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Multi-scale morphologic variability of the North Fiji Basin ridge (Southwest Pacific)

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ABSTRACT

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Two cruises of the French–Japanese STARMER joint project carried out with the submersibles *Nautile* (1989) and *Shinkai* 6500 (1991), have been devoted to the in situ exploration of the North Fiji Basin ridge. Four areas, located near 16°20′, 17°, 18°50′ and 19°S have been explored during 42 dives. At 16°20′S, the axial zone trending N160° corresponds to a prominent graben with walls 1000 m high. Tectonic features and recent screes are present, and the hydrothermal activity is characterized by sporadic fluid discharge. At 17°S, present accretion is confined to a high dome less than 1900 m deep and cut in its axial part by a wide graben trending N15°. At this site, hydrothermal features of two types are observed: fossil chimneys of sulfides, and active vents, made of anhydrite and expelling water at 285°C. The site at 18°50′S is located on top of an axial dome, very similar to those of the East Pacific Rise. Small fissures and very fresh volcanic flows argue for a present-day activity, with weak evidence of tectonics. Hydrothermal emanations with animal colonies are found scattered over the whole area. The fourth site, at 19°S, shows old and viscous lavas and a very mature tectonic activity, compared to the preceding station which is located only 20 km northward. Large-scale variations have been detected between three segments. Different thermal regimes can explain the distinct morphologies observed. Decakilometric scale variations do occur between stations 14, with volcanic predominance, and "19°S", where tectonic activity is dominating. Finally, small-scale variations are observed on sites 4 and 14, where volcanic features gradually give way to tectonic structures. The North Fiji Basin ridge—with an intermediate average spreading rate—shows tectonic, volcanic and hydrothermal variability, ranging from 1 km to tens of kilometres and related to a temporary fine scale organisation of the accretionary processes.

Introduction

The North Fiji Basin is a complex marginal basin created 10 Ma ago at the boundary of the Pacific and Indo-Australian crustal plates, between two subduction zones of opposite polarity: the New Hebrides trench, to the west, and the Tonga–Kermadec trench, to the east (Fig. 1). The North Fiji Basin (NFB) ridge has been surveyed between 1987 and 1991 in the frame of the Japanese–French STARMER project, collecting geological, geophysical, geochemical and biological data along 900 km of the active spreading system. These data have been invaluable guides for the selection of diving sites.

Two cruises (STARMER 89 and *Yokosuka* 91) were devoted to the in situ exploration of the spreading axis with the submersibles *Nautile* and *Shinkai* 6500 (Auzende et al., 1991b, 1992). Four areas (Fig. 2), respectively, located on three major segments of the spreading axis at 16°20′S, 17°S, 18°50′S and 19°S have been explored during 42 dives.

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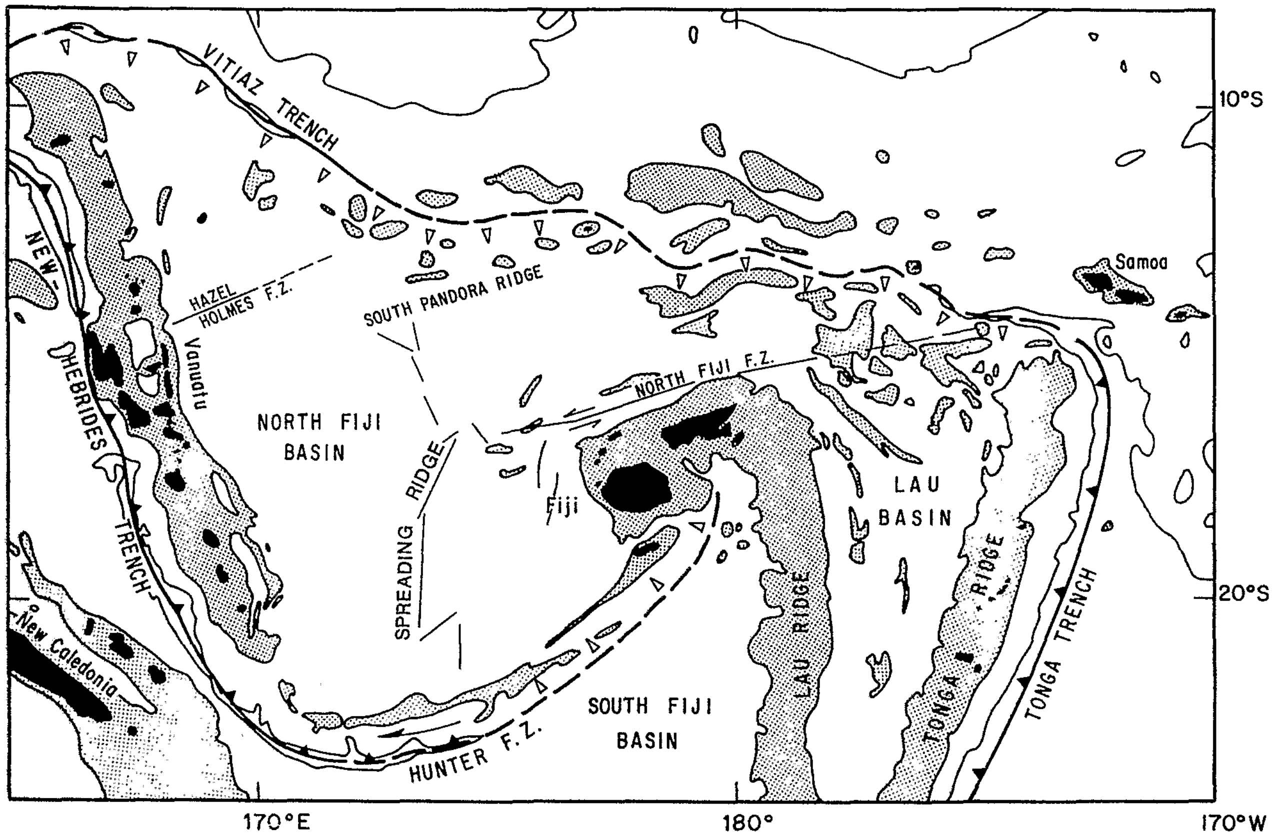

Fig. 1. Geodynamic position of the North Fiji Basin and the central spreading center. (Modified from Kroenke et al., 1991.)

In this paper, we first briefly describe general characteristics of the different major segments of the NFB spreading ridge where in situ exploration was carried out. Secondly, we describe in detail the morphology and volcanic, tectonic and hydrothermal processes at each area visited by submersible. Then, we compare the morphology of the NFB spreading axis from one site to the other and discuss the morphologic variations observed in respect to the general characteristics of the ridge and in relation to spreading processes.

The North Fiji Basin spreading centre

The spreading axis is located in the central part of the North Fiji Basin (NFB), between 173°E and 174°E, and 14°50′S and 21°40′S (Figs. 1 and 2). It encompasses four major segments characterized by different orientations. The main difference of the NFB spreading axis with mid-ocean ridges is that boundaries between major segments are not fracture zones. These boundaries are structures such as overlapping spreading centres (Auzende et al., 1988a; Lafoy, 1989), propagating rifts (Ruellan et al., 1990; De Alteriis et al., 1993) and non transform offsets, as previously described at other mid-oceanic ridges (Hey, 1977; Hey et al., 1980; Macdonald and Fox, 1983). The complicated general geometry of the NFB spreading axis (Fig. 2) is possibly due to the opening of the basin in a complex back-arc setting, between two active major plate boundaries of opposite polarity.

From north to south, the present day accretion system consists of the following four segments (Fig. 2),

– a N160° ridge, located north of 16°50′S and more than 250 km long, is formed by several en echelon 8–10 km wide grabens limited by more than 1000 m high subvertical walls (Fig. 3a). The floor of these grabens lies at a depth between 4000 and 4500 m. A neovolcanic ridge (Fig. 3a), 2–3 km wide and 400–500 m high, is observed in the central part of these axial grabens. It marks the present-day accretionary axis (Gràcia, 1991, 1992) and represents the last emission of magma. These morphological features are similar to those present

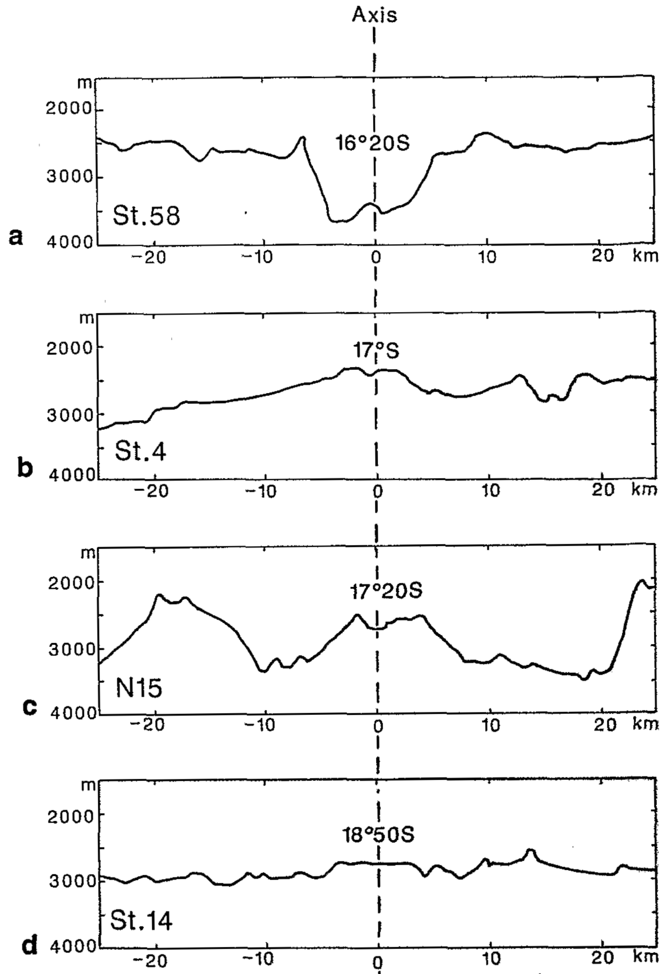

Fig. 3. Bathymetric cross sections of each dive station. (a) Station 58 on the N160° axis. (b) Station 4 at 17°S on the N15° axis. (c) 17°20'S on the N15° axis. (d) Station 14 at 18°50'S on the N-S axis. Note the morphologic variability between them. Vertical exageration = 5.

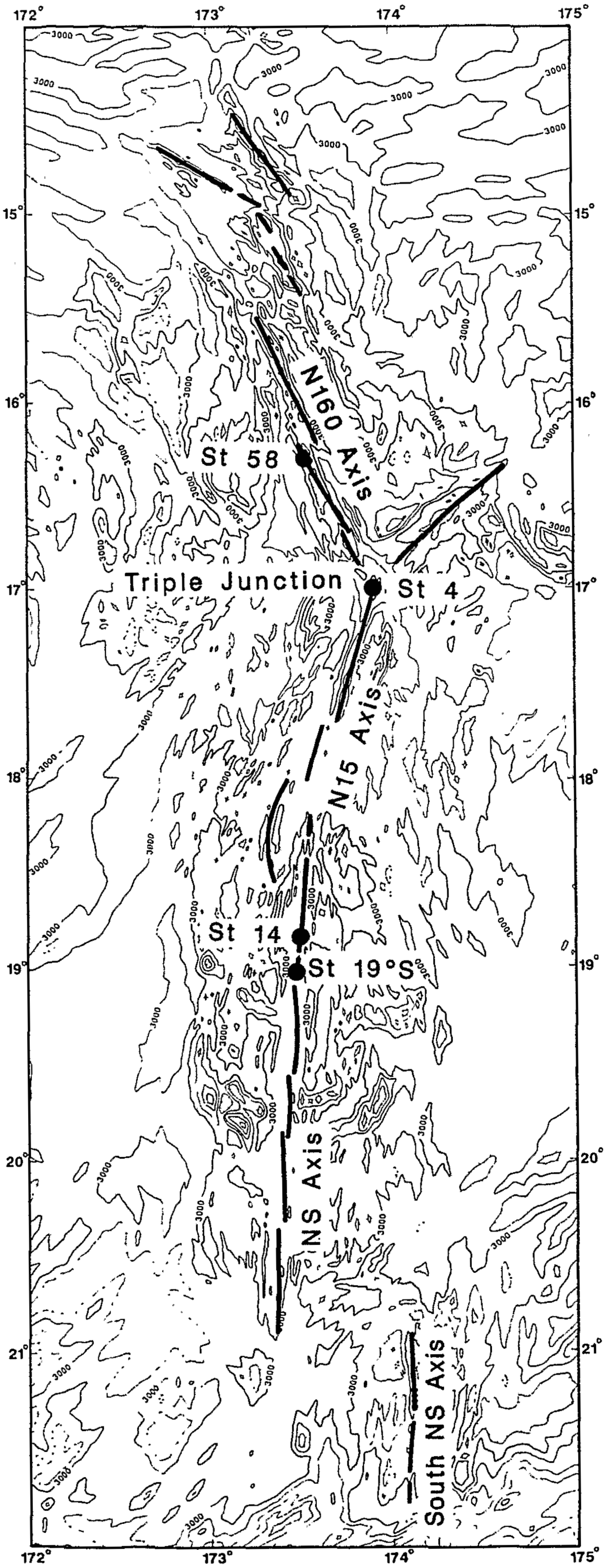

Fig. 2. Bathymetric map of the North Fiji Basin spreading ridge. The four segments and the North Fiji Fracture Zone are distinguished. Triple junction is located at 16°50'S. Dive stations are marked by black points.

at slow spreading centres, such as the Mid-Atlantic Ridge (Gente, 1987; Sempéré et al., 1990; Purdy et al., 1990). The spreading rate is not well constrained by magnetic data. Auzende et al. (1991a) infer a rate of about 5 cm/yr, whereas Huchon et al. (1994-this issue) suggest that the spreading rate is lower, 3 to 4 cm/yr.

– a N15° ridge, extending some 140 km from 16°50'S to 18°10'S. This ridge lies at a depth of 2600 m to the south and culminates at 1900 m at its northern tip. It is characterized by N15° lineations concentrated in a 50 km wide belt created on an older N–S pattern (Auzende et al., 1988a). The general axial morphology is characterized by a 10 km wide dome towering 500 m high over the adjacent ocean floor. and split by a 2 km wide central graben (Fig. 3c). At the northern end of the N15° ridge, the width of the dome increases and reaches 20 km (Fig. 3b). Magnetic anomalies suggest an age of 1 Ma for the N15° segment. The calculated spreading rate is 5.4 cm/yr at 17°30′S (Huchon et al., 1994-this issue).

– a N–S ridge, which extends from 18°10′S to 21°S with an approximate length of 280 km. From south to north the axis is gradually displaced through dextral offsets of a few hundreds of metres (Gente, 1987). An important OSC was recognized at 19°50′S (Gente, 1987; Auzende et al., 1988a). Towards the north at 18°10′S, the ridge exhibits a remarkable V-shape structure which is interpreted as the mark of the N–S propagation of the axis within the N15° segment (Ruellan et al., 1990; De Alteriis et al., 1993). Axial morphology is similar to the one observed on the East Pacific Rise (Macdonald, 1982) with a 5 to 8 km wide central dome, rising 200–300 m over the surrounding seafloor (Fig. 3d). An axial graben, ten to hundred metres wide and some tens of metres deep, can be observed locally. Magnetic anomalies up to 2A (3.5 Ma) have been identified, and the average calculated spreading rate is 7.6 cm/yr at 20°S. It tends to decrease northwards down to 7 cm/yr at 19°S (Huchon et al., 1994-this issue).

– a southernmost N–S ridge, located south of 21°S, with a length of 150–200 km, is offset over some 80 km to the east of the N–S segment by a N45 feature (Maillet et al., 1986). This last segment has a very irregular axial morphology and the precise location of the active axis is still not well known.

At 16°50′S, the N15° and N160° segments intersect with the western tip of the North Fiji Fracture Zone (NFFZ; Fig. 1) which consists of a triangular deep graben (Fig. 2). The intersection domain which corresponds to the 16°50′S R.R.F. triple junction as defined by Lafoy et al. (1990), is also characterized by important volcanic constructions culminating at less than 1600 m and located on the edges of the triangular graben (Lagabrielle et al., 1994-this issue).

The present-day spreading ridge of the NFB, characterized by the N–S, N15° and N160° spreading segments and by the NFFZ possibly results from the reorganization of an older N–S spreading axis. This reorganization was induced by the propagation of the NFFZ, in response to oceanic opening in the northern Lau Basin, at 1 Ma (Auzende et al., 1988b).

The general trend of the major segments along the NFB spreading axis varies from N–S over N15° to N160° (Fig. 3). These variations will be discussed later. The dive results from the local exploration of each major segment are first discussed in terms of structural, volcanic and hydrothermal processes.

Dive results

The STARMER cruise was carried out in June 1989 with the French submersible *Nautile* and its mothership *Nadir* in the frame of the STARMER project. The *Yokosuka* 91 cruise in October 1991, with the new Japanese submersible *Shinkai* 6500 and its mothership *Yokosuka*, was partly devoted to revisiting hydrothermal sites previously explored by the *Nautile* (Auzende et al., 1991b) and discovered during deep-towed camera exploration (Auzende et al, 1988a; Jollivet et al., 1989). The *Yokosuka* 91 cruise was the first scientific cruise of the *Shinkai* 6500. In total 42 dives were carried out along the North Fiji Basin spreading ridge, focused on four main stations, from north to south (Fig. 2): station 58 on the N160° axis, station 4 at the northern tip of the N15° axis and stations 14 and "19°S", located both on the N–S axis, but on different elementary segments.

Station 58

The site is located between 16°18′S and 16°20′S, and 173°32′E and 173°34′E (Figs. 2 and 4) on the southernmost deep graben of the N160° branch of the NFB axis (Fig. 4). The area is characterized by a deep (3800 m), circular (9 km wide and 10.5 km long) and symmetrical graben bordered by two vertical walls (more than 1000 m high each)

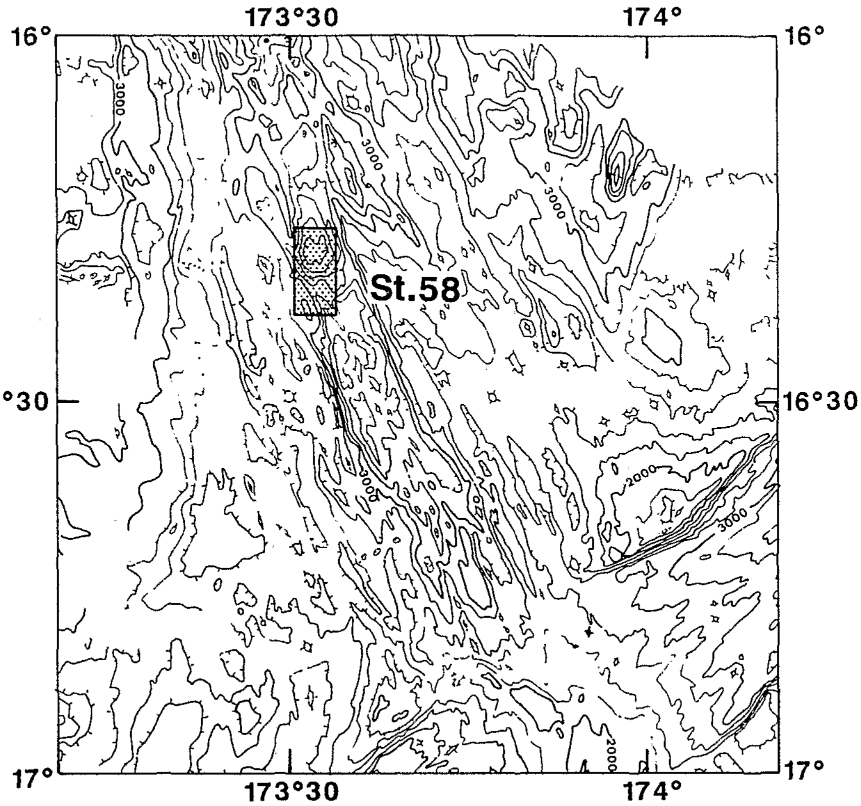

Fig. 4. Bathymetric map of the southern part of the N160° segment and location of station 58. Contour interval = 200 m.

as is shown on the bathymetric section across the axial graben (Fig. 3). This graben opened within an important triangular volcanic massive culminating at less than 1900 m depth. A N170° trending median ridge which culminates at less than 2800 m in its southern part is observed in the graben (Fig. 3a). Its direction is slightly oblique to the axis of the graben. The ridge which is 6.5 km long and 500 m wide deepens northward (3760 m). Three dives (88, 89 and 90) were conducted on the area of station 58 (Fig. 5). This site, where significant methane and manganese anomalies have been previously measured during the *Seapso* 3 cruise in 1985 (Auzende et al., 1988a), was surveyed again during the *Yokosuka* 90 cruise (Auzende et al., 1991a).

Structure

The objectives of the dives were to explore the median ridge, along three differently oriented tracks. Dive 88 explored the lowest part of the ridge along a N–S track. Dive 89 was devoted to the survey of the southern part of the main graben, from 200 m east to the median ridge to the eastern wall, along a W–E track. A N–S zig-zag survey of the crest of the ridge up to its summit was performed during dive 90 (Fig. 5).

The graben floor is buried under an important sedimentary blanket (a few metres in the external zones to a few centimetres in the axial part of the neovolcanic ridge). Sedimented zones are flat or show gentle slopes and exhibit concentric bioturbation traces and small sand mounds. Living organisms such as echurians, penatulids, crinoids, holoturians, sponges, shrimps, snake fishes, are very commonly observed along the entire dive. Funnel alignments in sediment, showing a N130°–140° main trend and decimetre size fissures lacking any sedimentary cover where volcanic seafloor is exposed, represent very recent tectonic features. One depression, 2 m × 5 m wide, exposes purely white material. It possibly represents sediments bleached by hydrothermal alteration. In addition, layers of indurated sediments are exposed in some areas. This suggests, if we assume an average sedimentation rate of 20 mm/kyr (Chase, 1971), that no volcanic activity occurred at least during the last 10,000 years.

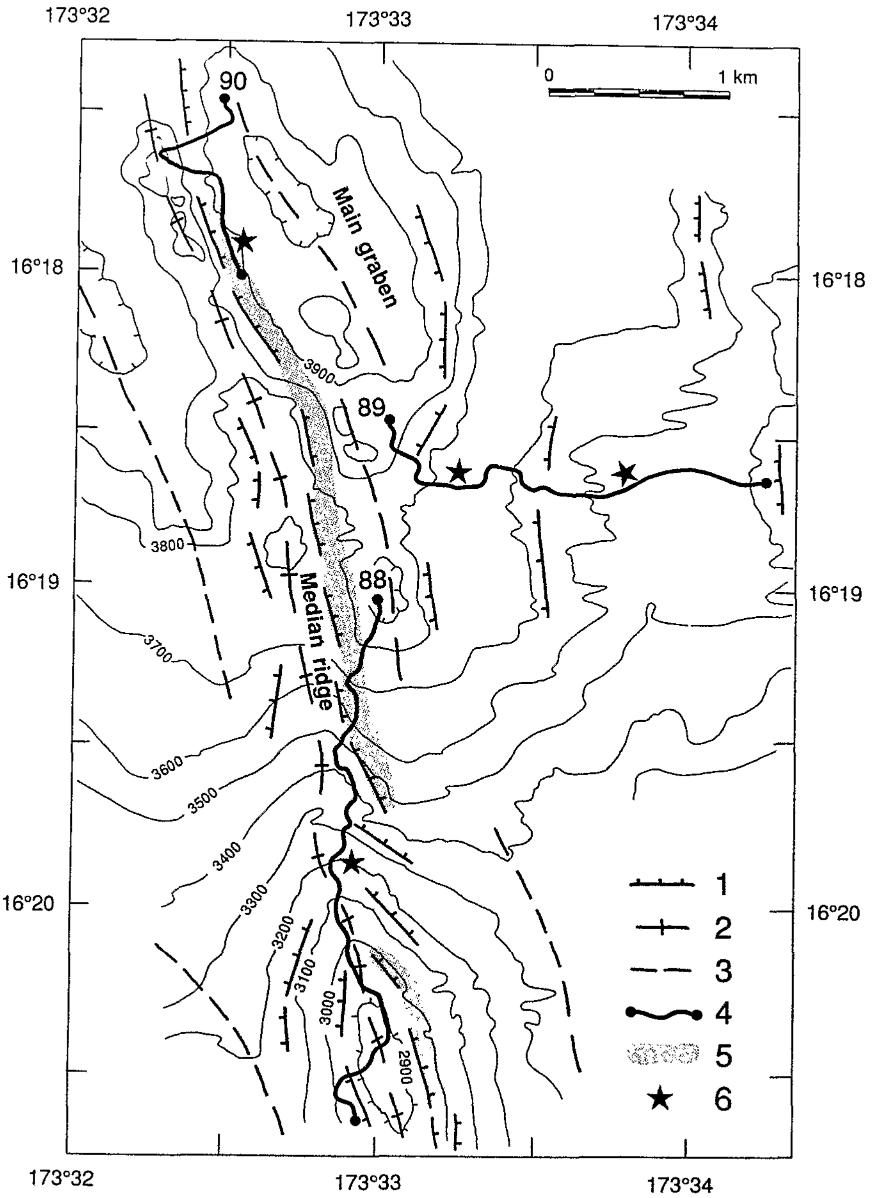

Fig. 5. Detailed bathymetric and morphostructural sketch of station 58. Contour interval = 100 m. *1* = Scarps, *2* = highs, *3* = lows, *4* = dive track, *5* = active area, *6* = hydrothermal deposits.

The scarps bordering the median ridge (Fig. 10) are formed by a succession of several steps, 15–20 m high, forming a 100 m high main scarp. They show a spur-like morphology with important mass wasting and gravitationally displaced blocks. At the foot of the scarps, debris slopes are made of chaotic basaltic blocs, gravels and sands, often graded downslope and covered by a dust of pelagic ooze. The fault scarp strikes are mainly N160°–N170° and the slope gradients are 30°–40°. Several transverse N30°–N40° oriented fractures and fissures cut through this features. These fractures are often the paths for basaltic debris avalanches.

Volcanism and hydrothermalism

The scarps expose sections of fresh pillow lava and lava tubes. During dive 90, at 3819 m depth, an important basaltic wall has been observed, probably a vertical section of columnar jointed sheet-flows similar to those observed along the eastern branch of the triple junction during STARMER dive 7 (Lagabrielle et al., 1994-this issue). On the flat areas covered by sediments, scattered small black fragments occur which appear to be pieces of fresh volcanic glass. At the edge of the ridge, white sedimentary patches associated with fissures cutting through the talus are observed. They are possible indications of fossil hydrothermal activity in this area. In many places, as reported on Fig. 5, dark-brown stained blocks, probably oxides or sulfides, are associated with temperature anomalies. Along the eastern scarp, the most important temperature anomalies range from 0.05° to 0.03°C. These anomalies are associated with fissures showing that this area is tectonically and hydrothermally active (Fig. 5). This hydrothermal activity is not continuous but is characterized by rather sporadic discharges. This is also suggested by Nojiri et al. (1990), from the detection of hydrothermal plumes in the water column through time.

In summary, the present-day accretion at station 58 is concentrated along the neovolcanic median ridge emplaced at the axis of the graben. The activity is mainly tectonic in nature with development of east-facing faults on the surveyed flank of the ridge. Finally, dive observations allow to conclude that, at least in the southernmost graben of the N160° segment, accretion processes are dominated by tectonic activity.

Station 4

This station is located on the northern tip of the N15° axis, between 173°53′E and 173°57′E, and 16°57.5′S and 17°02′S, very close to the RRF 16°50′S triple junction (Figs. 1 and 2). At this latitude, the N15° ridge of the NFB spreading axis is constituted by a 20 km wide volcanic dome culminating at 1900 m depth and split by a 2 km wide, 100–150 m deep, N15° trending axial graben (Fig. 3b). Twenty two dives were carried out in this area where an active white-coloured smoker was observed during deep-towed camera exploration in 1988 (Jollivet et al., 1989). Thus, the main objectives of the dives were to explore the most hydrothermally active part of the axial graben and to sample hydrothermal rocks, fluids and communities.

Structure

Three structural domains can be identified along the axial graben at station 4 (Fig. 6):

– The northern domain, north of 16°58.5′S: the floor of the 2 km wide axial graben is affected by small-scale fissures and faults. The general trend of the fissures is N15°–N20° but other directions such as N160°–N170° and N60° are also present. They are interpreted as reflecting the directions of the N160° segment and the western tip of the North Fiji Fracture Zone respectively, both branches of the 16°50S triple junction (Figs. 1 and 2).

– The central domain, between 16°58.5′S and 17°S: this domain has been explored during most of the dives conducted at station 4. The walls bounding the axial graben consist of successive steps. The eastern wall, looking inwards, shows a vertical offset of 80 metres. The foot of the wall is covered by a chaotic talus. The floor of the graben consists of a succession of small horsts and grabens, 10–50 m deep and less than 200 m wide each. The central horst, where the more intense hydrothermal activity has been identified, trends obliquely (N05°–N10°) with respect to the main N15° structures. Active tectonism on this domain is represented by fresh fissures (Fig. 7a), faults and decimetric to metric aligned funnels. The most tectonically active zone is located in the central part of the graben, in a 500 m wide area where hydrothermal activity also occurs.

– The southern domain, between 17°00.5′S and 17°02′S. The axial graben is wider (2.5 km) than in the former domains. In its middle part, the graben is rifted by a 500 m wide and 100 m deep depression in turn split by two restricted grabens 5–10 m deep and 100 m wide, each separated by a central horst. Scarps and fissures trend N15°–N20°, and fresh talus bounding the ridge walls are present all over the area.

Volcanism

Although the axial zone in station 4 is almost completely covered by sediments (5–10 cm) (Fig. 7a and b) and thus appears to be volcanically quiet, the lavas are fresh except those which have locally undergone hydrothermal alteration (Eissen et al., 1991). Basalts in this area exhibit the typical

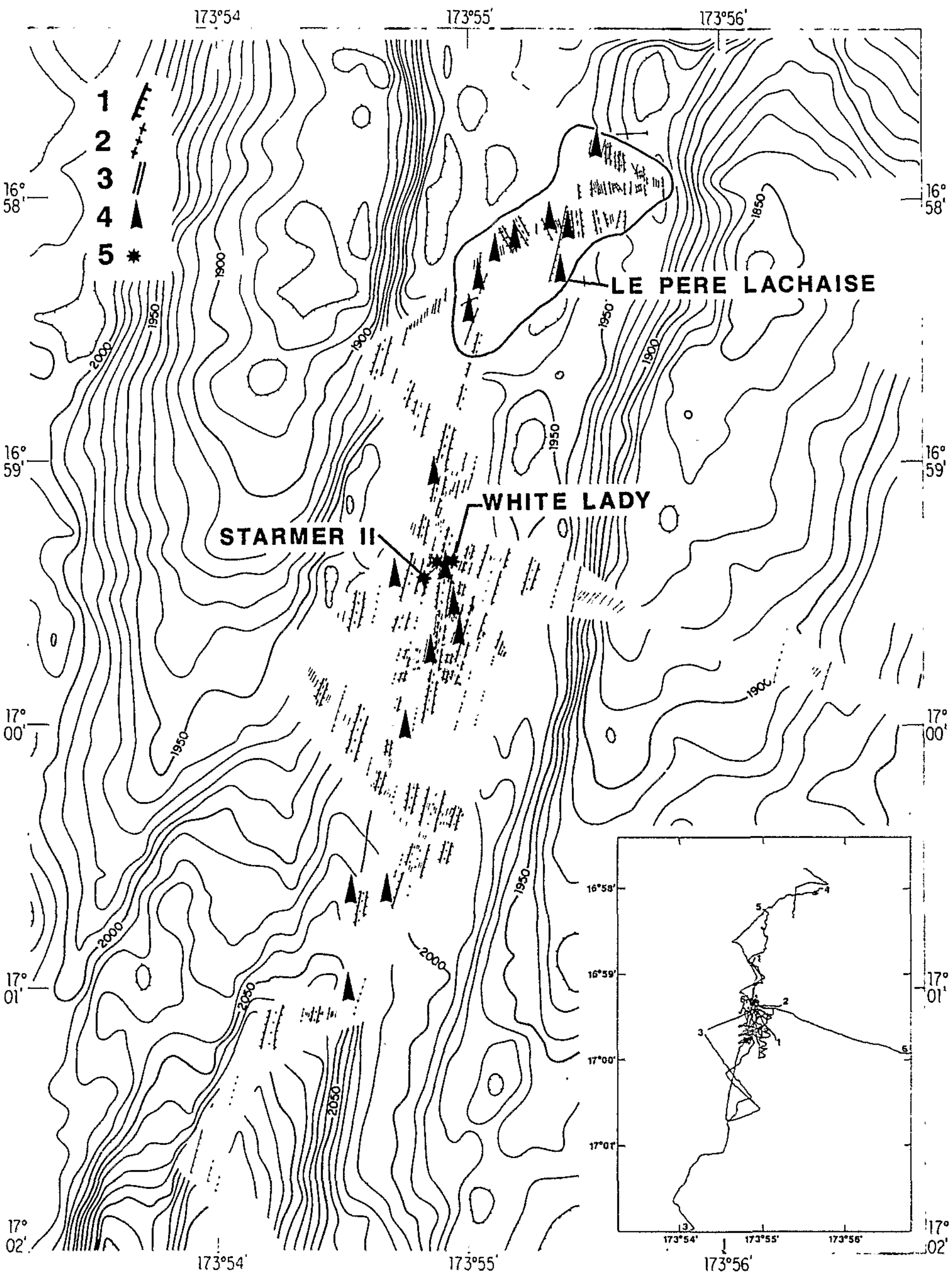

Fig. 6. Detailed bathymetric and morphostructural sketch of station 4. *1* = Scarps, *2* = highs, *3* = fissures, *4* = fossil chimney, *5* = active smoker. Small box: dives locations.

morphology of lavas from oceanic spreading centres (tubes and pillows, fluid lavas, lava lakes and massive flows) (Ballard and Moore, 1977; Francheteau et al., 1978; Ballard et al., 1979; Macdonald, 1982). Fluid lavas, mainly lobate, form lava lakes which exhibit collapse and pillar structure (Fig. 7b). Lava lakes show the freshest basalts with the less important sedimentary cover and thus probably represent the last volcanic event in this region. They cover the floor of the whole graben in the northern domain, are restricted to the 500 m wide tectonically and hydrothermally axial active zone in the central domain, and they occupy the very central axial zone in the southern domain. This shows that the volume of the last erupted lavas decreased considerably from north to south along station 4. Laterally, viscous lavas covered by sediments were observed.

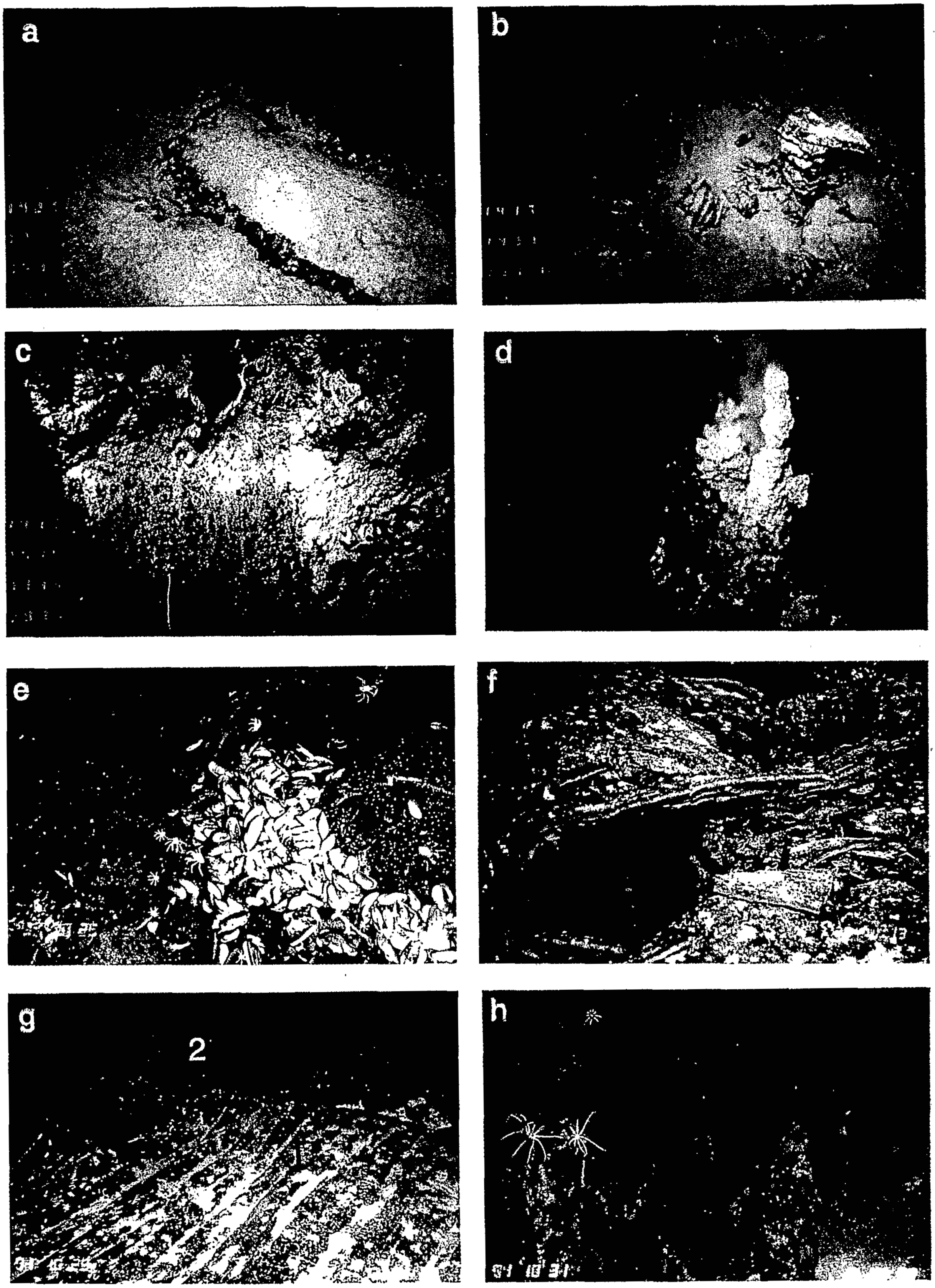

Fig. 7. Bottom photographs taken by the *Nautile* and *Shinkai* 6500 on the North Fiji Basin Axis. Station 4: (a) open fissure on the bottom of the main graben, (b) pillars of foundered lava lakes covered by sediments, (c) hydrothermal patches and deposits in the graben wall, (d) the White Lady smoker. Station 14: (e) animal colonies associated with low temperature diffusions, (f) foundered lava lake, (g) contact between sheet flow lavas (*1*) and draped lavas (*2*). Station "19°S": (h) fossil chimneys forest with ophiuridae.

Hydrothermalism

Both fossil and active hydrothermal activities are found at station 4. Fossil hydrothermal deposits are represented by inactive sulfide mounds and chimneys. An important (4 km^2) fossil field of sulfide chimneys, some of them reaching 20 m high, the "Père Lachaise" field, was discovered in the northern part of station 4 (Fig. 6), where structures with different orientations (N20°–N160°–N60°) are crossing. Inactive chimneys were also observed in the axial part of the graben, in the central and southern part of station 4. Inactive hydrothermal deposits also occur in the whole surveyed area as yellow-brown patches on fault scarps (Fig. 7c) and as impregnations in sediments, commonly associated with dead animal communities (mussels, gastropods).

In the central part of station 4, between 16°59.1'S and 17°S, hydrothermal activity is observed in an area of 200 × 200 metres wide in an area affected by recent fissuration. It is associated with fresh volcanic rocks, which generally are covered by sediments. On the top of the central horst, a 3 m high, white anhydrite smoker has been discovered: the "White Lady" (Fig. 7d). This chimney, expelling transparent, metal poor fluids (Grimaud et al., 1991), seats on an older, 7 m high and 5 m wide sulfide dome. The maximal temperature measured here was 285°C (Auzende et al., 1991b; Bendel et al., in press). Two hundred metres to the west, on the westlooking wall of a 20 m high horst (Fig. 6), 6 similar active chimneys constitute the "STARMER II" site. The maximal temperature measured was 296°C. Living animal communities including gastropods, shrimps, galatheans and crabs are associated with the active vents. The graben located between the hydrothermally active ridges supporting the "STARMER II" site and the "White Lady" (Fig. 6) is also hydrothermally active. The floor of the graben is intensely fissured and two white smokers where observed at the foot of small, 1 m high fault scarps. Relatively low temperature fluids (10°C) diffuse through the fissures, which are also colonized by animal communities.

In summary, at station 4, the NFB ridge morphology is dominated today by tectonic activity, as shown by the existence of a 2 km wide, 100 m deep graben at the summit of the ridge. Volcanism should have been very important before the formation of the central graben 40,000 years ago (2 km opened at a rate of 5 cm/yr) to built a 500 m high ridge. These suggestions from the bathymetric study (Fig. 3b) are verified and detailed after diving observations: the freshest volcanics are covered by a few centimetres thick sedimentary blanket, and tectonic activity dominates.

The axial domain of station 4 appears finally to be characterized by a sequence of at least two major hydrothermal events. The basal sulfide mounds do represent an early phase of hydrothermal construction. A second phase of hydrothermal activity occurred in the middle part of the graben in the central domain, superimposed onto the older sites but associated with recent fissures and the youngest volcanic rocks. These rocks are covered by a thin veneer of sediments, suggesting that present-day hydrothermal activity is not related to this last volcanic event.

Stations 14 and 19°S

The two following stations are located both on the N–S ridge but on two distinct elementary segments, separated each by a small offset less than 1 km wide (Lafoy, 1989) (Fig. 8):

Station 14

Station 14 is located on the N–S segment of the NFB ridge (Fig. 2), between 18°47.7'S and 18°51'S, at the south of the V-shaped domain interpreted as a ridge propagator (Ruellan et al., 1990; De Alteriis et al., 1993). The station lies on the flat top of the axial dome, which shows a typical fast spreading ridge morphology (Fig. 3d) (Gente et al., 1986; Gente, 1987). In 1988, during the *Kaiyo* cruise, a deep-tow camera survey revealed the existence of fossil hydrothermal activity at station 14. Three dives with the submersible *Nautile* were devoted to the exploration of this area during the STARMER cruise in 1989, and were followed by 13 dives with the *Shinkai* 6500 during the *Yokosuka* cruise of 1991 (Fig. 9b).

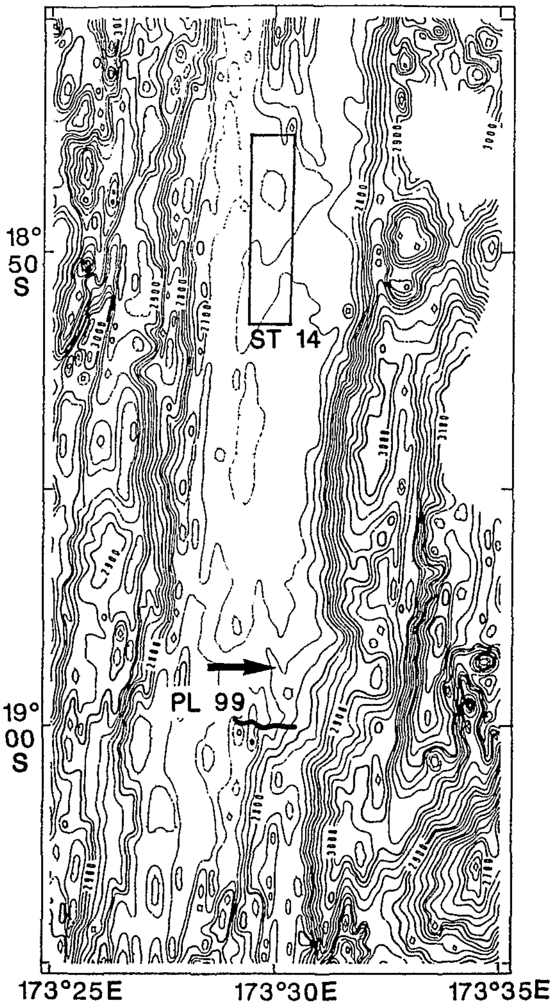

Fig. 8. Sea-beam map of the central part of the N–S segment, and location of stations 14 and "19°S". The small arrows indicates an axial offset, placing each station on two different elementary segments.

Tectonics

Three distinct domains characterized by different structural patterns have been surveyed (Fig. 9a):

– On the first domain, north of 18°49.4′S, the ocean floor is tectonized by only poorly defined grabens and N05° trending fissures or constituted by uncollapsed lava-lake tops. In this area, the axis is pinpointed by hydrothermal sites (Fig. 7e), except in its northern part, explored during dive 82 (Fig. 9a), where lavas are almost totally covered by sediments. Hydrothermal activity was not observed.

– In the second area, between 18°49.4′S and 18°50′S, the axis is marked by a N10° trending, 200 m wide and only 20 m deep graben (Fig. 10). This graben is bounded on both sides by successive steps of foundered lava-lakes, a few metres high. The floor of the graben, at 2725 m, is occupied by fresh basalt breccias devoid of sediments and by pillars of lava-lakes, one to a few metres high. En echelon fissures trending N170° and N10° are frequently observed in the N05° oriented graben, indicating recent tectonics (Fig. 9c). These directions are different from those of the ridge and could reflect a situation of instantaneous stress. Such fissures will probably reorganize later on.

– South of 18°50′S, a 70 m wide graben which seems discontinuous was observed at the summit of the axial dome during dive 98.

Volcanism

The main result of the observations made at station 14 is that extremely fresh basalts, mostly lava lakes, have been observed on the floor of the axial graben. The lava lakes (Fig. 7f) are especially located in the axial zone. In the most tectonized areas, these lava-lakes are collapsed. They exhibit drain-back features, 4 to 5 m high vertical pillars aligned along a N–S direction, and lava debris on the floor of the axis. Sheet flows (Fig. 7g(1)) and draped lavas (Fig. 7g(2)) are present both on and off-axis. Sheet-flows and filling depressions often exhibit flow-lines and eddies, with some furrows of very glistening and fresh volcanic glass. They are always spotted by sediments, in contrast to the draped lavas lying upon them. This suggests that draped lavas represent the last eruption at the axis or off-axis (Ondréas, 1992; Ondréas et al., 1993). Chaotic zones formed by breaked lavas are also found off-axis. Sections of lava-tubes are exposed along the steepest slopes and abundant pillow-lavas were observed on the ocean floor in the north of station 14, in the area explored during dive 82.

Hydrothermalism

Active hydrothermalism characterized by diffuse vents of low temperature fluids (5°C) and brown or yellow stains associated with living animal colonies are frequent over the entire station. The fluids are expelled at the top of lava-lakes or through debris resulting from the collapse of lava-lakes. No active hydrothermal chimneys have been discovered on station 14, but numerous evidences of fossil hydrothermalism such as extinct sulfide

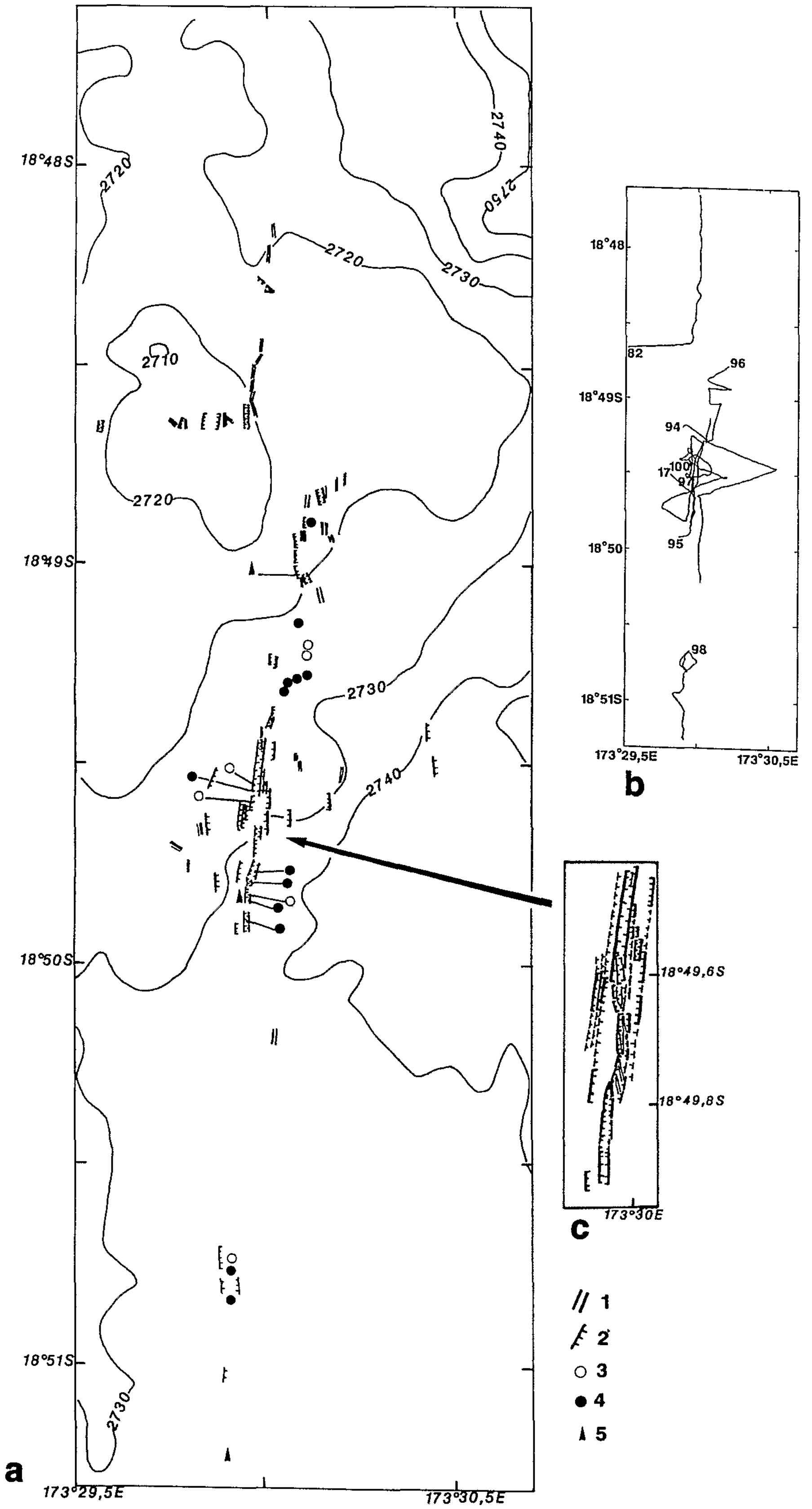

Fig. 9. (a) Detailed bathymetric and morphostructural sketch of station 14. (b) Dive locations. (c) Detail of the area comprised between 18°49.4′S and 18°50′S. *1* = Fissures, *2* = scarp, *3* = fossil hydrothermal site, *4* = active hydrothermal site, *5* = fossil chimney.

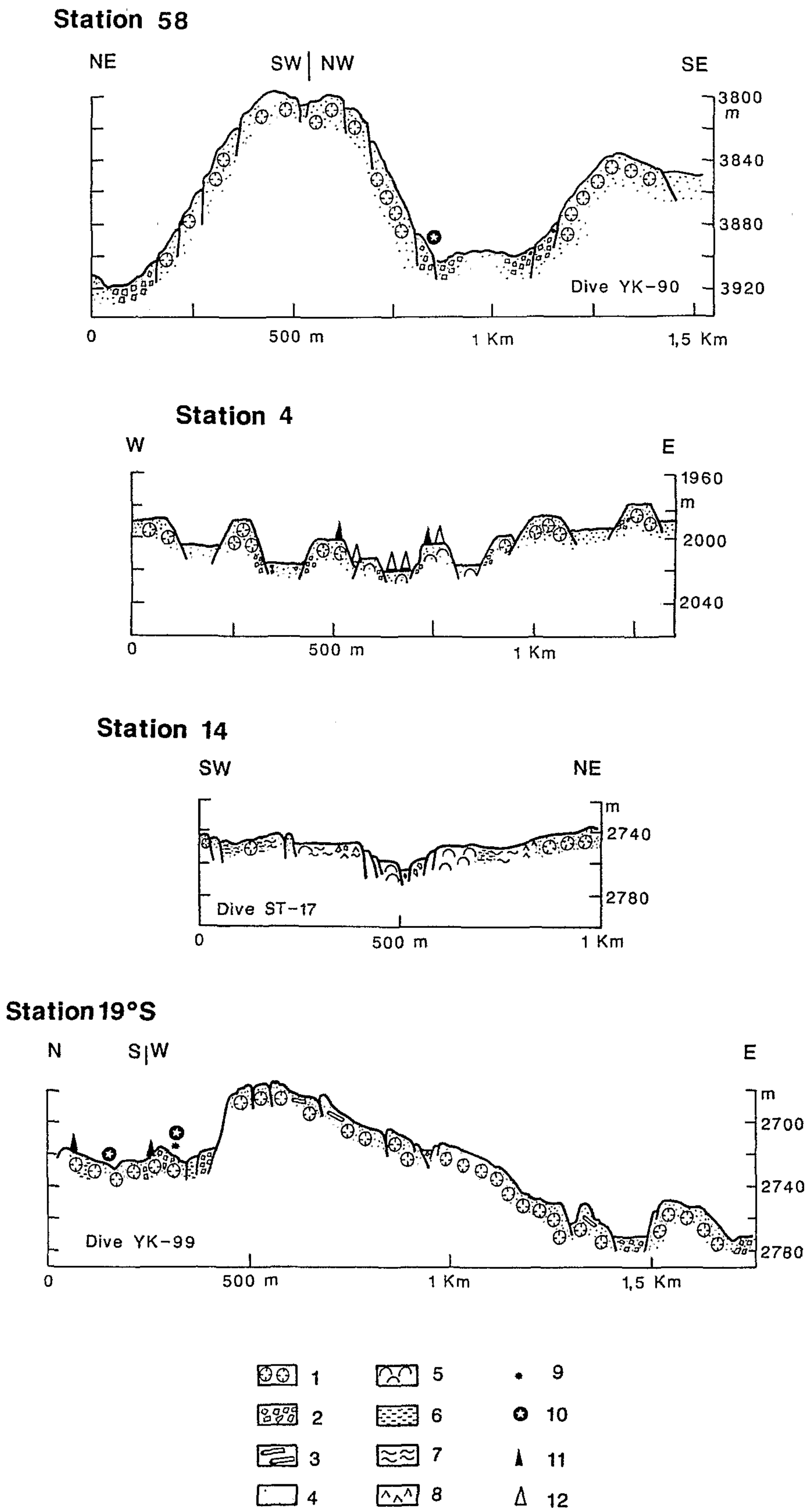

Fig. 10. Geological sections* based on in situ observations at stations 58, 4, 14 and "19°S", respectively. *1*=Pillow lavas, *2*=breccia, *3*=lava tubes, *4*=sediments, *5*=lobate lavas, *6*=sheet flows, *7*=draped lavas, *8*=chaotic zones, *9*=low temperature hydrothermal fluids, *10*=hydrothermal deposits, *11*=fossil chimneys, *12*=active smoker. *N.B. All these sections are at the same scale, but they have different significance: At station 58, the section represents the neovolcanic ridge located in the central part of the graben; at station 4, the section shows the inner part of the graben; and at stations 14 and "19°S", the section represents the whole axial zone.

chimneys associated with dead animals (mussels, gasteropods, galatheans, crabs) are reported. "Forests" of inactive chimneys, up to 10 m high, are located within the axial graben or on the first steps of the external walls. As observed during dive 100, some of the chimneys are probably very recent. One of them, collapsed into the axial fissure, contained dessicated polychete worms indicating that high temperature hydrothermal activity terminated very recently (Bendel, 1993).

In summary, the present-day axis is formed by very fresh fluid lavas dominated by lava lakes. Tectonic features are rarely observed and both fossil hydrothermal features, like chimneys or deposits, and active hydrothermalism, such as low temperature emanations are found. At station 14, the N–S segment is clearly dominated by volcanism.

Station "19°S"

One dive was carried out at the spreading axis at 19°S, 20 km south of station 14. At 19°S, the N–S segment consists of a 8 km wide dome, topped by two 40 m high ridges separated by a 300 m wide, 50 m deep, axial graben (Fig. 8). The dive track crosses the axis from the base of the eastern ridge to the western wall of the axial depression. The N–S trending walls are constituted by a high scarp exposing pillow-lava sections (Fig. 10). Scree deposits at the foot of the scarps are indicators of recent tectonic activity. Pillow-lavas and lava-tubes are common volcanic features in the area, even along the axis. A sedimentary cover of a few centimetres is present all along the dive track. Forests of fossil sulfides chimneys lie on the floor of the graben and on the first step of the wall (Fig. 7h). Dead animals are found either isolated or associated with hydrothermal deposits around chimneys. Low temperature fluids are venting in the axial graben, at the foot of the western wall, associated with worms and yellow-brown inactive hydrothermal deposits containing sulfides and oxides.

In station "19°S", the erupted lavas are older and more viscous, and the tectonic activity is more mature, compared to station 14.

Discussion

Four restricted areas located along 3 morphologically distinct spreading segments of the NFB ridge were surveyed in detail. Each station shows original morphologic, volcanic, tectonic and hydrothermal characters representative of particular states of the North Fiji spreading centre activity. The variability of these characters and their significance with respect to the mechanism of oceanic accretion will be discussed in detail below.

Morphologic variations were observed on different scales: between the three major segments on a large scale (> 100 km), between two areas (station 14 and station "19°S") located 20 km apart on the N–S segment, and on a very small scale (1 km) on two special sites (stations 14 and 4). These morphologic variations do not all have the same significance and will be explained below.

Large-scale variations

All the main segments of the NFB axis, more than 100 km long, are separated by major features, such as a propagating rift (between the N–S and the N15° segments) and a triple junction (between the N15° and N160° segments). Dive stations are located on different segments of the North Fiji Basin ridge axis (Fig. 2). Each segment is characterized by a particular morphostructure and evolutive state.

On the N160° segment (at station 58), magmatism is remarkably weak. This corresponds to a slow-ridge morphology related to a dominant tectonic activity (Figs. 3a and 10). However, the N–S segment at station 14 has a fast-spreading ridge morphology (Figs. 3d and 10). This segment clearly shows dominant volcanic activity. In this way the N15° segment morphology at station 4 can be explained as being an intermediate state between those characterizing the N160° and N–S segments. The topography of the N15° ridge (Fig. 3b and c) suggests that it was built during an important magmatic event, but the presence of a 2 km wide, 100–150 m deep axial graben, indicates recent tectonic activity.

The spreading rate along the whole ridge decreases northwards from 7.6 cm/yr at 20°S to 4 cm/yr at 16°30′S (Huchon et al., 1994-this issue).

Around 16°50′S, and separated by the Triple Junction, the N160° and N15° segments present almost the same spreading rate of about 4–5 cm/yr, however, there is a remarkable variation in axial topography (Fig. 3). This independence between axial morphology and spreading rate suggests different thermal regimes between the segments. The N160° segment shows a deep graben and an axial neovolcanic ridge similar to that of "cold" slow spreading ridges. This argues for a low thermicity budget. On the other hand, the dome shapes that characterize the N15° and N–S segments are indicative of a "hot" source below the axis, suggesting a high thermal supply related to a volcanic state.

The axial topography of the N160° segment is due to an exceptionally low magmatic budget, which contrasts with the high magmatic supply for the N–S and N15° segments. Thus, along the same spreading ridge and less than 150 km apart, we found three segments reflecting different volcano-tectonic states, conditioned by exceptionally low or high magmatic budgets. Thermal modelling will be carried out in an attempt to understand the existence of such different thermal states between three segments of the same spreading ridge (Gràcia et al., 1993).

Decakilometric scale variations

In the N–S principal segment. we can identify morphologic variability at a decakilometric scale, inferred here from submersible studies but also visible from bathymetric analysis. This variability is present between stations 14 and "19°S", separated by 20 km but belonging to the same N–S segment. The comparison between stations allows us to see that erupted lavas are more viscous and less recent, the sedimentary cover is more important, and the axial graben is deeper and wider at "19°S" than at station 14 (Fig. 11).

Although the spreading rate would be similar at both stations we observe a prevalence of volcanism or tectonics depending on the location along the N–S segment.

We notice from the bathymetric map (Fig. 8), that stations 14 and "19°S" belong to two distinct elementary segments, separated by a small offset (< 1 km) corresponding to a topographic low

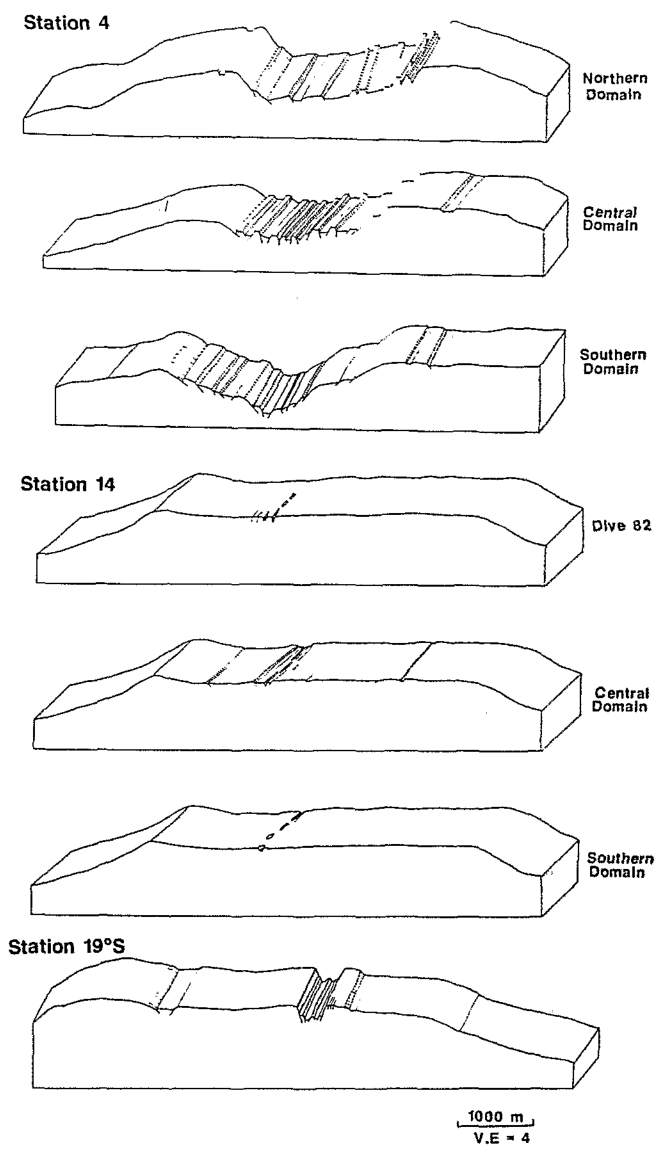

Fig. 11. Schematic view of morphostructural variations along strike between stations 4, 14 and "19°S".

(Lafoy, 1989). Station 14 is located on the central part of an elementary segment, whereas station "19°S" is at the end of the other one. For numerous authors (Sempéré and Macdonald, 1986; Macdonald et al., 1991; Haymon et al., 1991) magma is preferentially erupted in the middle of a segment corresponding to a topographic high and migrates, all along the axis, from the centre to the extremities of the magma chamber. In consequence, the central part of the segment has more opportunities than the ends to be characterized by a magmatic state. The morphostructural variations between the stations 14 and "19°S" and their position on the segment tend to support these ideas. However, we propose that additional dives should be carried out on an elementary segment in order to verify this idea.

Numerous studies on the East Pacific Rise (E.P.R.) have emphasized the same kind of morphologic variations described here. At 12°50′N, Gente et al. (1986), show a 6 km variability between an area where tectonism dominates and a second one where the tectonic activity is lower and volcanism more recent. Vaslet (1993) show similar results on the East Pacific Rise near 13°N. Other studies on several stations of the E.P.R., between 17°30′S and 21°30′S (Renard et al., 1985), show also at this scale, a juxtaposition of areas with and without tectonism.

Small-scale variations

Variations of the order of 1 to a few kilometres are present on stations 4 and 14. These stations represent a survey area of about 8 km^2.

At station 4, where tectonic activity dominates, these morphological variations are observed in the central graben along 10 km of the ridge axis (Fig. 11). From north to south, the volume of most recently erupted lavas decreases while tectonic structuration increases. The most structured areas correspond to those where the smallest amount of lavas were erupted. This volcano-tectonic evolution of the spreading centre at station 4 allows direct comparison with the Snake Pit neovolcanic ridge on the Mid Atlantic Ridge at 23°22′N (Gente et al., 1991). The orientations of scarps and fissures at station 4 also vary from the north, where oblique features (N60°, N160°) are common, to the south, where they are rare. This predominance of volcanism and oblique structures in northward direction is probably related to the 16°50′S triple junction.

On station 14, all over the area, the lavas are extremely fresh (Fig. 7f). We are able to identify small-scale variability between areas with increasing tectonism and other ones, where the tectonic activity is insignificant (Figs. 9a and 11). This kind of variability is also described on the East Pacific Rise at 13°N by Vaslet (1993) where different areas are called morphologic units.

Variations seen on station 14 can be explained by two hypotheses.

First, considering a well-formed graben all along the area, eruption would have taken place on very localised sites, covering the pre-existing graben. But we have not observed any in situ evidence of contacts between graben walls and freshly erupted lavas.

Second, considering a recent volcanic event in the whole area, the present-day graben would be formed only at narrow and restricted zones. This hypothesis fits well with submersible observations.

Hydrothermalism

Numerous evidences for present-day hydrothermal activity, as well as remnants of fossil hydrothermalism have been found along the N–S and N15° segments of the NFB spreading axis. Active venting has not been observed during submersible exploration along the N160° segment, but clear evidences are reported from deep-water chemical analysis that hydrothermal fluids were being emitted in 1985 (Auzende et al., 1988a; Nojiri et al., 1990). Hydrothermal activity presently occurs at the N–S spreading ridge as seeps, with low temperature fluid emanations (<20°C) associated with living animal communities. Similar low temperature fluids are also found on the N15° spreading ridge, associated with high temperature fluids venting through anhydrite smokers. The chemical composition of the fluids indicates an initial temperature of 350°C before mixing with seawater (Grimaud et al., 1991). This present-day high temperature hydrothermal activity is strictly located in areas where the freshest volcanics are exposed and where the tectonic activity is important. In the case of the N15° ridge, the youngest volcanics are covered by several centimetres of sediment, indicating that present-day high temperature hydrothermal activity is not directly related to this volcanic episode. Nevertheless high temperature fluid emission suggests a magma chamber activity and a future volcanic event.

At station 14, on the N–S spreading ridge, volcanism was emplaced very recently, but all conditions which allowed intense hydrothermal activity (represented by fossil sulfide chimneys) are now gone. Because tectonic intensity had not changed, we suggest that deep heat supply is not sufficient to keep this high temperature venting.

Moreover, if a renewal of favourable conditions occurs at this site, high temperature hydrothermal events are expected.

Fossil hydrothermal sites are represented as sulfide spires and mounds. The more abundant fossil sites are observed in the rifted spreading axis, i.e. at station 4, along the N15° spreading axis, and at station "19°S" on the N–S segment. Such observation leads to propose that during periods of high magmatic production, chances to bury the sulfide edifices under lavas strongly increase. This has been suggested elsewhere in the Pacific (Renard et al., 1985) and is one of the main reasons why hydrothermal deposits are larger in the Atlantic ridge (Snake Pit, TAG field) than on the East Pacific Rise (Rona, 1988).

Mineralogical data have been obtained from an inactive chimney explored during dive 100 at station 14 (Bendel, 1993). The chimney appears to result from precipitates of very high temperature fluids unmixed with seawater. These data also show the very young age of the chimney. Finally, this indicates that vigorous hydrothermal activity occurred recently at station 14, probably in relation with the formation of the axial fissure.

Conclusions

A synthesis of the submersible observations made during the STARMER and *Yokosuka* 91 diving cruises allows to present an overview of the present-day tectonic, volcanic and hydrothermal activity of the major segments of the North Fiji Basin spreading system. Each dive station shows an original character with respect to processes of accretion. Stations where magmatic features are dominant coexist with other ones where very recent tectonic processes have affected previous volcanics. This morphostructural variability has been observed at different scales.

At a large scale, between the 3 stations, we observe a very different axial morphology although the spreading rate is quite similar. We suggest that the morphology of the N160° segment is due to a low magmatic budget, whereas that of the N15° and N–S segments is related to a high magmatic supply. There is an opposite thermal regime between the north and the south of the 16°50′S triple junction. More detailed studies will be carried out. Variations at medium and small scale can be revealed by submersible observations along ridge segments, which show an apparently uniform topography. At a decakilometric scale, between stations 14 and "19°S" we observe different morphologies depending on the location, either in the central part or in the extremity of an elementary segment, along the axis. Such morphologies can be linked with the shape and boundaries of the magma chamber. Finally, small-scale variations have been observed on stations 4 and 14. These variations show that, at this small scale, magma is temporarily erupted in a random way and tectonic activity takes place in narrow and restricted areas.

Concerning the hydrothermal activity, only traces have been found on the N160° segment. In contrast, both extinct and active examples are found on the N–S and N15° segments and, especially, high temperature activity on the N15° segment. Our detailed studies carried out on this hydrothermal feature suggest that this kind of activity is linked to both nascent magmatism and fissuring. Similar conclusions were reached at other oceanic sites (Kappel and Ryan, 1986; Gente, 1988; Auclair, 1988; Schminke and Bednarz, 1990).

Acknowledgements

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References

Auclair, G., 1988. Processus de métallogénie dans les amas sulfurés océaniques. Contribution à l'étude du comportement des éléments chalcophiles dans les processus hydrothermaux. Thesis Univ. Bretagne Occidentale, Brest, 340 pp.

Auzende, J.M., Eissen, J.P., Lafoy, Y., Gente, P. and Charlou, J.L., 1988a. Seafloor spreading in the North Fiji Basin (Southwest Pacific). Tectonophysics, 146: 317–351.

Auzende, J.M., Lafoy, Y. and Marsset, B., 1988b. Recent geodynamic evolution of the North Fiji Basin (SW Pacific). Geology, 16: 925–929.

Auzende, J.M., Okuda, Y., Bendel, V., Ciabrini, J.P., Eissen, J.P., Gràcia-Mont, E., Hirose K., Iwabuchi, Y., Joshima, M., Kisimoto, K., Lafoy, Y., Lagabrielle, Y., Marumo, K., Matsumoto, T., Mitsuzawa, K., Momma, H., Murai, H., Naka, J., Nojiri, Y., Ortega Osorio, A., Ruellan, E., Tanahashi, M., Tupua, E. and Yamaguchi, K., 1991a. Propagation "en échelon" de la dorsale du Bassin Nord-Fidjien entre 16°40S et 14°50S (Yokosuka 90–Starmer). C. R. Acad. Sci. Paris, Sér. II, 312: 1531–1538.

Auzende, J.-M., Urabe, T., Bendel, V., Deplus, C., Eissen, J.-P., Grimaud, D., Huchon, P., Ishibashi, J., Joshima, M., Lagabrielle, Y., Mevel, C., Naka, J., Ruellan, E., Tanaka, T. and Tanahashi, M., 1991b. In situ geological and geochemical study of an active hydrothermal site on the North Fiji Basin ridge. In: K.A.W. Crook (Editor), The Geology, Geophysics and Mineral Resources of the South Pacific. Mar. Geol., 98: 259–269.

Auzende, J.M., Tanahashi, M., Bendel, V., Fujikura, K., Geistdoerfer, P., Gràcia-Mont, E., Joshima, M., Kisimoto, K., Mitsuzawa, K., Murai, M., Nojiri, Y., Ondréas, H., Pratt, C. and Ruellan, E., 1992. Résultats préliminaires des plongées du Shinkai 6500 sur la dorsale du Bassin Nord Fidjien (SW Pacifique)—Programme STARMER. C. R. Acad. Sci. Paris, Sér. II, 314: 491–498.

Ballard, R.D. and Moore, J.G., 1977. Photographic Atlas of the Mid-Atlantic Ridge. Springer, New York, 114 pp.

Ballard, R.D., Holcomb, R.T. and Van Andel, T.H., 1979. The Galapagos Rift at 86°W: 3. Sheet flows, Collapse pits, and Lava Lakes of the Rift Valley. J. Geophys Res., 84(B10): 5407–5422.

Bendel, V., 1993. Cadre géologique et composition des minéralisations hydrothermales en contexte arrière-arc: Exemple de la dorsale du Bassin Nord Fidjien (Sud-Ouest Pacifique). Doct. Thesis Univ. Bretagne Occidentale, Brest. Vol. 1, 259 pp.; Vol. 2, 173 pp.

Bendel, V., Fouquet, Y., Auzende, J.M., Lagabrielle, Y., Grimaud, D. and Urabe, T., in press. Metallogenesis at a triple junction system: The White Lady hydrothermal field in the North Fiji Back-arc basin, SW Pacific. Econ. Geol.

Chase, C.G., 1971. Tectonic history of the Fiji Plateau. Geol. Soc. Am. Bull., 82: 3087–3110.

De Alteriis, G., Auzende, J.M., Bendel, V., Gràcia Mont, E., Huchon, P., Lagabrielle, Y., Ondréas, H., Ruellan, E. and Tanahashi, M., 1993. Propagating rifts in the North Fiji Basin (Southwest Pacific). Geology, 21: 583–586.

Eissen, J.P., Lefèvre, C., Maillet, P., Morvan, G. and Nohara, M., 1991. Petrology and geochemistry of the central North Fiji Basin spreading centre (Southwest Pacific) between 16°S and 22°S. In: K.A.W. Crook (Editor), The Geology, Geophysics and Mineral Resources of the South Pacific. Mar. Geol., 98: 201–239.

Francheteau, J., Juteau, T., Needham, D., Rangin, C. and Cyamex Team, 1978. Naissance d'un océan. CNEXO, 84 pp.

Gente, P., 1987. Etude morphostructurale comparative des dorsales océaniques à taux d'expansion variés. Schéma d'évolution morphologique de l'axe des dorsales: liaisons avec l'hydrothermalisme. Doct. Thesis Univ. Bretagne Occidentale, Brest, 371 pp.

Gente, P., 1988. Modèle sur la relation entre la structure de l'axe des dorsales et l'activité hydrothermale. Colloque National sur l'Hydrothermalisme Océanique. (Brest, 22–24 Novembre, 1988.) Abstr.

Gente, P., Auzende, J.M., Renard, V., Fouquet, Y. and Bideau, D., 1986. Detailed geological mapping by submersible of the East Pacific Rise axial graben near 13°N. Earth Planet. Sci. Lett., 78: 224–236.

Gente, P., Mevel, C., Auzende, J.-M., Karson, J.A. and Fouquet, Y., 1991. An example of a recent accretion on the Mid-Atlantic Ridge: the Snake Pit neovolcanic ridge (MARK area, 23°22'N). Tectonophysics, 190: 1–29.

Gràcia, E., 1991. Etude morphostructurale du segment N160 de la dorsale du Basin Nord-Fidjien. Analyse des données de la campagne Yokosuka 90. Rapport de D.E.A., Univ. Bretagne Occidentale, Brest, 65 pp.

Gràcia, E., 1992. El segment N160 de la Conca Nord-Fijiana (Pacific sud-ouest): Morfoestructura d'un eix d'acreció d'edat quaternària dins una conca marginal. Ms. Thesis, Univ. Barcelona, Spain, 145 pp.

Gràcia, E., Auzende, J.M., Tisseau, C. and Huchon, P., 1993. Recent evolution of the North Fiji Basin ridge from bathymetric and magnetic data: thermal outcomes. Terra Abstracts. Abstr. Suppl. No. 1 to Terra Nova, 5. (EUG VII, Strasbourg, France, April 4–8, 1993.) p. 109.

Grimaud, D., Ishibashi, J.I., Lagabrielle, Y., Auzende, J.M. and Urabe, T., 1991. Chemistry of hydrothermal fluids from the 17°S active site on the North Fiji Basin ridge (SW Pacific). Chem. Geol., 93: 209–218.

Haymon, R.M., Fornari, D.J., Edwards, M.H., Carbotte, S., Wright, D. and Macdonald, K.C., 1991. Hydrothermal vent distribution along the East Pacific Rise crest (9°09'–54'N) and its relationship to magmatic and tectonic processes on fast-spreading mid-ocean ridges. Earth Planet. Sci. Lett., 104: 513–534.

Hey, R., 1977. A new class of "pseudofaults" and their bearing on plate tectonics: A propagating rift model. Earth Planet. Sci. Lett., 37: 321–325.

Hey, R., Duennebier, F.K. and Morgan, W.J., 1980. Propagating rifts on mid-ocean ridges. J. Geophys. Res., 85: 3647–3658.

Huchon, P., Gràcia, E., Ruellan, E., Joshima, M. and Auzende, J.-M., 1994. Kinematics of active spreading in the central North Fiji Basin (SW Pacific). In: J.-M. Auzende and T. Urabe (Editors), North Fiji Basin: STARMER French–Japanese Program. Mar. Geol., 116: 69–87.

Jollivet, D., Hashimoto, J., Auzende, J.M., Honza, E., Ruellan, E., Dutt, S., Iwabushi, Y., Jarvis, P., Joshima, M., Kawai, T., Kawamoto, T., Kisimoto, K., Lafoy, Y., Matsumoto, T., Mitsuzawa, K., Naganuma, T., Naka, J., Otsuka, K., Otsuki, A., Rao, B., Tanahashi, M., Tanaka, T., Temakon, J.S., Urabe, T., Veivau, T. and Yokokura, T., 1989. Premières observations de communautés animales associées à l'hydrothermalisme arrière-arc du Bassin Nord-Fidjien. C. R. Acad. Sci. Paris, Sér. III, 309: 301–308.

Kappel, E.S. and Ryan, W.B.F., 1986. Volcanic episodicity and a non-steady state rift valley along Northeast Pacific Spreading centers: evidence from Seamarc I. J. Geophys. Res., 91(B13): 13925–13940.

Kroenke, L., Price, R.C and Jarvis, P.A., 1991. North Fiji

Basin Northern Limb of the Triple Junction. Sidescan Sonar Imagery and Bathymetry 1:250.000. In: Pacific Seafloor Atlas, Hawaii Inst. Geophysics, Honolulu, HI, Sheet 14.

Lafoy, Y., 1989. Evolution géodynamique des bassins marginaux Nord-Fidjien et de Lau (SW Pacifique). Doct. Thesis Univ. Bretagne Occidentale. Brest, 261 pp.

Lafoy, Y., Auzende, J.M., Ruellan, E., Huchon, P. and Honza, E., 1990. The 16°40'S Triple Junction in the North Fiji Basin (SW Pacific). Mar. Geophys. Res., 12: 285–296.

Lagabrielle, Y., Auzende, J.M., Eissen, J.P., Janin, M.C. and Cotten, J., 1994. Geology and geochemistry of a 800 m section through young upper oceanic crust in the North fiji basin (Southwest Pacific). In: J.-M. Auzende and T. Urabe (Editors), North Fiji Basin: STARMER French–Japanese Program. Mar. Geol., 116: 113–132.

Macdonald, K.C., 1982. Mid-ocean ridges: fine scale tectonic, volcanic and hydrothermal processes within the plate boundary zone. Ann. Rev. Earth Planet. Sci., 10: 155–190.

Macdonald, K.C. and Fox. P.J., 1983. Overlapping spreading centres: new accretion geometry on the East-Pacific Rise. Nature, 302: 55–58.

Macdonald, K.C., Scheirer. D.S. and Carbotte, S.M., 1991. Mid-ocean ridges: Discontinuities, segments and giant cracks. Science, 253: 986–994.

Maillet, P., Eissen, J.P., Lapouille, A., Monzier, M., Baleivanualala, V., Butscher, J., Gallois, F. and Lardy, M., 1986. La dorsale active du bassin Nord Fidjien entre 20°S et 20°53S: Signature magnétique et morphologie. C. R. Acad. Sci. Paris, Sér. II, 302: 135–140.

Nojiri, Y., Ishibashi, J.I., Kawai, T., Otsuki, A. and Sakai, H., 1990. Hydrothermal plumes along the North Fiji Basin spreading axis. Nature, 342: 667–670.

Ondréas, H., 1992. Etude par submersible de la morphostructure d'un segment de dorsale: Exemple de la station 14 sur l'axe du BNF. Rapport de D.E.A. Univ. Bretagne Occidentale, Brest, 59 pp.

Ondréas, H., Ruellan, E., Auzende, J.M., Bendel, V., De Alteriis, G., Gràcia-Mont, E., Lagabrielle, Y. and Tanahashi, M., 1993. Variabilité morphostructurale à l'échelle kilométrique de la dorsale du Bassin Nord Fidjien: Exploration *in situ* du segment compris entre 18°50S et 19°S. C. R. Acad. Sci. Paris, Sér. II, 316: 115–122.

Purdy, G.M., Sempéré, J.C., Schouten, H., Dubois, D.L. and Goldsmith, R., 1990. Bathymetry of the Mid-Atlantic Ridge, 24°–31°N: a map series. Mar. Geophys. Res., 12: 247–252.

Renard, V., Hekinian, R., Francheteau, J., Ballard, R.D. and Backer, H., 1985. Submersible observations at the axis of the Ultra-fast-Spreading East Pacific Rise (17°30' to 21°30'S). Earth Planet. Sci. Lett., 75: 339–353.

Rona, P.A., 1988. Hydrothermal mineralization at oceanic ridges. Can. Mineral., 26: 431–465.

Ruellan, E., Auzende, J.M. and Maillet, P., 1990. L'axe d'accrétion actif Nord–Sud du Bassin Nord-Fidjien au sud de 18°30'S. Soc. Geol. Fr., Séance Spécialisée "Oceans". (Sophia-Antipolis, 6–7 Décembre 1990.) p. 63.

Schminke, H.-U. and Bednarz, U., 1990. Pillow, sheet flow and breccia flow volcanoes and volcano-tectonic hydrothermal cycles in the Extrusives Series of the northeastern Troodos ophiolite (Cyprus). In: J. Malpas, E.M. Moores, A. Panayiotou and C. Xenophontos (Editors), Ophiolites, Oceanic Crustal Analogues. Proc. Symp. "Troodos 1987". Cyprus.

Sempéré, J.C., Purdy, G.M. and Schouten, H., 1990. The segmentation of the Mid-Atlantic Ridge between 24°N and 30°40'N. Nature, 344: 427–431.

Vaslet, 1993. Apport des images du sonar latéral SAR à l'étude de la structure fine des dorsales rapides. Application sur les relations entre tectonisme–magmatisme–hydrothermalisme (Exemple de la dorsale Est Pacifique entre 13°20'N et 11°50'N). Doct. Thesis Univ. Bretagne Occidentale, Brest, 336 pp.

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Multi-scale morphologic variability of the North Fiji Basin ridge (Southwest Pacific)

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