to 24°N.

The aforementioned three causes may mutually amplify effects and so contribute to localizing the ESP–WSP boundary as the surficial expression of a subhorizontal rheological boundary in the forearc lithosphere. Shallower lithosphere above this boundary dominates the response of forearc lithosphere beneath the ESP, causing the forearc to fracture in response to along-strike extension and seamount subduction. This provides channels for fluids which serve to localize serpentinization of the lithosphere along fractures beneath the ESP. The end result is a close association of forearc faulting and fracturing, fluid flow, and localization of serpentinization, the surficial expression of which is the ESP. The thicker lithosphere beneath the WSP allows ductile deformation at depth, and the lack of pervasive fracturing coupled with a diminished flow of fluid from the subducted slab leads to the greater stability of the inner forearc and the relatively subdued surficial expression of the WSP.

The final cause of geological complexity in the Mariana forearc manifests as the progressive transition from nearly normal convergence in the south to highly oblique convergence in the north. Figure 10(b) shows the relative motion between the Pacific and Philippine plates, after Seno (1989). We have previously pointed out the uncertainties in precise determination of relative motion between these two plates, but in spite of these problems it is still apparent that convergence is nearly orthogonal to the trench in the south and becomes progressively more oblique to

the north. We cannot prove that the highly linear structures that dominate the outer forearc north of 20° are strike-slip faults, but the fact that these structures become more important to the north (as plate convergence becomes increasingly oblique) is most readily explained by such a model. The southernmost part of the inferred strike-slip faults extends almost as far as 18°N, where the relative convergence according to Seno (1989) lies at an angle of 30° to the trend of the trench. These strike-slip faults become increasingly important northward while extensional forearc structures become progressively less well-developed in the same direction.

Two final points should be made regarding the Mariana forearc. First, the frontal arc of the Marianas lies along that portion of the forearc where orthogonal convergence is occurring. We do not know what is the relationship between orthogonal convergence and uplift of the frontal arc, but this behavior may contain important clues about how stresses are transmitted across the forearc; second, there is little evidence of forearc canyons analogous to those identified further north in the Izu forearc (Klaus & Taylor 1991; Smoot 1997; Taylor & Smoot 1984). This may reflect relatively low sediment supply in the south; alternatively, this may reflect continued deformation of the forearc. Forearc submarine canyons initially develop along faults (Smoot 1997), but to grow in size they must be able to maintain a channel for sediment dispersion. Tectonic activity especially in the outer portions of the forearc can disrupt these channels and halt canyon development. All of the processes that are identified here (hydration of forearc lithosphere, along-strike extension, and strike-slip faulting north of 18°N) should still be active in the southern IBM arc system, with the result that the Mariana forearc is still being deformed. It may be that the formation of submarine canyons is related to how long the forearc has been stable. The abundance of mature forearc canyons in the northern IBM forearc and the absence of these features in the Mariana forearc thus may result from the relative tectonic stability of the former and continued faulting and uplift of the latter. The hallmark of the northern IBM forearc (canyons) and that of the Marianas (serpentine mud volcanoes) thus may simply signify the stability of the former and instability of the latter.

CONCLUSION

The Mariana forearc is a wonderfully complex and dynamic tectonic system that also serves as one end-member of the forearc continuum: the non-accretionary forearc. The bathymetric overview presented here allows us to sketch in broad strokes the general processes responsible for its present configuration and opens the door to a wide range of potential investigations into its evolution. Several kinds of studies are called for. Global Positioning Satellite (GPS) campaigns are needed to constrain relative motion between the Philippine and Pacific plates and the Mariana platelet. Such studies will also help constrain deformation within the Mariana platelet. We need better coverage of the forearc using sea floor imaging systems such as Izanagi and HAWAII MR-1 in order to identify areas of active faulting, serpentinite diapirs, and other tectonically active areas. We need a better seismic network in order to resolve where the deformation is presently concentrated within the forearc, and fault-plane solutions are needed to test the idea that strike-slip faulting is important in the northern Mariana forearc. We need better seismic reflection and refraction studies to define the geometry of sedimentary basins and constrain forearc crustal and mantle lithospheric structure. Especially, we need multichannel seismic work to better define the complex interrelationships between forearc faulting and the location of serpentine mud volcanoes. Finally, we need further deep ocean drilling to resolve forearc structures in detail and their relationship to variations in structural provenance of the forearc. We hope that this essay serves to stimulate these and other studies of this paradigmatic forearc.

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