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Hydrological and chlorofluoromethane measurements of the Indonesian throughflow entering the Indian Ocean

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Abstract. The Java Australia Dynamic Experiment high-resolution February-March 1992 conductivity-temperature-depth and chlorofluoromethane section obtained between Australia and Bali and on the sills between Flores, Sumba, Sawu, Roti, and the Australian continental shelf allows detailed examination of the water masses distribution and their inferred circulation. A sharp hydrological front between the Indonesian waters and the southern Indian Ocean waters is found between 13°S and 14°S in both seasons (February-March 1992 and August 1989). It separates the high-salinity surface waters to the south from the lower-salinity surface waters derived from the Indonesian Seas to the north. It reaches the surface in February 1992, whereas it was capped by a particularly low salinity surface layer in August 1989. Near Bali, the NW monsoon of February-March produces large intrusions of low-salinity water from the Java Sea, through Lombok Strait in the upper 100 m. At depth, the North Indian Intermediate Water, flowing along the Indonesian coast, brings salty, low-oxygen and low-chlorofluorocarbon water. It enters the Sawu Sea through Sumba Strait toward the east, while it undergoes strong mixing with the Indonesian Seas water. The primary pathway of the Indonesian waters is found north of the front and south of the North Indian Intermediate Water, between 13°S and 9°30'S, and the associated salinity minimum can be followed all across the Indian Ocean.

Introduction

The western boundary of the tropical Pacific is not continuous and Pacific water can flow through the Indonesian archipelago into the Indian Ocean. The sea level is, on average, higher at the western equatorial Pacific boundary than in the eastern Indian Ocean. The resulting pressure gradient sets up a flow predominantly toward the Indian Ocean, with strong seasonal and interannual variability [*Wyrtki*, 1987; *Kindle et al.*, 1989]. The throughflow is supposed to represent one of the two interocean links for the warm water route, the upper part of a global-scale oceanic cell [*Gordon*, 1986; *Broecker*, 1991]. Recent modeling studies confirm the importance of this throughflow and the consequent heat and salt transports [*Cox*, 1982; *Kindle et al.*, 1989; *Semtner and Chervin*, 1988; *Godfrey and Weaver*, 1991]. Different estimates of the magnitude of the throughflow, by various indirect methods and for different seasons, vary from 2 to 22 $10^6 m^3 s^{-1}$ toward the Indian Ocean [*Wyrtki*, 1961; *Godfrey and Golding*, 1981; *Cox*, 1982; *Piola and Gordon*, 1984; *Fine*, 1985; *Fu*, 1986; *Gordon*, 1986; *Kindle et al.*, 1987; *Murray and Arief*, 1988; *Toole et al.*, 1988; *Godfrey*, 1989; *Kindle et al.*, 1989; *Semtner and Chervin*, 1992; *Wijffels et al.*, 1992; *Wajsowicz*, 1993; *Masumoto and Yamagata*, 1993; *Fieux et al.*, 1994; *Qu et al.*, 1994; Meyers et al., 1995; *Miyama et al.*, 1995; *C. Maes and P. Delecluse*, On the throughflow input on the Indonesian Seas and the Pacific Ocean, submitted to *Journal of Geophysical Research*, 1995].

Water mass analysis shows that most of the thermocline waters derive from the North Pacific Ocean (North Pacific Subtropical Water, North Pacific Central Water, North Pacific Intermediate Water [Fine et al., 1994]). They enter the Celebes Sea south of Mindanao and flow through Makassar Strait; this is the "western route" [*Wyrtki*, 1961; *Linstrom et al.*, 1987; *Lukas et al.*, 1991; *Ffield and Gordon*, 1992; *Bingham and Lukas*, 1994] (Figure 1). Then, they have two ways to flow out toward the Indian Ocean as follows: the direct way for the upper layers through the narrow Lombok Strait (sill depth around 350 m [*Murray and Arief*, 1988]) and an indirect way through the Banda Sea, where they undergo strong vertical mixing and mixing with deeper waters from the South Pacific (South Pacific Central Water, Antarctic Intermediate Water), entering directly from the north of the Banda Sea (the "eastern route") through the Halmahera, the Maluku, and the Seram Seas [*Ffield and Gordon*, 1992]. From the Banda Sea they spread westward into the Indian Ocean [*Rochford*, 1966; *Wyrtki*, 1971; *Gordon*, 1986] through the following two routes (Figure 1): the north Timor route through Ombai Strait, between Alor and Timor, enters the Savu Sea and flows out toward the Indian Ocean through Sumba, Savu, and Roti Straits, the exits of the Savu Sea; the south Timor route goes through the Timor Basin and the Timor Channel, between Roti and the Australian continental shelf near Ashmore Reef. The sill depths along these two routes, being around 1200-1300 m, concern deeper waters than the Lombok Strait route (there is also another possible route for lower thermocline water from the Pacific

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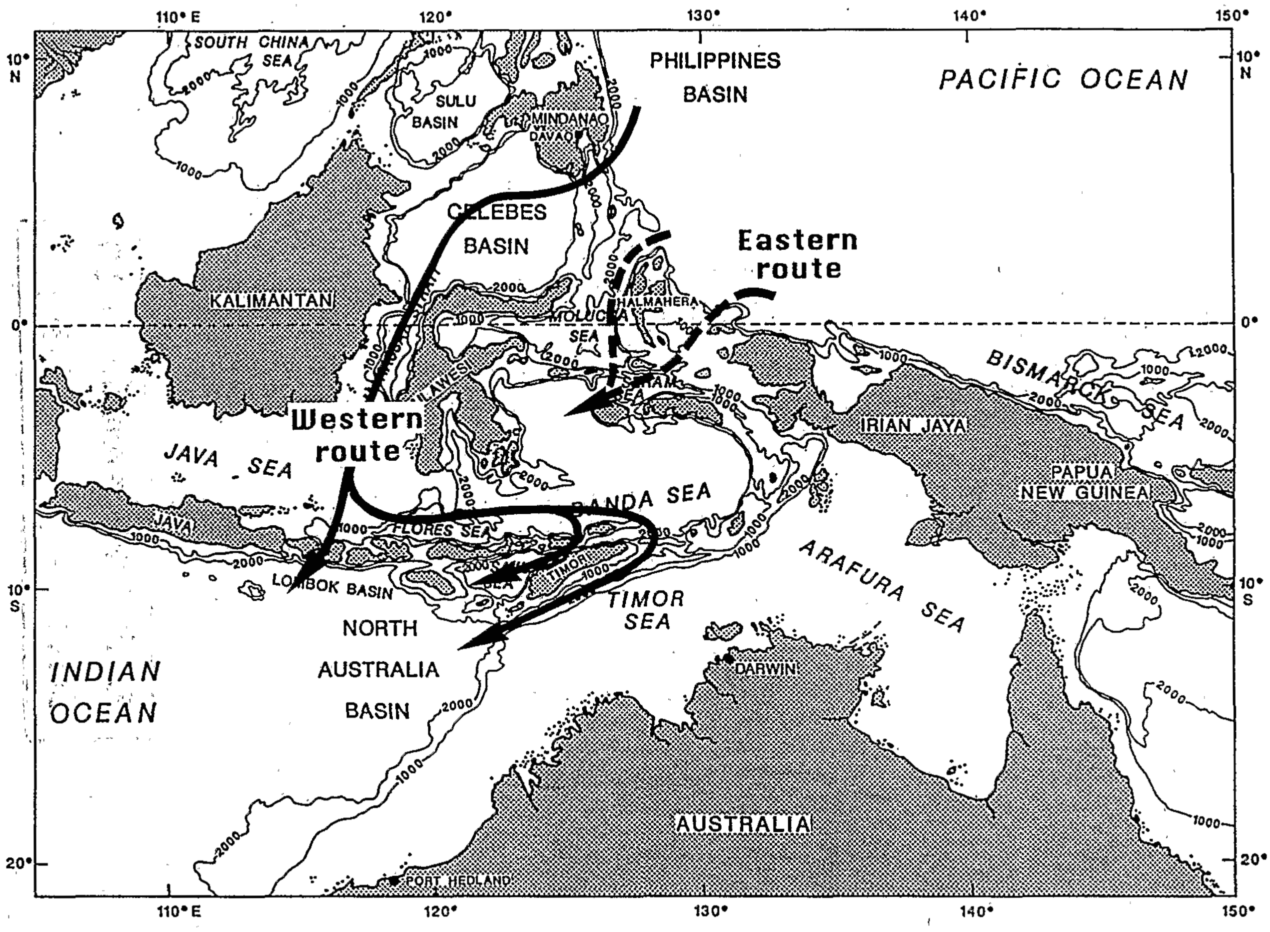

Figure 1. The Indonesian Seas and the possible routes of the throughflow after *Ffield and Gordon* [1992] and *Wyrtki* [1961].

through the Seram Sea and the Aru basin, which could join the water coming from the south Banda Sea into the eastern Timor Sea toward the Indian Ocean [*Van Aken et al.*, 1988]).

In order to study the Pacific-Indian throughflow during the eastern and western monsoons (in August and February), the Java Australia Dynamic Experiment (JADE) program has been set up between French and Indonesian research laboratories. It includes the determination of the characteristics of the water masses of the whole water column together with tracer measurements. The area studied is at the southern exits of the Savu and Timor Seas and across the easternmost basin of the Indian Ocean, between the Australian continental shelf and Bali (Figures 1 and 2). This coproject between Indonesia and France started with the JADE '89 cruise in August 1989 which gave the characteristics induced by the eastern monsoon [*Fieux et al.*,1994]. In order to measure the characteristics at the opposite season, the JADE '92 cruise was set up in February-March 1992. The Australia-Bali section was repeated with a denser sampling, and sections were made across the straits. This paper is focused on water mass analysis from the 1992 data and comparison with the 1989 results.

Data Collection

The JADE '92 cruise took place during the NW monsoon season, on board the R/V *Marion Dufresne* of the Institut Français pour la Recherche et la Technologie Polaires (IFRTP). Between Port Hedland (northwest Australia) and Bali (Indonesia), 29 conductivity-temperature-oxygen-pressure hydrographic stations were occupied down to the bottom. To get 36 water samples, three casts (0-300 dbar, 0-1500 dbar, 0-near bottom) were carried out at each station deeper than 2200 m. The stations were, at the maximum, 55 km apart and were closer near the boundaries, particularly near the Indonesian coast, where the last stations were 11 km apart (Figure 2). The first station was done on the Australian continental shelf and the last one in 630 m of water, 11 km off the Bali coast, west of Lombok Strait. Therefore the section intersects all the waters carried from the Pacific Ocean through the Indonesian Seas toward the Indian Ocean as well as the waters coming from the Indian Ocean. Owing to the encounter with a tropical cyclone in the middle of the section, the intermediate stations, 29, 27, 25, and a repeat of 24 were made after the port of call in Banyuwangi (east Java). Sections were also made in each channels with several repeated casts (Figure 2). All together, it amounts to 151 conductivity-temperature-depth (CTD) casts. These channels represent all the possible passages from the Banda Sea toward the Indian Ocean. The CTD probe was a Neil Brown Mark III equipped with an oxygen sensor. The CTD was mounted with a General Oceanics rosette sampler fitted with 12 bottles of 12 L each. The inside rubbers of the bottles had been replaced by metallic springs and the O-rings had been baked at 60°C under vacuum to reduce as much as possible the atmospheric chlorofluorocarbone (CFC) contamination of the

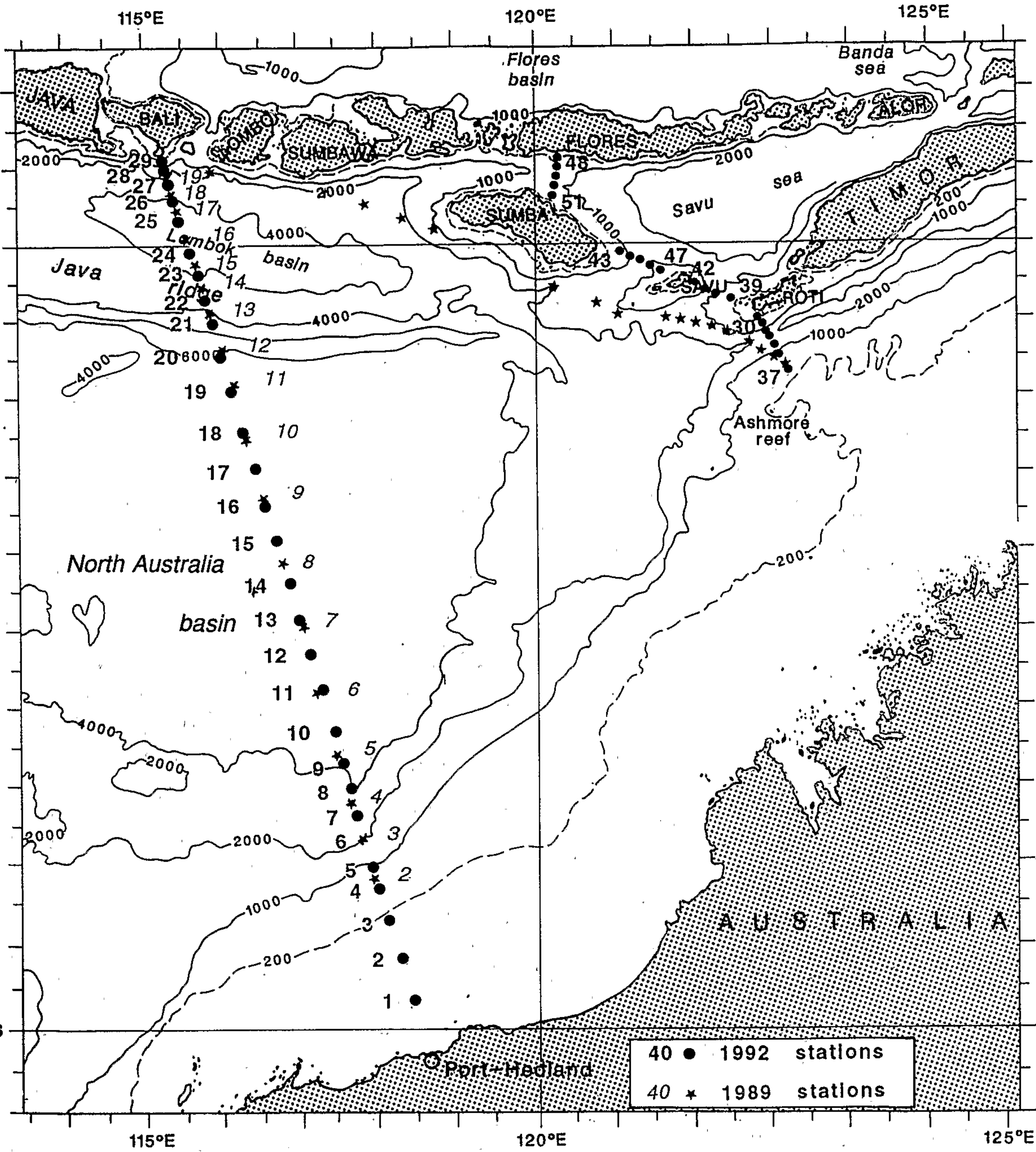

Figure 2. Locations of the Java Australia Dynamic Experiment (JADE) 92 and JADE 89 stations.

samples.The rms of the differences between the salinity and the oxygen measured by the Neil Brown CTD and the measurements made on board for the calibration with a Guildline portable salinometer (which has itself an uncertainty of 0.003) is 0.0028 (per standard unit of the 1978 Practical Salinity Scale) for the salinity and is 0.039 mL/L for the oxygen values (calibrated with the Winkler method, which has an uncertainty of 0.02 mL/L or 0.5 µmol/kg). The temperature and the pressure sensors have been calibrated in Brest Center after the cruise. The maximum difference between the temperatures given by the CTD and the calibrated temperatures after the cruise is less than 0.0005°C, but the temperature reference has an absolute uncertainty of ± 0.003°C. The rms of the differences between the pressure given by the CTD and the calibration data is 0.21 dbar, with an absolute uncertainty of ± 5 dbar. The potential density anomaly (σ_θ in kilogram per cubic meter) was calculated from the International Equation of State of Sea Water, 1980. Analysis of CFCs, CFC-11 and CFC-12, was carried out by gas chromatography and electron capture detection [*Bullister and Weiss*, 1988], calibrated against a primary standard measured at Scripps Institute of Oceanography (SIO 1986 calibration scale). Duplicated CFC-11 and CFC-12 analyses of surface water samples give relative errors of ± 2 %. The detection limit, determined through the standard deviation of the concentration for 12 bottles closed at a same deep level with very low CFC content, is 0,006 pmol/kg for CFC-12 and 0,013 pmol/kg for CFC-11.

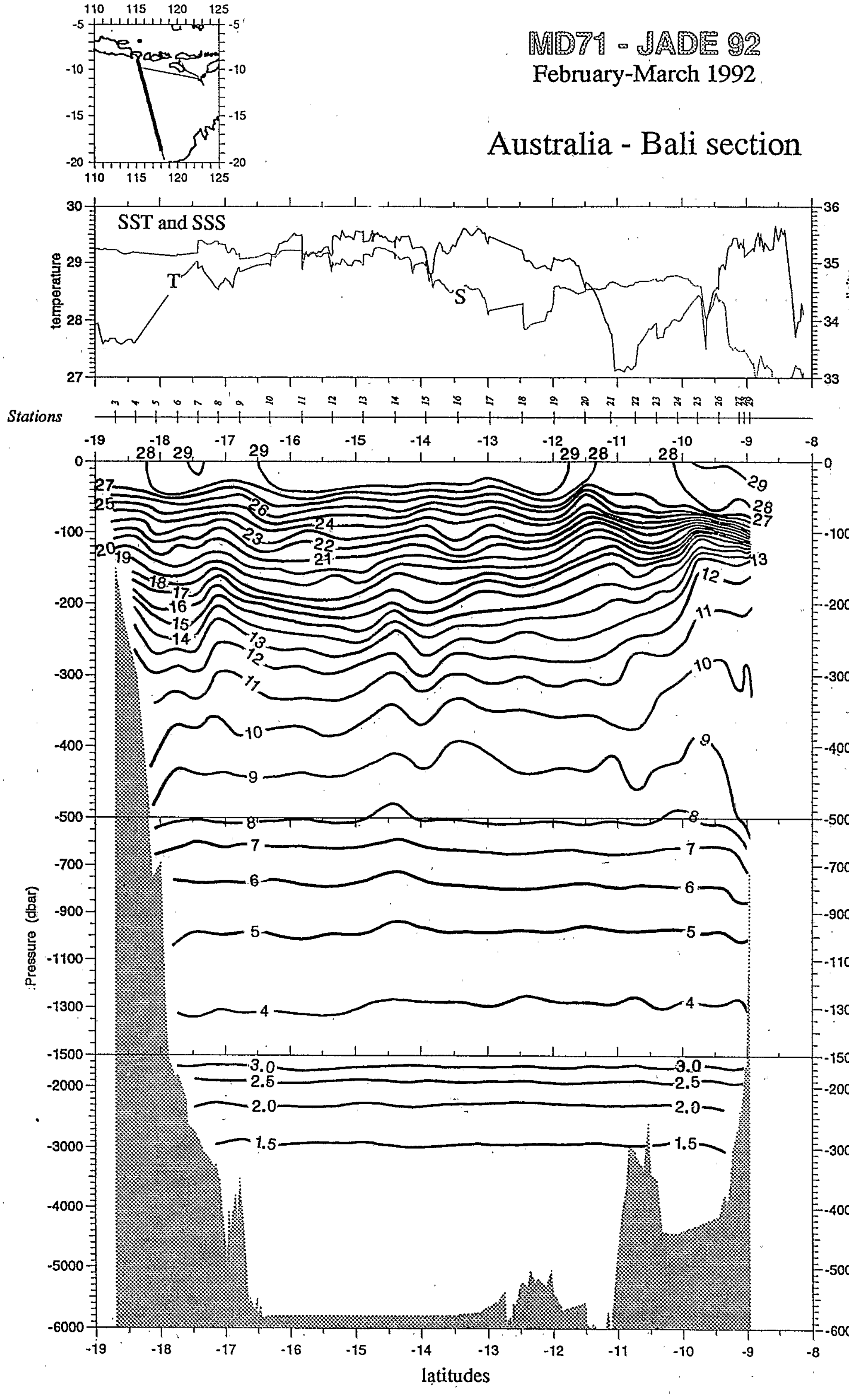

Figure 3a. Potential temperature section between Australia and Bali (lines at 500 dbar and 1500 dbar note a change of scale).

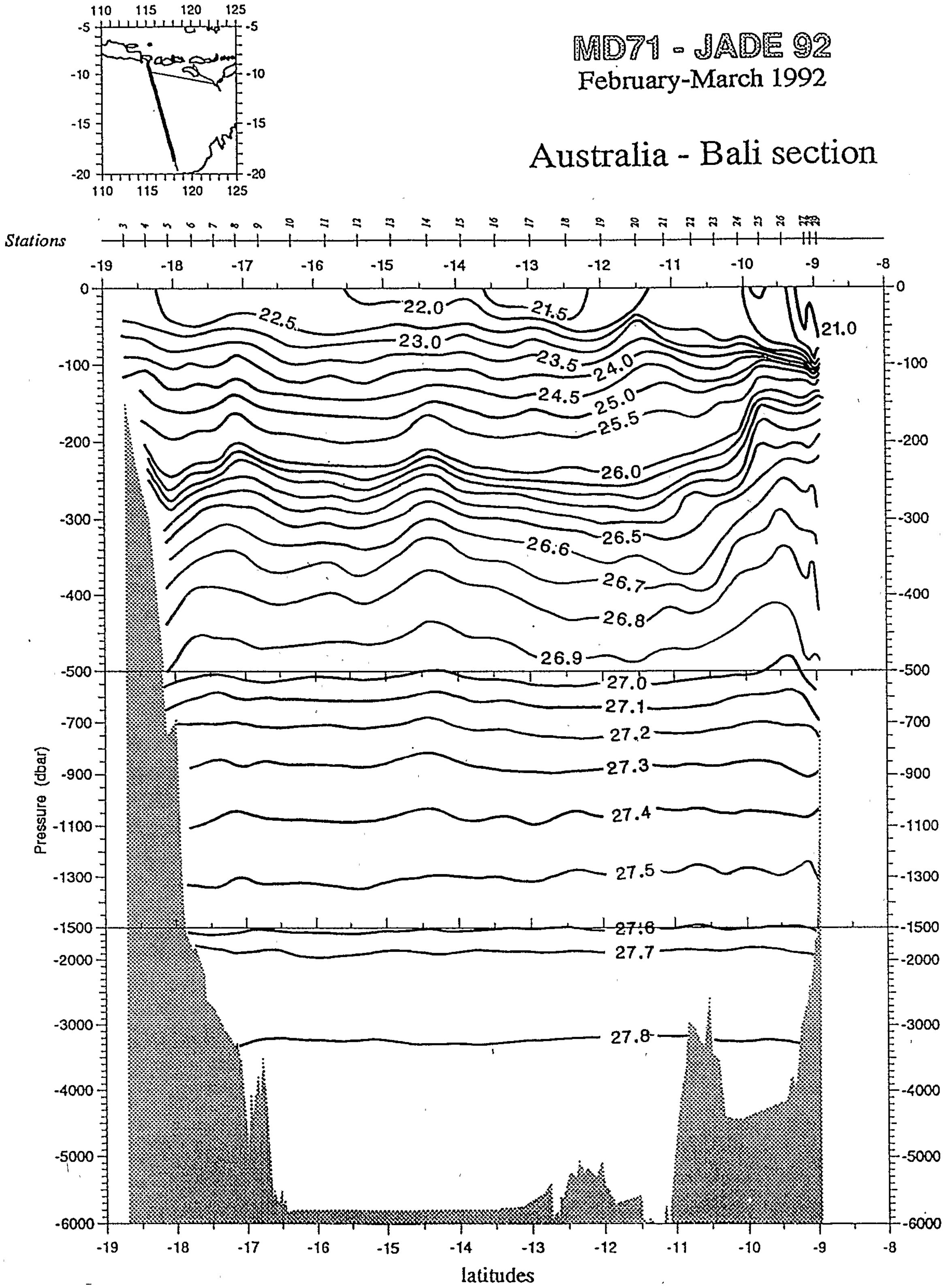

Figure 3b. Density anomaly section between Australia and Bali (isoline interval = 0.5 for σ_θ<26.0, 0.1 for σ_θ>26.0).

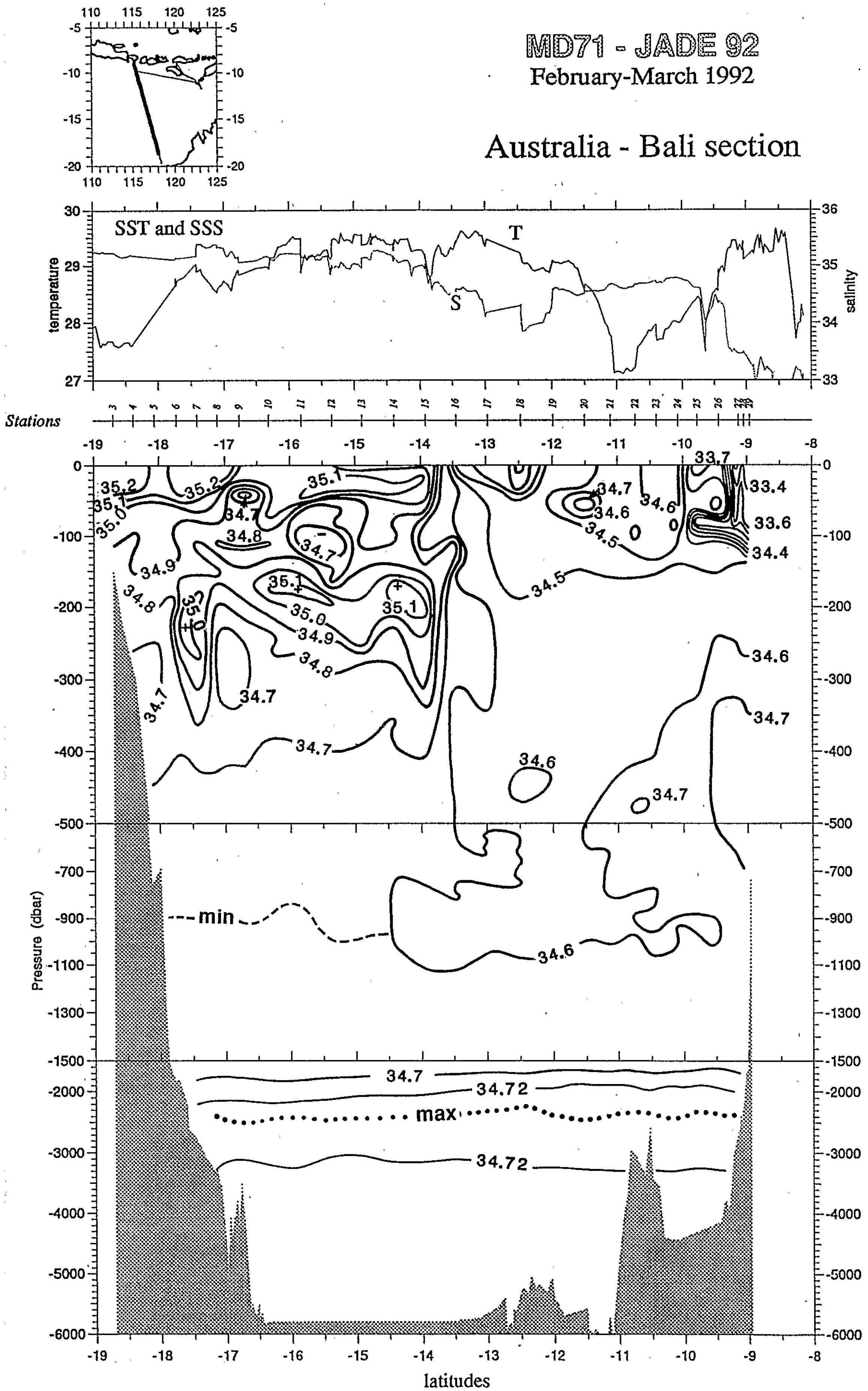

Figure 3c. Salinity section between Australia and Bali (the dashed line indicates the salinity minimum around 900 dbar, the dotted line indicates the deep salinity maximum corresponding to the Indian Ocean DeepWater).

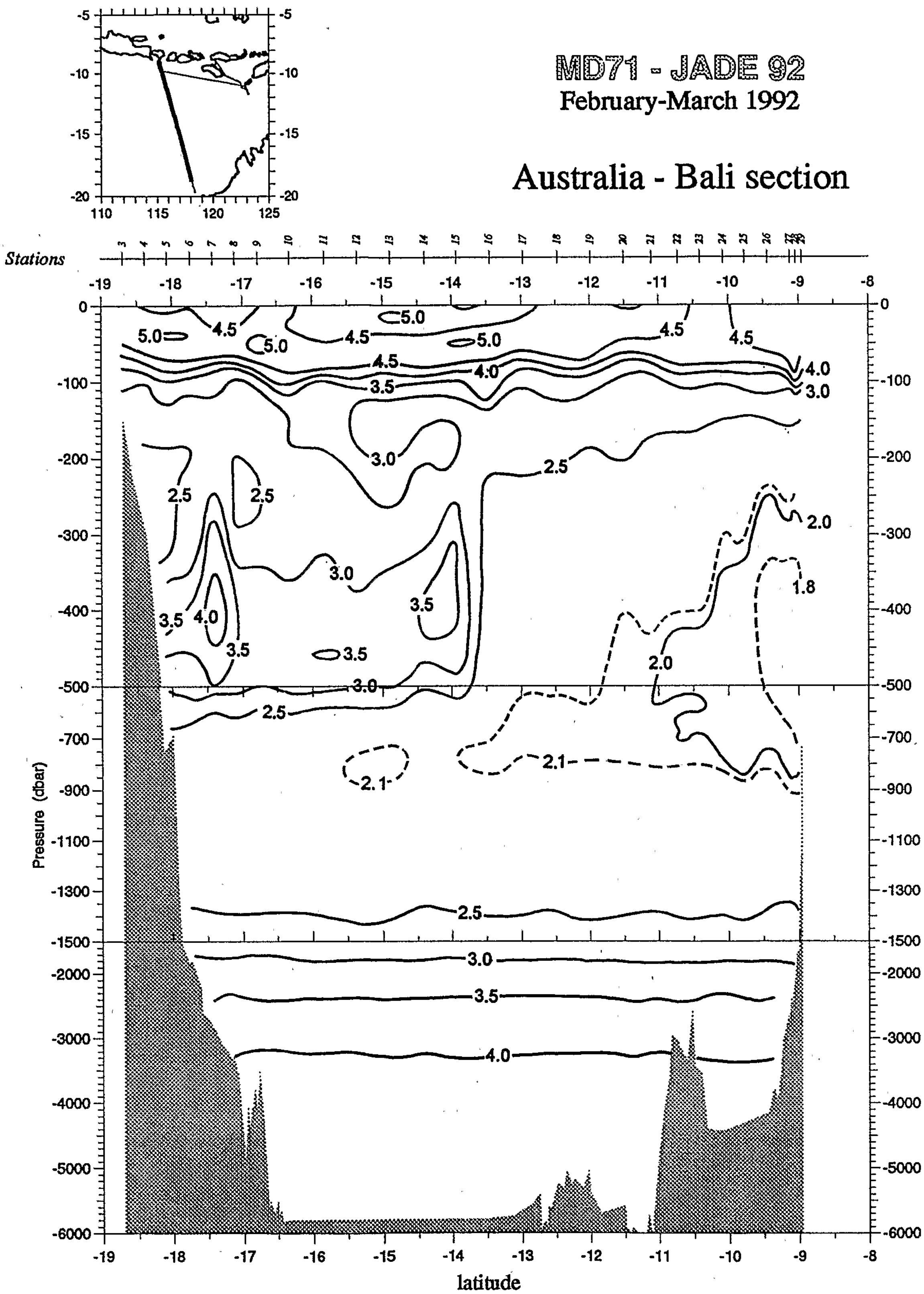

Figure 3d. Oxygen section between Australia and Bali (in milliliters per liter).

Water Mass Analysis

The potential temperature, density anomaly, salinity, oxygen, and CFC-11 content distributions are presented for the Australia-Bali section (Figures 3a-3e).

Surface Layer

The highest temperatures (>29°C) are located in the center of the section, between 16°30'S and 12°S, and in the 110 km off Bali (Figure 3a). The lower surface temperatures between

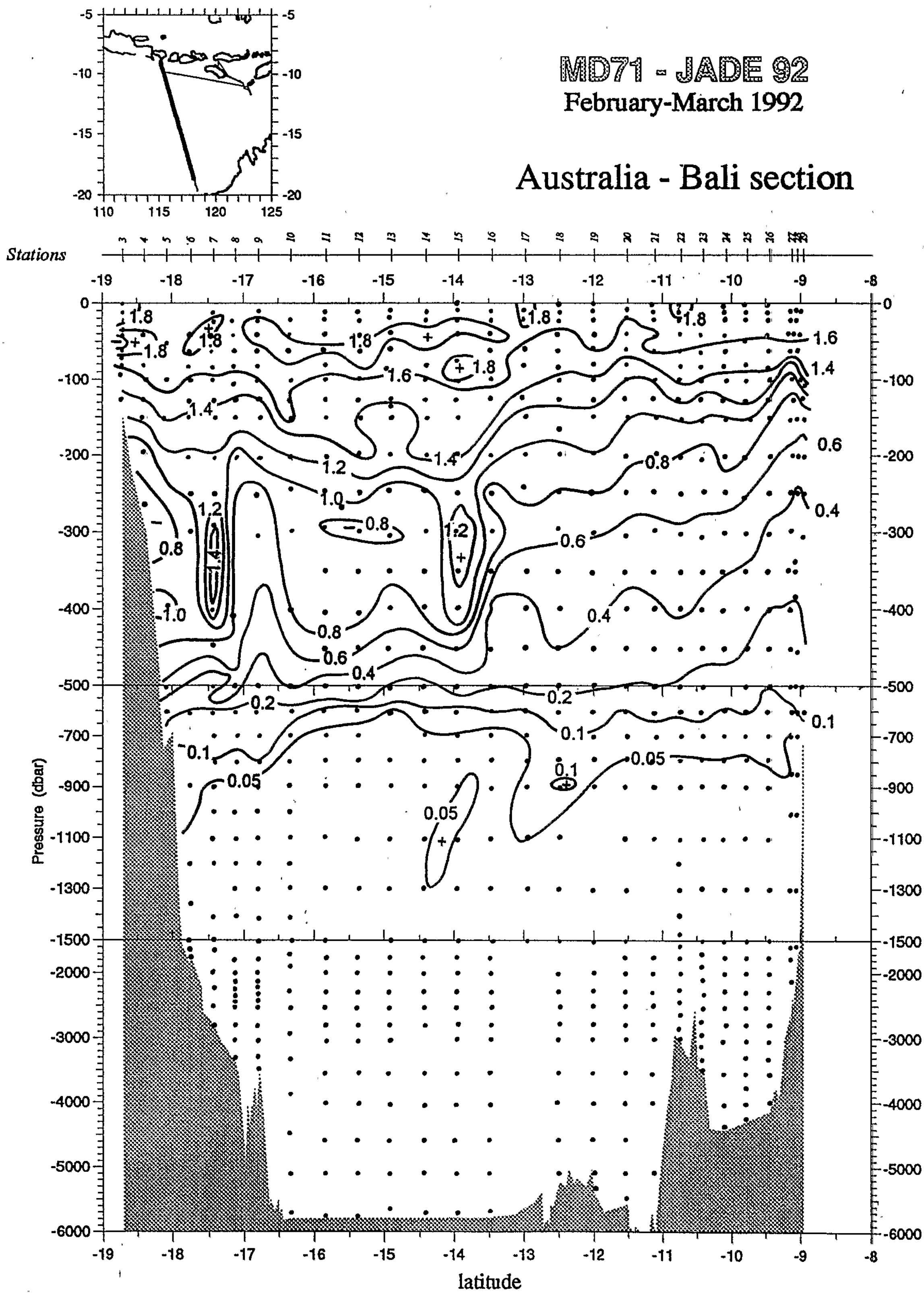

Figure 3e. Chlorofluorocarbon-11 (CFC-11) section between Australia and Bali (in picomoles per kilogram).

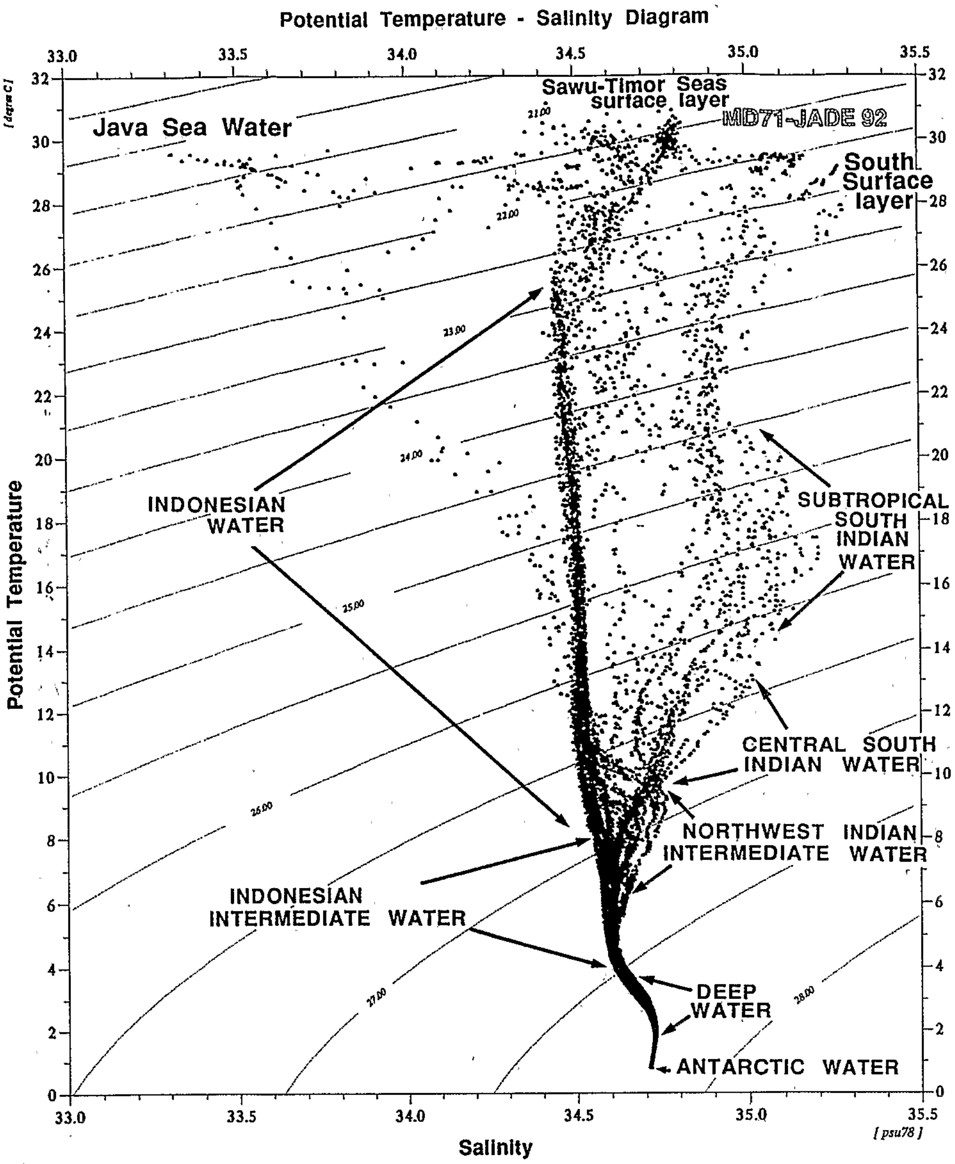

Figure 4a. The θ-S and θ-O_2 diagrams for all the JADE 92 stations (including the Australia-Bali section and sections in the channels) showing water masses involved.

10°S and 11°S are possibly the effect of the strong cyclone that blew over that region just before the measurements and could have induced upwelling and vertical mixing in the area. Above the thermocline the salinities are very variable (Figure 3c). A sharp front around 13°S-14°S separates high subtropical salinities in the south (S>35.0), due to the high evaporation effect in the northwest of Australia, from lower tropical salinities in the north (S<34.6), marking the influence of the Indonesian Seas throughflow affected by exchanges with the atmosphere. Particularly low salinities (S<34) occur in the upper 100 dbar close to Bali, corresponding to waters coming from the Java Sea through Lombok Strait. The low salinity of the Java Sea is due to the intensification of river discharge and rainfall during that season. The measurements close to the coast of Bali show that the extension of this low-salinity water varies with time. It was found, south of Lombok, between stations 24 and 26, on March 1 and reached station 24, 37 km to the south, 6 days later. At station 20, around 60 dbar, salinities higher than 34.7 are an indication of the recirculation of southern waters in the region north of the hydrological front. South of the front, between 15°S and 16°S around 100 dbar and at station 9 around 50 dbar, salinities lower than 34.7 represent mixing with water from the Indonesian channels.

The upper thermocline (between 27°C and 20°C) ($22.5<\sigma_\theta<24.5$) is located between 35 and 150 dbar in the southern part of the section near the Australian continental shelf (Figure 3a) and shrinks in the north, where in the 110 km off the Bali coast, the same isotherms are located, respectively, between 80 and 110 dbar. The downward slope of the 27°C isotherm (upper part of the thermocline) from station 20 to the Bali coast is contrasted by the upward slope of the 20°C isotherm, up to station 25, reflected in the density anomaly section (Figure 3b). These features express the effect of the westerly winds which pile up light waters toward the Indonesian coast, forming an upward dynamic height slope

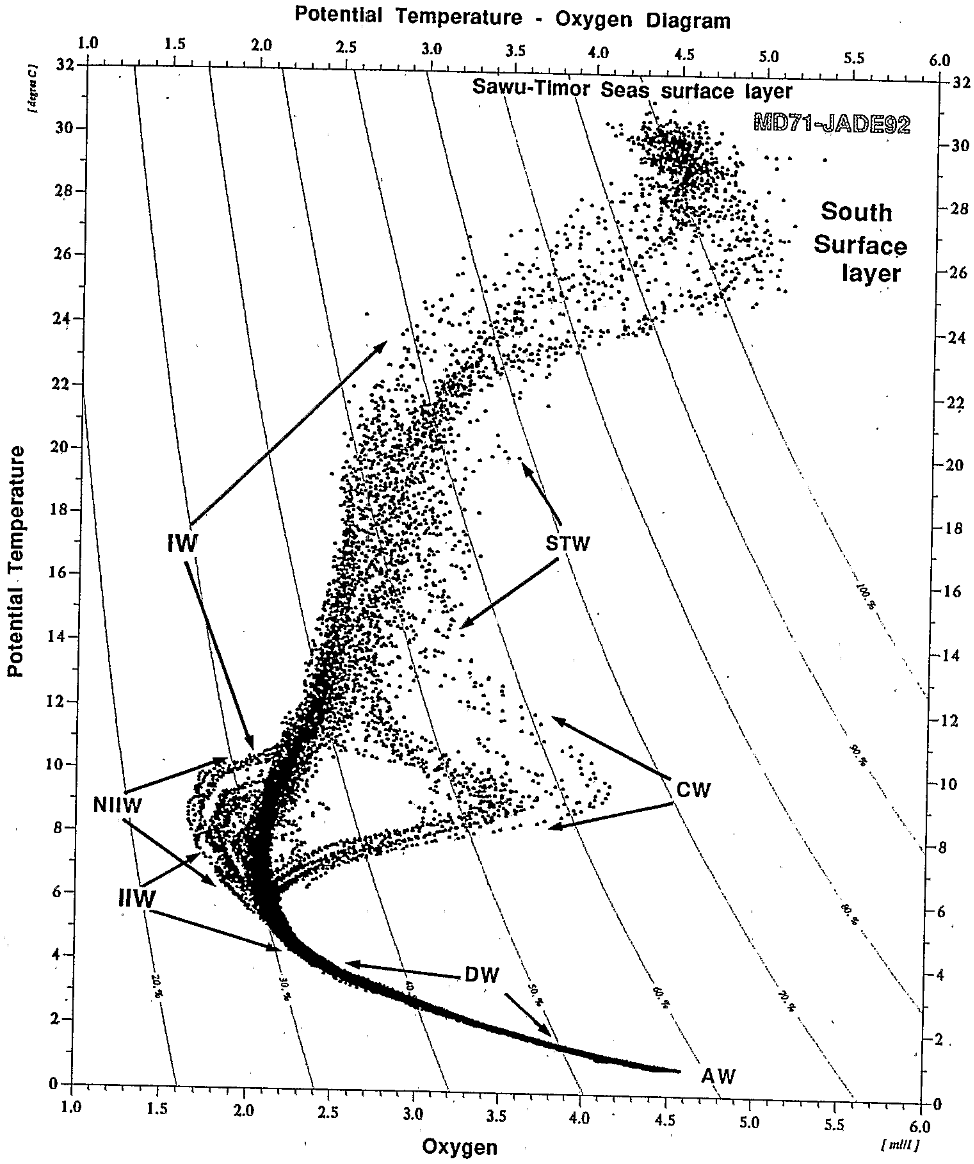

Figure 4a. (Continued)

toward the coast, which produces a downwelling, noticeable in the temperature, density, and oxygen sections (Figures 3a, 3b, and 3d), and generates, in the upper layers during that season, an eastward coastal current; this is the Java current [*Wyrtki*, 1961; *Rochford*, 1969; *Quadfasel and Cresswell*, 1992]. The invasion of low-salinity water near the coast increases the dynamic height, thus enhances the effect of the eastward winds on the surface eastward circulation.

Intermediate Waters

In the lower part of the thermocline, between 150 and 270 dbar ($24.5<\sigma_\theta<26.5$), the hydrological front is located at the same latitude (13°S-14°S) (Figures 3c, 3d, and 3e). South of the front, the Subtropical South Indian Water (STW), characterized by a salinity maximum (Figure 3c and Figure 4a) formed by excess of evaporation over precipitation in latitudes 25°S-35°S of the southern Indian Ocean [*Warren*, 1981], is present in two cores. The northern core extends between stations 10 and 15 with salinities higher than 35.0 in the 160 to 250-dbar layer ($24.5<\sigma_\theta<26.5$) (Figure 3c). CFC-11 enrichments coincide with the salinity extrema of the STW (between stations 10-12 and 14-15) (Figure 3e). In the southern core, detached from the Australian continental slope (stations 6 and 7), the salinity maxima values are slightly lower. Between those two cores and along the continental slope, at stations 4-5 and 8-9, the decrease of salinity, oxygen, and CFC-11 contents indicates mixing with lower-salinity, lower-oxygen, and relatively lower CFC-11 content waters which could be of Banda Sea origin. On the 18°S section the lower salinities were also present near the Australian shelf at that level [*Warren*, 1981, Plate 2) and could be the signature of southward flow, entraining lower salinities and lower oxygen water mixed with water of Indonesian Seas origin. "Ridges" on the temperature and density section at stations 4, 8, and 14 are traces of an eddy-like circulation structure, which could explain the water mass distribution in several cores (Figures 3a and 3b).

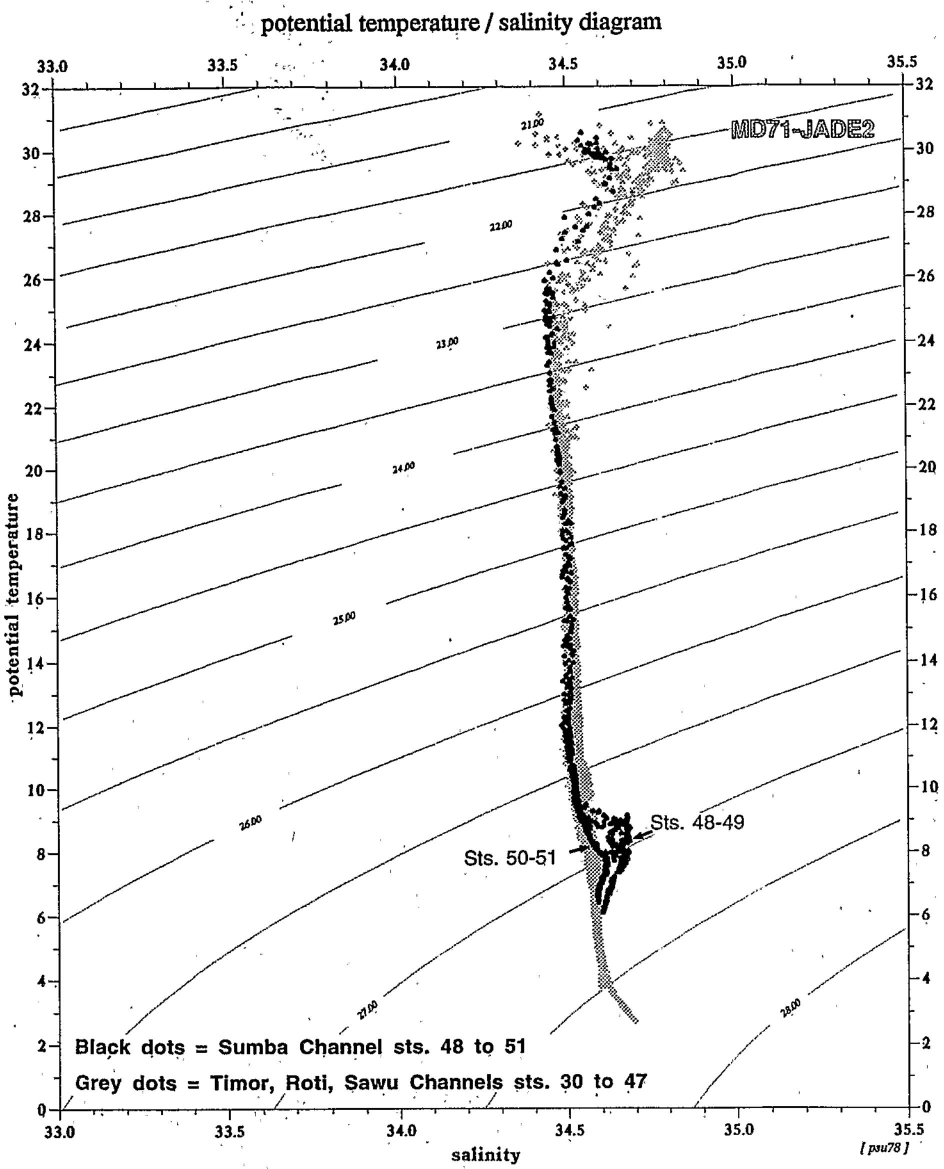

Figure 4b. The θ-S and θ-O_2 diagrams for the channel sections: stations in Sumba Channel are solid, all others are stippled.

Deeper, between 270 and 500 dbar ($26.2<\sigma_\theta<26.9$), the South Indian Central Water (CW) is characterized by high-oxygen values correlated with high CFC-11 contents between 18°S and 14°S (stations 5 to 15, Figures 3d and 3e). The CW maxima (O_2 >3.5 mL/L) are found around 400 dbar in two cores located around 17°30'S and 14°S (stations 5-8 and 14-15, with the highest values at station 7 in the southern core), which also correspond to CFC-11 maxima (F-11>1.2 pmol/kg) at the same locations. It is the continuation of the maximum formed by vertical convection in the southern Indian Ocean, in latitudes 40°S-45°S, near the subtropical convergence [*Warren*, 1981; *Toole and Warren*, 1993, *Fine*, 1993]. The extension of this water mass is mostly bounded by the hydrological front (Figures 3c-3e).

Below the surface layer, which undergoes exchanges with the atmosphere, the waters coming from the different Indonesian channels are characterized by lower and vertically homogeneous salinity and slightly lower CFC-11 content (Figures 3c, 3e, 4a, 4b, and 4c). They are found north of the front (13°S-14°S). Between $26.8<\sigma_\theta<27.4$, the salinity range is particularly small; 34.59-34.60 from station 16 to station 21 (13°30'S-11°S). This is a sign of the direct input of the throughflow waters, which will be discussed later.

Between 250 and 1000 dbar ($26.5<\sigma_\theta<27.4$), adjacent to the Indonesian coast, a water mass is characterized by salinities higher than 34.65, associated with oxygen contents lower than 2 mL/L, values which are not found in the Indonesian Seas, where they are all higher [*Broecker et al.*,1986; *Van Aken et al.*, 1988; *Van Bennekom*, 1988] (Figures 3c, 3d, 4a, 4b, and 4c). However, there is an exception at the bottom of the Savu Sea, around 3000 m, where oxygen goes down to 1.84 mL/L, but it is much below the sill depths which are between 800 and 1150 m. These low-oxygen contents are also associated to a minimum of CFC between 250 and 650 dbar (0.1<CFC-11<0.4 pmol/kg; see Figure 3e). These characteristics are related to the high-salinity, low-oxygen North Indian Intermediate Water (NIIW) diluted by spreading and mixing through the equatorial band [*Wyrtki*, 1971] and

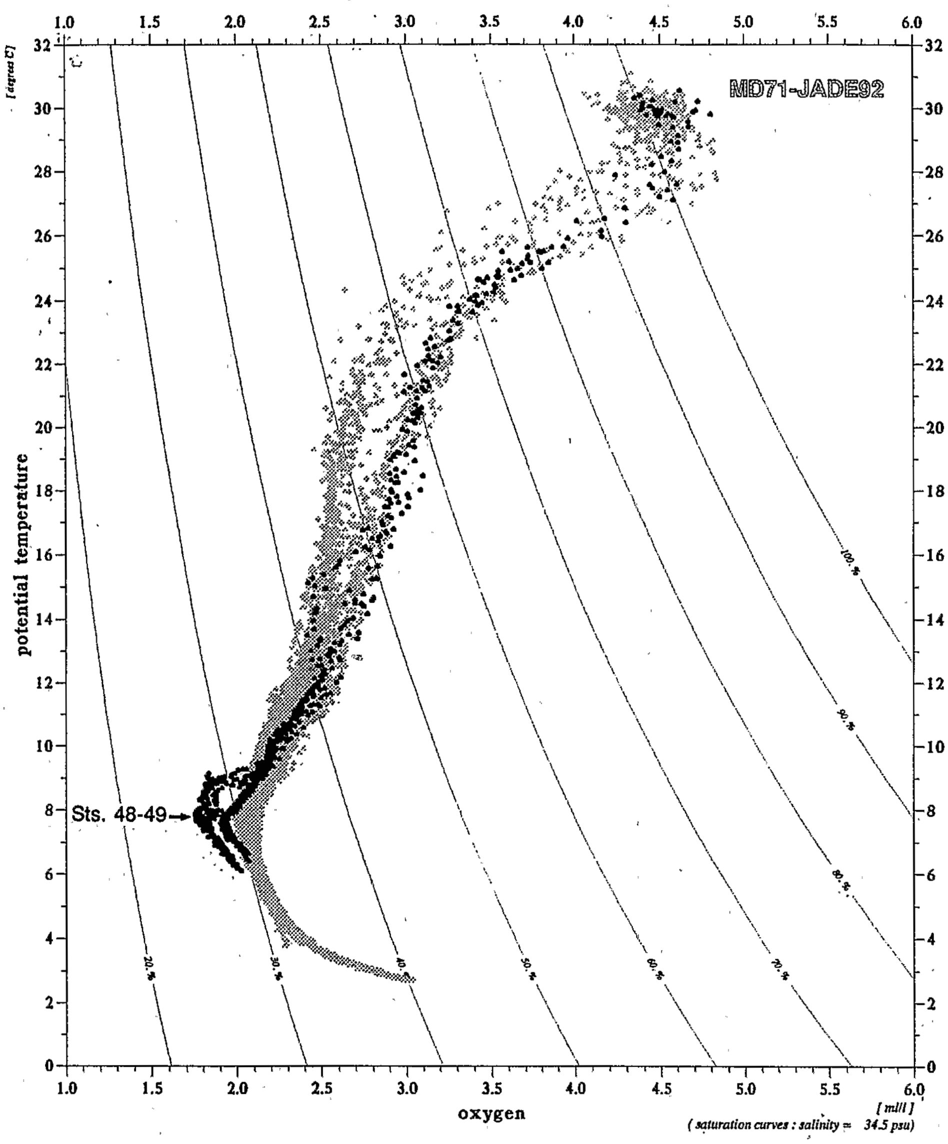

Figure 4b. (Continued)

flowing southeastward along the Sumatra and Java coasts [*Fieux et al.*, 1994]. The core of this water mass is broader than in August 1989 and can be traced to 11°S (stations 22-29). The NIIW influence is mostly pronounced between 400 and 500 dbar, around the $\sigma_\theta = 26.9$ level, where the maximum salinity value is higher in 1992 (S = 34.764 at station 27) and the concentration in the oxygen minimum is lower (O_2 = 1.65 mL/L). Close to the coast of Bali, the corresponding slope of the isolines are downward toward the coast, corresponding to an eastward flow. The lower limit of the NIIW is marked by a salinity minimum, located between $27.3<\sigma_\theta<27.4$, which represents mixing with the water coming from the Savu Sea in the north of the section.

Deep and Bottom Waters

From the study of the θ-S profiles, the salinity maximum found around 2400 dbar, with values between 34.723 and 34.725 south of 12°S and slightly higher (between 34.727 and 34.729) in the north, characterizes the Indian Ocean Deep Water (IDW) (Figures 3c and 4a). Below $\sigma_\theta = 27.50$, all the IDW is slightly more saline north of station 19. This indicates an entrance of the IDW in the easternmost Indian Ocean, along the northern boundary of the basin. As depth increases, the salinity and the temperature decrease and the oxygen increases toward a maximum at the bottom of 4.58 mL/L or 199 μmol/kg (Figures 3a, 3c, 3d, and 4a). This demonstrates the influence of the cold Antarctic Water, which can reach the area through the Perth basin as a deep western boundary current on the eastern flank of the 90°E ridge [*Warren*, 1981]. The coldest bottom temperature is found at the deepest station in the Java trench at 5877 dbar (θ = 0.788°C, O_2 = 4.57 mL/L, S = 34.715; station 21). In the Lombok basin, the characteristics are less extreme (at the deepest station, 4370 dbar; S = 34.717; θ = 1.016°C; O_2 = 4.14 mL/L, station 24) and correspond to a sill depth of around 3500 m located west of Sumba at the eastern end of the Java Ridge.

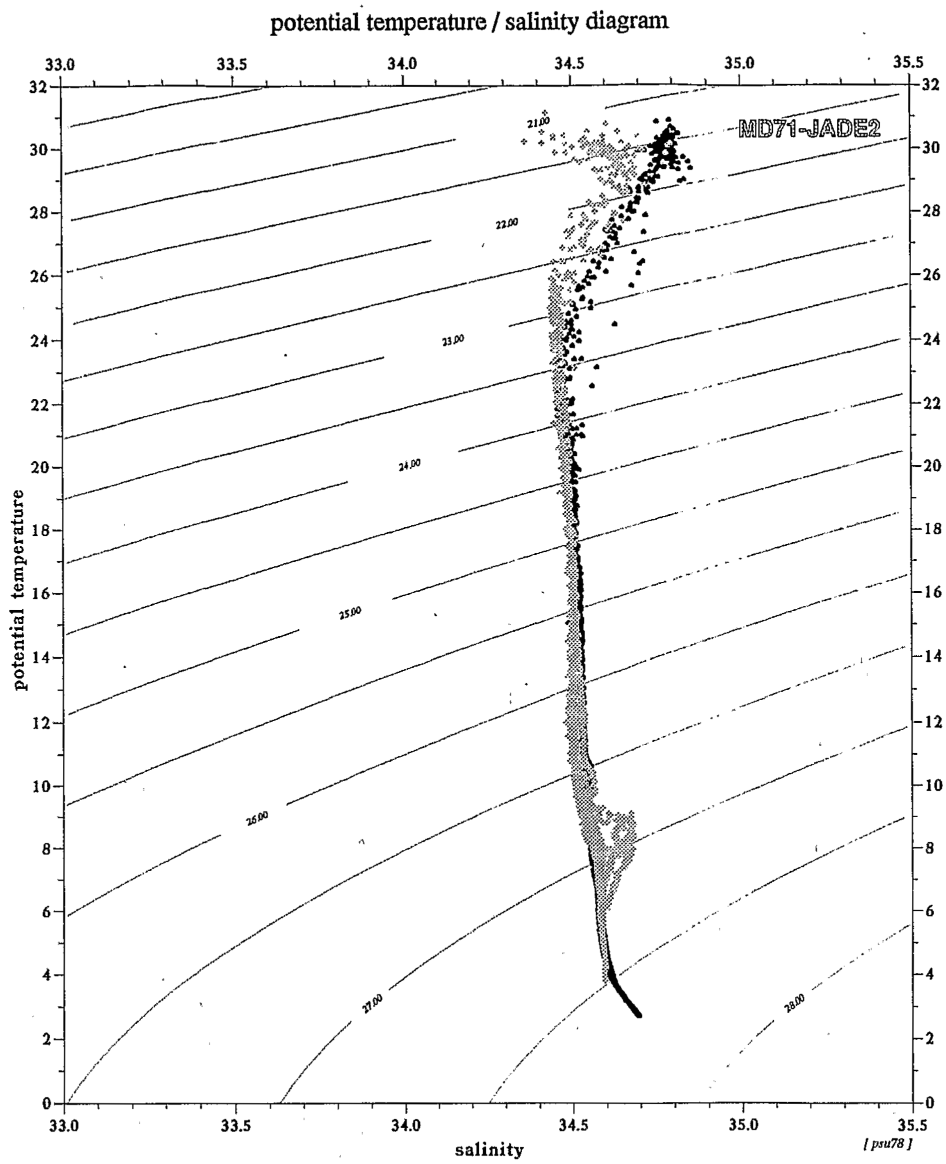

Figure 4c. The θ-S and θ-O_2 diagrams for the channel sections: stations in Timor Channel are solid, all others are stippled.

Discussion

Usually the hot and wet season is during the NW monsoon, accompanied by light winds, and the cooler and drier season is during the SE monsoon [*Wyrtki*, 1961]. In February-March 1992 (Figure 3a), as expected, the surface waters were warmer (more than 2°C) than in August 1989. In contrast, the surface salinity seasonal variations were abnormal. In August 1989, during the usually dry season, the surface salinities were particularly low (33.7<S<34.1) with respect to historical data [*Wyrtki*, 1961). In 1992 the surface salinity varies over a large range, from 35.2 in the south to 33.3 in the north, but the mean salinity in the 0 to 200-dbar layer was higher than in 1989 (Figure 5), contrary to the expected seasonal variation, as February is during the wet season. February 1992 corresponded to an El Niño episode, which reduces the precipitation over the Indonesia-Australia region, and August 1989 occurred at the end of a La Niña event, which enhances the precipitation over the region [*Deser and Wallace*, 1990]. This could explain the reversed seasonal salinity variations observed between August 1989 and February 1992.

The sharp hydrological front separating waters from the southern Indian Ocean from waters from the Indonesian Seas is located at the same latitude during the two seasons (13°S-14°S). In February 1992 it reaches the surface, whereas in August 1989 the upper part was destroyed by the large invasion of low-salinity water, due to the high precipitation and the effect of the Ekman transport to the south during that season.

The STW characterized by a salinity maximum is divided into two cores in both seasons. The southern core, detached from the Australian continental shelf, is thicker than the northern core. It is located at the same latitude (17°30'S) in both seasons. The northern core is found at 15°S in 1989. In

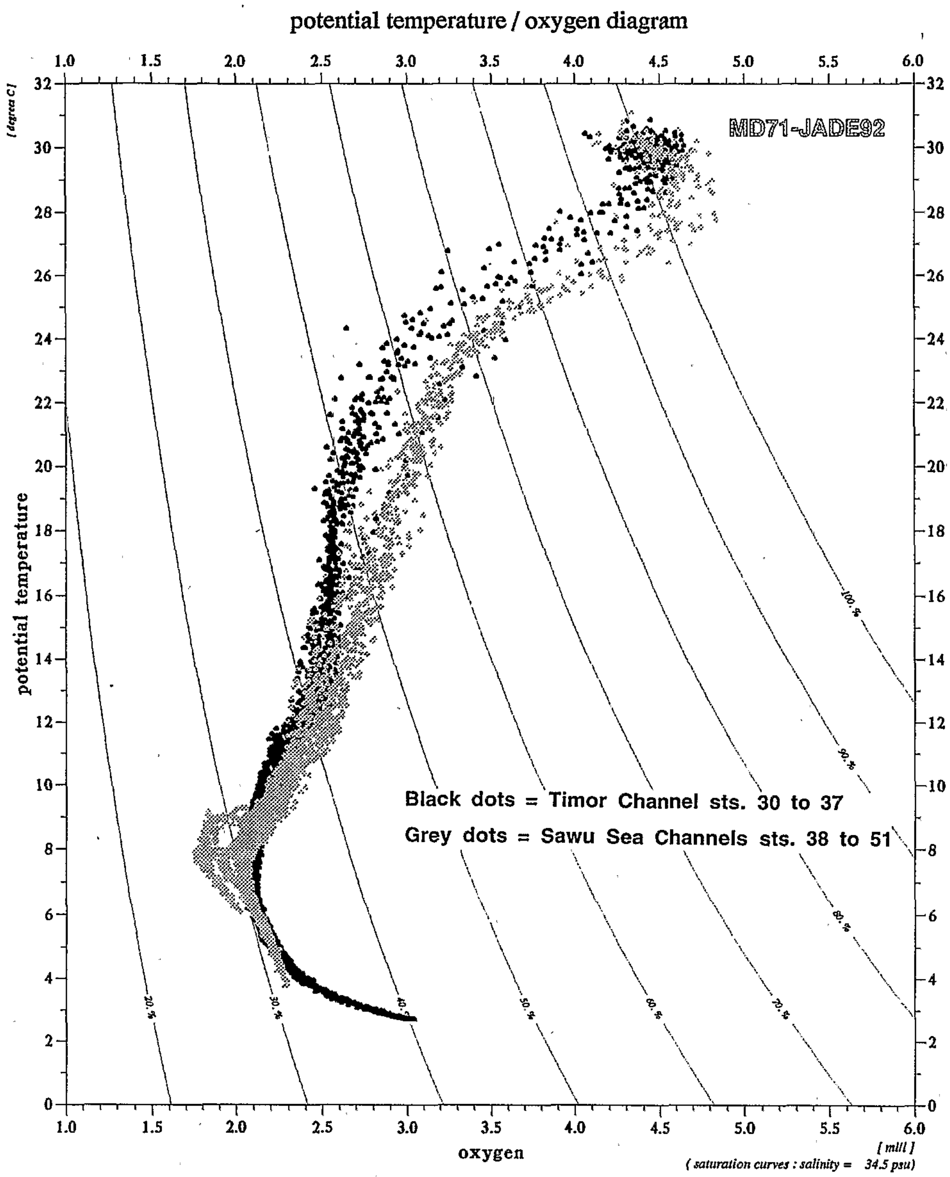

Figure 4c. (Continued)

1992 it stretches from 16°30'S to 14°S. Below the STW cores, the CW cores characterized by oxygen and CFC maxima are found at the same latitudes (Figures 3d and 3e).

The salinity maximum and the oxygen minimum of the NIIW measured in 1992 are more extreme than in 1989. This could be due either to the fact that in 1989 the stations were sparse near the Indonesian coast (difficult to make CTD stations because of very strong current shears) or to stronger transport in 1992. In August 1989, as the stations were too far from Sumba Strait, it was not possible to conclude if this water mass entered the Savu Sea or not. In February-March 1992 the possibility of making stations in Sumba Strait allowed us to trace the NIIW entering the Savu Sea. The core of the NIIW, already altered by mixing with Indonesian waters, was thicker on the northern side of the strait, flowing along the Flores slope, with a salinity maximum of 34.676 and a CFC-11 minimum and an oxygen minimum of 1.76 mL/L around 600 dbar (Figure 4b) (compare with 34.764 and 1.65 mL/L south of Bali). It seems to undergo strong mixing in the Savu Sea and recirculation to the southwest. Remnants of it are detected on the northern sides of Savu Strait and Roti Strait. The oxygen minimum associated with a slight increase of salinity around 550-650 dbar in the Timor Channel (Figure 4c) could be an altered signature of either this water mass or a different water mass coming from the Aru Basin, which is slightly more saline than the south Banda Sea water [*Van Aken et al.*, 1988]. Detailed profiles of salinity and oxygen in south Banda Sea, east Savu Sea, east Timor Basin, and west Aru Basin would allow us to check a possible circulation of this water mass around Timor, through the Banda Sea, which has been already suggested by *Wyrtki* [1961], or from the Seram Sea and the Aru Basin.

Deeper, in the Timor Channel, below $\sigma_\theta = 27.5$ (1300-1400 dbar), the salinity and the oxygen increases mark the intrusion of the upper part of the IDW into the Timor basin toward the east, which is permitted by the deep sill (1895 m). This water is below the shallower sills in the east of the Timor basin (around 1300-1400m), and some mixed part of it may be drawn back toward the Indian Ocean by the throughflow water coming from the Banda Sea. A similar situation is described in

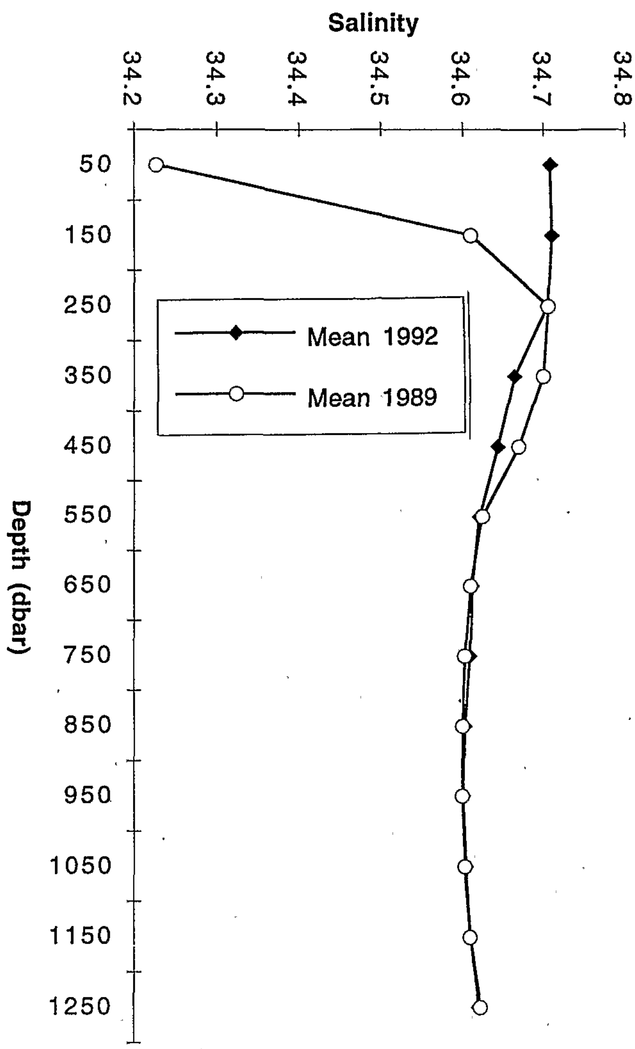

Figure 5. Mean salinity profile on the Australia-Bali section in February 1992 and in August 1989.

the Flores Sea, south of Makassar Strait sill, where the flow entrains deeper water which is compensated by lower thermocline water drawn from the Banda Sea [*Gordon et al.*, 1994]. The Snellius II expedition data suggest that there is a small leak of that IDW into the Aru Basin, where water of 34.64 and 2.42 mL/L flows over the sill, between the Timor Sea and the Aru Basin, which is around 1450 m [*Van Aken et al.*, 1988]. The IDW undergoes vertical mixing with the Intermediate Indonesian Water (IIW) while it is drawn back toward the Indian Ocean between 1300-1350 and 1650-1700 dbar. This transition layer is observed in both water mass characteristics (Figure 6) and in the direct current measurements made on the Timor sill [*Cresswell et al.*, 1993; *Fieux et al.*, 1994; *Molcard et al.*, this issue]. This layer presents a high temporal variability, due to the tidal and internal waves effects; at the deepest station the repeated casts show a fluctuation of several tens of meters for the same isopycnal. Near the bottom of that station, the homogeneity of all the characteristics over nearly 100 dbar could be the result of strong vertical mixing, due to the interaction with the bottom on the sill as in Lifamatola Strait [*Van Aken et al.*, 1988].

In the straits, at the exits of the Savu Sea (Sumba, Savu, and Roti Straits), the salinity is slightly lower in the upper layer (σ_θ<26.7), due to more precipitation and direct influence of water from the Flores Sea, and is higher in the lower layer (26.7<σ_θ<27.4), due to the influence of the NIIW, than in the Timor Channel (Figures 4b and 4c). Below the thermocline, down to 4°C, the structure is nearly isohaline, particularly in the Timor Channel. It is characteristic of the Indonesia Seas effect (Figures 4a-4c). Then, the Indonesian waters (IW), entering the eastern Indian Ocean through the channels, are modified through mixing on their southern side with the STW and the CW and on their northern side with the NIIW (Figure 4a). Deeper, they undergo mixing with the upper part of the IDW.

The respective influences of the CW, NIIW, and IW are examined on σ_θ=26.80, a level located near 400 dbar. The spatial distributions of salinity and oxygen present similar features that permit us to infer the circulation (Figures 7a and 7b). The IW that penetrates the area through the openings of Timor Channel, Roti Strait, and Savu Strait is characterized by lower salinity and intermediate oxygen and CFC-11 contents. The NIIW, flowing along the Indonesian Arc from the equator, brings salt, low oxygen, and low CFC-11 contents. Sumba Strait carries mostly the continuation of the NIIW, modified by mixing with the IW, toward the Savu Sea. The slightly modified IW is found principally north of the hydrological front and south of the NIIW. The limit of the influence of the NIIW is located at 10°45'S (station 22). The distribution of the different characteristics on σ_θ=26.80 surface can be considered as the result of along-isopycnal mixing of these three water masses, which ultimately, find their way toward the west between 11°S and 13°30'S, which corresponds to the South Equatorial Current.

CFC-11 and oxygen add constraints to the classical hydrological tracers, in order to improve the circulation schemes. Figures 8a and 8b give the respective oxygen and CFC-11 distributions on the Australia-Bali section at two different levels, 200 and 400 m depth, respectively, corresponding to the most pronounced influence of the STW and CW. At those levels both oxygen and CFC-11 contents drop rapidly between 14°S and 13°S, corresponding to the hydrological front. At 400 m depth the characteristics of the CW are reduced at 17°S and 14°30'S (stations 8 and 13) by mixing with lower CFC waters; the low-oxygen, low CFC-11 contents of the NIIW are noticeable north of the section. At the 200-m level the front looks less sharp on the oxygen distribution than on the CFC-11 one, which is probably the result of biological consumption south of the front.

The CFC11-oxygen diagram (Figure 9) below CFC-11=1.2 pmol/kg clearly shows two different distributions south and north of the hydrological front (stations 8,13,15, and 25-28). The CFC11-oxygen relationship is more regular for the northern stations of the Australia-Bali section (stations 25 to 28) than for the stations located south of the front (stations 8, 13, and 15). The high variability observed in the diagrams of the southern stations is due to the relative influences of STW and CW, which bring high-oxygen and CFC-11 contents between 200 and 500 m depth. The CW input is quite noticeable through the CFC11-oxygen diagram for station 15 (O_2>150 μmol/kg, CFC-11>1 pmol/kg; Figure 9) and somewhat less important for stations 8 and 13. For shallow depths (< 250 m), waters from Sumba Channel are similar to the northern stations 25-28. It is different for the Timor

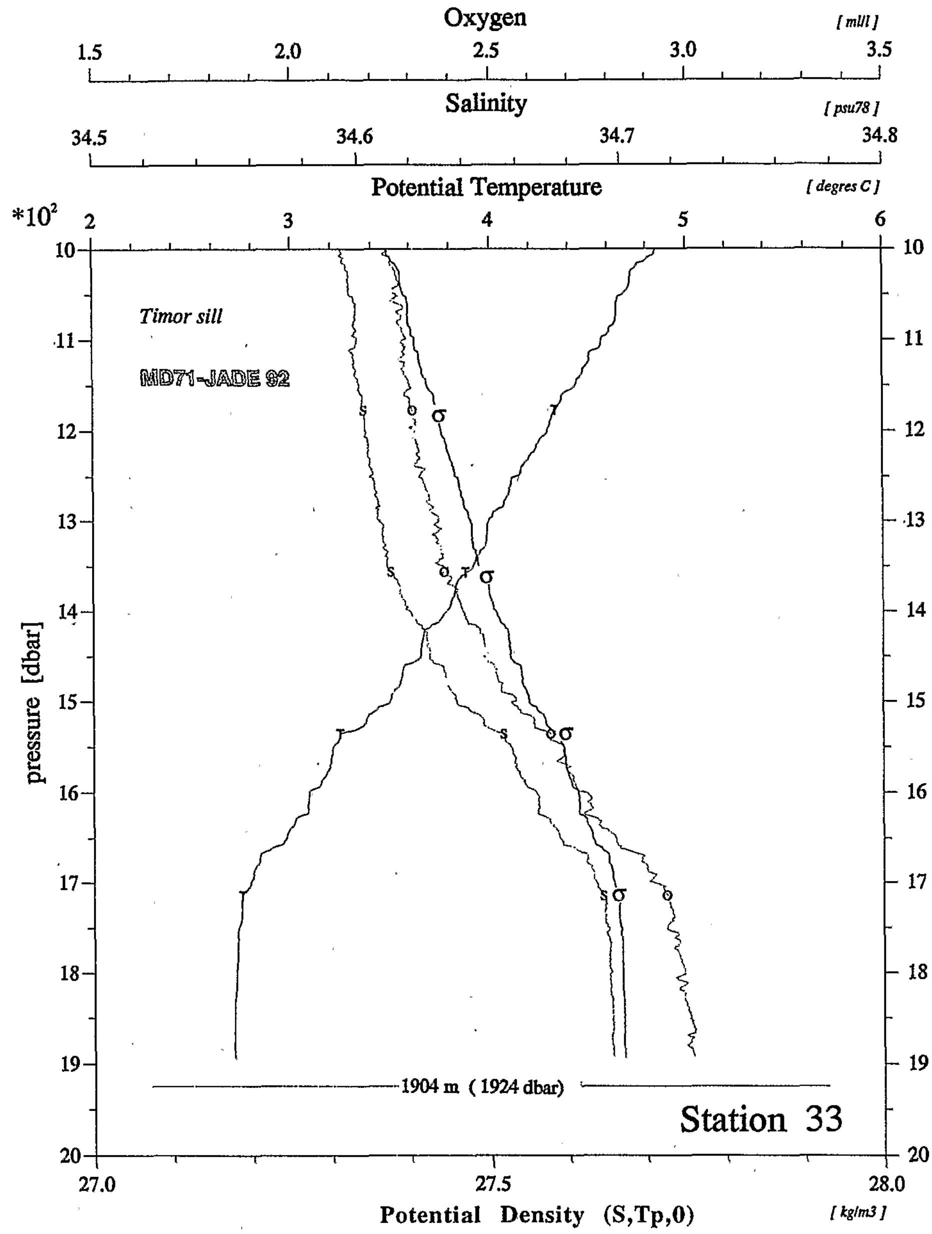

Figure 6. Detailed profiles of T, S, O_2, and σ_θ on Timor sill.

Channel; in this depth range (<250 m) the Timor Channel waters (station 35) greatly influence the water mass composition of some of the Australia-Bali southern stations (stations 8 and 13) as was seen on Figure 8. At depth (CFC11<0.4 pmol/kg), in the straits, waters have different characteristics; in Sumba Strait (station 49), lower CFC-11 and oxygen contents than in Timor Strait (station 35) indicate the influence of the NIIW (stations 25-28).

From the detailed study of the θ-S and θ-O_2 diagrams of the stations in the channels and between Australia and Bali (Figures 2, and 4a-4c), the direct impact of the Indonesian water in the Australia-Bali section, with minimum mixing, can be sorted out into two layers (Figure 10). The IW upper layer is located below the surface layer (influenced by either the very low salinity water coming from the Java Sea through Lombok Strait or the high salinity from the southern channel) and above 350 dbar. It extends between 13°S and 9°30'S. As expected, the characteristics of this water mass correspond more closely to the Savu Sea characteristics in the north of that layer and to the Timor Sea ones in the south.

The lower layer, corresponding to the Intermediate Indonesian Water (IIW), named Intermediate Banda Sea Water by *Rochford* [1966], fills the region between 14°30'S and 11°S (Figure 10). Its lower limit is around 1100-1300 dbar, which represents the sill depths of the Savu Sea and the NE Timor Sea. It is thicker between 13°S and 11°30'S, where its upper limit reaches 500 dbar. It is characterized by a isohaline structure, even more vertically isohaline than the upper layer (34.59-34.61 between σ_θ = 26.8 and 27.4). It corresponds to low and homogeneous oxygen content and slightly higher CFC-11 concentrations (> 0.05 pmol/kg) than in the south at those depths. CFC-11 concentrations reflect the IIW input from deep layers of the straits (Figure 3e); at 900 dbar, CFC-11 concentrations are higher in the straits than on the Australia-

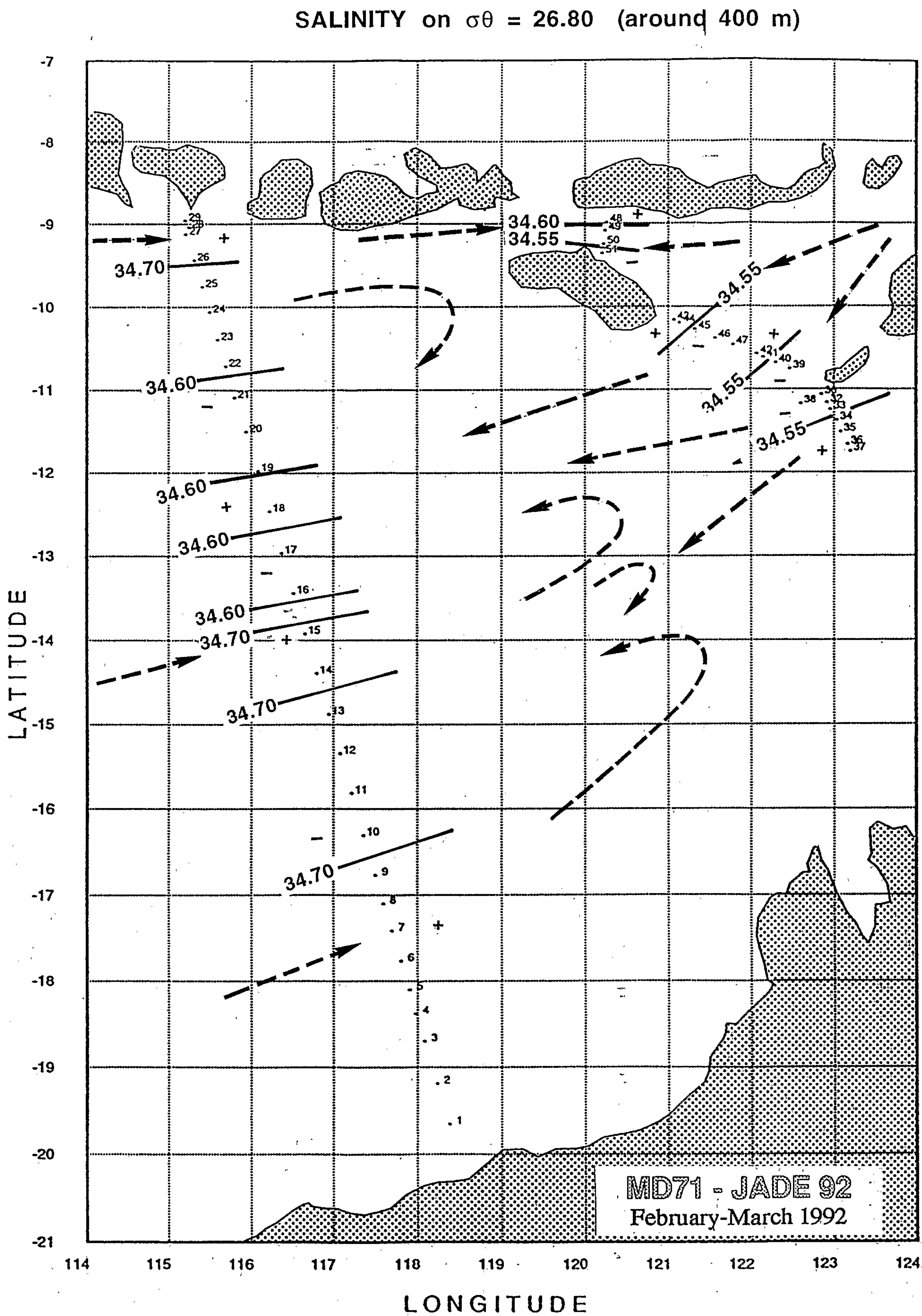

Figure 7a. Spatial distribution of salinity on $\sigma_\theta = 26.8$ for February-March 1992.

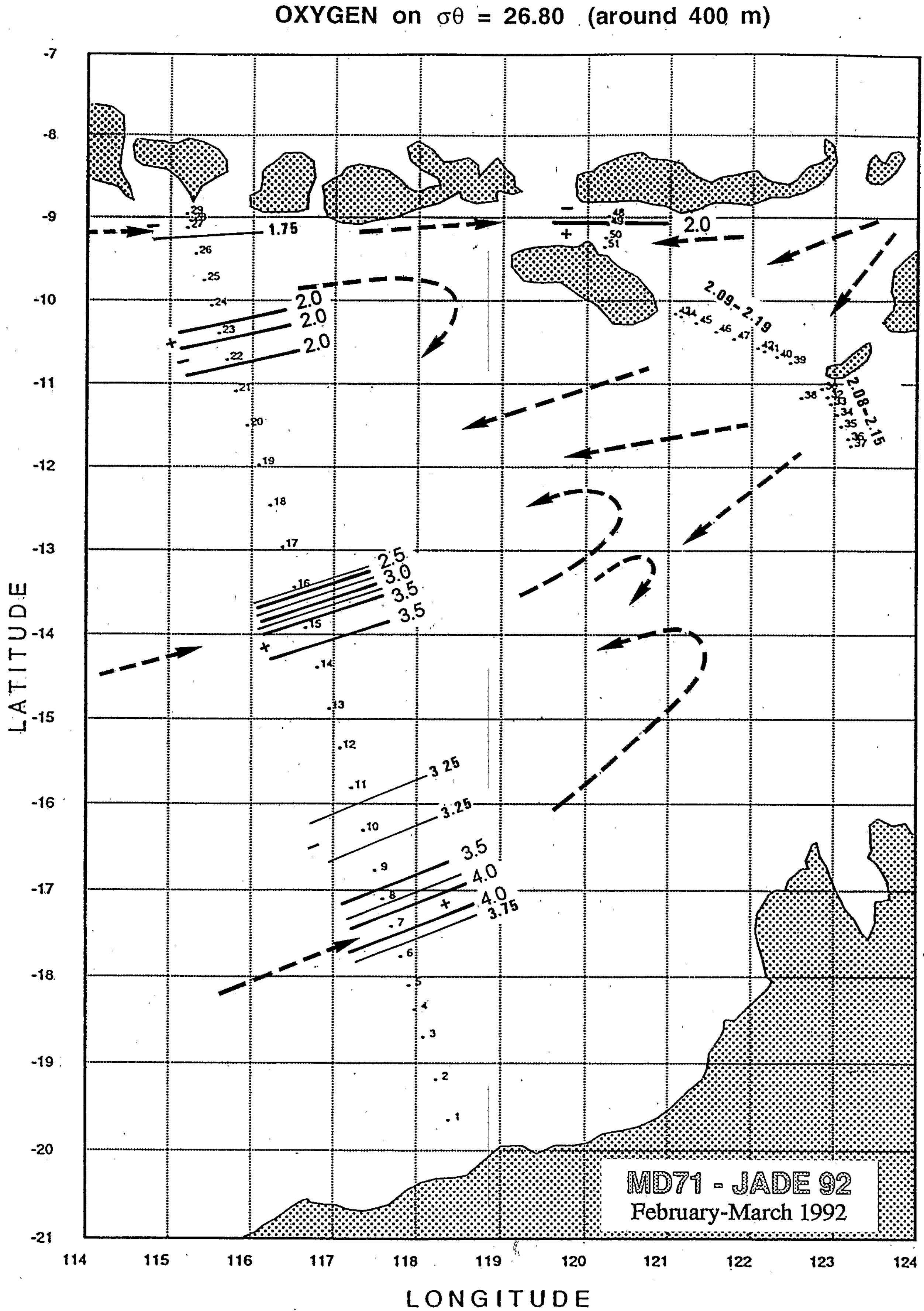

Figure 7b. Spatial distribution of oxygen on σ_θ = 26.8 for February-March 1992.

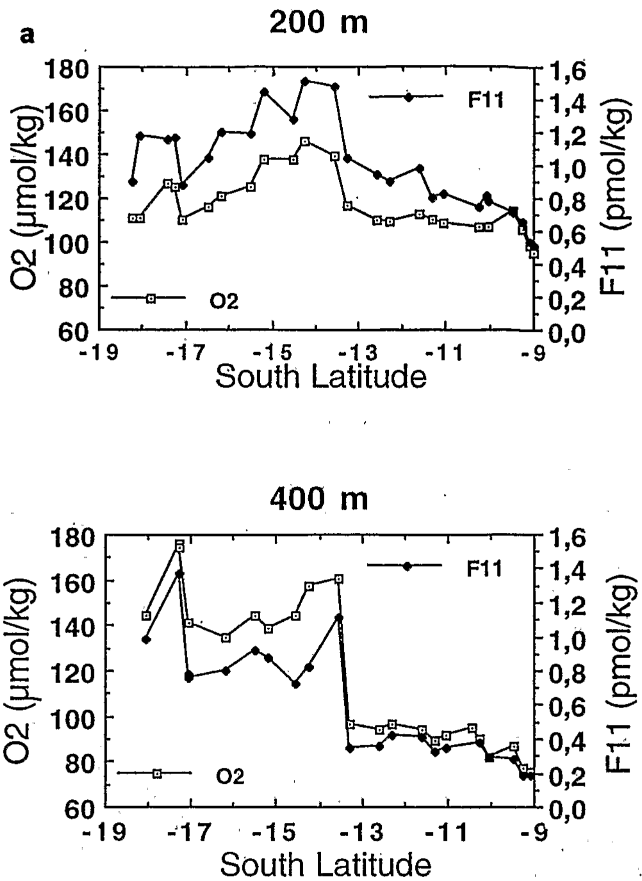

Figure 8. Variation along the Australia-Bali section of oxygen and CFC-11 contents at (a) the 200 m level and (b) the 400 m level.

Bali section, which means that the Banda Sea tracer enrichment at depth due to vertical mixing [*Gordon and Fine*, 1996] is still discernable at that level. Between 350 and 600 dbar the waters from the Indonesian channels are mixed, either with CW south of station 19 or with NIIW north of station 21. The levels of the maximum influence of these water masses are shown in Figure 10 by the arrows. It is interesting to note that this level corresponds to a minimum in the flow through Timor Passage [*Molcard et al.*, this issue]. The intermediate salinity minimum, between 900 and 1100 dbar, marks the influence of the northern channel waters, north of station 22; in the south, between 600 and 1100 dbar, where the salinity is very homogeneous, it could be the result of the mixing of IIW with remnants of AIW from the south Indian Ocean.

The effect of the Indonesian Seas on the water masses is quite peculiar; they act as a "mixer." At their entrances on the western Pacific boundary, water masses with different characteristics get driven into the Indonesian archipelago by the pressure gradient between the western Pacific Ocean and the eastern Indian Ocean [*Wyrtki*, 1987; *Ffield and Gordon*, 1992]. At the end of their path through the archipelago, either north or south of Timor, the signatures of the different water masses from the Pacific have disappeared. The mixing in the area is known to be particularly high, due to strong tidal currents that can reach the deepest layers [*Broecker et al.*, 1986; *Van Aken et al.*, 1988; *Murray et al.*, 1990; *Ffield and Gordon*, 1992; *Molcard et al.*, 1994; *Hautala et al.*, this issue] and due to the effect of the winds through upwelling and downwelling, depending on the season [*Van Aken et al.*, 1988]. Then, at the entrance to the Indian Ocean they encounter other water masses coming from the Indian Ocean with higher salinity: the STW and the CW on their southern side and the NIIW on their northern side. They undergo strong mixing, but, nevertheless, they keep a vertically isohaline structure characteristic of the modified Upper and Intermediate

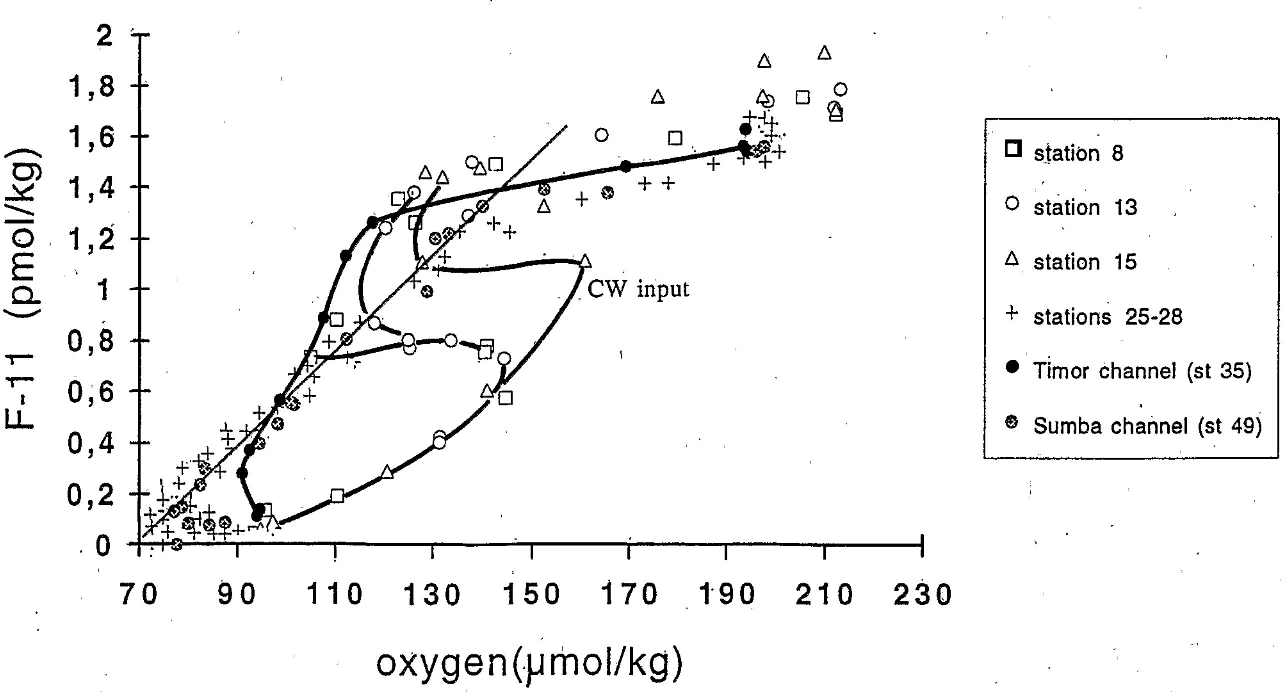

Figure 9. CFC-11/oxygen diagram for stations 8, 13, 15, and 25 to 28 on the Australia-Bali section and for stations in Sumba and Timor Channels.

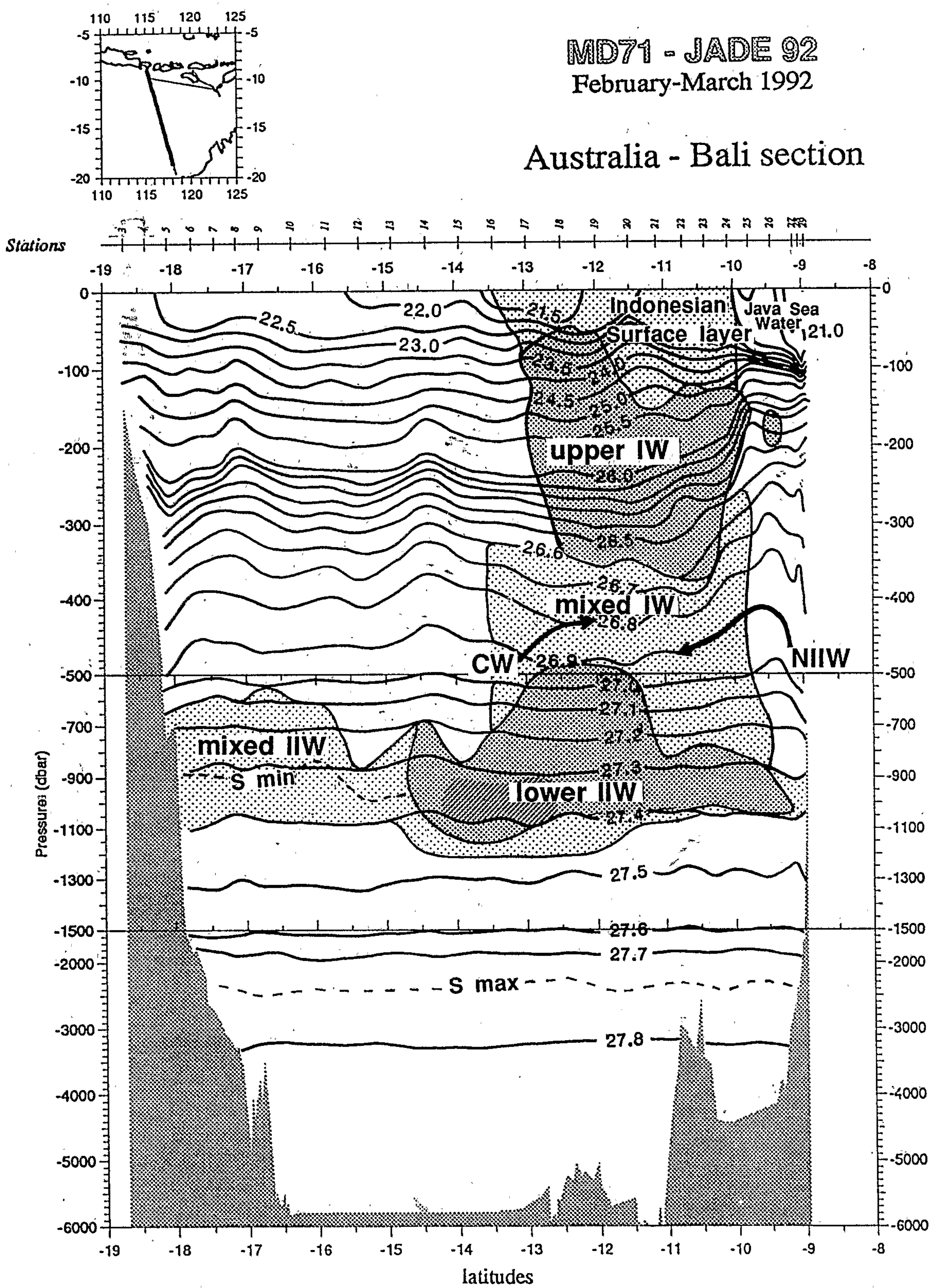

Figure 10. Distribution of the direct impact of the Indonesian waters on the Australia-Bali section. Darker shading represents Indonesian Intermediate Water (IIW) in the lower layer and mixing of the different Indonesian channel waters in the upper layer; the lighter shading represents Indonesian surface layer or, at depth, mixed Indonesian water influenced by South Indian Central Water (CW), North Indian Intermediate Water (NIIW), or Antarctic Intermediate Water (AIW), with nearly homogeneous salinity. It is superimposed on the density anomaly section.

Indonesian Water down to 1100-1300 dbar, which can be followed all across the Indian Ocean, separating the southern and the northern Indian Ocean water masses at those depths.

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