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# GEOPHYSICS AND TECTONIC DEVELOPMENT OF THE CAROLINE BASIN

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## FOREWORD

This report provides an analysis of the geology and geophysics of a tectonically complex ocean area. The information presented can be used to delineate physiographic provinces and geoacoustic parameters and for more informed planning for future oceanographic measurements in this region.

C. H. Bassett
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Contradictory hypothesis on the origin of the Caroline Basin suggested that an attempt be made to arrive at a reasonable synthesis of basin origin. This thesis attempts such a synthesis.

The principal conclusions reached are that the Caroline Basin formed by a complex sea floor spreading mechanism in Tertiary time behind a southward advancing island arc. Mantle plume development in the eastern basin during

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this time may have formed the Eauripik Rise through blockage of westward axial mantle flow at a transform dam. Non-uniform cessation of spreading began in Upper Oligocene, together with the obduction of the southern portion of the ancestral ridge onto New Guinea, with concurrent northward subduction of basin crust at the southern base of the remnant northern ancestral ridge. An extensional trough opened in the northern ridge and expanded until collision with the eastward advancing Yap-Palau arc in Upper Miocene.

# PREFACE

This report was originally presented as a thesis to the University of Alaska. It is a continuation of a study of the Caroline Basin area begun by the author in 1975, which was the first attempt at a tectonic interpretation of this geologically complex area. Since that time, numerous papers relating to the tectonic interpretation of the Caroline Basin and its margins have appeared. Their divergent and often contradictory viewpoints require that an attempt be made to arrive at an interpretive synthesis of the regional tectonics. By carefully considering all available data and hypotheses concerned with the area, this thesis will attempt such a synthesis.

I gratefully acknowledge the generosity of Jeffrey K. Weissel, Lamont-Doherty Geological Observatory, for making additional magnetic and seismic reflection data available to me, and James E. Andrews for the University of Hawaii magnetic data. I also wish to thank David W. Handschumacher, Naval Oceanographic Research and Development Activity, and Peter R. Vogt, Naval Research Laboratory, for furnishing magnetic modeling programs, and Howard C. Jack, Naval Oceanographic Office, for his skill in modifying and adapting the final program for the available computer.

I am especially grateful to David B. Stone, University of Alaska, for his guidance in the preparation of this report.

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# INTRODUCTION

The age and gross tectonic relationships of the southwest Pacific area are shown in Figure 1. As can be seen, this area encompasses one of the world's most complex tectonic regimes.

The Caroline Basin is a $1.3 \times 10^6$ $km^2$ oceanic basin lying north of New Guinea and south of the West Caroline Ridge. It is bounded on the east and west by the Mussau Trough and the Palau Trench, respectively. The basin is divided into roughly equidimensional sub-basins, the East and West Caroline Basins (Fig. 2), by the arcuate, northward-trending, Eauripik Rise. These basins have typically oceanic crust as determined by the seismic refraction work of Den and others (1971).

The age of the Caroline Basin crust was determined to be Tertiary by Deep Sea Drilling Project (DSDP) core recoveries at sites 62 and 63 (Winterer and others, 1971), shown in Figure 2.

Many hypotheses on formation and history of the basin have been advanced. Winterer and others (1971) offered the possibility that the basin was formed by sea-floor spreading from the Eauripik Rise. Moberly (1972) proposed that the basin crust was formed during the Middle to Late Oligocene time behind a southward advancing island arc, now welded against northern New Guinea. Presumably, the present-day Caroline Ridge would then represent the remnant or third arc described by Karig (1971) at similar island arc systems.

In a discussion of the results of leg 30 of the DSDP, the Scientific Staff (1973) proposed that the Caroline Basin was formed not by arc

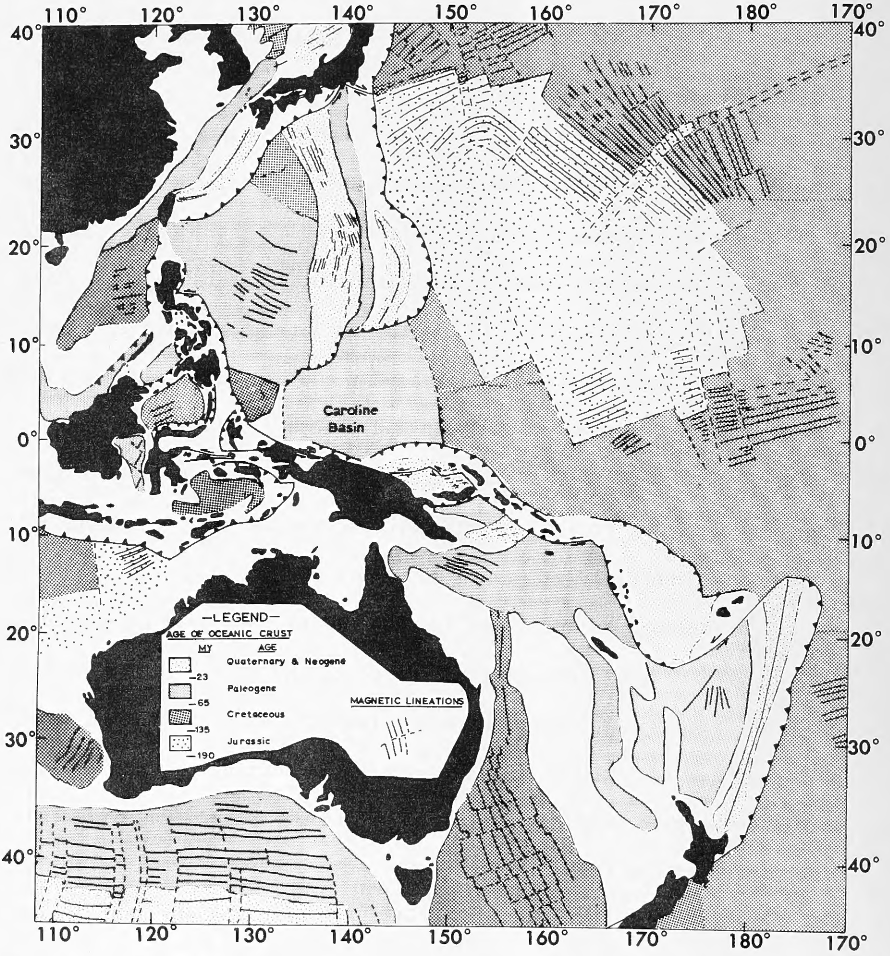


Figure 1. Generalized tectonic and crustal age chart of the western Pacific. Modified from Hilde and others (1977); Watts and others (1977), and Hayes and Taylor (1978).

Figure 2. Track location and geophysical information plotted on bathymetric contour chart of the Caroline Basin (after Bracey, 1975). Contour interval 200 fathoms (366 m). Lines A-G and 1-15 are NAVOCEANO tracks. L-D and UH lines are tracks from Lamont-Doherty Geophysical Observatory and the University of Hawaii, respectively.

spreading centers on, and parallel to, the Eauripik Rise, separated by numerous northeast-striking transform faults.

Mammerickx (1978) offered another interpretation, based heavily on the significance of bathymetric features. She too proposed a two-phase sea-floor spreading scheme in which the Kiilsgaard and West Caroline Troughs (Fig. 2) are remnants of a former continuous spreading axis, active from about 38 m.y. B.P. until 31 m.y. B.P. and 28 m.y. B.P., respectively. At approximately 31 m.y. B.P., she proposed that the spreading center jumped to the axis of the Eauripik Rise, and persisted at a rate of 5 cm/yr until 26 m.y. B.P. This axis consisted of a series of short northeast-oriented spreading segments separated by northwest-striking transform faults. She also proposed a triple ridge-junction at the location of DSDP site 62 (Fig. 2), with a bifurcation of the spreading axis extending southeast to the Manus Trench along the present bathymetric axis of the rise.

Weissel and Anderson (1978), using additional geophysical data, identified a spreading axis on the extreme eastern margin of the basin. This axis was active from about anomaly 13 to anomaly 9 time (approximately 28.5 - 36 m.y. B.P.). The axis is associated with a bathymetric trough which the authors identified as an extension of the Kiilsgaard Trough. They also concur with Mammerickx that the West Caroline Trough is an inactive spreading center, although they did not assign any age to the magnetic anomalies flanking the trough. The authors further contend, on the basis of morphology and sediment thickness, that the Ayu Trough (Fig. 2) is a spreading center, active from about 10 - 12 m.y. B.P. or, alternatively, from about 20 m.y. B.P. to the present time.

The Sorol Trough (Fig. 2) is believed by Weissel and Anderson (1978) to be an active extensional feature, forming the northern margin of a Caroline Plate.

As can be seen from the above synopsis, the interpretations of the tectonic origin and development of the Caroline Basin differ significantly. While there is a general agreement as to the mode of origin (sea-floor spreading) of the basin, there is divergent opinion as to the nature and age of the inception of spreading, and the direction, continuity, and longevity of that spreading. The following sections will attempt to arrive at a reasonable synthesis of these diverse interpretations by a rigorous examination of the available geophysical and geological data.

# DATA COLLECTION AND REDUCTION

## Navigation

All navigation for the tracks shown in Figure 2 with the exception of 12 through 15 was controlled by satellite fixes. Accuracy for these tracks is estimated to be within ± 1.0 km. The older tracks (12 - 15) were controlled with a combination of dead reckoning, celestial fixes, and Loran-A. Accuracy for these tracks is estimated to be within ± 15 km.

## Bathymetry

The compilation of the bathymetry shown in Figure 2 has been discussed by Bracey (1975). His statement that the chart should be regarded as a generalization is emphasized. Even with the limited additional bathymetric data collected since the publication of Bracey's chart, an accurate, detailed depiction of the bathymetry of the area is impossible.

## Seismic Epicenters

Epicenter information for the period 1961 - 1971 was furnished by the National Earthquake Information Center, National Oceanic and Atmospheric Administration. All events are shown, with no restrictions on the quality of the epicenters, and are only intended to show the general distribution of seismic activity in the area today.

## Seismic Reflection

Seismic reflection data shown in this report were collected with a sparker sub-bottom profiling system in the case of the NAVOCEANO profiles, and with an airgun system in the case of the Lamont-Doherty and University of Hawaii data. All references to "basement" are to acoustic basement. In all cases, vertical units shown on both seismic profiles and the isopach chart are seconds of two-way travel time. Data may be converted to approximate sediment thickness by using a standard sediment velocity of 2 km/s. The isopach chart (Fig. 13) was constructed using values of two-way reflection time averaged over 1 - 2 hour periods (15-40 km).

## Gravity

Gravity data used in this report were furnished by the Defense Mapping Agency Aeronautical Center, Gravity Services Branch. Gravimeters used were of the vibrating-string and gimbal suspended LaCoste and Romberg types. Meters were referred to base stations in the western Pacific established as part of the World Standard Gravity Net (Wollard and Rose, 1963). Free air gravity anomalies were computed by subtracting the theoretical gravity value, derived from the 1967 Geodetic Reference System formula: $g= 978.03185(1.0 + 0.00527889 \sin^2 \text{Lat.} + 0.000023462 \sin^4 \text{Lat.})$, from the observed gravity value. Bouguer anomaly values were computed using the density values 2.67 $gm/cm^3$ and 1.027 $gm/cm^3$ for crust and ocean water respectively.

A detailed discussion of the accuracies of the gravity data, as well as a free air gravity chart compiled from all available data in the Caroline Basin area is to be found in Watts and others, 1978.

## Heat Flow

Heat flow data were abstracted from the references shown in Figure 2. Values are in heat flow units (HFU), each unit being equal to $10^{-6}$ cal/cm$^2$ sec.

## Magnetics

Magnetic total intensity data were collected with proton precession magnetometers on all tracks shown in Figure 2 with the exception of tracks 15 and 16. Data for these lines were collected with the Vector Airborne Magnetometer (VAM) described by Schoensted and Irons (1955). A detailed analysis of this vector data will be given in a later section. Accuracy of the proton precession magnetometer is ± 1 nt, while that of the VAM is ± 15 nt in total intensity.

The magnetic data distribution was inadequate for the preparation of a contour chart, and only profiles are shown in this report. The profiles are residual (or anomalous) data obtained by subtracting the International Geomagnetic Reference Field (IGRF) 1975 (IAGA Div. I Study Group, 1976), corrected for annual change to the date of the observations, from the observed magnetic values.

Due to an inadequate description of the annual change in some areas, caused by the unrealistic coefficients used in the IGRF, long-wavelength positive or negative anomalies with amplitudes of up to several hundred nanoteslas may be introduced into the residual profiles. An illustration of this problem may be found in Bracey (1968). To correct the problem, an arbitrary value (determined visually) was added to the IGRF so that the resultant residual profiles were evenly distributed about the zero line represented by the ship's track in Figure 12. An adjustment of this type is also discussed in Weissel and Hayes (1978). Since only the relatively short-wavelength anomalies are considered in this interpretation, this procedure has no effect on the conclusions. It is necessary, however, to point out that the "zero line" has no physical significance.

# GEOPHYSICAL OBSERVATIONS

## Seismic Reflection Profiles

East-west seismic reflection profiles across the Ayu Trough are shown in Figure 3. This trough, together with the contiguous Palau Trench, forms the western margin of the Caroline Basin. The trough is sediment-free, and there is an increase in sediment thickness in either direction from the trough. This is particularly apparent in profile L-D 2. Note also the dramatic increase in sediment thickness east of the Mapia Trough and west of the Ajoe-Asia Island Ridge shown on profile A.

Another feature of interest is the sediment-free trough west of the Ajoe-Asia Island Ridge at 130.5°E shown on profile A. The bathymetry of Figure 2 indicates that this feature may extend for at least 150 km to the northeast, parallel to the Ayu Trough, but without substantiating bathymetric and seismic reflection evidence the possibility of a northward extension of this sediment-free feature cannot be confirmed.

Figure 4 shows seismic reflection profiles in the West Caroline Basin. The western profiles (1-4) exhibit a particularly rough basement surface. There is a broad, low basement arch fronting the New Guinea Trench, and the basement reflector can be seen to dip southward and disappear beneath the trench at about the 8.0 sec level. Sediment thickness increases to the south in all profiles.

An internal reflector, believed by Bracey (1975) to be identical to "horizon X" identified by Den and others (1971) as a nannofossil

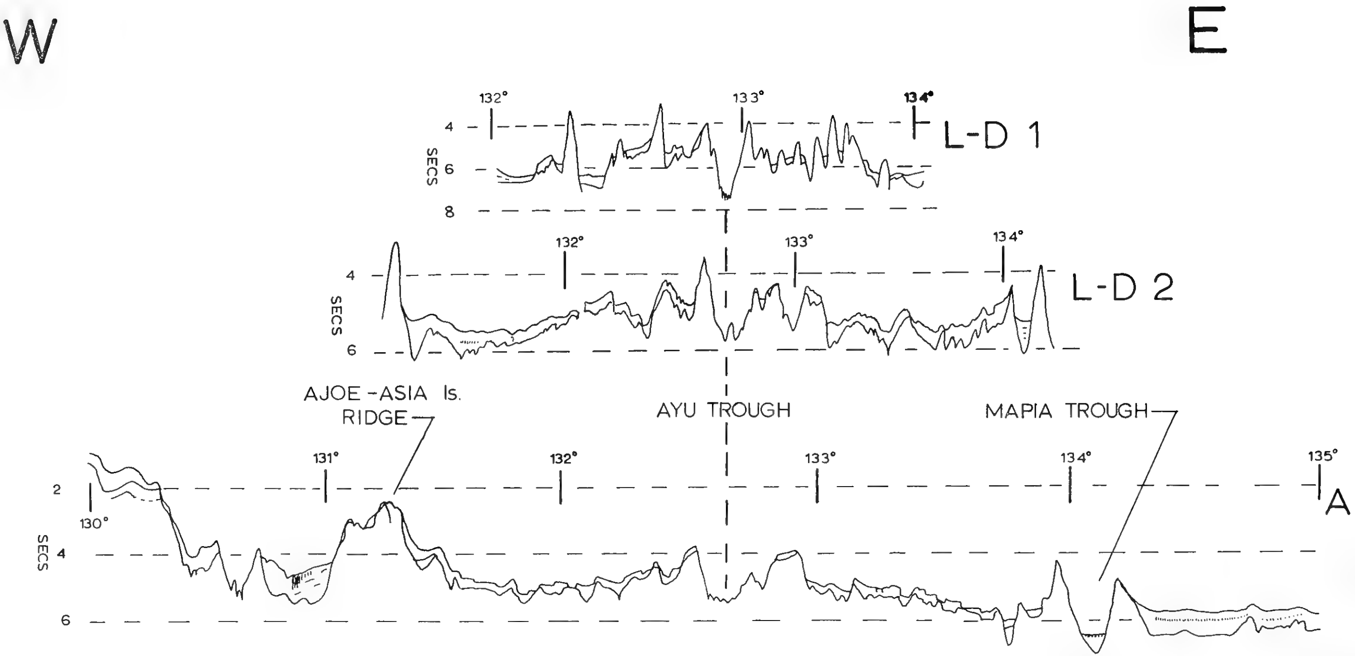


Figure 3. Line drawings of seismic reflection profiles across the Ayu Trough (from Bracey, 1975; Weissel and Anderson, 1978) located in Fig. 2. Vertical scale is in seconds of two-way acoustic travel time. Longitude crossings marked by short vertical lines.

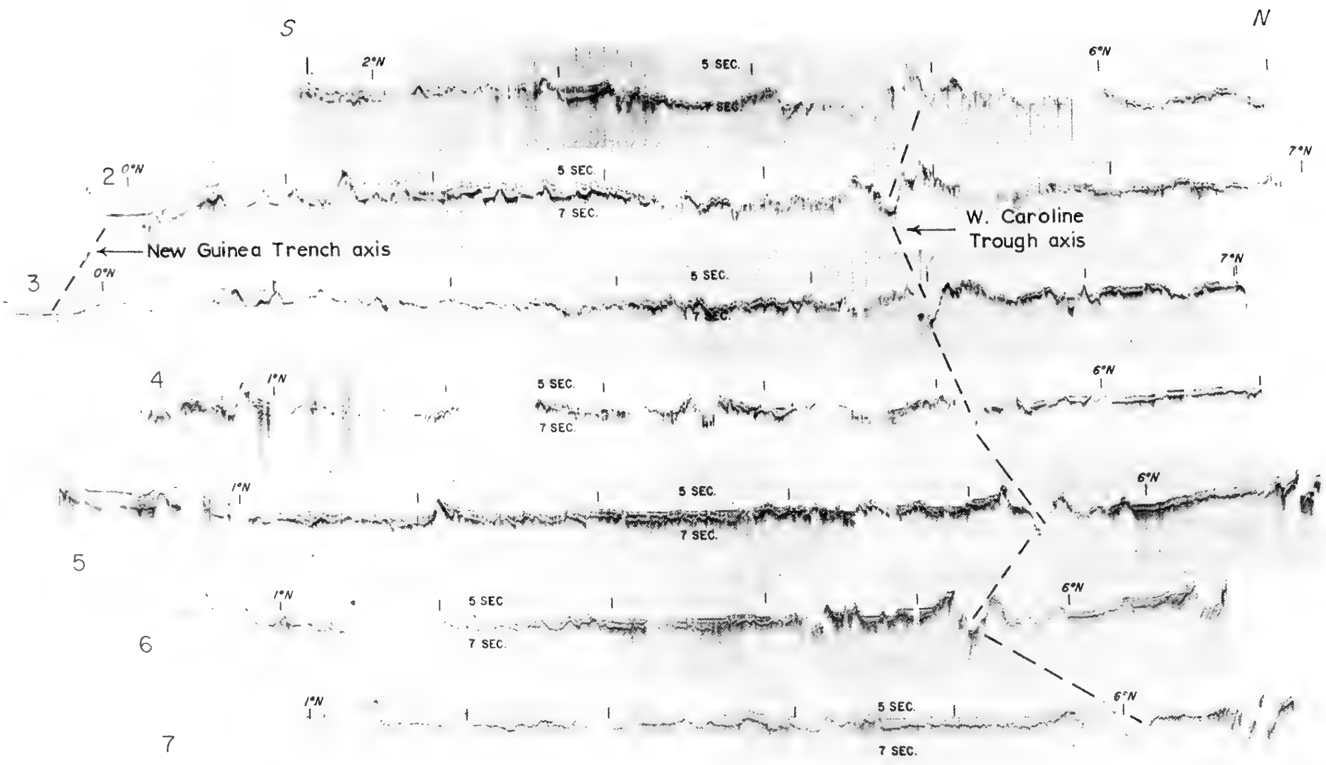


Figure 4. Seismic reflection profiles (after Bracey, 1975) in the West Caroline Basin (located in Fig. 2). Latitude crossings marked by short vertical lines. Vertical scale as in Fig. 3.

chalk bed of early Middle Miocene age, can be seen on the southern portions of all profiles.

The northern end of the profiles cross the West Caroline Trough, a feature striking ENE for 900 km across the northern portion of the western basin. The eastern end of this feature is definitely trough-like in morphology, as shown in profiles 5 - 7 (Fig. 4). The eastern trough contains some sediment ( 0.5 sec), and the sediments on its flanks appear relatively undisturbed. Note also the apparent increase in sediment thickness away from the trough axis, particularly noticeable in profiles 5 and 6. The northern end of these profiles (5 - 7) terminate in features proposed by Bracey and Andrews (1974) to be the remnants of a northward dipping subduction zone flanking the southern margin of the western Caroline Ridge, a possibility to be discussed in a later section.

In contrast to the trough-like morphology of the eastern end of this feature, the western end (profiles 1 - 3) is characterized by a sediment-free topographic high with a central valley of 1.0 - 2.0 sec relief, and a width of 20 - 30 km, centered between areas of absent or disturbed sedimentary cover.

Figure 5 is an enlargement of the northern end of profiles 1 - 3 which more clearly illustrates these phenomena. Profile 1 shows a gradual increase in sediment thickness away from the axial trough (at 5°N), with a sharp change in sediment thickness across the 1.0 sec escarpments at 4.15°N and 6.0°N. There appears to be another increase in sediment thickness to the south of the 0.5 sec

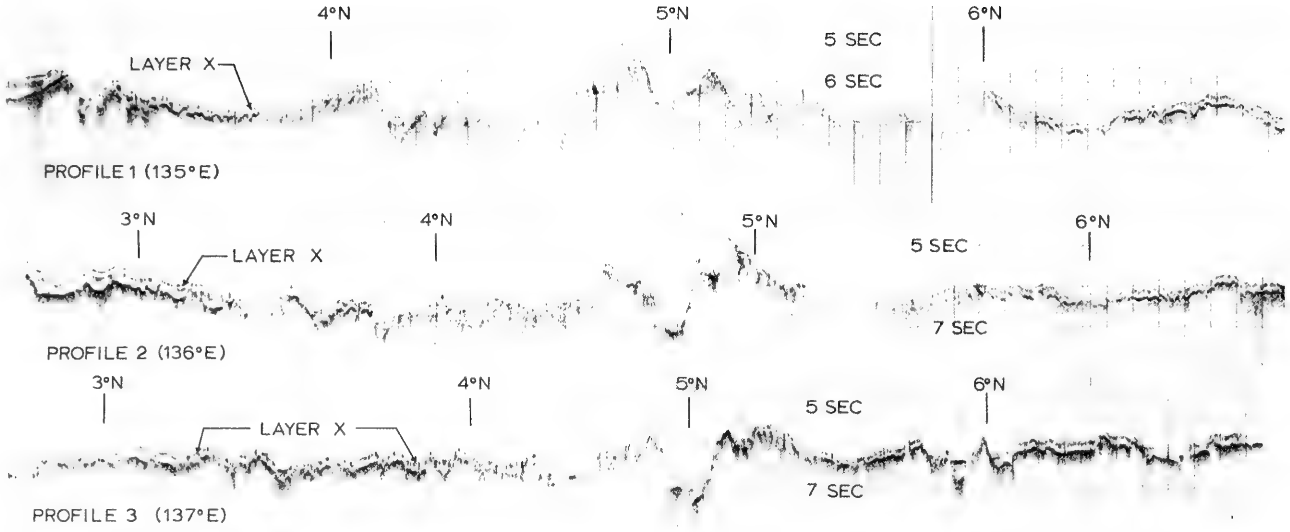


Figure 5. Enlarged segments of profiles 1-3, Fig. 4 (after Bracey, 1975). Vertical scale as in Fig. 3.

escarpment at 3.3°N. Profile 2 also shows an absence or severe disturbance (the quality of the seismic record here is very poor) between the axial valley (4.75°N) and 5.6°N and 3.8°N to the north and south. Here again a short segment of intermediate sediment thickness is seen to the south (between 3.4°N and 3.8°N).

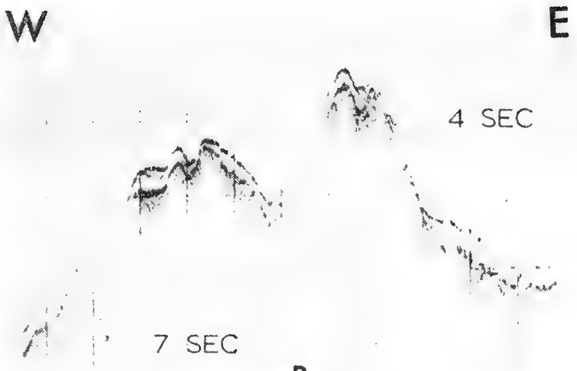
Profile 3 shows that the absent or disturbed sediment extends southward to about 4°N from the valley at 5°N. Again there is some indication of an intermediate thickness from 4°N southward to about 3.3°N. The northward extent of absent sediment seems to be 5.3°N.

As indicated in Figure 5, on the western profiles horizon X is only found well to the south of the axial valley, while Figure 4 shows that on the eastern profiles it can be traced to the trough from the south, and continues northward of the trough (profiles 5 and 6).

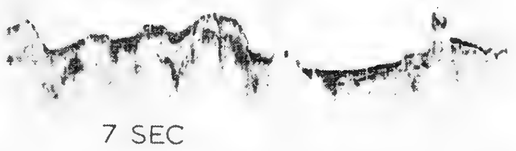
The area between profiles 3 and 4 (Fig. 4) seems to be the transition zone between the regime of undisturbed sediments flanking the eastern trough, and absent or highly deformed sediments flanking the axial valley to the west. As can be seen, there seems to be an area of disturbed sediment extending about 30 km to the north and south of the axial valley, but this does not compare to the 100 km or more missing on profiles 1 - 3. Furthermore, the intermediate sediment thickness zone does not appear on this profile or on those to the east (profiles 5 - 7). Profile 4 also shows a curious trough-like feature at 3.5°N, in many respects similar to the northern trough.

Figure 6 contrasts the thin sediment cover found on the northern margin of the West Caroline Basin (profiles B and D) to the thick sediments to the south (profiles E and F). It also shows the rough

Figure 6. East-west seismic reflection profiles at the northern and southern sides of the Caroline Basin (after Bracey, 1975). located in Fig. 2. Vertical scale as in Fig. 3.



B



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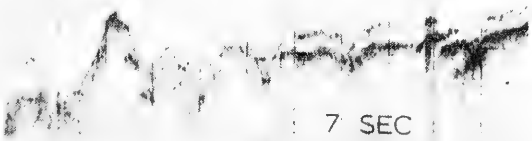

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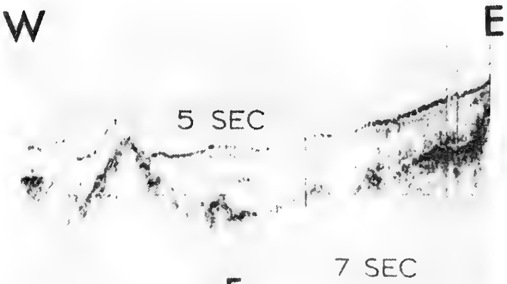


E

F

G

basement surface found on the inner wall of the New Guinea Trench (profile C), and the peculiar zone of high basement relief found at the southern end of the Eauripik Rise (profile G).

Figure 7 shows north-south seismic reflection profiles on the Eauripik Rise (profile 8) and in the East Caroline Basin (profiles 9 - 11; L-D 5). The profiles are aligned (vertical dashed line labeled A) about a magnetically defined extinct spreading axis. The magnetic anomaly identifications used for this definition will be examined in a later section.

The Eauripik Rise (profile 8) exhibits a relatively smooth basement surface south of $5^{o}$N, broken only by local relief in the form of basement knolls, some of which penetrate the sediment surface. North of $5^{o}$ the profile shows considerable basement relief as the profile approaches it's northern terminus in a purported extinct trench (Bracey and Andrews, 1974) at $7^{o}$N.

The remaining profiles in this figure exhibit varied and extensive basement relief. On two of the profiles the proposed extinct spreading axis appears as a collapsed basement arch (profile 9) or block (profile 10) between bounding escarpments of about 1.0 sec relief. On Profile 11 only the southern escarpment appears, as a trough-like feature at $3^{o}$N. This trough, together with the southern-most trough in Profile 10, forms the Kiilsgaard Trough shown in Figure 2. The proposed extinct spreading axis location on this profile is marked only by short-wavelength basement relief typified by numerous side-echo reflections on the seismic record.

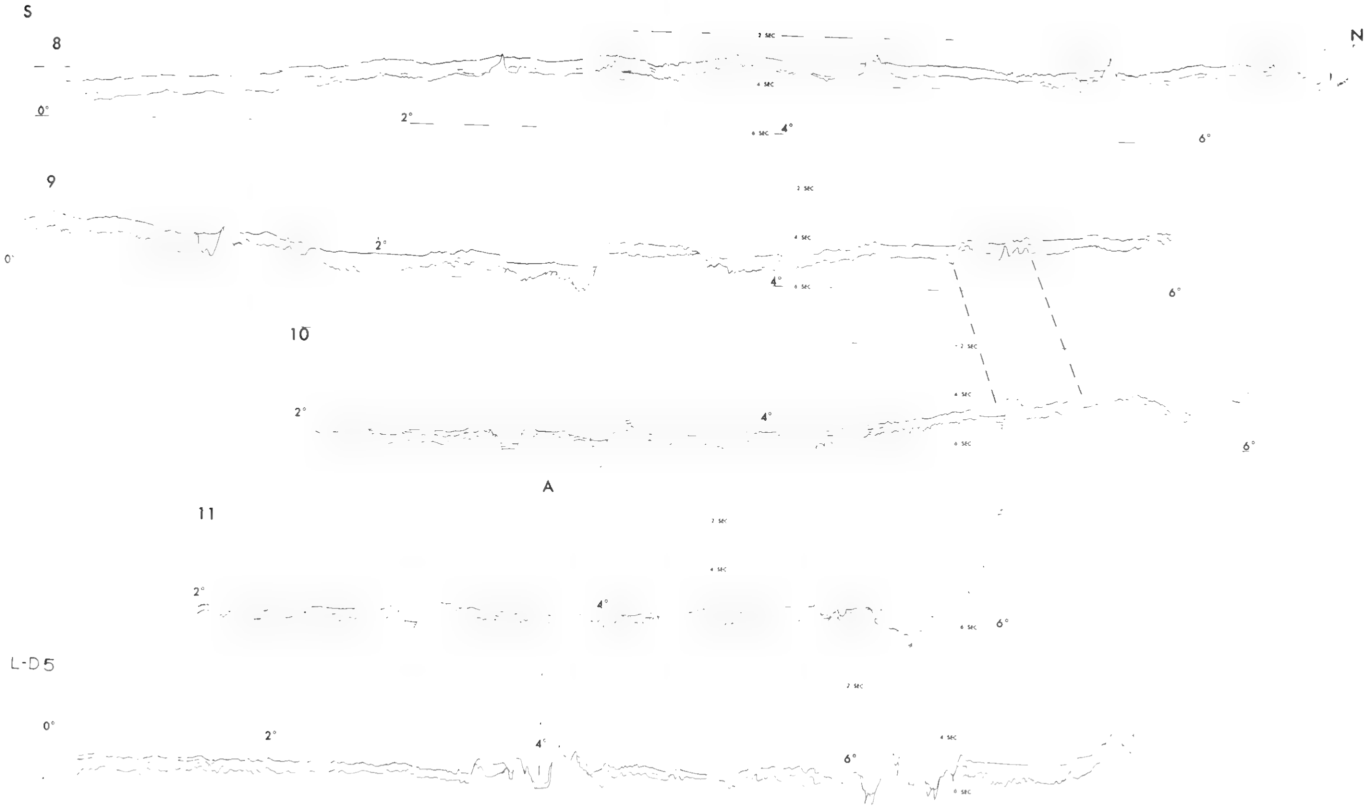


Figure 7. Line drawings of seismic reflection profiles in the East Caroline Basin (from Bracey, 1975; J. Weissel, personal communication, 1980), located in Fig. 2. Vertical scale as in Fig. 3.

Profile L-D 5 has the most clearly defined axial feature, both morphologically and magnetically. It takes the form of an uplifted or uparched block incised by an axial valley. Note that only on profiles L-D 5 and 11 is there a definite indication of an increase in sediment thickness in either direction from the proposed axis.

The prominent block-like feature on profile 10 extending from 5.0° - 5.35°N is believed to be continuous with (connected by dashed lines on Fig. 7) the feature located on either side of 5°N in profile 9. The distance between these two profiles is only 60 km at this location (Fig. 2). This feature has a very deleterious effect on the identification of magnetic anomalies as will be seen.

The northern end of profile 11 shows evidence of the northern Caroline Basin subduction margin proposed by Bracey and Andrews (1974). The resemblance of the features between 5° and 6°N to present-day subduction zones is particularly striking. The feature on profile L-D 5 at 6°N is not so analogous, although it does have analogy to features identified by Bracey and Andrews (1974) as the western remnants of the proposed subduction zone (their Fig. 4). An indication that this feature, whatever its origin, forms the northern boundary of the basin, is given by the sharp increase in sediment thickness to the north.

## Heat Flow

The mean value of the 12 heat flow measurements in the Caroline Basin, exclusive of those less than 0.5 HFU (discarded for reasons discussed in detail by Sclater, 1972), is 2.11 ± 0.69 (s.d.) HFU. This is considerably higher than the mean 1.50 HFU value accepted as the Pacific Ocean average (Von Herzen and Lee, 1969), but is in excellent agreement with the mean value of 2.0 - 2.2 HFU found by Watanabe and others (1977) in extensional marginal Pacific basins formed in Early to Mid-Tertiary time. They attribute this anomalous heat flow to significant differences in the properties and evolution of the lithosphere below extensional basins, principally a thinner lithosphere.

Note that these measurements apply to extensional "back-arc" basins (Karig, 1971) at island arc environs. The relevance of the apparent analogous heat flow regime between the "back-arc" basins studied by Watanabe and others (1977) and the Caroline Basin will be evident in a later section on regional evolution.

### Earthquake Epicenters

Figure 2 shows that the Caroline Basin is essentially aseismic, at least within the ten year time frame (1961 - 1971) of the earthquake observations. Noting that there may be relatively large errors in some of the earthquake locations, there are 3 shallow events in the vicinity of the New Guinea Trench, but there is no indication of a southward dipping seismic zone that would indicate any active subduction. There are also shallow epicenters landward of the Manus Trench, but again there is no seismic indication of a subduction zone.

An excellent summary of the focal mechanism determinations in the area to the south of the Caroline Basin (Bismarck Sea; New Guinea) is given in Hayes and Taylor (1978). The mechanisms found show a complex system of left-lateral faulting in the Bismarck Sea connecting poorly defined NE-striking active spreading axes (Malahoff and Bracey, 1974; Connelly, 1976; Taylor, 1979).

The northern New Guinea focal mechanisms shown by Hayes and Taylor (1978) indicate an extremely complex tectonic regime. The principal stress seems to be NE-SW directed horizontal compression across a broad zone which extends along the entire northern part of the island, connecting on the east with the Bismarck Sea seismic zone and on the west (at Japen Island) with the left-lateral Sorong Fault.

A focal mechanism determination for an earthquake (at 0.2°S/132.4°E) near the small trench north of the "birds head" of New Guinea by Fitch (1972), indicated SSW-oriented thrusting with some components of strike-slip motion.

There are several shallow epicenters in the Ayu Trough. Weissel and Anderson (1978) made a focal mechanism determination for one event (at 2.9°N/132.8°E) for which they found a strike-slip mechanism. Of the two possible solutions, they preferred a N60°W plane with right-lateral motion.

Earthquake activity is very sparse at both the Palau and Yap Trenches relative to the activity at other trench-island arc systems. At the Yap Trench, Fitch (1972) determined one event (at 8.7°N/137.7°E) to be an east-west thrusting mechanism.

There are only two shallow events in the Sorol Trough. No focal mechanism determinations have been done on these earthquakes.

Of the three diverse (shallow and intermediate depth) epicenters scattered along the eastern margin of the Caroline Basin, one mechanism determination has been made by Weissel and Anderson (1978). Although somewhat ambiguous, the solution did indicate maximum horizontal stress along a NE-SW axis.

## Magnetic Anomalies

The magnetic anomaly data are fundamental to any interpretation of the age and tectonic history of the Caroline Basin. It is fortunate that the results of the DSDP (Winterer and others, 1971) allow a Mid to Upper Tertiary time "window" to be applied to the model anomaly profiles to which the observed data must be compared in order to establish the age sequence in the basin.

Figure 8 compares observed total intensity anomaly profiles in the West Caroline Basin to anomalies computed from a sea-floor spreading reversal model (LaBrecque and others, 1977). In the eastern part of the basin, anomalies are identified from 13 (36 m.y.) in the south to the extinct spreading axis at ~ 27 m.y. B.P. expressed by the West Caroline Trough as predicted by Mammerickx (1978). North of the trough, only anomaly 9 is found, which, assuming symmetric and continuous spreading from this axis, would confirm the hypothesis of Bracey and Andrews (1974) that the troughs along the southern flank of the Caroline Ridge represent the remnants of an extinct subduction zone.

At the western side of the basin a symmetric anomaly correlation (Fig. 8, profiles 1, UH1, UH2, 2, 3) about the seismically defined

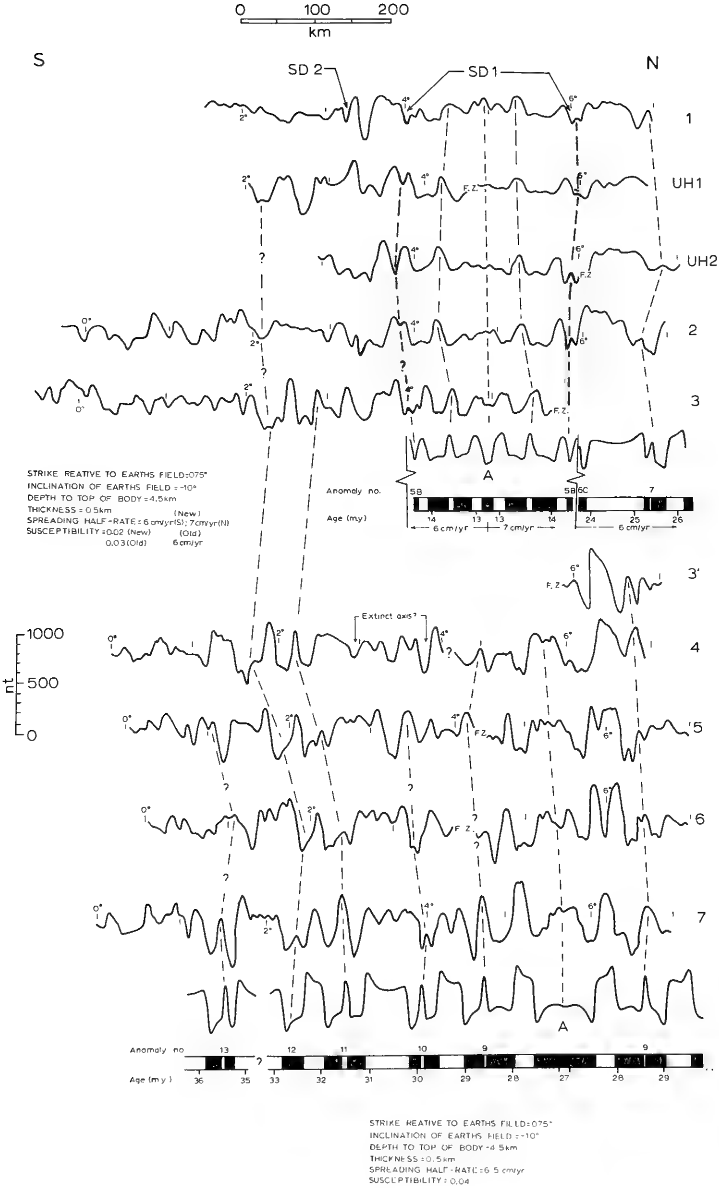


Figure 8. Observed magnetic profiles (located in Fig. 2) in the West Caroline Basin compared to model profiles based on the reversal sequence of LaBrecque and others (1977). Shaded bodies have positive polarity.

ridge axis can be made from 12.5 m.y. B.P. to about 14.5 m.y. B.P. (anomaly 5B). This region corresponds to the inner sediment discontinuity (SD 1) previously noted in the seismic data.

A second spreading sequence, intermediate between the older spreading to the south and this later spreading, is proposed in the intermediate sediment thickness region between the older, thicker sedimentary cover to the south and the younger spreading region (between SD 1 and SD 2). This sequence is tentatively identified as the period beginning prior to anomaly 7 ($>$26 m.y.) and persisting to anomaly 6C time ($\sim$23.5 m.y.).

It must be emphasized here that model identifications for these short spreading segments are extremely tenuous. The absence of seismic layer X in the younger sequence limits its age to $<$18 m.y. B.P., which agrees quite well with the age of the model sequence shown, and the model spreading rate agrees with earlier rates, with the exception of evidence shown by the model comparisons of asymmetrical rates on either side of the axis discussed below.

The intermediate spreading region between SD 1 and SD 2 has identifiable magnetic anomalies only to the north of the axis, and indicates highly asymmetric spreading during this intermediate period. Anomalies cannot be identified in the southern intermediate area, possibly because spreading was too slow to generate recognizable anomalies. SD 2 is not found on the northern side of the axis, having presumably been ingested into the subduction zone at the north side of the basin.

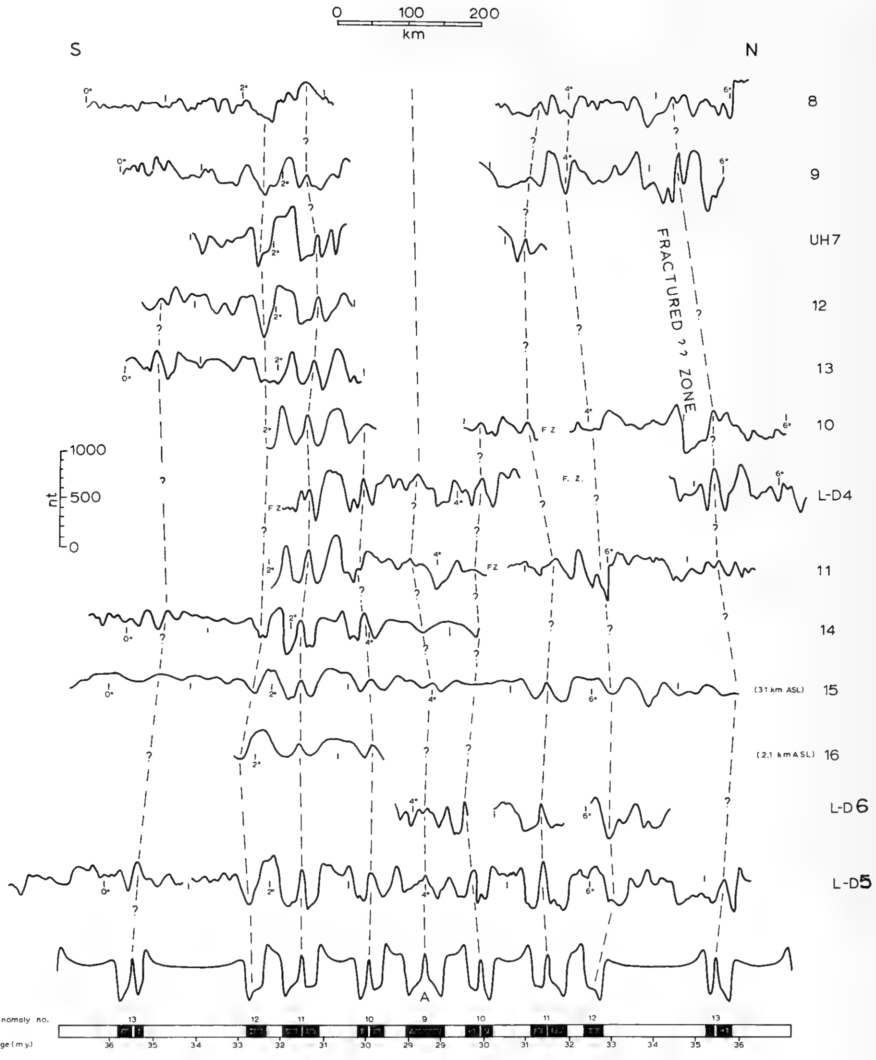
Figure 8 also shows that a gap is required between the model profile reversed polarity period between anomalies 12 and 13 in order to match the observed data. To match the observed data during this time the reversal period must be decreased by about 1.5 m.y. Whether this is the result of a slowing of the spreading rate over the 3.0 m.y. reversal period, or a complete cessation of spreading for 1.5 m.y. cannot be determined.

It is also evident from Figure 8 that the southward extent of identifiable anomalies diminishes to the west. This may be due to the relative increase in basement disturbance in this area indicated on the seismic profiles. This basement disturbance may have been caused by the arching of the oceanic crust as it approached the New Guinea Trench.

Figure 9 shows magnetic anomaly identifications in the East Caroline Basin and on the Eauripik Rise. Because of apparent differences in the time of cessation of spreading indicated by the profiles, those profiles showing older cessation time are "split" at the axis of symmetry in order that they may be compared to the youngest profile.

It is apparent that spreading in the East Caroline Basin ceased at different times in different parts of the basin. In general it can be said that the cessation of spreading progressed from west to east across the basin, stopping at about 31 m.y. B.P. in profile 9, and about 28.5 m.y. B.P. in profile L-D 5 (Weissel and Anderson, 1978).

The inception of spreading seems to have been synchronous in both the East and West Caroline Basins, at a time prior to anomaly 13 time.



STRIKE REATIVE TO EARTHS FIELD: 075°
INCLINATION OF EARTHS FIELD = -10°
DEPTH TO TOP OF BODY = 4.5 km
THICKNESS = 0.5 km
SPREADING HALF-RATE: 6.0 cm/yr
SUSCEPTIBILITY = 0.04

Figure 9. East Caroline Basin Profiles compared as in Figure 8.

In the west basin, spreading at the older, eastern part of the axis (profiles 4 - 7, Fig. 8) persisted for about 1.5 m.y. longer than the youngest part of the east basin spreading axis.

From the above observations it is clear that the spreading history of the Caroline Basin is not comparable to the uniform spreading histories of the larger ocean basins. It appears that the history is very diverse, with hiatuses, episodic temporal incongruities, and possible reactivation of old spreading axes.

Additional information on the source of the magnetic anomalies can be gained from analysis of the component data perpendicular to (X'), and parallel to (Y') the strike of the magnetic lineations. For example, the model studies above are based on the premise that the magnetic anomalies are essentially 2-dimensional (length:width $>$ 3:1). Although the anomalies appear to be 2-dimensional, in the absence of sufficient data for contouring the only positive way to determine this is through the Y' component, which only records anomalies due to 3-dimensional sources (Blakely and others, 1973), and theoretically should be zero over 2-dimensional sources.

At the magnetic inclinations found in the Caroline Basin area ($0^{\circ}$ - $12^{\circ}$S), contributions to the total intensity vector (F) by the induced magnetization from the vertical (Z) component should be minimal. The major contribution should come from the horizontal (H) component. Significant Z anomalies would therefore indicate strong remnant magnetization.

Before examining the above components, a brief description of the instrument and methods used in vector data collection is warranted. These data have been collected in large quantities in all the world's oceans by the Naval Oceanographic Office's project MAGNET aircraft, and are available for studies of this type.

The component data used in this study were collected on track 15 (Fig. 2), and are shown in Figure 10. Basically, the instrument used for magnetic vector measurement was a gimbal suspended flux-gate magnetometer mounted in a magnetically compensated aircraft. The instrument measures F, inclination or dip (I), and magnetic heading (MH) directly, with probable errors of ± 7.5 nt in F; 3 minutes of arc in I, and 5 minutes of arc in MH. Ordinarily, aircraft true heading (TH) is determined for declination (D) measurements by celestial observations, averaged over 100 seconds; taken at 5 minute time intervals. Unfortunately, during the transit of the Caroline Basin the sky was overcast and TH could not be determined by this method. An alternative method had to be developed.

It was decided to use the N-1 Gyroscopic Compass, corrected for gyro error (Ge) to determine the TH. The Ge was found by using the 5 minute D measurements based on celestial observations made earlier and later in the flight, which were assumed to be accurate, combined with MH and gyrocompass headings (G) taken at the same time. Ge for several observations is then determined by: Ge=(G-MH)-D (west D negative). The mean Ge for several observations was found to be $6^{o}30'W \pm 5'$(s.d). TH may then be determined by first visually "smoothing" the G analog trace,

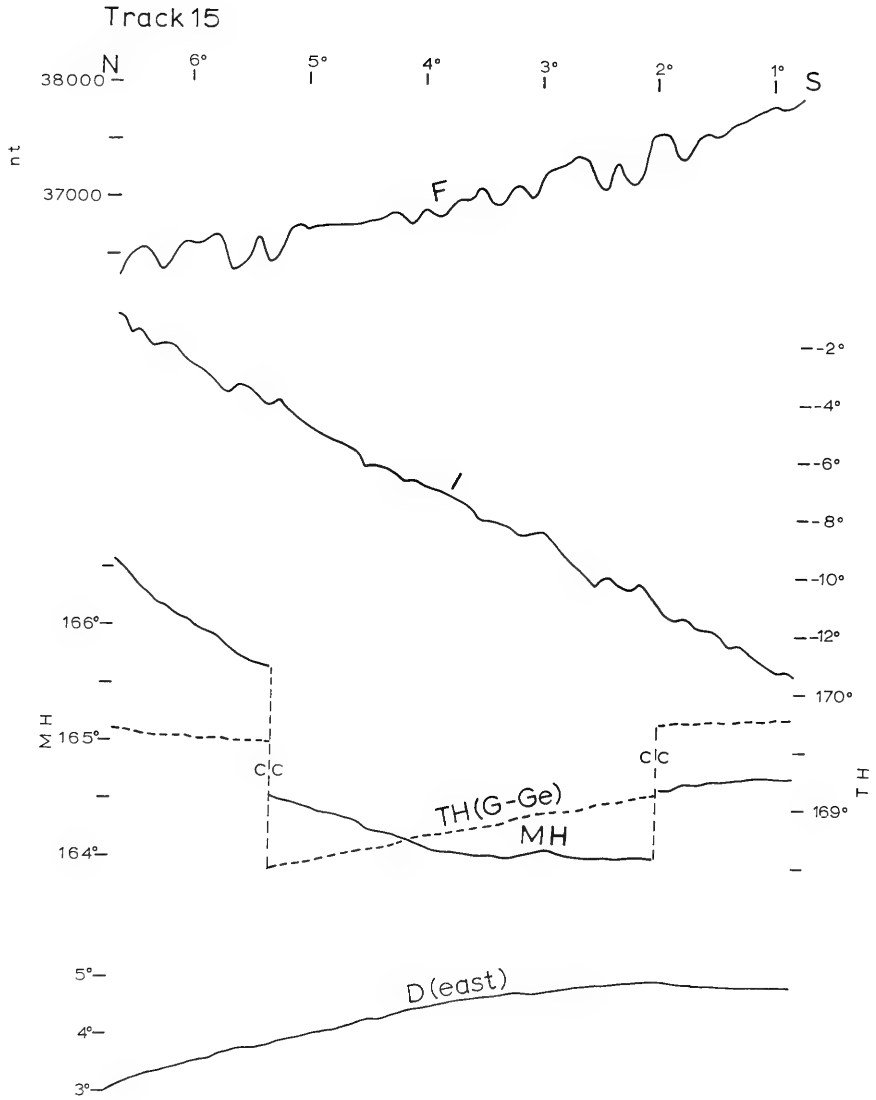


Figure 10. Observed magnetic components (F; I , and aircraft heading elements (TH; MH) used in the computation of D. C/C represents a course change.

which contains aircraft oscillatory motion caused by auto-pilot "hunting" and any turbulence. In this case the oscillations had a period of about 80 seconds and an amplitude of about 90 minutes of arc. "Smoothing" consisted of drawing a mean line through the oscillations. This is a somewhat primitive but effective technique, and accuracy of the mean line is estimated at ± 3 minutes of arc. Automated filtering routines are available that would accomplish the same purpose, but I doubt that they would achieve any significant improvement in accuracy. The TH (G-Ge) may be determined for any desired time interval, since the analog data are continuous. In this case the data were sampled at 1.0 minute time intervals (approximately 6.4 km). Considering that the average wavelength of the F anomalies at this flight elevation (3.1 km ASL) is about 25 km, this sample interval should be sufficient to adequately describe the anomalies.

The MH analog trace contains the same oscillations as does the G trace and is reduced in the same manner.

With these two observations (TH; MH), D: (TH-MH) is established. These computed observations are shown in Figure 10 together with observed F and I.

Figure 11 shows anomalous (subscript a) magnetic components (IGRF removed) computed from the information shown in Figure 10. $Y'_a$ is relatively smooth as it should be if the source anomalies are in fact 2-dimensional. Some small ($<100$ nt) anomalies are present that may result from local 3-dimensional bathymetric features (Blakely and others, 1973) that are not particularly well defined on the bathymetric chart (Fig. 2).

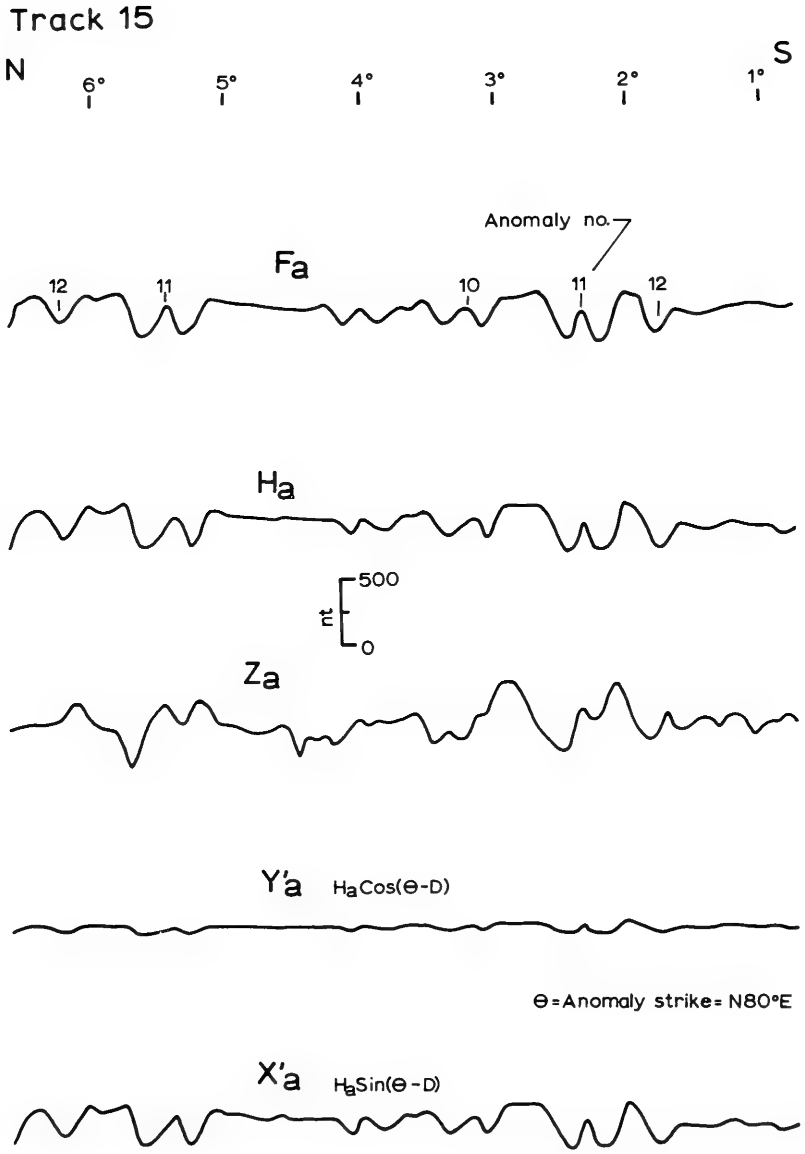


Figure 11. Anomalous magnetic component data (IGRF removed) computed from the information in Figure 10.

$Z_a$ has surprisingly large amplitudes considering that the ambient earth's field at this location is almost entirely horizontal (H), the ratio H:Z being 10:1. This implies that the anomaly sources were either formed at a time when the earth's field at this location was significantly different from the ambient field, or were formed at a different location and then physically moved to their present site.

In a study of the magnetic properties of basalts from DSDP sites in the western Pacific, Marshall (1978) found that the remnant magnetization (Jn) of basalts from DSDP Site 63 averages 0.020 emu/cc. This is a very high value, comparable to the Jn found in fresh basalts from Mid-Ocean Ridge axes (Vacquier, 1972; Lowrie, 1977), and the highest found in the 7 sites studied. The volume susceptibility (k) was also found to be unusually high for marine basalts, averaging 0.0028 as compared to the average of 0.0007 reported by Vacquier (1972). This gives a Koenigsberger (Q) ratio of 21, where Q = Jn/kF, the ratio of remnant to induced magnetization; F being the total magnetic intensity at the sample location. This value of Q is less than half the average oceanic value of 48 (Vacquier, 1972), but a remnant magnetization 21 times greater than induced is still large enough to account for the large $Z_a$.

The data of Marshall can also be used to compute a value called "apparent susceptibility" (Vacquier, 1972) to be used in model calculations. Apparent susceptibility (kap) is defined as the sum of remnant and induced magnetization divided by the field strength: kap = (Jn + kF)/F. Using F = 0.38 Oe, the present value of F in the Caroline Basin, kap = 0.055. However, in order to produce model anomaly amplitudes equal to the observed anomalies, a kap of 0.04 was required (Figs. 8 and 9). Assuming the values of Jn and k are correct, and representative of the magnetic conditions in the basin, and assuming an increase in the magnetized layer thickness used in the model computations is ruled out (which may be unrealistic), then the earth's field value must be increased to 0.54 Oe to reproduce the required kap of 0.04. This 70% increase in F is further indication that the ambient field and the field that produced the anomalies are quite different.

Marshall (1978) also made paleolatitude determinations from the basalt samples at DSDP Site 63. He found that the remnance direction (Ir), after demagnetization, ranged from $-43^{\circ}$ to $+3^{\circ}$, with a mean of $-8.0^{\circ} \pm 7.8^{\circ}$ (s.d.). Using the assumption that the earth's field was largely dipolar, the corresponding paleolatitude is $-4^{\circ}$.

As pointed out by Marshall, there are serious limitations on the accuracy of this latitude determination in addition to the wide angular dispersal of Ir indicated by the $7.8^{\circ}$ standard deviation. First, since there was no azimuthal orientation of the DSDP cores, there is an ambiguity as to whether the latitude lies in the northern or southern hemisphere. Secondly, Cenozoic secular variation may cause dispersion of the Ir with a standard deviation of $\pm 10^{\circ}$. This last effect can be minimized by averaging the measurements.

The only positive way of determining whether the Ir was acquired in the southern hemisphere is to show that it is clearly associated with normally polarized crust. A linear projection of Site 63 along the direction of anomaly strike (N80$^{\circ}$E) to the nearest magnetic profile (L-D 5) would indicate that the site is located in the positive anomaly block just after (north of) anomaly 13. However, the uncertainty of anomaly identifications in this area, and the hazard of extrapolating from the unknown to the known, make this manuever indecisive.

In spite of these difficulties, Marshall's results, when combined with the results of the component study, particularly the high Z:H ratio, give a clear pattern of anomalous magnetic behavior. Considering the consistency of northward movement found at other paleomagnetic sites in the Pacific, and the agreement between the results of Marshall and projected northward movement of the Pacific Plate by other sources (summarized in Marshall, 1978), a 550 km northward movement of this site (from 4$^{\circ}$S to 1$^{\circ}$N) since its formation is certainly plausible.

# TECTONIC SYNTHESIS

## Caroline Basin

Figure 12 is a summary areal display of the magnetic model studies of Figures 8 and 9. Fracture zones (F.Z.) are required by the relative offsets of the anomaly patterns as shown in the above figures. They are drawn normal to the anomaly strike as would be required if they are the result of transform faulting between spreading-ridge segments (Menard and Atwater, 1968). Note that their crossings of the seismic reflection profiles (Figures 4 and 7) are usually marked by features that could conceivably be interpreted as fractures or fracture zones, but the ambiguity of this evidence, as well as the exact strike of the fracture zones is emphasized. It is further emphasized that the sparsity of data may also mask other small-scale complexities not depicted here.

While it is apparent from Figure 12 that the two sub-basins have had a similar mode of occurence (sea-floor spreading), their evolution was by no means identical. Spreading appears to have commenced in both basins at some time prior to anomaly 13 time (>36 m.y. B.P.) along ENE oriented spreading axes (with the notable exception of the area between F.Z. 4 and F.Z. 8, where the spreading direction is more nearly E-W), and progressed at a relatively constant over-all spreading half-rate of 6.0 - 6.5 cm/yr (with another notable exception in the eastern part of the West Caroline Basin noted above) until sometime after anomaly 11 time (~31 m.y. B.P.). At this time spreading apparently ceased (or slowed) at the western side of both basins but continued at the eastern sides, ending after anomaly 9 (~27 m.y. B.P.) time in the eastern part

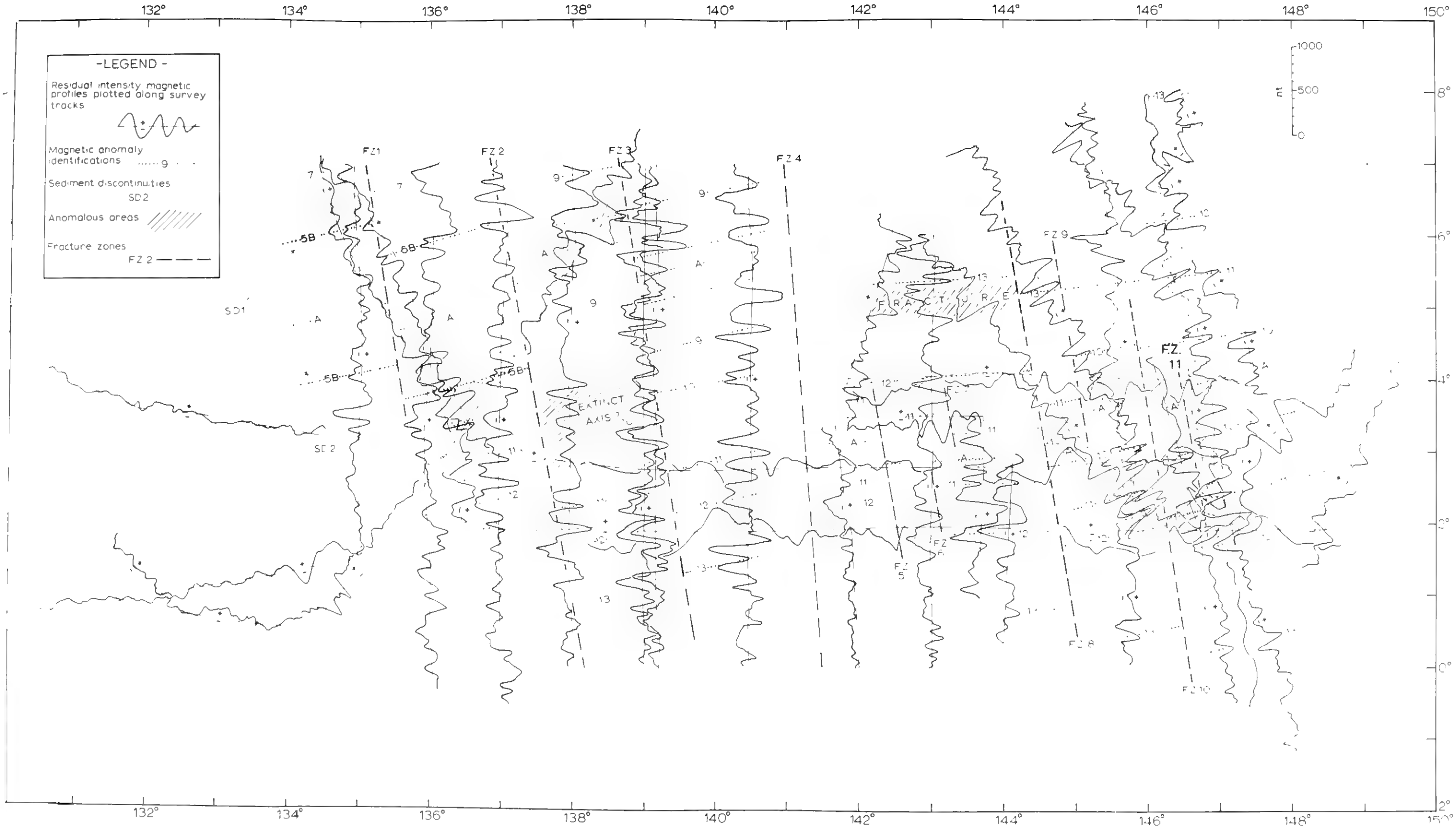


Figure 12. Summary areal display of the results of the model studies of Figs. 8 and 9. Survey tracks identified in Fig. 2.

of the West Caroline Basin, and at anomaly 9 (~28.5 m.y. B.P.) time in the eastern part of the East Caroline Basin. It is not clear whether this stoppage progressed at a steady rate across the basins or was an abrupt stoppage of different segments of the spreading axis at progressively later times. The lack of any significant sedimentary discontinuities in the seismic profiles of the East Caroline Basin (Fig. 7) would indicate that in this area the stoppage progressed at a relatively constant rate in contrast to the West Caroline Basin.

In the West Caroline Basin (west of F.Z. 2) there appears to have been a subsequent period of spreading intermediate between the older spreading and a final stage beginning at about anomaly 5B (~14.5 m.y. B.P.) time. This intermediate stage is marked on the south (between SD 2 and SD 1) by the lack of correlateable magnetic anomalies and the sharp decrease in sediment thickness from south to north across a topographic boundary (SD 2) noted above. The sediment in this southern intermediate area also show the presence of layer X (Fig. 5), which indicates that the crustal age exceeds 18 m.y. B.P.

In the northern intermediate zone, magnetic anomalies are tentatively identified for the interval 23.5-25.5 m.y. B.P. The age of inception of this period of spreading is unknown, the older crust and the northern limb of discontinuity (SD 2) having presumably been ingested into the subduction zone at the northern margin of the basin. As noted earlier, spreading was highly asymmetric; the northern limb moving much more rapidly than the southern limb. The term asymmetric spreading is used rather loosely here. As pointed out by Hayes (1976) the difference between continuous asymmetric spreading and small-scale discrete jumps of the spreading axis which are too small to be resolvable with the existing data is largely a matter of semantics.

There are indications in both the magnetics and seismic data (Fig. 4, profile 4) that the southern limb of intermediate spreading may have extended further to the east. The trough in profile 4 and the apparent "extra" segment of magnetic anomalies seen on this profile may represent a "failed" segment of the intermediate spreading axis. Note that these features are continuous with the SD 2 boundary to the west.

The final stage of sea-floor spreading in the Caroline Basin also occured west of F.Z. 2 (Fig. 12). It spanned a minimum of 2 m.y. between 12.5 - 14.5 m.y. B.P. The criteria used in the identification of this feature are essentially identical to some of those used by Bracey (1975), with the exception that in this case I can show symmetry of magnetic anomalies about the proposed spreading axis (Fig 8). As in the case of the intermediate spreading, there are also indications here of asymmetric spreading rates, the northern limb moving more rapidly than the southern.

While Bracey's (1975) anomaly identifications were in part correct, he erroneously selected the wrong strike direction, partially invalidating his interpretation. To paraphrase some criteria used in addition to magnetic anomaly identifications by Bracey: (1) The seismic profiles crossing this part (west of F.Z. 2) of the West Caroline Trough (Fig. 4) are dissimilar to those to the east, both in morphology and in sediment thickness. The western profiles show a sediment-free topographic high with a central valley and a gradual increase in sediment thickness away from the high. If one can use the mean sediment accumulation rates (Winterer and others, 1971) for the two DSDP sites (62 and 63) during the past 15 m.y. (20m/m.y.) as representative of accumulation rates throughout the Caroline Basin, then the sediment thickness in the oldest part of this spreading area should be about 300 meters. This agrees quite well with the seismic data. On the other hand, the eastern profiles show a trough, in some cases flanked by ridges, with relatively thick sediments extending up to, and in some cases into, the trough. (2) Horizon X is absent in the western profiles for some distance both south and north of the topographic high. In the east, on the other hand, it can be traced to the trough from the south, and in some cases, to the north of the trough.

As pointed out by Vogt and others (1969), spreading discontinuities such as those exhibited in this area may result from one or more of the following processes: (1) Total stoppage and later reactivation of a spreading center; (2) shift in the ridge axis; (3) change in spreading rate; (4) change in spreading direction, and (5) change in the mode of spreading (from normal to oblique). From among these causal mechanisms, no one can be selected with any degree of certainty as the cause of the West Caroline Basin discontinuities. The sharp change in sediment thicknesses across both the old-intermediate and intermediate-young boundaries certainly indicate a drastic reduction, if not a complete stoppage, in spreading rates, and are remarkably similar to the sediment thickness vs. age diagram developed by Vogt and others (1969, their Fig. 3) to identify spreading discontinuities.

There is no indication in the magnetic data of changes in mode or direction of spreading, although these possibilities cannot be excluded in the southern intermediate area where no anomalies have been identified. There is also no definite indication of a spreading axis shift, although as stated earlier this possibility cannot be discounted, nor is there any positive evidence of change of spreading mode.

Within the possibilities offered, I favor spreading cessation and reactivation to account for the two discountinuities, even though this appears to be the rarest form of discontinuity (Vogt and others, 1969). The fact that the younger spreading axis and the older sea floor have similar spreading half-rates of 6 - 7 cm/yr would indicate that there was no radical change in spreading rates during these widely separated (18 m.y.) times, and although asymmetrical, the intermediate spreading rate was also of the same magnitude.

The sediment isopachs (Fig. 13) lend some credence to the above interpretations, particularly as to the location of certain fracture zones. The narrowing of the thin sediment cover area enclosed by the 0.2 sec contours toward the ENE from about 5°N/135°E to 6°N/140°E indicates an age increase toward the ENE. Note also that sediment thicknesses  0.4 sec in this area do not extend westward of 138°E. Particularly striking is the "nosing" of the 0.4 sec contour to the south between 135°E and 140°E, exactly as predicted by the magnetic anomaly age offset between F.Z. 2 and F.Z. 3.

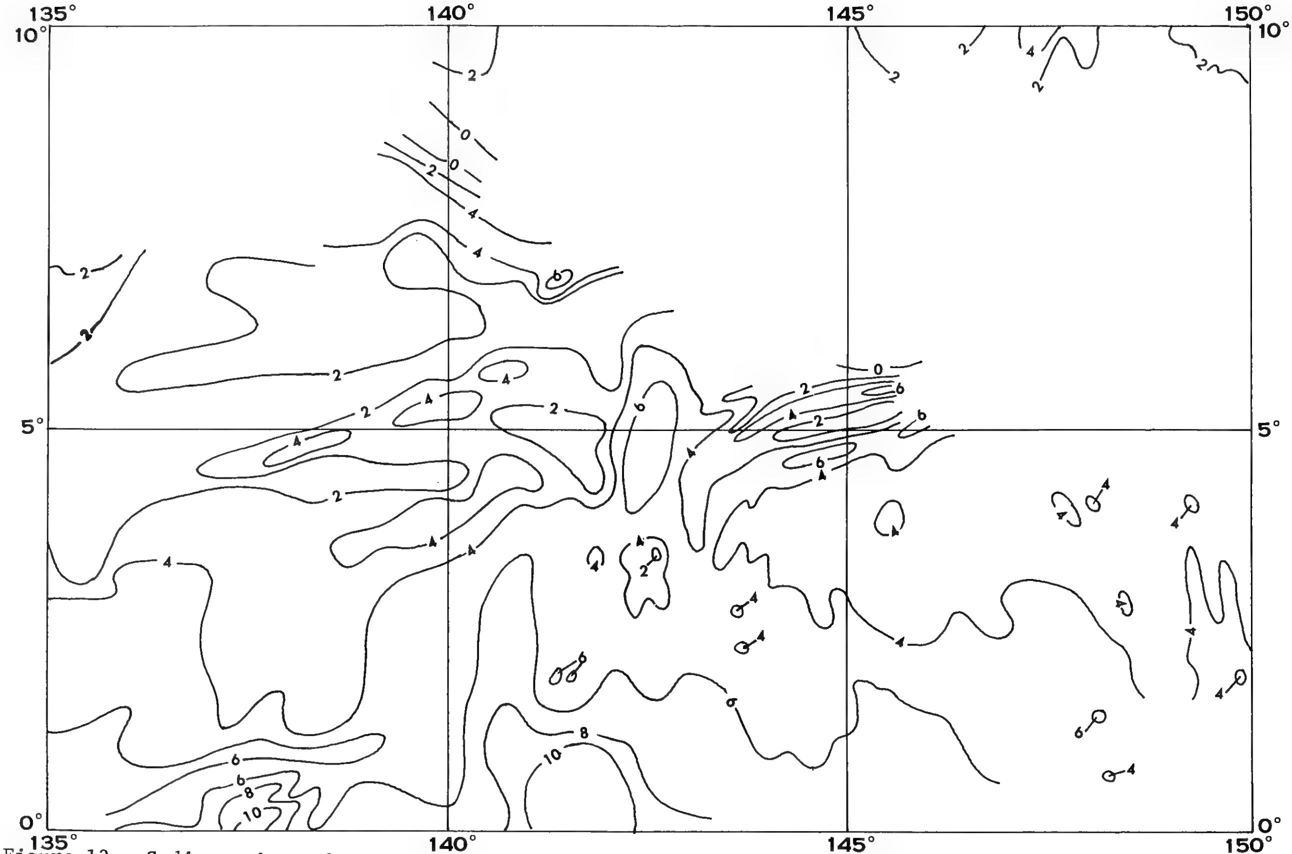


Figure 13. Sediment isopachs in the Caroline Basin. Modified from Mrozowski and Hayes (1978) with the addition of unpublished data. Contours are in $10^{-1}$ seconds of two-way reflection time.

With the exception of those anomalies on the extreme eastern side, the identification of magnetic anomalies in the East Caroline Basin was even more difficult than the identification of those in the West Caroline Basin. The only clear-cut identifications that extend across the entire basin are those on the southern side (Figs. 9; 12). However, working north from the clearly established anomalies, and considering the geometry of the area as well as the seismic reflection evidence, reasonable inferences as to anomaly sequences can be made.

One of the most striking aspects of Figure 12 is the 325 km left-lateral offset of the spreading axes in the east and west basins along an inferred fracture zone (F.Z. 4) at the western margin of the Eauripik Rise. This is by far the greatest axial offset in the entire Caroline Basin.

The eastern basin is characterized by short, discontinuous fracture zones in contrast to the proposed continuous offsets in the western basin. These discontinuous fractures are characteristic of asymmetrical spreading (Hayes, 1976), and evidence of asymmetry may be seen in the varying distances from the extinct axis to certain key anomalies on either side of the axis across these fractures. A mean increase of 15 - 20% in the northern limb spreading rate relative to the southern limb is indicated. Note that the arguments given earlier as to the difficulty of distinguishing asymmetrical spreading from discrete ridge jumps still apply. In this instance it would be particularly difficult to recognize any small-scale additional or partial anomalies caused by ridge jumps, although none are readily apparent.

There does appear to be a slight ($5^o$) change in spreading orientation west of F.Z. 8, the only fracture that extends across the entire basin. This area (between F.Z. 8 and F.Z. 4) is also the locus of the block-like basement feature extending eastward from the Eauripik Rise (Fig. 2; Fig. 7, profiles 9 and 10) mentioned earlier. This feature is labeled "fracture" in Figure 12, and occurs just south of (after) anomaly 13. I speculate that this feature may be related to the change in spreading orientation, and that its counterpart may be found on the southern side of the basin by future seismic reflection surveys.

There is no indication in either the magnetic anomalies or the sediment column that the East Caroline Basin experienced the sort of spreading discontinuities found in the West Caroline Basin. Spreading cessation seems to have progressed rather uniformly and permannently from west to east across the basin as individual spreading segments died out. This cessation occured over a time span of roughly 3 m.y., from about 31 m.y. B.P. in the west to about 28.5 m.y. B.P. in the east.

### Eauripik Rise

The Eauripik Rise (Fig. 2) is a 300 km wide arcuate (concave eastward), north-trending bathymetric feature. Relief averages 2 km above the adjacent ocean basins.

The results of the seismic refraction work of Den and others (1971) over the rise indicate a crustal "root" under the rise extending to a depth of about 20 km, 14 km of which is composed of layer 3 (average p-wave velocity of 6.98 km/sec) oceanic crust, as opposed to the 4 km thickness of layer 3 crust in the adjacent basins.

Figure 14 contrasts bathymetric (plotted from Fig. 2) and gravity profiles over the Eauripik Rise and the eastern part of the West Caroline Trough, which through magnetic anomaly identification has been shown to be an extinct spreading center since about 27 m.y. B.P. The Eauripik Rise Bouguer gravity profile shows a broad negative over the rise typical of aseismic oceanic rises isostatically compensated by underlying mass deficiencies. See for example: Goslin and Sibuet (1975); Bowin (1973) . This compensation is in complete agreement with the seismic results of Den and others (1971). The West Caroline Trough Bouguer anomaly exhibits no such low.

When compared to the thermal contraction model curve for oceanic crust, which predicts crustal age as a function of depth (for example: Parker and Oldenburg, 1973), the depths of the crust adjacent to the West Caroline Trough (4.24 km) plot at about 25 m.y. B.P., in good agreement with the magnetic age. On the other hand, the crustal depth at the Eauripik Rise ( 2 km) yields an age of less than 1.0 m.y. B.P., in complete disagreement with the DSDP Site 62 minimum age determination of 26 m.y. B.P. (Winterer and others, 1971).

Mammerickx (1978) discounted the results of Den and others (1971) and following Winterer and others (1971), proposed that the rise is an inactive (since 26 m.y. B.P.) spreading center. The facts cited above, and the additional fact that the recognized east-west trending magnetic anomalies extend from the East Caroline Basin onto the flanks

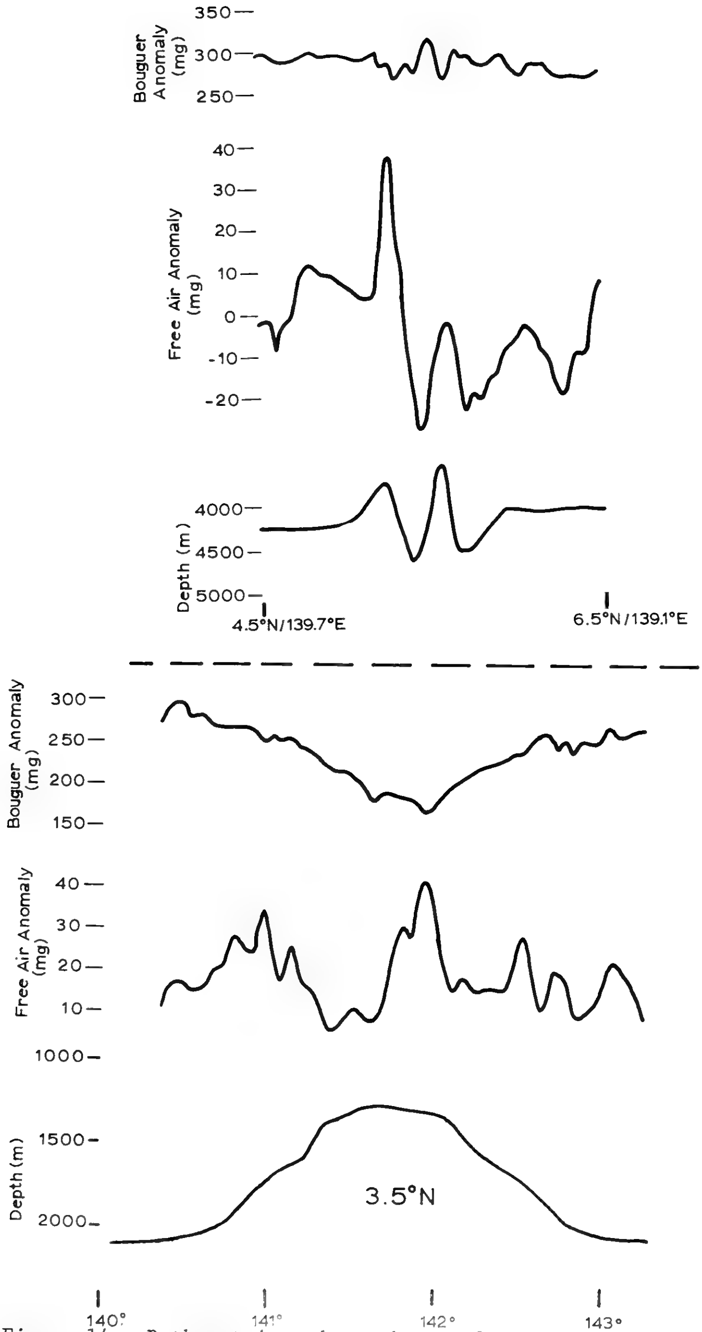


Figure 14. Bathymetric and gravity profiles across the West Caroline Trough (top) and Eauripik Rise (bottom). Geographic locations shown at bottom of each profile.

of the rise, and possibly to the rise crest (Fig. 12) would seem to preclude this possibility.

Weissel and Anderson (1978) suggested that the Eauripik Rise is the result of excess magmatism along a "leaky" transform fault. I would certainly agree that there is transform faulting associated with the rise as indicated by the 325 km offset of the spreading axes on either side of the rise.

Vogt and Johnson (1975) considered the effect of a "transform dam" on asthenospheric flow from a ridge (spreading axis) centered mantle plume (Wilson, 1965; Morgan, 1971) located "upstream" from the transform. Partial melts from the mantle plume flow through a pipe-like conduit between the spreading plates at depths of 5 - 75 km. The amount and velocity of the melt depends on the radius and depth of the pipe (lower viscosity melts occur near the top of the pipe). When the flow encounters a transform fault, partial or total blockage of the flow may ensue. This blockage is due to the crustal age differential across the transform resulting in a concomitant change in lithospheric thickness (Parker and Oldenburg, 1973). Thus the older, thicker lithosphere abutting the axial pipe retards that part of the partial melt flow occuring above its base. This part of the flow may "pile up" along the transform, resulting in a linear topographic ridge or rise.

Vogt and Johnson (1975) concluded that for a partial melting zone between 5 and 75 km depth at a spreading center whose half-rate is 6 cm/yr, a "downstream" transform with an offset of 325 km (as is the case with the Eauripik Rise) could be expected to block 10 - 100%

of any longitudinal flow along the spreading axis. The major characteristics of such a "transform dam" would be: (1) Accumulation of ultrabasic slushes and increased basic volcanism along the upstream side of the dam. (2) A transform fault along only one side of the constructional ridge formed by the basalt discharge. (3) The constructional ridge would have the same age as the adjacent accretional crust on the upstream side of the fracture.

The Eauripik Rise demonstrates all the above characteristics. The presence of extrusive basalt at DSDP Site 62 as well as other nearby igneous features (Winterer and others, 1971) indicates that volcanism was occuring on the rise even after the cessation of spreading in the East Caroline Basin. This fact is somewhat puzzling, considering that spreading at this location ceased at about 31 m.y. B.P. (although continuing until 28.5 m.y. B.P. to the east). A possible explanation is that the old spreading axis still served as a conduit for basalts formed at a still marginally active hotspot located to the east, but that the discharge volume was insufficient to support spreading.

The 325 km offset of magnetic anomalies along the western flank of the rise indicates that this flank was the site of the most extensive transform faulting in the Caroline Basin. Those faults on the eastern flank of the rise are relatively minor and are discontinuous. The relatively steep bathymetric gradients (Fig. 2) on the west flank of the rise also indicate that this was the locus of extensive faulting.

Although the magnetic anomaly identifications on the rise are somewhat tenuous, it does appear that they continue onto the rise from the east, and they are certainly not continuous with the western basin anomalies.

Among the hypotheses offered, I favor the possibility that the Eauripik Rise formed as a result of transform damming, blocking the flow of mantle material along the spreading axis from a mantle plume located to the east. The peculiar "collapsed arch" structure of the proposed eastern spreading axis (Fig. 7) is quite different from the structure of the proposed western axis (Fig. 4), and may be indicative of a different spreading regime associated with a mantle plume environment. This is, however, a speculative proposal.

With the evidence presently available it is not possible to determine the origin of the Eauripik Rise, although the hypothesis that it was a sea-floor spreading center can be discounted. A possible resolution of the rise origin may come from geochemical analysis of the basalt recovered from DSDP Site 62. It has been found (Goslin and Sibuet, 1975) that aseismic ridges such as the Ninety-east, Cocos, Walvis, and Iceland-Faeroes ridges have unique rare-earth compositions that differ markedly from spreading-ridge and island-arc basalts.

## Basin Margins

The most notable feature of the Caroline Basin margins is that with one exception they appear to be, or have been, subduction zones. The kinematics of these zones presently ranges from inactive to probably active.

Figure 15 gives a graphic summary of Caroline Basin and margin tectonics, which together with Figure 2, should be referred to in order to locate areas covered in the following discussion.

The notable exception to the subduction marginal regime is the Ayu Trough. The seismic reflection profiles of Figure 3 demonstrate the sediment distribution patterns of known spreading axes as stated earlier. Seismic reflection profiles shown in Hamilton (1979, his Figure 141) indicate that this sediment-free area extends at least as far north as 4.5°N, though attenuated in horizontal extent.

Weissel and Anderson (1978) proposed that the Ayu Trough was an active extensional feature, based on the absence of sediments from the central rift and the presence of a limited number of earthquake epicenters (Fig. 2) in the trough. They considered the possibility that opening of the trough commenced at about 20 m.y. B.P. (based on basement depths) about a pole of opening at 7°N/133°E, and proceeded at a half-rate of 0.6 cm/yr. An alternative scheme of the authors (based on extrapolated sedimentation rates), was that the spreading began at 10 - 12 m.y. B.P. and progressed at 2 cm/yr until about 6 m.y. B.P. when it slowed to about 0.4 cm/yr.

Analyses of basalts dredged from the trough by Fornari and others (1979) support the spreading concept. The basalts show chemical affinities with mid-ocean ridge basalts.

The magnetic anomalies across the trough (Fig. 12) have very low amplitudes as would be expected if they result from N-S oriented crustal features formed at this low magnetic latitude, and are inconclusive in

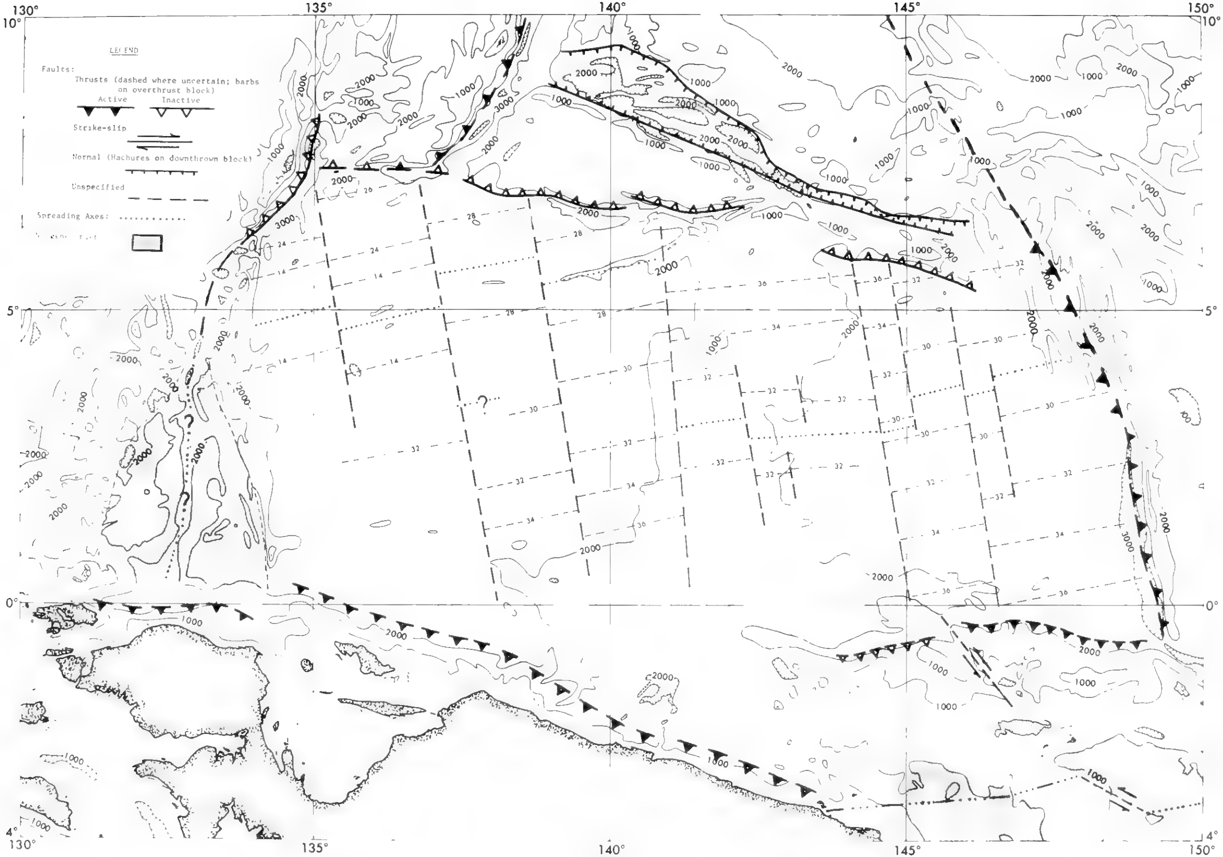


Figure 15. Tectonic interpretation chart of the Caroline Basin and margins on 1,000 fm (1,852 m) contour interval bathymetric base. Isochrons at 2 m.y. interval shown by light dashed lines.

identifying any spreading axis. Magnetic symmetry about the trough axis would be a positive test for sea-floor spreading at this location, but it will probably require a detailed ($<$10 km track spacing) E-W survey pattern over the trough to establish any conclusive magnetic evidence.

The gravity data of Watts and others (1978) show a small free air minimum ($<$ 25 mgal) associated with the trench axis, with flanking free air highs of 100 mgal. While not inconsistent with a spreading origin for the trough, these anomalies could equally well result from other structural origins (graben, fracture zone, etc).

The data presently available certainly do not negate the contention of Weissel and Anderson that this is a Neogene spreading area.

The marginal area between the Ayu Trough and the Palau Trench is an enigma. Although marked on Figure 15 as a possible fracture zone, its origin or present characteristics are unknown. Hamilton (1979) extends the "belt of rough topography" shown in his reflection profiles northward to the Palau Trench itself, and it may well do so. This area would then probably represent an axis of incipient or failed Neogene Spreading. Its northern terminus near the proposed pole of opening of the Ayu Trough may explain the limited E-W lateral extent of this northern segment.

The Palau and Yap Trenches are similar to each other, and atypical of most oceanic trenches in that the distance between the axis of the trench and the island-arc is only 40 - 50 km as opposed to the 150 km separation at most island-arc systems (Weissel and Anderson, 1978).

Island-arc volcanism commenced in the Palau Islands at least by Eocene time (Dietz, 1954) and subduction may now be inactive as indicated by the low level of seismicity (Fig. 2).

Rocks recovered in dredging of the Palau Trench are metamorphosed (zeolite and greenchist grade) basics and ultrabasics (Coleman and Irwin, 1977), grossly similar to those dredged on the inner-wall of the Yap Trench, with the exception that amphibolite grade metamorphism appears in some of the Yap rocks (Coleman and Irwin, 1977; Hawkins and Batiza, 1977).

Hawkins and Batiza offered a somewhat complicated but plausible mode of origin for the Yap arc which may be applicable to the Palau arc, since many of their characteristics are the same. They proposed that the introduction of the Caroline Ridge into the Yap Trench essentially blocked subduction from the east and caused the eastward obduction of Phillippine Sea (Parece-Vela ?) crust and mantle material over the volcanic arc due to the continuing E-W horizontal compression of the colliding plates. This would account for the metamorphic mineral assemblage and the foreshortened arc-trench gap.

In the Palau arc, where the same features are found, there are bathymetric features (seamounts; ridges) to the east of the trench that may have also contributed to subduction blockage. The younger, more bouyant crust (the intermediate spreading) in the western Caroline Basin may also have been detrimental to subduction along the southern part of the trench (Fig. 15). The equivocal nature of this hypothesis as applied to the Palau Trench kinematics is stressed.

Whatever the present-day nature of Ayu Trough-Palau Trench tectonics, I follow Bracey (1975), in that these features earlier were directly related to the Palau-Kyushu Ridge system, and acted as a transform fault that separated the Tertiary Philippine Sea-Caroline Basin spreading axes, and subsequently became a westward-dipping subduction zone (Uyeda and Ben Avraham, 1972).

Separating the Parece-Vela Basin and the NW Caroline Basin is a trench-like feature (Fig. 2) marked on Figure 15 as a possible inactive subduction zone. As proposed by Bracey (1975) this feature may have a varied structural history: (1) A subduction zone during the earlier period of West Caroline Basin formation (from prior to 36 m.y. B.P. until 27 m.y. B.P.). (2) A fracture zone, with right-lateral sense of offset, as the Yap arc moved westward from the Palau-Kyushu Ridge (Karig, 1971) during the period 25 - 20 m.y. B.P. (3) Possible reactivation of subduction during the final phase of West Caroline Basin spreading (12.5 - 14.5 m.y. B.P.).

A N-S seismic reflection profile shown in Hamilton (1979, his Fig. 139) crosses the eastern end of this feature at 137°E, and exhibits definite trench-like morphology. Hamilton considered the feature at this location to be a SW extension of the Yap Trench (his Fig. 136), which it may well be, but Figure 2 shows that the trench-like morphology extends westward to the Palau Trench, and it is hard to imagine that this E-W feature is a continuation of the N-S Yap Trench.

Extending eastward from this feature are a series of morphologic features considered to be the remnants of an extinct northward-dipping subduction zone (Bracey and Andrews, 1974; Bracey, 1975; Mammerickx, 1978; Weissel and Anderson, 1978). Hamilton (1979) objected to this interpretation, mainly on the basis that the features do not look much like present-day trenches. This is true in the case of some of them, although Bracey and Andrews (1974) made a qualitative attempt to explain their present morphology. The compelling evidence that these features are in fact trench remnants is to be found in the magnetic data. If one accepts the anomaly identifications made earlier, and agrees that there was symmetrical crustal accretion from the ridge axis, then it is clear from Figure 15 that at least 400 km of crust (created during a minimum period from 28 - 36 m.y. B.P.) has vanished at the northern side of the West Caroline Basin. Unless this crust was somehow shoved up over the Caroline Ridge, it is difficult to see where else it could have gone other than down a subduction zone.

The above arguments also apply in the East Caroline Basin. At least one of the widely spaced seismic profiles (Fig. 7, profile 11) gives clear indications of subduction at the northern side of the basin.

Seismic reflection profiles across the Sorol Trough (Bracey and Andrews, 1974; Weissel and Anderson, 1978; Fornari and others, 1979) indicate that the narrower eastern end of the trough (east of 143°E) contains about 200 - 300 meters of sediment both in the trough and on surrounding areas. The wider western end of the trough shows a considerable increase in topographic complexity. There are indications of a sediment-free area at the base of the southern escarpment some 50 - 60 km wide, with the remaining area to the north containing up to 500 meters of sediment, principally ponded between bathymetric highs. Sediment thicknesses on the ridge crest and flanks are also of this magnitude.

Dredging at the western end of the trough (Coleman and Irwin, 1977) recovered fresh pillow-basalts and diabase, typical of active spreading ridges. Fornari and others (1979) also dredged typical spreading ridge rocks (although heavily weathered) from the base of the northern escarpment near the center of the western end (near 8.5°N/141.5°E).

To the east (near 7.5°N/142°E), Fornari and others dredged fresh pillow basalts with strong chemical affinities to the DSDP Site 57 basalt, described by Ridley and others (1974) as a transitional basalt, high in Fe, $P_2O_5$, and $TiO_2$, "characteristic of Oceanic islands and island chains".

At a third site (near the southern escarpment at about 8.5°N/139.5° E) Fornari and others recovered the same transitional basalt together with ultramafics similar in chemistry and metamorphic grade to those recovered from the inner-walls of the Mariana, Yap, and Palau Trenches.

Of the 4 DSDP holes drilled on the Caroline Ridge and its flanks (Fig. 2), only two (57;58) reached basalt, which was determined to be of Upper Oligocene or Lower Miocene age by Fisher and others (1971). Ridley and others (1974) established a potassium-argon age of 23.5 m.y. B.P. for the basalt at site 57.

The basalt forms a smooth, flat surface similar to that found by Karig (1971) west of the West Mariana Ridge, and is generally believed to be a flow, since the overlying sediments at Site 57 are unaltered

(Ridley and others, 1974). That this area may have an unusual thickness of layer 2 crust is indicated by the results of a reversed seismic refraction profile shot nearby (at 8.7°N/143°E) by Gaskell and others (1958). This profile indicates a layer 2 thickness in excess of 4 km. Ridley and others point out that this basalt flow may mask older oceanic crust and sediments (possibly Jurassic) on the northern Caroline Ridge and in the area to the north.

Bracey and Andrews (1974) proposed that the Sorol Trough is an extinct inter-arc basin formed behind the northward dipping trench system at the northern Caroline Basin margin; coeval with the Oligocene spreading.

Weissel and Anderson (1978) felt that the Sorol Trough is an active, obliquely-opening transform feature representing the present northern boundary between the Pacific and Caroline plates, a view shared by Hamilton (1979).

Vogt and others (1976) attribute the Caroline Rise to westward movement of older ocean crust over a Neogene mantle plume, a view similar to that proposed by Clague and Jarrard (1973). The rise subsequently blocked the Yap-Mariana Trench system, and the Sorol trough formed as a result of the "incipient breakup of the Pacific Plate."

It is difficult for this author to understand why a transform plate boundary should form along the center of one of the most massive features in the southwest Pacific. Why did it not form instead along the southern flank of the ridge where the extinct trench provided a pre-existing zone of NW-SE crustal weakness, or along the northern flank where the thinner crust would be easier to breach?

To answer my own somewhat rhetorical question, I think that any transform boundary (leaky or otherwise) that may now exist in the Sorol Trough followed a pre-existing zone of weakness. I follow the proposal of Bracey and Andrews (1974) that the Sorol Trough is a remnant inner-arc basin. The basin was created during rapid northward subduction of Caroline Basin crust beneath an existing island arc in late Oligocene (27-24 m.y. B.P.?).

Rift formation was accompanied by voluminous outpouring of transitional basalts along the opening rift. These basalt flows may have covered earlier crust and sediments, perhaps extending as far north as the present-day Mariana Trench, as may be indicated by the low heat flow values (0.6-0.9 HFU) found at the 3 locations in this area (Hamilton, 1979), which would indicate a much older crust than the Oligocene basalts presently found there indicate (see for example: Sclater and others, 1976), and are in sharp contrast to the 2.11 HFU thermal regime of the Oligocene Caroline Basin crust.

The thickness of layer 2 crust found on the Caroline Ridge, noted earlier, is comparable to the 6 km thickness found at the West Mariana Ridge (Bibee and others, 1979), a region of tectonic activity analogous to that proposed here. Whether there are chemical similarities between the West Mariana Ridge basalts and those found here is unknown.

There are, however, affinities between the metamorphic rocks dredged from the southern escarpments of the Sorol Trough by Fornari and others (1979), and the metamorphic assemblage recovered from the eastern base of the West Mariana Ridge at DSDP Site 453 (Scientific Staff, 1978). Although higher in metamorphic grade (amphibolite vs greenschist), the tectonic deformation exhibited by the Sorol Trough metamorphics would certainly not be surprising if they represent part of the deformed crust and upper mantle found on the inner-wall of an island arc subduction zone, exposed in the deeply rifted Sorol Trough.

Rifting in the Sorol Trough probably ceased earlier in the east than in the west, perhaps as a result of the earlier cessation of spreading in the East Caroline Basin lowering subduction rates, or perhaps as result of the attempted ingestion of the low-density Eauripik Rise into the subduction zone south of the Caroline Ridge as proposed by Bracey (1975). Rifting continued in the west, accompanied by the appearance of mid-ocean ridge type basalts in addition to the continuing transitional basalt flows at the northern trough margin, until collision of the West Caroline Ridge and Basin with the eastward advancing Yap-Mariana island arc system (Bracey, 1975; Vogt and others, 1976) at about 24 m.y. B.P. At this time, spreading activity ceased in the West Caroline Basin, as did inner-arc spreading and all other magmatic activity in the Sorol Trough.

A final pulse of West Caroline Basin activity from 14.5-12.5 m.y. B.P. may have reactivated the western Sorol Trough inner-arc spreading, and the fresh pillow basalts found near the SW margin of the trough may reflect this activity. The apparent lack of sediments in this area of the trough is certainly comparable to the sediment absence found at the younger West Caroline spreading zone, and may indicate coeval activity and age.

Whether the limited contemporary seismic activity within the Sorol Trough represents left-lateral transform motion as proposed by Weissel and Anderson (1978), or is simply the result of normal faulting caused by isostatic adjustments in the relatively young trough awaits earthquake mechanism determinations.

Weissel and Anderson present convincing evidence (seismic reflection; earthquake mechanism) for eastward directed overthrusting of the Caroline Plate over the Pacific Plate in a broad zone extending N35°W from the northern end of the Mussau Trough at 3.5°N, to the northern limit of their data at 6°N. This area is characterized by rough ridge-trough bathymetry (Fig. 2). They attribute this zone to NE-SW horizontal compression about a Caroline-Pacific pole of rotation at 13°N/144°E, with an angular velocity of about 7°/10 m.y. There is presently no information as to how far north this deformed zone may extend. The bathymetry (Fig. 2), together with the scattered earthquake epicenters (Bracey and Andrews, 1974, their Fig. 2) gives some indication of tectonic activity along a broad zone extending northward to the southern Mariana Trench, a presently inactive (south of 12°N) feature characterized by normal faulting in the island arc to the west (Bracey and Ogden, (1972).

There is some indication that the Oligocene magnetic lineations may extend northward beyond the eastern limit of the West Mariana Ridge in this disturbed zone (Figs. 9 and 15), but this is somewhat speculative, particularly in the case of anomaly 13.

If the pole position of Weissel and Anderson is correct, the relative compressional motion of the Pacific and Caroline Plates should decrease to the north, and the relative motion between the plates could conceivably change to a relative left-lateral motion of the Pacific Plate along a transform boundary. Again there is no evidence at present to either refute or support this possibility.

South of 3.5°N, the Caroline-Pacific Plate boundary, while still compressional, apparently changes from overthrusting of the Caroline Plate to underthrusting of the plate along the Mussau Trench. This trench is generally considered to be the site of incipient subduction (Bracey and Andrews, 1974; Bracey, 1975; Kogan, 1976; Weissel and Anderson, 1978).

Bracey and Andrews (1974) felt that the former Pacific-Philippine plate boundary, marked by the Yap-Palau-Ayu Trough may now be extinct, or may be in the process of becoming inactive. They felt that there has been a relatively recent shift to a Pacific-Caroline Plate margin extending from the Mariana Trench at 12°N/145°E to the southern end of the Mussau Trench. While the nature of the northern portion (6°N-12°N) of the boundary is as yet unclear, I follow their interpretation.

It is likely that the Manus Trench (at least the eastern part - Fig. 15) marks part of the present-day southern boundary of the Caroline Basin. There is general agreement (Krause, 1972; Malahoff and Bracey, 1974; Connelly, 1976; Taylor, 1979) that there is NW-SE sea-floor spreading, at a half-rate of some 6.5 cm/yr, in the eastern Bismarck Sea. The spreading axis has been active for about the past 3.5 m.y. This spreading is probably of the inner-arc basin type, formed over the NW dipping New Britain subduction zone, and is probably responsible for pushing the Manus Arc, an Oligocene feature (Coleman and Packham, 1976) northward from New Britain over the Caroline Plate along the Manus Trench.

It is not clear that such spreading presently occurs in the western Bismarck Sea. Figure 15 shows the western extension of the Bismarck seismic zone as a leaky transform fault. Connelly (1976) felt that this feature may have been the site of earlier spreading, but magnetic anomalies have not yet been identified. I agree with Connelly that this feature was at some earlier time a spreading center, and I speculate that it pushed the western segment of the Manus Arc over the Caroline Plate in a manner similar to that on the east. That this segment of Manus Trench may now be inactive is indicated by the decrease in seismic activity from east to west across the arc (Fig. 2; Johnson, 1979, Fig. 9).

I believe this segment of Manus Trench is now inactive, as indicated on Figure 15, and the present Caroline Plate margin is coincident with the E-W leaky transform on the eastern side of the Bismarck Sea.

Northern New Guinea is generally considered to be the result of a collision between the Australia-South New Guinea landmass and a northward subducting island arc, moving relatively southward, in late Oligocene-early Miocene time (Moberly 1972; Hamilton, 1979; Johnson, 1979).

This collision is expressed by a south to north series of deformed Mesozoic-Cenozoic shelf sediments, a central ophiolite belt, and a northern zone of submarine mafic and intermediate rocks. Hamilton (1979) took these to be evidence of obduction of the arc over the older New Guinea landmass. This obduction apparently proceeded from west to east across the area.

At some later time (Upper Miocene ?) the obduction changed to a southward subduction of the Caroline Basin beneath northern New Guinea, creating volcanism along the northern coast.

Whether this subduction zone is still active is not certain. Hamilton (1979) shows seismic reflection profiles along the northern margin of New Guinea (east of the profiles shown above) that indicate a trench-like feature extending to the southern limit of Figure 15, or the intersection of the Bismarck transform with the New Guinea mainland. His tectonic map shows an inactive trench extending to the east from this point.

As pointed out by Bracey (1975), earthquakes at the southern margin of the Caroline Basin are located mainly on the Island of New Guinea, and are not clearly associated with the New Guinea Trench. There is an earthquake mechanism determination that indicates southward underthrusting beneath the trench north of Vogelkop, as noted earlier, but there is no clear indication that this is the case to the east.

All indications are that the southwestern Caroline Plate margin is now located in a broad, complex zone of NE-SW horizontal compression and relative left-lateral movement in northern New Guinea (for example: Hamilton, 1979; Johnson, 1979).

I agree with Bracey (1975) that an earlier (Oligocene-Miocene) Caroline Plate boundary was probably composed of a single subduction zone extending from Vogelkop eastward to a possible present-day expression of the northward directed subduction at New Britain, a pre-Eocene arc (Johnson, 1979). Subduction polarity probably reversed on the west after collision and initiated a period of obduction, beginning in late Oligocene. The New Britain arc is now the sole survivor of the earlier north directed subduction.

Inner-arc spreading subsequently split New Britain, creating the Bismarck Sea and moving the Manus arc relatively northward over the Caroline Basin.

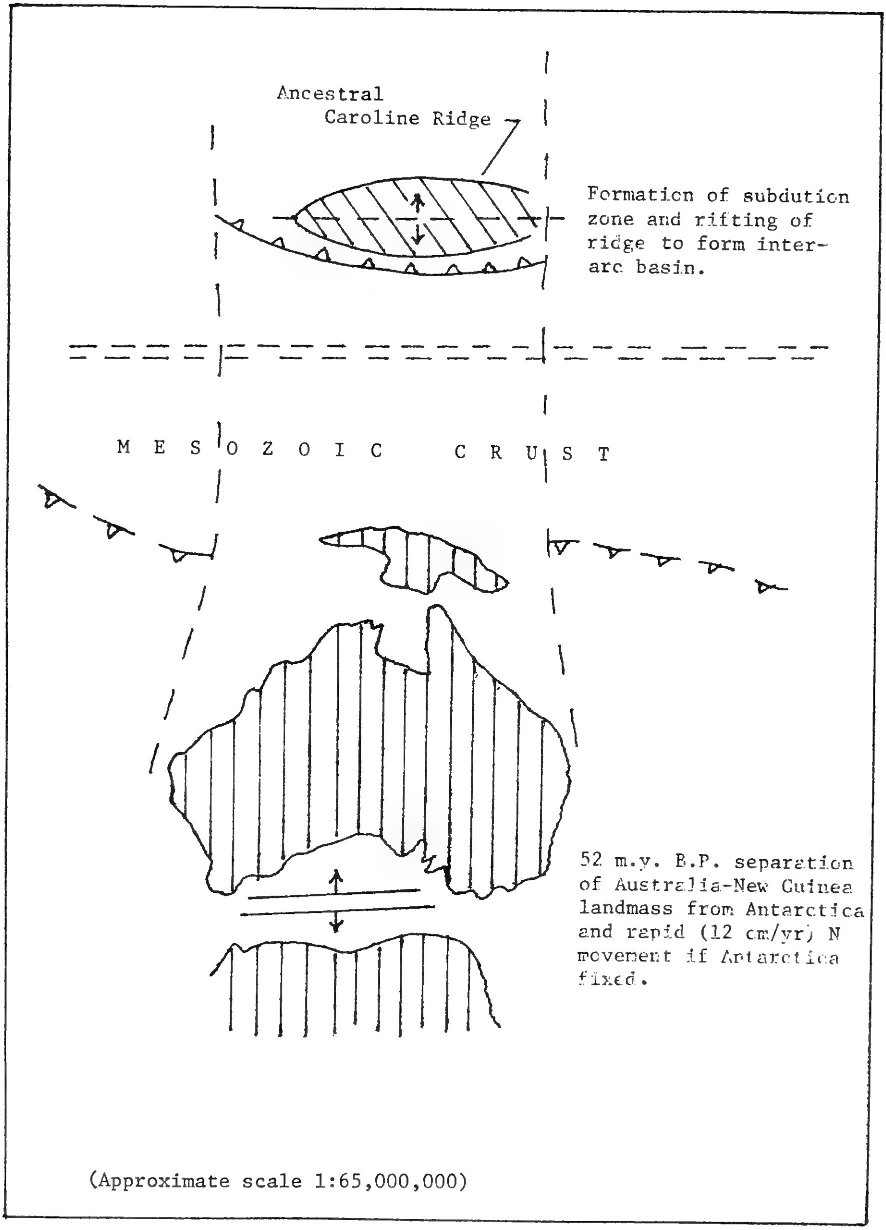
This tectonic synthesis of the Caroline Basin and its margins has incorporated relevant elements of all earlier interpretations. It suffers from the chronic scientific ailment - lack of data, and will certainly not be the definitive study of the area, which awaits that additional data.

## Regional Evolution

The following section attempts a simplified graphical reconstruction (Figs. 16 - 19) of the evolution of the Caroline Basin and it's margins from 52 m.y. B.P. to the present. Only those crustal plates directly involved in that evolution are considered, and no attempt is made to integrate this evolution with the complex tectonic history of the surrounding areas.

Note that the "ancestral Caroline Ridge" referred to in the graphics is purely hypothetical. It was probably represented by some zone of weakness in the Mesozoic crust (fracture zone; subduction zone; volcanic pile; etc), but its exact nature is unknown.

The schematic graphics are self-explanatory, and only the salient time periods in the evolution are noted on the figures.

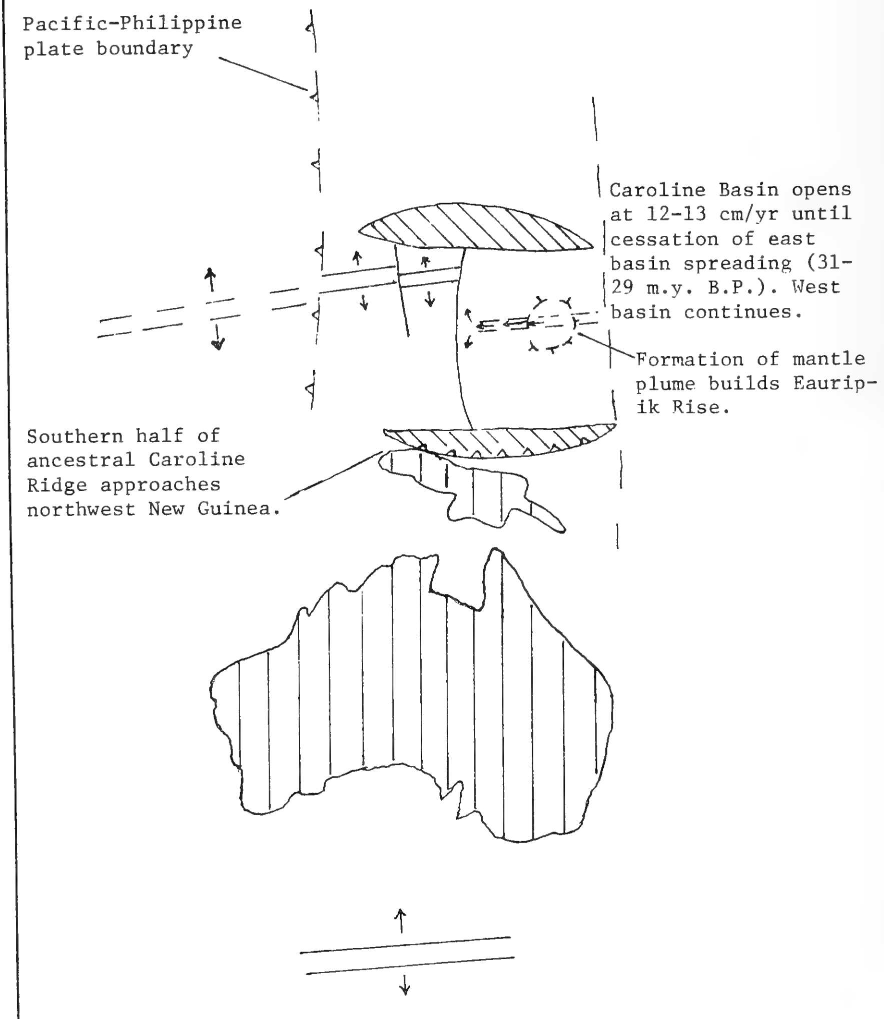


Formation of subdution zone and rifting of ridge to form inter-arc basin.

52 m.y. B.P. separation of Australia-New Guinea landmass from Antarctica and rapid (12 cm/yr) N movement if Antarctica fixed.

(Approximate scale 1:65,000,000)

Figure 16. Evolution of the Caroline region: 52-40 m.y. B.P.



(Approximate scale 1:65,000,000)

Figure 17. Evolution of the Caroline region: 40-27 m.y. B.P.

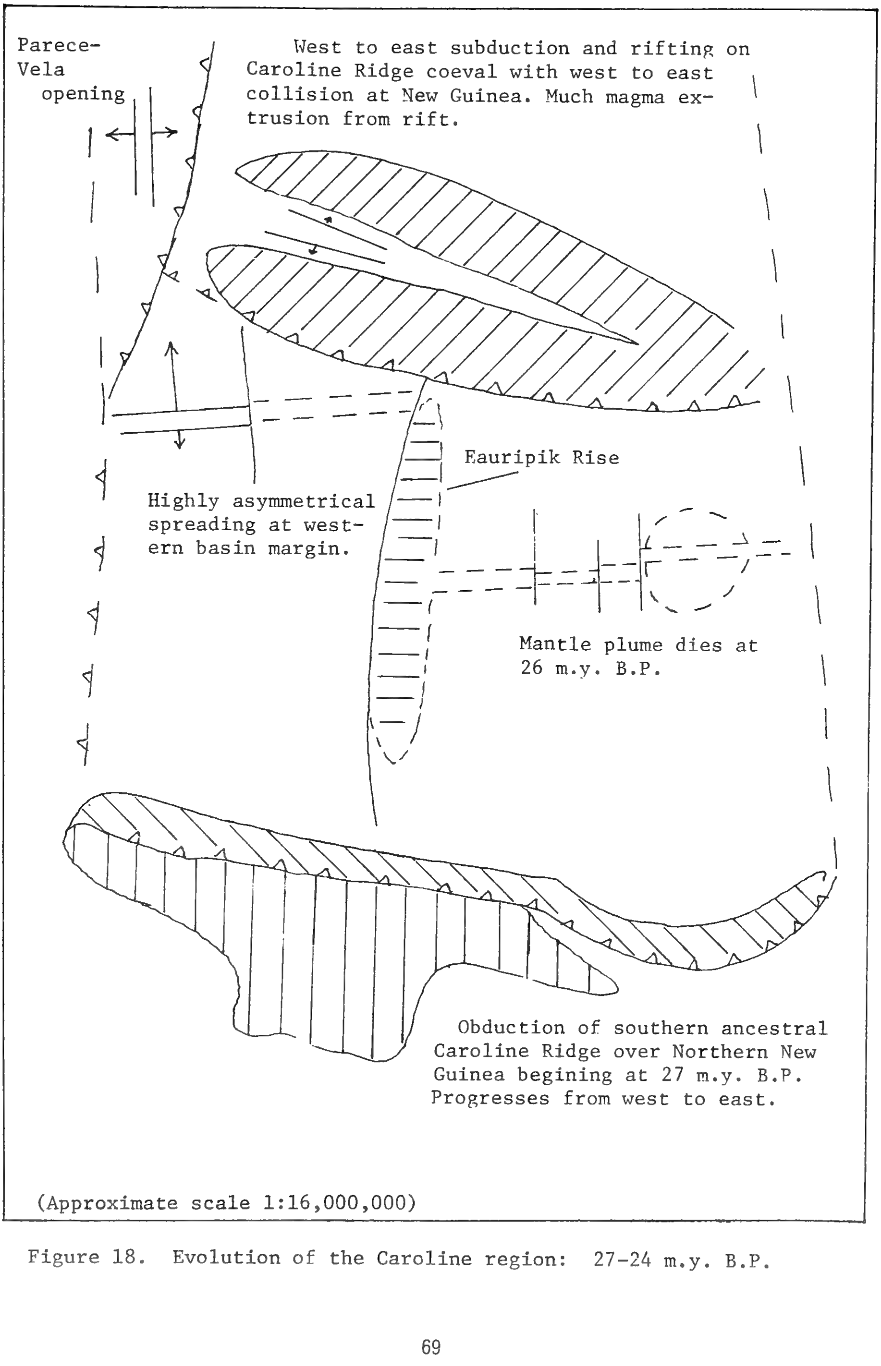


Figure 18. Evolution of the Caroline region: 27-24 m.y. B.P.

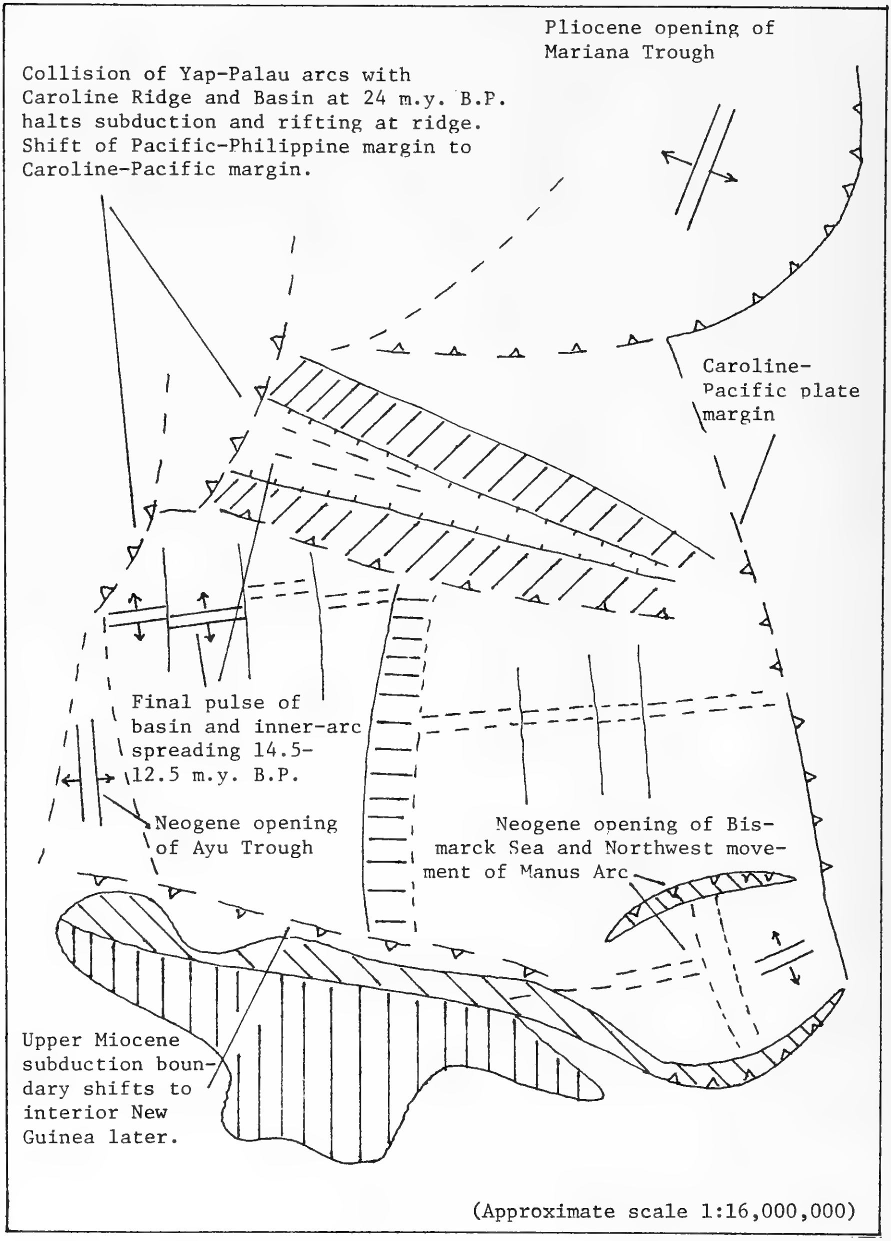


Figure 19. Evolution of the Caroline region: 24-0 m.y. B.P.

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# GEOPHYSICS AND TECTONIC DEVELOPMENT OF THE CAROLINE BASIN

DEWEY R. BRACEY

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