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THE CONTROL OF DEPOSITIONAL DEPTH, TECTONIC UPLIFT, AND VOLCANISM ON SEDIMENTATION PROCESSES IN THE BACK-ARC BASINS OF THE WESTERN PACIFIC OCEAN[1]

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ABSTRACT

Nine sediment types are recognized in cores recovered by the Deep Sea Drilling Project from back-arc basins in the western Pacific. These include submarine fan turbidites, debris flows, silty basinal turbidites, biogenic pelagic carbonate sediments, resedimented carbonates, biogenic pelagic silica sediments, pyroclastics, hemipelagic clays, and pelagic clays. Most of these sediments were deposited independent of basinal rifting (spreading) processes. The transition from biogenic pelagic carbonate sediments into overlying pelagic clays is the only sedimentary sequence dependent on basinal tectonic processes, through post-rifting subsidence associated with heat loss. Hemipelagic clays and silty turbidites are controlled by sediment yield from continental sources and by climatic change, whereas deposition of biogenic pelagic sediments depend on ocean circulation and on latitudinally-defined productivity zones. Coarse pyroclastics are the product of local volcanic periodicity, whereas ash deposition is controlled by seasonal changes in atmospheric circulation. Resedimented carbonates occur in response to slope instability caused by chemical solution or seismicity. Submarine fan turbidites and debris flows are derived from andesitic volcanic arc and obducted land sources. A direct correlation is established between the frequency and periodicity of preserved turbidite deposition on fans and rates of known tectonic uplift and sediment yield in associated sources. Deposition of both fan and debris-flow systems depends on large rates of tectonic uplift in sources, followed by establishment of mature drainage systems that control the sediment yield to fan sites in back-arc basins. Absence of such fan systems in back-arc basins implies that source terrains were characterized by minimal rates of tectonic uplift. The nine sediment types in back-arc basins indicate deep-water deposition. Their association in the basins is governed by their depth-dependent processes of sedimentation rather than tectonic processes per se. The degree of preservation of particular depth zones within other tectonic domains governs the resulting association of preserved sediment types also.

INTRODUCTION

The association of sedimentary and tectonic events has been of interest to geologists since Bertrand (1897) suggested that a correlation existed between sedimentary facies and tectonic elements. With the advent of plate tectonics, new relationships of sedimentary facies to tectonic domain have been suggested (Dott and Shaver 1974; Dickinson 1974). Most of their examples were from complex tectonic terrains characterized by at least two or more tectonic events, including superimposed and resurgent tectonic events.

Several important questions still exist regarding attempts to relate sedimentary facies (and the record of their processes of deposition and diagenesis) to tectonic events. First and foremost, how and why do tectonic processes influence sedimentary processes? Second, can one establish a causative relationship between ~~sedimentary processes and~~ tectonic processes in modern tectonic domains which have been subjected only to a

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Appendix 11

SUMMARY OF RECRUITMENT POLICY

The following policies apply to recruitment of academic appointees:

I. AFFIRMATIVE

single cycle of tectonism and deformation? Are sedimentary processes and associated depositional systems dependent in their temporal and spatial distribution on tectonic processes, or is sedimentation independent of tectonics and if so, why?

This paper aims to address these problems in a single tectonic domain that is still active during its first cycle of development. This tectonic domain is the back-arc basin province of the western Pacific Ocean. Sediment data was obtained from observation and compilation of data from cores recovered by the Deep Sea Drilling Project (DSDP).

Back-Arc Basin History.—The development of back-arc basins on overriding plates of active continental margins has been studied by workers in several geophysical field campaigns (Karig 1970, 1971, 1975; Hayes 1980, 1983) and in drilling programs by the Deep Sea Drilling Program (DSDP). These studies suggested that most back-arc basins form by rifting, indicated mostly by a striped magnetic anomaly pattern in the basin center, which is typical of spreading centers (Watts and Weissel 1975; Watts et al. 1977; Weissel 1981; Karig et al. 1978). Transform faulting in the basins forms a rough topography and unstable spreading patterns (Karig et al. 1978; Hussong and Sinton 1983). Both the acoustic and real basement of the basins consist of oceanic crust almost identical to mid-ocean-ridge tholeitic basalt (Hawkins 1977). Rifting processes are expressed both symmetrically and asymmetrically in the magnetic-anomaly pattern. The duration of rifting tends to range from five to 16 m.y. (Weissel 1981) and, in a few cases, multiple rifting events are known. The basins are characterized by a history of large heat flow which appears to correlate well with times of rifting or the several million years after rifting ceased (Karig 1971; Karig et al. 1978). Older basins, therefore, are characterized by normal heat flow, whereas the youngest basins show large rates of heat flow.

DSDP Sites.—Sites 53 and 54 (Fischer, Heezen et al. 1971), Sites 203, 205, 206, and 210 (Burns, Andrews et al. 1973), Sites 285, 286, and 287 (Andrews, Packham et al. 1975), Sites 290, 291, 292, 293, 294, 295, 297, 299, 300, 301, and 302 (Karig, Ingle et al. 1975), Sites 442, 443, 444, 445, and 446 (Klein, Kobayashi et al. 1980), Sites 449 and 450 (Kroenke, Scott et al. 1981) and Site 453 (Hussong, Uyeda et al. 1981) were used in this paper (fig. 1). Drilling results and their synthesis with known regional geology are reviewed in the initial report citations listed with the above sites.

The depositional history of sedimentation in these basins is poorly known and was developed on a leg-by-leg basis in an uneven fashion because of variable rates of sediment recovery and the interests of the shipboard party. Thus Bouma (1975) described turbidite deposition in the Toyama submarine fan, Klein (1975*a*, 1975*b*) described depositional facies from the southwest Pacific, and White et al. (1980) reported on the lithofacies and sedimentary petrology of sediments from the Northwest Philippine Sea. No overall synthesis of sediment data exists from these 34 sites.

Methods.—Sediment types were defined in DSDP cores according to their lithology, sediment texture, association of sedimentary structures, vertical sequences of structures and lithologies, biogenic structures, and mineral composition. These features were identified from core examination by the author on ship and on shore at the DSDP West Coast Repository, La Jolla, California. Shore-based and shipboard descriptions in the individual Initial Reports cited earlier supplemented many of the observations.

Stratigraphic intervals in which different sediment types occur were tabulated, and their age was recalibrated using shore-based and shipboard paleontological zonations. Nine sediment types occur in the back-arc basins of the western Pacific; their age and depth intervals by site are summarized in Klein and Lee (1984, their table 1).

SEDIMENT TYPES

Debris Flows.—Debris flows are predominantly thick- to medium-bedded conglomerates. These conglomerates are massive—almost no stratification is observed. Local horizons of parallel laminae are extremely rare. Reverse-graded bedding was observed in a few instances. Clast size ranges from granule to small cobbles with the mean approximately pebble-size. The clasts are dispersed in a matrix of volcanic sand and silt with accessory volcanic glass shards (fig. 2*A*, 2*B*, 2*C*). Some clasts show slight imbrication

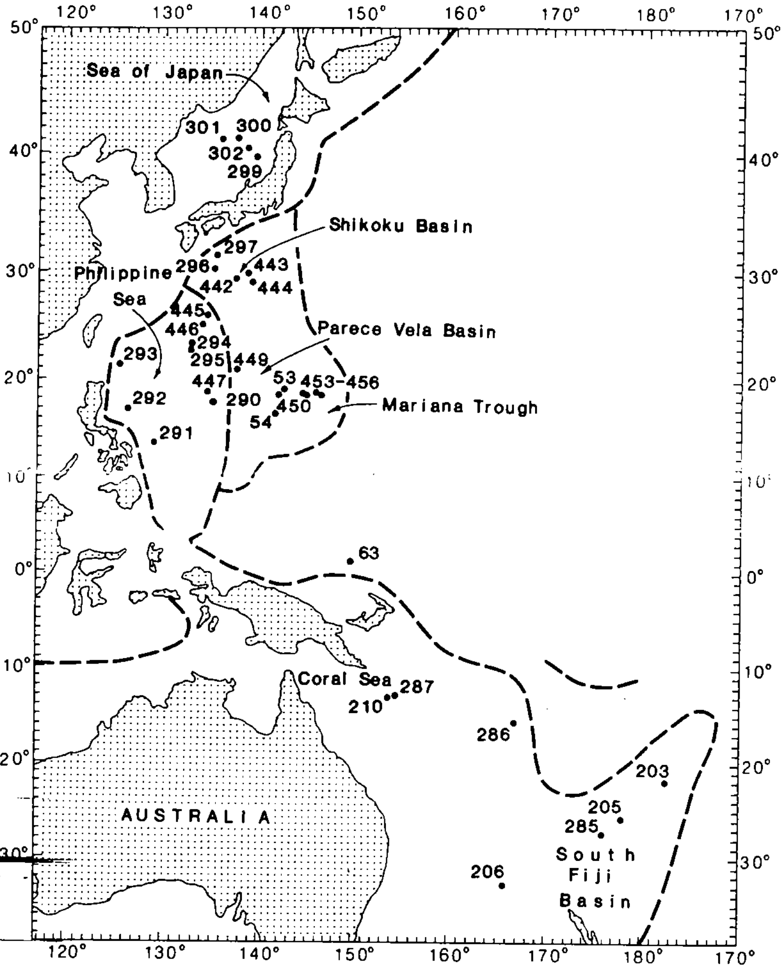

FIG. 1.—Location of Deep Sea Drilling Project Sites in back-arc basins of the Western Pacific.

and a framework fabric (fig. 2*B*, 2*C*). The larger clasts consist primarily of basalt and andesitic volcanic rock fragments. Accessory clasts of granodiorite, hornblende schist, rhyolite, chert, limestone fragments and sandstones are also present, and intraformational fragments of mudstone (fig. 2*A*) were observed. Associated with the clasts are fragments of shallow-water fossils including corals, bryozoans and molluscs (fig. 2*A*), and foraminifera (fig. 2*B*).

Debris flows were observed in cores recovered from the New Hebrides Basin (Site 286), the southwest Philippine Basin (Site 290), the edge of the Daito Basin (Site 445), and the west side of the Parece Vela Basin (Site 447). Debris flows comprise 1.2% of the total thickness of cores recovered from back-arc basins by DSDP (see Klein and Lee, 1984 their table 2).

Sandy debris flows, possibly of fluidized flow origin, also were observed, particularly at Site 445 where a medium-grained sandstone containing dish structures was recovered (fig. 2*D*). The dish structures have been related to a remobilized fluidized debris flow by Busch (1976). The boundary conditions between both classes of gravity transport and deposition are sufficiently transitional that a continuum must be recognized (Lawson 1982), hence the incorporation of these particular sandstones with the debris flows.

Submarine Fan Depositional System.—Submarine-fan depositional systems consist mainly of interbedded turbidite sandstone

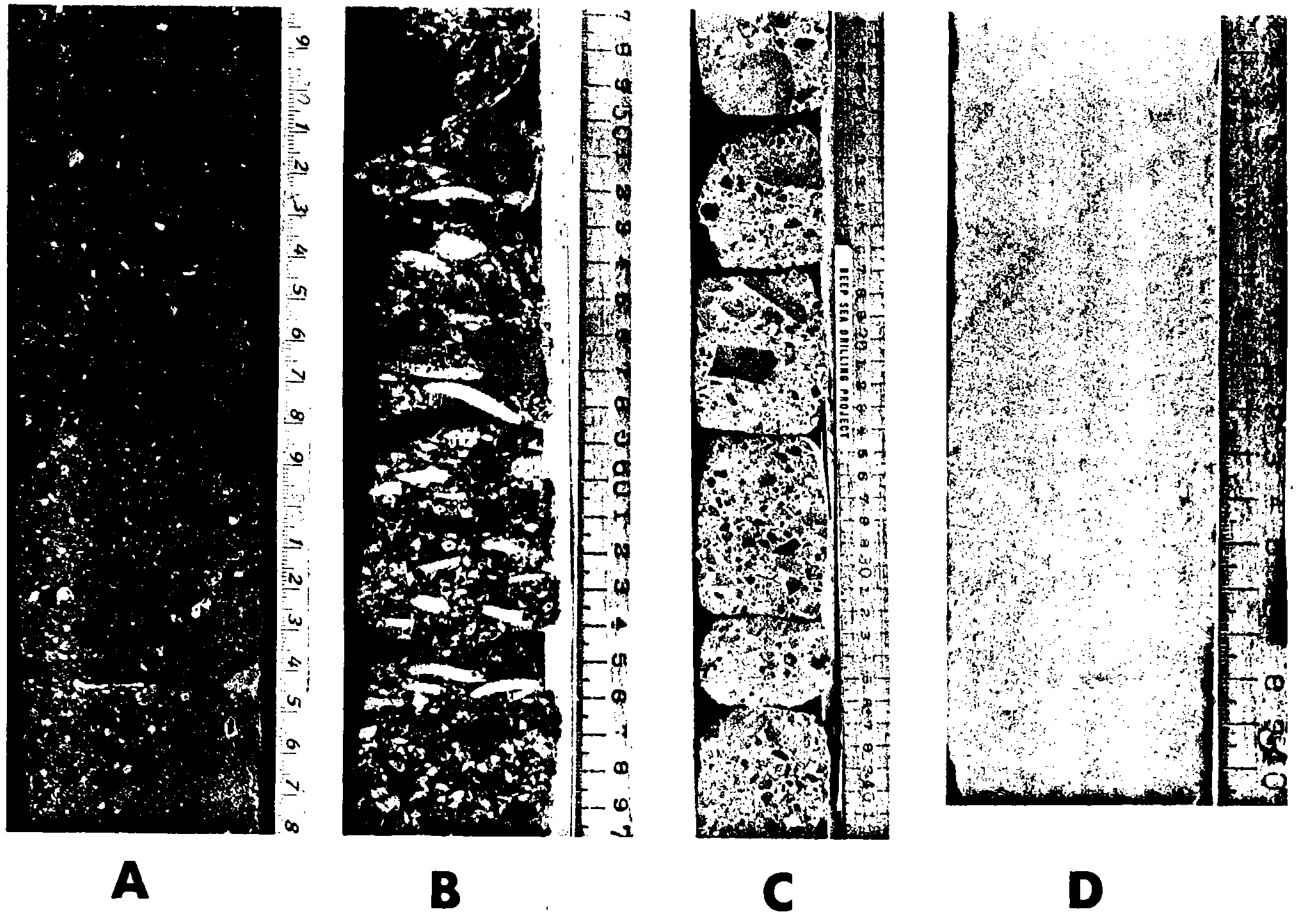

FIG. 2.—(*A*) Debris flow conglomerate. Andesitic volcanic rock fragments (dark) and shallow-water fossils (white) consisting of foraminifera, corals, bryozoans, pelecypods, and intraformational sedimentary rock fragment (between 94 and 95 cm). New Hebrides Back-arc Basin. 286-22-3 (78–98 cm). Scale in cm. (*B*) Debris flow conglomerate with andesitic rock fragments (dark and light gray), and shallow-water fossils (white) including *Nummulites boninensis* fragments. North side of Daito Basin. 445-74-3 (47–67 cm). Scale in cm. (*C*) Debris flow conglomerate with angular volcanic rock fragments, West Philippine Basin. 290-8-5 (5–42 cm). Scale in cm. (*D*) Dish structures in debris flow sandstone. North side of Daito Basin. 445-57-7 (23–40 cm). Scale in cm.

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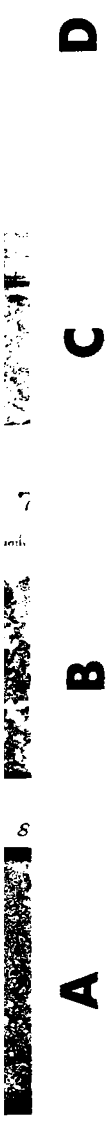

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and mudstone. These fans are recognized from a combination of sediment data, morphology, and seismic thickness. At Site 299 in the Toyama Fan, fan morphology was determined from bathymetric mapping (Nash 1981), and seismic data (Karig, Ingle et al. 1975) and sediment data (Bouma 1975; Nash 1981). In the Shikoku Basin, contour mapping of sediment thickness from seismic surveys (Karig 1975; White et al. 1980) shows a midfan system at Site 297 and distal fan toes (mostly of hemipelagic clays) at Sites 442, 443, and 444. In the Coral Sea Basin, a major fan was penetrated at Sites 210 and 297, with morphological expression and seismic surveying confirming the sedimentological interpretation (Burns, Andrews et al. 1973; Andrews, Packham et al. 1975).

Within the submarine-fan depositional system, two subsystems were recognized which differ in lithology, texture, sedimentary structure associations, bedding style, occurrence and vertical sequence. These are the inner and midfan subsystem and the outer-fan subsystem.

The Inner and Midfan subsystem consists of interbedded thin- to medium-bedded sandstones and mudstones. Locally, pebble horizons occur. The sandstones are predominantly coarse-grained, with accessory medium-grained layers. The sand-sized components are sub-rounded to angular and contain volcanic rock fragments of basalt, microdolerite, augite, olivine, orthopyroxene, clinopyroxene, and plagioclase. Carbonate fragments of shallow-water foraminifera, pelecypods, and recrystallized limestone occur in accessory quantities. Traces of glauconite and quartz were observed.

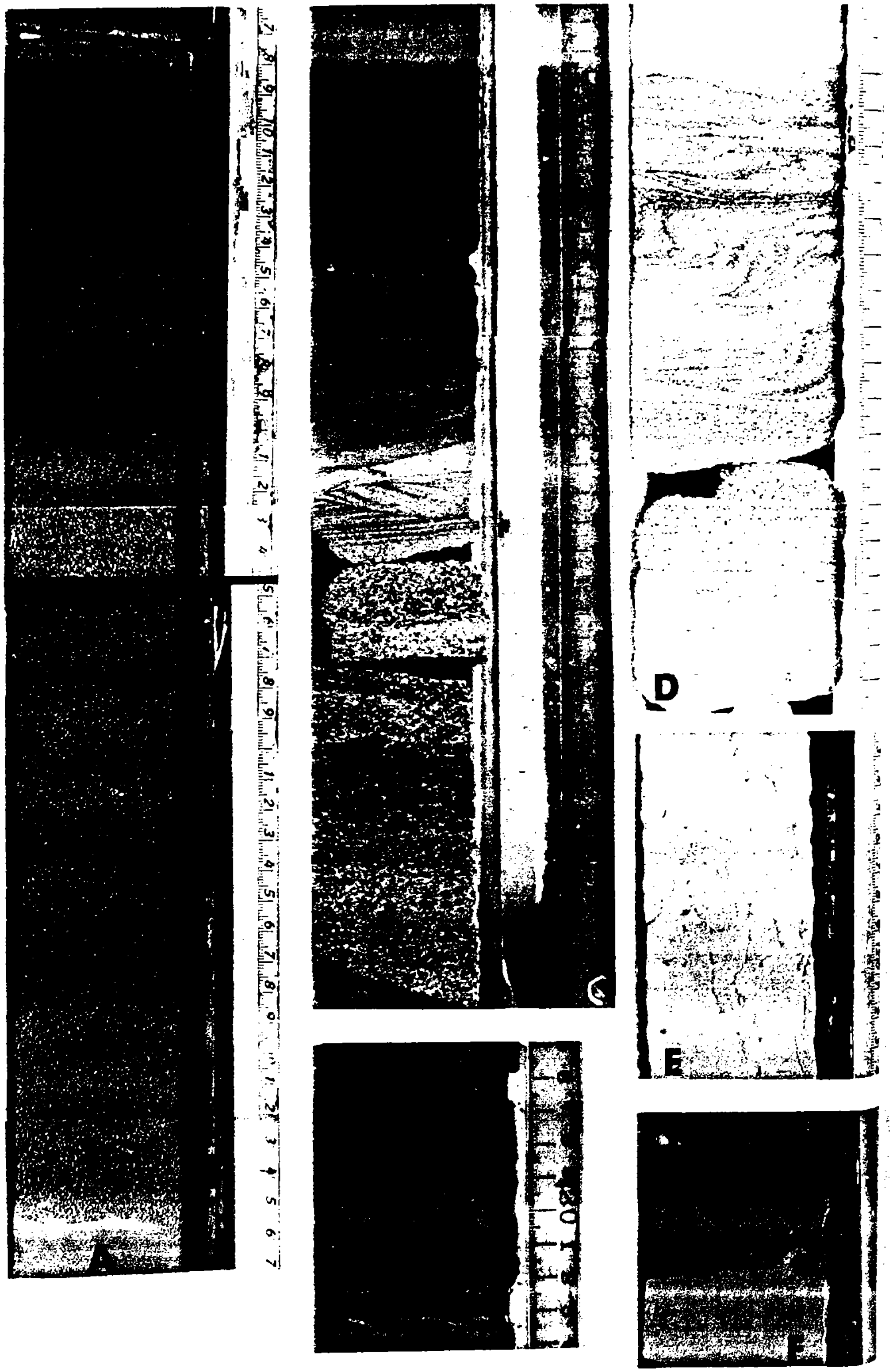
Various sedimentary structures occur in these sandstones. They include flame structures (fig. 3*F*), load casts (fig. 4*E*, 4*F*), microfaults (fig. 3*C*), slump folds, micro-cross-laminae (fig. 3*B*, 3*D*), convolute laminae (fig. 3*D*), in-phase waves, dewatering pipes (fig. 3*E*), multiple graded bedding (fig. 3*A*), and gradational tops of sandstone beds. Complete Bouma sequences are rare but were observed from several sites including 445 and 446 (fig. 3*C*, 3*D*). Partial Bouma sequences are more common (fig. 3*A*), the T_{bde} type of sequence being observed most frequently. Coarse-tail graded bedding has been found also. Trace fossils are common in this subsystem in several sites, with *Zoophycos*, *Chondrites*, *Planolites*, and *Spirophycos* having been reported (Andrews, Packham et al. 1975; Ekdale 1980). Mudstones within this subfacies are massive to parallel-bedded. Thin, well-sorted silty laminae alternating with thin clayey to silty-clayey laminae are most common within these parallel-laminated mudstones.

The Inner and Midfan subsystem occurs at Sites 285, 286, 299, 445, and 446. This subsystem comprises 6.2% of all material recovered in back-arc basins by DSDP with the entire submarine-fan system comprising about 20% of the total thickness of sediment recovered.

The Outer Fan subsystem consists of interbedded sandstone, siltstone, and mudstone distinguished from the Inner and Midfan subsystem by its thin-bedded, medium- to fine-grained sandstones. The sands and sandstones in this system are well-sorted, and the grains are well-rounded to sub-rounded. Sand clasts are composed of andesitic and basaltic volcaniclastic fragments and plagioclase. Sedimentary structures include parallel-laminae, micro-cross-laminae, and graded bedding. Lower sandstone contacts are generally sharp, whereas the upper contact may be either gradational or sharp. Partial Bouma sequences are present, with the T_{cde} and T_{de} sequence being most common. Some of these sequences, such as at Site 299, were deposited in the inter-channel fan region of submarine fans (Bouma 1975). Mudstone layers interbedded with these sandstones are medium- to thin-bedded with silty parallel laminae.

Within this subsystem, very fine sand, silt, and clay are organized in a cyclic fashion. The cycles consist of a sharp base and a basal very fine sand to silty sand, overlain by a silt or siltstone. These silts grade upward into a silty clay, which caps the cycle or in turn grade upward into a clay or claystone (see Klein 1975*b*, his fig. 7). These cyclic alternations were observed at Sites 210 and 287 in the Coral Sea Basin, where they were attributed to outer fan development following tectonic uplift of the Owen-Stanley Range (Klein 1975*a*, 1975*b*; 1984), and at Site 299 in the Sea of Japan (Bouma 1975), where they appear to be of interchannel fan origin.

This subsystem is 13.9% of the total sediment thickness recovered from back-arc ba-



sins by DSDP; the entire submarine fan depositional system comprises 20.0% of the entire recovery of sediment cores. The Outer Fan subsystem was observed in cores recovered from Sites 210, 296, 287, 297, 299, 446, and 453.

Silty Basinal Turbidites.—These turbidites are characterized by silt and siltstones, with both sandy silt and clayey-silt present; they are interbedded with clay, claystone, and silty clay. Interbedded volcanic ash layers are common.

The silts and interbedded lithologies are thin-bedded. Individual silt grains are angular to subangular and contain plagioclase, orthopyroxene, clinopyroxene, magnetite, palagonite, and zeolites. Sedimentary structures present include graded bedding, parallel laminae, micro-cross-laminae, and bioturbation.

The lithologies and structures are organized into a vertical sequence consisting of a sharp basal scour overlain by a graded silt or siltstone (locally sandy), which grades upward into a clayey silt and is capped with clay or claystone. Sequences of similar silty basinal turbidites were reported from a Pliocene and Miocene back-arc basin sequence in Hokkaido Island, Japan (Klein et al. 1979).

These turbidites comprise 5.7% of the total volume (as determined from thickness) of sediment cores recovered by DSDP from back-arc basins. They were observed only in cores recovered from Sites 293 and 301.

Hemipelagic Clays.—These sediments consist of interbedded and mixed clay and silt showing fair sorting, and contain illite, chlorite, montorillonite, kaolinite, muscovite, quartz, orthoclase, plagioclase, smectite, and zeolites (Chamley 1980*a*, 1980*b*). Interbedded thin ash layers are extremely common, as are thin chert layers and thin biogenic pelagic carbonate and silica pelagic ooze. Some of

FIG. 3.—(*A*) Multiple graded beds in sandstone, th
New Hebrides Basin. 286-26-3 (7–47 cm). Scale in c
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laminated "C" interval (127–132 cm), the inter-bedd
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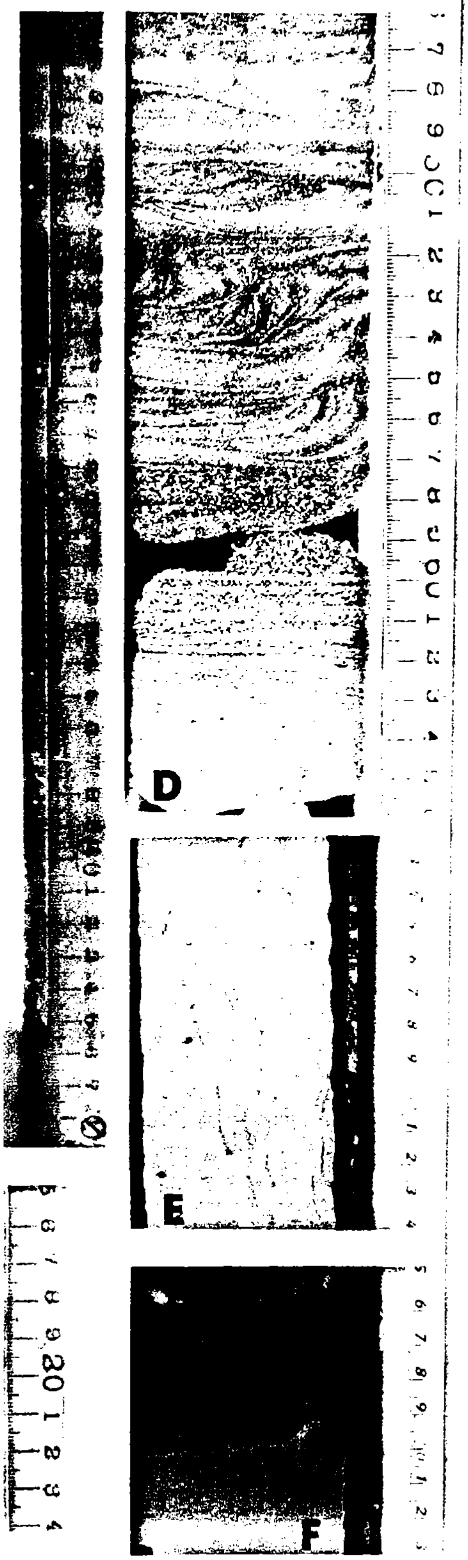
Hebrides Basin. 286-29-3 (125–133 cm). Scale in cm.



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The stratigraphic distribution of clay minerals at most sites is variable, except in the northwest Philippine Sea. Here Chamley (1980*a*, 1980*b*) demonstrated that, since the early Miocene, the illite content relative to other clay mineral types has increased up to the present time. This increased illite content was attributed to coeval global cooling trends causing changes in the nature of clay mineral weathering in the Chinese mainland which acted as a source. Thus, in this case, climatic change controls clay mineral content.

Sedimentary structures observed in these varicolored hemipelagic clays include bioturbation, mottling, parallel laminae, and graded bedding (in ash layers). Most of the clays, however, are structureless.

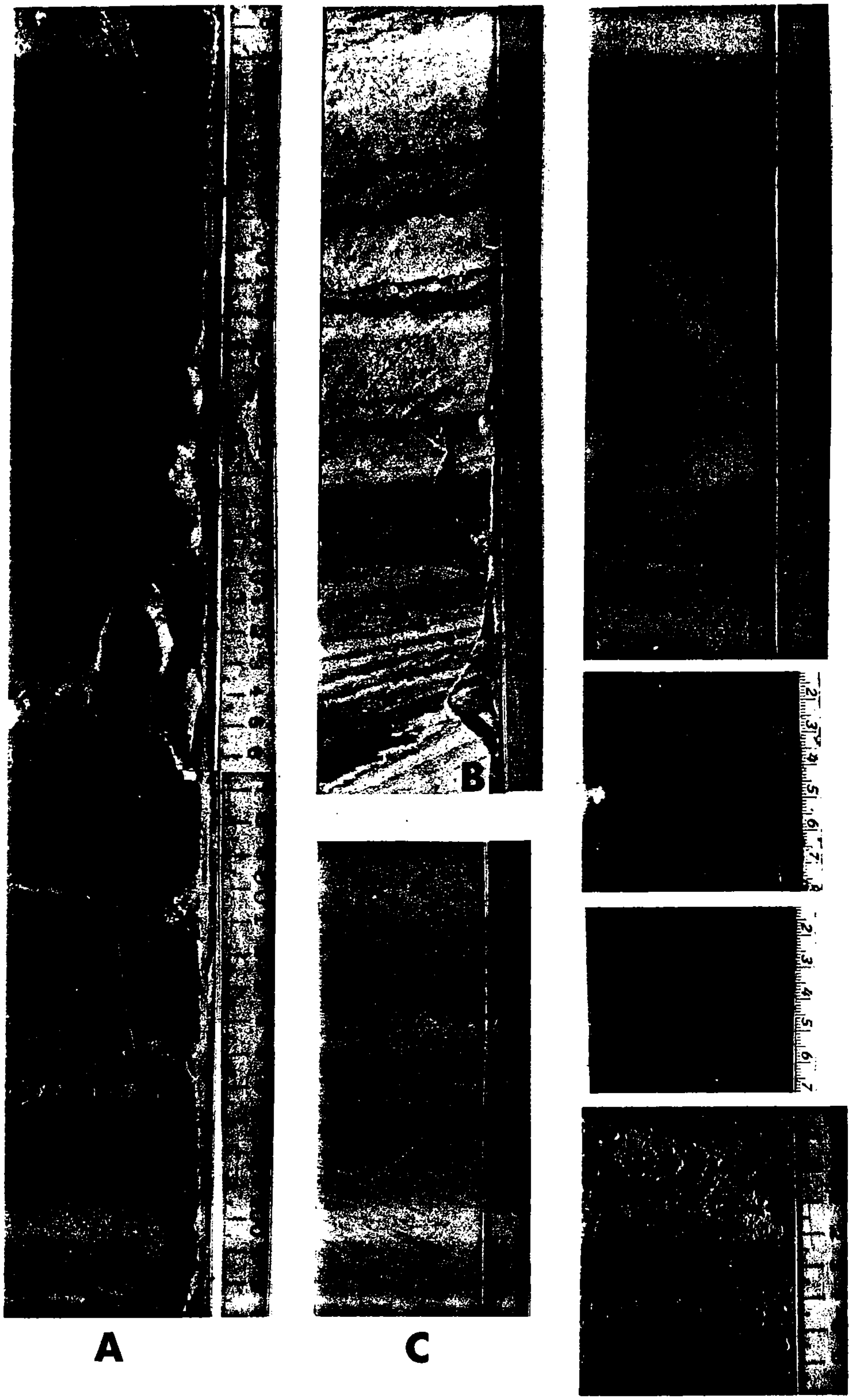
Hemipelagic clays are the second-most widespread sediment type in back-arc basins, comprising 21.8% of the total thickness of cores recovered from these basins by DSDP. They occur at Sites 53, 206, 210, 298, 290, 291, 294/295, 297, 301, 302, 442, 443, 444, 446, 453, 454, and 456.

Pelagic Clays.—This sediment consists of red or dark reddish brown, structureless clay. It contains iron-manganese micronodules, quartz, plagioclase, orthoclase, magnetite, volcanic glass, montmorillonite, illite, smectite, foraminiferal remains, diatoms, and sponge spicules. At a few sites, very thin layers of volcanic ash are interbedded within these clays.

This clay comprises 4.2%, volumetrically, of the thickness of sediment recovered by DSDP from back-arc basins. It was observed only at Sites 63, 205, 285, 286, 294/295, 446, 447, 449, and 450, usually in the uppermost part of the stratigraphic section recovered at each site.

Biogenic Pelagic Silica Sediments.—

FIG. 3.—(*A*) Multiple graded beds in sandstone, the upper one grading into parallel-bedded sandstone. New Hebrides Basin. 286-26-3 (7–47 cm). Scale in cm. (*B*) Complete Bouma sequence in sandstone with graded "A" interval (133 to 148 cm), the parallel-bedded "B" interval (132 to 133 cm), the micro-cross-laminated "C" interval (127–132 cm), the inter-bedded silt and clay "D" interval (120–127 cm) and the pelagic clay "E" interval (114–120 cm). Daito Basin. 446-39-1 (114–149 cm). Scale in cm. (*C*) Micro-faulted sandstone layer. North side of Daito Basin. 445-71-1 (15 to 24 cm). Scale in cm. (*D*) Close-up of part of a complete Bouma Sequence showing upper part of graded interval (63 to 66 cm), parallel-laminated "B" interval (59–63 cm), and convolute bedded and micro-cross-laminated "C" interval (46 to 59 cm). North side of Daito Basin. 445-71-1 (48–66 cm). Scale in cm. (*E*) Vertical water escape pipes in mudstone. New Hebrides Basin. 445-71-1 (48–66 cm). Scale in cm. (*F*) Flame structure in base of graded sandstone. New Hebrides Basin. 286-29-3 (125–133 cm). Scale in cm.



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(32–37 cm). Scale in c

These are very fine-grained radiolarian, diatomaceous, or silicoflagellate oozes or chert. In some instances, other components are present including clay, pumice fragments, quartz, nannofossils, and plagioclase. The cherts occur either as massive layers (such as at Site 445) or as nodules. Interbedded volcanic ash layers occur and are very thin.

This sediment type comprises 4.3% of the total thickess of cores contained by DSDP from back-arc basins, and occurs at Sites 53, 291, 301, 302, 445, and 449.

Biogenic Pelagic Carbonates.—This is the most dominant lithology in western Pacific back-arc basins. It consists of fine-grained ooze, chalk, and limestone with the principal components being pure end members of nannofossils and foraminifera or mixtures of these two organisms. Some of the oozes are clayey, with up to 40% hemipelagic clay. Radiolaria, sponge spicules, and silicoflagellates are subordinate components. Besides clay minerals, quartz, feldspar, opal, and zeolites occur in the clayey carbonates, as do chert nodules and layers. Volcanic ash layers, although very thin, also occur.

The only observed sedimentary structures consist of parallel laminae separated by larger and small concentrations of foraminifera, or laminae of ash interbedded with carbonate materials. Generally, these sediments lack distinctive sedimentary structures. Biogenic mottling was observed, however (Ekdale 1980).

Volumetrically, pelagic carbonates comprise 23.8% of the total thickness of sediment recovered by DSDP from Pacific back-arc basins. They were observed at Sites 53, 63, 203, 205, 206, 210, 285, 286, 287, 292, 297, 443, 445, 449, and 456.

Resedimented Carbonates.—Resedimented carbonates consist also of nannoplankton and foraminiferal ooze, chalk, or limestone and contain the identical mineral components as the Biogenic Pelagic Carbonates. The distinguishing characteristics are the presence of reworked nannoplankton and foraminifera and a variety of sedimentary structures indicating resedimentation by gravity processes. Shallow-water foraminiferid, coralline algal, pelecypod, coral, and bryozoan fragments are mixed with the deeper-water biogenic components. Oolites have been recovered from a few sites.

Well-developed sedimentary structures are the chief diagnostic feature in these sediments. Several workers (Klein 1975*a*, 1975*b*; White et al. 1980) report graded bedding (fig. 4*A*), parallel bedding (fig. 4*A*), microfaults (fig. 4*B*), distorted burrows (fig. 4*C*), slump folds (fig. 4*D*), slump blocks, load casts, and micro-cross-laminae. Some of these structures are organized into partial Bouma sequences, including $T_{a,b,e}$ (fig. 4*A*) and $T_{b,c,e}$. One such sequence was resedimented a second time because it is traversed by slump faults with associated offsets (fig. 4*A*).

These carbonates comprise 9.5% of the total sediment thickness recovered by DSDP from back-arc basins. Although observed only at Sites 206, 286, and 445, it is noteworthy that 80% of the total carbonate section at Site 445 (White et al. 1980) and approximately 23% of the total carbonate section at Site 206 is represented by reworked carbonate, suggesting that this mode of sedimentation may be more widespread in oceanic settings than previously supposed (Klein 1975*b*).

Pyroclastics.—Pyroclastics are composed of volcanic ash and tuff that contain glass shards, altered glass, vesicular glass, clay minerals, quartz, feldspar, pyroxene, pyrite, foraminifera, nannofossils, radiolarians,

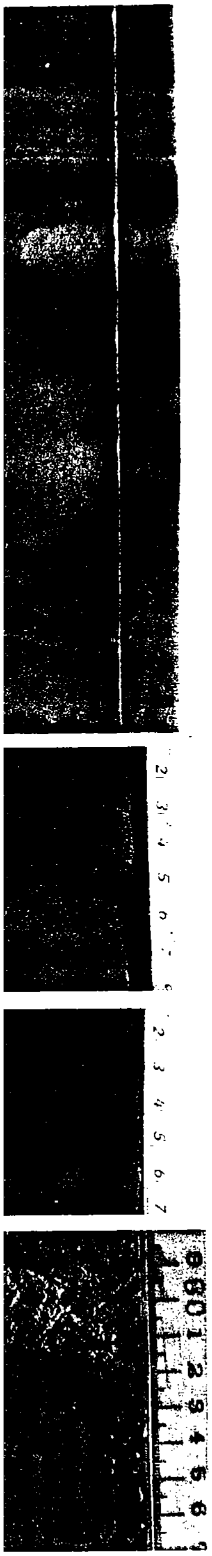

FIG. 4.—(*A*) Resedimented carbonate organized into partial Bouma Sequence with sharp base, overlain by graded and parallel-laminated foraminiferal sand (95–102 cm) overlain by graded nannoplankton-foraminiferal ooze, and capped by nannoplankton-bearing clay (62 to 80 cm). Entire sequence cut by two slump faults. North side of Daito Basin. 445-36-4 (62–103 cm). Scale in cm. (*B*) Microfaulted beds in resedimented carbonate. North side of Daito Basin. 445-51-4 (7–35 cm). Scale in cm. (*C*) Resedimented carbonate showing bioturbation. Upper interval (28 to 35 cm) is undisturbed, whereas sediment below (35 to 45 cm) is disturbed. Lower part represents debris flow unit that has been deformed, whereas upper part represents rigid plug on top of debris flow. North side of Daito Basin. 445-52-2 (128 to 146 cm). Scale in cm. (*D*) Slump fold in resedimented carbonate. North side of Daito Basin. 445-51-3 (25–46 cm). Scale in cm. (*E*) Load pocket and load cast at base of graded sandstone. New Hebrides Basin. 286-25-4 (12–18 cm). Scale in cm. (*F*) Load casts at base of graded sandstone with small flame structures. New Hebrides Basin. 286-29-2 (32–37 cm). Scale in cm. (*G*) Graded ash bed. Shikoku Basin. 297-8-3 (78 to 87 cm). Scale in cm.

sponge spicules, and plant debris. The ash and tuff beds consist of coarse silt to medium- and fine-grained sand. Lithified ash and pumice pebbles are common. Many of the ash beds are graded (fig. 4*G*), with parallel laminae, mottling, and some unidentified burrow features. Thick graded ash beds and coarse pyroclastic beds such as at Sites 447 and 450 occur as aprons fringing large volcanic cones or active volcanoes (Rodolfo and Warner 1980; Karig 1983).

Pyroclastics comprise 9.5% of the total thickness of sediment cores recovered from back-arc basins by DSDP. Accessory ash beds are common within all sediment types, but their thin nature makes it difficult to determine their volumetric proportion. Pyroclastics occur at Sites 53, 54, 203, 205, 285, 286, 290, 297, 302, 442, 444, 447, 450, and 455.

RELATIONSHIP OF SEDIMENT TYPES TO GEODYNAMIC EVENTS

Sedimentation and Rifting Processes.—Rifting is the primary tectonic process forming back-arc basins. It occurs in a mode and scale similar to sea-floor spreading processes in mid-ocean ridges. Magnetic anomalies are the primary evidence for rifting, exhibiting symmetrical or asymmetrical striped patterns which are progressively older from the spreading center to the basin flanks (Watts et al. 1977; Weissel 1981). The magnetic anomaly ages of each of the back-arc basins drilled by DSDP were summarized by Klein and Lee (1984, their table 3).

Correlation diagrams were constructed to compare the timing of sediment types, rifting processes, and andesitic volcanism (figs. 5 to 11) in each of the back-arc basins so as to establish a causal connection among these processes. Examination of these diagrams shows three relationships pertaining to tectonic and sedimentary processes. First, the presence of a large variety of sediment types is independent of either time or tectonic processes. Second, the upward (or younging) transition from biogenic pelagic carbonates to pelagic clay is controlled, as shown later, by basin subsidence in response to heat loss. The third relationship is among submarine fan-systems, debris flows, and tectonic uplift in source terrains (See Klein 1984; and discussion to follow). Figures 5 through 11 demonstrate these relationships on a basin-by-basin comparison.

In the Sea of Japan (fig. 5), rifting occurred during Miocene time (21 to 9 MY) and then ceased (Kobayashi and Isezaki 1976). None of the Deep Sea sites reached basement. The oldest recovered sediments are of Upper Miocene age and were deposited well after rifting ceased. Post-rifting sedimentation is variable and included submarine fan, biogenic pelagic silica, hemipelagic clay, and silty turbidite deposition.

In the Shikoku Basin (fig. 6), rifting began in mid-Oligocene time (25 MY), whereas sedimentation began in earliest Miocene time (22.5 MY) in the western and northern parts of the basin (Sites 297, 442). Here sedimentation consists primarily of hemipelagic clay, although some submarine fan deposition occurred at Site 297 in the northern Shikoku Basin before and after rifting ceased (14 MY). Sedimentation continues into the present, dominated by hemipelagic clay.

Rifting in the Parece Vela Basin (fig. 6) started in mid-Oligocene time (30 MY) and ceased in the early Miocene (17 MY). The oldest sediments are earliest Miocene in age (22.5 MY) and consist of pyroclastics found at Sites 53 and 54. Slightly younger biogenic carbonates, interbedded and capped with pelagic clay, were recovered at Site 449. Pyroclastic sedimentation and biogenic sedimentation occurred simultaneously with rifting. The pyroclastic deposition represents part of a regional pattern of volcanism (Kennett et al. 1977) and, although this volcanism appears to be independent of basinal rifting events (Scott and Kroenke 1980), some argue that it was concurrent with back-arc spreading (Karig 1983). Pelagic clay deposition at Sites 449 and 450 followed basinal rifting but required basinal subsidence below the CCD. This subsidence is dependent on heat loss in the basin as the heat-flow regime shifted from a larger rate during rifting to a normal rate after rifting ceased. In this case, fluctuations in the CCD produced a repeated succession (fig. 6).

Rifting in the West Philippine Basin (fig. 7) occurred from early to late Eocene (52–37 MY). Sedimentation was coeval with the latest stages of rifting at only three sites; the other sites recovered sediment deposited after rifting. In this basin, no particular sediment type was found to be coeval with rifting.

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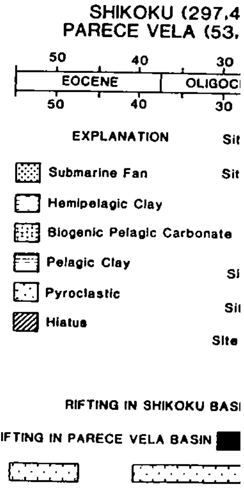

FIG. 6.—Correlation di
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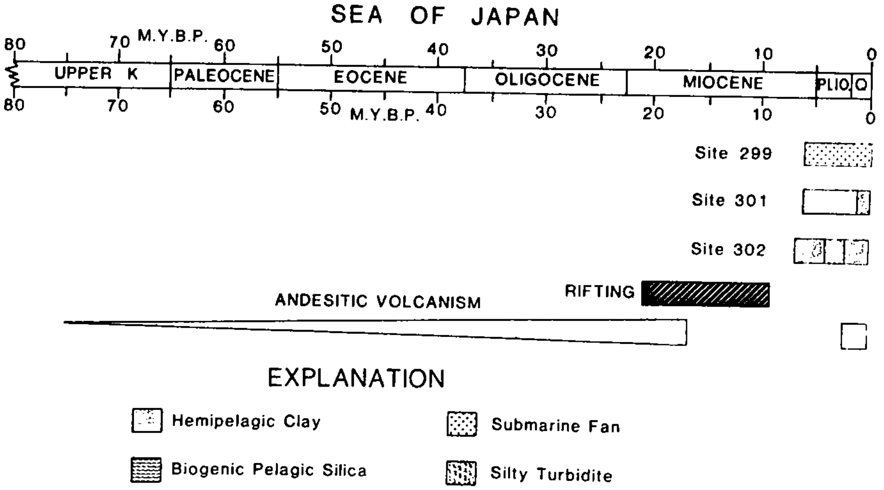

FIG. 5.—Correlation diagram showing distribution of sediment types, times of rifting (Kobayashi and Isezaki 1976) and duration of andesitic volcanism (Sugimara et al. 1963; LeBas 1982) in Sea of Japan and Japanese Islands, respectively (B—sites penetrating basement).

In the Mariana Trough, rifting started in late Miocene time (7 MY) and has continued to the present (fig. 8) in an unstable mode (Hussong and Sinton 1983). The oldest sediments penetrated are Pliocene (5 MY). Hemipelagic clays, debris flows, submarines fans, and biogenic pelagic carbonates occur coevally with rifting.

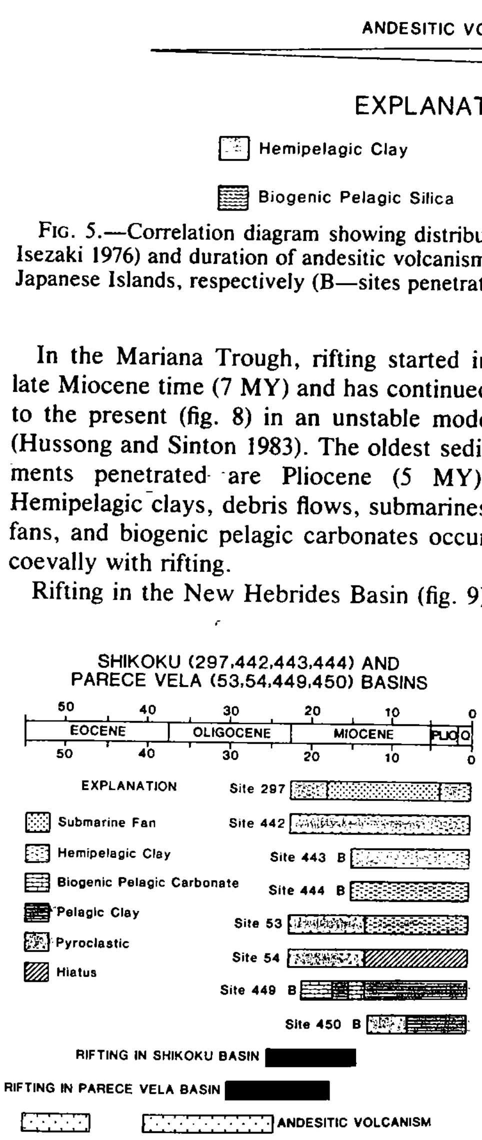

FIG. 6.—Correlation diagram showing distribution of sediment types in DSDP sites and times of rifting in Shikoku Basin (Kobayashi and Nakada 1978; Shih 1980) and Parece Vela Basin (Langseth and Mrozowski 1981) and duration of volcanism in adjoining arc terrains (Shiraki et al. 1978) (B—sites penetrating basement).

Rifting in the New Hebrides Basin (fig. 9) began in earliest Eocene time (55 MY) and ended in the late Eocene (42 MY). During the latest stage of rifting, both submarine fan and debris flow sedimentation occurred from sediment yield off New Caledonia (Kroenke 1982). The pelagic biogenic carbonate-to-pelagic clay transition occurs in this basin and records a history of basin subsidence below the CCD by heat loss. The middle-to-late Miocene hiatus at this site was attributed to changes in ocean circulation associated with rifting of Australia from Antarctica (Andrews, Packham et al. 1975).

Rifting in the South Fiji Basin (fig. 10) was limited to the Oligocene (32–26 MY), concurrent with times of pyroclastic and biogenic pelagic carbonate deposition only (Site 205). Pelagic clay and submarine fans occur also, with the pelagic clays having been emplaced after basin subsidence below the CCD. The Miocene hiatus at Site 205 is attributed to changes in ocean circulation associated with rifting of Australia from Antarctica (Andrews, Packham et al. 1975).

In the Lau Basin (fig. 10), rifting started in earliest Pliocene (5 MY) and has continued to the present. Concurrent sedimentation consists of pyroclastic and biogenic pelagic carbonate deposition only (Site 203).

Figure 11 compares times of rifting with sedimentation in the Daito Basin, East Caroline Basin, and Coral Sea Basin. Data from the New Caledonia Basin (Site 206), for

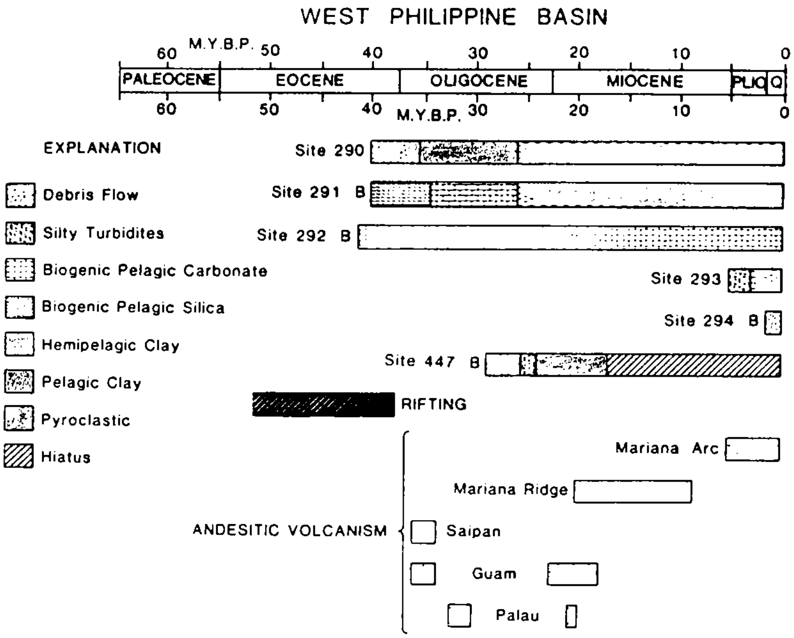

FIG. 7.—Correlation diagram showing distribution of sediment types in DSDP sites and times of rifting in West Philippine Sea (Louden 1977; Watts et al. 1977; Mrozowski et al. 1982), and times of andesitic volcanism in adjoining arc sources (Scott and Kroenke 1982; Hussong and Uyeda 1981; Meijer et al. 1983). (B—sites penetrating basement).

which no rifting age determination exists, are shown also. These basins are so grouped because no age determinations exist for potential volcanic arc sources adjoining the basins. In all these basins, variable sedimentation events may or may not be coeval with rifting (fig. 11) because the controlling processes of sedimentation are independent of rifting.

Summary of Sedimentation-Rifting Relations.—Even cursory examination of Figures 5 through 11 shows that rifting events have occurred coevally with a large variety of sedimentation events, but that the two processes operated independently. In this case, a coincidence represented by an association of sedimentation and rifting events does not

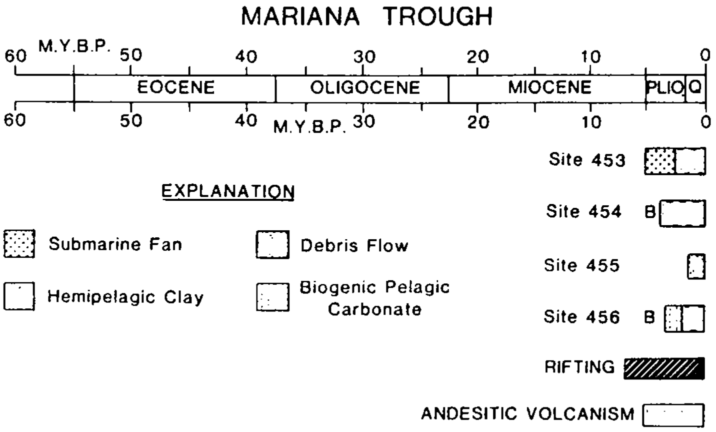

FIG. 8.—Correlation diagram showing distribution of sediment type in DSDP sites and rifting (Hussong and Uyeda 1981) in Mariana Trough, and duration of andesitic volcanism in adjoining arc sources (Scott and Kroenke 1982; Hussong and Uyeda 1981; Meijer et al. 1983).

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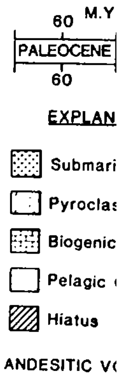

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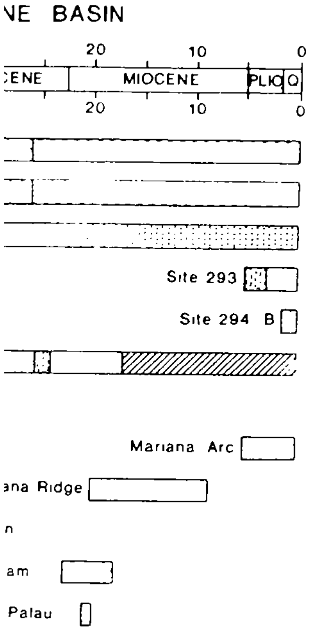

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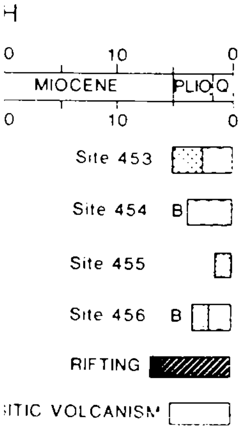

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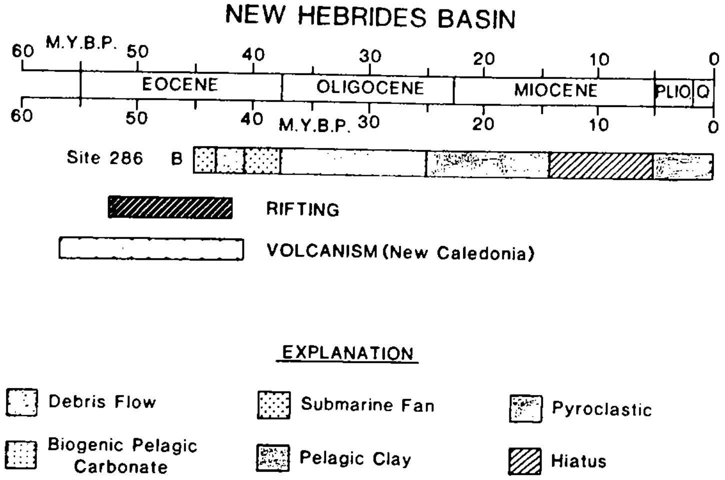

FIG. 9.—Correlation diagram showing distribution of sediment types at Site 286, times of rifting in New Hebrides Basin (Lapouille 1978; Weissel et al. 1982) and duration of andesitic volcanism in New Caledonia (Lillie and Brothers 1970) which acted as source for clastic wedges. (B—site penetrating basement).

produce a correlation of sedimentation and tectonic processes.

First, the role of rifting in these basins is to provide a sink where sediment may accumulate. Once the rifted basin forms, sedimentation processes depend on ocean current circulation, latitudinal arrangement of biogenic productivity zones (controlling biogenic silica and carbonate deposition), position of continental land masses, regional volcanism, and sediment yield from tectonically-uplifted arc sources.

Second, rifting also controls the water depth where sedimentation occurs, a factor crucial for preservation of biogenic carbonates. If the basin floor occurs above the CCD, preservation of biogenic carbonate systems is favored in appropriate latitudes. However, once rifting ceases in the basin, the heat flow rate slows, causing basinal subsidence, including subsidence below the CCD, and thus favoring preservation of the younging trend from pelagic carbonates to pelagic red clay with small sediment accumulation rates. If land sources occur next to such a subsided basin, however, pelagic-clay deposition would be masked by hemipelagic clay (as in the Shikoku Basin).

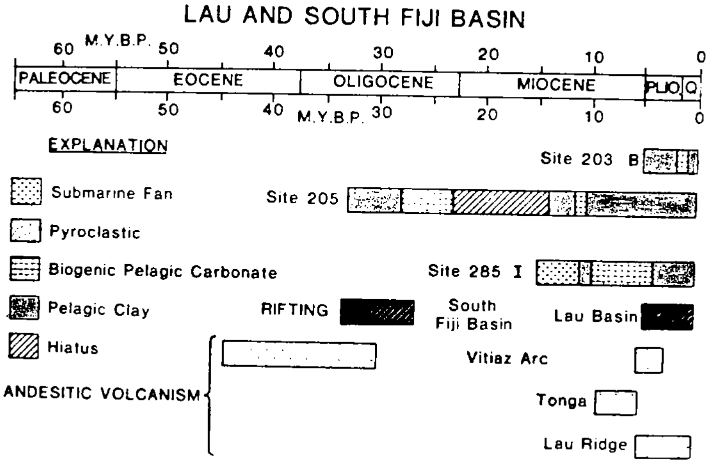

FIG. 10.—Correlation diagram showing distribution of sediment type and times of rifting in Lau (Lawver et al. 1976) and South Fiji (Weissel and Watts 1975; Davey 1982) basins, and andesitic volcanism in adjoining arc sources (Ewart et al. 1977; Gill et al. 1984). (B—site penetrating basement).

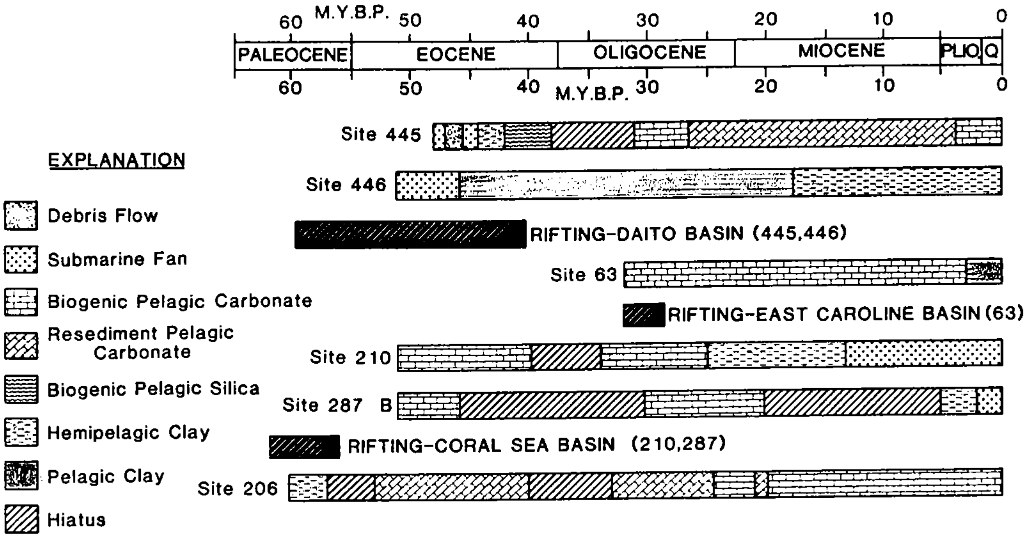

FIG. 11.—Correlation diagram showing distribution of sediment type and times of rifting in Daito Basin (Klein and Kobayashi 1980, 1981), the East Caroline Basin (Weissel 1981), the Coral Sea Basin (Weissel and Watts 1979) and the New Caledonia Basin (Site 206). (B—site penetrating basement).

Volcanism and Rifting Processes.—The relation of arc volcanism to rifting (spreading) processes in back-arc basins is controversial. In the West Philippine Basin and the Mariana Ridge, Scott and Kroenke (1980) concluded that major volcanism was confined to two periods of maximum activity, one during the Eocene-Oligocene (42–32 MY) and the other during the Miocene (20–9 MY). These volcanic maxima do not coincide with basinal spreading events, but instead are dependent on regional events (Kennett et al. 1977).

In contrast, Karig (1983) suggested that increases in preserved volcanic material are coeval with active rifting in the West Philippine and Parece Vela Basins and the Mariana Trough. Correlation diagrams (figs. 5–10) indicate that arc volcanism preceded rifting and continued into the early or middle stages of rifting events in the Sea of Japan and the Shikoku, Parece Vela, New Hebrides, South Fiji, and Lau Basins, or occurred coevally with rifting in the Mariana Trough.

In the West Philippine Basin, these relationships are less distinct because the remnant arc that was active presumably during basinal rifting is the Kyushu-Palau Ridge. The only age determinations for this ridge are by Ozima et al. (1977) using ^{40}Ar-^{39}Ar methods and yielding ages of 42.0 to 49.4 MY, coeval with rifting in the West Philippine Basin (Karig 1983). However, Harrison (1983) demonstrated many uncertainties in ^{40}Ar-^{39} age determination, uncertainties demonstrated also by Ozima et al. (1980), who reported ^{40}Ar-^{39}Ar ages from intrusive sills at Site 446 that were *older* than their ^{40}K-^{40}Ar ages and the paleontological ages of host sediments (McKee and Klock 1980). Thus the ^{40}Ar-^{39}Ar ages were not used in constructing figure 7. In the Japanese Islands, there is additional evidence for an increase of volcanic extrusives (Sugimara et al. 1963) concurrent with Miocene rifting in the Sea of Japan. From figures 5 through 10, it appears that the timing of both rifting and arc volcanism are related, as Karig (1983) suggested, despite the uncertainties posed by the Kyushu-Palau Ridge dates on which he relied.

Volcanism and Sedimentation.—In the back-arc basins of the western Pacific, dispersal and deposition of ash beds and other pyroclastic sediments appears to be controlled by three processes: (1) Regional and tectonically-controlled volcanism (Kennett et al. 1977; Karig 1983) accounts for the availability of volcanic ash and pyroclastics, (2) proximity to island arc and seamount sources accounts for most of the thicker units preserved as aprons, and (3) seasonally-controlled atmosphere circulation patterns control ash dispersal into the basins.

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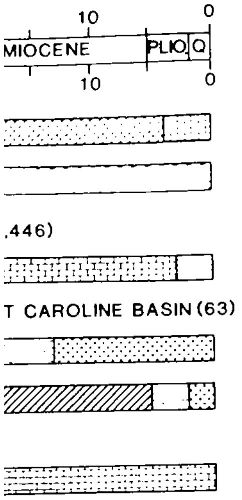

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1) Pyroclastic sediments, mainly airfall ash and submarine ejecta, depend on regional volcanism which occurs both within and adjacent to back-arc basins. Pyroclastic sedimentation patterns are more variable, however, because other volcanic sources, regional patterns, or other geodynamic processes are involved. Figures 6, 7, 9, and 10 show timing of pyroclastic deposition in the Parece Vela, West Philippine, New Hebrides, Lau and South Fiji Basins, respectively. Comparing pyroclastic deposition in these basins with times of andesitic arc volcanism (fig. 6, 7, 9, 10) in adjoining island arcs demonstrates that such volcanism occurs concurrently with pyroclastic deposition only in the West Philippine Basin during the early and middle Oligocene (fig. 7), and in the South Fiji Basin (Site 205) during the middle Oligocene (fig. 10). Rodolfo (1981) suggested a similar correlation between Site 450 pyroclastic deposition in the Parece Vela Basin and volcanism on the Mariana Ridge. In the remaining basins where pyroclastic systems occur, no such relationship exists (figs. 6, 9) because these pyroclastics were derived, probably, from sources other than adjacent island arcs, including submarine volcanoes whose age is not known.

Timing of pyroclastic deposition at Sites 53, 54, and 450 in the Parece Vela Basin (fig. 6) is known to be contemporary with regional volcanic episodes in the Mariana Ridge (remnant arc adjoining this basin) and elsewhere in the West Philippine Basin (Scott and Kroenke 1980, p. 298, their table 1; Karig 1983; fig. 7). This Miocene pyroclastic deposition is contemporary also with a second maximum of regional volcanism from 20 to 9 MY (Scott and Kroenke 1980). At Site 290 (fig. 7) in the West Philippine Basin, Oligocene pyroclastic deposition occurred concurrently with volcanism in Saipan, Guam, and Palau, which may have served as source areas. This Oligocene event occurred concurrently with the late stage of Scott and Kroenke's (1980) first volcanic maximum and the earliest stages of their first minimum of volcanism in the West Philippine Basin.

Neogene volcanism in the Circum-Pacific has occurred in a periodic fashion (Kennett et al. 1977) with major episodes known from the Quaternary and Middle Miocene and subordinate episodes known from the Late Miocene and Early Pliocene. These episodes appear to have caused deposition of Quaternary and Pliocene pyroclastics in the Lau Basin (Site 203), Late Miocene pyroclastics in the South Fiji Basin (Sites 205, 285), and Quaternary and Pliocene pyroclastics in the New Hebrides Basin (Site 286). Potential sources include known areas of concurrent volcanism (Kennett et al. 1977) such as Fiji (for Sites 203, 205, 285), the New Hebrides (for Site 286), and possibly New Zealand.

2) Although ash beds occur as thin layers throughout the back-arc basin cores, the preservation of thick pyroclastic beds as aprons is much rarer, being confined to five basins, all around island arcs (Rodolfo and Warner 1981; Karig 1983) (fig. 6, 7, 9, and 10).

3) With active volcanism occurring both regionally and in adjoining arcs (Kennett et al. 1977; Scott and Kroenke 1980; Karig 1983), some explanation is required to account for the distribution of ash beds. In the Lesser Antiles arc, a chance separation exists between volcaniclastic, gravity-deposited sediment (pyroclastic aprons of Rodolfo and Warner 1981) and wind-transported ash (Sigurdsson et al. 1980). On the west side of that arc, the Granada Basin receives volcaniclastic turbidites and debris flows only, whereas larger volumes of ash and pyroclastics occur on the eastern side of that arc only (and gravity sediments are absent) because of prevailing tropospheric westerly wind systems (Sigurdsson et al. 1980). Thick pyroclastic accumulations occur close to the arc.

Meteorological maps of the present-day western Pacific (The Times Atlas of the World 1977) indicate that, during January, the back-arc basin provinces north of the equator are dominated by cold-air outbreaks from Siberia, whereas south of the equator, westward-flowing trade winds (southeast trades) occur (fig. 12). During July, the monsoon systems provide a northward-flowing system of winds north of the equator, whereas the southeast trade winds continue to develop westerly-flowing wind systems south of the equator (fig. 13).

These present-day wind patterns provide some clues to potential dispersal for some airfall ash in the back-arc basins. Thus, the Japanese Island Arc is a major source of ash into the Shikoku Basin, the Parece Vela Basin, and the northern part of the West Philippine

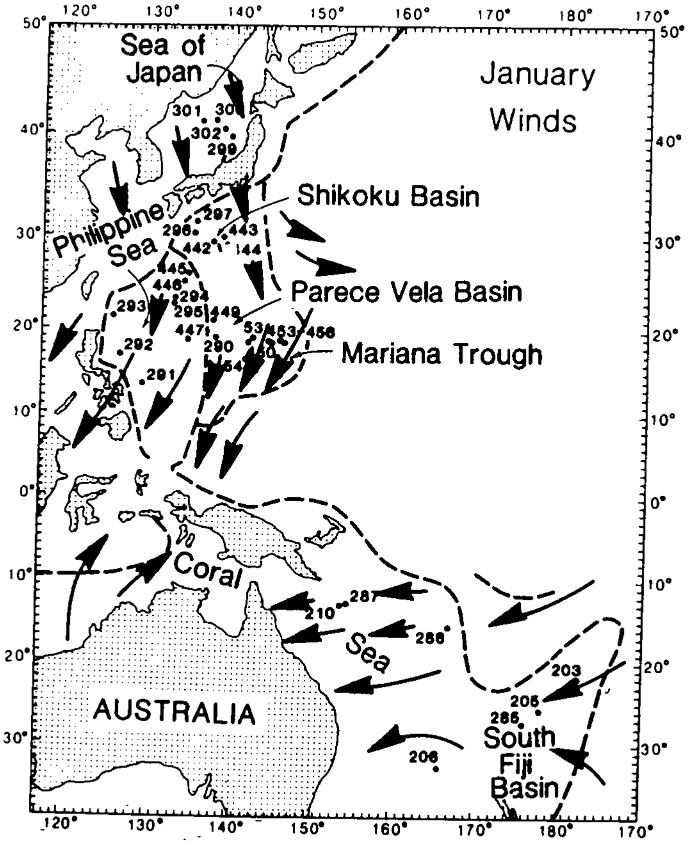

FIG. 12.—Map of DSDP sites in western Pacific back-arc basins showing present-day wind directions during January. (Wind directions after Times Atlas of the World 1977).

Basin during January (fig. 12). Thicker apron-like accumulations developed locally by a combination of gravity flow and (perhaps) past wind dispersal off the Kyushu-Palau Ridge (a remnant arc), possibly accounting for thick pyroclastics at Site 290, as would similar dispersal off the Mariana Ridge into the Parece Vela Basin. Thicker pyroclastic accumulations in the New Hebrides Basin (Site 286), the South Fiji Basin, and the Lau Basin (Site 203) are derived from a similar combination of gravity flow and airborne systems involving westerly-flowing air masses over the New Hebrides (for Site 286) and the Lau Ridge. During July (fig. 13), the wind systems north of the equator move in a northerly direction, so ash from the Japanese Islands would be dispersed into the Sea of Japan, whereas Guam, Saipan, and the southern Mariana Arc would act as sources for ash beds in the Shikoku and Parece Vela basins and the Mariana Trough. South of the equator, the wind systems during July are directed west-northwest and, as a consequence, ash derived from New Zealand and the Tonga arc would be dispersed into the South Fiji and Lau basins. The New Hebrides Basin would receive only small volumes of ash during that season. These wind directions may be the cause of significant present day ash accumulations in some back-arc basin sites. During Cenozoic time while the basins formed, it would be expected on paleogeographic and paleoclimatological grounds (Parrish 1981, 1982; Parrish and Curtis 1982; Marsaglia and Klein 1983) that wind dispersal patterns were similar to the present day but shifted later in response to larger-order regional tectonic trends (cf. Kinoshita 1980).

In summary, deposition and dispersal of ash beds and other pyroclastic sediments is controlled by the three processes mentioned previously: regional and tectonically-con-

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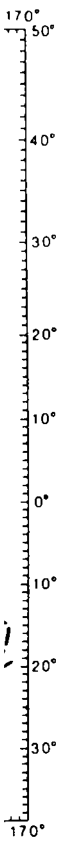

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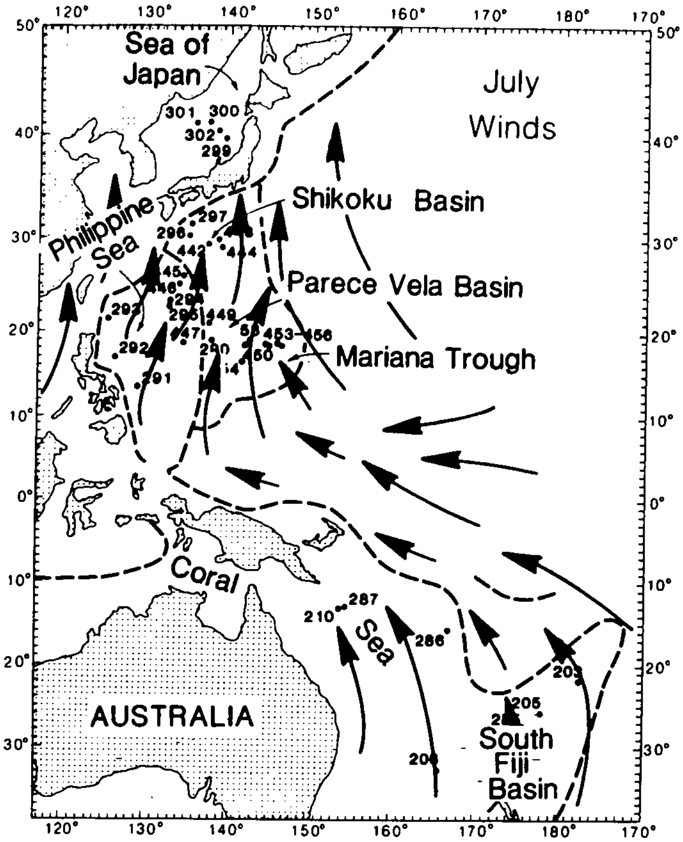

FIG. 13.—Map of DSDP sites in western Pacific back-arc basins showing present-day wind directions during July. (Wind directions after Times Atlas of the World 1977).

trolled volcanism (Kennett et al. 1977; Karig 1983), proximity to island arc and seamount sources, and seasonally-controlled atmospheric circulation. Combination of wind dispersal patterns with the larger-order periodicity of volcanism reported by Kennett et al. (1977), as well as basin rifting (Karg 1983), appears to explain the limited distribution of pyroclastics in the back-arc basins.

Tectonic Uplift of Island Arc Sources and Basin Sedimentation.—Both submarine fan deposits and debris flows are derived from island arc sources and their associated shallow-water zones, as indicated by the presence of andesitic volcanic rock fragments and resedimented shallow-water fossils (Klein 1975*a*, 1975*b*; Karig and Moore 1975; White et al. 1980). Deposition of these submarine fan and debris flow systems is restricted to the earliest stage of basin rifting (figs. 5 to 11), though deposition of these sediments is independent of rifting processes. Fan and debris flow deposition is known to occur coevally with the last stages of andesitic volcanism (figs. 5 to 11).

Three basins, the Coral Sea, Shikoku, and the Sea of Japan, contain submarine-fan systems adjoining sediment sources whose geological history is well known. Analysis of these fan systems in the Coral Sea and Sea of Japan showed a direct correlation between rate of tectonic uplift and both the frequency (number of events per time interval) and periodicity (number of years between events) of preserved graded turbidite cycles recovered in DSDP cores (Klein 1984). At Sites 210 and 287 in the Coral Sea Basin, Miocene to Holocene terrigenous turbidites are derived from the ancestral Owen-Stanley Range of Papua (Burns, Andrews et al. 1973; Andrews, Packham et al. 1975; Klein 1975*a*, 1975*b*, 1984). This range owes its origin to obduction of the Pacific Plate onto the Indian-Australian Plate from Eocene to Pliocene time; maximum uplift was suggested for Miocene and early Pliocene time (Davies and Smith 1971).

Table 1 summarizes the frequency and periodicity of turbidite graded cycles observed in cores recovered from Sites 210 and 287. At Site 210, the largest frequency and periodicity of deposition of graded turbidite cycles occurred coevally with early Pliocene uplift of the Owen-Stanley Range (Davies and Smith 1971). The time-delay in turbidite deposition during Miocene time is attributed in part to the great distance of this site from terrigenous sources, as well as a delay in establishing a mature-enough river system to generate a sufficiently large sediment yield into the basin. The large turbidite frequency and shorter periodicity during early Pliocene time is concurrent also with a high stand of sea level (Vail et al. 1977).

A progressive change in frequency and periodicity of turbidite deposition at Site 210 occurred during the Late Pliocene and Pleistocene (table 1), indicating either a cessation of uplift or decreasing rates of tectonic uplift and associated decreasing sediment yields (cf. Yoshikawa 1974) in the Owen-Stanley Range. At Site 287, the more distal fan site, turbidite cycles were deposited no earlier than Late Pliocene and continue to the present but show an increase in preserved turbidite frequency and periodicity from Late Pliocene through Late Pleistocene time. This increase may well be caused by larger rates of denudation and sediment yield associated with increased relief triggered by global Pleistocene eustatic sea level fall.

In the Sea of Japan, outer levee, channel, and overbank sediments were recovered at Site 299 (Karig, Ingle et al. 1975; Boume 1975; Nash 1981). Individual turbidites are organized also into graded cycles (Bouma 1975, p. 494, his table 1), derived from the Hida Range of Honshu Island, Japan, and encompass a time-stratigraphic interval from perhaps as early as Late Miocene to the Holocene.

The history of tectonic uplift, volcanicity, and sediment yield in the Hida Range is known since Late Miocene time. Tectonic uplift rates for the Hida Range of Honshu were negligible during the Miocene and Pliocene (Sugi et al. 1983; Matsuda et al.

TABLE 1

TEMPORAL DISTRIBUTION OF GRADED CYCLES IN CORAL SEA BASIN

	SITE 210			SITE 287			
Age	Number of Cycles	Frequency of Cycles[a]	Periodicity of Turbidite Events (in Years)	Number of Cycles	Frequency of Cycles[a]	Periodicity of Turbidite Events (in Years)	Process
Late Pleistocene	58	58	17,241	33	66	15,152	SEA LEVEL CHANGES
Early Pleistocene	50	60	13,333	8	16	50,000	
Late Pliocene	63	126	11,111	7	14	100,000	
Early Pliocene	185	370	4,865	000	000	000	UPLIFT, OWEN-STANLEY RANGE
Late Miocene	122	244	28,688	000	000	000	

[a] Corrections as per Klein (1984).

1967). During Quaternery time, however, the Hida Range experienced tectonic uplift rates ranging from 1.0 to 1.5 km (equivalent to uplift rates of 555 to 833 m per million years) in response to collision tectonics (K. Nakamura personal comm. November, 1983). This tectonic uplift is coeval with a marked increase in andesitic volcanism (Sugimara et al. 1963). Surveys of sediment yield from present rivers in Honshu show that the furthest upstream reservoirs are largest in the Hida Range in comparison to small sediment yields in adjoining areas of low relief and smaller rates of tectonic uplift (Yoshikawa 1974; Ohmori 1978; Tanaka 1982). The post-Miocene rate of sediment accumulation in Honshu Island basins also parallels the rate of tectonic uplift of the Hida Range (Niitsuma 1978).

Table 2 summarizes the preserved turbidite frequency and periodicity from the Toyama submarine fan at Site 299. These data show a progressive increase in preserved turbidite frequency and decreased periodicity from Pliocene time to Late Pleistocene time, paralleling the tectonic uplift history of the Hida Range sediment source. Deposition of Toyama submarine fan sediments, therefore, correlates with a time of known large rates of tectonic uplift, andesitic volcanism, and large rates of sediment yield in the Hida Range. Although this time period was also a time of lower sea level (Vail et al. 1977), the amount of increased relief by sea level reduction in Toyama Bay during the Pleistocene is 10% or less of the tectonic uplift rate (Klein 1984) and represents only a minor factor in increasing sediment yield and the frequency and periodicity of preserved turbidites on the Toyama submarine fan.

Late Early-to-Middle Miocene submarine fan deposition was observed at Site 297 in the northern part of the Shikoku Basin; these sediments were derived from the southern part of Honshu Island (Karig 1975; Karig Ingle et al. 1975). Deposition occurred concurrently with a period of maximum volcanism in Japan (Sugimara et al. 1963) and a major period of tectonic uplift on southern Honshu Island (Matsuda et al. 1975; Sugi et al. 1983). Fan deposition ceased when sediment from the Japanese Island arc was diverted into the Nankai Trough during Early Pliocene time (Karig 1975; Karig Ingle et al. 1975). The fan deposition in the Shikoku Basin during a time of known large tectonic uplift rate and increased volcanism is similar to the tectonic and sedimentary relationship observed in the Toyama submarine fan.

Both debris flows and submarine fan sediments have been observed in DSDP sites in the West Philippine Basin, Mariana Trough, New Hebrides Basin, South Fiji Basin, and the Daito Basin (figs. 7 through 11). The sources of all these fans, except in the Daito Basin, are known, and the timing of andesitic volcanism in these sources is shown in figures 7 through 10. A correlation can be established between fan deposition and andesitic volcanism in source terrains in all cases except the South Fiji Basin, where a time-lag is indicated. Because no data exists on past or current rates of tectonic uplift in these andesitic source terrains, correlation cannot be established between tectonic uplift rate and fan deposition. Nevertheless, coeval fan deposition and andesitic volcanism suggests that increased relief by a volcano-building process is a prerequisite for fan deposition in these cases.

The absence of submarine fan depositional systems in other back-arc basins implies that the adjoining island arcs did not undergo a history of significant tectonic uplift. For instance, Pagan Island in the Mariana Arc reached a present-day elevation of 800 over the past 2 m.y. (Hussong, Uyeda et al. 1981), an uplift rate of 400 m per m.y. This rate is half of the rate of tectonic uplift determined for Rota Island in the Mariana Arc (Yonekura 1982, 1983). Site 456 adjoins Pagan Island, yet no submarine fan system occurs there; only debris flow pyroclastic aprons occur at Site 455, which is located closer to Pagan Island (fig. 8). It appears that a tectonic uplift rate greater than 400 m per m.y. approximates the minimum rate needed to generate the requisite sediment yield to develop submarine fans.

In summary, submarine-fan and debris flow deposition in back-arc basins requires large rates of uplift in their source areas, with or without associated andesitic volcanism, as demonstrated by analysis of turbidite periodicity and timing of fan deposition in the Coral Sea Basin, the Sea of Japan, and the Shikoku Basin, where increased rates of tectonic uplift may (Honshu Island) or may not (Owen-Stanley Range) be coupled with vol-

Age	Cycles	Cycles[a]	(in Years)	Cycles	Cycles[a]	(in Years)	Process
Late Pleistocene	58	58	17,241	33	66	15,152	SEA LEVEL CHANGES
Early Pleistocene	50	60	13,333	8	16	50,000	
Late Pliocene	63	126	11,111	7	14	100,000	
Early Pliocene	185	370	4,865	000	000	000	UPLIFT, OWEN-STANLEY RANGE
Late Miocene	122	244	28,688	000	000	000	

[a]Corrections as per Klein (1984).

TABLE 2

TEMPORAL DISTRIBUTION OF GRADED TURBIDITES, SITE 299

Age	Number of Turbidite Cycles	Frequency of Turbidite Cycles[a]	Periodicity of Turbidite Events (in Years)	Process
Late Pleistocene	161	161	6,211	UPLIFT, VOLCANISM AND SEA LEVEL CHANGES
Early Pleistocene	52	52	15,384	
Late Pliocene (?) Early Pliocene (?) Late Miocene (?)	69	86	102,232	

[a] Correction as per Klein (1984).

canism. A time-delay between tectonic uplift and the onset of fan deposition is controlled by the time required to develop a drainage system large enough to generate sediment yield into the back-arc basins. Most of the sediment eroded from these tectonically uplifted zones is transported by means of low-gradient, short-length streams lacking a coastal plain. Consequently, the bulk of this sediment accumulates on submarine fans regardless of sea level fluctuations. The absence of submarine fans in back-arc basins implies that potential sources, mostly island arcs adjoining the basins, were not subjected to large rates of tectonic uplift.

CONCLUSIONS

The sediment fills of the back-arc basins of the western Pacific Ocean are characterized by a large variety of sediment types whose distribution is controlled by an equally variable number of sediment processes. Processes controlling deposition in these basins include latitudinally-controlled biogenic productivity and oceanic circulation (for biogenic pelagic carbonate and biogenic silica pelagic sediments), continental sediment yield and climate (for hemipelagic clays and silty turbidites), regional volcanism and wind patterns (for pyroclastic aprons and ash beds), basin subsidence (for pelagic clays), and either large rates of uplift in source terrains or a coupling of andesitic volcanism and large rates of uplift of andesitic volcanic arc sources (for submarine fans and debris flows). Figure 14 shows a schematic summary of these sediment types in a series of back-arc basins flanking a subduction zone extending from pole to pole; it shows also the effect of continental land masses, latitude, uplifting arcs and sources, and basinal subsidence below the CCD to indicate the variety of sediment combinations possible within individual or multiple back-arc basins.

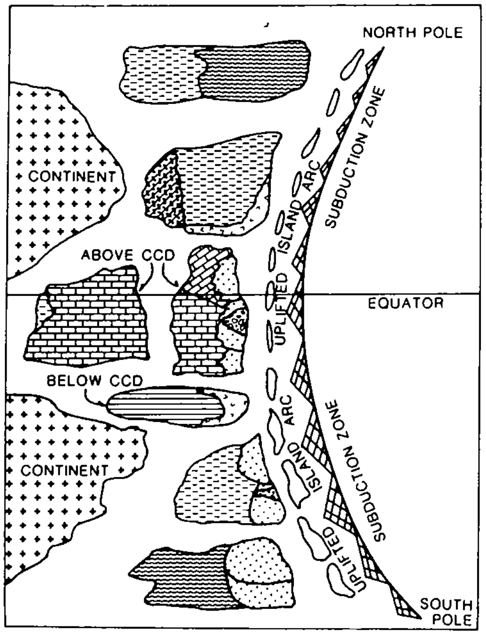

FIG. 14.—Synthetic summary of distribution of sediment types in back-arc basins along a longitudinal subduction zone extending from pole to pole. Latitudinal control of biogenic pelagic sediments is shown, as is occurrence of fans and debris flows near island arcs characterized by large uplift rates. Occurrence of continentally-derived hemipelagic clays, randomly-distributed pyroclastics, silty turbidites and tectonically-controlled pelagic clays also shown. Symbolic coding as per figures 5 through 11.

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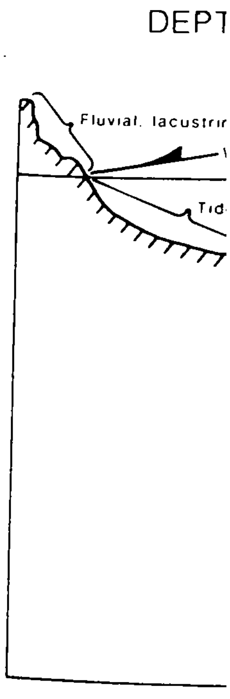

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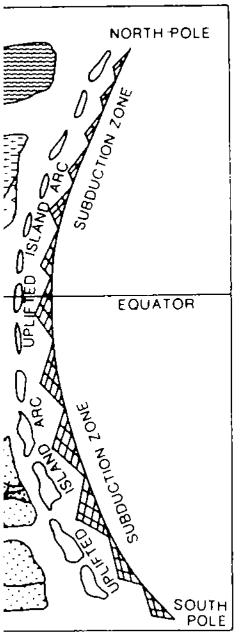

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In the back-arc basins of the western Pacific, tectonics control sedimentation in these basins in two direct ways. First, it determines the water depth of deposition, which controls the preservation of pelagic biogenic carbonates. Second, if tectonic uplift rates in source areas are large, a sediment yield is generated which accumulates in the back-arc basins as debris flows and submarine fans. Such uplift occurs in areas of plate convergence by obduction and collisions, or areas of andesitic volcanism with associated volcano building. In andesitic arcs, tectonic uplift is followed by a time lag required to generate appropriate relief and relatively well established drainage systems so as to provide a sufficiently large sediment yield to develop submarine fans and debris flows in the back-arc basins. A close correlation exists between large frequency and short-term periodicity of turbidite deposition on submarine fans (tables 1 and 2) and large rates of tectonic uplift in three basins (Coral Sea, Sea of Japan, Shikoku) and demonstrates clearly the role of tectonic uplift as a variable on submarine fan and debris flow deposition. This tectonic uplift masks the role of sea level fluctuations on fan sedimentation. Recognition of ancient counterpart back-arc basins requires determination of the geographic position of such a basin on the overriding plate of a paleo-subduction zone, a basement of tholeitic basalt, and a variability of sediment styles, rather than a specific sediment association.

The depth of the depositional surfaces in the back-arc basins of the western Pacific occurs within a limited deep-water range which controls the variety of sediment processes interpreted from DSDP sediment cores. The role of water depth on sedimentation is well known (fig. 15), but less appreciated is the role of tectonics in controlling water depth. It seems appropriate, therefore, to compare briefly the water depths of sediment deposition and associated depth-dependent processes of sedimentation with broad tectonic settings, because identical water depths occur in different tectonic settings (fig. 15). For that reason, nonmarine, coastal, and shelf depositional systems tend to show a greater degree of preservation in rifted basins, cratons,

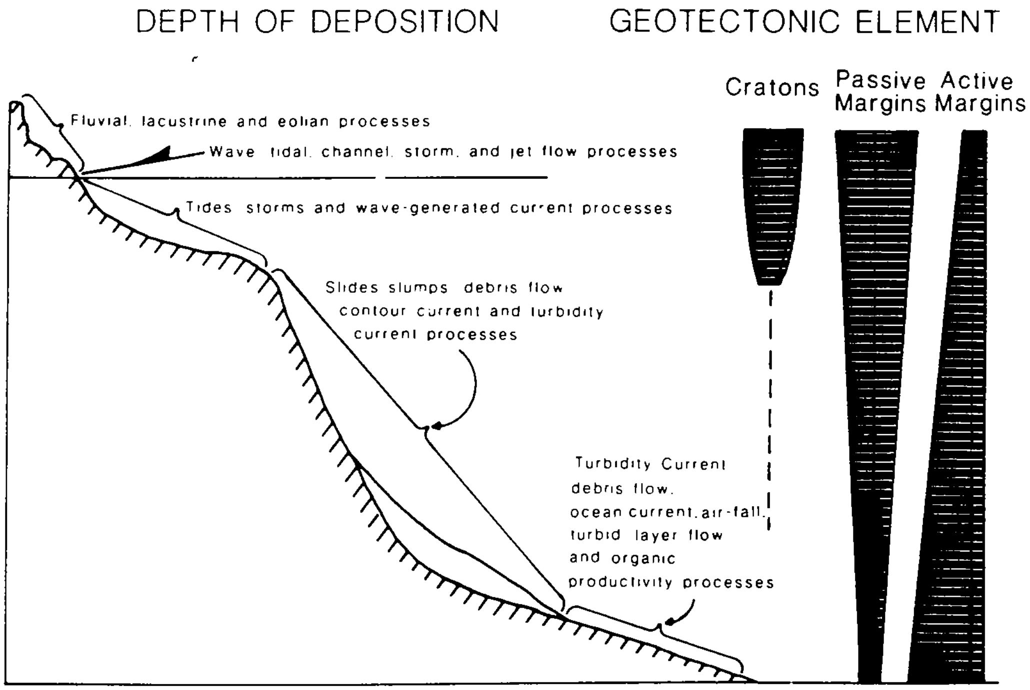

FIG. 15.—Comparison of depositional processes and depth zonation with tectonic setting. Width of bands for tectonic setting show relative degree of preservation of depth zones in each tectonic setting shown.

and passive margins. Preserved slope and continental rise systems occur in relatively equal proportions in both passive and active continental margins. Deep-water sediment systems are preserved in trenches, back arc basins, fore arc basins, mid-ocean ridges, and deep, subsiding ocean basins. Because the distribution of tectonic setting overlaps so many zones of water depth (fig. 15), a large variety of sediment systems and sediment processes will occur with respect to tectonic domain, and the association of variable sediment types with a specific tectonic settling will be a function of the preserved water depth within that tectonic domain. Thus, it is water depth that appears to be the key link that correlates sedimentation and tectonic processes and, at the same time, accounts for recurring patterns of sediment variability. Expressed in another way, tectonic processes control the distribution of water depth zones in a specific tectonic domain, and this water depth distribution controls in turn the distribution of sediment processes and lithologies.

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