In situ geological and geochemical study of an active hydrothermal site on the North Fiji Basin ridge

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ABSTRACT

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In June 1989 a diving cruise by the submersible *Nautile* was carried out on the North Fiji Basin spreading ridge. The objective of the cruise was a geological and geochemical study of the active spreading axis and associated hydrothermal processes. This operation was the third cruise of the French–Japanese Starmer project following the two cruises of the R.V. *Kaiyo* in 1987 and 1988.

Six dives along the spreading axis between 16°58' and 17°00S show that the axial graben consists of alternating N15–trending horsts and grabens. Extinct hydrothermal sites have been observed all along the graben. These consist of fossil chimneys, oxide staining and dead shells. At 16°59'S an active chimney has been discovered and called the "White Lady" because of its almost exclusively anhydrite composition. This chimney expels a peculiar water characterized by low chlorinity and a 285°C maximum temperature. In the northern extremity of the N15 axis a wide fossil hydrothermal site has been explored and sampled. It is located in an area cut by N15, N140 and N60-trending faults and fissures.

Introduction

During the last five years the North Fiji Basin Ridge (Southwest Pacific) has been intensively studied during oceanographic cruises carried out by French, American and Japanese institutions (Fig.1). The main goal of these cruises was to study, by means of precise Seabeam and Seamarc II mapping and seismic and magnetic surveys, the active spreading system of the North

Fiji Basin and associated hydrothermal processes. This work was carried out as a French–Japanese project involving the Japanese Science and Technology Agency and IFREMER. After the Seapso III cruise (Auzende et al., 1986, 1988a, b) of the R.V. *Jean Charcot* in 1985, the objective of the *Kaiyo* 87 and 88 cruises was the complementary Seabeam mapping of the North Fiji Basin spreading axis between 16°S and 22°S and a systematic sampling (water and rocks) and deep-tow
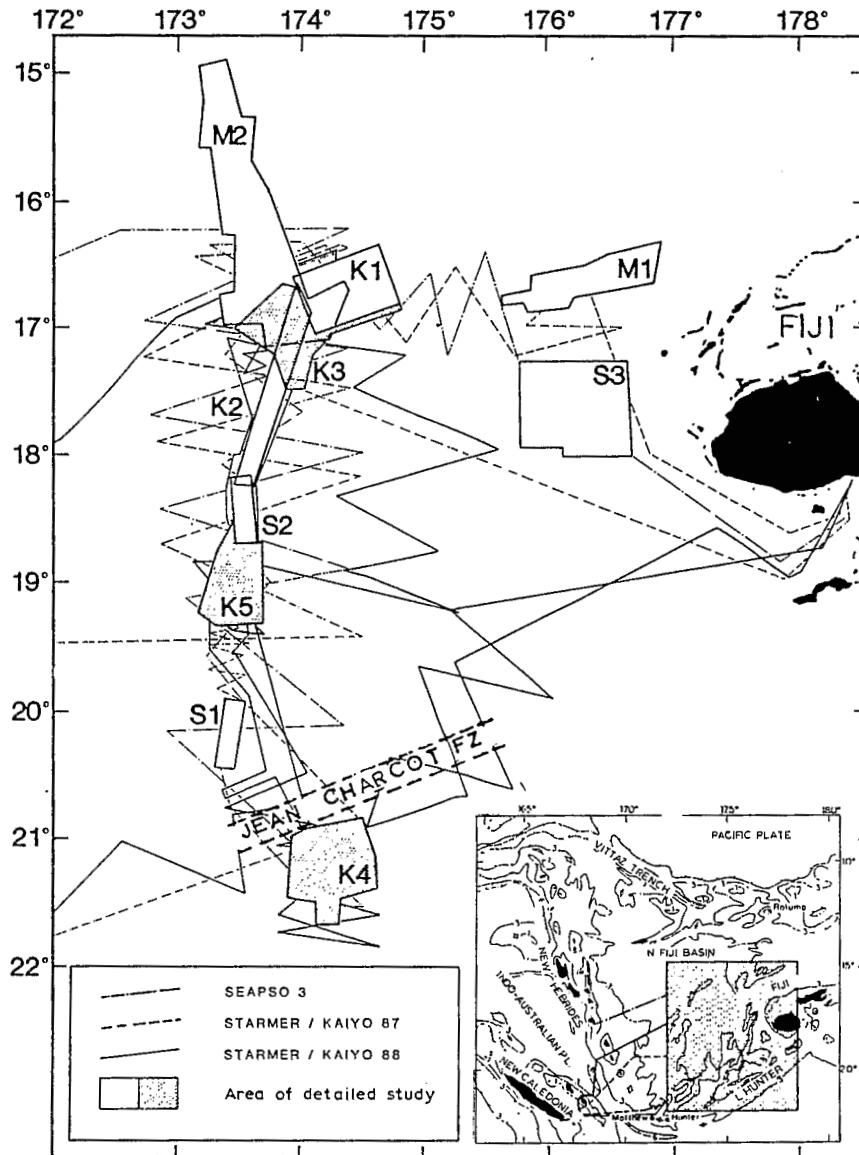
Fig.1. Location map of Seapso III (S), *Kaiyo* 87 and 88 (K) and *Moana Wave* (M) cruises.

(video and stills) at about every 10 miles along the axis.

The main results on ridge axis structure obtained during the previous cruises can be summarized as follows (Fig.2). In the southernmost part of the survey area south of 21°S (Ruellan et al., 1989), the axis area is centred on 174°10E and shows a very complicated pattern with double ridges, seamounts and transverse faulting. The width of the area suggests that the present-day axis could be an incipient rift propagating through older oceanic

crust created during the previous stages of opening (between 10 and 0.7 Ma) (Auzende et al., 1988b) of the North Fiji Basin. The rate of opening in this southern domain is about 2.5 cm/yr, which is low compared to the northern part.

Between 21°S and 18°10'S, the axial domain is characterized by a roughly N–S trending 200 km wide succession of highs and lows converging toward 18°10'S where the width of the area is only 160 km. This fan-shaped opening is confirmed by magnetic data between anomalies 1 and 2A (3 Ma)
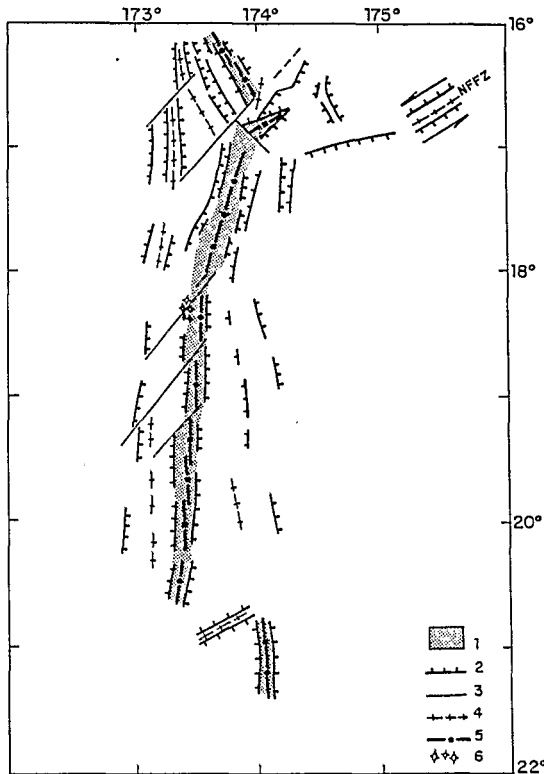
Fig.2. Sketch of the North Fiji Basin axis after Lafoy et al. (1990). *1* = axial area; *2* = normal faults; *3* = transverse faults; *4* = ridges; *5* = present-day active axis; *6* = volcanoes. *NFFZ* = North Fiji Fracture Zone.

(Auzende et al., 1988c, 1990) giving a 7.8 cm/yr total rate in the south and 5.2 cm/yr at 18°10′S.

The axis itself is centred on 173°25′E with an average depth of 2600 m. The elevation with respect to the adjacent oceanic bottom is about 200 m. The transverse morphology of the ridge is variable, ranging from domes, through plateaus to faulted grabens. The along-strike morphology shows the same variability, defining elementary segments a few tens of kilometres long which are bounded by transverse features (N45 faults, offsets and overlapping spreading centres). To the south, this area is cut by a wide N45 transform fault which offsets the ridge by about 80 km (Maillet et al., 1989; Ruellan et al., 1989).

From 18°10′S to 16°40′S (Fig.3) the trend of the spreading axis changes from N–S to N15–20. Here, it is characterized by a decreasing width and higher elevation with respect to the adjacent oce-

anic bottom. The total spreading rate in this area is about 4.6 cm/yr between the central and J (Jaramillo, 0.97 Ma) anomalies. Anomalies 2 and 2A have not been identified in this zone.

North of 16°40′S the trend of the ridge is N160. In this area, the precise location of the present-day active axis is difficult to establish. The accretion system consists of a wide and deep graben (more than 4000 m) flanked by two high ridges. The axial magnetic anomaly overlaps the graben and the eastern ridge. This situation obscures the precise location of the active axis.

Both the N15–20 and N160 ridges are flanked by N–S horsts and grabens inherited from the previous phase of opening (Auzende et al., 1988c). The change of direction is dated by the magnetic anomalies to be younger than 1 Ma.

The North Fiji Fracture Zone is another major feature of the North Fiji Basin (Chase, 1971; Green and Cullen, 1973; Carney and MacFarlane, 1982; Brocher and Holmes, 1985). This zone is delineated by numerous seismic events (Hamburger and Everingham, 1986; Hamburger and Isacks, in press; Louat and Pelletier, 1989) from 174°E to its junction toward the east with the northern end of the Tonga Trench. The focal mechanisms show a strike-slip sinistral motion along the fracture relative to the eastward displacement of the northern part of the North Fiji Basin with respect to the Fiji Island Platform (Hamburger et al., 1988). The geometry of the fracture shows a main N55–60 trend relayed eastward by roughly N–S highs and depressions. This non-linearity associated with sinistral motion has created pull-apart basins or compression zones all along the fracture.

The western end of the North Fiji Fracture Zone constitutes the third arm of the 16°40′S triple junction and consists mainly of a wide graben bounded by N60 and N45 faults. The axial part of the graben is occupied by a 20 km long "V"-shaped volcanic zone (Lafoy et al., 1990).

Results of the Starmer diving cruise

Structure

In June 1989, the French submersible *Nautile* and its mothership *Nadir* carried out a diving

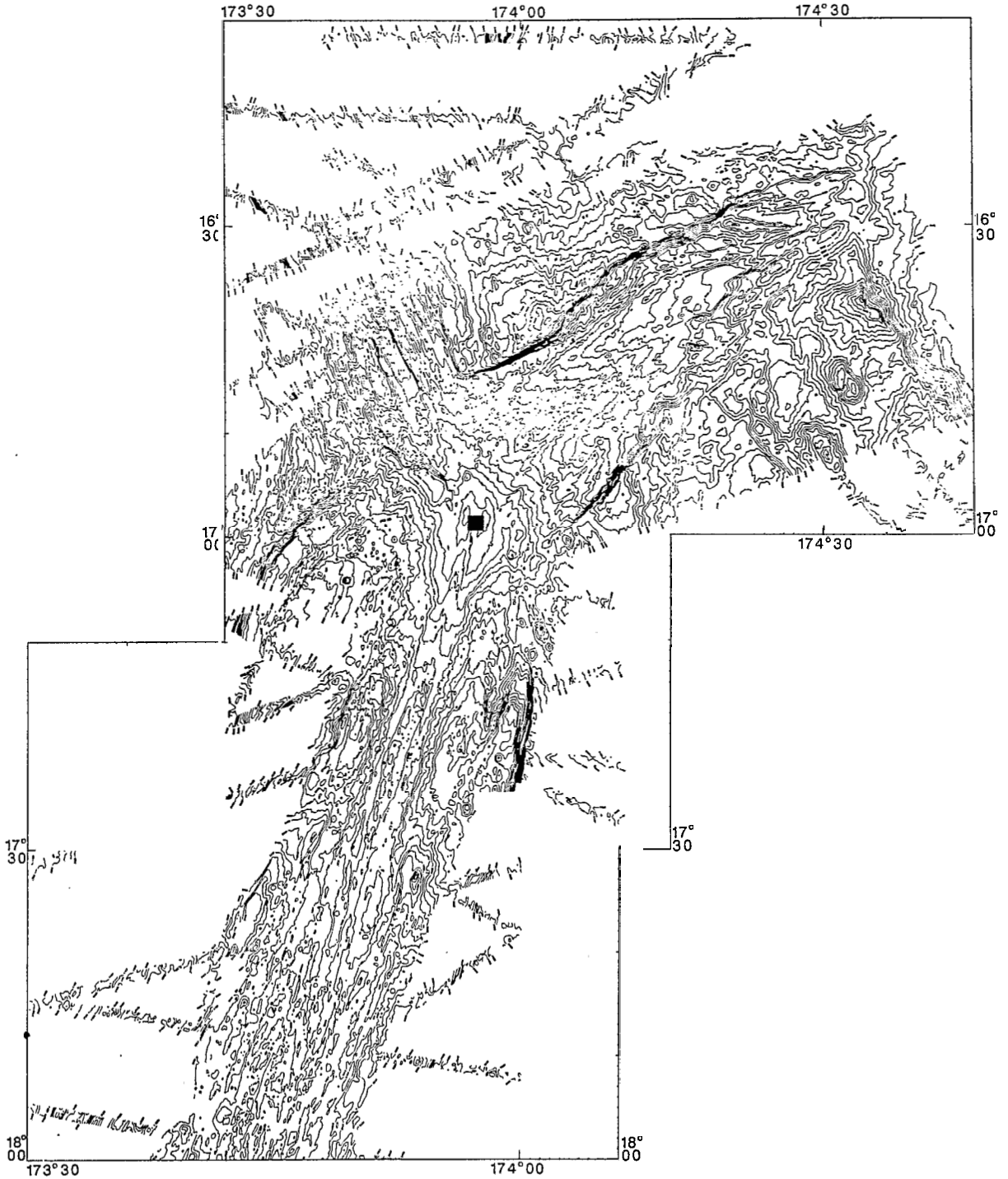Fig.3. Seabeam map of the 16°40 triple junction. The black square indicates the location of the Starmer dives.

cruise on the spreading axis of the North Fiji Basin. One of the main goals of the Starmer project was to locate possible hydrothermal activity related to the accretion processes. Taking into account the manganese and methane anomalies in the water column (Auzende et al., 1988b), we selected several sites on the axis for detailed investigations. One of them is located in the northern part of the N15 axis between 16°50' and 17°10'S.

The axial zone (Fig.4) is occupied by a large, high dome cut by a 2 km wide axial graben. The total width of the dome is 18 km and its elevation with respect to the adjacent ocean bottom is 500–600 m. The top of the dome culminates at a depth of less than 1900 m, which is unusual in a spreading ridge context. The axial graben (width of 2 km) is also unusual for a ridge segment that developed in the same manner as other spreading ridges with intermediate rates of opening, like the East Pacific Rise (EPR) at 21°N (Cyamex, 1981). This northern area is truncated to the north by a major N140 striking fault.

Deep-tow photographs and video surveys were carried out in this area during the *Kaiyo* 87 and 88 cruises in order to obtain new information on geology and hydrothermal activity. Two deep-two profiles show that the seafloor in the central graben is covered with pillow lavas, sheet flows and basaltic breccias. Lava lakes with pillar structures were found along the deep axis of the graben. The amounts of pillow lava and sheet flows are almost equal. The sediment cover is thin. Numerous fissures (0.2–3 m wide) and fault scarps (2–30 m high) were observed within the central graben. Their prominent strike is parallel to that of the central graben. An active vent of the "white smoker" type was discovered at the foot of a steep scarp (16°59.4'S, 173°54.8'E, 1985 m deep). Some inactive yellowish mounds were also found at this site. Several biological communities composed of living mussels, galatheid crabs, brachyuran crabs and other small organisms were also found at this site (Jollivet et al., 1989).

These preliminary results were used to select the diving sites for the third cruise of the Starmer project. One of the selected sites is located in the axial graben on top of the dome constituting the northern tip of the N15 axis. Six *Nautile* dives were devoted to a detailed exploration of the axial graben between 16°58'S and 17°00'S. The dive tracks were positioned to explore the most active part of the axial graben and to locate the hydrothermal vents (Fig.4) (Auzende et al., 1989).

The simplified structural map (Fig.5) was produced from a compilation of observations made during the six *Nautile* dives. From 17°S to 16°58'S, the axial domain consists of alternating N15–trending horsts and grabens. In detail, this system includes two lateral grabens a few tens of metres wide and 10–20 m deep, bounded toward the axis by two horsts of similar proportions enclosing a central graben. This central graben is remarkably constant along the explored area, with a width of 200 m. The tectonic features observed are essentially normal faults oriented N15 (corresponding to scarps bounding the aforementioned structures), and N15 open fissures in the substratum. The width of these fissures varies from a few centimetres to some metres. They are especially common in the main graben and near the slopes bounding the lateral horsts. Except for the scarps, the whole area is covered by a thin sedimentary layer, indicating the absence of recent volcanic activity.

Evidence of fossil hydrothermal activity (oxide staining, fossil chimneys, dead mussels) is distributed all along the main graben. At 16°59'S, in the axial part of this graben, there is a circular area extending few tens of meters with fossil hydrothermal deposit from which emerge a few reddish stumps representing eroded chimneys. The thickness of these deposits can reach 5–7 m in this area. The active site of the White Lady is located in the middle of this old structure (Fig.6a). The White Lady is a 3 m high twin chimney composed entirely of anhydrite. The three main smokers of this chimney emit a transparent shimmering water that reaches temperature of 285°C and contains few particles. Many smaller secondary vents surround it at its base. Important colonies of animals (gastropods, mussels, crabs, galatheans and cirripeds) live around these vents (Fig.6b).

Basalts in this area exhibit the typical morphology of lavas from oceanic spreading ridges (tubes and pillows, fluid lavas, lava lakes and massive flows). The fluid lavas and lava lakes are concentrated along the axial part of the central graben.
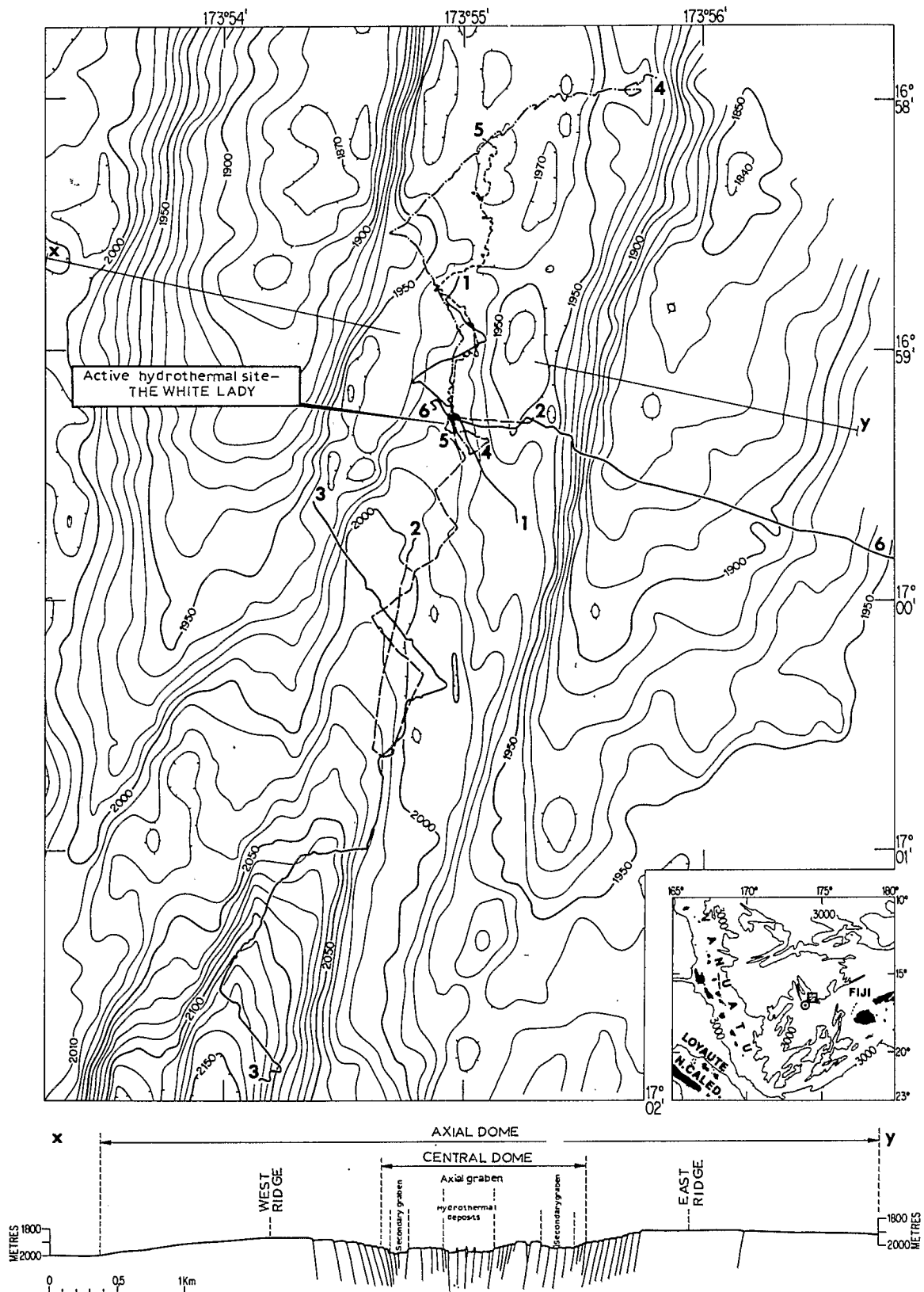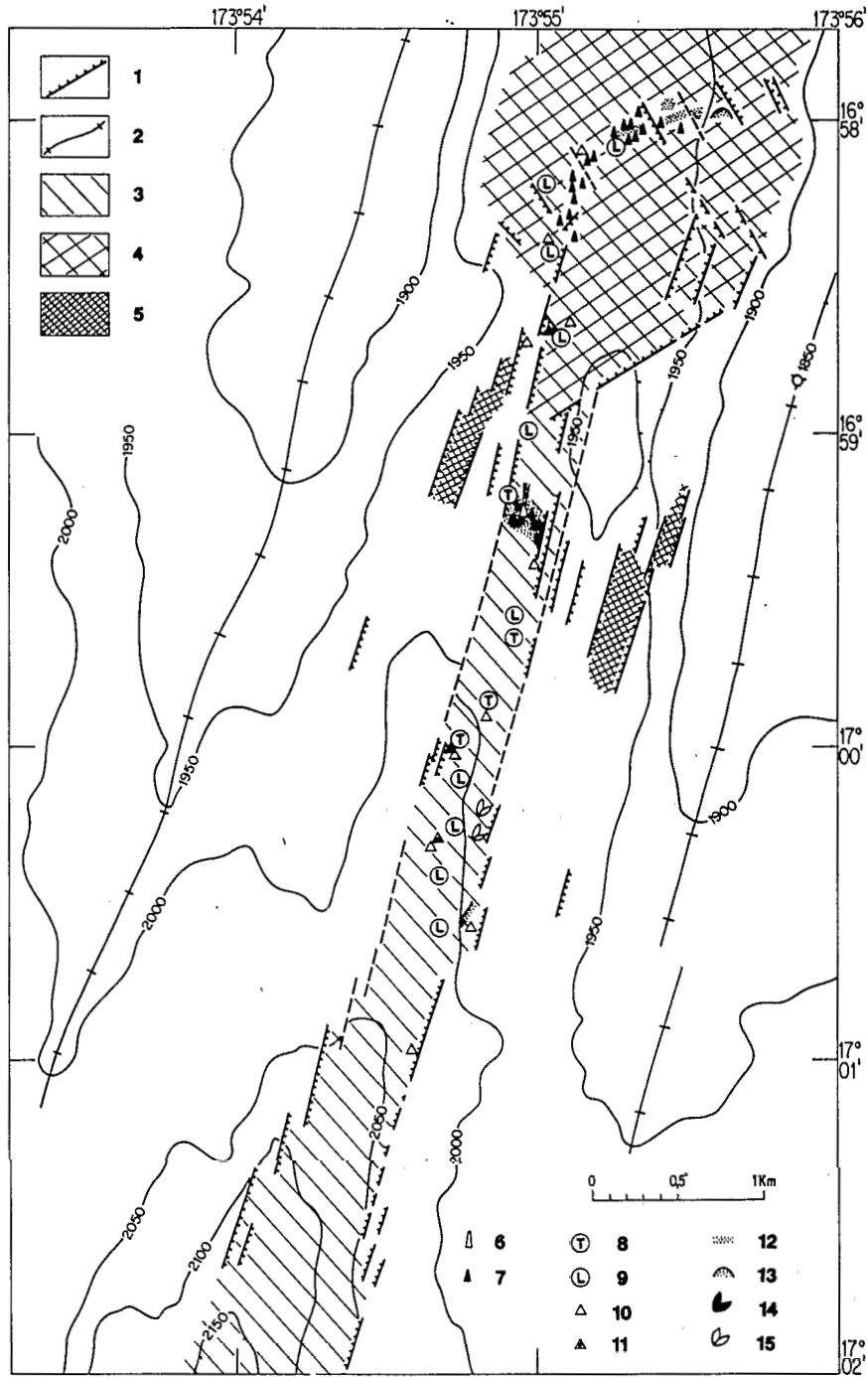
Fig.4. Location map of the Starmer *Nautile* dives.

Fig.5. Geological and structural sketch map of the axial graben. *1* = normal fault; *2* = crest; *3* = main axial graben; *4* = intersection zone; *5* = secondary graben; *6* = active hydrothermal site; *7* = fossil chimneys; *8* = temperature anomaly; *9* = lava lake; *10* = yellow hydrothermal staining; *11* = black hydrothermal staining; *12* = sulphide deposit; *13* = sulphide mound; *14* = living animal colonies; *15* = dead animal colonies.
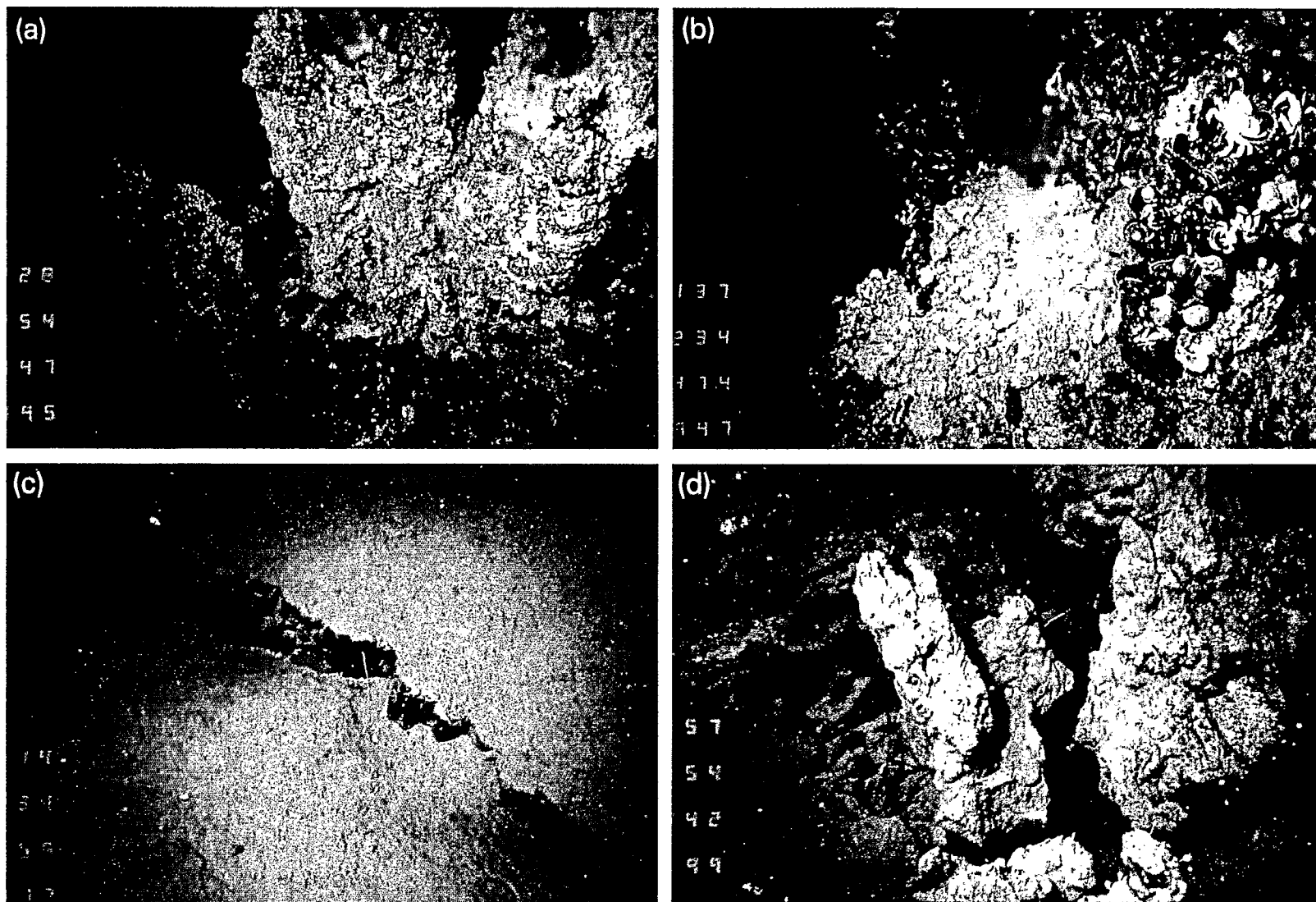
Fig.6. Photographs of the bottom of the axial graben. The approximate surface covered by the pictures is 5 × 5 m. (a) The White Lady active chimney. (b) Living gastropods at the foot of the White Lady. (c) Open fissure on the bottom of the main graben. (d) Fossil chimneys and deposits in the intersection zone.

The lava tubes and pillow lavas are abundant along fault scarps bounding the graben and are associated with a few massive flows; they also build small ridges parallel to the axis associated with fluid lavas. Lava tubes and a few fluid flows make up the bottom and the flanks of the secondary grabens.

North of 16°58.30'S, the axial domain is less distinct. The system of three parallel grabens progressively disappears and is replaced by a more diffuse, wide area, which we have called the intersection domain. Two families of normal faults and fissures (Fig.6c), which are oriented N15 and N140 respectively, can be distinguished. The first family parallels the main trend of the ridge, whereas the second is parallel to the eastern edge of this ridge.

In the intersection domain, the seafloor consists mainly of collapsed lava lakes showing different fill levels and basaltic pillars. At the northern end of the explored area, an important fossil hydrothermal field has been discovered (Fig.6d) Within an area of approximately 1 km², the hydrothermal deposits (sulphides or oxides) are several metres thick and are marked by a cemetery of big extinct chimneys (called the "Père Lachaise site"), some of which may reach 20 m in height.

Sulphides

The sulphide chimney beneath the White Lady consists mainly of pyrite and marcasite, with subordinate amounts of wurtzite, sphalerite, chalcopyrite and covelite. This simple mineral assemblage is similar to that of the EPR system (e.g. Haymon and Kastner, 1981). However, the ore in the North Fiji Basin is characterized by a dendritic growth texture of pyrite and marcasite. Anhedral sphalerite and chalcopyrite fill the pores of, and partly replace, the dendritic marcasite and pyrite. Pyrite replaces marcasite in some cases. This texture suggests that the chimney was originally formed as a skeletal framework of dendritic marcasite created by rapid quenching of hydrothermal fluid which was replaced successively by other sulphides including pyrite, sphalerite and chalcopyrite. This hypothesis is supported by the common occurrence of extremely porous and friable chimneys of dendritic marcasite at the very large inactive hydro-

thermal area about 1 km north of the White Lady. The big sulphide chimneys of this area are relatively poor in copper and zinc and lack sulphate minerals.

Fluid chemistry

The hydrothermal water samples were collected in titanium syringe samplers and were drawn on board the *Nadir* shortly after recovery of *Nautile*. The compositions of the seven samples collected at the White Lady active site range from a few percent hydrothermal water to nearly pure 285°C fluid. They show linear trends in the element concentration vs. Mg diagrams (Grimaud et al., submitted) (Fig.7). Assuming that $Mg = 0$ mmol/kg in the pure end member, we can calculate the extrapolated element concentrations of the parent hydrothermal water end member (see Table 1).

All the extrapolated element concentrations of the parent end member are significantly lower than those of all other hydrothermal systems. Chloride (255 mmol/kg) and sodium (210 mmol/kg), which are by far the major anion and major cation, have especially low concentrations out of the range of
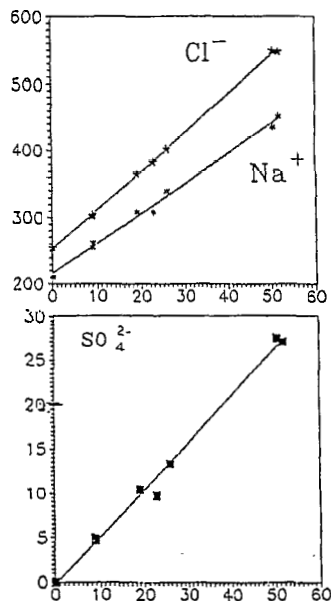

Fig.7. Some element concentrations vs. Mg^{2+} concentrations in the North Fiji Basin water samples. Concentrations are in mmol/kg.

TABLE 1

Some North Fiji Basin water sample compositions and calculated end member chemistry. Values in mmol/kg

	1ST1-2	1ST5-2	1ST5-3	1ST6-2	End Member
Na	308	255	435	262	210
Mg	22.6	8.6	50.4	8.9	0
Cl	383	302	549	304	255
SO$_4$	9.7	4.9	27.4	4.7	0

the fluids collected at the EPR, Juan de Fuca Ridge, Galapagos Spreading Centre (Von Damm, 1988) and mid-Atlantic Ridge (Campbell et al., 1988). Only one fluid from the ashes vent field in the caldera of axial volcano on the Juan de Fuca Ridge (Butterfield et al., 1988; Massoth et al., 1989) has similar Cl^- and Na^+ concentrations.

In spite of these low concentrations, the characteristic elemental ratios K/Na^+ and Ca/Sr and the temperatures calculated using the classical geothermometers Na–K–Ca and Na–Li are close to the usual values which were found for the other seafloor hydrothermal systems (Von Damm, 1988). The constancy of these elemental ratios and calculated temperatures suggests that the sub-seafloor conditions are very similar at all of the sites studied and that the major cations would be controlled by a greenschist-type assemblage of minerals.

The low salinity of the North Fiji Basin hydrothermal water requires an examination of whether the solution has undergone phase separation.

Such a phase separation would result in the formation of one vapour-like phase with lowered salinity and one liquid-like phase with increased salinity (a brine). Dissolved species will be depleted in the vapour but phase separation will not significantly modify the elemental ratios. This is what we observe in the North Fiji Basin hydrothermal waters where the concentrations are very low and the concentration ratios quite similar compared to the EPR and mid-Atlantic Ridge hydrothermal waters. Thus we can estimate that the North Fiji Basin waters partly originate from the condensation of a vapour-like phase created during transit somewhere below the seafloor.

Like Von Damm (1988), we can conclude that the North Fiji Basin hydrothermal waters could result from three-component mixing including "normal" hydrothermal water, low-salinity fluid from condensed vapour, and brine.

Conclusion

The preliminary results of the Starmer diving cruise have established the present-day tectonic and hydrothermal activity of the ridge segment explored by the French submersible *Nautile*. The main manifestations of this activity are intense fracturing and fissuring (aligned along different structural features of the area): N15-trending faults parallel the main orientation of the ridge, N60 faults are those of the North Fiji Fracture Zone, and the N140 fault comprises the major fault bounding the N15 ridge to the north.

The present-day hydrothermal activity is exclusively located in the axial part of the main graben. It is represented by an active chimney named the White Lady, which is constructed of anhydrite lying on fossil sulphide deposits. This chimney expels a relatively low-temperature (285°C) water characterized by the lowest alkali metal concentrations ever observed, and low concentrations of silica, Fe and Mn. Therefore, these waters are very different compared to the waters sampled on the East Pacific Rise and the mid-Atlantic Ridge.

The large fossil hydrothermal field located at the northern tip of the N15 ridge occurs at the junction of three different fracture trends. This emphasizes the relationship between intensity of fracturing and hydrothermal activity.

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