

Spreading mode of backarc basins in the western Pacific

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Abstract

A number of phases are suggested in backarc spreading. Extension of the arc lithosphere is followed by spreading and formation of oceanic crust in the backarc basin. In some basins, a third phase of rifting with a reorientation of the spreading direction occurs. During the second and third phases, spreading is governed by rotation about a nearby pole, and spreading axes are oblique to the transform faults. This contrasts with the geometry of mid-oceanic ridges where the ridges are on great circles perpendicular to the transform faults. Three spreading models are defined according to the various angular relations between transform faults and spreading axes. Backarc basins facing the Pacific Plate tend to open with axes spaced among adjacent ridge segments on projections parallel to the spreading axes (Type I spreading mode). In some cases, new spreading occurs in the contiguous area forming overlapped spreading axes (Type II spreading mode). Initial spreading to form a backarc basin tends to spread with both spaced and overlapped axes (Type III spreading mode). Inner backarc basins intercalated with other basins between the Pacific Plate also tend to spread with Type III spreading mode. Spreading modes and possible mechanisms for these formations in the backarc basins in the western Pacific are discussed.

1. Introduction

Several models have been proposed for the formation of backarc basins. However, there does not seem to be a unique solution for the formation of backarc basins (e.g. Tamaki and Honza, 1991). Most backarc basins associated with arcs in the western Pacific appear to have formed since the Tertiary (Table 1). Backarc basins seem to have an intimate relationship with the subduction activity which also corresponds to the duration of the formation of marginal basins. This relationship is also well demonstrated in the backarc basins of the Tertiary Arc Chain located in the central and southwestern rim of the Pacific Plate (Honza, 1991).

The direction of the spreading axis is usually not traced to the Euler pole and is oblique to the trend of

the transform faults in the backarc basins. This is in contrast to the mid-oceanic ridges where ridges are on great circles perpendicular to the trend of the transform faults; however, fluctuations occur in most ridges. Oblique spreading can be attributed to a low asthenosphere viscosity associated with intrusion in the initial phase of the opening as is suggested in the Reykjanes Ridge where the ridge is associated with the Iceland volcanic center (Lachenbruch, 1976).

During initial continental rifting, extension of lithosphere is suggested in the Atlantic continental margin where extension of lithosphere caused partial melting by decompression of passive upwelling asthenosphere (e.g. McKenzie and Bickle, 1988; White and McKenzie, 1989). Some relicts of stretched continental fragments are also suggested in the initial rifting of the backarc basin, as was illustrated in the

Table 1
Spreading mode of backarc basins in the western Pacific

Backarc basin	Spreading mode				Euler pole ^a		Age of formation ^b		Reference for pole determination
	1st		2nd		1st	2nd	Final		
	Ist	2nd	Final	Ist	2nd	Final	(Ma)	(Ma)	
Japan Basin	II		II		34.0°N, 129.0°E	35.8°N, 122.0°E	25–15	Jolivet and Huchon (1991)	
Shikoku Basin	I		I	25.5°N, 137.8°E	18.0°N, 137.0°E	23.0°N, 134.0°E	30–15	This paper	
Parece Vela Basin	III		II			30.4°N, 133.6°E	30–17	This paper	
West Philippine Basin	I		I	7.8°N, 88.0°E	4.6°N, 13.1°E	20.0°N, 95.0°E	60–35	Hilde and Lee (1984)	
South China Basin	III		III(W), I(E)		0.3°S, 80.2°E	0.2°N, 95.9°E	32–16	Brias et al. (1993)	
Andaman Basin	I		III(W), I(E)		13.3°N, 106.5°E		13–R	This paper	
West and East Caroline Basins	I				7.0°S, 145.0°E	4.0°N, 128.0°E	37–29	Weissel and Anderson (1978)	
Manus Basin	I			on 10°S			4–R	Hamilton (1979)	
Woodlark Basin	III		I(N), II(S)		13.4°S, 171.5°E		–R	(This paper)	
North Fiji Basin	I		I		28.2°S, 179.2°W		8–R	(This paper)	
Lau Basin							5.5–R	This paper	
South Fiji Basin			I			19.7°S, 177.8°E	35–28	This paper	
						22.6°S, 179.6°W			
Coral Basin			I			1.0°S, 127.0°E	62–56	Weissel and Watts (1979)	
Tasman Basin			I			14.0°S, 142.0°E	82–60	Weissel and Hayes (1977)	

Both confirmed and estimated phases are listed. Unknown initial rifting and phases which have the same mode as prior to spreading are not listed in some basins. Modern basins are listed in the second phase, not in the final phase, except for the Woodlark Basin which may be in the initial rifting phase. Most poles of rotation are computed by the authors who identified magnetic anomalies on the basis of tracing on a great circle.

^a E, W, N and S: each part of the basin showing blocked mode.

^b R = Recent.

Japan Basin (Tamaki et al., 1992). These fragments are considered to have intrusions as suggested in the Atlantic margin.

The second phase is emplacement of oceanic crust in the central area of the basin associated with spreading. In this phase most backarc basins are formed by relative rotational movement of continents about a nearby pole. These rotational movements are commonly identified from magnetic anomalies in the basins. In detailed surveyed areas, a few or several phases are suggested for spreading in backarc basins, including a change of the rotational pole and a jump of the spreading axis.

Directional difference between the spreading axis and the total spreading direction of the basin is also observed in the focal mechanism of modern rift areas such as the Andaman, Manus and Lau Rifts where the lateral slip vector or strike-slip vector also cause active shallow seismicity (Eguchi et al., 1979, 1987, 1989). The Andaman Rift bounds the Eurasia and Burma plates. The Manus Rift belongs to the boundary zone between the Pacific and India–Australia plates. However, the Woodlark and Lau rifts open within the India–Australia Plate. Some modern backarc rifts form plate boundaries and some are within a plate.

Several scale experiments of oblique spreading acting on a brittle–ductile system suggest various occurrences of sinistral, dextral strike-slip, oblique slip, and/or normal faults according to the angle between the spreading axis and bulk extension direction during formation (Withjack and Jamison, 1986; Tron and Brun, 1991). Oblique spreading and extensional transform zones are analyzed on the basis of the experiments in the Manus and Lau basins and some onshore fault systems (Taylor et al., 1994).

Oblique spreading of backarc basins in the western Pacific is examined in this paper to delineate their spreading mode.

2. Spreading mode of backarc basins

Backarc basins in the western Pacific are postulated to be formed by relative rotational movements of continents, commonly forming an arc at one side. In some basins, the Euler pole of rotation is determined from fitting the geometry or geology of both

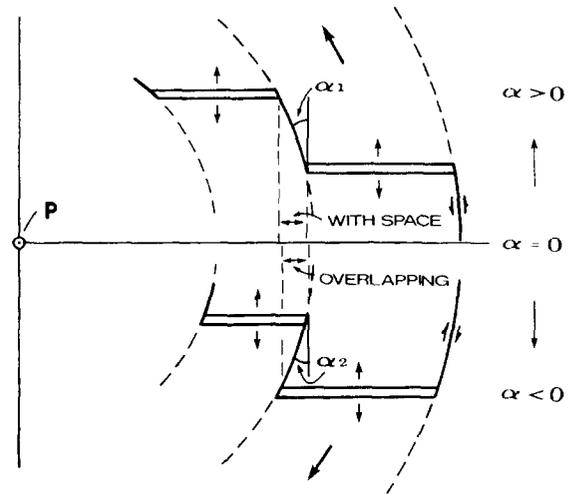


Fig. 1. Backarc spreading with nearby Euler pole P . Spreading axes are oblique to the transform faults. There are two types of spreading depending on the angle α .

continents on the side or from continental paleomagnetic orientations suggesting a finite spreading direction. In some basins, the Euler pole of rotation is determined with an assumption that ridges are on a great circle traced to the Euler pole of rotation where fluctuations of ridge directions are averaged.

If the axis is not on a great circle, the spreading axis and transform faults can have three relationships with respect to the angle α between the spreading axis and the transform fault (Fig. 1). The first is when the projection of two contiguous rift axes do not overlap ($\alpha > 0$). The second type is opposite rotation with overlap ($\alpha < 0$); here α not overlapping is defined as positive and α with overlap is negative. The third is $\alpha = 0^\circ$, which represents the spreading of mid-oceanic ridges; nevertheless, some oblique spreading is suggested in most mid-oceanic ridges.

Within each backarc basin, spreading with angle α positive is defined as Type I, α negative is Type II, and α both positive and negative is Type III mode (Fig. 2). Magnetic lineations are not well defined in some backarc basins due to few survey lines and deformation subsequent to spreading. In these cases, it is difficult to identify whether α is equal to 0° or both positive and negative. For this reason, spreading with $\alpha = 0^\circ$ is also included in Type III.

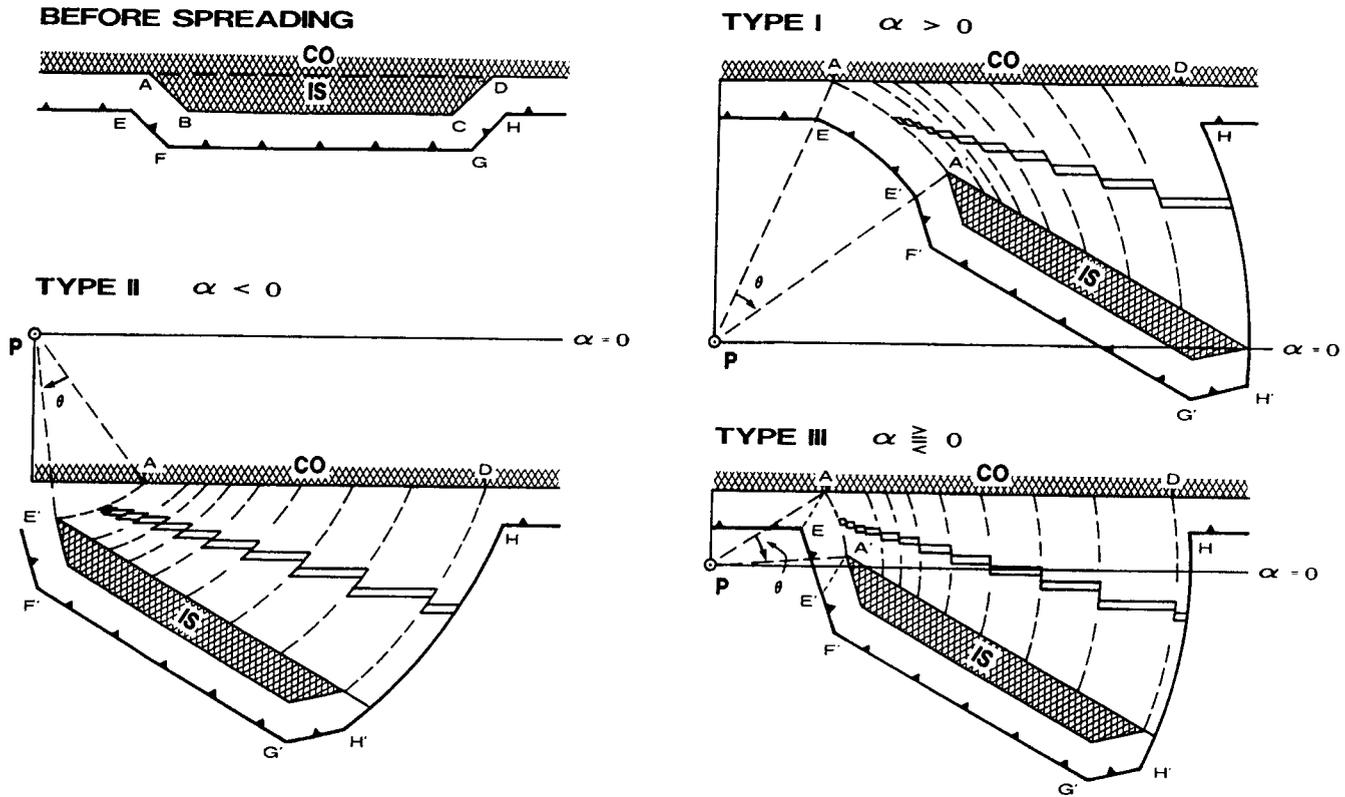


Fig. 2. The three possible idealized types of backarc spreading based on the angle α . The backarc basin is assumed to be formed with relative symmetrical movement for the continent *CO* and the arc *IS* with θ (30°) clockwise rotation.

If the finite rotation with a symmetrical spreading around a pole to form a backarc basin is 30° ($\theta = 30^\circ$), the symbol for this movement is ROT[P,30°] (Fig. 2). The initial extension of lithosphere is also assumed to be formed with the same rotation. *IS* (i.e. island arc) moves with respect to *CO* (i.e. continent) forming a new trench along the line *E–F'* with a relative retreat movement. This is commonly observed in the backarc basins in the western Pacific. The Euler pole for the movement of *IS* and *CO* is *P* which is obtained from transform faults in the idealized spreading. A transform fault or a trench to form a plate boundary occurs on the maximum spreading side depending on the relative direction of the oceanic plate movement. Concerning the line between *H* and *H'*, the line between the spreading axis and *H* is relatively fixed with additions of lateral movement at the spreading side associated with the opening; the line between the spreading axis and *H'* is laterally moving in association with the opening.

In Type I, the lateral slip vector was a large component from *E* to *F'*. The area within *A–A'–E'–E* in Type I may consist of extended continental crust or may form an arc in this area. The transform fault with a retreat of *IS* is a main component along *A–E'* in the formation of Type II mode. Space is required to retreat along *A–E'* in this type. In Type III, the lateral slip vector is smaller than in the other types between *E* and *H'*. Some rifts in a backarc basin form a plate boundary, such as the Andaman and Manus rifts. In these cases, transform faults are traced over the backarc basin to form a plate boundary.

Spreading modes proposed in this paper are based on the idealized model for ridges and transform faults. Some ridges fluctuate in parallel arrangement and some are blocked showing a different mode in a basin.

3. Spreading modes of backarc basins in the western Pacific

Backarc basins in the western Pacific have been examined to identify the spreading mode on the basis of magnetic anomaly lineations. Some backarc basins are not sufficiently surveyed to solve the magnetic anomalies. Marginal basins, such as the Bering Sea

and Banda Basins, are postulated to have an origin as trapped oceanic crust (Cooper et al., 1976; Lapouille et al., 1985). They are not discussed in this paper. For some basins listed here also there is no unequivocal identification of the magnetic anomaly lineations. In some basins identification of magnetic lineations does not cover the whole basin. However, the spreading mode is defined if there are critical magnetic identifications, even if the basin has not yet been completely surveyed.

Fourteen backarc basins were examined in this paper on the basis of magnetic anomalies, and seismicity which occur in the spreading axes and transform faults of modern spreading basins (Table 1, Fig. 3). Spreading axes are not parallel to adjacent ridge segments in about half of the examined basins. However, spreading mode is detectable in these basins from averaged arrangements. In some basins, the spreading mode is blocked in a few units bounded by a topographic high or a large fracture zone. In this case, the spreading mode is defined in units.

In most basins finite or stage rotation poles were computed by the authors who identified the magnetic anomalies. These computations are based on the rotation on great circles in which the points of isochrons are grouped to defined segments of either magnetic lineations or transform faults, and paired before computation (Hellinger, 1981; Chang, 1987) or based on minimizing the misfit area obtained when matching the two lines defined by the picks of conjugate magnetic anomalies (Sloan and Patriat, 1992). The computations for each phase are available to define the spreading mode. However, some poles are averaged and some are revised to identify the spreading mode in this paper. They are listed in Table 1.

3.1.1. Japan and Yamato basins

The basins were formed from 25 to 15 Ma, or even earlier (Tamaki et al., 1992). The magnetic anomalies are not identified in these basins because of the complicated lineations in the basins. However, possible spreading axes have been proposed for both the Japan and Yamato basins (Kobayashi and Isezaki, 1976). A number of rotational spreading models have been proposed on the basis of paleomagnetic measurements of volcanic rocks in southwestern Japan (Otofujii and Masuda, 1983). Two phase

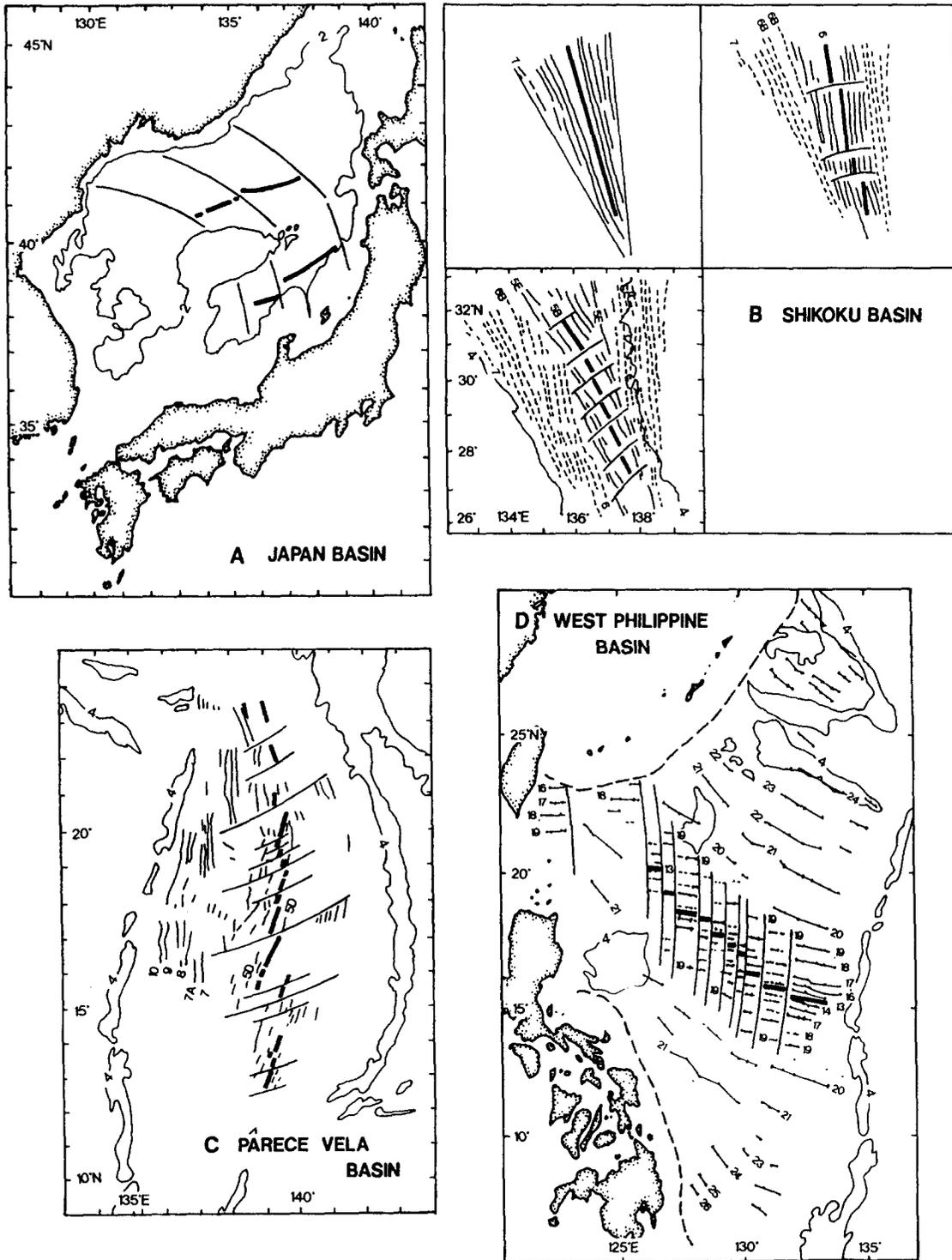


Fig. 3. Spreading patterns of the (A) Japan, (B) Shikoku, (C) Parece Vela, (D) West Philippine, (E) South China, (F) Andaman, (G) Caroline, (H) Manus, (I) Woodlark, (J) North Fiji, (K) Lau, (L) South Fiji, (M) Coral and (N) Tasman basins. Some poles are recomputed.

spreadings have been suggested from the transcurrent faults in northern Japan (Jolivet and Huchon, 1991) which are illustrated in this paper. Both first spreading in the Japan Basin and second phase spreading in the Yamato Basin are identified to be Type II mode (Fig. 3A).

3.1.2. Shikoku Basin

From the detailed survey, four spreading phases are distinguished in the Shikoku Basin, from 30 to 15 Ma (Okino et al., 1994). The first is a spreading with $\alpha = 0$ (Type III); however, a different mode is suggested in the truncation of magnetic anomalies

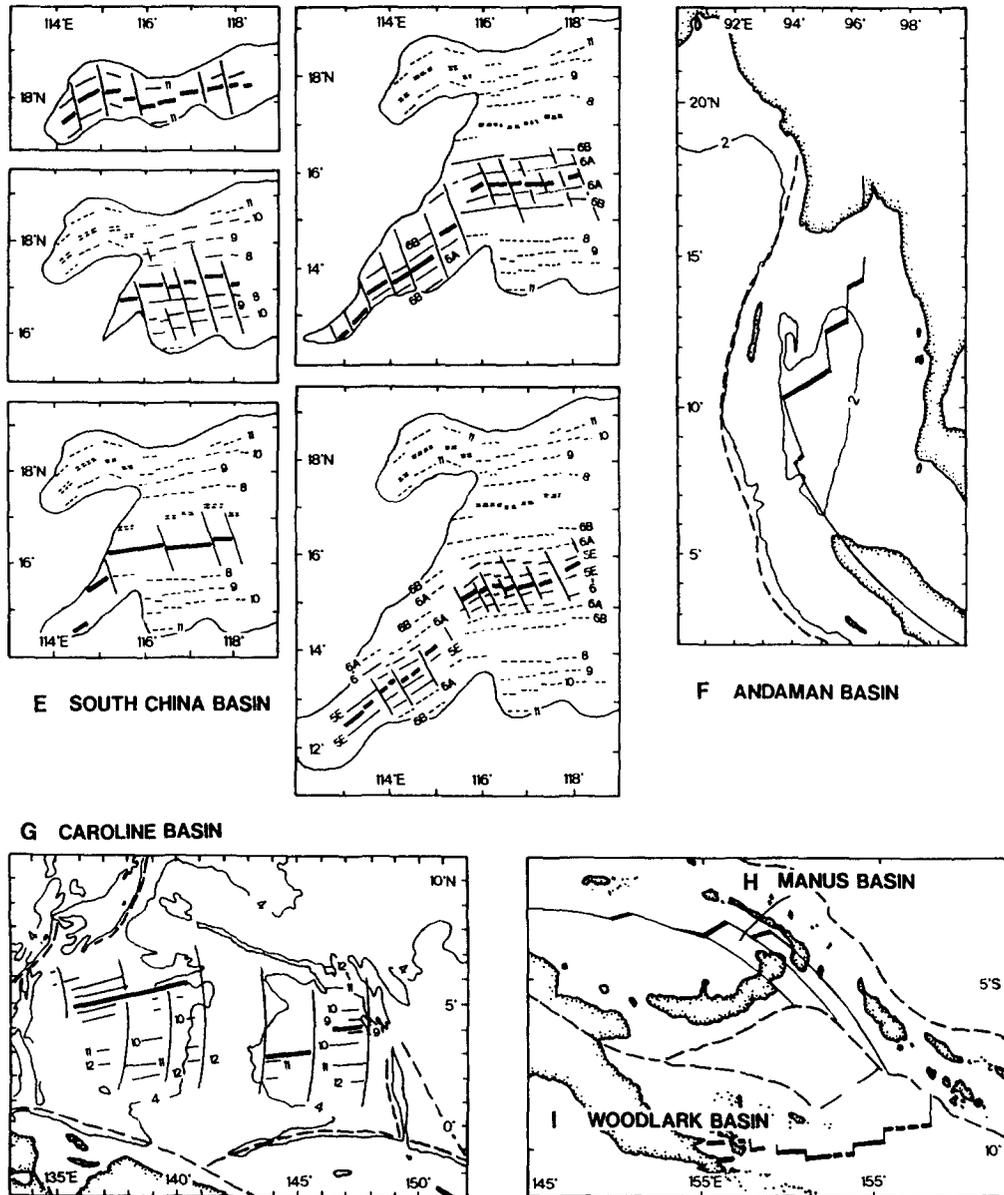


Fig. 3 (continued).

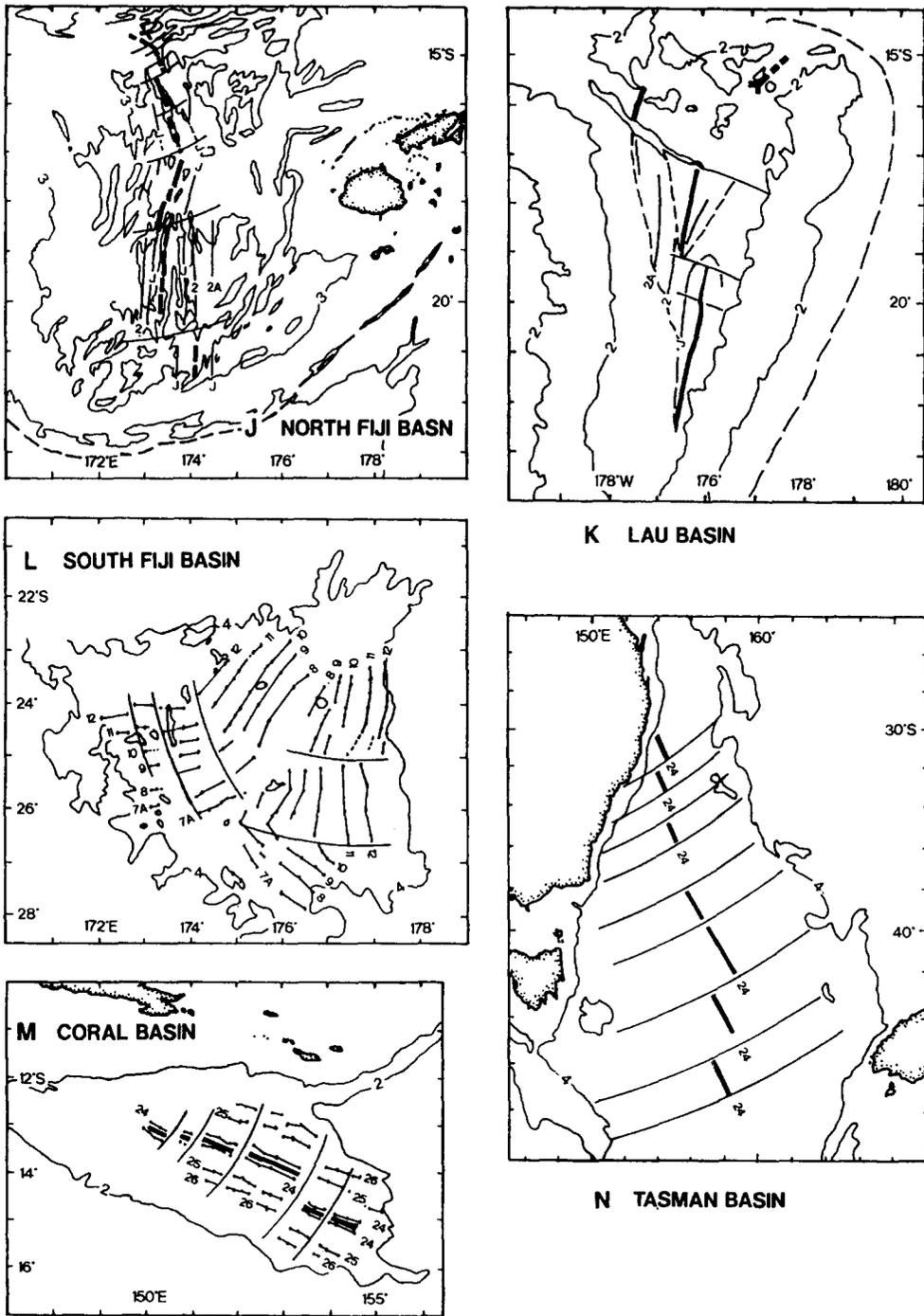


Fig. 3 (continued).

toward the margin of the basin in the later phase of the initial spreading (Fig. 3B). The spreading axis jumped east at anomaly 6. Final spreading is from anomaly 5E to 5B showing symmetrical spreading. Transform faults are revised after Okino et al. (1994) in this paper. Second and reoriented third phases are Type I mode spreading (Fig. 3B). Fourth is eruption of seamounts and knolls along the prior spreading axes which is not illustrated in Fig. 3B. The eastern limb of the spreading is interpreted to be east of the younger volcanic ridge (the Nishi–Shichito Ridge) as was suggested by Shih (1980) and Chamot-Rooke et al. (1987), not in the present margin of the basin (Kobayashi and Nakada, 1979).

3.1.3. *Parece Vela Basin*

The basin was formed from 30 to 17 Ma (Mrozowski and Hayes, 1979). The total spreading shows Type II mode, although the magnetic lineation in the basin is not well determined, especially in the younger rifts from 18 to 17 Ma (Fig. 3C). The uncertainty in the youngest anomaly may be due to ridge jumps near the end of the spreading.

3.1.4. *West Philippine Basin*

Many models have been proposed for the spreading pattern of this basin. The model of Hilde and Lee (1984) is selected in this paper to examine the spreading mode. Two phase spreadings are distinguished from 60 to 35 Ma, spreading NE–SW from 60 to 45 Ma and N–S-trending spreading from 45 to 35 Ma. The latter spreading is associated with a reconfiguration of the Central Basin Spreading Center into short E–W segments offset by closely spaced N–S transform faults. Both phases show Type I spreading mode; however, the first stage may have an α of nearly zero (Type III mode) (Fig. 3D).

3.1.5. *South China Basin*

Magnetic anomalies from 11-5D have been identified by Taylor and Hayes (1983) in this basin. The magnetic anomalies have been re-examined using additional surveys and four to five phases were distinguished during spreading from 32 to 16 Ma (Brias et al., 1993). The spreading was asymmetric and included at least one ridge jump at anomaly 7. The latter authors calculated 10 finite and stage rotation poles between the time of magnetic anomalies

11 and 5C. Type III mode spreading is defined in the earlier phases between anomalies 11 and 7. After the formation of the southwestern basin from anomaly 7, the southwestern basin shows Type III and eastern basin shows Type I spreading modes (Fig. 3E). This suggests that two modes exist in the basin.

3.1.6. *Andaman Basin*

Although this basin is not faced to the Pacific Plate but to the India–Australia Plate, its spreading mode is examined in this paper for reference. The basin is an active basin formed since 13 Ma (Lawver and Curray, 1981). Spreading axes and transform faults consist of a plate boundary between the India–Australia and Burma plates. Spreading axes and associated transform faults are identified from seismicity (Eguchi, 1984). The spreading is defined to be Type I mode (Fig. 3F). The Central Sumatra Fault is a trace of the same circle from the transform fault in the southern margin of the basin. However, that in the northern margin is not traced to the onshore transcurrent fault in eastern Burma.

3.1.7. *Caroline Basin*

This basin consists of two parts of the West Caroline and East Caroline basins intercalated by the Eauripik Rise. Magnetic anomalies in the basins show an E–W-trending lineation from 37 to 29 Ma (Weissel and Anderson, 1978). The role of relative motion between the West Philippine and Caroline plates has been defined (Karig, 1975). From these data, the East Caroline Basin is identified to have Type I spreading mode and the West Caroline Basin has Type III spreading mode judging from magnetic anomalies (Fig. 3G).

3.1.8. *Manus Basin*

This is a modern basin. Magnetic anomalies along the rift zone have been measured in this basin (Taylor et al., 1991). Spreading axes and associated transform faults are also identified from the seismicity and swath survey (Hamilton, 1979; Taylor, 1979; Eguchi et al., 1987; Taylor et al., 1994). An extensional transform zone is associated with the spreading axis in the central basin (Taylor et al., 1994). The spreading of the basin is identified to be Type I mode (Fig. 3H).

3.1.9. Woodlark Basin

This is also a modern basin. Magnetic data in the basin (Weissel et al., 1982) suggest that it is forming with Type III mode spreading (Fig. 3I). The rifts appear to have a pole with nearly $\alpha = 0$ (Table 1).

3.1.10. North Fiji Basin

Magnetic lineations in this basin are complicated. First phase opening occurred approximately 8 Ma with a NW–SE trend; the next stage opening occurred 3.5–4.5 Ma with a N–S trend (Malahoff et al., 1982; Auzende et al., 1988). The present phase of spreading is suggested to have begun 1.2 Ma (Tanahashi et al., 1991). A triple junction is observed at 17°S, 174°E. The NEE-trending graben traced from the junction shows little activity now. This triple junction was formed by the formation of a next phase NNW-trending opening in the northern basin (Tanahashi et al., 1991; Lagabrielle et al., 1994). The total spreading vector for both the northern and southern spreading may be in the same direction (Lafoy et al., 1990). Spreading mode of the initial phase may be Type I; however, more data are required for confirmation. The northern spreading is defined to be spreading with Type I and the southern spreading is Type II mode (Fig. 3J) having two modes in a basin as in the South China Basin. The present phase may have a different pole, but this cannot be determined with certainty due to a lack of conclusive magnetic lineation data.

3.1.11. Lau Basin

This is an active basin formed since 4–5.5 Ma (Hawkins, 1994). Approximately the western half of the basin and the northern part of the Peggy Ridge are suggested to be attenuated crust and rifted paleo- and active arc complexes (Parson and Hawkins, 1994). N–S-trending magnetic lineation is dominant in the southeastern basin. Two phases for the formation of the basin are suggested in the magnetic anomalies (Parson and Hawkins, 1994) revised after Weissel (1977). The spreading center propagated toward the south forming a fan-shaped basin. The spreading mode is interpreted to be Type I mode (Fig. 3K), although it apparently shows Type III mode spreading. This is the result of the different ages in the margin of the basin due to the southward

propagation as observed in the earlier spreading mode in the Shikoku Basin.

3.1.12. South Fiji Basin

This basin was formed from 35 to 28 Ma, having a triple junction. The southwestern part of the basin is missing probably because of subduction (Watts et al., 1977; Weissel, 1981), or possibly because of a shift of spreading rate and a jump of the spreading axis toward the southwest, assuming a few phases for the formation of the basin. Two rotation poles are suggested in the magnetic lineations. The spreading mode of both lineations is Type I mode (Fig. 3L).

3.1.13. Coral Basin

Magnetic anomalies in this basin suggest the formation of the basin from 62 to 56 Ma (Weissel and Watts, 1979). Magnetic lineations strike N70°W, almost parallel to the northern margin of the Queensland Plateau. Two blocks are distinguished from the magnetic anomalies bounded by a fracture zone. The basin is defined to have spreading mode Type I (Fig. 3M).

3.1.14. Tasman Basin

Four finite rotational phases are distinguished in this basin from 82 to 60 Ma, based on magnetic data (Hayes and Ringis, 1973; Weissel and Hayes, 1977). The rotational movement was fast, reaching 19°, in the earlier phase, but its rotation rate decreased during the later phase to 2.55° in the final phase (Weissel and Hayes, 1977). The spreading mode of the basin is interpreted as Type I mode (Fig. 3N).

4. Distribution pattern of the three spreading modes in the western Pacific

In the initial phase of their formation, some backarc basins appear to start spreading with Type III mode, e.g. the Shikoku, South China and Woodlark basins; they appear to have a pole nearly $\alpha = 0$. However, the initial phase is not detectable in most basins. In this phase, most basins facing the Pacific Plate tend to spread with Type I mode; e.g. the Coral, Tasman and West Philippine basins, from the latest Cretaceous to early Paleogene; the Shikoku, East Caroline and South Fiji basins, in the late Paleogene

to early Neogene, Andaman; and the northern North Fiji and Lau basins, the from Neogene to Quaternary.

Some basins spread with Type II spreading mode,

such as the Japan, Parece Vela and southern North Fiji basins. They are associated with contiguous Type I spreading mode basins such as the Shikoku and northern Fiji basins. This implies that if the

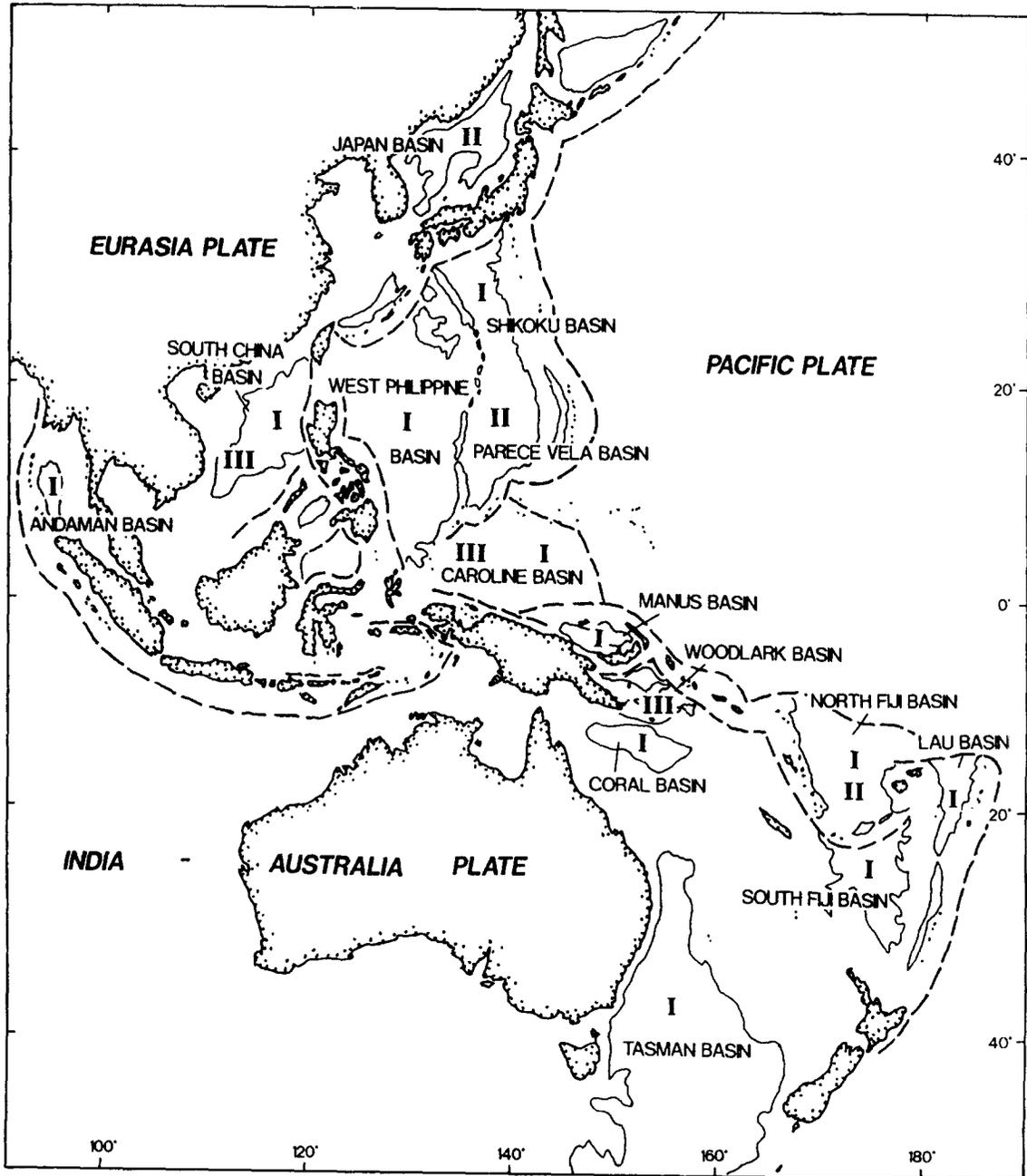


Fig. 4. Spreading mode of the backarc basins in the final phase in the western Pacific. Backarc basins which initially faced the Pacific Plate tend to spread according to the Type I spreading mode. Type II mode spreading occurs alternatively with Type I mode in some areas.

backarc basin faced the Pacific Plate, the basin initially formed with Type I spreading mode. The basin tends to spread with Type II mode, if the next spreading followed in the contiguous area. As was suggested earlier, it is difficult to form Type II spreading in a backarc basin, except if some space is guaranteed to retreat in the pole side. If there is an association with backarc formation in the contiguous area, space may be provided to form Type II spreading mode in the next phase of spreading. (Fig. 4)

Type III spreading mode is observed in the South China, West Caroline and Woodlark basins. These basins appear not to have faced the Pacific Plate at the beginning of their spreading. The West Caroline Basin opened after the formation of the West Philippine Basin and may be considered a kind of “inside basin”, not formed by association with an arc facing the Pacific Plate.

5. Discussion

The spreading mode in backarc basins can be deduced from the identification of spreading axes which show a characteristic feature to define the spreading mode. However, some spreading episodes are different from the idealized spreading patterns in Fig. 2. Some first phase spreading axes forming backarc basins appear to be not in a straight line but segmented. This is observed in the Woodlark Basin, where spreading is in the first phase, and in the South China Basin, where the oldest magnetic lineations are segmented. Some spreading axes are not parallel to contiguous ridge segments and do not show a step feature with a continuous descending or climbing pattern but an irregular distribution with contiguous axes. Most spreadings in mid-oceanic ridges also show such an irregular feature, not concentrated in a pole on a great circle when the pole is computed by grouping and minimizing methods. This feature may be due to the fundamental character of the oceanic plate.

There may have been more phases in some of the basins during their formation, which is suggested by their magnetic anomalies. However, they are masked by deformation, such as segmentation, which has caused a complicated pattern. Therefore they are difficult to identify with the data presented here.

The formation of triple junctions is observed in the North, South Fiji and Lau basins; however, the formation ages are different. In the North Fiji Basin, the triple junction is not formed throughout the formation of the basin but in a restricted period. The formation mechanism of triple junctions also remains enigmatic.

Some contiguous backarc basins are suggested to be genetically related. This is indicated by approximately the same formation age and related spreading mode of the formation. This suggests that backarc spreading is formed with an intimate relationship with the surrounding plate kinematics, rather than by upwelling of plumes or slab-induced or asthenospheric flow models. Backarc basins in the western Pacific appear to be formed with constrained plate kinematics, based on their formation mode.

6. Conclusion

A number of distinct phases are suggested in the formation of backarc basins. Extension of lithosphere is followed by spreading and formation of oceanic crust in the backarc basin. Spreading in the backarc basin is governed by relative rotation about a nearby pole; spreading axes are oblique to transform faults.

1. Three spreading modes are defined from various angular relations between transform faults and spreading axes on the basis of rotational movement about a nearby pole and spreading axes oblique to transform faults.
2. Backarc basins faced to the Pacific Plate tend to spread with axes spaced among contiguous axes on projections parallel to the spreading axes through the Euler pole of rotation (Type I spreading mode).
3. Subsequent spreading which occurs in the contiguous area tends to form overlapped spreading axes (Type II spreading mode).
4. Initial rifting and inner backarc basin intercalated with another basin between the Pacific Plate tend to spread both spaced and overlapped axes (Type III spreading mode).
5. Spreading modes which can be seen in the western Pacific imply that spreading in backarc basins is formed with an intimate relationship with the surrounding plate kinematics.

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