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The northern New Hebrides back-arc troughs: history and relation with the North Fiji basin

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Abstract

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The New Hebrides back-arc troughs (southwest Pacific) are located between the New Hebrides trench-arc system and the active North Fiji marginal basin. They are restricted to the southern and northern segments of the arc and were generally related to effects of the Indo-Australian subducting plate (rolling-back and/or subduction of the d'Entrecasteaux ridge). A detailed bathymetric and magnetic survey over the northern back-arc troughs is used to propose a new model for the origin of the New Hebrides back-arc troughs. The northern troughs extend over a width of 60 km and are composed of N–S trending grabens and horsts, discontinuous along strike and associated with volcanism. The troughs are disrupted southward at 13°30′S, where the Hazel Holme fracture zone intercepts the New Hebrides island arc. The E–W trending Hazel Holme fracture zone is an extensional feature bisecting the North Fiji basin. In its western end, the Hazel Holme fracture zone is composed of a succession of horsts and grabens striking N90°–N100°E. Geometrical and structural relationships between the back-arc troughs and the Hazel Holme fracture zone suggest that both these extensional features result from the same process and are closely linked. The northern troughs-western end of the Hazel Holme fracture zone region is dominated by N130°–135°E trending magnetic lineations typical of oceanic crust. These lineations are oblique to the horsts and grabens systems, and are characteristic of the old North Fiji basin oceanic crust. Consequently we conclude that the northern back-arc troughs are partly developed on the North Fiji basin oceanic basement and that extensional tectonic processes postdate the oldest North Fiji basin oceanic crust. Morphological and structural evidence suggests that both the back-arc troughs and the Hazel Holme fracture zone are recent, still active and result from NE–SW extensional tectonics. Because other tectonic features throughout the North Fiji basin are related to the same stress field, it is inferred that such a NE–SW extension could be a large-scale deformation affecting the North Fiji basin. It is proposed that the back-arc troughs are primarily related to this recent extension within the North Fiji basin, but their locations along the arc are also influenced by the subduction of the d'Entrecasteaux ridge which produces, south of 13°30′S, nearly E–W trending compression and prevents the formation of troughs. Possibly, these recent extensional tectonic processes result from a major reorganization in the spreading process of the North Fiji basin, and could be as young as 0.6–0.7 Ma.

Introduction

The New Hebrides arc and North Fiji basin are often selected as a typical example of an island arc-back-arc basin system extending along a converging plate boundary. Nevertheless this system exhibits several unusual features: (1) the marginal basin (i.e. North Fiji basin) lies partly between two opposite subduction zones (i.e. the Tonga and New Hebrides subduction zones) bounding the Pacific and Australo-Indian plates (Fig. 1); (2) the

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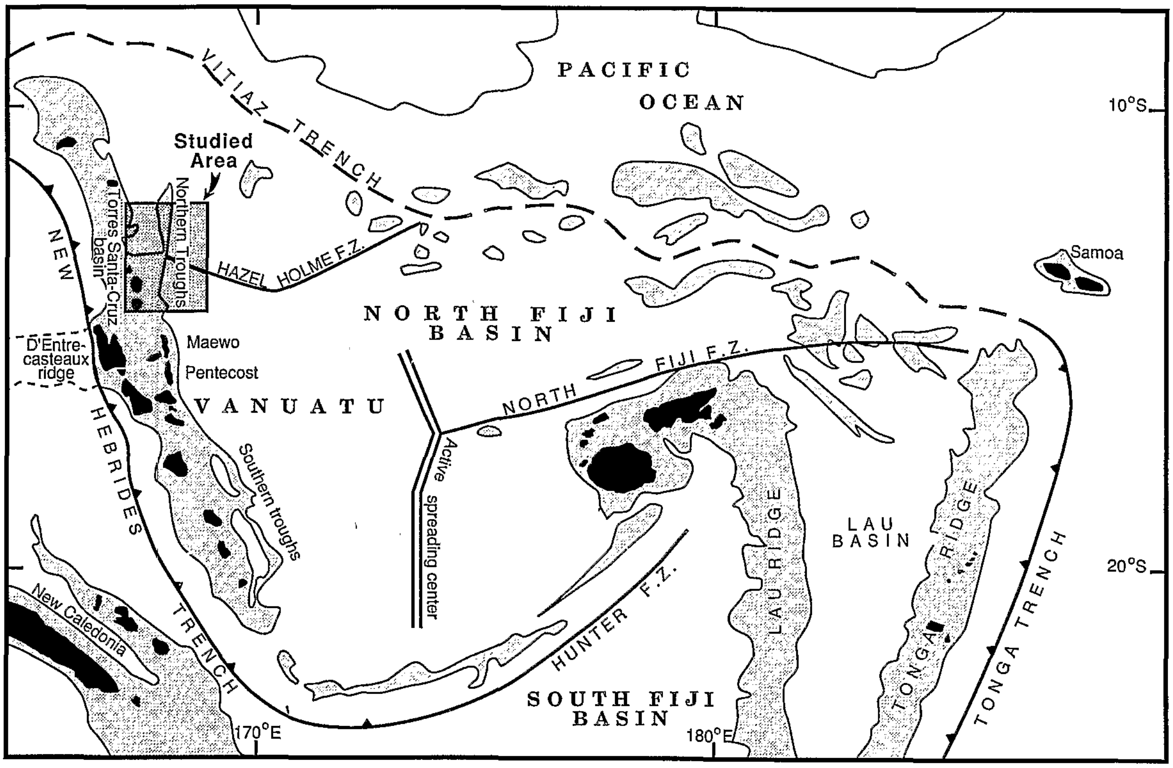

Fig. 1. New Hebrides arc-trench system and North Fiji basin in the Southwest Pacific. Main tectonic features are shown by heavy lines.

marginal basin is unusually large and shaped as an equilateral triangle, surrounded westward by the New Hebrides island arc, southeastward by the Hunter fracture zone and northward by the fossil Vitiaz subduction zone (Fig. 1); (3) the active spreading centre trending N–S to N10°E in the southern part of the basin and N160°E farther north (Auzende et al., 1988a), is oblique with regard to the New Hebrides arc and located beyond the deepest part of the New Hebrides slab (Fig. 1); (4) back-arc troughs lie at the New Hebrides arc–North Fiji basin junction. Such extensional features located between an active subduction zone and the active back-arc spreading axis are unknown among other back-arc systems. These particularities make the New Hebrides arc–North Fiji back-arc basin system unique. Thus, the North Fiji basin must not be considered as a typical example of oceanic back-arc opening.

The New Hebrides back-arc troughs are discontinuous along the arc (Fig. 1). The southern troughs (also named the Coriolis troughs) lie south of 17°30′S (Puech and Reichenfeld, 1969; Dubois et al., 1978; Monzier et al., 1984), while the northern troughs lie north of 13°30′S (Karig and Mammerickx, 1972). No extensional feature exists in the central back-arc domain, east of Maewo and Pentecost Islands, in front of the d'Entrecasteaux ridge subduction (Collot et al., 1985).

Different interpretations concerning the origin and age of the back-arc troughs have been proposed. Although the bathymetry and structure of the northern troughs were poorly known in comparison with the bathymetry and structure of the Coriolis troughs, the northern troughs have often been considered as the northern equivalent of the Coriolis troughs. Karig and Mammerickx (1972) described the New Hebrides back-arc troughs as en-échelon basins related to extensional stress perpendicular to the arc and associated with dextral strike-slip motion parallel to the arc. Luyendyk et al. (1974) suggested that the northern troughs are younger than the southern ones and represent the first stage of an oceanic opening. Dubois et al.

(1978) proposed that the back-arc troughs are caused by convection cells associated with the subducting plate, the extension occurring along weak zones related to previous transcurrent faults. These authors described strong magnetic anomalies in the axial part of back-arc troughs, interpreted as the signature of dense intrusive bodies. Collot et al. (1985) suggested that extension in the northern and southern troughs could be a consequence of collision between the d'Entrecasteaux zone and the central part of the New Hebrides arc. They also noted that the incompletely known spreading pattern of the North Fiji basin might also have a significant influence on both the active tectonics of the New Hebrides arc and the general stress block distribution. During the Seapso 2 cruise (ORSTOM-IFREMER, November 1985) parts of the northern and southern back-arc troughs were surveyed with Seabeam (Récy et al., 1986). These authors described volcanism associated with the troughs and proposed that the N30°–N40°E trending extension results from an incipient rifting stage. Ruellan et al. (1987) proposed that back-arc trough tectonics initiated during the Middle Miocene, when the North Fiji basin rifting took place. More recently, on the basis of petrological, geochemical and radiometrical ($^{40}K/^{40}Ar$) studies, Monjaret (1989) proposed that formation of the troughs is often polyphased and is diachronous from north to south (the beginning of trough formation is 6.5 Ma in the southern troughs and 2.8 in the northern trough).

This paper is devoted to the detailed morphological and structural study of the northern back-arc troughs which merge southward with the Hazel Holme fracture zone, a major E–W trending feature crosscutting the North Fiji basin and reaching the New Hebrides arc at the southern end of the northern back-arc trough domain (Fig. 1). Updated bathymetric and magnetic maps of the Northern back-arc troughs and the western end of the Hazel Holme fracture zone are presented. These maps are mainly based on new data which include Seabeam swaths recorded during the Seapso 2 (ORSTOM-IFREMER, 1985) and Multipso (ORSTOM, 1987) cruises on-board the R/V "Jean Charcot"; wide-beam echo-sounding profiles obtained during the Eva 13 (ORSTOM, 1986) and Eva 14 (ORSTOM, 1987) cruises on-board the R/V "Coriolis" and magnetic data recorded during the four previously mentioned cruises (Fig. 2). These maps also include data from earlier cruises: Austradec 1, 3 and 4 (ORSTOM-CNEXO-CEPM, 1971, 1975, 1976), Chain (Woods Hole O.I., 1971) and Geovan 2 (ORSTOM-CCOP-/SOPAC, 1980) (Fig. 2).

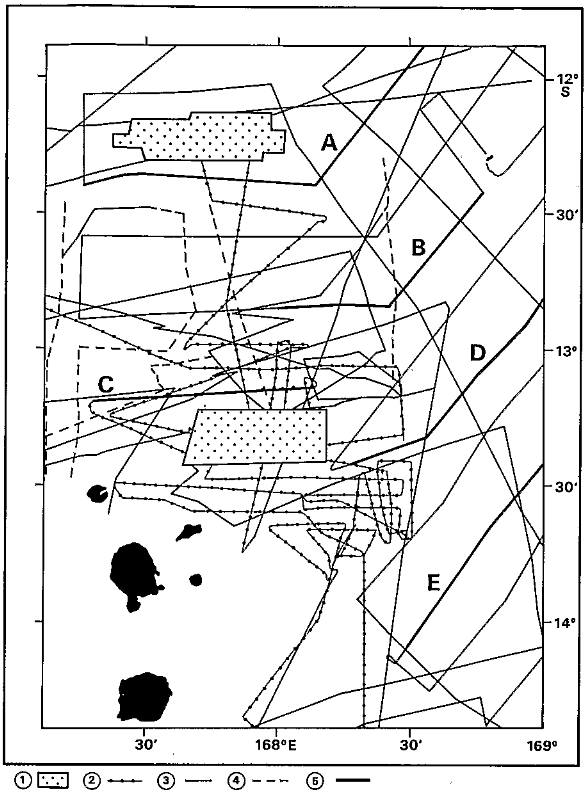

Fig. 2. Magnetic and bathymetric track lines used in this study. *1* = area of full Seabeam coverage; *2* = Seabeam and magnetic lines; *3* = bathymetric and magnetic lines; *4* = bathymetric lines; *5* = single channel seismic reflection lines shown in Figs. 5–9.

Morphology and structure

The bathymetric map (Fig. 3) was drawn using Seabeam maps (areas of full Seabeam coverage are reported in Fig. 2.), Seabeam strips and wide-beam echo-sounding lines outside the areas of full Seabeam coverage. The structural map is mainly based on Seabeam swaths, conventional echo-sounding lines and single-channel seismic profiles (Figs. 2 and 4). Magnetic data and dredged samples have been also fruitful for the structural interpretation, specially for the identification of volcanoes.

The studied back-arc zone can be divided into three parts (Figs. 3 and 4): the western region characterized by the N–S trending troughs (i.e. northern back-arc troughs), the southeastern area with the N100°E Hazel Holme fracture zone and the northeastern domain.

(1) *The troughs* are located between 167°25′E and 168°15′E, disappearing south of 13°30′S at the junction with the Hazel Holme fracture zone. Farther south, the troughs are replaced by the volcanic islands of the New Hebrides arc bounded

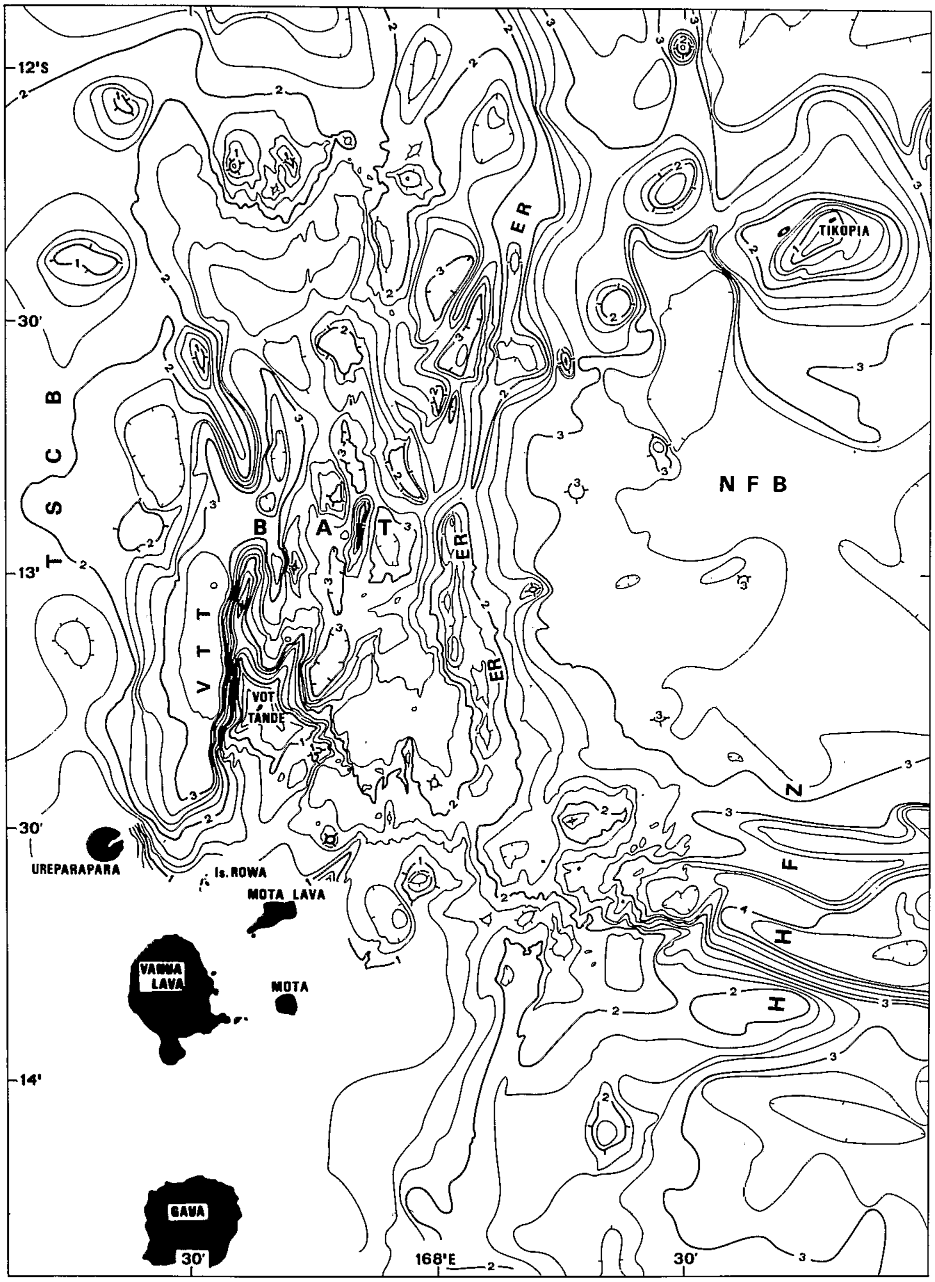

Fig. 3. Bathymetric map of the northern New Hebrides back-arc troughs. Contours are 250-m intervals. Depth in kilometres. TSCB—Torres Santa-Cruz sedimentary basin; BAT—back-arc troughs; VTT—Vot Tande trough; ER—Eastern Ridge; HHFZ—Hazel Home Fracture zone; NFB—North Fiji basin.

eastward by a small depression trending N20°E which was interpreted, by Ravenne et al. (1977) and Dubois et al. (1975, 1978) as the continuation of the northern troughs (Figs. 3 and 4). This depression is restricted in size, weakly expressed by bathymetric contours and shifted eastward with regard to the northern troughs (Fig. 3). Consequently, this feature may not be the continuation of the northern troughs but is probably associated with the Hazel Holme fracture zone which interrupts the trend of the northern troughs. The northern troughs extend northward at least up to

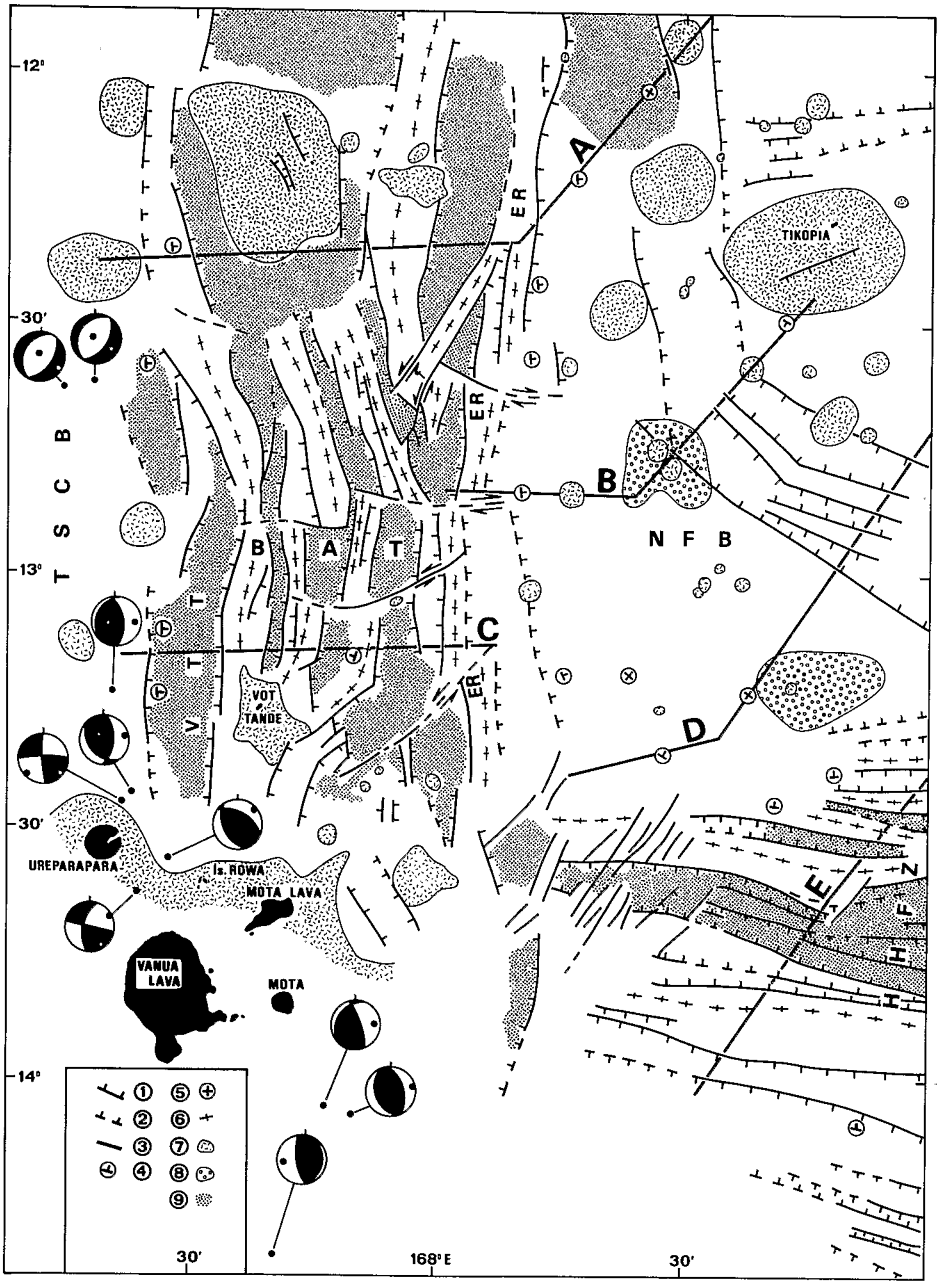

Fig. 4. Structural map of the northern New Hebrides back-arc troughs. *1* = normal fault; *2* = small and/or inferred normal fault; *3* = transverse tectonic lineation (arrows indicate strike-slip fault); *4* = inclined bedding; *5* = horizontal bedding; *6* = structural high; *7* = volcano; *8* = lava flows; *9* = major graben. TSCB—Torres Santa-Cruz sedimentary basin; BAT—back-arc troughs; VTT—Vot Tande trough; ER—Eastern Ridge; HHFZ—Hazel Home Fracture zone; NFB—North Fiji basin.

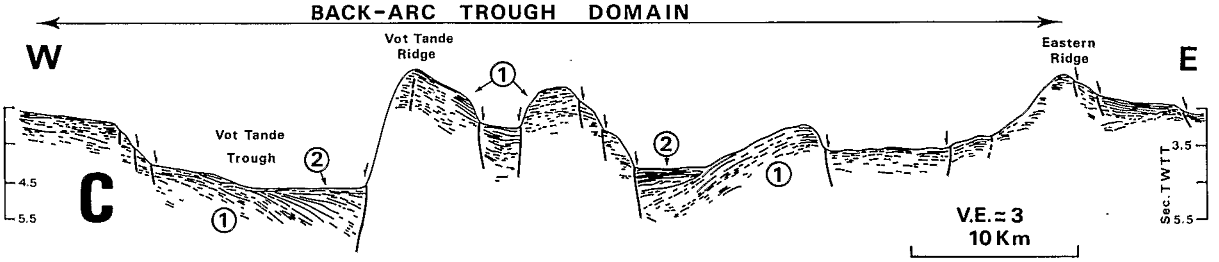

Fig. 5. Seismic line C bisecting the back-arc troughs in the southern part of the studied area (location in Fig. 2). *1*—lower sedimentary sequence; *2*—upper sequence.

11°S (Karig and Mammerickx, 1972; Dubois et al., 1978) but are not mapped owing to the scarcity of data.

The trough area consists of a complex succession of horsts, grabens and half-grabens trending NNW–SSE to NNE–SSW. The deepest trough (called Vot Tande trough) reaches a depth of 3500 m and developed along the eastern edge of the Torres Santa-Cruz sedimentary basin (Figs. 3 and 4). This trough is well-developed in its southern part and bounded eastward by a major normal fault scarp higher than 2000 m (Fig. 5). An almost continuous ridge (the Eastern Ridge) trending N–S and culminating between −1250 and −1500 m forms the eastern border of the trough area (Fig. 4). Transversely, the back-arc trough domain is composed or three of four grabens or half-grabens (Figs. 4 and 5) ranging from 3000 to 3500 m in depth and discontinuous along strike. The discontinuity and the sudden disappearance of structures, as well as the changes in structural trends, suggest transverse strike-slip faults associated with extension. N45°–N60°E trending left-lateral and N90°–N110°E trending dextral conjugate strike-slip faults are inferred from detailed bathymetry (Fig. 4). They clearly affect the Eastern Ridge and often underline the endings of small grabens (Fig. 4).

The seismic reflection cross-sections exhibit thick sedimentary series in grabens as well as on horsts (Fig. 5). As a general rule these series, derived from nearby volcanic islands, thin eastward away from the emergent volcanic arc (Figs. 7 and 8) and correlate with the upper part of the

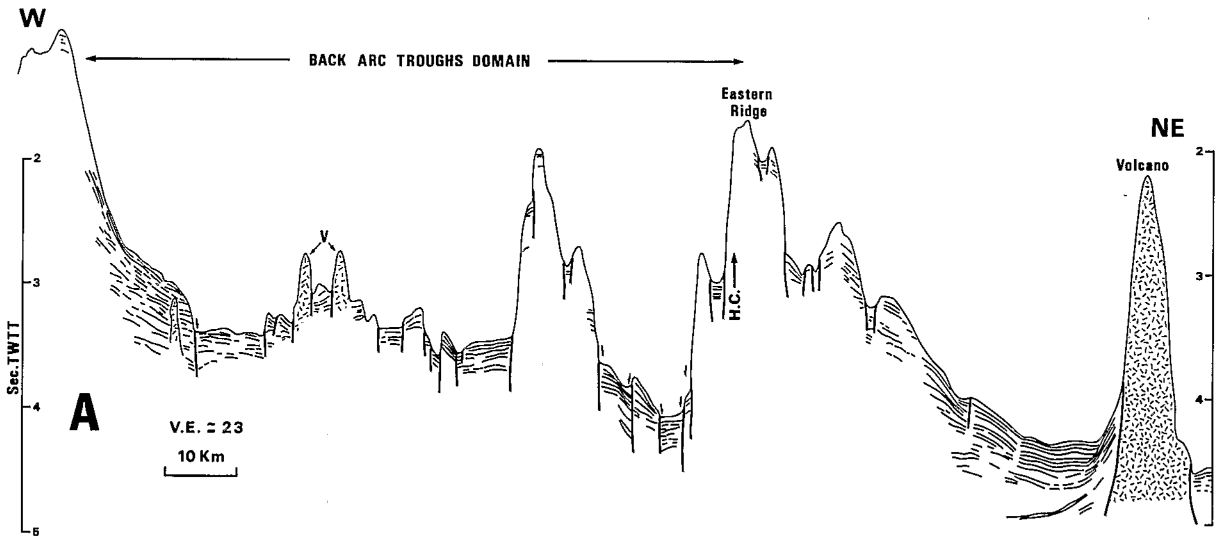

Fig. 6. Example of a seismic line bisecting the back-arc troughs in the northern part of the studied area (line A, location in Fig. 2). V—volcano; HC—heading change.

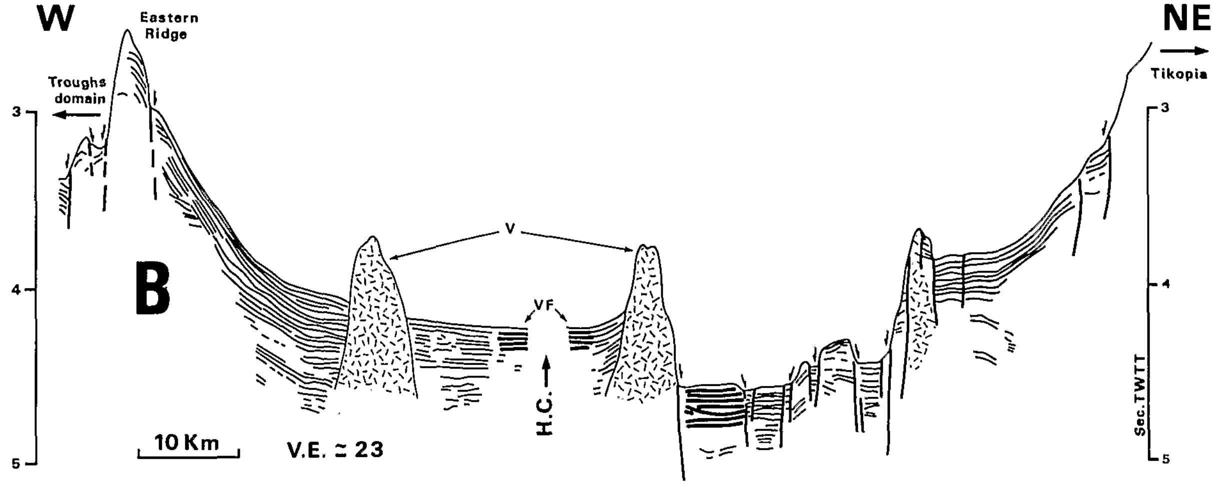

Fig. 7. Seismic cross-section B east of the back-arc troughs (location in Fig. 2). V—volcano; VF—volcanic flows; HC—heading change.

volcano-sedimentary series known in the Torres Santa-Cruz basin. This upper part is up to 1.2 s TWT (second two-way travel time) thick and ranges in age from the Late Miocene to the Present (Katz, 1988). Numerous volcanoes are spread over the northern and southern parts of the back-arc troughs (Figs. 4 and 6). The sedimentary series are composed of two sequences. The 0.5 to 1.2 s TWT thick lower sequence is tilted in grabens and horsts as well (sequence 1, Fig. 5). In the main western graben, the most recent layers of this sequence present a fan-shaped structure dipping eastward (Fig. 5) and suggesting that the early extensional tectonic processes, responsible for back-arc trough genesis, are synchronous with the uppermost deposits of this lower sequence. Farther east this sequence consists of parallel layers dipping westward (Fig. 5). In the grabens, this lower sequence is unconformably overlain by a 0.2–0.3 s TWT thick upper sequence which also exhibits a fan-shaped geometry east of Vot Tande ridge (sequence 2, Fig. 5). Although the upper sequence postdates the initial extensional phase, its structure argues for a present-day extensional tectonics.

All seismic cross-sections through the eastern flank of the Eastern Ridge exhibit a 0.4–0.6 s TWT thick sedimentary sequence tilted eastward (Figs. 6, 7 and 8). This sequence is considered

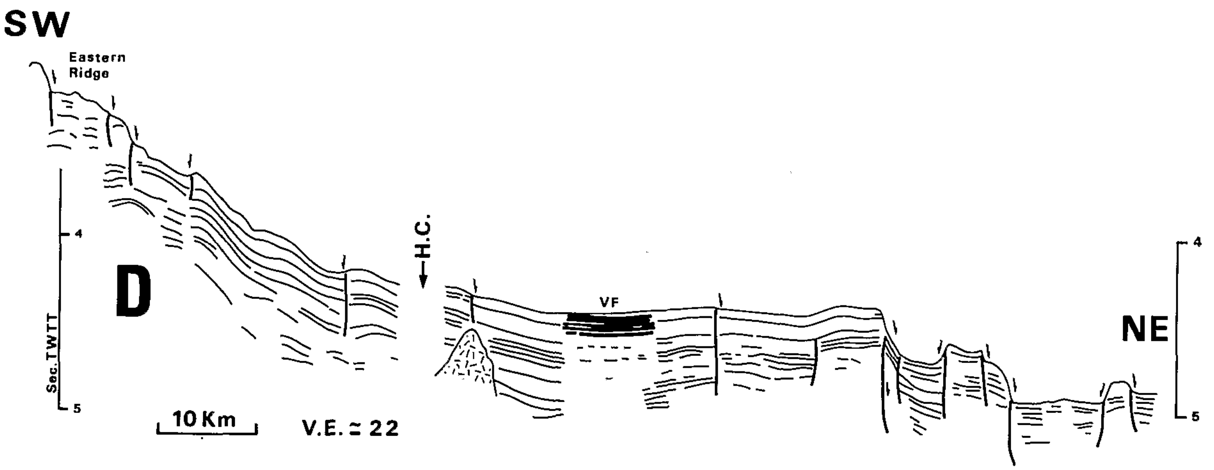

Fig. 8. Seismic cross-section D east of the back-arc troughs (location in Fig. 2). V—volcano; VF—volcanic flows; HC—heading change.

equivalent to the lower sequence previously described. The upper sequence which fills in the western troughs is missing. Consequently, we conclude that: (1) no morphological trap existed west of the Eastern Ridge during the deposition of the lower sequence derived from the nearby New Hebrides arc; (2) extensional tectonics created depressed areas acting as traps which prevent deposition of the upper sequence east of the troughs. To the west, the earlier stage of trough formation is synchronous with the most recent layers of the lower sequence. Farther east, the major tectonic event postdates this lower sequence. Thus, extensional tectonics propagated progressively from west to east.

Abundant volcanism is located within the troughs (Fig. 4). In the southern part, several small cone-shaped volcanoes are scattered on the flat bottom of the large trough east of Vot Tande islet. At the northern end of the study area a large complex volcanic cone lies in the central part of the largest trough (Fig. 4). Relationship between volcanism and troughs appears complex. Certainly some edifices predate the formation of the troughs as, for example, the Vot Tande volcanic islet belonging to the Vot Tande Ridge which appears as a horst between two large grabens. One must notice that the Vot Tande islet is located in northern continuation of the Gaua-Vanua Lava and Mota Lava volcanic line (Fig. 4). Probably the New Hebrides volcanic arc, at the latitude of the troughs, exists but is mostly submerged due to collapse. Moreover, seismic profiles clearly indicate that some volcanoes perforate the whole sedimentary series of the troughs, as for example the small volcanic cones located in the trough east of the Vot Tande islet (Fig. 4). This volcanism postdates the beginning of trough formation. During the Seapso 2 cruise, numerous volcanic samples were dredged on both volcanoes and fault scarps (Récy et al., 1986; Monjaret et al., 1987). Geochemical analysis indicates that most volcanic samples dredged bear island arc affinities with no important difference between the island arc volcanism and the back-arc trough volcanism (Monjaret et al., 1987). K/Ar radiometric datings indicate that volcanic activity began 4.8 Ma ago (on the Vot Tande ridge), and was important and roughly continuous from 4.1 Ma to the present in the troughs and/or on the islands (Monjaret, 1989; Monjaret et al., in prep.). In addition, some samples of oceanic basalts (MORB) were dredged along fault scarps in the northern part of the troughs. They are 12.4 Ma old (K/Ar datings) and could be related to the old North Fiji basin oceanic basement (Monjaret, 1989; Monjaret et al, in prep.). Monjaret (1989) infers from the age of volcanic edifices located on the bottom or on the flanks of the troughs a minimum age of 2.9–2.7 Ma for the northern trough formation whereas tectonic phases took place 4.1–1.7-1.5 Ma ago in the Coriolis troughs.

(2) *The Hazel Holme fracture zone* transects the North Fiji basin from the Vitiaz trench to the New Hebrides island arc (Chase, 1971). This fracture zone trends ENE–WSW in its eastern part and becomes WNW–ESE west of 171°E and N100°E near the New Hebrides arc (Fig. 1). In the study area (Figs. 3 and 4), the Hazel Holme fracture zone reaches a width of 60 km and has a rough topography linked to a succession of tight ridges and grabens striking N90°–N100°. The westernmost end of the Hazel Holme fracture zone is V-shaped; the horsts and grabens of the southern and northern part of the fracture zone are less developed westward than the ones forming the central part. The axial graben is the largest (Fig. 4). This graben is 4500 m deep, and is bounded by 2000–2500 m high scarps along the southern flank (Figs. 3 and 9). Small scarps predominate south of this graben while the area north of it is characterized by a rough topography. Morphology and single-channel seismic lines suggest that the Hazel Holme fracture zone is an extensional tectonic feature. Tilting of the upper part of the sedimentary sequence (Fig. 9) evidences recent and still active tectonics.

In the westernmost part of the fracture zone, Seabeam data exhibit many N40°–N45°E structural lineations (Figs. 3 and 4). These lineations are mainly developed at the western end of the large central graben, in the northern back-arc troughs–Hazel Holme fracture zone intersection area. However, such structures may also exist further east, but are poorly mapped owing to the lack of Seabeam data. These N40°–N45°E structural lin-

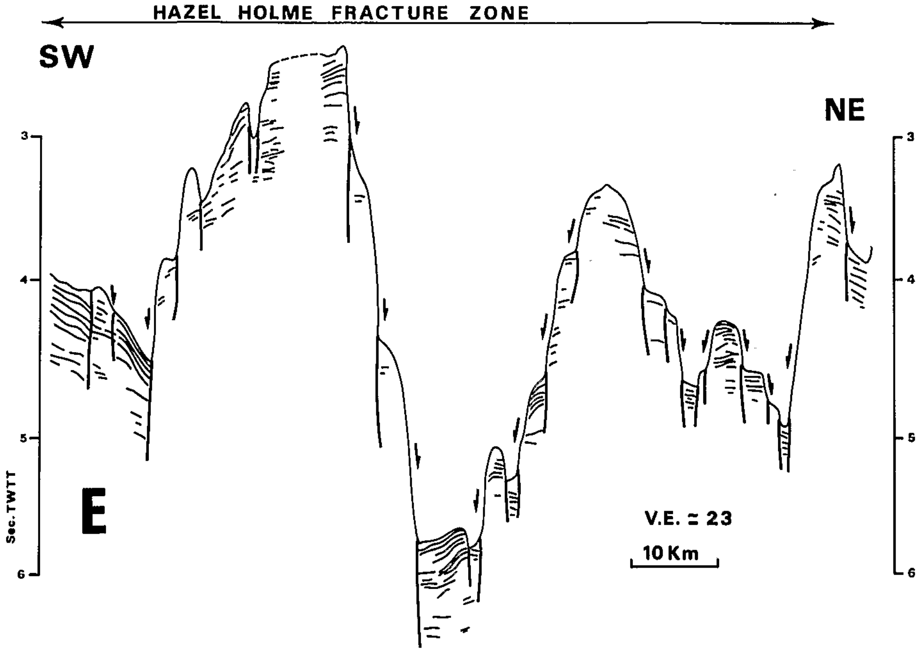

Fig. 9. Seismic cross-section E across the Hazel Holme fracture zone (location in Fig. 2).

eations correspond to tight parallel ridges which could result from strike-slip motion. However, these lineations do not affect the main N90°–N100° structures. These lineations parallel both the left-lateral strike-slip fault occurring in the back-arc trough domain and the eastern flank of the small half-graben east of Vanua Lava Island (Figs. 3 and 4).

(3) *The northeastern domain* is characterized by an almost flat bottom, about 3250 m deep, on which lie some large cone-shaped volcanoes. A continuous sedimentary sequence thins eastward across the area (Figs. 7 and 8). This sequence is tilted eastward and northward, respectively east of the back-arc troughs domain and north of the Hazel Holme fracture zone (Figs. 6, 7 and 8). Farther east, this sequence is cut by active normal faults, with small throws, trending N110°–N120°E and N–S (Figs. 7 and 8). These two strikes parallel those of the Hazel Holme fracture zone and back-arc troughs respectively.

Abundant volcanism, previously only known on Tikopia Island (Fryer, 1974), is present in this northeastern domain. Most of the volcanoes concentrate along N–S and N110°E trending normal faults (Fig. 4), which suggest that volcanism and extensional tectonics are closely related. Profiles B and D (Figs. 7 and 8) locally exhibit high-amplitude superficial seismic horizons which contrast with the seismic facies of the primary sedimentary sequence. Because these horizons are restricted to the neighbourhood of the volcanoes (Fig. 4), we interpret them as lava flows or very coarse volcaniclastics derived from volcanic complexes. The sedimentary sequence is tilted at the base of several volcanoes (Figs. 6 and 7), but it is not clear whether the tilting is due to the volcanic event or to the deposition on the flank of the pre-existing volcano. The tilted sedimentary sequence is locally unconformably overlain by a horizontal upper sequence (northeastern end of line A, Fig. 6) which is clearly more recent than the volcano.

Three lines of evidence argue for a recent volcanism: (1) Tikopia island is the remnant part of a young volcano 80,000 years old (K/Ar age, Fryer, 1974); a lake, in the central part of this small island, occupies a pit-crater (Hughes, 1978); (2) the previously mentioned high-amplitude seismic horizons developed around some volcanoes appear only in the uppermost part of the sedimentary sequence (Figs. 4, 7 and 8); (3) the distribution of volcanoes appear to be controlled by normal faults which are active since they affect the whole sedimentary sequence.

Magnetism (Figs. 10 and 11)

Magnetic anomalies were processed using the IGRF 80 reference field. Diurnal variations were considered small enough to be ignored and no correction was applied. The average of measurement difference at ship track intersections within a cruise or between different cruises being 16 nT, magnetic anomalies map was drawn with 100 nT intervals (Fig. 10).

Two trends of lineation appear on the magnetic map (Fig. 10). In the northeastern corner of the map E–W trending magnetic lineations exist. These lineations largely extend east of the study area and characterize a recent stage of the North Fiji basin oceanic opening (Pelletier et al., 1988). The largest part of the map is characterized by alternate positive and negative 30–40 km wide magnetic lineations, ranging from −200 to +400 nT and trending N130°–N135°E (Figs. 10 and 11). High-amplitude dipolar anomalies induced by volcanoes locally disrupt the NW–SE trend (Fig. 10). Size and amplitude of the NW–SE magnetic anomalies are typical of oceanic basement. These N130°–N135°E trending lineations are oblique with regard to the northern back-arc trough and Hazel Holme fracture zone structural trends. The magnetic map clearly indicates that these lineations extend continuously from the central part of the northern troughs to the area lying east of the troughs which is part of the North Fiji basin (Figs. 3 and 10). Such NW–SE magnetic lineations are well known in the North Fiji basin, east of the New Hebrides arc and southwest of the Fiji Islands; they characterize the oldest part of the North Fiji basin oceanic crust (Luyendyk et al., 1974; Malahoff et al., 1982; Larue et al., 1982; Maillet et al., 1986; Auzende et al., 1988a; Pelletier et al., 1988). Thus, it can be concluded that the NW–SE anomalies within the back-arc troughs are part of the magnetic pattern of the North Fiji basin. Extensional tectonic processes of the troughs and Hazel Holme fracture zone are largely superimposed on the oceanic basement of the North Fiji basin and thus postdate the oldest North Fiji basin spreading phase. Because the NW–SE lineations end westward near 167°40′E, we propose that the New Hebrides arc–North Fiji basin boundary lies near 167°40′. It should be noticed that the Vot Tande trough, in the western part of the trough area (Fig. 4), is located west of this boundary, suggesting that troughs are also partly developed on the eastern edge of the New Hebrides island arc. West of 167°40′, dipolar magnetic anomalies suggest the presence of submarine volcanic complexes (Figs. 4 and 10). In this area Katz (1988) described recent intrusions observed on seismic profiles. This volcanism is likely a part of the northern continuation of the active volcanic arc known farther south on Gaua, Vanua Lava and Ureparapara Islands (Figs. 3 and 4).

The magnetic anomaly axial trend differs slightly between longitudes 168° and 168°30′E. High and low magnetic axes drawn in Fig. 11 are deduced from detailed magnetic tracks and a more detailed magnetic map with 25 nT contour intervals. They exhibit change in direction occurring along two lines striking NNE–SSW (Fig. 11). These lines are interpreted as kinks caused by large left-lateral strike-slip fault zone. This fault zone is located at the junction between the back-arc troughs and the Hazel Holme fracture zone and parallels the left-lateral strike-slip across the N–S back-arc trough area and the tectonic lineations of the Hazel Holme fracture zone western end. Consequently, we propose that this feature is related both to the back-arc trough and Hazel Holme fracture zone tectonics.

Magnetic anomalies induced by volcanism located within the trough area are limited in size. No magnetic anomaly is elongated along the strike of the troughs. Thus, the trough domain must be considered as a collapse zone resulting from tensional tectonics but not as an already individualized spreading zone as early proposed by Luyendyk et al. (1974).

Discussion about structure and age of the troughs

Bathymetric and structural data described in the previous sections argue for a close relationship between the back-arc troughs and the Hazel Holme fracture zone. Katz (1988) connects them through

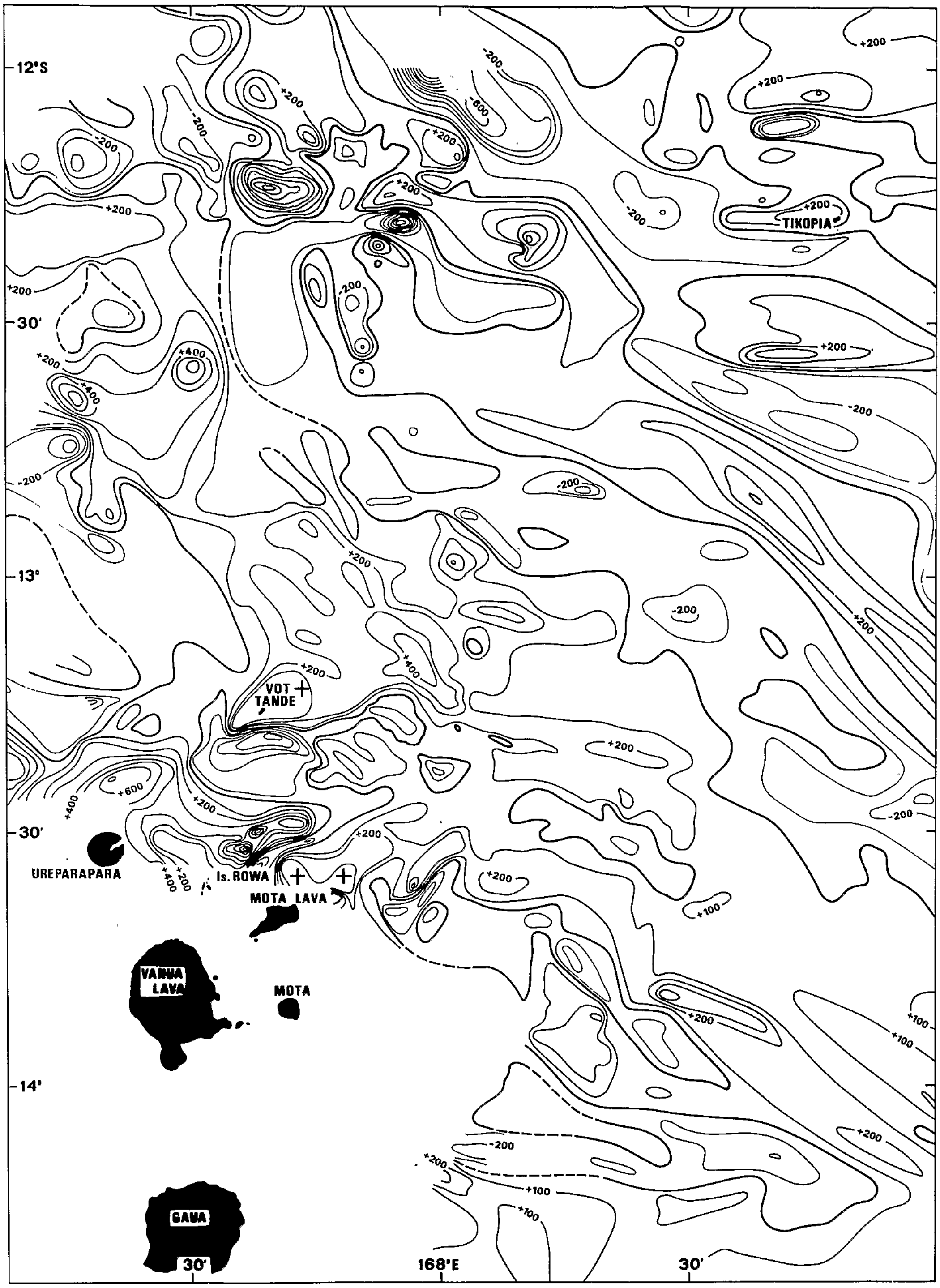

Fig. 10. Magnetic map. Contours are 100 nT intervals. Heavy lines are 0 nT contours.

a curved and continuous collapsed zone. The bathymetric map clearly indicates that the transition is sharp and that the southern limit of the back-arc troughs lies at the western end of the Hazel Holme fracture zone. Morphological and seismic data suggest that: (1) the back-arc troughs and the Hazel Holme fracture zone mainly result from extensional tectonics; (2) this tectonic phase

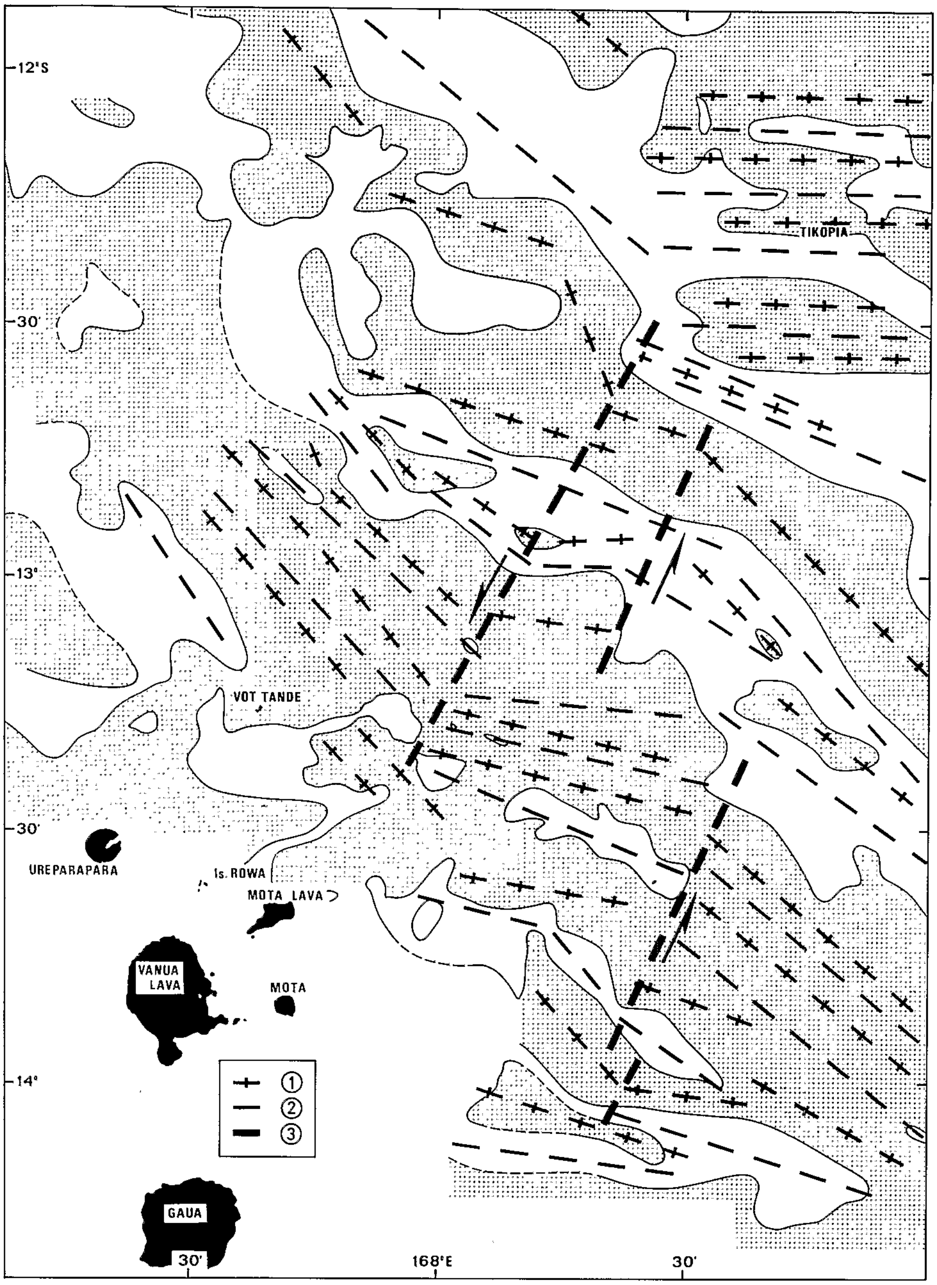

Fig. 11. Magnetic sketch. *1* = high axis; *2* = low axis; *3* = inferred left-lateral strike-slip faults. Zone of positive magnetic anomalies are dashed.

is still active in the back-arc troughs as well as in the Hazel Holme fracture zone. Because the two closely-related structures are evolving simultaneously, it is reasonable to propose that they result from a common stress field. According to the respective trends of normal faults (N–S in the back-arc troughs and N90°–N100°E in the Hazel Holme fracture zone) and to the N40°–N45°E trending structural lineations occurring at the junction area (Fig. 4), a NE–SW trending extension is inferred. In this scheme, the lineations at the junction area mark the extensional stress axis. Minor left-lateral and right-lateral strike-slip components occur respectively in the back-arc troughs and in the Hazel Holme fracture zone. Such NE–SW direction of extension is consistent with the plate tectonics in this area (Louat and Pelletier, 1989). Indeed, an extension in the NE quadrant is required within the northern back-arc troughs to explain the large discrepancy between the observed direction of convergence along the New Hebrides trench deduced from thrust-type focal mechanism solutions and the direction of motion between the Pacific and the Indo-Australian plates given by the RM-2 model of Minster and Jordan (1978) which assumes no back-arc opening (Louat and Pelletier, 1989).

An updated geographical compilation of shallow earthquakes (0–70 km) occuring in the study area for the period 1977–1987 with magnitude large enough to have a focal mechanism determination is reported on the structural map (Fig. 4). No event with focal mechanism solution is available in the back-arc troughs or in the western end of the Hazel Holme fracture zone. Ten events are located in the western and southwestern part of the study area. Their solutions can be divided in two groups. Near the latitude of 12°30′S, west of the troughs, two focal mechanisms document NE–SW trending normal faulting (Fig. 4 and Table 1). Such extensional stress orientation disagrees with the NE–SW extensional tectonics inferred in the troughs using morphology and structural data. Because these two events are not located within the troughs but west of them in the New Hebrides arc domain, their normal faulting solutions are not necessarily related to trough tectonics but more likely record local deformation within the arc. The eight other solutions are thrust and strike-slip faultings sharing a common ENE–WSW *P* axis (Table 1). The two strike-slip solutions and the two thrust solutions, located near Ureparapara island have been determined during the same swarm (December 7, 1987), suggesting that the two types of solutions are closely associated. The epicentres of these eight events are distributed along a line trending SSE–NNW and passing through the volcanic islands south of the troughs. They delineate the northern end of the New Hebrides back-arc compressive belt which extends further south up to 17°S (Louat and Pelletier, 1989). This back-arc compressive belt ends near 13°30′S and is replaced northward by the northern New Hebrides back-arc trough tectonics. This drastic change coincides with the Hazel Holme fracture zone–New Hebrides arc intersection. Thus a kind of triple junction exists near 13°30′S, 167°30′–168°00′E immediately north of Mota Lava and Ureparapara islands. The southern branch corresponds to a compressional zone, the northern branch to an extensional zone (i.e. the northern New Hebrides back-arc troughs) and the eastern branch to the extensional Hazel Holme fracture zone (Louat and Pelletier, 1989; Pelletier and Louat, 1989).

The age of the beginning of the extensional tectonics which creates the back-arc troughs and the Hazel Holme fracture zone is difficult to accurately ascertain. The N130°–N135°E trending lineations of magnetic anomalies are oblique to the back-arc troughs and the Hazel Holme fracture zone. These anomalies are typical of oceanic crust and suggest that back-arc troughs have been superimposed on an old oceanic substratum which predates the extensional tectonics of the troughs. Possibly anomalies 4 and 5 are present in the study area (Pelletier et al., 1988). Such NW–SE magnetic lineations exist farther south in the North Fiji basin where Malahoff et al. (1982) recognized anomaly 4 (8 Ma). Consequently, back-arc trough formation postdates the oldest part of the North Fiji basin oceanic crust (8 Ma). The Hazel Holme fracture zone crosscuts E–W trending magnetic lineations which are younger than the NW–SE ones and possibly include anomalies 2 and 2A (Pelletier et al., 1988). Assuming that the Hazel Holme fracture zone and the northern back-arc troughs are contemporaneous, the beginning of the extensional tectonics should be younger than 2–3 Ma.

Three lines of evidence deduced from morphology and seismic profiles suggest that the beginning of extension (the major tectonic phase in the northern back-arc troughs) is recent:

(1) In the case of an old back-arc trough tectonics it is impossible to explain the thick sedimentary sequence observed east of the troughs on the North Fiji basin. Indeed, in this case the troughs should have trapped sediments derived from the New Hebrides arc and restricted deposits eastward.

(2) It was shown that the beginning of trough

TABLE 1

Focal mechanism parameters for earthquakes presented in Figs. 4 and 12 *

Date	Lat. (° S)	Long. (° E)	Depth (km)	NP1		NP2		P axis		T axis		Ref.	Location
				az. (°)	pl. (°)	az. (°)	pl. (°)	az. (°)	pl. (°)	az. (°)	pl. (°)		
5/19/86	12.63	167.23	52	205	32	36	58	323	77	122	13	1	NBAT
5/19/86	12.62	167.30	33	217	31	37	59	307	76	127	14	1	NBAT
7/20/79	13.23	167.34	39	194	20	355	71	90	26	255	63	7	CBA
12/7/87	13.45	167.36	33	270	80	179	83	225	2	134	12	1	CBA
12/8/87	13.43	167.38	33	142	34	8	64	81	16	316	64	1	CBA
12/7/87	13.63	167.39	48	196	69	287	88	60	13	153	16	1	CBA
12/7/87	13.56	167.45	33	156	44	300	52	47	4	149	71	1	CBA
11/12/86	14.34	167.67	33	1	21	166	69	260	24	67	66	1	CBA
7/8/87	14.05	167.77	58	208	22	343	74	85	27	232	58	1	CBA
7/6/87	14.07	167.83	48	159	42	347	48	73	3	306	87	1	CBA
6/19/82	14.67	167.84	35	149	31	359	62	78	16	300	70	2	CBA
1/3/87	14.99	167.92	15	158	32	357	60	80	14	292	72	1	CBA
5/12/80	14.52	167.93	38	195	42	340	53	86	6	193	72	8	CBA
10/5/82	15.61	168.01	40	203	37	349	58	93	11	215	70	2	CBA
11/16/82	14.59	168.03	31	150	24	337	66	65	21	253	69	2	CBA
2/18/80	14.90	168.03	24	171	29	7	62	91	17	295	72	8	CBA
11/29/78	15.50	168.07	47	165	39	2	52	84	7	317	80	6	CBA
4/5/82	15.02	168.08	32	162	34	2	58	84	12	303	74	2	CBA
4/3/82	15.03	168.09	24	173	19	330	72	66	27	229	63	2	CBA
11/26/87	16.35	168.12	18	149	71	58	88	105	12	12	15	1	CBA
11/27/87	16.37	168.12	29	151	69	60	87	107	12	14	17	1	CBA
11/27/87	16.26	168.13	33	194	32	341	62	83	16	218	69	1	CBA
11/27/87	16.31	168.14	29	165	48	33	54	100	3	4	63	1	CBA
12/28/81	15.01	168.15	37	159	28	357	64	81	18	285	69	3	CBA
11/27/87	16.22	168.17	30	339	45	211	58	278	7	174	61	1	CBA
12/8/79	15.80	168.31	32	183	43	17	48	100	3	351	82	7	CBA
4/26/83	15.91	168.41	22	154	41	25	61	93	11	343	61	4	CBA
8/19/82	19.03	169.58	28	297	16	187	84	113	49	264	37	2	C
4/9/77	19.09	169.58	28	289	48	178	68	134	48	238	12	5	C
10/9/80	19.28	169.75	31	316	42	119	50	332	79	217	4	8	C
6/14/86	19.10	169.78	16	130	45	306	45	128	90	38	0	1	C
10/2/85	19.50	169.84	38	123	43	307	47	260	88	35	2	1	C
12/25/85	14.07	170.01	33	282	67	15	83	241	21	146	11	1	HHFZ
11/21/84	14.51	171.09	24	19	82	109	90	244	6	334	6	1	HHFZ
11/21/84	14.50	171.16	23	297	75	27	88	253	12	161	9	1	HHFZ
1/14/85	14.42	171.19	33	46	69	138	84	270	10	4	19	1	HHFZ
5/23/83	13.80	171.25	34	284	62	29	63	247	41	156	1	4	HHFZ
11/23/84	14.31	171.28	33	300	66	33	83	259	22	164	12	1	HHFZ
11/23/84	14.17	171.33	33	275	65	179	76	229	7	135	28	1	HHFZ
8/31/84	17.96	172.15	29	279	38	132	57	88	70	208	10	1	WASC
12/19/84	17.04	172.47	34	298	34	107	56	356	79	201	11	1	WASC

* NP = nodal plane; NBAT = Northern back-arc troughs; CBA = compression in the back-arc (in front of the d'Entrecasteaux ridge subduction); C = Coriolis troughs; HHFZ = Hazel Holme fracture zone; WASC = west of the active spreading centre.

References: 1 = Preliminary Determination of Epicentres, Monthly listing, US. Dep. of the Interior, Geological Survey, National Earthquake Information Service; 2 = Dziewonski et al., 1983b; 3 = Dziewonski and Woodhouse, 1983; 4 = Dziewonski et al., 1983a; 5 = Dziewonski et al., 1987a; 6 = Dziewonski et al., 1987b; 7 = Dziewonski et al., 1987c; 8 = Dziewonski et al., 1988.

tectonics migrated eastward; it is synchronous with the uppermost layers of the lower sequence in the Vot Tande trough (the westernmost graben of the trough system), and is dated by the unconformity of the upper sequence farther east. Just west of the troughs, in the Torres Santa-Cruz basin, the thickness of the Upper Miocene, Pliocene and Quaternary series reaches 1.2 s TWT (Katz, 1988). By comparison, the thickness of the upper sequence (i.e. 0.2–0.3 s TWT) implies a very recent age for the tectonics.

(3) The lower sedimentary sequence observed in grabens as well as on horsts looks like the Miocene to present sedimentary series known farther east in the Torres Santa-Cruz basin; this indicates that tectonics postdates deposition of this sequence.

The still active extension is demonstrated by: (1) the faults which are always well-expressed by bathymetric contours; (2) the slightly fan-shaped upper sedimentary sequence; (3) dipping of the uppermost layers on the eastern flank of the Eastern Ridge bounding back-arc trough area; (4) tilting of sedimentary layers in the Hazel Holme fracture zone.

On the basis of petrological, geochemical and radiometrical (K/Ar) studies, Monjaret (1989) proposed that back-arc trough formation is polyphased. Back-arc trough tectonics should begin first in the Coriolis troughs at 4.1–3 Ma. In the northern troughs extension began at 2.8–2.3 Ma and is almost synchronous with the second phase observed in the Coriolis troughs (2.7 to 2.2 Ma). We infer from this study that the northern back-arc trough tectonics is slightly more recent than the age proposed by Monjaret (1989). Monjaret (1989) and Monjaret et al. (in prep.) also reported an age of 12.4 Ma for oceanic basalts dredged on the fault scarp located east of the northern main volcanic complex (Fig. 4). Because back-arc troughs are partly developed along the eastern edge of the New Hebrides arc and partly superimposed on the North Fiji basin oceanic crust most of the radiometric ages, obtained in this area, are more likely related to the North Fiji basin oceanic basement and the New Hebrides island arc volcanism. This hypothesis is strongly supported by three lines of evidence: (1) the oldest age obtain on oceanic-type lavas is similar to the ones of the magnetic anomalies 5 and 5A (12 Ma) which are supposed to be present in the study area; (2) the volcanism of the troughs present no important geochemical difference with the New Hebrides arc volcanism; (3) the northern continuation of the New Hebrides volcanic line, known on Gaua and Vanua Lava, probably exists at the latitude of the northern troughs but is collapsed. We think that K–Ar ages reported by Monjaret et al. (1987 and in prep.) and Monjaret (1989) do not necessarily record the age of back-arc troughs.

Discussion about the origin of the troughs

Because the northern and southern back-arc troughs are in the same structural position with regard to the New Hebrides island arc, these two extensional zones are often related to the same tectonic process. However two important differences exist between the northern and the southern troughs: (1) the southern troughs (i.e. Coriolis troughs) include only two grabens or half-grabens parallel to the arc, whereas the morphology and structure of the northern troughs are more complex and oblique to the arc; (2) the N–S active spreading axis is present in the southern part of the North Fiji basin, whereas an E–W spreading axis is inferred from magnetic data east of the northern back-arc troughs (Pelletier et al., 1988; Auzende et al., 1988b). Based on the symmetry of the location of troughs with respect to the d'Entrecasteaux ridge, and on the lack of extension in front of it, Collot et al. (1985) proposed that subduction/collision of this ridge can be invoked to account for lateral back-arc trough formation. In front of the d'Entrecasteaux ridge, numerous focal mechanisms document a nearly E–W striking compressional stress in the back-arc area (Fig. 12). This suggests that the subduction of the d'Entrecasteaux ridge causes compression in the back-arc area and consequently prevents troughs formation in the central back-arc zone. Subduction of such a high-positive bathymetric feature of the plunging plate certainly controls the geographical distribution of the back-arc troughs by modifying the local stress field in the overriding plate, but it

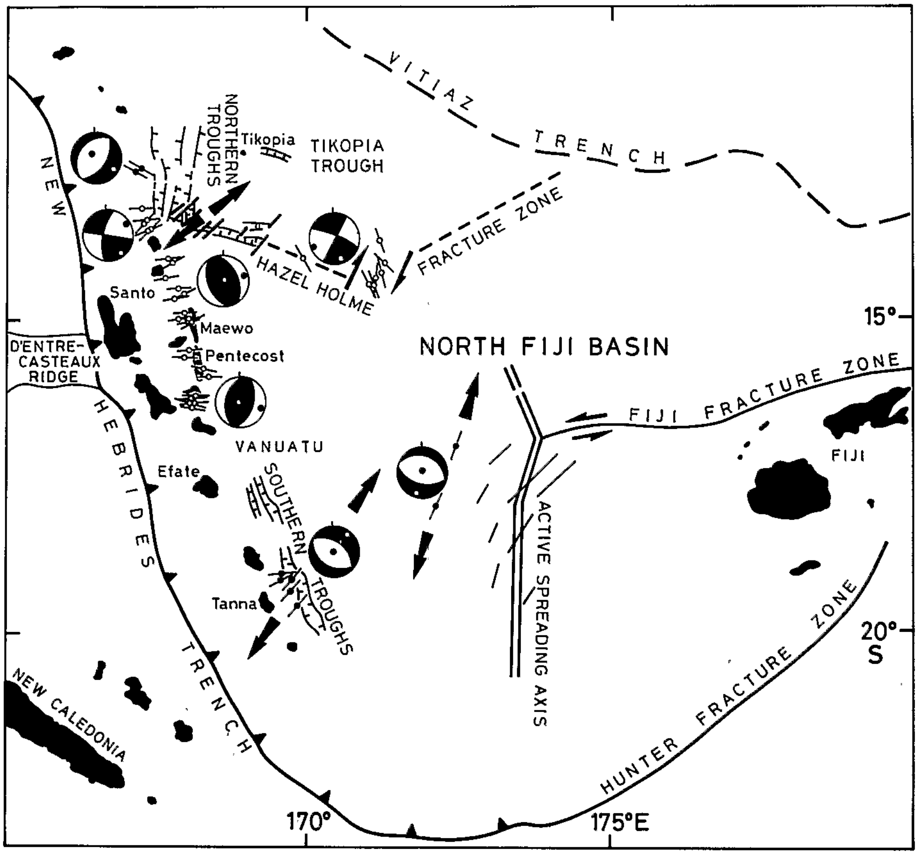

Fig. 12. Schematic chart showing major tectonic features of the North Fiji basin and related stresses. Arrows indicate direction of extension or transform motion. Epicenters from shallow earthquakes (0–70 km) for the New Hebrides back-arc domain and part of the North Fiji basin (north of 20°S and east of 172°30′E) are represented by circles. *T* or *P* axes are shown by a line: open circles = events with thrust and strike-slip type solutions (back-arc compressive belt); filled circles = events with normal or strike-slip type solutions (back-arc troughs and North Fiji basin). One sphere represents several similar solutions.

is not definitely proved that collision of the d'Entrecasteaux ridge is the mechanism responsible of the back-arc trough formation.

In contrast we believe that back-arc troughs are genetically associated with the recent tectonic development of the North Fiji basin. The northern troughs are closely related to the Hazel Holme fracture zone which is a young and seismically active tectonic feature of the North Fiji basin (Pelletier et al., 1988; Hamburger and Isacks, in press; Louat and Pelletier, 1989), and several structural and seismological data listed below are consistent with the inferred NE–SW trending extensional tectonics of the northern troughs (Fig. 12).

(1) A N30°E trending extension occurs in the Coriolis troughs (Récy et al., 1986). This direction of extension has been deduced from structural analysis based on Seabeam mapping, and is consistent with five focal mechanisms which document normal faulting associated with a NE–SW *T* axis (Fig. 12 and Table 1).

(2) N25°E and N45°E trending tectonic lineations have been detected using Seabeam data along the N–S North Fiji basin spreading centre (Auzende et al., 1986, 1988a; Lafoy et al., 1987).

(3) Two focal mechanisms of shallow earthquakes located west of this spreading axis are related to normal faulting associated with a NNE–SSW extensional strike (Fig. 12 and Table 1).

(4) The Tikopia trough, a 65 km long, 10 km wide and 1500 m deep graben trending WNW–ESE, was recently discovered north of the

Hazel Holme fracture zone and southeast of Tikopia island (Pelletier et al., 1988).

(5) Such stress orientation can also be inferred along the Hazel Holme fracture zone from morphological and seismological data (Fig. 12).

Different interpretations have been proposed concerning the nature of the Hazel Holme fracture zone. Based on a vector analysis of plate motion, Chase (1971) postulated an E–W right-lateral transform motion with oblique compression on the western end of the Hazel Holme fracture zone. Luyendyk et al. (1974) also suggested E–W right-lateral motion but reported that there is no evidence for a compressional component at the transform fault. Using a few focal mechanisms Eguchi (1984) proposed an E–W striking compression while Hamburger and Isacks (in press) suggested a NNW–SSE extension. Pelletier et al. (1988), using data from a recent cruise, described this feature as a 100 km wide zone composed of a succession of N90°–N100°E tight ridges and grabens and the Hazel Holme fracture zone as the result of extension. Based on morphology, focal mechanisms and vector analysis of plate motion, Pelletier and Louat (1989) and Louat and Pelletier (1989) proposed that the Hazel Holme fracture zone results from a N25°E extension. Shallow seismicity is scattered along the Hazel Holme fracture zone. Although the morphology indicates extension, no event with normal faulting solution was recorded but all the mechanism solutions show strike-slip faulting (eight events) with SSE–NNW T axis and nodal planes perpendicular (NNE–SSW) and parallel to the structure. Most of these events (7) concentrate between 171°–171°20′E and 13°50′–14°30′S where Pelletier et al. (1988) postulated transverse faults. Epicentres of four events occurring during the November 21–23 swarm cluster along the NNE–SSW trend. Consequently we propose that these mechanisms document a right-lateral transform motion in a NNE–SSW opening context.

The afore-mentioned data lead to the conclusion that the North Fiji basin is affected by a NNE–SSW to NE–SW extensional stress which induces numerous tears through the oceanic crust. This extension is evidenced by the northern and southern back-arc troughs, the Hazel Holme fracture zone, the Tikopia trough and a set of earthquakes associated with normal and strike-slip fault motion. This widespread extensional deformation occurs simultaneously with the opening along the active spreading axis of the North Fiji basin (Fig. 12). In this sense, the spreading is not sufficient to completely account for the deformation occurring within the North Fiji basin and caused by the relative motion between the two large Indo-Australian and Pacific plates. Additional widespread deformation is locally required (as for example the proposed NE–SW stretching) and is probably the consequence of reorganization in the spreading process. Auzende et al. (1988a, b) showed that the geodynamics of the North Fiji basin is complex and the system extremely unstable. These authors proposed two reorganizations in the accretion process of the North Fiji basin. The first one, also documented by Maillet et al. (1986, 1989), is dated by the anomaly 2′ (3 Ma) and corresponds to a change in the spreading direction from NE–SW to E–W. The second reorganization occurred at 0.6–0.7 Ma and was due to the beginning of activity of the left-lateral Fiji fracture zone, resulting in a ridge–ridge–transform triple junction centred a 173°30′E and 16°40′S (Lafoy et al., 1987). Because the Hazel Holme fracture zone is superimposed on the young E–W magnetic anomalies (Pelletier et al., 1988) and closely associated with the northern back-arc troughs, possibly the NE–SW extensional tectonic processes affecting the whole North Fiji basin and responsible for the creation of back-arc troughs are as young as the Fiji fracture zone and the RRT triple junction (0.6–0.7 Ma). Such an age is compatible with the herein presented morphological and structural data arguing that the northern back-arc troughs are recently created. It is also supported by new results concerning the plate tectonics of the Southwest Pacific. Pelletier and Louat (1989) postulated an extensional rate of 5.5 cm/year in the northern back-arc troughs, which implies that troughs are extremely recent since no lineation of magnetic anomaly is genetically associated with the troughs.

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