From intracratonic extension to mature spreading in back arc basins : Examples from the Okinawa, Lau and, North Fiji Basins

West Pacific
Back arc basins
Structure
Accretion
Geochemistry

Ouest Pacifique
Bassins arrière arc
Structure
Accrétion
Géochimie

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ABSTRACT

Three cruises (POP 1, SEAPSO 3 and SEAPSO 4) carried out during the "Tour du Monde" of the R.V. Jean Charcot allow us to obtain new structural and geochemical data for the Okinawa, North Fiji and Lau basins. Taken together, the structural and geochemical data illustrate a difference in evolution stages of these sites. The less evolved stage is represented by the Okinawa basin, where accretion is evidenced only by volcanic intrusion into a thinned continental crust. The most evolved stage is illustrated in the North Fiji basin, where the present-day accretion can be directly compared to the East Pacific Ridge. The Lau basin displays an intermediate stage with a complex system of accretionary ridges. This difference in the evolution stage is translated in the nature and geochemistry of the rocks : in the Okinawa trough they are basalts, andesites and dacites enriched in hydromagmaphile and rare earth elements. In the Lau basin they are typical N. Morb basalts in the central part of the basin and intermediate composition between Morb and andesites on Valu Fa ridge. Lastly, the North Fiji basin axis provides only typical Morb basalts.

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RÉSUMÉ

De l'extension intracratonique a l'ouverture océanique dans les bassins arriere Arc : exemples des bassins d'Okinawa, de Lau et Nord Fidjien

Trois campagnes (POP 1, SEAPSO 3 et SEAPSO 4), réalisées pendant le «Tour du Monde» du Jean Charcot, nous ont permis d'obtenir de nouvelles données structurales et géochimiques concernant les bassins d'Okinawa, Nord Fidjien et de Lau. Les données structurales et géochimiques illustrent leurs stades d'évolution différents. Le bassin d'Okinawa, où l'accrétion se manifeste uniquement par des intrusions volcaniques dans une croûte continentale amincie, représente le stade le moins évolué. La bassin le plus évolué est le bassin Nord Fidjien, où l'accrétion actuelle est en tous points comparable à celle de la dorsale Est Pacifique. Le bassin de Lau représente un stade intermédiaire avec un système complexe. La différence d'évolution se traduit dans la nature des roches et leurs caractéristiques géochimiques : dans le fossé d'Okinawa, ce sont des basaltes, des andésites et des dacites enrichies en éléments hygromagmaphiles et en terres rares. Dans le bassin de Lau, ce sont des basaltes médioocéaniques typiques dans la partie centrale du bassin, alors que dans la partie méridionale, sur la ride de Valu Fa, ils sont intermédiaires entre basaltes médioocéaniques et andésites. Dans le bassin Nord Fidjien enfin, n'ont été prélevés que des basaltes médioocéaniques typiques.

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INTRODUCTION

Since the Karig (1971) definition of the West Pacific marginal basins, numerous geological and geophysical investigations have been made which permit a more precise definition and reveal that the creation and evolution of there back-arc basins do not result in a single outcome.

During the past five years, the increase in back-arc basin studies has mainly, been due to several ODP programs and to international projects on sea floor hydrothermal activity. Between 1983 and 1987, the French research Vessel "Jean Charcot" completed an "Around the World" programme. A main goal of the project was to study accretion and its associated processes in the Pacific Ocean. In order to compare these processes in different geodynamic contexts, part of the studies was focused on the back-arc basins of the West and Southwest Pacific Ocean.

In the West Pacific Ocean (Fig. 1), the selected surveyed areas were the South China Sea (Pautot *et al.*, 1986) and the Okinawa Trough (Sibuet *et al.*, 1987) during the Nanhai and Pop I cruises respectively. The objective was the study of marginal basins between the Eurasian and subducting Pacific plates. In the Southwest Pacific (Fig. 1), the selected areas were the Lau and North Fiji basins at the boundary of the converging Pacific and Indo-Australian plates. The five cruises of the Seapso project were devoted to the study of accretion and convergence in this domain.

The purpose of this paper is to compare the accretionary processes in the Okinawa trough and the Lau and North Fiji basins, using conventional geophysical and geological data as well as the multi-narrow-beam high-precision bathymetric system (Seabeam). The main trace element and isotopic results of recovered samples are also presented here because they constitute a major basis for comparing basins.

A common characteristic of these three basins is that they are located at the converging boundary between the Pacific oceanic plate and large continental plates (Australia and Eurasia).

Figure 1

Geodynamic setting of the Okinawa, North Fiji and Lau basins in the West Pacific. 1. Subduction zones; 2. Fossil subduction zones.

MAIN CHARACTERISTICS OF THE OKINAWA, LAU AND NORTH FIJI BASINS

The Okinawa Trough This is a back-arc basin located behing the Ryukyu Trench and Ryukyu island arc. The trough is 60-100 km wide in the south and reaches a maximum width of 230 km in the north. The water depth decreases from south (2300 m) to north (200 m). According to Wageman *et al.* (1970), Herman *et al.* (1978) and Sibuet *et al.* (1987) the Okinawa Trough is a product of Plio-Pleistocene phase of opening which developed within the Ryukyu arc and an older (Miocene or older) subsiding basin. It can be divided in three main domains depending on their opening stage (Fig. 2).

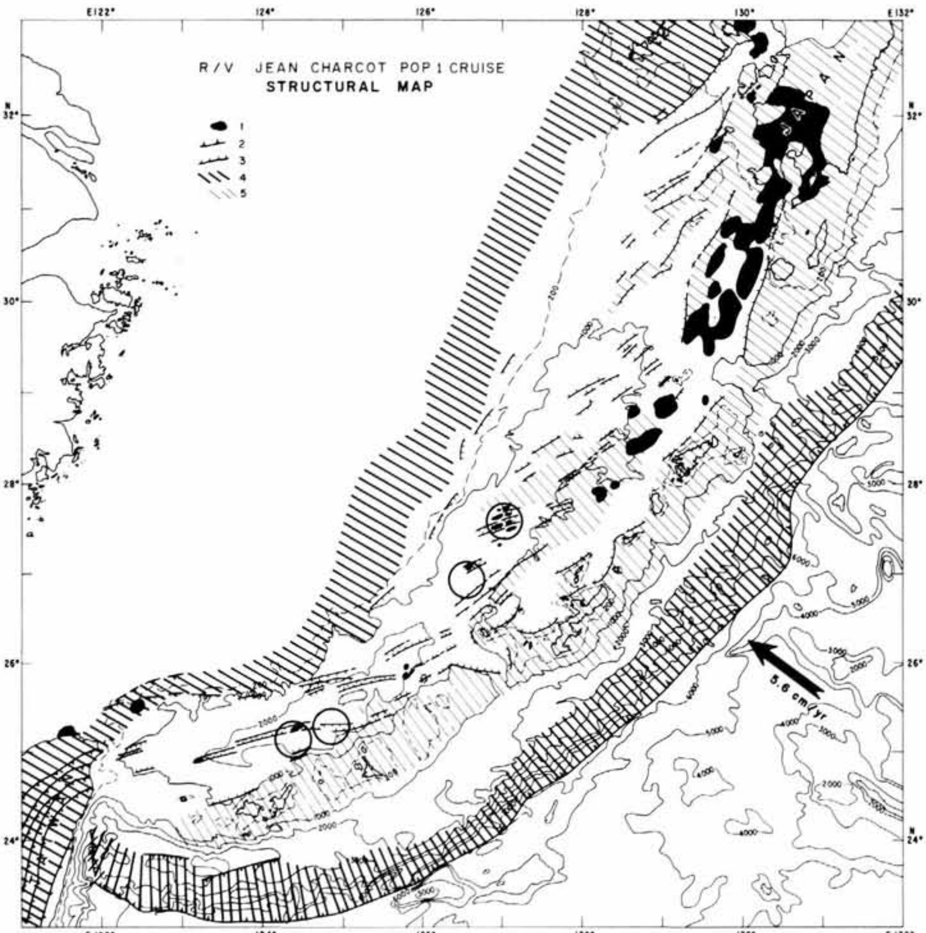

Figure 2

Geological and structural map of the Okinawa trough established from available seismic data (Sibuet et al., *1987). 1. Present-day arc volcanism; 2. Trench axis; 3. Normal faults; 4. Trench slopes and accretionary complex; 5. Taiwan-Sinzi folded* belt. *Circles indicate the sampling sites.*

The Northern Okinawa Trough is a structurally-controlled (120-120 km long) intracontinental basin striking N40° and N60° and with up to 8 km of sediment. Considerations on the presence of Pliocene rocks in an oil well (Nash, 1979) confirmed by a dredge haul from the RV "Jean Charcot" cruise imply that the main tilting related to extensional stresses occurred in late Pliocene – Early Pleistocene time and affected the entire sedimentary cover (Letouzey and Kimura, 1985; Sibuet *et al.*, 1987). The distribution of half-grabens and tilted blocks results in a roughly N50°, right-lateral, "en échelon" trending. Vertical displacement and associated horizontal extension along the faults bounding the tilted blocks increase and decrease along strike giving the blocks a twisted geometry. There are no transform faults between the observed normal faults bounding the extensional grabens.

The Southern Okinawa trough is a broad, deep, flat basin with more than 2 km of sediments. The Late Pleistocene to present-day extension within the basin is recorded by the deformation and faulting of the entire sedimentary sequence and by scarce volcanic intrusions. Seismic profiles suggest that this limited amount of the volcanic crust may be the first manifestation of oceanic crust (Sibuet *et al.*, 1987).

The main part of the Southern Okinawa trough is a subsiding continental basin with the amount of extension increasing toward the axis. Any neoformed oceanic crust must be restricted to a very narrow band less than 40 km wide, and may consist only of localized volcanic intrusions. As in the Northern Okinawa trough, there is no evidence of transform faults between the "en échelon" axial depressions.

The Middle Okinawa trough is a transitional area between the northern trough, characterized by a thinned continental crust, and the southern trough characterized by an "en échelon" system of depressions, the bottom of which is interpreted as oceanic crust. This transitional area has been named Vamp (Volcanic Arc rift Migration Phenomenon area) by Sibuet *et al.* (1987) and was mapped by Seabeam during the Pop 1 cruise. The bathymetric map shows a succession of parallel ridges elongated N70°E. The central elongated volcanic ridge is associated with a positive magnetic anomaly (Davagnier *et al.*, 1987). A two-dimensional model computed from magnetic anomalies is consistent with these ridges being linear dyke intrusions through a thinned continental crust rather than a product of typical sea floor spreading.

In conclusion, the creation of the Okinawa Trough resulted from a polyphase back-arc extension related to the main subduction of the Philippine plate beneath the Eurasian plate. This opening was initiated in the southern portion of the trough and then moved northwards.

The Lau basin (Fig. 3)

He is located at the convergent boundary between the Pacific and the Indo-Australian plates between the Tonga arc to the west and the Lau-Colville ridge to the east. Its width decreases from 300 km at 16°S to less than 100 km at 24°S. The magnetic anomalies pattern and elevated heat flow values and the relative shallow depth favour the formation of the Lau basin by an active spreading centre (Sclater *et al.*, 1972; Hawkins, 1974; Hawkins and Melchior, 1985). The Lau basin was surveyed during two recent cruises of the RV "Jean Charcot" (Seapso 4-1986 and Papnoum-1987) Additionally, two cruises of the RV "Sonne" mainly focussed on the southern part of the basin between 19°S and 23°S.

In the southern part of the basin, between 19°S and 23°S, previous studies permitted the distinction of two major features (Foucher *et al.*, 1988; Ruellan *et al.*, in press) (Fig. 4).

The Valu Fa ridge is an elongated volcanic ridge striking N15-20 parallel to the Tonga and Tofua arcs. A multichannel seismic profile (Morton and Sleep, 1985) shows a strong deep reflector beneath the ridge, which has been interpreted to be the top of a 3.5 km deep magma chamber. The Valu Fa ridge was intensively surveyed during the Seapso 4, Papnoum and SO35-SO48 (RV "Sonne") cruises. Complete Seabeam coverage between 21°15'S and 22°42'S shows that the ridge is divided in two N15-20 striking segments, 7 to 10 km wide and 200 to 500 m high. The ridge crest is a dome at a relatively constant depth of 1900 m, over most of its length but deepening at its north end. North of 21°26'S there is a 100 m depth axial graben appears at the dop of this feature. The seismic data indicate that the ridge extends as far north as 20°50'S beneath the sedimentary cover.

The second major feature of the Lau basin is a N-S system of elongated horsts and grabens overlaid by a thin (less than 200 m) sedimentary cover extending on both sides of the Valu Fa ridge (Fig. 5). In its axial part, centred on 176°30'E, between 18°30'S and 22°S, appears a ridge characterized by an elevated topography and a total lack of sedimentary cover. This topographic axis may correspond to the central magnetic lineation defined by Weissel (1977) and Larue *et al.* (1982). From south to north, the linearity of the axis is disturbed by transverse structures which look like overlapping spreading centres, offsets and

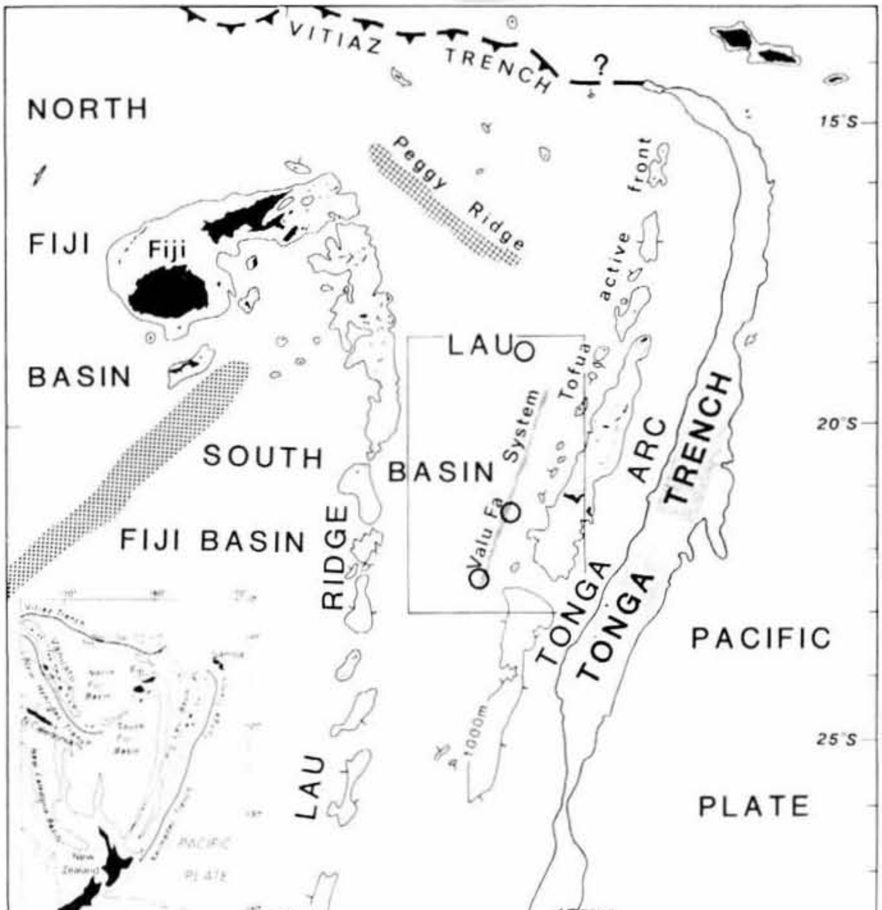

Figure 3

Geodynamic setting of the Lau basin. Box corresponds to the studied area.

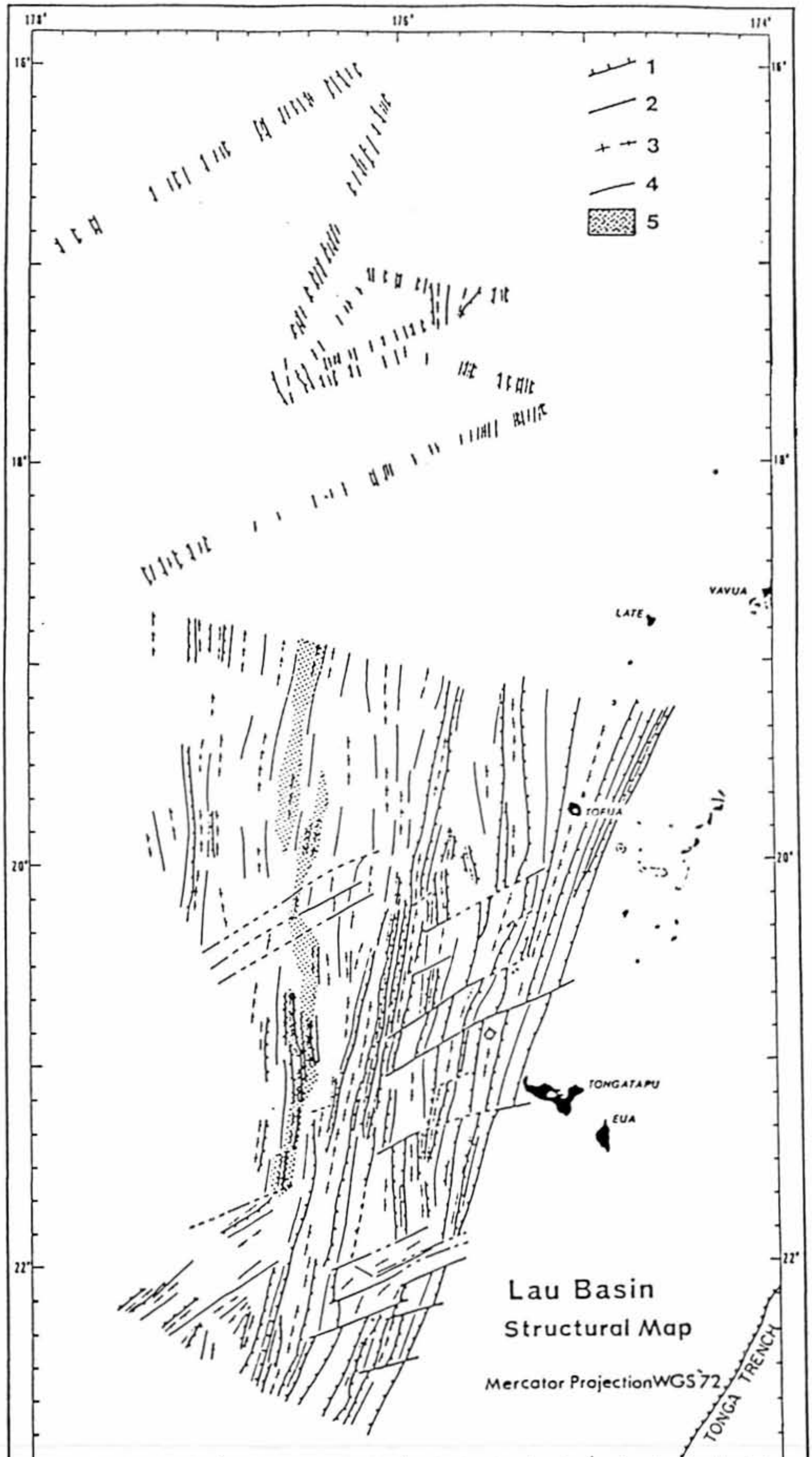

Figure 4

Structural map of the Lau basin after Ruellan et al. *(in press). 1. Normal fault scarps; 2. Strike slip faults; 3. Ridge crest; 4. Lows; 5. Axial spreading area. Squares indicate the sampling area.*

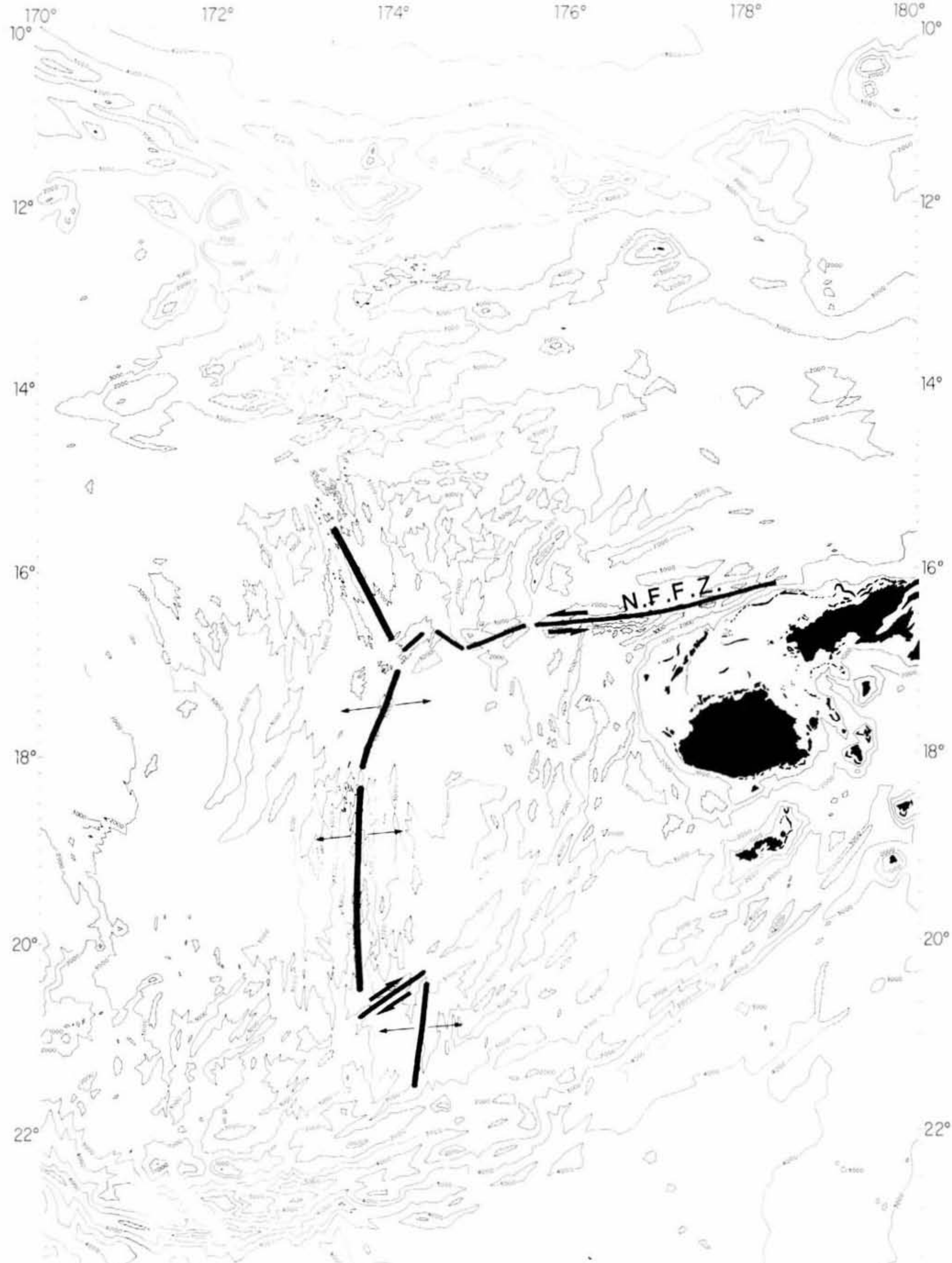

Figure 5

Simplified bathymetric map of the North Fiji basin with indication of the spreading axis location (after Mazé, Auzende et al., *in preparation). NFFZ = North Fiji Fracture Zone.*

the strike-slipe effects of N45 faults. This N45 fault pattern appears to extend outside of the axial region, on both sides of Valu Fa ridge (Fig. 4).

In the northern part of the basin, the N20 axis described by Stackelberg *et al.* (1985) can be interpreted as the northern prolongation of the N-S axis existing south of 18°30'S. Northward, the main feature is the N140 trending Peggy ridge. This 30 km wide, 150 km long and 500 m high ridge is interpreted as a NW-SE accretionary system located at the junction between the N20 axis, the northern part of the North Fiji basin and the poorly known north-eastern par of the Lau basin. These three features define a triple junction located around 17°S. The nature of this triple junction (R.R.R. or R.R.FZ.) depends on whether the Peggy ridge is truly an accretion axis or perhaps a fracture zone.

Magnetic data (Sclater *et al.*, 1972; Lawver *et al.*, 1976; Weissel, 1976; Malahoff *et al.*, 1979, 1982) confirm the existance of N-S lineations in the central part of the basin. However, spreading ages proposed by different authors vary between 5 and 2.5 Ma. Davagnier (1986) interpreted that magnetic and seismic profiles are consistent with an opening age around 3 Ma, synchronous with the last spreading rearrangement in the North Fiji basin (Auzende *et al.*, 1988; Ruellan *et al.*, in presse).

In its southern part, the Lau basin could be considered a back-arc basin which began to open 3 Ma ago along a NS spreading axis. The N45 strike-slip faults previously described would represent the flow lines of the spreading (Ruellan *et al.*, in press). In this scenario, the relationships between the strike-slip motion anf the rotation of the Tonga arc resulted in the recent creation of the Valu Fa ridge as a dextral transtensional system. This model could explain the uplift of Valu Fa and its present-day activity.

In its northern part, the kinematic evolution of the Lau basin must be closely related to the southern part of the North Fiji basin and also to the Tonga arc. This part of the basin is extremely complex and, given the poverty of data, its structure cannot presently be determined.

The North Fiji Basin

He is a marginal basin located between the converging pacific and Indo-Australian plates (Fig. 1). It is limited by the Vitiaz fossil subduction zone to the North, the New Hebrides arc to the west, the Fiji platform to the east and the Matthews-Hunter arc to the south (Fig. 5).

The compilation of the Seapso 3 and Kaiyo 87 Seabeam, magnetic and single channel seismic data have permitted the definition of the main characteristics of the spreading axis of the North Fiji basin (Fig. 6). In the southernmost part of the surveyed area, between 21°S and 18°10'S, the axial domain is characterized by an approximately NS trending succession of highs and depressions, about 200 km wide, decreasing to 160 km near 18°10'S. This fan-shape opening is confirmed by the magnetic data (Auzende *et al.*, 1988 c and in press) which suggest a 7.8 cm/y total spreading rate between anomalies 1 and 2A (3Ma) in the south and 5.2 cm/y at 18°10'S.

The axis itself is centred on 173°25'E with an average depth of 2600 m. The elevation with respect to the adjacent oceanic floor is about 200 m. The transverse morphology of the ridge is highly variable with the presence of domes, plateau and faulted grabens. The along-strike morphology shows the same variability. Nevertheless, segments a few tens of kilometres in length which are limited by transverse features (N45 faults, offsets and overlapping spreading centre) can be defined.

In the south, this area is cut by a large N45 transform fault which offsets the ridge by about 80 km (Maillet *et al.*, 1989). From 18°10'S to 16°40'S the orientation of the spreading axis changes from N-S to N15-20 exactly at the intersection of a N45 fault. The total spreading rate in this area is around 4.6 cm/y between anomalies 1 and J (Jaramillo-0.97 Ma). Anomalies 2 and 2A have not yet been identified here.

North of 16°40'S, the ridge trends N160. However, the precise location of the present-day active axis is difficult to define. The accretion system which has been surveyed by seamarc II (Moana wave cruise, 1986) and Seabeam profiling (Seapso 3 (1985) and Kaiyo 87 cruises) consists of a wide and deep graben (more than 4000 m) flanked by two ridges. The axial magnetic anomaly overlaps the graben and the eastern ridge but cannot give a precise location for the active ridge axis. The total width of the N160 system is about 120 km but, given the uncertainty of the axis location, it is not possible to establish the rate of opening accurately.

Both the (N15-20 and N160 ridges are flanked by N-S horsts and grabens inherited from the previous phase of opening (Auzende *et al.*, 1988c). The change of direction is youger than 1 Ma.

The North Fiji fracture zone, another major feature of the North Fiji basin (Chase, 1971; Green and Cullen, 1973; Carney and MacFarlane, 1982; Brocher and Holmes, 1985), is delineated by numerous seismic events (Hamburger and Everingham, 1986; hamburger and Isacks, in press; Louat and Pelletier, 1989) from 174°E to its eastward junction with the northern end of the Tonga trench. Focal mechanisms suggest strike slip sinistral motion along the fracture relative to the eastward displacement of the northern par of the North Fiji basin with respect to the Fiji island platform (Hamburger *et al.*, 1988). The geometry of the fracture shows a main (N55-60 trend relayed eastward by a system of highs and depressions oriented N-S. This non-linearity associated with sinistral motion has resulted in the formation of pull-apart basins and compression zones all along the fracture zone.

The western end of the North Fiji fracture zone is the third arm of the 16°40'S triple junction. It is mainly evidenced by a wide graben flanked by N60 and N45 faults. The axial part of the graben is occupied by a 20 km long "V" shaped volcanic zone (Lafoy *et al.*, in press).

Recent studies (Maillet *et al.*, 1989; Kaiyo 88 shipboard scientific party, in press) have provided new data con-

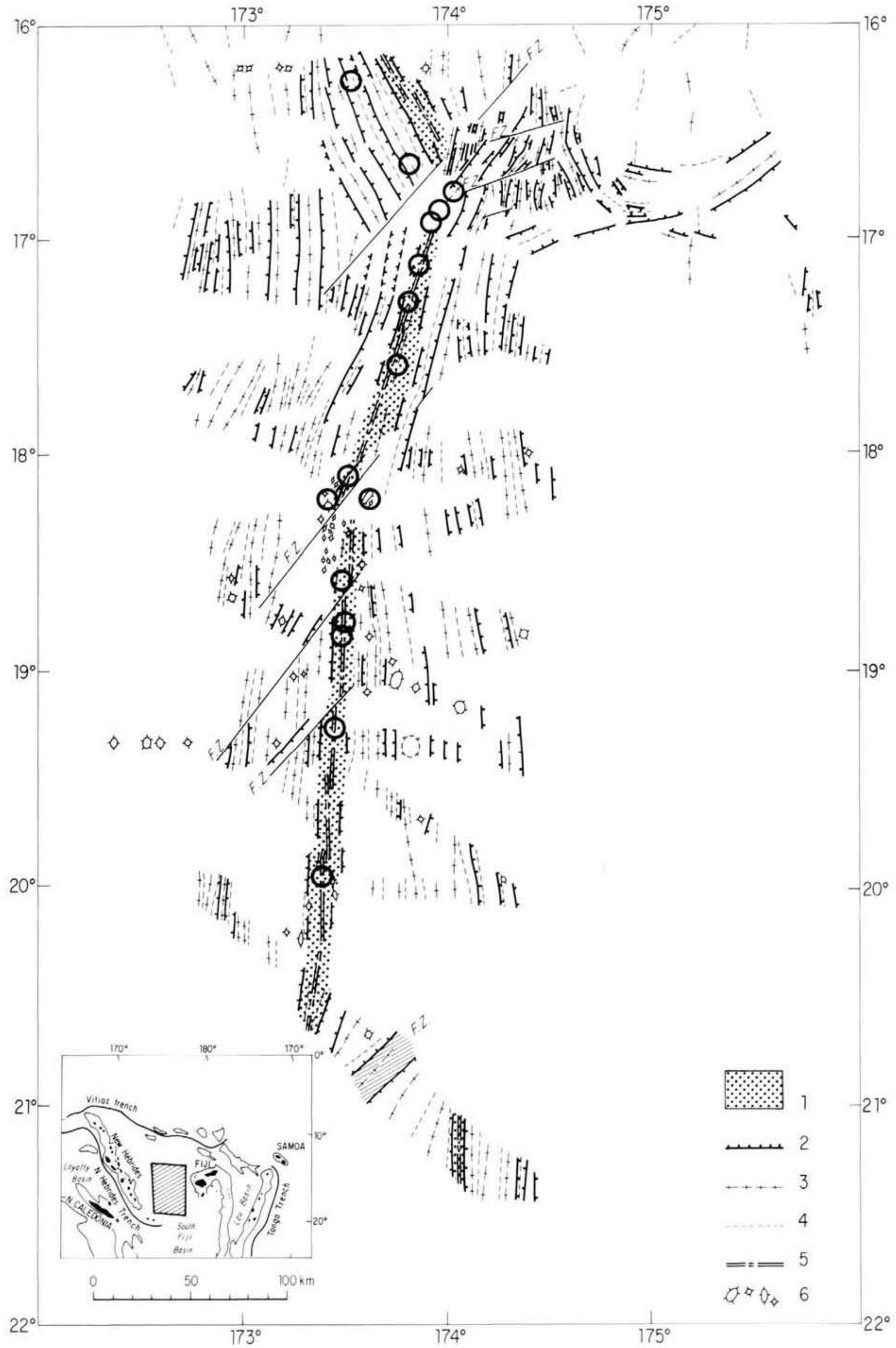

Figure 6

Structural map of the North Fiji basin (after Auzende et al., *1988a). 1. Axial area; 2. Normal faults; 3. Highs; 4. Lows; 5. Present-day axis; 6. Seamounts. The circles indicate the sampling sites.*

cerning the southern par of the basin between 20°30'S and 22°S. At 20°30'S, the axis is cut off and offset eastward by wide (N45 transform fault. To the south, the axis shows a double ridge structure flanked by elevated volcanic highs. The freshness of the dredged rocks, the temperature and manganese anomalies measured (Kaiyo 88 cruise, unpublished data) in the bottom waters and the observed axial magnetic anomaly indicate that this ridge is an active accretionary system. The evolution of the North Fiji basin can be summarized in three stages (Auzende *et al.*, 1988c). Between 10 Ma and 3 Ma, due to the collision between the Ontong-Java plateau and the Vitiaz zone, a reversal of the subduction polarity took place behind the New hebrides arc. The result wasthe clockwise rotation of the arc and the opening of the North Fiji basin by a N150 spreading ridge. 3 Ma ago, the New Hebrides arc began to collide against the "Loyauté" ridge which resulted in a change of the tensional stresses and to the reorientation of the spreading direction along an axial N-S ridge. More recently (less than 1 Ma) the strike slip motion along the North Fiji fracture zone leads to the rearrangment of the axis and the initiation of the 16°40'S triple junction.

CRUSTAL GEOCHEMISTRY AND EVOLUTION OF BACK-ARC BASINS

The trace element data used were obtained by neutron activation (C.E.N., Saclay) and XRF analysis (Ifremer, Brest). Isotopic data were obtained at the BRGM, Orléans, for the Okinawa trough samples and at the GDR, Brest, for the Lau and North Fiji basin samples. Analyses were all performed on fresh rocks. They are presented in a summarized form in figure 7 (Boespflug *et al.*, 1989).

Okinawa trough

Dredged basalts, landesites and dacites show chondrite-normalized extended rare earth element patterns enriched in most hydromagmaphile elements. They display large negative Ta-Nb anomalies which are characteristic of subduction zone environments (Joron and Treuil, 1977; Saunders *et al.*, 1980; Briqueu *et al.*, 1984; Ryerson and Watson, 1987). Sr and Nd isotopic ratios fall within the mantle array with a Sr range of 0.7040 to 0.7047 and a

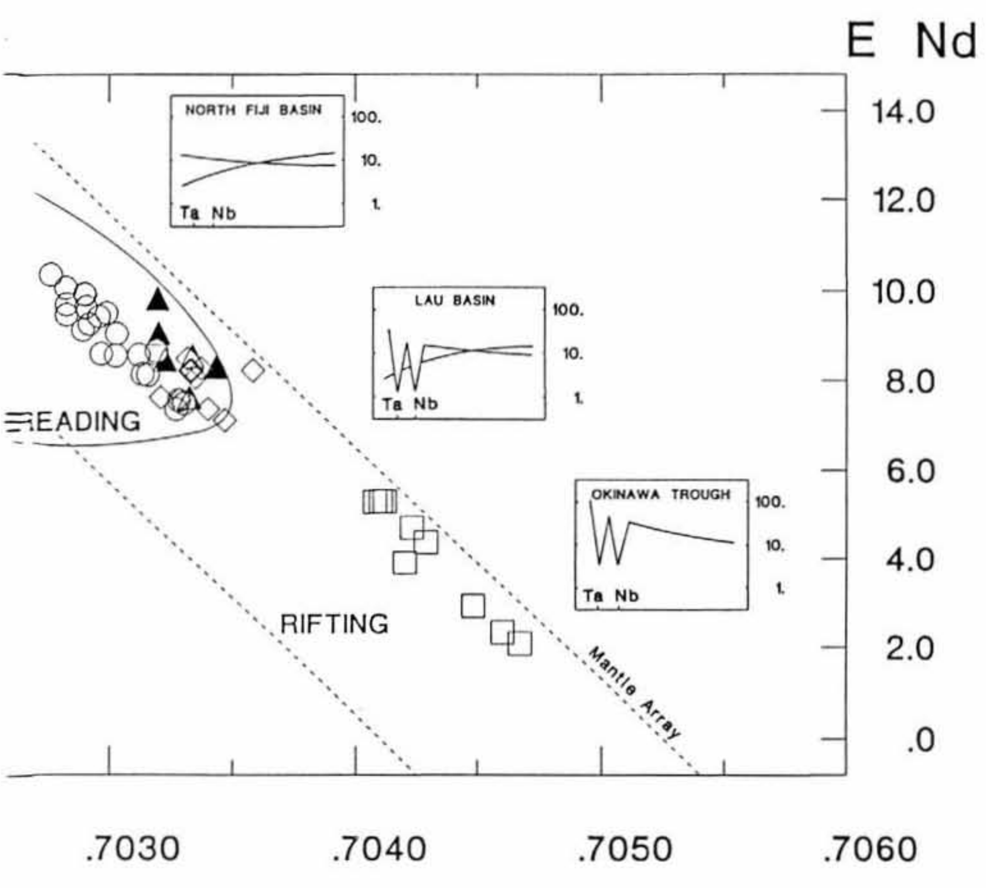

Figure 7

Mantle array diagram showing the different geochemical characteristics of the Okinawa trough, Lau and North Fiji basins. In the North Fiji basin, most of the samples show a N. Morb depleted plattern. Only few samples are of enriched Morb type. In the central part of the Lau Basin, the samples have a N. Morb type pattern, while in the southern part they show a slightly enriched pattern with Nb and Ta negative anomalies. Extended rare earth diagrams are drawn according to Bougault (1980) with normalization values shown in Briqueu et al. *(1984). Symbols used are squares : Okinawa trough; diamonds : Lau basin (Valu Fa ridge); triangles : Lau basin (central part); circles : North Fiji basin.*

well-correlated range of Nd isotopic composition of .Nd = + 5.3 to + 2.1. All samples have higher Cs/Rb ratios (0.056) than non-subduction-related oceanic magmas (0.013) (White and Patchett, 1984).

Lau basin

Two groups of samples were dredged and analysed. The first one includes pillow basalts from the central part of the basin. They have typical depleted N-MORB type extended rare earth patterns. The second group includes samples dredged on Valu-Fa Ridge. They display major element compositions intermediate between Morb and andesitic compositions with high Cs/Rb ration (0.022). Thet have slightly depleted to enriched extended rare earth patterns with negative Ta-Nb anomalies. In a mantle array diagram (figure 8) the isotopic compositions of both groups range from 0.7032 to 0.7036 with .Nd from + 9.8 to + 7.1. These results are in good agreement with those published by Jenner *et al.* (1987) and Volpe *et al.* (1988) for samples from the central part of the basin.

North Fiji basin

Tholeïtic basalts have been dredged along the central spreading axis of the basin. All samples but one show depleted characteristics. The single exception has a slightly enriched pattern with no Nb-Ta anomaly, such as is found on ridges from mature ocean basins (E-Morb).

Sr and Nd isotopic compositions are well correlated in the mantle array. They range from 0.7028 to 0.7033 for Sr and + 10.4 to + 7.4 for .Nd.

On the basis of their isotopic compositions, two groups of samples can be identified. The first group ($^{87}SR/^{86}Sr \approx$. 7029, .Nd ≈ + 9.9) includes samples from the N15 segment of the ridge. The second group ($^{87}SR/^{86}Sr \approx$. 7032, .Nd ≈ + 7.9) includes samples from the N160 and NS segments of the ridge. As discussed above, these two segments are related to different evolutionary stages of the ridge. Their geochemical characteristics reflect mantle source heterogeneities in relation to the evolution history of the ridge.

Comparison of the geochemistry of these three back-arc basins shows that both trace element patterns and isotopes reflect their evolution from

- an initial rifting stage (Okinawa trough) 2 Ma ago, with arc-like characteristics through
- a spreading stage which started in the Lau basin 3 Ma ago and where subduction features are more apparent closer to the arc (Valu-Fa ridge), and
- a mature stage with typical Morb features such as seen in the North Fiji basin which started to open 10 Ma ago.

COMPARISON BETWEEN THE OKINAWA, NORTH FIJI AND LAU BASINS: CONCLUSIONS

The structural and isotopic geochemistry data give coherent information which indicates that the Okinawa, North Fiji and Lau back-arc basins show a gradation from an embryonic stage to a quite mature stage in their accretionary processes.

The earliest stage is represented by the Okinawa trough, where we may note accretionary phenomena characterized by a Plio-Pleistocene intracratonic polyphase evolution evolving from simple extension in the continental crust to the onset of linear dykes which suggests the first stage of formation of oceanic crust. The sampled rocks vary from basalts to andesites and dacites characterized by subduction zone environment isotopic ratios.

The Lau basin, about 3 Ma old, results from the rotation of the Tonga arc in relation with the eastward subduction of the Pacific plate. The structures associated with the opening of the Lau basin display a complex accretionary system with a RRR or RR FZ triple junction in the northern par of the basin. In the southern part of the basin, the accretion may be distributed along two ridges : a N-S one which is not well known, and the Valu Fa ridge, parallel to the Tonga arc. The relative role of these two ridges is still uncertain. The N-S ridge is characterized by tholeitic basalts while on the Valu Fa ridge the geochemistry indicates an intermediate composition between Morb and andesitic arc.

The North Fiji basin is older. Its evolution can be summarized in two stages : an early stage characterized by the rotation of the New hebrides arc between 10 and 3 Ma, and a second stage characterized by the functioning of a N-S accretion axis at least in the southern part of the basin. This axis is very similar in structure and petrochemistry to the East Pacific Rise which shows that the basin is mature. All the rock samples are of typical Morb composition. The isotopic compositions confirm the two recent stages of evolution of the basin although it is difficult to understand the precise relationships between the superficial structuration and the change of geochemistry characteristics.

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