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Hydrography above the Mid-Atlantic Ridge (33°-40°N) and within the Lucky Strike segment

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Abstract. As part of the French-American Ridge Atlantic program the French-American Zero-Angle Photon Spectrometer and Rocks (FAZAR) cruise conducted water column studies between 33 and 40°N along the Mid-Atlantic Ridge (MAR) to detect hydrothermal activity and map its influence. This paper describes the large-scale hydrography within the axial valley, with particular emphasis on the hydrothermally active Lucky Strike segment (37°17'N). The FAZAR study area is affected by the presence of the Azores Current and Mediterranean Water (MW). Although the MW core has been mapped as far north as 50°N off the ridge, the northern boundary of the MW within the MAR in the FAZAR study area exists as a strong front south of the Azores platform. This front is most likely caused by the shallower ridge crest becoming a physical barrier to the MW. The Lucky Strike segment lies within this front and, as a result, has complicated hydrography which can obscure hydrothermal temperature and salinity anomalies.

Introduction

The French-American Ridge Atlantic (FARA) project was established to study geophysical and geochemical ridge crest processes between 15° and 40°N on the Mid-Atlantic Ridge (MAR). As part of this program, the French-American Zero-Angle Photon Spectrometer and Rocks (FAZAR) cruise in August-October 1992 conducted basalt and water column surveys to examine the relationship among hydrothermal activity, bathymetry, and petrology. A map of the FAZAR study area (33°-42°N) and the water stations is shown in Figure 1. The water-sampling program concentrated on the region south of 40°N, where the ridge was sampled at a frequency of approximately two stations per segment (an average of about 17 km intervals). Additionally, an in-depth water column survey was conducted in the hydrothermally active Lucky Strike region to examine hydrothermal processes on a segment scale.

Hydrothermal activity within Lucky Strike was discovered during the FAZAR cruise [*Klinkhammer et al.*, 1993; *Langmuir et al.*, 1993b] and has since been documented with submersible dives [*Fouquet et al.*, 1994; *Langmuir et al.*, 1993a]. This segment lies between 37°05' and 37°33' N, just north of the French-American Mid-Ocean Undersea Study (FAMOUS) region, and about 400 km southwest of the Azores islands. The ridge valley is about 2200 m deep, reaching depths greater than 2500 m in the northeast section. The most dominant feature of the segment is a large volcano in the middle of the valley, reaching up to 1600 m in depth. This structure is the site of high-temperature venting [*Fouquet et al.*, 1994; *Langmuir et al.*, 1993a]. Discussion of the hydrothermal anomalies from this area is presented elsewhere (C. Wilson et al., Hydrothermal anomalies in the Lucky Strike segment, submitted to *Earth and Planetary Science Letters*, 1995).

Effects of the Mediterranean Water (MW), the Azores Current, and ridge crest topography complicate the hydrography in the FAZAR region. Previous studies of the distribution of MW near the MAR used sections across one portion of the axis [*Joyce*, 1981; *Sy*, 1988] or within a small region of the valley [*Katz*, 1970], which yielded information at just one location along the ridge. The FAZAR data set gives a unique opportunity to study physical characteristics within a 630-km portion of the axial valley of the MAR. In this paper the hydrography from this high-resolution station-spacing data set is presented.

Data Collection and Processing

Water sampling on FAZAR was done with two systems, a conductivity-temperature- depth (CTD) and rosette hydrocast unit from Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), and a sled instrument package designed and constructed at Oregon State University (OSU). The hydrocast system was used primarily during the first leg of the cruise, while the OSU sled system was used for towing operations during the second leg in selected areas where hydrothermal activity had been detected during the first leg.

The OSU sled package consisted of an open framework of stainless steel pipe 0.9 m by 0.9 m by 2.4 m in dimension, capable of being towed at 2-4 km/h. It was equipped with a Sea-Bird Electronics (SBE) 9/11 plus CTD operating at 24 Hz and fitted with modular temperature and conductivity sensors and a Paroscientific digiquartz pressure sensor. Four analog instruments were interfaced with a CTD underwater unit, a Sea Tech transmissometer to measure 660-nm wavelength beam transmission through a 25-cm path, a Chelsea aquatrack MK III fluorometer operating as a nephelometer at 420 nm to measure backscattered light at 90° to the incident light path, a zero angle photon spectrometer (ZAPS) using solid-state chemistry with fluorescence signal detection to measure levels of dissolved Mn [*Klinkhammer*, 1994], and a Simrad Mesotech Systems model 807 echo sounder/altimeter. Results from the ZAPS instrument are presented elsewhere [*Klinkhammer et al.*, 1995]. Water

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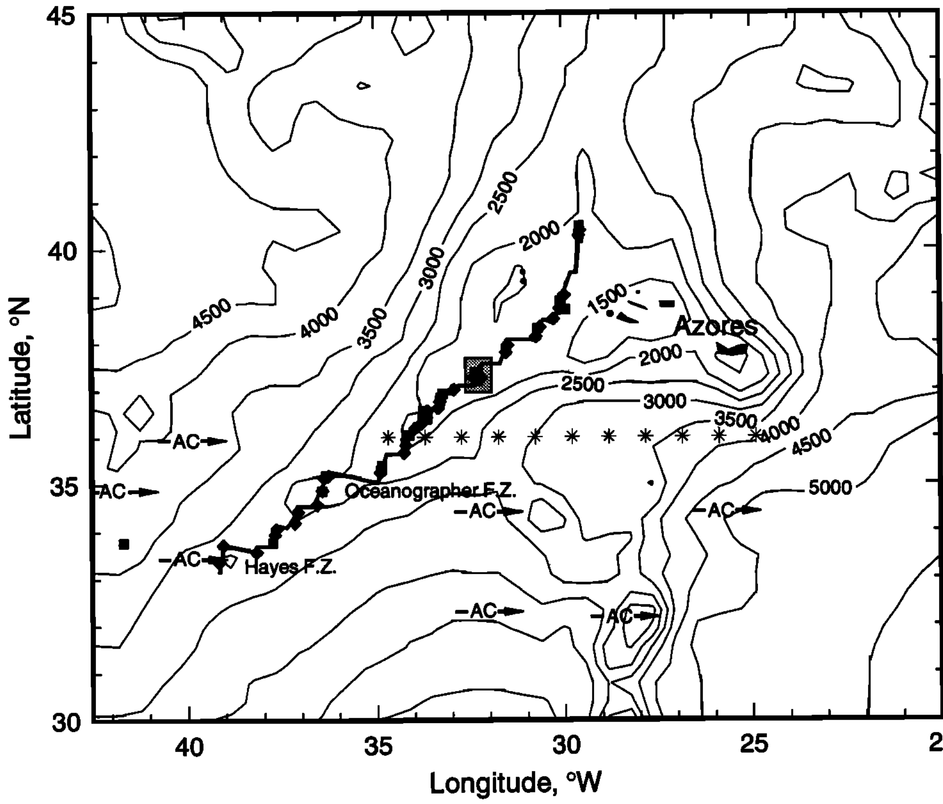

Figure 1. Map of the French-American Zero-Angle Photon Spectrometer and Rocks (FAZAR) cruise study region and the position of water stations. Sled stations are marked with squares, and hydrocasts are indicated with diamonds. The region of the Lucky Strike segment is boxed. The bottom bathymetry is in meters. The thick solid line represents the ridge axis segmentation [*Detrick et al.*, 1995]. Positions of the Azores Current previously described in the literature [*Gould*, 1985; *Harvey and Arhan*, 1988; *Sy*, 1988] are marked AC. The region of the transitional water type described in the text is marked by asterisks. FZ is fracture zone.

sampling on the sled was done with a General Oceanics rosette with six 5-L Niskin bottles. The CTD data and GPS data from a Garmin model number MRN-100 Global Positioning System satellite receiver were interfaced to a computer to create a real-time display of the position and track line of the ship and a calculated position for the sled; for the towed deployments the sled position was to have been based on ship position and the slant distance to the sled. However, owing to the loss of the sled's responder at sea, the ship position was taken for the position of the sled. The IFREMER hydrocast unit had a SBE 9/24-Hz CTD interfaced with a Paroscientific digiquartz pressure sensor, the ZAPS instrument, and a rosette fitted with sixteen 8-L Niskin bottles.

The CTDs had precisions of ±0.002°C for temperature, ±0.003 practical salinity units (psu) for salinity, and ±1 dbar for pressure. The hydrocast and sled CTDs performed similarly. A hydrocast and a sled cast taken at the same location within a few hours of one another produced virtually identical salinity profiles. Both sets of data were compared to and were consistent with data from TOPOGULF, a program which conducted meriodional CTD sections along the east and west flanks of the MAR between 24° and 53°N, as well as several sections normal to the ridge axis [*TOPOGULF Group*, 1986].

Background

A good understanding of the regional background hydrography is necessary to determine the perturbations caused by hydrothermal venting. For instance, differences in deep salinity stratification result in cool, relatively fresh equilibrium plume anomalies in the Atlantic, while Pacific anomalies are warm and salty [*Speer and Rona*, 1989]. Although a great deal of work in the FAZAR region has been done as a result of the TOPOGULF program [*Arhan*, 1987; *Harvey and Arhan*, 1988; *Sy*, 1988], the complicated hydrography in this area is still not well understood. There are two main factors which influence this region. The Azores Current (AC) creates a permanent front southeast of the Azores islands. The Mediterranean Water, a tongue of warm, salty water, exits the Gibraltar sill at 36°N and moves westward across the Atlantic Basin between 700 and 1200 m depth. Water below the MW core has an enhanced salinity down to 2300 m, apparently due to the downward flux of salt through salt fingering (diapycnal mixing) [*Kawase and Sarmiento*, 1986; *Schmitt*, 1981]. This situation is further complicated by the fact that the MW core does not mix uniformly in its eastward extension into the Atlantic. There is a considerable decrease in the intensity of the MW core at the ridge crest [*Katz*, 1970].

The locations of the Azores Current observed in previous studies [*Gould*, 1985; *Harvey and Arhan*, 1988; *Sy*, 1988] are indicated in Figure 1. Although it penetrates to at least 2000 m, the effect of the AC on the movement of MW is uncertain. For example, *Gould* [1985] stated that the AC primarily influences the surface waters (above 400 m) and that the AC does not affect the salinity distribution of the water in or below the MW core.

Gould went on to remark that a separate branch of the AC, the Southeast Azores Current (east of the Azores and outside the FAZAR study area), was a greater barrier for the spread of MW [*Käse and Siedler*, 1982]. TOPOGULF sections along the east and west flanks of the MAR showed the MW core extending south of the AC front [*Harvey and Arhan*, 1988]. However, both these studies examined the AC off-axis from the MAR. A TOPOGULF transect across the MAR indicated that the AC does act as a barrier for the MW [*Sy*, 1988]. In summary, it is likely that the combined effects of the MAR topography and the shear of the AC diminish the strength of the MW core at the MAR.

In areas outside the influence of the Azores Current the strength of the MW salinity core also decreases across the MAR. While the sill depth of the MAR is not shallow enough to be a physical barrier for the MW, the topography is believed to induce intensified vertical mixing at the ridge crest [*Katz*, 1970; *Sy*, 1988]. This decrease in the MW strength at the MAR is evident in several ways. There are sharp isopycnal salinity discontinuities at the ridge axis [*Katz*, 1970]. From the magnitude of these discontinuities, Katz estimated that there is a tenfold increase in the diffusion of the MW salinity core at the ridge crest compared to off-axis. In addition, an overlay of the MW salinity anomaly and bottom topography shows the MW tongue following the topography of the MAR (on the isopycnal σ_θ=27.7, about 1200 m depth) [*Joyce*, 1981, Figure. 2]. The absence of salt fingers, a phenomenon that develops due to the different diffusivities of temperature and salinity, has been cited as another indication of vigorous mechanical mixing occurring at the ridge crest [*Katz*, 1970]. Salt fingers are characteristic of the MW east of the ridge [*Tait and Howe*, 1968; *Zenk*, 1970]. Evidently, enhanced mixing at the ridge crest does not allow enough time for the distinct molecular diffusivities to operate and prevents the development of salt fingers there.

However, the decrease in the strength of the MW does not always coincide with the MAR. In some cases the decrease of the MW strength is manifest less as a front and more as a transitional water type that extends over considerable distances. For example, sections along 36°N taken in 1959 [*Fuglister*, 1960] and in 1981 [*Roemmich and Wunch*, 1985] both had isopycnal salinity discontinuities extending almost 1000 km off-axis from the ridge crest (between 25°and 35°W) [*Arhan*, 1987, Figure 12; *Katz*, 1970, Figure 15]. Salinity along the isopycnal σ_t=27.64 (as shown by *Katz* [1970]) is plotted for both datasets in Figure 2 (top panel). In general, there is a westward decrease of salinity except between 25° and 35°N, where the salinity stays nearly constant at 35.45. As can be seen in Figure 1 (asterisks), the location of this feature spans the entire width of the Azores Platform. The transitional water type is also evident by the broadening of the area between the 35.5 and 35.6 isohalines in the salinity section of the 1981 data set (Figure 2). However, this feature extends farther east (to 20°N) than the isopycnal salinity discontinuity.

Strong temperature inversions are characteristic of the MW core [*Joyce*, 1981; *Katz*, 1970] and are seen throughout the FAZAR region. They are produced by lateral mixing of MW and cooler, fresher, eastern type water [*Katz*, 1970]. The spatial and

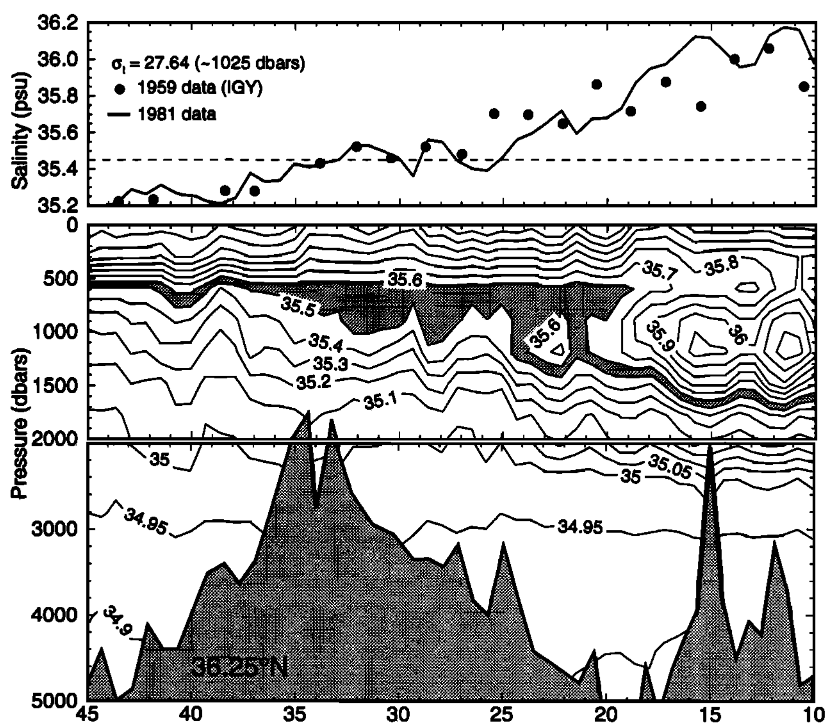

Figure 2. Salinity section along 36.25°N from the 1981 dataset of *Roemmich and Wunsch* [1985]. There is a vertical scale change and a change in the spacing of the salinity isobars at 2000 dbar. The contour line of the isopycnal σ_t=27.64 is shown against salinity for the 1981 data (top), while the circles represent individual data points from the International Geophysical Year data [*Fuglister*, 1960]. The transitional water between 25° and 35°N with a salinity of ~35.45 is seen in both data sets. This water is also seen in the salinity section as the broadening of the area between the 35.5 and 35.6 isohalines (the shaded region, bottom), although this feature extends slightly farther east (to 20°N).

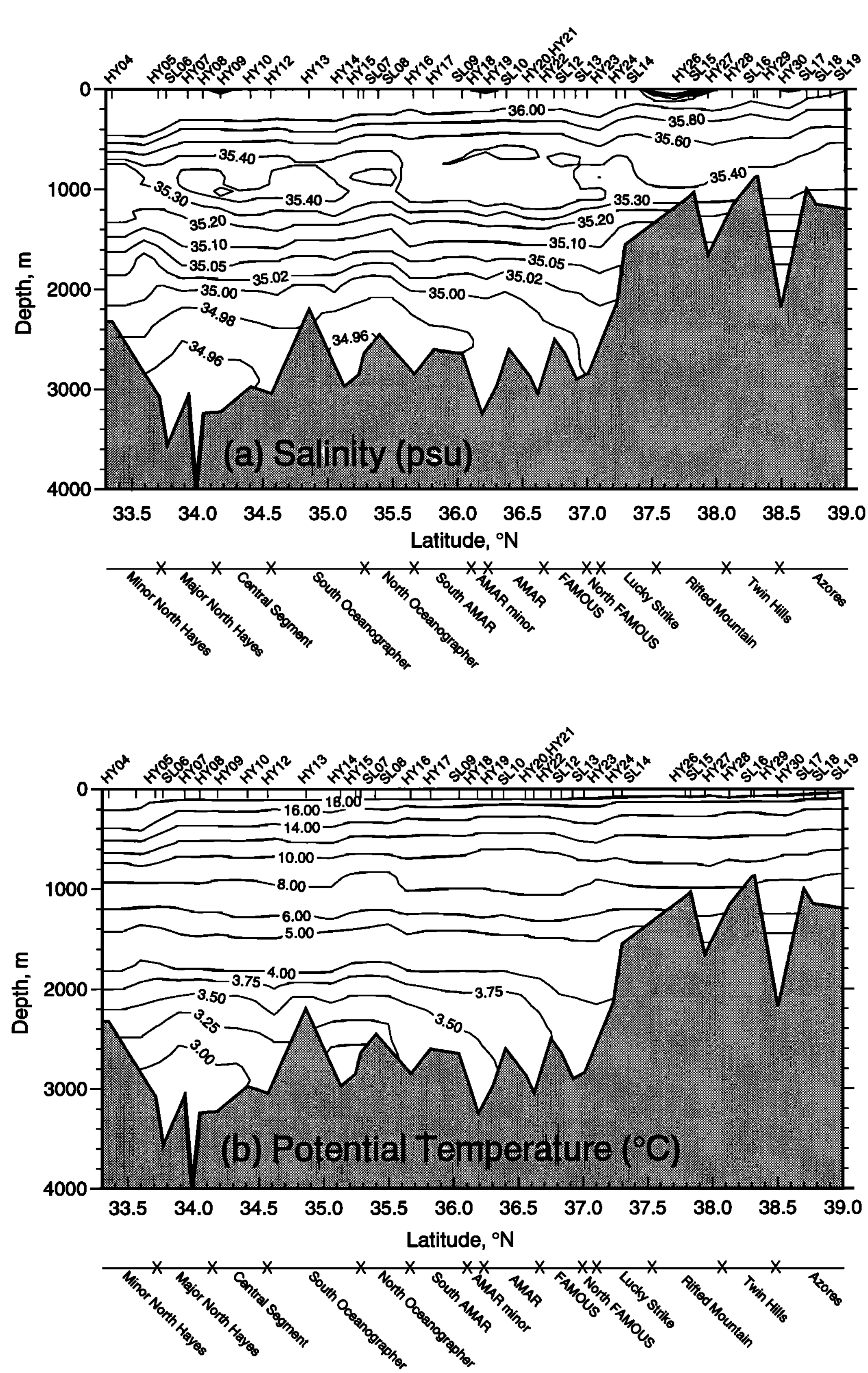

Figure 3. Sections of (a) salinity, in practical salinity units (psu) (b) potential temperature, in degrees Celsius and (c) sigma-θ, in kilograms per cubic meter versus depth, for the FAZAR study region between 33.5°and 39°N. Stations are plotted along latitude, although they follow a line through the axis of the Mid-Atlantic Ridge (MAR). The longitude changes from 39°10'W in the south (hydrocast HY04) to 30°04'W in the north (sled deployment SL19). The boundaries of the ridge segments are shown along the bottom. Station locations are designated by tics across the top.

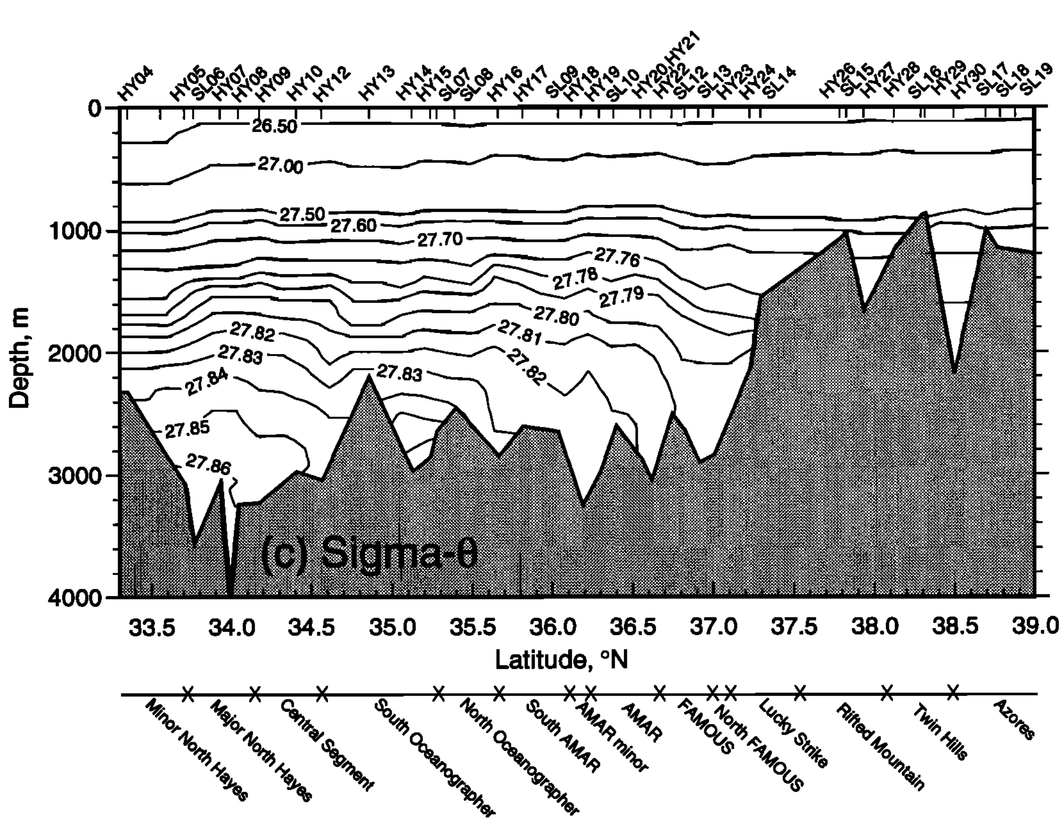

Figure 3. (continued)

temporal scales of these inversions are not known, although one studied at 34°N remained unchanged over a distance of 4 km and 15 hours [*Joyce*, 1981].

Results

Salinity, temperature, and density hydrographic sections for the portion of the MAR that had the highest-resolution station spacing (33.5° to 39°N) are shown in Figure 3. These sections are composed of both hydrocast (HY) and vertical sled deployments (SL) that were taken between September 5 and 18. The bottom shoals to the north as the Azores are approached (see also Figure 1). It is important to note that the bottom topography shown represents the depth within the axial valley. The depth of the valley wall in this region of the MAR generally follows the regional trend of the depth of the axial valley, and the valley wall typically rises up about 1500 m. South of 37°N, the average sill depth is thus around 1500 m, which is below the depth of the MW core. However, north of 37°N, the ridge crest is shallow enough to become a barrier for the MW.

The core of the MW can be seen by the deepening of the 35.40 isohaline on the salinity section at 700-1200 m depth between 34° and 37°N (Figure 3a). MW is also identified on the salinity versus σ_θ section (Figure 4), where it is represented by water more saline than 35.35 psu (denoted by shading). The maximum vertical penetration of the high-salinity water occurs at 36.0°-36.7°N and near 34°W. The use of the S = 35.35 psu isohaline to identify the MW is consistent with previous work [*Katz*, 1970]. Using the International Geophysical Year (IGY) data, Katz defined salinities less than 35.3 psu as western type water along the isopycnal $\sigma_\theta = 27.64$. Along the same surface he defined the MW as salinities greater than 35.5 psu at 40°N and greater than 35.7 psu at 36°N, while a third water mass, a transition type water, existed at 36°N with salinities of around 35.5 psu (see Figure 2). Salinities are shown along the same isopycnal in Figure 5 for comparison. They range from 35.25 to 35.62 psu, representing the presence of both western type water and transition type water, which we call MW here. The lowest values, indicating western type water, are found southwest of the AC in the North Hayes region (<33.7°N) and northeast of the Lucky Strike segment (>37.5°N). Low salinities are also seen in an eddy north of the Oceanographer fracture zone (FZ), which is discussed in more detail in the next section.

The deep influence of the MW can be seen in the waters underlying the MW core as shown by the salinities along the isopycnals $\sigma_\theta = 27.80$ and $\sigma_\theta = 27.83$ in Figure 5. The strongest MW influence occurs south of the Oceanographer FZ along both the $\sigma_\theta = 27.80$ and $\sigma_\theta = 27.83$ isopycnals. Salinity decreases to the north along both isopycnals. The MW influence extends farther south along the deeper isopycnal $\sigma_\theta = 27.83$, and its southern boundary appears to be outside the FAZAR study region. The MW influenced water has clearly shifted south in the deeper water relative to its location in the upper layer (σ_θ=27.64). This shift is consistent with the results of *Arhan* [1987], which indicate a vertical shear in the MW; water above 1200 m moves westward, and the deeper water moves southwestward.

The Azores Current

The Azores Current can be seen on the salinity and temperature sections of Figure 3 as the steplike shoaling of the isohalines and isotherms north of the Hayes FZ. It is evident from Figure 4 as the sharp front at around 34°N, the southern limit of the MW. The location and depth range of the AC (it extends down to at least 1700 m on the isopycnal $\sigma_\theta = 27.80$) are consistent with previous descriptions of the AC [*Gould*, 1985; *Sy*,

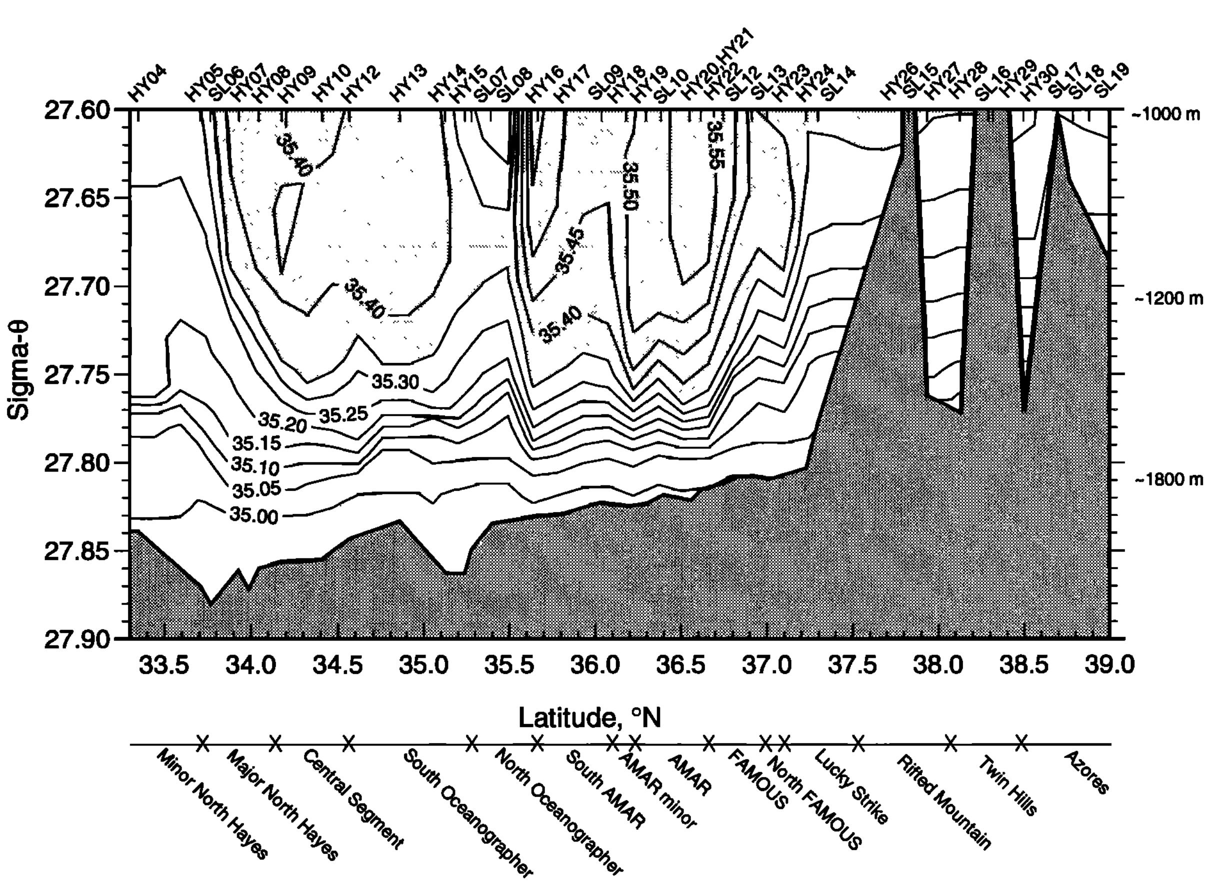

Figure 4. Salinity plotted against sigma-θ section for the FAZAR study region. The top boundary, the isopycnal $\sigma_\theta = 27.6$, corresponds to around 1000 m depth. The shaded region, water saltier than 35.35 psu, represents the Mediterranean Water (MW).

1988]. It is clear from Figure 5 that within the MAR the AC is a barrier for the southeastward spread of MW above 1700 m (the isopycnal $\sigma_\theta = 27.80$), consistent with the findings of *Sy* [1988]. There are sharp salinity gradients at the AC along isopycnals $\sigma_\theta = 27.64$ and $\sigma_\theta = 27.80$ but not along the deeper isopycnal $\sigma_\theta = 27.83$.

The FAZAR data set also reveals a feature, which is most likely an eddy, located north of the AC at the Oceanographer FZ. Here the MW core has been compressed, with fresher water intruding at both the top and bottom of the core. The freshwater intrusion can be seen as an upward doming down to nearly 2000 m. This feature covers an area of around 18 km by 5 km. Meandering of the AC is well documented [*Gould*, 1985; *Käse et al.*, 1985; *Siedler and Emery*, 1985; *Sy*, 1988], and it has been suggested that these meanders develop into westward propagating eddies [*Gould*, 1985]. The feature is most likely an eddy and not a meandering branch of the AC as shown by the isopycnal field (Figure 3c). A current would produce a net increase or decrease in the isopycnal depth which is not evident here. Furthermore, the depth of the 18° isotherm, which has been used as a defining factor for the presence of the AC [*Gould*, 1985], does not change in this area as it does at the AC front.

The Northern MW Front

There is a considerable decrease of the MW salinity within the MAR axial valley between 36.7° and 37.4°N (80 km). This frontlike feature can be seen in the salinity and σ_θ sections (Figures 3a and 3c), but it is more obvious in Figure 4. A large salinity gradient, as much as 0.2 psu over < 25 km, occurs at 36.7°N at about 1300 m depth. This transition is stronger than either the AC front or the MW transitions described by *Joyce* [1981], which had salinity changes of 0.15 psu over 100-150 km. However, the AC front more strongly affects the deep water as shown by the sharp salinity change along the isopycnal $\sigma_\theta = 27.8$ in Figure 5. In contrast, the northern front has little or no effect on the salinities along this isopycnal. The northern MW front seems to be topographically influenced. It occurs 100 km south of the sharp rise in the Azores Platform, and it is most likely the result of the shallower valley walls becoming a barrier to the MW. An important point about this front is that while it is strongest at around 36.8°N, it extends over a wide region that includes the Lucky Strike segment. The deep water within the Lucky Strike segment is fresher on isopycnal surfaces than the bulk of the water in the FAZAR region to the south.

Geostrophic Transport

The geostrophic transport along the FAZAR section (33.5°-39°N) is shown in Figure 6. The net transport is 10 Sv to the east. *Sy* [1988] calculated 31 and 23 Sv of eastward transport in sections east and west of the MAR in larger-scale sections (the east section covered 24°-51.8°N and the west, 24°-46.8°N). The net transport within the FAZAR region in Sy's sections was small. There was 2 Sv to the east in the western section and 4 Sv to the west in the eastern section. However, the magnitudes of the eastward and westward components were much larger within the FAZAR region of these sections. The magnitudes of the individual eastward and westward components were around 40 Sv for the section west of the MAR and around 20 Sv for the

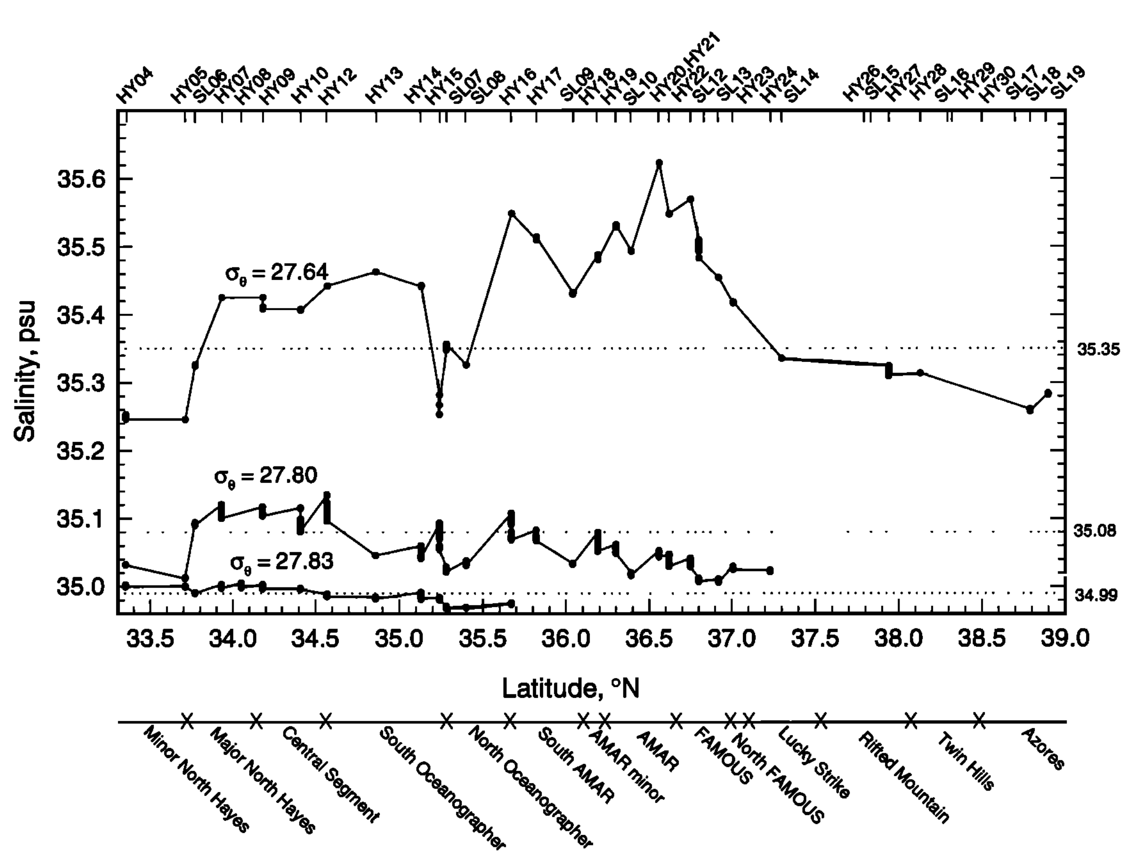

Figure 5. Salinities along three isopycnals, $\sigma_\theta = 27.64$ (around 1015 m), $\sigma_\theta = 27.80$ (around 1700-2000 m), and $\sigma_\theta = 27.83$ (around 2100-2400 m). Salinities above the dashed lines represent water influenced by the Mediterranean Water (MW).

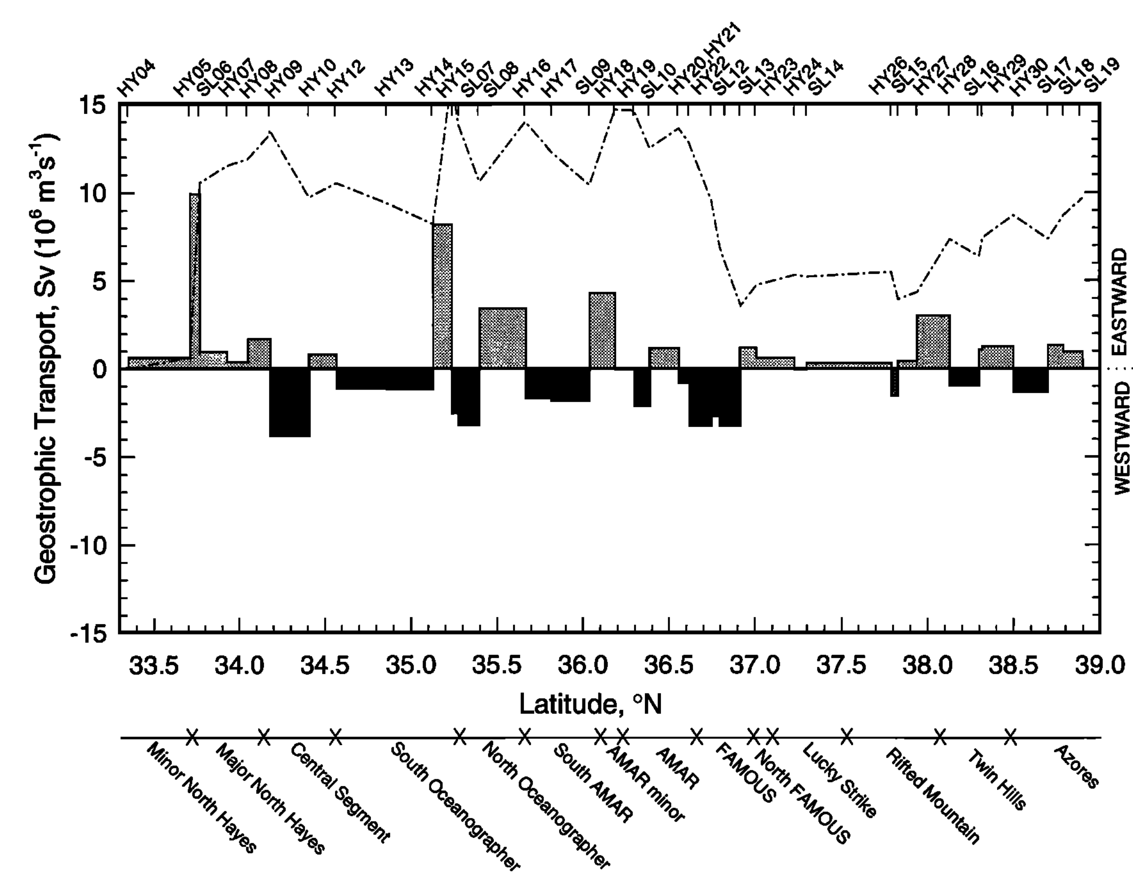

Figure 6. Geostrophic transport in the FAZAR region, calculated using a 2000-m bottom reference and 50-m depth intervals. The cumulative south to north transport is shown by the dash-dotted line.

section east of the MAR. The larger values in the western section are probably the result of the presence of the AC, which was not encompassed in the eastern section.

Strong eastward transport, around 11 Sv, is observed at the AC (Figure 6). This value is consistent with previous calculations of 12 Sv transport across the AC [*Gould*, 1985; *Sy*, 1988]. Although the eastward transport (8 Sv) near the Oceanographer FZ is comparable to the transport of the AC, it is nearly canceled out by the westward flow to the north, and the net transport across this region is not large. This low net transport affirms the interpretation of this feature as an eddy rather than a branch of the AC.

The northern front of the MW coincides with an area of strong westward flow, 11 Sv, between 36.5°-37°N. This apparent current was not evident in the work of *Sy* [1988]. The transport is similar in magnitude to that of the AC. There is a strong correspondence between the cumulative geostrophic transport and the salinity distribution. The region of highest eastward transport in Figure 6 corresponds to the core of the MW as depicted in Figure 4 and on the 27.64 isopycnal in Figure 5.

Temperature and Salinity in the Lucky Strike Region

The potential temperature versus salinity (θ-S) data within the Lucky Strike segment is shown in Figure 7, overlaid with a general scheme of the θ-S diagram from *Sy* [1988, Figure 14b]. Sy's data are from a section which transected the MAR 130 km north of the Lucky Strike segment but did not include any data directly in the axial valley. There are two main differences evident between this off-axis data and the Lucky Strike data. One is in the deep water, below 8°C, where the off-axis data show a clear separation of the western and MW water masses down to around 4.5°C. However, the water masses in the Lucky Strike data set cannot be distinguished below 7.5°C, suggesting that mixing is occurring throughout the water column. Lateral mixing on this scale is consistent with the observation that the Lucky Strike θ-S relation falls right between the deep water of the eastern and western water masses in Figure 7.

The second difference occurs in the waters above 8°C, where two water masses can be distinguished. The saltier data within Lucky Strike lie in the transition between the two off-axis water masses, although they are more clearly in the domain of the western type water. There are no profiles that are clearly MW type only. The freshwater mass (Figure 7, dotted lines) has salinities as low as 35.24 psu. This water is fresher than Sy's salinities off-axis to the west, which are all above 35.28 psu. The difference between the water masses within Lucky Strike is temporally related. The fresher profiles, HY24, HY25, and SL14 (downcast), were taken during the first leg of the cruise, while the other profiles were taken about 3 weeks later. This observation is consistent with the suggestion of *Käse and Zenk* [1987] that strong pulses of both cold subpolar water and MW are common in this region. In summary, the deep water within Lucky Strike appears as an intermediate water type between western type water and MW. The middepth water (700-1000 m, 8°-10°C) is

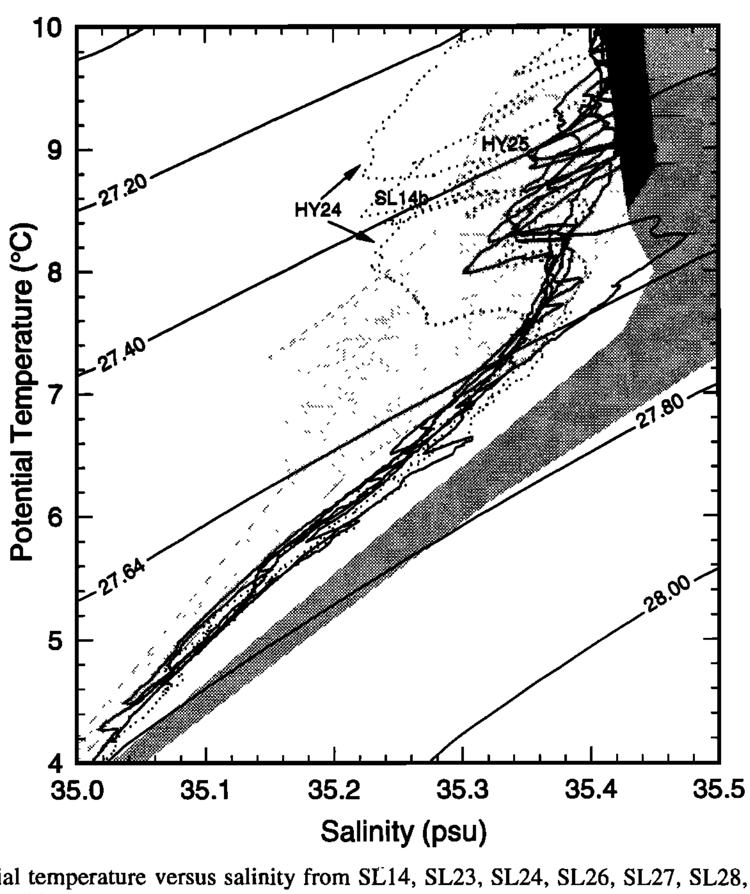

Figure 7. Potential temperature versus salinity from SL14, SL23, SL24, SL26, SL27, SL28, and SL30 and from HY24 and HY25 within the Lucky Strike region. The sled data are the initial vertical downcasts and do not include towed data. A stylized reproduction of the off-axis data presented by *Sy* [1988, Figure 13b] is overlaid on the plot. The darker gray represents water east of the ridge (the MW type water mass), and the lighter gray represents water west of the ridge. Western type water and intermediate type water can be distinguished above 7.5°C. Labeled are the profiles that indicate the most extreme western type water.

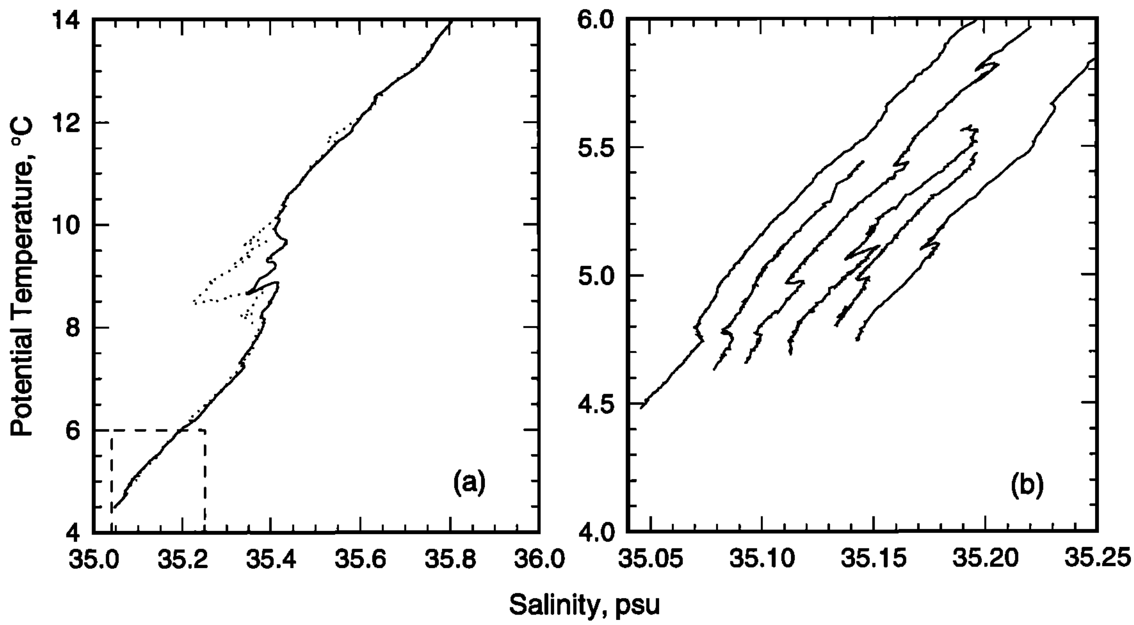

Figure 8. Potential temperature versus salinity from SL14 showing two scales of temperature inversions. (a) The downcast (solid line) and upcast (dotted line) of the tow, which were separated by around 3 hours and 1.5 km. A large temperature inversion is visible in the upcast but not the downcast. (b) The towed profiles, separated by salinity offsets of 0.015 psu.

much more heavily influenced by western type water, although this influence appears to vary in time.

Two scales of temperature inversions are seen within Lucky Strike. The large temperature inversions between 8° and 10°C are similar to ones described in earlier studies [*Joyce*, 1981; *Katz*, 1970]. The θ-S diagram for SL14 (Figure 8a) shows a strong inversion, $\Delta\theta$=0.3°C in 25 m, in the upcast that is not present in the downcast. The upcast and downcast were separated by 3 hours and 1.5 km. The distances and times between downcasts and upcasts for all deployments made within Lucky Strike ranged between 0.1 and 15.5 km and 2.9 and 10.5 hours. Of the eight deployments, only two sets of casts showed a similar structure in the temperature inversions of the downcast and the upcast, and these occurred on the nontowed deployments when the sled remained in approximately the same location. This inversion demonstrates a greater degree of temporal and spatial variability than the study of a temperature inversion by *Joyce* [1981], which showed little change over 15 hours and 4 km. It suggests that the mixing processes within Lucky Strike are more vigorous than during Joyce's study, which was also in a front.

In addition to these large inversions, smaller temperature inversions are seen deeper in the water column. The largest of these are about $\Delta\theta$=0.05°C over 15 m as shown in Figure 8b. Temperature inversions of this scale have also been seen in off-axis regions. For example, temperature inversions are seen down to 2000 m (roughly 4°C) both east and west of the MAR between 25° and 35°W [*Sy*, 1988] and at a background station 240 km west of the MAR taken during the FAZAR cruise. Temperature and salinity variations along isopycnals within the Lucky Strike segment are considerable. The variations are large enough to produce the observed temperature inversions from lateral mixing of water within the segment. Additionally, the observed ranges are larger than typical hydrothermally produced anomalies, which indicates that the likelihood of detecting hydrothermal anomalies from measurements of temperature and salinity alone is small at Lucky Strike.

Conclusions

The FAZAR region is an area of enhanced ridge crest mixing and complicated hydrography due to the interplay of the Azores Current, the MW, and bottom topography. Within the Mid-Atlantic Ridge valley the AC acts as a barrier to the southern spread of deep MW down to 2000 m. The core of the MW lies north of the AC (34°N) and south of a strong front at 36.7-37.4°N. Isopycnal salinities change as much as 0.25 in less than 20 km at the northern boundary of the MW. This front is most likely guided by topography as it occurs just south of the Azores platform which acts as a physical barrier for the MW. If this is true, it would make this front a relatively permanent feature. This result is important for interpreting hydrothermal studies within the Lucky Strike segment. Large ranges of temperature and salinity on isopycnals are present in this segment, as well as temperature inversions produced by lateral mixing on isopycnal surfaces. These combined factors make the detection of hydrothermally produced temperature and salinity anomalies difficult. The use of chemical tracers is needed in this region to fully resolve hydrothermal anomalies.

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References

Arhan, M., On the large scale dynamics of the Mediterranean outflow, *Deep Sea Res., Part A*, *34*, 1187-1208, 1987.

Detrick, R. S., H. D. Needham, and V. Renard, Gravity anomalies and crustal thickness variations along the Mid-Atlantic Ridge between 33°N and 40°N, *J. Geophys. Res.*, *100*, 3767-3787, 1995.

Fouquet, Y., J.-L. Charlou, J.-P. Donval, J. Radford-Knoery, H. Pellé, H. Ondréas, M. Ségonzac, I. Costa, N. Lourenço, and M. K. Tivey, Geological setting and comparison of the Menez Gwen and the Lucky Strike vent fields at 37°17'N and 37°50'N on the Mid-Atlantic Ridge. Preliminary results of the DIVA1 Diving Program (abstract), *Eos Trans. AGU*, *75 (44), Fall Meet. suppl.*, 313, 1994.

Fuglister, F. C., *Atlantic Ocean Atlas of Temperature and Salinity Profiles and Data From the International Geophysical Year of 1957-1958, Woods Hole Oceanogr. Inst. Atlas Ser.*, Vol. 1, 209 pp., Woods Hole Oceanogr. Inst., Woods Hole, Mass., 1960.

Gould, W. J., Physical oceanography of the Azores Front, *Prog. Oceanog.*, *14*, 167-190, 1985.

Harvey, J., and M. Arhan, The water masses of the Central North Atlantic in 1983-84, *J. Phys. Oceanogr.*, *18*, 1855-1875, 1988.

Joyce, T. M., The influence of the Mid-Atlantic Ridge upon the circulation and dynamics of the Mediterrenean Water southeast of the Azores, *J. Mar. Res.*, *39*, 31-52, 1981.

Käse, R. H., and G. Siedler, Meandering of the subtropical front southeast of the Azores, *Nature*, *300*, 245-246, 1982.

Käse, R. H., and W. Zenk, Reconstructed Mediterranean salt lens trajectories, *J. Phys. Oceanogr.*, *17*, 158-163, 1987.

Käse, R. H., W. Zenk, T. B. Sanford, and W. Hillard, Currents, fronts and eddy fluxes in the Canary Basin, *Prog. Oceanogr.*, *14*, 231-257, 1985.

Katz, E. J., Diffusion of the core of Mediterranean Water above the Mid-Atlantic Ridge, *Deep Sea Res.*, *17*, 611-625, 1970.

Kawase, M., and J. L. Sarmiento, Circulation and nutrients in middepth Atlantic waters, *J. Geophys. Res.*, *91*, 9749-9770, 1986.

Klinkhammer, G. P., Fiber optic spectometers for in-situ measurements in the oceans: The ZAPS probe, *Mar. Chem.*, *47*, 13-20, 1994.

Klinkhammer, G. P., C. S. Chin, and C. Wilson, Surveys of the FARA section of the MAR for hydrothermal activity during FAZAR (abstract), *Eos Trans. AGU*, *74 (16) Spring Meet. suppl.*, 380, 1993.

Klinkhammer, G. P., C. S. Chin, C. Wilson, and C. R. German, Venting from the Mid-Atlantic Ridge at 37°17'N: The Lucky Strike Hydrothermal site, in *Hydrothermal Vents and Processes*, edited by L. M. Parson, C. L. Walker and D. R. Dixon, 87-96 pp., Geol. Soc. Spec. Publ. 87, London, 1995.

Langmuir, C. H., et al., Geological setting and characteristics of the Lucky Strike vent field at 37°17'N on the Mid-Atlantic Ridge (abstract), *Eos Trans. AGU*, *74 (43), Fall Meet. suppl.*, 99, 1993a.

Langmuir, C. H., et al., Rock and water sampling of the Mid-Atlantic Ridge from 32-41°N: Objectives and a new vent site (abstract), *Eos Trans. AGU*, *74 (16), Spring Meet. suppl.*, 380, 1993b.

Roemmich, D., and C. Wunch, Two transatlantic sections: Meridional circulation and heat flux in the subtropical North Atlantic Ocean, *Deep Sea Res., Part A*, *32*, 619-664, 1985.

Schmitt, R. W., Form of the temperature-salinity relationship in the central water: Evidence for double-diffusive mixing, *J. Phys. Oceanogr.*, *11*, 1015-1026, 1981.

Siedler, G., and J. Emery, Strong current events related to a subtropical front in the Northeast Atlantic, *J. Phys. Oceanogr.*, *15*, 885-897, 1985.

Speer, K. G., and P. A. Rona, A model of an Atlantic and Pacific hydrothermal plume, *J. Geophys. Res.*, *94*, 6213-6220, 1989.

Sy, A., Investigation of large-scale patterns in the central North Atlantic: The North Atlantic Current, the Azores Current, and the Mediterranean Water plume in the area of the Mid-Atlantic Ridge, *Deep Sea Res., Part A*, *39*, 31-52, 1988.

Tait, R. I., and M. R. Howe, Some observations on thermohaline stratification in the deep ocean, *Deep Sea Res.*, *15*, 275-280, 1968.

TOPOGULF Group, TOPOGULF- A joint programme initiated by IFREMER, Brest and IfM, Kiel, Vol 1, *Data report 154*, 183 pp., Berichte aus dem Institut für Meereskunde, Kiel, Germany, 1986.

Zenk, W., On the temperature and salinity of the Mediterranean Water plume in the northeast Atlantic, *Deep Sea Res., Part A*, *17*, 627-631, 1970.

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